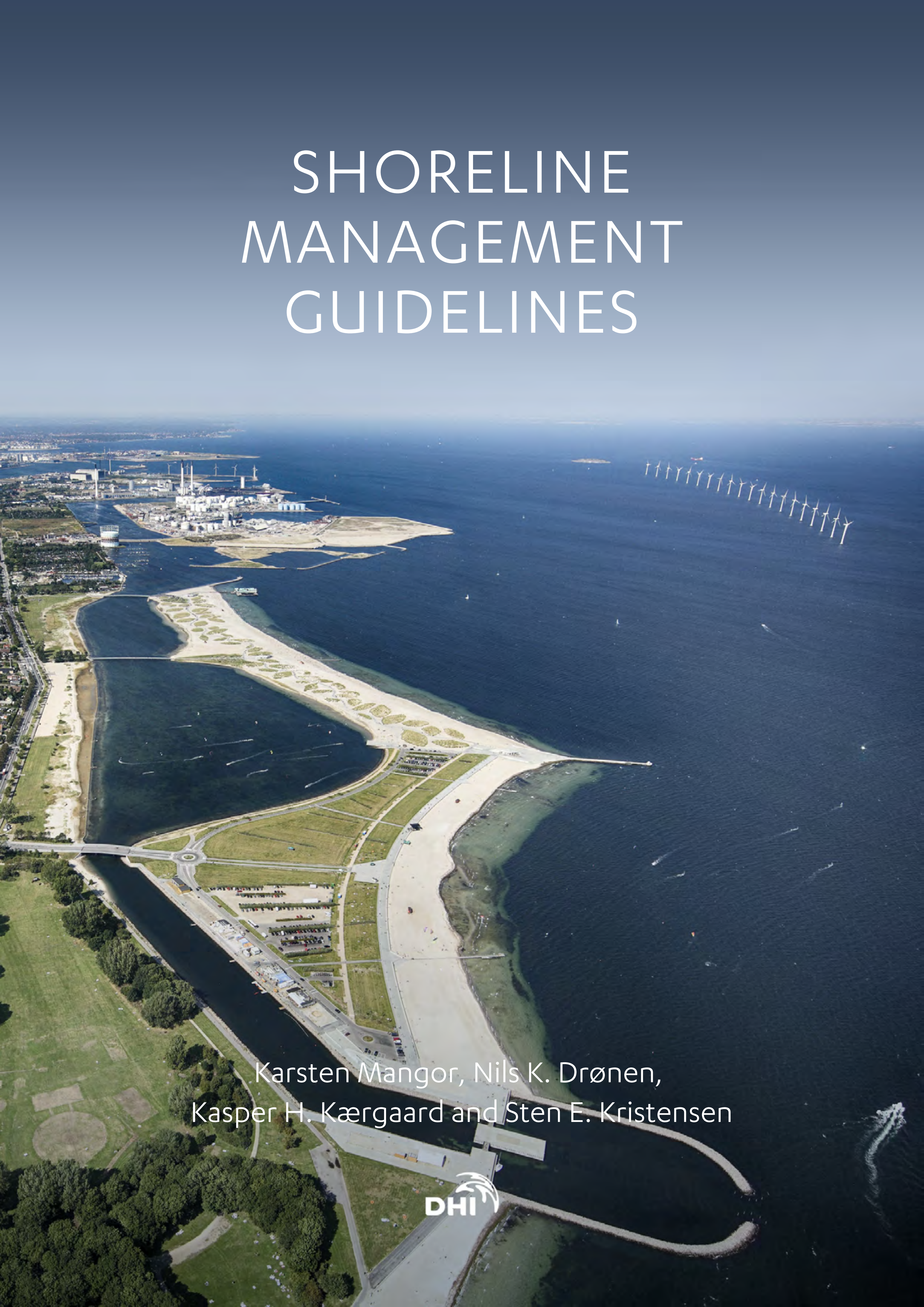
SHORELINE MANAGEMENT GUIDELINES



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Amager Beach Park, August 2009, courtesy of Jan Kofod Winther

Preface

The Shoreline Management Guidelines is a basic handbook on coastal processes and shoreline management presented in common language providing a basic understanding for processes and shoreline management issues, however it is not a design manual for coastal protection. We have attempted to prepare a practical handbook suitable for all stakeholders working with or interested in coastal processes and shoreline management, such as private stakeholders, planners, authorities and engineers providing all parties with a common knowledge base.

The present handbook is the 4th edition of the Shoreline Management Guidelines, which was originally published in 2001. This revision supplements with issues related to effects of climate changes on the coast and how adaptation to these changes is handled in a sustainable and optimal way.

The PIANC publication: “Countries in Transition (CIT): Coastal Erosion Mitigation Guidelines, Report no 123 – 2014” was published in 2014 by a Working Group headed by Karsten Mangor. This publication was heavily inspired by the Shoreline Management Guidelines 2004 but also much new stuff was developed. The present update of the Shoreline Management Guidelines from 2004 is similarly heavily inspired by the PIANC Report no 123 – 2014 but again containing much new information.

The most important climate change parameter related to shoreline management is the expected Sea Level Rise (SLR) but changed pattern of storminess will also have an impact on the coasts.

The SLR has mainly two impacts along our coasts:

- Increasing risk of flooding of low lying coastal areas, which is catastrophic in nature because it may hit large areas with very short notice
- Increasing risk of coastal erosion. However, this will come gradually as the sea level rises

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Hørsholm, Denmark
February 2017

CONTENTS

1 Background

Coastal engineers, planners, administrators, private landowners and politicians should have a common basis as background for planning sustainable human activities along the coasts. In particular the following issues are important:

- coastal processes
- goals for management strategies
- management possibilities and solutions
- adaptation to climate changes

These subjects have been dealt with in numerous textbooks and scientific papers; however these media are not easily accessible to planners, decision-makers and other interested parties, as most of these publications are written and read mainly by researchers. Many of the textbooks are too scientific and too voluminous (and thus time-consuming) for non-specialists to access, and many of the papers are very specialised, either as regards scientific topic or geographical setting. Furthermore, they are published in conference proceedings and journals, which are not - and should not be - standard references for planners and decision-makers.

Most of the required knowledge is therefore only available to specialists. However, the authorities make decisions concerning shoreline management based on their understanding of the subject. Consequently it is the responsibility of scientists and engineers to communicate their knowledge to the public so that it is easily understood.

The recipients of this knowledge are:

- The landowners facing the problems, who often are the main contributor for financing coast protection schemes

- The authorities responsible for planning and approval of shoreline management schemes

- Consulting engineers, who are responsible for designing shoreline management schemes

- The decision-makers, public officers and politicians

Shoreline Management Guidelines aims to fill the gap between the professional coastal scientific community on one side and the above mentioned parties on the other. It offers a relatively short but scientifically correct guide to:

- coastal processes
- holistic management concepts
- environmentally sound shoreline management interventions
- coastal adaptation to climate changes
- up to date investigation methodology

1.1 What are the problems - and how to address them

The problem we face is the accelerating number of conflicts between development on the coast and coastal erosion/coastal flooding; these conflicts are further aggravated by the climate changes. The development pressure on land in combination with the progressing coastal erosion leads to requirements for coast protection, and in many cases subsequent deterioration of our shores. There are many reasons why most coastal regions throughout the world suffer from these problems despite the high level of coastal engineering and the science of coastal processes available today.

Many human activities deprive our shores of a natural supply of sand, such as river regulation works - often far away from the coast – and sand mining in rivers. In addition, the construction of harbours, inlet regulation jetties, maintenance dredging, hard coast protection works and the ongoing Sea Level Rise, all add to the problem. With less sand available our formerly natural and stable sandy beaches will suffer from erosion.

Lack of sustainable planning has, in many cases, permitted urbanisation and infrastructures too close to eroding coastlines, which has aggravated the consequences of chronic erosion. Nowadays, most countries have a legislation, which enforces restrictions on construction activities near the coastline and forces project developers to perform impact assessment studies for coastal projects and to implement remedial measures as part of the project if negative impacts are identified. In most cases there is also nature protection legislation, which promotes sustainable development through requirements to re-establishment of recreational beaches and requirements to preservation of natural beaches. The main problem is that there is normally no budget for fulfilling the requirements to re-establishment and preservation of the coastal resources (sandy beaches).

The climate changes are global problems, which will cause a general Sea Level Rise in the future and which will add to coastal erosion and flooding problems.

Many causes of past and present coastal erosion have a long history and a geographically complex background. It is evident that most of these causes *cannot* be removed within the scope of a typical coastal protection project.

The important elements when dealing with coastal erosion and beach restoration problems are:

1. To investigate the causes of the problem
2. To define the goals for the shoreline management project and to resolve conflicting interests. This phase can also be described as *definition and acceptance of the shoreline management strategy for the project area*
3. To define the financing of the project
4. To engage a qualified group of consultants to assist in achieving the goals of the agreed shoreline management strategy

Coastal engineers' expertise lies especially within items one and four, but items two and three are just as relevant.

This means that:

- coastal engineers must improve their communication and management skills, and
- all other involved parties must improve their basic understanding of the coastal area and of the engineering possibilities

These Guidelines are intended to facilitate this process for the benefit of our valuable shores.

1.2 Some thoughts on Shoreline Management

There is always a delicate balance between the requirements of primary protection against coastal erosion on one hand and protection of the dynamic coastal landscape and sandy shores on the other hand.

Historically, protective measures have been reactive in nature and have concentrated on preventing loss due to coastal erosion. This type of protection has, throughout the world, resulted in loss of the beach and it has had a serious impact on the dynamic coastal landscape. Such protection measures are “coast protection”, not “shore protection”.

1.3 How to read these guidelines

These Guidelines are separated into three parts but the chapters are numbered continuously through the various parts:

- PART 1: Metocean Conditions, Coastal Processes and Coastal Classification,
  Chapters 2 through 9
- PART 2: Guidelines,
  Chapters 10 through 19
- PART 3: Hydraulic Study Methodology as Support for Shoreline Management,
  Chapters 20 through 22
- References and Index are presented in Chapters 23 and 24.

The purpose of Part 1 is to give the reader a basic understanding of the metocean forces acting on the coast and the coastal processes resulting from these forces and how these processes results in coastal changes. Part 1 is opened with a definition of coastal terms to ensure common understanding and meaningful communication and Part 1 is terminated by coastal classification, which is a very useful concept to summarise the status of a coastal section. Part 1 is mainly intended for the interested, non-specialist reader who wants a better understanding of what is happening and why and for the engineer who is venturing into an unfamiliar area and wants an introduction to the subject. The focus is therefore not on the theoretical and numerical side of issues, but on provision of a general understanding of the coastal processes. Practically only very few equations are included in order not to exclude non-scientists from understanding the text. Part 1 should be read from start to finish at least once and can then later be used to look up specific topics or words.

The experienced coastal engineer can skip Part 1 and go directly to Part 2, which contains sections on the following subjects:

- Causes of coastal erosion and coastal flooding including impact of climate changes
- Vulnerability and risk classification for erosion
- Vulnerability and risk classification for coastal flooding
- Planning concepts in the coastal zone
- Coastal projects
- Design philosophy including adaptation to climate changes
- Shore protection, coast protection and sea defence methods with special emphasis on coastal adaptation to climate changes

- Water front development schemes
- Environmental Impact assessment and Morphological Impact Assessment

Part 2 will assist the reader, whether an engineer or a planner, in formulating a suitable strategy for the problem at hand and in selecting realistic solutions. This part can be read from start to finish or used as a reference book.

Part 3 provides guidance in study methodology as support for shoreline management projects divided in data collection and field investigations, numerical modelling and physical modelling

Chapter 23 presents a list of references common for all chapters. In order to make the Guidelines easier to read there are only few references in the text. Chapter 24 presents a subject index.

Results from numerical modelling have been used throughout this book to illustrate coastal processes. The DHI software “MIKE Powered by DHI” has been applied to make these illustrations.

PART 1: Metocean Conditions, Coastal Processes and Coastal Classifications

2 Introduction

The main emphasis of the PART 1 of the Guideline is coasts dominated by loose and consolidated sediments. Consequently the Guideline deals with processes and management of coastal landscapes which are shaped through hydrodynamic forces acting on the coast thereby leading to sediment transport and morphological processes. These processes lead to the formation and development of beaches, cliffs, dunes, sand spits, barrier islands, tidal flats, deltas, tidal inlets, etc.

This PART 1 of the Guideline aims at giving a basic understanding of the metocean forcings and hydrodynamic processes in the coastal area, and how they affect the coastal landscapes. Part 1 contains the following chapters:

Chapter 3: Coastal Terms

Chapter 4: Beach Materials

Chapter 5: Metocean and other Forcings of Importance for Shoreline Management

Chapter 6: Climate Changes

Chapter 7: Transport and Morphological Processes

Chapter 8: Classification of Coastal Profiles

Chapter 9: Classification of Coastlines

3 Coastal Terms

To ensure sound communication it is important to define the coastal terms used in coastal engineering and shoreline management. Therefore, definitions of terms for coastal features, processes and management issues are given in the following, see also the *coastal profile* in Figure 3.1.

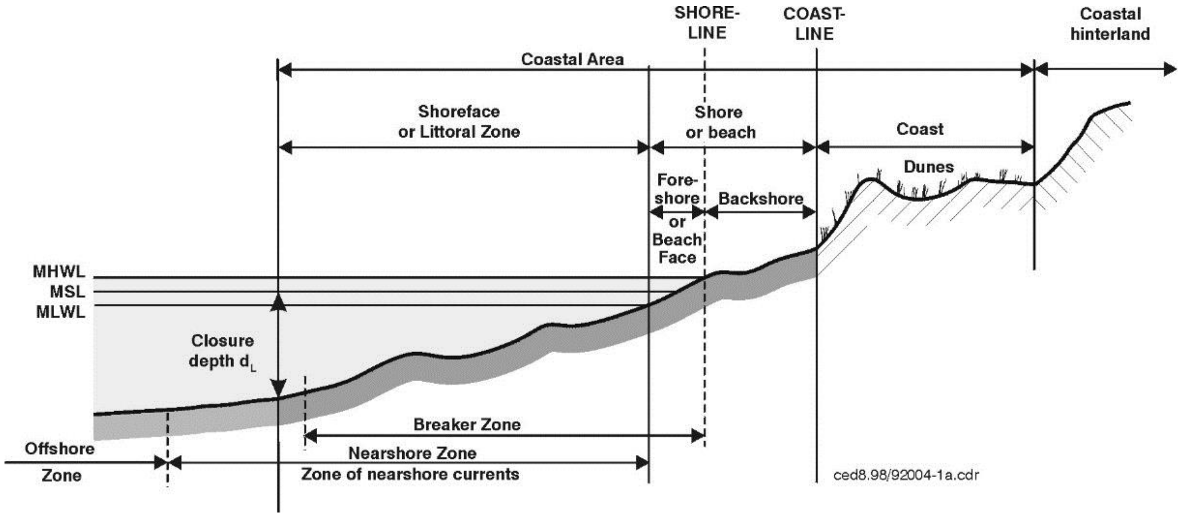


Figure 3.1 Definition of coastal terms, mainly from Shore Protection Manual, 1984.

3.1 Definition of coastal terms

ANGLE OF INCIDENCE (α): The angle between the wave propagation direction and the normal to the coastline or the angle between the wave front and the coastline. The deep water angle of incidence is denoted α_0.

ARMOURING (manmade): Armouring is a structure designed to either prevent erosion of the upland property or protect eligible structures from the effects of coastal wave and current action. Armouring includes certain rigid passive coastal structures such as geotextile bags or tubes, seawalls, revetments, bulkheads, retaining wall or similar structures, but does not include active structures such as jetties, groynes or detached breakwaters, which has the purpose of trapping sand or preventing sedimentation in an inlet, etc.

ARMOURING (natural): Natural armouring occurs in an erosive environment with a graded sediment, where the flow and waves tend to remove the finest grains. The coarser material is then left as a more erosion-resistant residual layer.

BACKSHORE: The part of the beach lying between the foreshore and coastline. The backshore is dry under normal conditions, is often characterised by berms and is without vegetation. The backshore is only exposed to waves under extreme events with high tide and storm surge.

BAR: A submerged shore parallel formation of sand or gravel built in the breaker zone due to the action of breaking waves and cross-currents. There can be several rows of bars. Bars are very mobile formations, which tend to be in dynamic equilibrium with the presently occurring wave and tide conditions, which means that they are constantly changing. The overall tendency is that the bars are moving seawards during storm wave conditions and landwards during conditions dominated by smaller waves and swell. At intervals there are gaps in the bars formed by the rip currents, see under: Rip currents.

BEACH or SHORE: The zone of unconsolidated material that extends from the mean low water line to the place where there is a marked change in material or physiographic form, or to the line of permanent vegetation (the effective limit of storm waves and storm surge), i.e. to the coastline. The beach or shore can be divided in the foreshore and the backshore.

BEACH BERM: A nearly horizontal shore parallel berm formed on the beach due to the landward transport of the coarsest fraction of the beach material by the wave uprush. There may be several beach berms and in some cases no berms. Under normal conditions a beach berm is formed on the upper part of the foreshore, and over the backshore during severe events. During dry periods berms are often formed across openings to minor streams and lagoons, such blocking are also referred to as bar formations.

BEACH FILL: The supply of beach sand for the construction of an artificial beach.

BEACH NOURISHMENT: Means the maintenance of an eroding beach by supplying of new beach sand. The nourished sand will consequently also be eroded as the nourishment does not make the beach stable. This means that regular maintenance is normally required.

BEACH PARK: A beach park is a scheme which consists of new artificial beaches, stabilising coastal structures and filling/reclamation, which in combination provides new recreational facilities. The artificial beaches shall be exposed to wave action and shall have a stable plan and profile shape.

BEACH QUALITY SAND: Well sorted marine sand that is similar to the native beach sand in both colouration and grain size, and is free from construction debris, stones, clay or other foreign matter.

BEACH RESTORATION: Means the placement of sand on an eroded beach for the purposes of restoring it as a recreational beach, maybe also restoration of coastal structures and providing storm protection for upland properties.

BREAKER-ZONE or SURF-ZONE: There is no clear definition of the breaker-zone, but it can be defined as the zone extending seaward from the shoreline that is exposed to depth-limited breaking waves. The outer limit of the breaker-zone is called the BREAKER-LINE. However, the instantaneous width of the surf-zone varies with the instantaneous wave conditions. In this context we define the surf-zone as the zone valid for the yearly wave climate defined by the significant wave height $H_{S,\ 12\ h/y}$, which is the wave exceeded 12 hours per year. The width of the breaker/surf-zone can thus be defined as the width of the zone within which $H_{S,\ 12\ h/y}$ breaks. The breaker/surf-zone is somewhat narrower than the littoral zone. It is evaluated that 80 to 90% of the yearly littoral transport takes place within the breaker or surf-zone.

CLOSURE DEPTH: The depth beyond which no significant seabed changes take place due to littoral transport processes. The closure depth can thus be defined as the depth at the seaward boundary of the littoral zone. According to (Hallemeyer, 1981) the closure depth can be calculated using the expression:

$$d_l = 2.28 H_{S,12h/y} - 68.5 \frac{H_{S,12h/y}^2}{g T_s^2}$$

where d_l is the closure depth relative to mean low water-level, $H_{S,12\ h/y}$ is the nearshore significant wave height exceeded 12 hours per year, and T_s is the corresponding significant wave period. This definition is valid for "normal" sandy coastal profiles.

COAST: The strip of land that extends from the coastline inland to the first major change in the terrain features, which are not influenced by the coastal processes. The main types of coastal features are dunes, cliffs and low-lying areas, possibly protected by dikes or seawalls.

COASTAL AREA: The land and sea areas bordering the shoreline, i.e. the coast, the beach and the nearshore area.

COASTAL CELL OR SEDIMENT CELL: A section of coastline in which the physical processes are relatively independent of the processes in adjacent cells. A coastal cell is bounded by physical features which exercise a major control on littoral processes, such as rocky headlands, inlets, ports and harbours, and other major coastal/offshore schemes.

(ACUTE) COAST EROSION: Erosion in the coastal profile. This is taking place in the form of scouring in the foot of the cliffs or in the foot of the dunes. Acute coast erosion takes place mainly during strong winds, high waves and high tides and storm surge conditions and also results in coastline retreat. Acute coast erosion is partially a reversible. The rate of erosion is correctly expressed in volume/length/time, e.g. in m^3/m/year, but erosion rate is often used synonymously with coastline retreat, and thus expressed in m/year.

(CHRONIC) COAST EROSION: The process of wearing away material from the coastal profile due to imbalance in the supply and export of material from a certain section. Erosion will take place on the shoreface and on the beach if the littoral drift export is greater than the supply of material to a certain area, this means that the level of the shoreface and of the beach will decrease. Chronic erosion thus occurs when the littoral transport increases in the direction of the net transport or if there is a deficit in supply of sand to the area in question.

COAST PROTECTION/DEFENCE: Three different protection/defence definitions are used as follows:

- COAST PROTECTION: Measures aimed at protecting the coast against coastline retreat, thus protecting housing, infrastructure, the coast and the hinterland from erosion often at the expense of losing the beach and the dynamic coastal landscape. Coast protection often consists of hard structures such as revetments or groynes.
- SHORE PROTECTION: Measures aiming at protecting, preserving or restoring the shore and the dynamic coastal landscape as well as protecting against coastline retreat to the extent possible.
- SEA DEFENCE: Measures aiming at protecting low-lying coast and coastal hinterland against flooding caused by the combined effect of storm surge and extreme astronomical tides. Sea defence often consists of dikes or seawalls of some kind, or in the form of artificial dunes.

COASTAL HINTERLAND: The land that extends landward of the coast and which is not influenced by coastal processes.

COASTAL ZONE: (General, wide planning-oriented characterisation): The interface between land and sea, delineated as the part of the land affected by its proximity to the sea, and the part of the sea affected by its proximity to the land. Typically with a width of the order 10-100 km.

COASTLINE: Technically the line that forms the boundary between the COAST and the SHORE, i.e. the foot of the cliff or the foot of the dunes. Commonly, the line that forms the boundary between the land and the water.

COASTLINE RETREAT: Coast erosion causes coastline retreat, i.e. landward movement of the coastline.

COASTAL SYSTEM: The morphological active coastal area consisting of the coast (dunes), the beach and the near shore area. The coastal system also encompasses creeks/lagoons and their ebb and flood tide shoals and zones of primary tidal influence.

DEVELOPMENT ACTIVITY: Any activity likely to alter the physical nature of the Coastal Zone in any way including construction of buildings and works, the deposit of waste or other material from outfalls, vessels or by other means, the removal of sand, sea shells, natural vegetation, sea grass and other substances, dredging and filling, land reclamation and mining or drilling for minerals, but excluding fishing activities.

DREDGING: The extraction, by any means, of seabed material in the offshore zone.

DUNE: Ridges or moulds of loose, windblown sand (fine to medium) forming on the backshore and on the coast, and forming the coastal features at certain locations. Dunes are more or less vegetated. Dunes are active coastal form elements subject to fluctuations in configuration and location and constituting a flexible sand reservoir. At eroding coasts they are moving backwards in parallel with the erosion process. Dunes act as a kind of flexible natural protection against erosion and flooding. If the vegetation is damaged by too much traffic or grazing, etc. the integrity of the dunes may be endangered.

EMERGENCY PROTECTION: A quick installation of a temporary revetment-type structure made by available material as response to "unexpected" coastal erosion. It is normally applied for securing buildings or infrastructure against unexpected erosion. It can consist of rock dumping, sand bagging or dumping of other kinds of material easily at hand, such as sand, different kinds of concrete elements, building materials, old tires, etc.

ENVIRONMENTAL IMPACT ASSESSMENT (EIA): A written analysis of the predicted environmental consequences of a proposed development activity, including (i) a description of the avoidable and unavoidable adverse environmental effects; (ii) a description of alternatives to the activity which might be less harmful to the environment, together with the reasons why such alternatives were rejected; and (iii) a description of any required irreversible or irretrievable commitments of resources required by the proposed development activity

EXCAVATION: Any mechanical or manual removal or alteration of consolidated or unconsolidated soil or rock material from or within the nearshore zone, beach and dune system.

FILLING: The deposition, by any means, of material in the coastal area.

FORESHORE or BEACH FACE: The zone between MLW and the seaward berm, which is equivalent to the upper limit of wave uprush at high tide. The latter is identical to the seaward beach berm. The foreshore can be said to be the part of the shore/beach, which is wet due to the varying tide and wave run-up under normal conditions, i.e., excluding the impact of extreme storm waves and storm surge. This means that the foreshore in morphological terms extends further up on the beach than the intersection between the MHW and the coastal profile (MHW line). However, for practical reasons the administrative upper delineation of the foreshore/beachface is defined as the intersection between the MHW line and the coastal profile, which is identical to the definition of the Shoreline.

IMPACTS: Those effects, whether direct or indirect, short-term or long-term, which are expected to occur as a result of human activity, such as construction works or by structures following the construction.

LAND: The area located landward the shoreline, which is identical to the area landward of the MHW line. This means that the land consists of the backshore, the coast and the coastal hinterland. This definition is identical to the one used on international sea charts.

LITTORAL ZONE or SHOREFACE: The active littoral zone off the low water line. This zone extends seaward from the foreshore to some distance beyond the breaker-zone. The littoral zone is the zone in which the littoral processes take place; these are mainly the longshore transport, also referred to as the littoral drift, and the cross-shore transport. The width of the instantaneous littoral zone varies dependent of the wave conditions. In the general context, the littoral zone is defined as the zone corresponding to the yearly wave climate. The width of the littoral zone can thus be defined as the width of the transport zone for the significant wave height, which is exceeded on average 12 hours per year, $H_{S,12\ h/y}$.

LITTORAL TRANSPORT: Littoral transport is the term used for the transport of non-cohesive sediments, i.e. mainly sand, along the foreshore and the shoreface due to the action of the breaking waves and the longshore current. The littoral transport is also called the longshore transport or the littoral drift.

LONGSHORE CURRENT or NEARSHORE CURRENT: The longshore current is the dominating current in the nearshore zone, it is running parallel to the shore. The longshore current is generated by the shore-parallel component of the stresses associated with the breaking process for obliquely incoming waves, the so-called radiation stresses, and by the surplus water which is carried across the breaker-zone towards the coastline.

MEAN TIDAL RANGE: The difference in height between mean high water and mean low water.

MITIGATION: An action or series of actions which will eliminate impacts caused by a proposed or existing coastal activity, typically the construction of a coastal structure, a port or port expansion.

MANAGEMENT UNIT: A management unit is a length of shoreline with coherent characteristics in terms of both natural coastal processes and land use. The MU is used as boundary for Shoreline Master Plans.

NEARSHORE ZONE: The zone extending seaward from the low water line well beyond the breaker-zone; it defines the area influenced by the nearshore currents. The nearshore zone extends somewhat further seawards than the littoral zone.

OFFSHORE ZONE: The offshore zone is not well defined. In relation to beach terminology, it is thus not clear if it starts from the littoral zone, from the breaking or from the nearshore zone. In the present context, the offshore zone is defined as the zone off the nearshore zone.

RECLAMATION: The deployment of material into the sea for building up new land.

RIP CURRENTS: At certain intervals along the shoreline, the longshore current can form a rip current. It is a local current directed away from the shore, bringing the surplus water carried over the bars in the breaking process, back into deep water. The rip opening (also known as rip channel) in a bar will often form the lowest section of the coastal profile, the location of the rip opening can often be recognised by less breaking than at adjacent stretches; a local setback in the shoreline is often seen opposite the rip opening. The rip opening travels slowly downstream.

SEA: The open coastal waters located seawards of the shoreline. The seawater is saline. This definition is identical with the definition of the sea in most nautical maps. The sea extends into major bays, but not into channels, creeks, rivers, estuaries and lagoons. These internal waters are characterised by often having brackish to fresh water.

SEA DEFENCE: See COAST PROTECTION/DEFENCE

SEA LEVEL RISE: The so-called greenhouse effect or global warming may cause a Sea Level Rise, which will have a great impact on the long-term coastal morphology. The possible and gradual Sea Level Rise will cause a general shoreline retreat and an increased flooding risk and has to be handled according to the local conditions.

SETBACK AREA: A strip along the coastal zone, where certain development activities are prohibited or significantly restricted.

SHORE PROTECTION: See COAST PROTECTION/DEFENCE

SHOREFACE: See LITTORAL ZONE

SHORELINE: The intersection between the mean high water line and the shore. The line delineating the shoreline on Nautical Charts (Sea Maps) approximates this Mean High Water Line.

The shoreline is not easy to identify in the nature in contrast to the coastline, which is based on a clear morphological shift between the shore and the coast.

SHORELINE CHANGE RATE: The average annual horizontal shift of the shoreline, based on recorded historical measurements. Future shoreline change rates can be established by numerical modelling of shoreline evolution.

SHORELINE MANAGEMENT: The act of dealing – in a planned way – with actual and potential coastal erosion and its relation to planned or existing development activities on the coast. The objectives of Shoreline Management are: a) To ensure the development activities in the coastal area follow an overall land use plan and a general environmental policy, b) To ensure the development activities in the coastal area does not contribute to or aggravate erosion, c) To ensure that development activities do not occur in sensitive areas, d) To ensure that erosion control techniques are cost-effective and socially and environmentally acceptable.

SHORELINE NORMAL: A directional reference meaning perpendicular to the shoreline, also referred to as the shoreline orientation.

SHORELINE RETREAT: shore erosion causes the shoreline to retreat.

SHORE PROTECTION: See COAST PROTECTION

STORM SURGE: Is the rise in water-level on an open coast as a result of the combined impact of the wind stress on the water surface causing wind setup, the atmospheric pressure reduction, decreasing water depth and the horizontal boundaries of the adjacent water. The storm surge does not include the effect of the astronomical tide. The storm surge at a location is inversely proportional with the water depth in the offshore area off the shoreline. This means that shores out to deep seas (e.g. The Mediterranean) will only be exposed to relatively small surge whereas shores out to shallow seas (e.g. The North Sea) can be exposed to high surge.

SURF BEAT: Oscillation in the water level on the foreshore due to variations in the wave set-up caused by wave grouping.

TIDAL FLAT: Shallow, often muddy, part of foreshore, which are covered and uncovered by the rise and fall of the tide. As a rule of thumb, a tidal flat normally develops when the relative tidal range RTR, defined as the ratio between the mean spring tidal range and the annual average H_S, is higher than 15.

TIDAL WAVE: The popular expression for an unusually high and destructive water level along a shore resulting from the combined effect of astronomical tide and meteorological surges. The expression 'tidal wave' also includes the influence of the associated waves.

TIDE or ASTRONOMICAL TIDE: The astronomical tide is generated by the rotation of the earth in combination with the varying gravitational impact on the water body of the sun and the moon. These phenomena cause predictable and regular oscillations in the water level, which is referred to as the tide. The astronomical tide at a specific location can be predicted and is published in Tidal Tables.

TSUNAMI: A tsunami is a group of a few waves with a period of tens of minutes, which is generated by sub-sea earthquakes. Tsunami waves are similar to shallow water waves and they travel over the oceans with the phase velocity for shallow water waves: $c_p = (gh)^{1/2}$. Consequently, tsunamis travel very fast in the deep oceans. If the water depth is 5000 m, the speed will be more than 200 m/s or about 800 km/hour. A tsunami is normally not very high in deep water, but when it approaches the coastline, the wave height increases drastically due to shoaling and the wave height can rise to more than 10 m. Tsunamis can therefore be very destructive for coastal communities and coastal facilities.

WAVE GROUPING: Gradual variation in the wave height in a train of waves due to successive groups of higher or lower waves.

WAVE SET-UP: An important phenomenon in the surf-zone hydrodynamics. This is a local elevation in the mean water level on the foreshore, caused by the reduction in wave height through the surf-zone. The wave set-up is proportional to the wave height at breaking. As a rule of thumb, the wave set-up is 20% of the offshore significant wave height. Gradients in wave set-up, e.g. in partly sheltered areas near port entrances, will generate local circulation in the surf-zone towards the sheltered area.

WAVE SWASH or WAVE UP-RUSH: The propagation of the waves onto the beach slope. The swash consists of an onshore phase with decelerating upwards flow (up-rush or swash) and an offshore phase with accelerating downwards flow (down-rush or backwash).

WAVE RUN-UP: The sum of the wave set-up and the wave swash.

4 Beach Materials

The sources of beach material are the landmasses bordering the sea and the rivers, supplying the coastal area with cohesive and non-cohesive materials. In order to fully understand the coastal morphology in a specific area, it is necessary to have some knowledge of the geology of the area and of the sediment supply from the rivers. Other more special factors may influence the characteristics of the coastal area, such as the local flora and fauna as in the cases of coral coastlines and mangrove coastal areas. However, coasts defined by biological systems will receive little attention here.

4.1 Materials supplied by rivers

Materials supplied to the coast by a river will be exposed to the hydrodynamic forces of waves and tides when reaching the coast. The supply of sediments to the coast by a river will result in the formation of a delta if sediments are delivered faster than they are dispersed by waves, tides and the associated currents. For further details on deltas see Subchapter 9.2.1 on Deltas.

Materials supplied to coastal areas by rivers fall roughly into categories defined by the physical characteristics of the sediment being either fine, cohesive sediments or non-cohesive sediments or a mixture of those.

4.1.1 Fine, cohesive sediments

Fine cohesive materials, such as clay and silt, also referred to as mud, are normally kept in suspension by the waves until they settle in deep water. Such materials will consequently not constitute a stable coastal profile in areas exposed to even moderate wave action. In areas with a mild wave climate and fine, cohesive sediments, the coast will typically have a very flat shoreface consisting of mud flats and the coastal hinterland is normally low. There will be no beaches, but the coastline will typically be bordered by mangrove or marsh vegetation. Mangrove coastlines are most common in the tropical rainforest climate belt with much precipitation and mild wind and wave climate. Marshy coastlines are most frequent in temperate climates and are often seen in estuaries and lagoons. An example of a mangrove coast is presented in Figure 4.1.

Figure 4.1 Mangrove coast, Port Klang, west coast of Malaysia, low wave exposure. Left: Overview, Right top: Mangrove, Right bottom: Fishing village on stilts on the mud flat at low tide.

4.1.2 Non-cohesive sediments

The most common non-cohesive material supplied to the coast is sand. When the sand is transported to the coastal area as sediment load from the rivers, its transport mode will change from current-dominated to wave-dominated. The ratio between the amount of material supplied by the river and the littoral transport capacity at the outfall point at the coast is the most important factor for the resulting coastal morphology in the transition zone between the river and the sea.

4.1.2.1 Supply from the river is larger than the littoral drift

The material supplied form a river to the coast will build up a delta If the supply from the river is *larger* than the littoral transport capacity. Delta coastlines will, in principle, accrete; however, if the position of river outlets shift, which is very often the case, very large fluctuations in the local coastlines can be the result.

Regulation of the river flow and sand mining in the rivers may result in a drastic decrease in the supply of material from the river and thereby influence coastal stability. Historically accreting coastlines of the delta will become unstable. An example of this is the erosion of the Nile Delta following the construction of the Aswan Dam as seen in Figure 11.12.

The shorelines in the delta area adjacent to the Pengkalan Datu river mouth in Terengganu, Malaysia also suffer from general erosion due to upstream river regulation works. This river delta is naturally shallow and morphologically dynamic due to seasonal variations in the river flow and in the wave climate. Consequently, the river mouth has been stabilised by regulation works in order to secure the navigation. This has added to the problems along the shoreline as sand accumulates at the upstream side and leeside erosion takes place at the downstream side. This situation is shown in Figure 4.2. The huge combined erosion due to the general erosion caused by the river regulation works and the downstream erosion caused by the river mouth regulation works is evident. This is a typical example of problems associated with river mouths at littoral transport coasts.

Figure 4.2 Example of accretion and erosion in delta area upstream/downstream, respectively, of Pengkalan Datu river mouth regulation works, Terengganu State, Malaysia.

4.1.2.2 Supply from the river is smaller than the littoral drift

The material supplied to the coastal area from a river will be transported along the shoreline at the rate supplied if the supply from the river is *smaller* than the littoral transport capacity, and no delta will be formed.

This will often result in the formation of stable crescent or spiral-shaped beaches in connection with rocky headlands (Figure 4.3). These otherwise stable beaches will also become unstable if the supply of sand decreases for one or the other reason. This phenomenon is discussed further in Chapter 11.2.4.

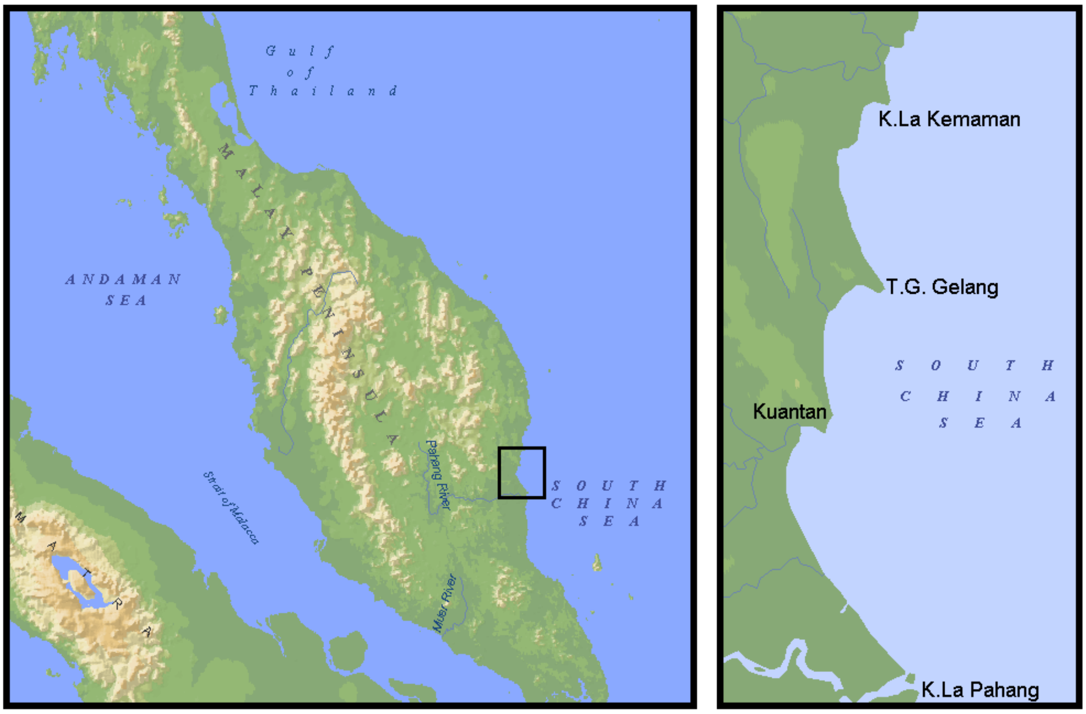


Figure 4.3 Crescent-shaped bays from the southern part of the East Coast of the Malaysian Peninsula.

4.1.3 Mixed supply of cohesive and non-cohesive material

Cases with a supply of both cohesive and non-cohesive sediments are often seen. The sand fraction of the supplied sediments will form sandy beaches adjacent to the river mouth, whereas the fine sediments will be transported beyond the littoral zone, where they will settle on the seabed. The beaches appear sandy, but it is important to be aware of the presence of the suspended fine sediment and the muddy seabed as this may potentially have important implications, e.g. in connection with sedimentation in ports or sea water intakes.

Mixed sediment supply from rivers is often found in tropical climates where the heavy precipitation causes seasonal discharge of mixed sediments from and where the wave climate prevents the fine sediments to settle on the beach. These areas are often dominated by monsoon and trade wind/wave climates, e.g. along the East Coast of the Peninsula Malaysia (monsoon climate) and in the Bight of Benin off the west coast of Africa (trade-generated swell climate).

4.2 Materials supplied by the erosion of the land masses due to wave, storm surge and wind action

The basic geology and landscape formations of the coastal landmasses can be very diverse. These Guidelines concentrate on sedimentary coastlines, which, due to their dynamic state, are the types of coastlines with the most problems. Sedimentary coastlines are, however, found adjacent to or in front of variety of coastal landscapes supplying more or less sediment to the coastline.

Rocky coastlines may support sandy beach stretches between rocky parts of the coastline without supplying much sediment. The hydrodynamic forces erode more easily sedimentary materials from somewhat softer geological formations at the coast such as moraine, till, sandstone and limestone thereby forming a coastal cliff or a bluff. The coastal cliffs further erode by falls, slides, slumps or flows. The cliff erosion is caused by marine erosion at the foot of the cliffs and/or by the slope processes driven by hydrology.

The eroded material supplies material to the littoral zone. When exposed to the hydrodynamic forces on the beach, these materials are sorted and transported. Very coarse materials, such as boulders, are left on the beach and this results in taluses. The medium coarse materials such as shingle or pebble can only be transported on the beach and on the inner shoreface, where they form steep shingle beaches. The finest fraction of the granular materials, the sand, is transported along the shore and shoreface by the littoral transport, and the sand also participates in the onshore/offshore transport processes whereby the sandy beaches and shorefaces are formed. The even finer fractions are washed out into deeper water and are normally not seen on the beaches. A typical cliff of moraine till material is presented in Figure 4.4.

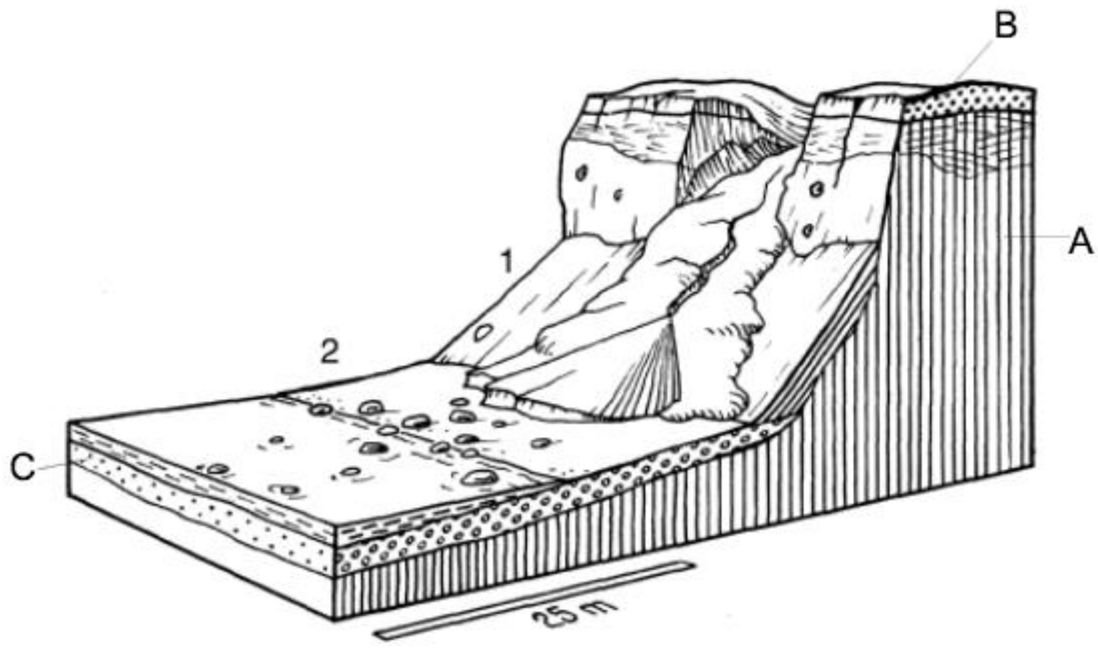


Figure 4.4 Boulder clay or till cliff.
1. Cliff with scees and talus. 2. Beach with boulders.
A. Moraine clay/till. B. Blown sand. C. Marine sediments After A. Schou.

The coast and the coastal hinterland, however, consist in many cases of sedimentary materials themselves. The materials may have been deposited in geological times by processes other than those active today or by the same processes that are active today, just at an earlier stage of morphological development. Present hydrodynamic forces reshape such landscapes more easily than the geological landscapes mentioned above, as they do not have any inherent cohesive or structural resistance against erosion. The most morphologically active coastal landscapes are those formed by sandy deposits.

4.3 Sources of sand for beach nourishment and beach fill

When a beach section is subject to erosion it is often due to one of the following two general imbalances in the local sediment budget:

- Deficit between the longshore supply of sand to the section and loss of sand from the same section (Chronic erosion)

- Offshore loss of sand during exposure to extreme waves and storm surges (Acute erosion)

There can be many specific reasons for the erosion as discussed in Chapter 11. One of the ways to mitigate beach erosion is by beach nourishment with suitable sand to compensate for the deficit, see Chapter 17.6.2 of the Guidelines. It is important to use sand with similar characteristics as the native sand in terms of mineralogy, granulometry and colour for beach nourishment in order to obtain a good result. The best suited sand for nourishment is sand from marine sources or from riverine environments, both of which have been sorted by water processes. Sand from land sources, such as sand from gravel pits, dune sand or desert sand is normally not well suited for nourishment purposes due to some of the following reasons:

- Poor sorting
- Too coarse or too fine
- High content of fines
- High content of coarse material

Similarly, it is also important to use suitable sand for building artificial beaches through beach fill, see requirements in Chapter 18.3.7.

5 Metocean and other Forcings of Importance for Shoreline Management

Wind, waves, and currents in combination with the local water levels are the main driving factors for the development of the coasts. These factors have been summarised as metocean forcings.

The word "metocean" is a composite word made from the words "meteorological" and "ocean", covering physical phenomena such as winds and atmospheric pressure variations, waves, currents and storm surges.

Astronomically generated tide and tidal currents as well as earthquake generated tsunamis are also included in this chapter whereas climate changes are discussed in Chapter 6.

5.1 Wind

The wind and the variations in atmospheric pressure are responsible for the generation of waves, wind set-up and storm surges as well as wind-generated currents. Furthermore, wind has a direct impact on the morphology of coastal areas through Aeolian transport of sand on the beach and in the dunes. Different wind climates will be discussed in this chapter.

Wind is movement of the air as a result of air pressure gradients typically in connection with low or high pressures.

- A region of low pressure (depression) is e.g. generated by local warming up of the earth's surface or regionally at mid-latitudes where warm air from the tropics meets cold air from the Polar Regions. These mid-latitudes depressions usually have well defined warm and cold fronts, as the warm air is forced to rise above the cold air. A wave-shaped distortion may appear on the front, and a low-pressure centre develops at the crest of the wave. A disturbance of this kind is called a wave depression. A typical low pressure storm is presented in Figure 5.1.
- A region of high pressure is e.g. generated by local cooling of the earth's surface

At the earth's surface winds are in principle blowing towards the centre of the low pressure and away from the high pressure centre; however, this general system is influenced by the Coriolis forces (resulting from the rotation of the earth) acting on the moving wind masses. The Coriolis force generates a deviation to the right of moving masses on the northern hemisphere and to the left on the southern hemisphere. This results in the typical air movements on the northern and southern hemisphere as presented in Table 5.1.

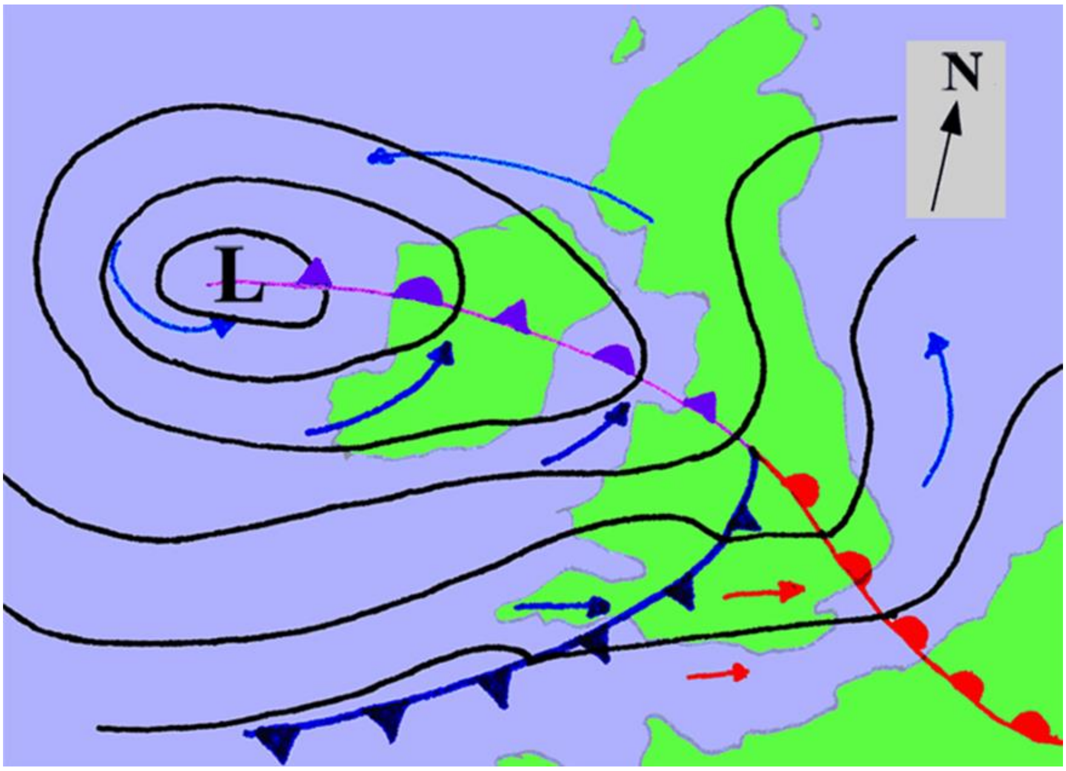


Figure 5.1 A fictitious synoptic chart of a low pressure storm (extratropical cyclone) affecting the UK and Ireland. The blue arrows between isobars indicate the direction of the wind, while the "L" symbol denotes the centre of the "low". Note the occluded, cold and warm frontal boundaries. www.wikipedia.org

Table 5.1 Circulation direction around low pressure (depression) and high pressure areas at northern and southern hemispheres.

Pressure system	Northern hemisphere	Southern hemisphere
Low pressure (Depression)	Counter clockwise	Clockwise
High pressure	Clockwise	Counter clockwise

The circulation around a high pressure and a low pressure on the northern hemisphere is presented in Figure 5.2.

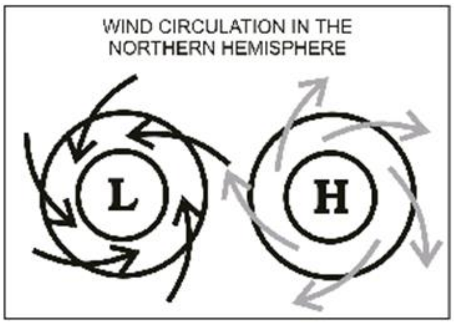


Figure 5.2 Plan view of surface air movement in a system of low and high air pressure at northern hemisphere.

The local wind conditions are a combination of i) large scale atmospheric circulations and ii) local wind fields caused by local pressure conditions and local front systems.

A generalised view on the large scale atmospheric circulations resulting from the temperature distribution is shown in Figure 5.3. The effects of the Coriolis forces can also be seen in Figure 5.3. Typical large scale circulation wind systems are i) the trade winds blowing from NE and SE on the northern and southern hemispheres, respectively, ii) the northern and southern hemisphere westerlies at mid-latitudes and iii) the polar easterlies. These wind systems are separated by the intertropical convergence zone (ITCZ) (Equatorial low), the horse latitudes or subtropical high pressure area at latitudes 30° to 35° N and S, and the polar front (low pressure), all characterised by comparatively low wind velocities.

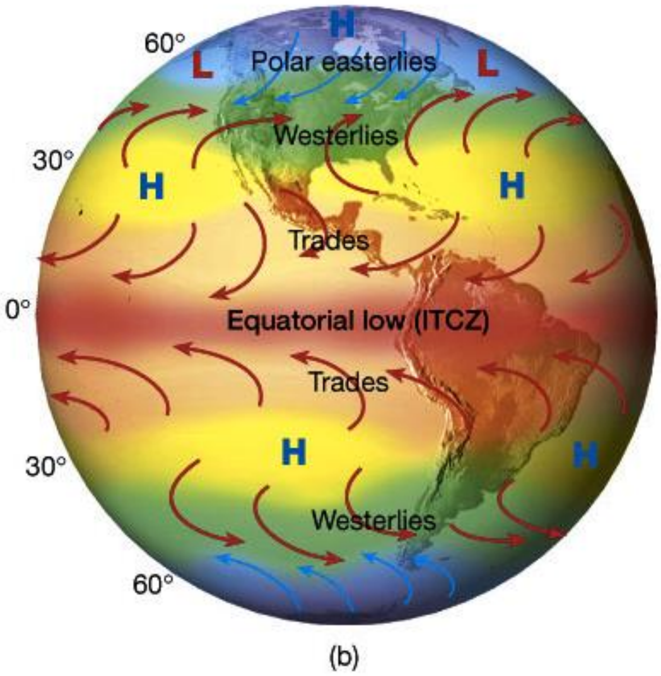


Figure 5.3 Actual wind patterns owing to land mass distribution (Lutgens and Tarbuck, 2001).

Taking into account the tilt of the earth's axis in orbit, the ITCZ will shift north and south during north summer and north winter, respectively. The resulting wind fields are shown in Figure 5.4.

This shift in the wind directions leads to the monsoons or the monsoon wind climate. Monsoons are wind systems that show a pronounced seasonal trend in direction. Well known monsoon climates can be found in India and Southeast Asia. Here, a well pronounced south-west monsoon occurs during the northern hemisphere summer months and the north-east monsoon during the northern hemisphere winter months. Monsoons also affect parts of Africa and South America.

Besides the large scale atmospheric circulations, local pressure differences are influencing the local wind fields, where the wind speed mainly depends on the gradients of the pressure. Low pressure systems are generating extratropical or tropical cyclones.

Tropical cyclones derive their energy from the warm tropical oceans and do not form unless the sea-surface temperature is above 26.5°C, although once formed, they can persist over lower sea-surface temperatures. Tropical cyclones can persist for many days and may follow quite erratic paths. They usually dissipate over land or colder oceans.

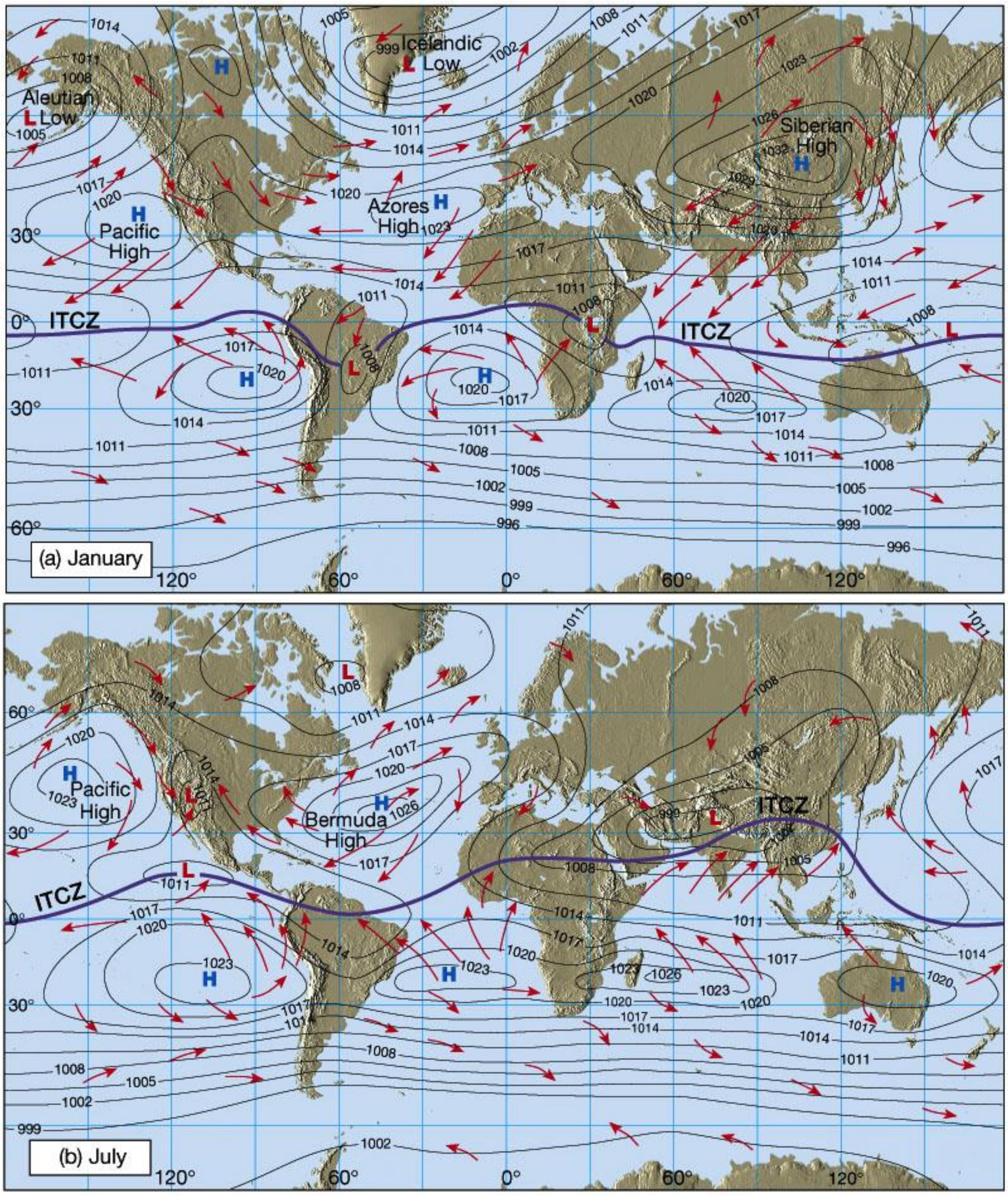


Figure 5.4 A) Southern shift of ITCZ in January.
B) Northern shift of ITCZ in July. (Lutgens and Tarbuck, 2001).

Extratropical storms/cyclones are a type of storm system formed in middle or high latitudes, in regions of large horizontal temperature variations where depressions develop. Extratropical cyclones present a contrast to the more violent cyclones or hurricanes of the tropics, which form in regions of relatively uniform temperatures. Depending on the area, wind speeds for extratropical storms can be 40 m/s or higher.

Tropical cyclones also called cyclones, typhoons or hurricanes are intense storms which arise over warm tropical oceans and are characterised by low atmospheric pressure, high winds, and heavy rainfall. The name used to characterise the tropical cyclone depends on where the weather phenomenon occurs:

- Hurricane: Atlantic and Northeast Pacific
- Typhoon: Northwest Pacific
- Cyclone: South Pacific and Indian Ocean

Formation of the tropical cyclones requires: 1) a pre-existing weather disturbance, 2) warm tropical oceans, i.e. sea temperature above 26.5° C, 3) moisture and 4) relatively light winds. Drawing energy from the sea surface and maintaining its strength as long as it remains over warm water, a tropical cyclone generates winds that exceed ~33 m/s. In extreme cases winds may exceed ~ 67 m/s, and gusts may surpass ~90 m/s. In addition to strong winds, torrential rainfall, and high waves as well as extreme storm surges may occur. Such a combination of high winds, high waves and high storm surges makes cyclones one of the most serious hazards for coastal areas in tropical and subtropical areas of the world. Consequently, tropical cyclones and their associated hazardous storm surges and storm waves constitute a critical impact on coasts in many tropical countries.

Tropical cyclones are normally generated between 5°S to 15°S and between 5°N and 15°N from where they travel northwards and southwards on the northern and southern hemisphere, respectively. However, once formed, they can persist over lower sea-surface temperatures. Tropical cyclones can persist for many days and may follow quite erratic paths. They usually dissipate over land or colder oceans. This means that tropical cyclones cover latitudes south and north of equator from ~30°S to ~5°S and from ~5°N to ~40°N (see Figure 5.5). Cyclones do not penetrate the area between 5°S and 5°N, as wind circulation does not occur so close to the equator due to the absence of the Coriolis force in this area. Note that cyclones do not form in the waters at either side of South America, neither in the southeast Pacific nor in the southwest Atlantic. This is due to too low water temperatures in these waters.

Intensities are internationally defined with the Saffir-Simpson intensity scale (Table 5.2).

Table 5.2 Saffir-Simpson Intensity Scale for Hurricanes/cyclones/typhoons.

Type	Category	Pressure (mb)	Winds (mph)	Winds (kmph)	Surge (meters)
Tropical Depression	TD	-----	< 39	< 62	-----
Tropical Storm	TS	-----	39-73	63-118	-----
Hurricane	1	> 980	74-95	119-153	1.2-1.5
Hurricane	2	965-980	96-110	154-177	1.6-2.4
Hurricane	3	945-965	111-130	178-209	2.5-3.6
Hurricane	4	920-945	131-155	210-250	3.7-5.4
Hurricane	5	< 920	>155	>250	>5.4

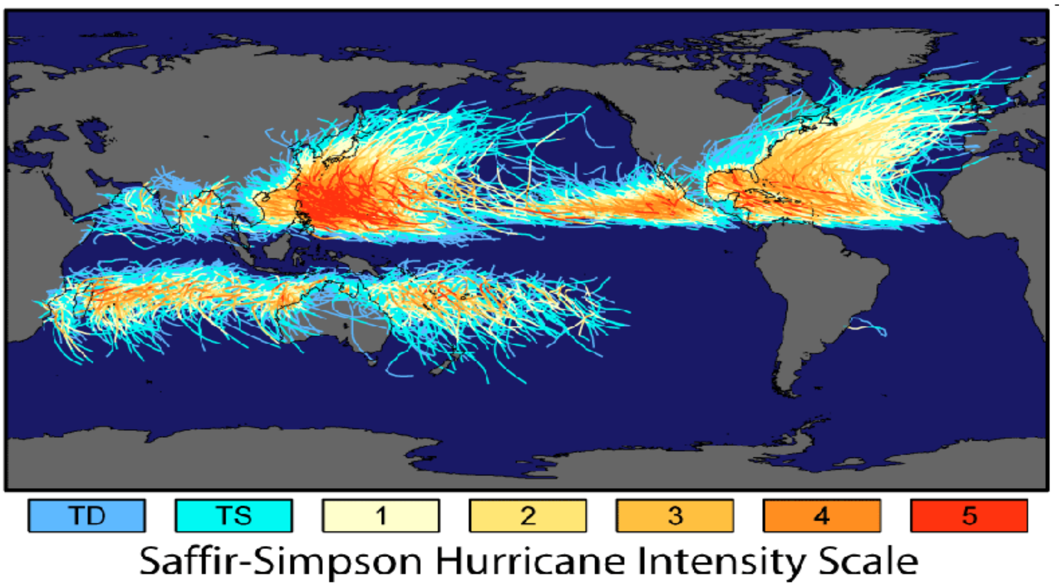


Figure 5.5 Paths and intensity of tropical cyclones.

Recordings of cyclones are normally done by following their tracks via satellite images and classifying their intensity according to a recognised intensity scale while statistical analysis of wind recordings is not a suitable measure because of the limited extent and their rare occurrence at a specific site. The number of cyclones and their intensity in a specific area can e.g. be presented in the form of an exceedance distribution of cyclones of different categories based on analysis of historical data on cyclone tracks and categories as seen in Figure 5.6.

Analysis of return periods for cyclones at a specific site can also be studied on basis of numerical modelling of historical cyclones or on basis of numerical modelling of possible cyclone generation, cyclone categories and cyclone tracks followed by a statistical analysis of the data.

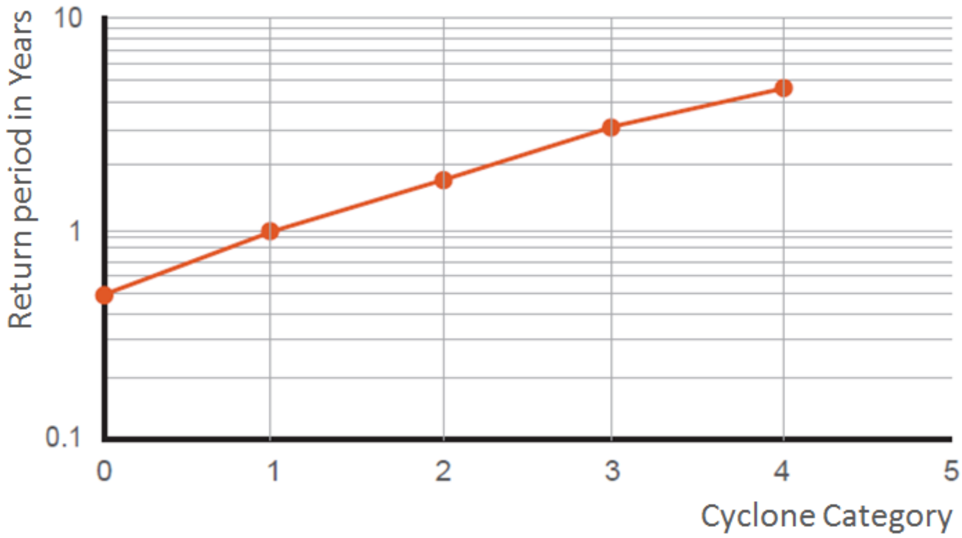


Figure 5.6 Return periods for different cyclone categories for a specific area.

In addition to larger scale events which, in a statistical sense, occur more or less randomly, everybody working in coastal engineering and observing the wave and water level conditions has to be aware of the existence of sea breezes and land breezes with daily period. The sea has a higher capacity of heat absorption and storage than the neighbouring land masses. During daytime the surface of the land warms up faster than the surface of the sea. Warm air over the land is rising and causes a local low pressure area. As a result, we have wind from the sea (sea breeze) with a maximum in the afternoon. During the night, the land masses are cooling down faster than the water masses. If the surface water temperature is higher than the surface temperature of the land, warmer air over the sea is rising and causes a local low. As a consequence, wind from land (land breeze) is blowing during the night with a maximum before sunrise.

Wind information is available as time series or after statistical processing as frequency distribution for many coastal areas worldwide on the basis of measurements and/or numerical models from the responsible weather services. Since the duration of storms and typical situations plays an important role for application in coastal protection, it is advisable to use time series of wind data, if available.

Measured wind data can be compiled using different sources with different aerial and time resolution. Measurements can be based on:

- Ship observations
- Measurement using drifter buoys
- Fixed, near coast sea stations
- Fixed, near coast land stations
- Satellite borne observations

5.2 Waves

Waves are often the most important and decisive parameters for coastal morphology and for coastal engineering structures. The term sea state covers the wind induced sea waves (sea) and the so called swell waves (swell). In oceanography, sea and swell are differentiated using the local wind velocity. Swell is propagating at a speed which is higher than the local wind velocity, and sea is propagating at a speed which is lower than the local wind velocity, respectively. In coastal engineering swell waves are often defined as waves which have been generated by wind fields far away from the actual locations and which have travelled over long distances, consequently swell is not associated with local wind conditions.

It is particularly important to analyse both sea and swell at ocean coasts, where both types are typically present simultaneously. The swell waves are in many cases the most important in the coastal processes during moderate sea states because the swell height increases drastically in the nearshore zone due to shoaling which means that the swell is dominating the wave breaking process. It is difficult to observe the sea states in such combined cases. The swell can hardly be visually observed off the shoreface because of their low steepness but the swell dominates the wave breaking. It is the opposite with the sea waves which are clearly observed off the shoreface because of their greater steepness whereas the sea cannot be observed in the breaking zone. An example of such a combined situation is presented in Figure 5.7, where both sea states can be seen in the satellite image but a visual observer would only be able to observe the sea waves. This is supported by the shoaling diagram in Figure 5.10.

Figure 5.7 Simultaneous sea (monsoon waves from E and swell from S) at Kadua River Mouth, Odissa State, India, January 2010. The swell is dominating the breaking process and the littoral processes. (Picture from Google Earth).

Waves can also be classified in *short waves*, which are waves with periods less than approximately 20 s, see Chapter 5.3, and *long waves* or long period oscillations, which are oscillations with periods between 20-30 s and 40 min, see Chapter 5.4. Water-level oscillations with periods or recurrence intervals larger than around 1 hour, such as astronomical tide and storm surge, are referred to as water-level variations, see Chapter 5.6. The short waves are divided in *wind waves (sea)* and *swell*, whereas long waves are divided into *surf beat*, *harbour resonance*, *seiche* and *tsunamis*.

Natural waves can be viewed as a wave field consisting of a large number of single wave components each characterised by a wave height, a wave period and a propagation direction. Wave fields with many different wave periods and heights are called *irregular*, and wave fields with many wave directions are called *directional*. A wave field can be more or less irregular and more or less directional.

5.3 Short waves

The short waves are the single most important parameter in coastal morphology. Wave conditions vary considerably from site to site, depending mainly on the wind climate and on the type of water area. The short waves are divided into:

Wind waves, also called storm waves, or sea. These are waves generated and influenced by the local wind field. Wind waves are normally relatively steep (high and short) and are often both irregular and directional, for which reason it is difficult to distinguish defined wave fronts. The waves are also referred to as short-crested. Wind waves tend to be destructive for the coastal profile because they generate an offshore (as opposed to onshore) movement of sediments, which results in a generally flat shoreface and a steep foreshore.

Swell are waves, which have been generated by wind fields far away and have travelled long distances over deep water away from the wind field, which generated the waves. Their direction of propagation is thus not necessarily the same as the local wind direction. Swell waves are often relatively long, of moderate height, regular and unidirectional. Swell waves tend to build up the coastal profile to a steep shoreface.

Figure 5.8 Irregular directional storm waves (including white-capping) and regular unidirectional swell.

5.3.1 Wave generation

Wind waves are generated as a result of the action of the wind on the surface of the water. The wave height, wave period, propagation direction and duration of the wave field at a certain location depend on:

- The wind field (speed, direction and duration)
- The fetch of the wind field (meteorological fetch) or of the water area (geographical fetch)
- The water depth over the wave generation area.

The effect of different wind speeds and the resulting wave conditions are illustrated in the photos in Figure 5.9, where the development of the sea from a more or less flat surface to extreme storm conditions is illustrated.

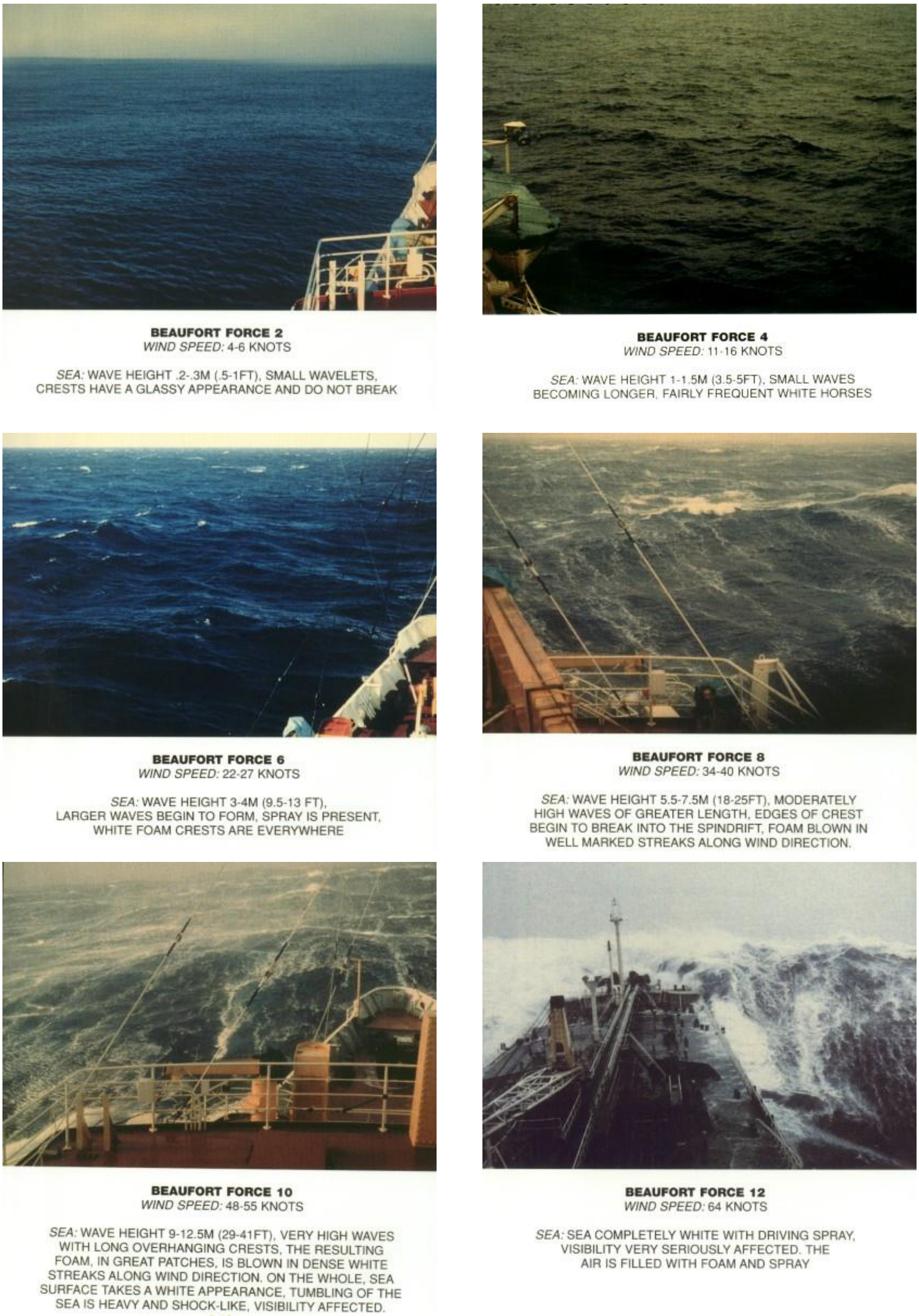


Figure 5.9 Waves at sea. Source: http://www.iklimnet.com/yachting/yachting_beaufort_scale.html

The wave height and the wave period are increasing with the energy input from wind stress and pressure variations until the waves start losing wave energy (energy dissipation) due to white capping effects and wave breaking, and bottom friction in shallow water. In addition, non-linear wave-wave interactions are changing the wave energy within the spectrum. The effects of atmospheric energy input, energy dissipation and non-linear wave wave-interactions are causing an increase of the wave energy until the input and dissipative terms are balanced and, consequently, the wave energy is no longer increasing and the generated waves have reached a state of equilibrium with “fully developed sea”. Besides the limited wind speed, other limiting factors on the development of waves can be a limited duration of the wind (duration limited sea) or length limitations of the fetch (fetch limited sea).

Wave conditions in a specific area can be estimated with four basic concepts, namely i) wave observations, ii) wave measurements, iii) wave forecast/hindcast formulas or diagrams and iv) numerical modelling. The simplest way is the application of wave hindcast diagrams and formulas, where wave heights, wave periods and wave directions can be derived based on the wind-velocity, wind-duration and fetch conditions in the specific area. The SPM (CERC 1984) diagrams for wave hindcast for deep and shallow water are the mostly used diagrams; however, the use of these diagrams has within the last decades been overtaken by the use of numerical models, see PART 3.

Swell is, as previously stated, wind waves generated elsewhere but transformed as they propagate away from the generation area. The dissipation processes, such as wave-breaking, attenuate the short period much more than the long period components. This process acts as a filter, whereby the resulting long-crested swell will consist of relatively long period waves with moderate wave height.

5.3.2 Wave transformation

Waves are transformed as a result of shallow water effects and due to interaction with structures, such as headlands or breakwaters.

The main types of wave transformations are:

Shallow water effects

- Changes of wave conditions with the water-level
- Wave shoaling
- Wave refraction
- Bottom friction
- Wave breaking
- Wave set-up/set-down
- Wave swash or wave uprush
- Wave run-up

Wave structure interaction

- Wave diffraction
- Wave reflection
- Wave transmission, overtopping and mass transport

The various types of wave transformation will be described in the following.

5.3.2.1 Change of wave conditions with water depth

The waves propagate with the wave velocity c.

$$c = L/T$$

Where
L = wave length
T = wave period

The period T of a regular wave is independent of the water depth whereas the wave propagation velocity c and the wave length L decrease with decreasing water depth.

5.3.2.2 Wave shoaling

Wave shoaling causes a change of the local wave height in shallow water as a consequence of the changes of the wave propagation velocity in shallow water. The shoaling coefficient $K_S=H/H_0$ describes the changes of the wave height relative to the deep water wave height as function of the water depth d and the deep water wave length L_0. Applying linear wave theory provides the correlation between K_S and d/L_0 as presented in Figure 5.10.

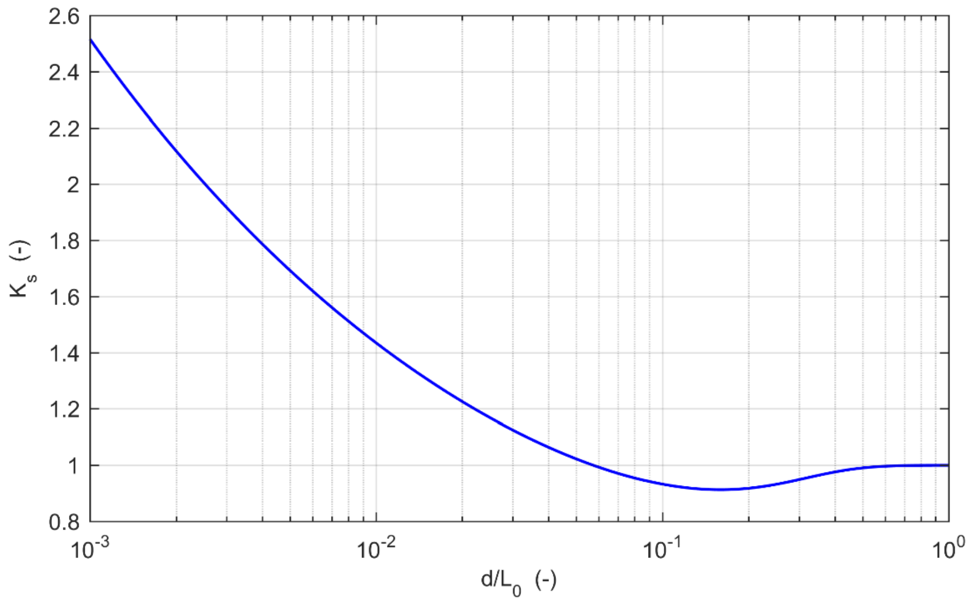


Figure 5.10 Shoaling diagram for linear wave theory.

It is seen that the shoaling changes the wave height when waves propagate from deep water into a water depth which is less than half the wave length. Initially the height is decreasing to about 90% of the deep water wave height, with further decreasing water depth; the wave height is increasing steadily. The process of wave shoaling is physically limited by wave breaking. It is seen that swell waves, which have much longer deep water wave lengths than sea waves, have a much larger KS value in the near shore area than sea waves. The shoaling is illustrated in Figure 5.11.

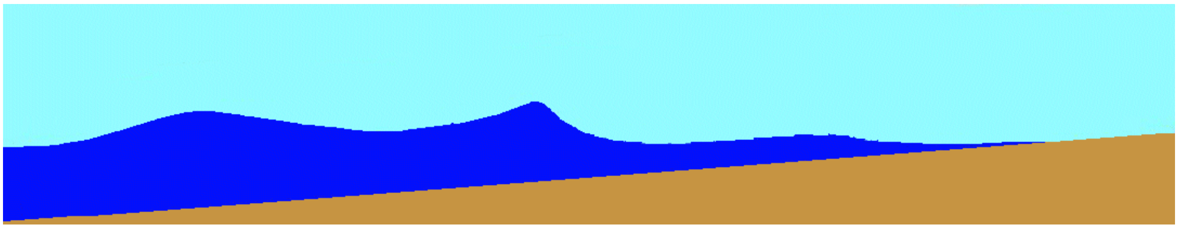


Figure 5.11 Shoaling on the shoreface and breaking on the beach.

5.3.2.3 Wave refraction

Depth-refraction is the turning of the direction of wave propagation when the wave fronts travel at an angle with the depth contours at shallow water. The refraction is caused by the fact that the waves propagate with less velocity in shallow water than in deep water. A consequence of this is that the wave fronts tend to become aligned with the depth contours. A typical wave propagation pattern towards a shore illustrating refraction, shoaling and wave breaking is presented in Figure 5.12. Currents can also result in refraction, so-called current-refraction.

Figure 5.12 Wave refraction, shoaling and breaking.

The associated process of wave energy concentration or spreading causes an increase or decrease of the wave height. The general patterns of the wave propagation due to refraction are shown in Figure 5.13. Wave patterns due to refraction are computed by numerical wave models according to the assumption that the energy flux between two wave rays remains constant.

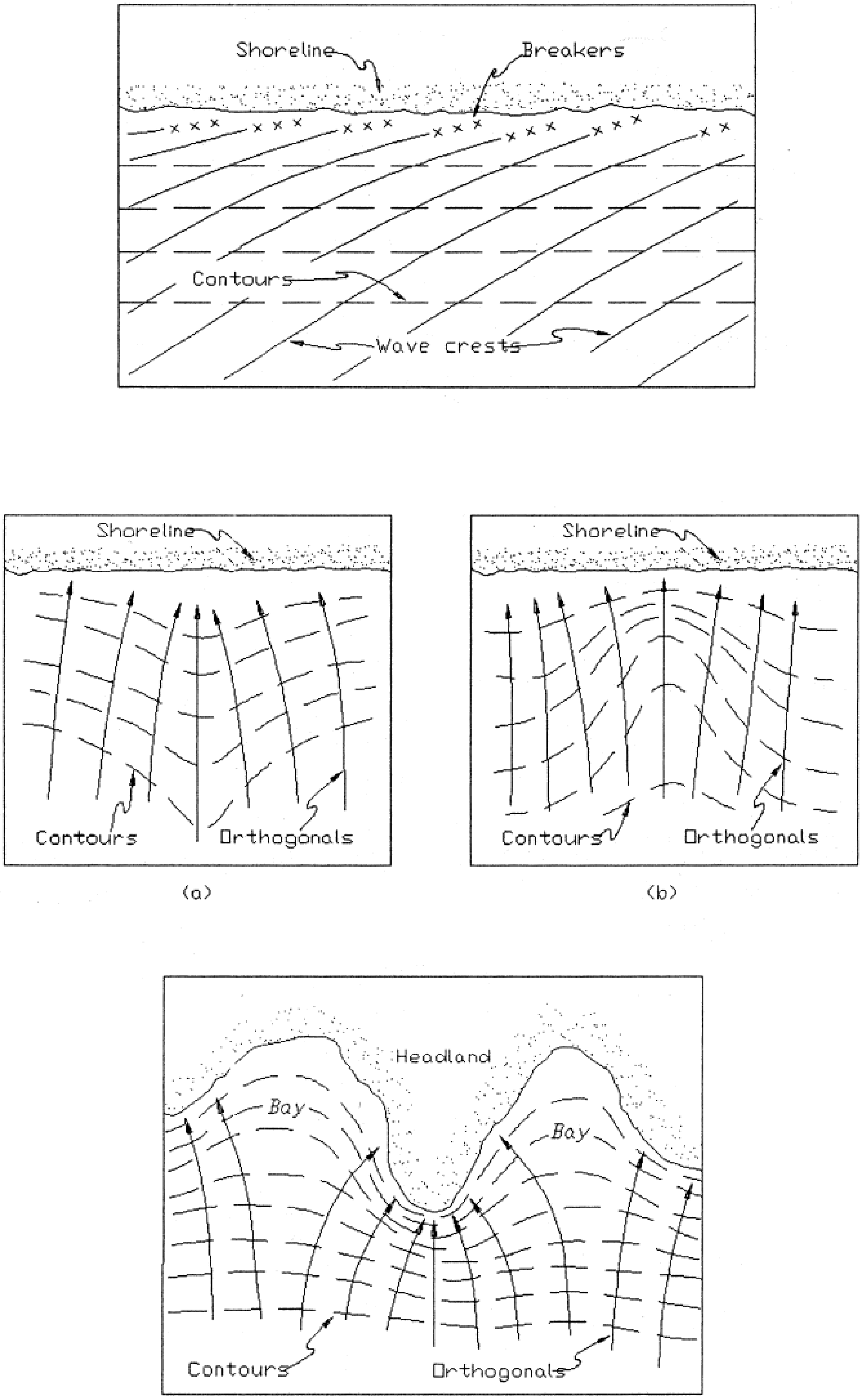


Figure 5.13 Refraction of waves (CEM, USACE 2002).

5.3.2.4 Bottom friction

Bottom friction causes energy dissipation and thereby wave height reduction as the water depth becomes more and more shallow. Friction is of special importance over large areas with shallow water.

5.3.2.5 Wave breaking

Depth-induced wave-breaking of individual waves starts when the wave height exceeds a certain fraction of the water depth ($H_b = r_b d$). As a rule of thumb $r_d \sim 0.8$ can be used at nearly horizontal (gently sloping) beaches but at steeper beaches the factor is higher. Breaking waves are generally divided into three main types, depending on the steepness of the waves and the slope of the beach/shoreface, see Figure 5.14:

- *Spilling* takes place when steep waves propagate over flat shorefaces. Spilling breaking is a gradual breaking which takes place as a foam bore on the front topside of the wave forms over a distance of 6 – 7 wavelengths.
- *Plunging* is the form of breaking where the upper part of the wave breaks over its own lower part in one big splash whereby most of the energy is lost. This form of breaking takes place in cases of moderately steep waves on moderately sloping shorefaces.
- *Surging* is when the lower part of the wave surges up on the foreshore in which case there is hardly any surf-zone. This form of breaking takes place when relatively long waves (swell) meet steep shorefaces. A large part of the wave energy is thereby reflected from the shoreline rather than dissipated in the breaking process.

Figure 5.14 Depth-induced wave-breaking: spilling, plunging and surging.

In addition to depth induced wave breaking waves also break if the waves are too steep. In deep water the theoretically limiting wave steepness is H/L = 1/7 = 0.142. This is often referred to as white-capping or top-breaking. White-capping can be observed at the part of Figure 5.1 which shows irregular directional storm waves and in Figure 5.9 for the higher wind forces.

5.3.2.6 Wave set-up

Wave set-up is a very important phenomenon in the surf-zone hydrodynamics. This is a local elevation in the mean water level on the foreshore, caused by the reduction in wave height through the surf-zone. The wave set-up is proportional to the wave height at breaking. As a rule of thumb, the wave set-up is 20% of the offshore significant wave height. Gradients in wave set-up, e.g. in partly sheltered areas near port entrances, will generate local circulation in the surf-zone towards the sheltered area.

5.3.2.7 Wave swash or wave uprush

Wave swash or wave uprush is the propagation of the waves onto the beach slope. The swash consists of an onshore phase with decelerating upwards flow (uprush or swash) and an offshore phase with accelerating downwards flow (downrush or backwash).

5.3.2.8 Wave run-up

Wave run-up is the sum of the wave set-up and the wave swash. The wave run-up is the maximum level the waves reach on the beach relative to the still water level. The run-up height exceeded by 2% of the run-up events is denoted $R_{2\%}$. The relationship: $R_{2\%} = 0.36g^{1/2}\tan\beta\, H_0^{1/2}\, T$ has been obtained in studies by Holman (1986) and Nielsen and Hanslow (1991). Tanß is the beach slope, and H_0 and T are the significant wave height and period at deep water. For typical storm waves this gives: $R_{2\%} \sim 6 \tan\beta\, H_0$.

5.3.2.9 Wave diffraction

Diffraction is the spreading of wave energy into areas which are sheltered by structures by energy transport perpendicular to the wave propagation direction. Diffraction occurs behind natural landscape elements, such as headlands and islands, see Figure 5.15, and behind manmade structures, such as breakwaters, see Figure 5.16.

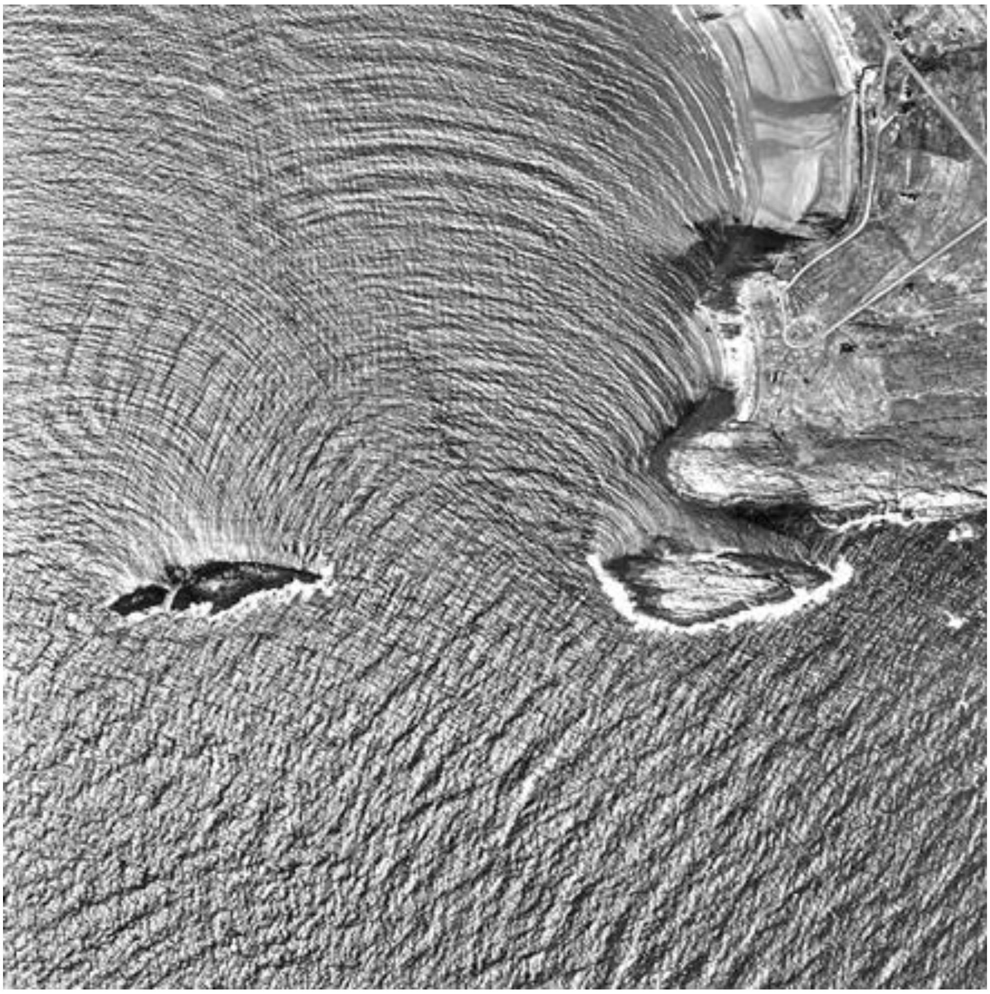


Figure 5.15 Wave diffraction behind island and behind coastal headland.
http://www.uwec.edu/boulteje/Boulter103Notes/30September_files/image005.jpg

Wave diffraction is of special importance for the design of port entrances, where diffraction allows waves to penetrate deep into the otherwise protected water bodies, see e.g. Figure 5.16. However, diffraction also leads to spreading of the wave energy penetrating a port entrance. This concept is used in e.g. bypass harbours, where the entrance is directly up against the prevailing waves and the diffraction is used to trap the penetrating wave energy in the outer harbour basin.

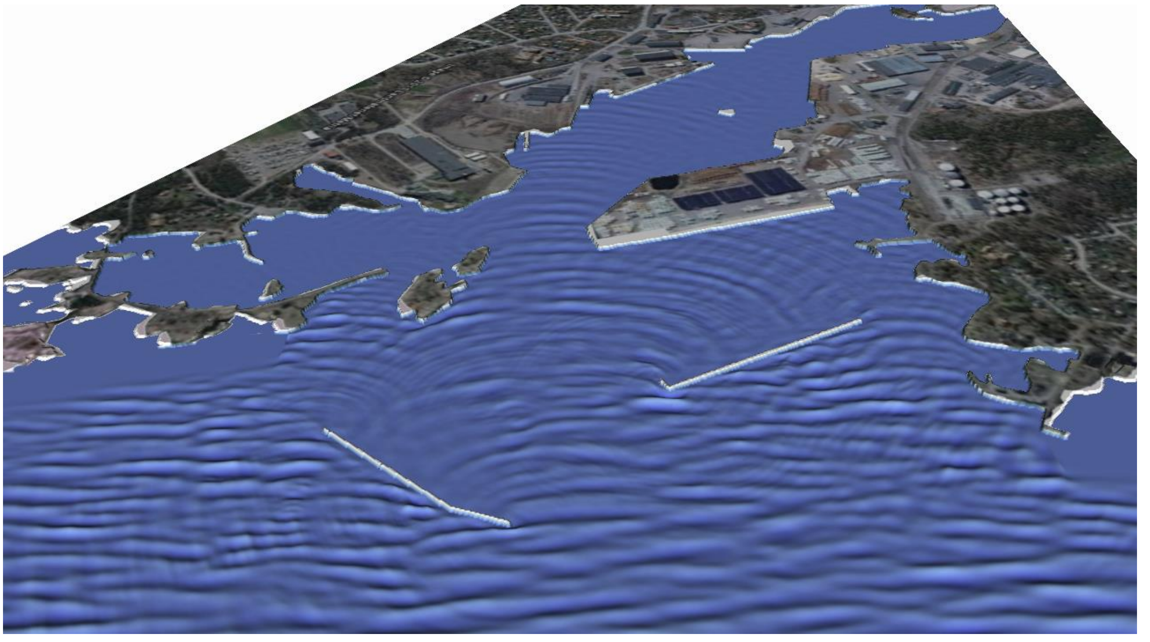


Figure 5.16 Wave diffraction in a port (from numerical simulation with a Boussinesq wave model).

5.3.2.10 Wave reflection

Reflection occurs when a wave interacts with a structure. The incoming wave energy is reflected at the structure like a mirror reflects the light. The degree of reflection is expressed by the reflection coefficient Kr.

$$Kr = Hr/Hi.$$

Where
Hr = height of the reflected wave
Hi = height of the incoming wave

If the waves approach oblique to the reflecting structure, the waves are reflected after the rule: Angle of incidence is equal to the emergent angle. The reflection coefficient is a function of the breaker index and the surface roughness.

5.3.2.11 Wave transmission, overtopping and mass transport

Part of the approaching wave energy is transmitted at partial permeable structures (e.g. low crested rubble mound breakwaters, permeable vertical walls and floating breakwaters). The degree of transmission is described by the wave transmission coefficient K_t.

$$K_t = H_t/H_i$$

Where
H_t = height of the transmitted wave
H_i = height of the incoming wave

Two processes important to the coastal processes take place during over-topping of low crested structures, wave transmission and the mass transport of water over the structure.

For *low crested rubble mound breakwaters the wave transmission* can be assessed using an approach developed by D'Angremond et al. (1996), see Figure 5.17. Approaches for other structures can be found e.g. in the CEM (USACE 2002).

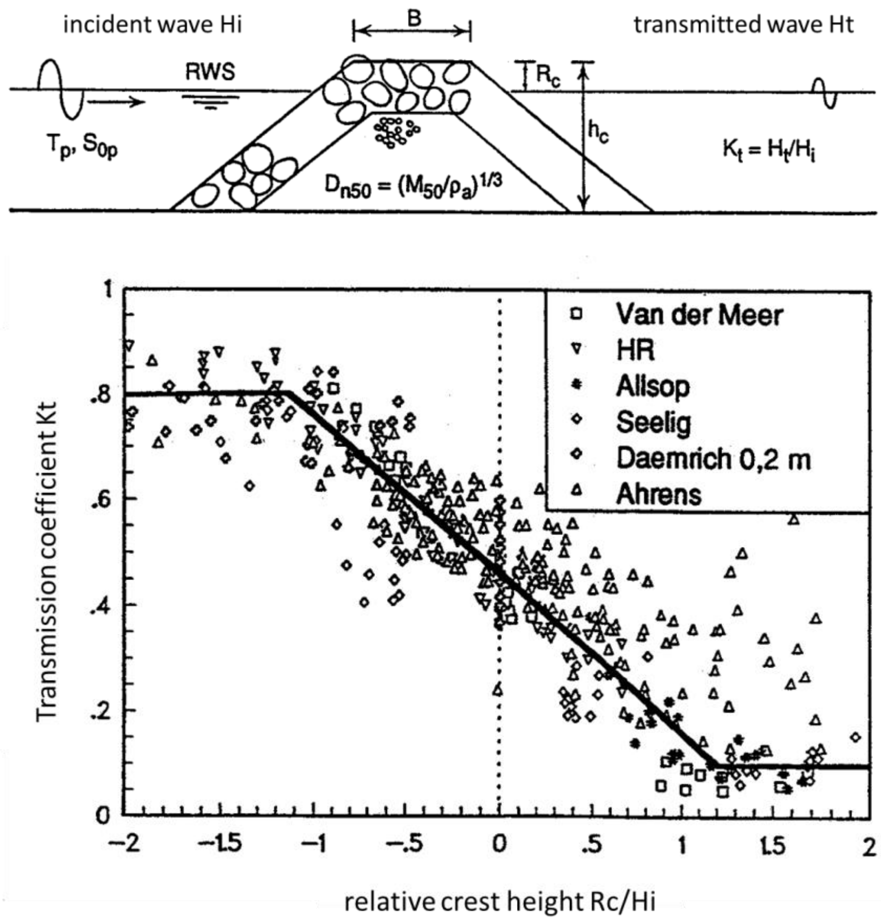


Figure 5.17 Wave transmission at low crested rubble mound structures (D'Angremond et al. 1996).

The *mass transport of water over a low crested structure* is important relative to the water balance and flow behind the low structure (low breakwater, bar or reef) because the surplus water behind the low structure may generate strong currents behind it as well as rip current at gaps or low sections of the reef/bar, which may cause offshore loss of sand and may be dangerous for swimmers. Overtopping waves are presented in Figure 5.18.

Figure 5.18 Wave-overtopping of breakwater in a flume test (upper) and in nature (lower).

Floating breakwaters may be used in relatively protected water areas (marina basins) to provide additional sheltering. They work by dissipating and reflecting part of the wave energy thereby also leading to *wave transmission*. No surplus water is brought into the sheltered area in this situation. The wave transmission coefficient K_t depends very much on the ratio L/w between the wave length L and the width of the floating structure w. As a rule-of-thumb the transmission varies between $H_t/H_i = 0.3$ for L/w = 3 and $H_t/H_i = 0.9 – 1.0$ for L/w = 8, see Figure 5.19.

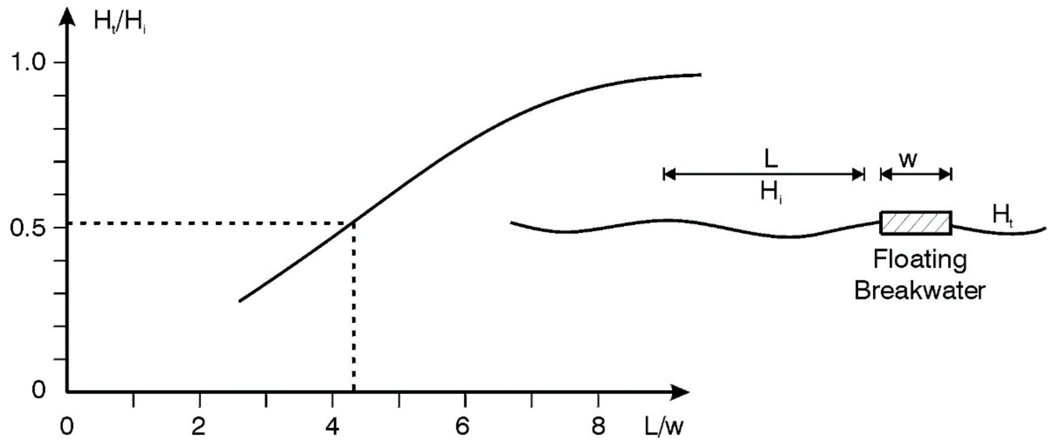


Figure 5.19 Rough relation between the transmission coefficient $K_t = H_t/H_i$ and the ratio L/w between the wave length L and the width of the floating structure w.

Consider the example of a pontoon width of w = 3 m, and a requirement of a wave transmission of min. K_t = 0.5. In this case the wave length should be smaller than L < 4.2w = 12.6 m, which corresponds to an approximate wave period of max. T = 2.9 seconds. Consequently, a floating breakwater can with this requirement only be used in situations with very small wave periods.

5.3.3 Statistical description of wave parameters

5.3.3.1 Short-term statistics and parameterisation

Wind induced ocean waves are irregular and random in terms of height, period and direction as already discussed, an example of a time series of wind waves at a fixed location is given in Figure 5.20.

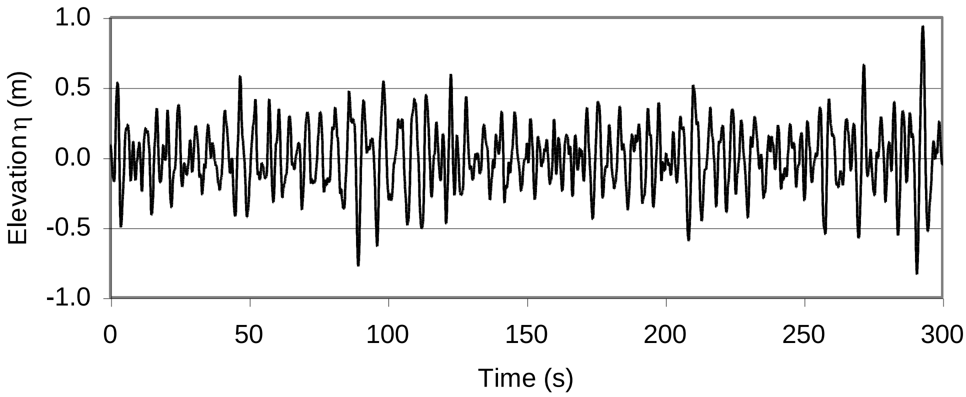


Figure 5.20 Time-series of individual wind generated waves or surface elevations.

Because of the random nature of natural waves, a statistical description of the waves is normally used. Wave recordings are typically analysed for 20-minute periods every 3 hours or similar, whereby a new discrete time series of statistical parameters is developed as described below.

For the description and assessment of sea state conditions it is obviously necessary to reduce the information to significant parameters, distribution-function or wave spectra. For the reduction of the information two principle ways are used.

- Analysis in the time domain
- Analysis in the frequency domain

The description of the wave conditions in the **time domain** is directly applied to the time-series of water level elevations as presented in Figure 5.20. Each single wave must be defined and analysed by individual wave height H and wave period T. World-wide accepted definition for individual waves in an irregular wave train is the zero-crossing definition of waves recommended by IAHR, see Figure 5.21.

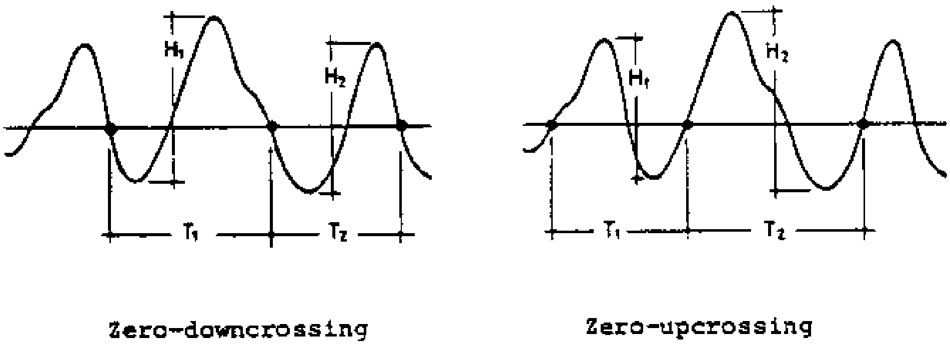


Figure 5.21 Definition of individual waves in an irregular wave train (IAHR)

The most common pave parameters used in coastal engineering derived from the time series of waves are:

- The *significant wave height*, $H_{1/3} = H_S$, is the mean of the highest third of the waves in a time-series of waves representing a certain sea state. This corresponds well with the average height of the highest waves in a wave train. H_s computed on the basis of a spectrum, is referred to as H_{m0}, see below

- The maximum wave height H_{max} is the maximum wave height in a wave train

- The *mean wave period*, $T_{m,}$ is the mean of all wave periods in a time-series representing a certain sea state

- The significant wave period $T_{1/3} = T_S$ is the mean period of the highest one third wave heights in a wave train

- The *mean wave direction*, θ_m, which is defined as the mean of all the individual wave directions in a time-series representing a certain sea state

In deep water the wave height distribution of the individual waves follows the Rayleigh-distribution. Based on the Rayleigh-distribution theoretical relationships between wave parameters are:

$$\overline{H} = 0{,}63 \cdot H_{1/3}$$

$$H_{1/10} = 1{,}27 \cdot H_{1/3}$$

$$H_{1/100} = 1{,}67 \cdot H_{1/3}$$

From the Rayleigh-distribution also the relation between significant wave height and maximum wave height can be derived. The most probable value for the relationship $H_{max}/H_{1/3}$:

$$\frac{H_{max}}{H_{1/3}} = 0,706 \cdot \sqrt{\ln N}$$

Where
N = Number of individual waves in the wave train.

For 1000 waves the ration between H_{max} and $H_{1/3}$ is 1.87.

As the basis for the description of waves in **frequency domain**, the time series has to be transferred from time domain into frequency domain. The analysis of an irregular time-series into frequency based sinusoidal components is performed by Fourier-transformation. The Fourier-transformations results in sinusoidal waves of different amplitudes (heights), periods and directions from which the energy density spectrum S(f) is derived.

An example of a wave energy density spectrum is given in Figure 5.22.

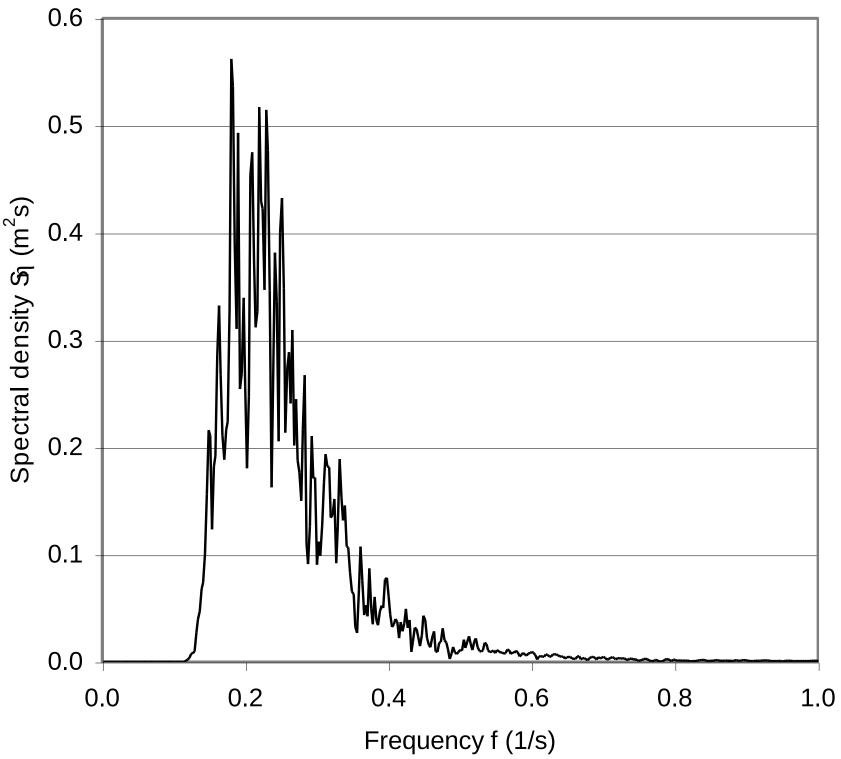


Figure 5.22 Wave spectrum: H_{m0}=1m, T_{02}=3.55s, T_p=5s (corresponding to peak frequency of 0.2 s^{-1}).

Characteristic and significant wave parameters in frequency domain are estimated from the moments of the wave energy density spectrum:

$$m_n = \int S(f) \cdot f^n \cdot df$$

The characteristic parameters in frequency domain are defined as follows:

- $H_{m_0} = 4 \cdot \sqrt{m_0}$, spectral derived significant wave height ~ $H_S = H_S$, significant wave height

- T_p = peak-period, $T_p = 1/f_p$, f_p = peak-frequency. The peak wave period, Tp, is the wave period with the highest energy. As a rule of thumb the following relation can be used: Tp ~ $5.3H_{m0}^{1/2}$ for storm waves
- $T_{0,1} = m_0/m_1$, significant wave period ~ $T_{1/3} = T_S$
- $T_{0,2} = \sqrt{m_0 / m_2}$, mean wave period ~ T_m
- Θ_m = mean wave direction
- Θ_p = Peak wave direction. The wave direction with the largest wave energy. Requires the wave energy to be split into directional bins. In case of mixed sea states the peak wave direction can be very different from the mean wave direction.

Other spectral wave parameters, especially for the description of the shape of the spectrum, are defined in IAHR (1986).

5.3.3.2 Normal wave climate and extreme wave conditions

The above described statistical wave parameters are often calculated from continuous or periodic time-series of the surface elevations; typically the parameters are calculated based on 20 minutes periods every three hours, whereby a new discrete time-series of the statistical wave parameters is constructed. This time-series is thereafter analysed statistically to arrive at a condensed description of the wave conditions as described in the following:

Wave information is needed over longer periods to evaluate the normal wave climate and the extreme wave conditions in a project area. The wave data has therefore to be analysed using different data parameters and different statistical methods in order to describe the normal wave climate and the extreme wave conditions at a site, respectively.

The first step in the description of the wave climate at a site is to describe the site in terms of location (open waters (ocean) or confined waters), bathymetry and the wind climate (western depression area, trade winds, monsoon winds, and cyclones) as this information governs the wave climate. These conditions provide a first hint of which wave climate one can expect at a given site and how the wave conditions can be analysed in connection with a project at a specific site.

Considering that we are at a site where some kind of wave data has been produced, either in the form of wave recordings or in the form of hindcasted wave data or other kind of data, which produces time series of relevant wave parameters, such as H_{m0}, T_p and Θ_m. A first overview of the wave data in a project area is given by a simple time series plot of the wave parameters for the entire period for which wave data is available. This is done to check the data in terms of the quality of the data and the characteristics of the wave climate related to the following items:

- Seasonal characteristics in terms wave height and directional distribution
- Distinct wave types (sea or swell waves)
- Temporal variability in wave climate, e.g. storm wave dominated climate (typical for the western depression area) or a more steady seasonal climate (monsoon climate or trade winds), etc.

Note that time series plots for a period of one or a few years of wave parameters in areas exposed to cyclones may not show any cyclone waves as cyclones typically occur relatively rarely

An example of such a time series plot is presented in Figure 5.23.

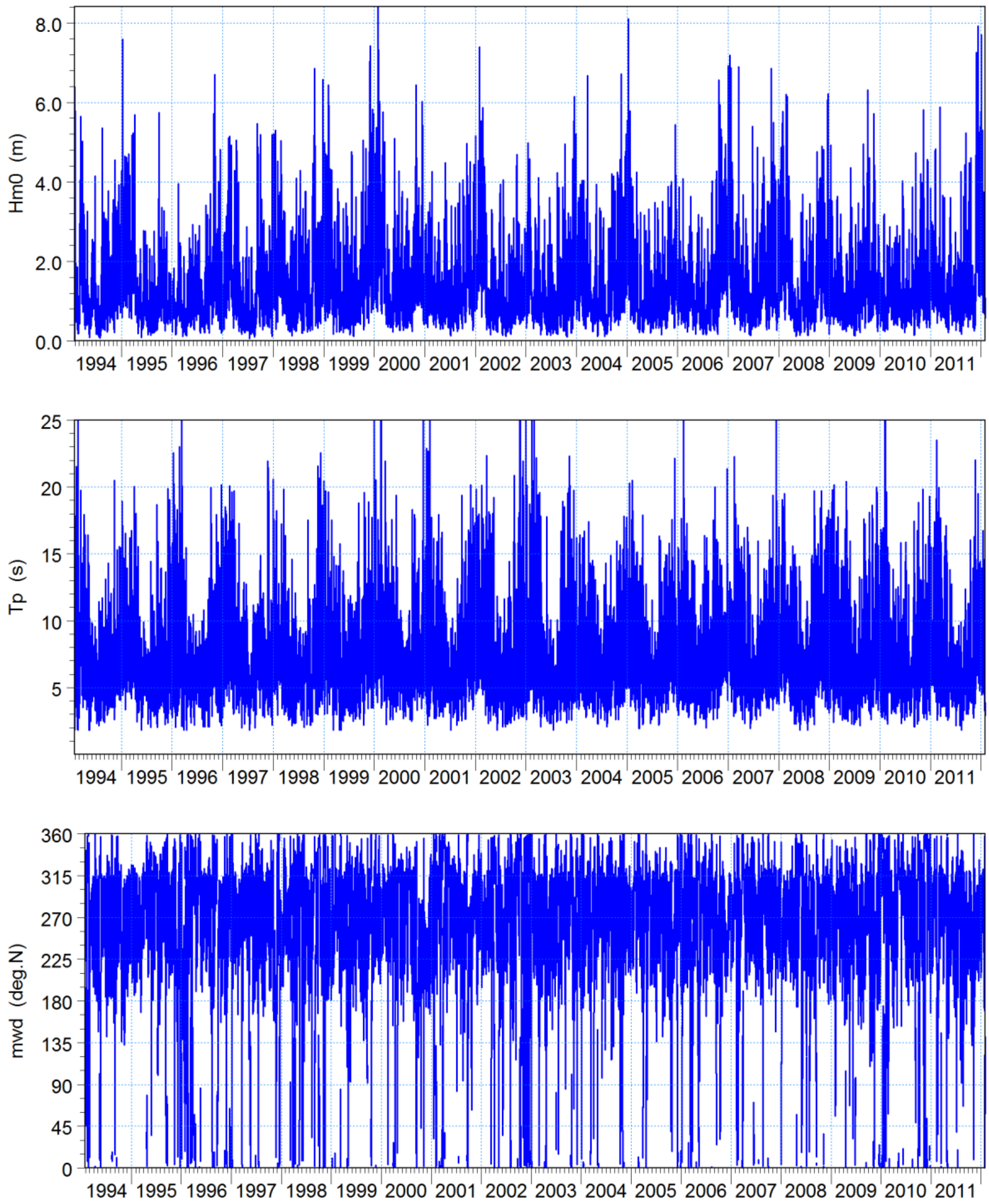


Figure 5.23 Time series plots of hourly values of H_{m0}, T_p and Θ_m based on wave hindcast from the West Coast of Denmark. Wave parameters from January 1994 to December 2012.

It is seen that this site is dominated by storm waves during winter with wave approaching from westerly directions. There is a relatively clear seasonality in the wave height.

The characteristics of the wave conditions emerging from the analysis of the general site conditions and from the time series plots provide inspiration as to how the data shall be analysed.

The wave climate is thus typically described on basis of continuous time series of wave parameters based on wave recordings and/or hindcast simulations. Wave parameters for analysis of the normal wave climate are typically extracted every hour or every third hour, assuming the duration of the events is equal to the interval between data extractions, typically based on a combination of one to two years wave recordings and/or one to two decades of hindcast simulations. Extreme wave conditions are typically analysed on basis of time series of maximum wave heights during individual and independent storm events or on basis of time series of maximum yearly wave heights for periods of not less than about 10 years. Cyclone waves require a special cyclone wave study.

Normal wave climate

The normal wave climate at a site is the description of the normally occurring wave conditions at the site. The normally occurring wave conditions at a site govern the littoral transport conditions, in contrast to the extreme wave conditions, which, however, also influence coastal processes in the form of acute erosion, breaching of dunes and coastal flooding events.

It is necessary to generate a comprehensive and sufficient data base for establishing a statistical description of waves in a project area. The data base has to be a (nearly) complete sample of wave measurements with constant resolution in time domain. In general it is necessary that the data base covers at least one (or more) complete climatic cycle(s) (years). Several years of data may be required for a complete description of the normal wave climate at a site especially if there is a great variability from year to year. However, the long term variability is typically described by wave hindcasting in regional wave models run for decades or via long term wind data and correlations between wind and wave conditions as long term wind data are often available from meteorological models or from recording stations.

Wave data from wave recording/hindcast modelling programmes often consists of continuous time series of statistical wave parameters, typically of H_S (H_{m0}), T_p and Θ_m and possibly also wind speed and wind direction data.

Such data is normally presented and analysed as described in the following.

- As time series plots of the individual parameters as presented in Figure 5.23
- Wave height directional distribution, a so-called wave rose as presented in Figure 5.24
- Directional frequency distribution of the wave heights as presented in Table 5.3
- Scatter diagrams of wave heights vs. wave periods as presented in Figure 5.25
- Wave height exceedance distribution for various wave directions as presented in Figure 5.26

The above analyses are often performed for seasons, for individual years and for all data combined.

From the directional frequency distributions shown in Table 5.3 and Figure 5.24 it is possible to identify typical wave heights in the area, and determine the predominant wave direction. For the examples shown in Table 5.3 and Figure 5.24 it is seen that waves predominantly approach the area from SW-NW, which is expected since the climate is extracted off a west facing coast.

Table 5.3 Directional frequency distribution (in pct.) of wave heights, based on a wave hindcast from the West Coast of Denmark (same wave climate as in Figure 5.23).

Hm0 (m)	NE 22.5 - 67.5	E 67.5 - 112.5	SE 112.5 - 157.5	S 157.5 - 202.5	SW 202.5 - 247.5	W 247.5 - 292.5	NW 292.5 - 337.5	N 337.5 - 22.5	All 0 - 360
0.0 - 0.5	0.397	0.376	0.426	0.844	1.754	2.059	4.984	0.984	11.8
0.5 - 1.0	0.742	0.752	1.360	2.885	5.898	6.183	11.455	2.605	31.9
1.0 - 1.5	0.094	0.130	0.589	1.713	5.081	5.882	8.212	0.953	22.7
1.5 - 2.0	0.007	0.008	0.091	0.685	3.515	4.253	4.665	0.237	13.5
2.0 - 3.0	0.000	0.000	0.006	0.188	3.677	4.712	4.676	0.101	13.4
3.0 - 4.0			0.000	0.016	1.169	1.941	1.622	0.006	4.8
4.0 - 5.0				0.001	0.279	0.704	0.541	0.000	1.5
5.0 - 6.0				0.000	0.035	0.210	0.153		0.4
6.0 - 7.0					0.004	0.086	0.023		0.1
7.0 - 8.0					0.001	0.017	0.005		0.0
8.0 - 9.0					0.000	0.003	0.003		0.0
9.0 - 10.0						0.000	0.000		0.0
10.0 <									0.0
Total	1.2	1.3	2.5	6.3	21.4	26.1	36.3	4.9	100.0

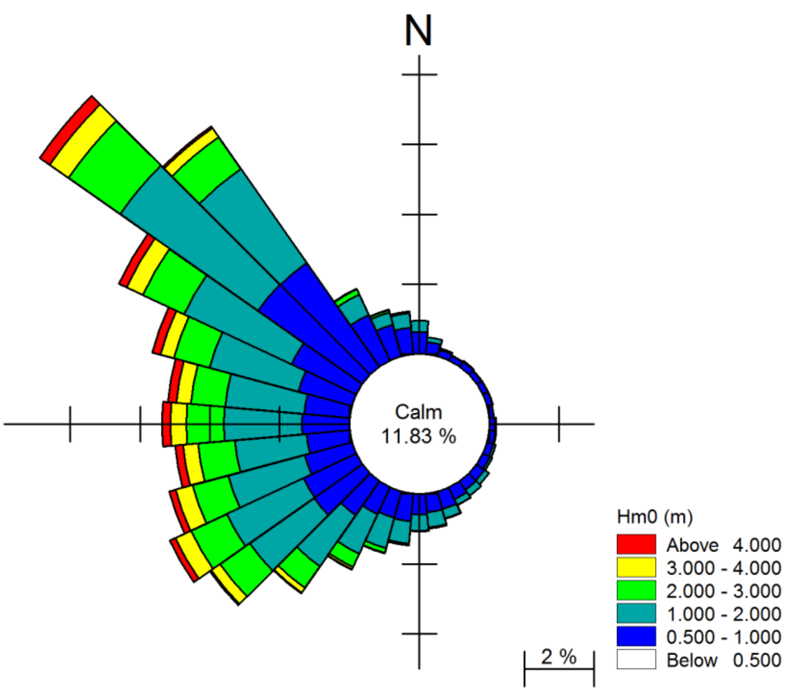


Figure 5.24 Wave height directional distribution, a so-called wave rose. Wave climate from the West Coast of Denmark (same data as in Figure 5.23).

The scatter diagram of wave height and wave period shown in Figure 5.25 shows that the wave climate consists of “locally generated” storm waves which more or less follow the general relationship $T_p=5.3\ H_{m0}^{0.5}$ (cf. Subchapter 5.3.3.1), and swell waves which consist of waves below 3 m in height with peak wave periods above approximately 10 s.

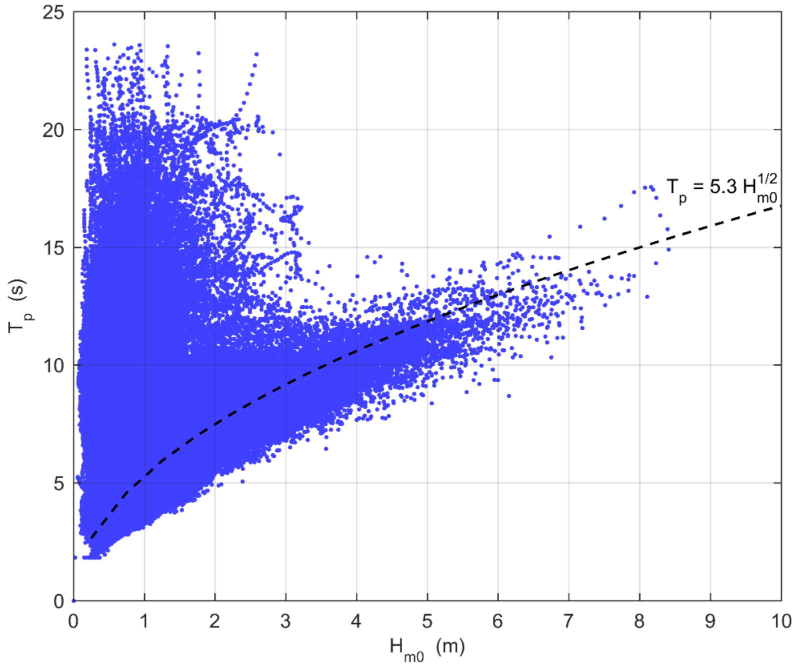


Figure 5.25 Scatter diagram of T_p vs. H_{m0}. Wave climate from the West Coast of Denmark. (same data as in Figure 5.23). The approximate relation between T_p and H_{m0} for storm waves is also shown.

Taking the cumulated sum of the wave height frequency distributions in Table 5.3 results in the wave height exceedance distributions shown in Figure 5.26. A wave height exceedance distribution is typically used to calculate probability of downtimes for certain wave height thresholds or calculation of the characteristic storm wave, $H_{s,\ 12h/year}$ which can be used to define closure depth (cf. Subchapter 7.3).

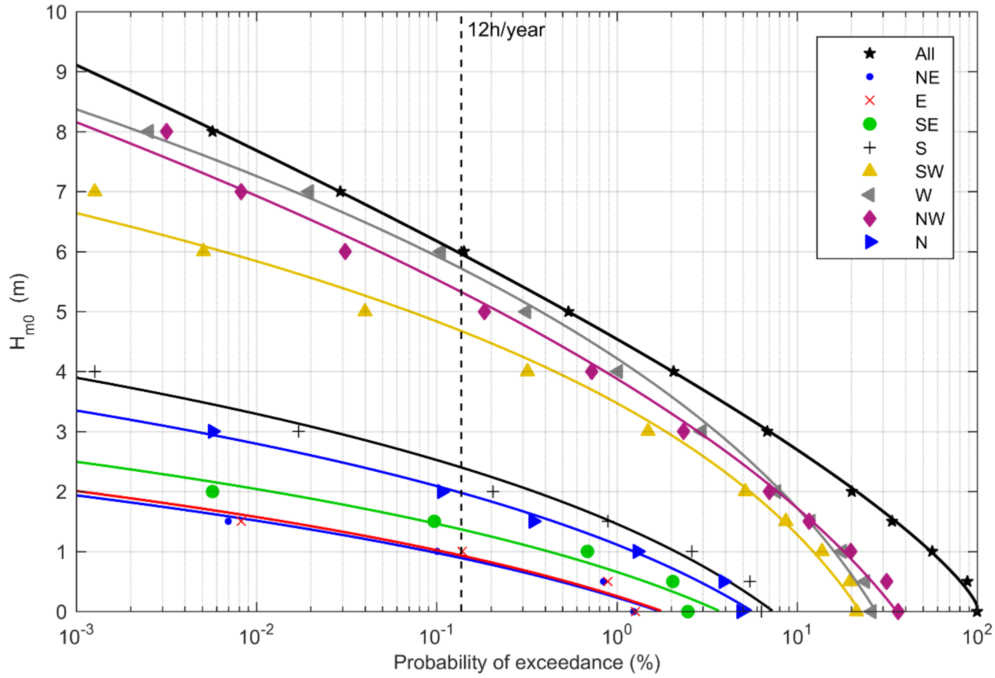


Figure 5.26 Wave height exceedance distribution for various wave directions. Wave climate from the West Coast of Denmark (same data as in Figure 5.23).

Extreme wave conditions

Extreme wave conditions, and their correlation to storm surge conditions, are of importance for the analysis of the effects of events on the coastal system, such as acute erosion, breaching of dunes/dikes and coastal flooding and for the purpose of designing coastal schemes, such as coast protection and sea defence schemes, as well as other coastal projects.

Extreme wave conditions are, as already mentioned, typically analysed on basis of time series of maximum wave heights (H_S) during individual and independent storm events or on basis time series of maximum yearly wave heights for periods of not less than about 10 years. Cyclone waves require a special cyclone wave study.

Examples of plots from extreme wave analysis at an offshore site based on analyses of data from 18 years of hindcast simulations are presented in the following. A time series plot of H_{m0} for the entire 18-year simulation period is presented in Figure 5.27, storm peak values over the threshold level of 4.8 m are marked with black dots.

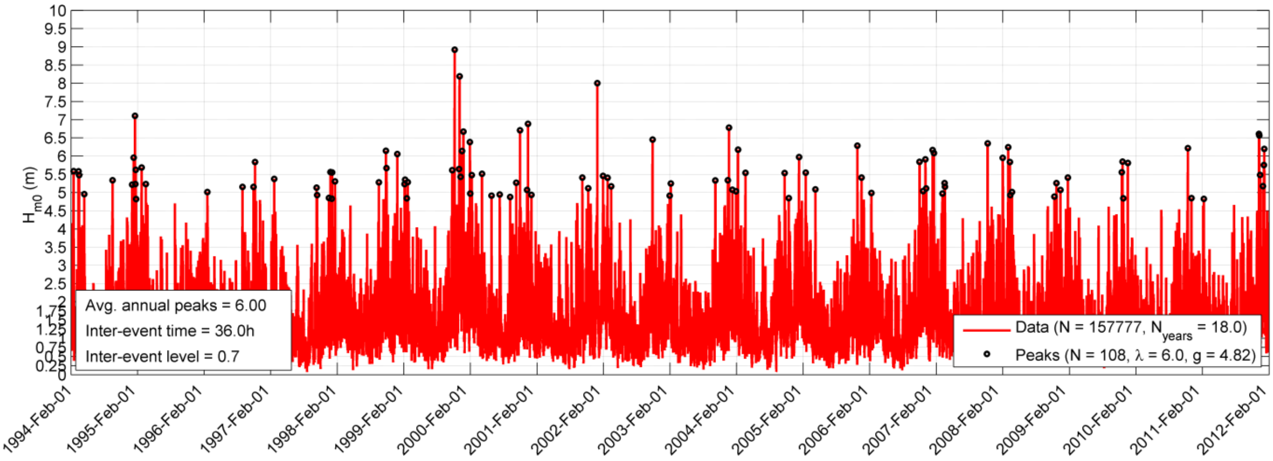


Figure 5.27 18 years of time series plot of simulated H_{mo} values. Storm peak values with a cut off level of 4.8 m are shown with black dots.

It is seen that there is a marked seasonal variation in the wave heights. The directional distribution of the data is presented in Figure 5.28 and it is seen that the predominant wave direction are in the interval W to NNW.

Extreme value analysis can be performed on monthly data and on directional data, or for all data combined, the latter analysis is presented in Figure 5.29. Extreme values of H_{m0} for recurrence periods of 1, 5, 10, 50 and 100 years are extracted. Normally different distributions are tested such as Weibull, Gumbel, Exponential and Log-Normal, etc. The Weibull distribution is often found to provide optimal fit for wave data.

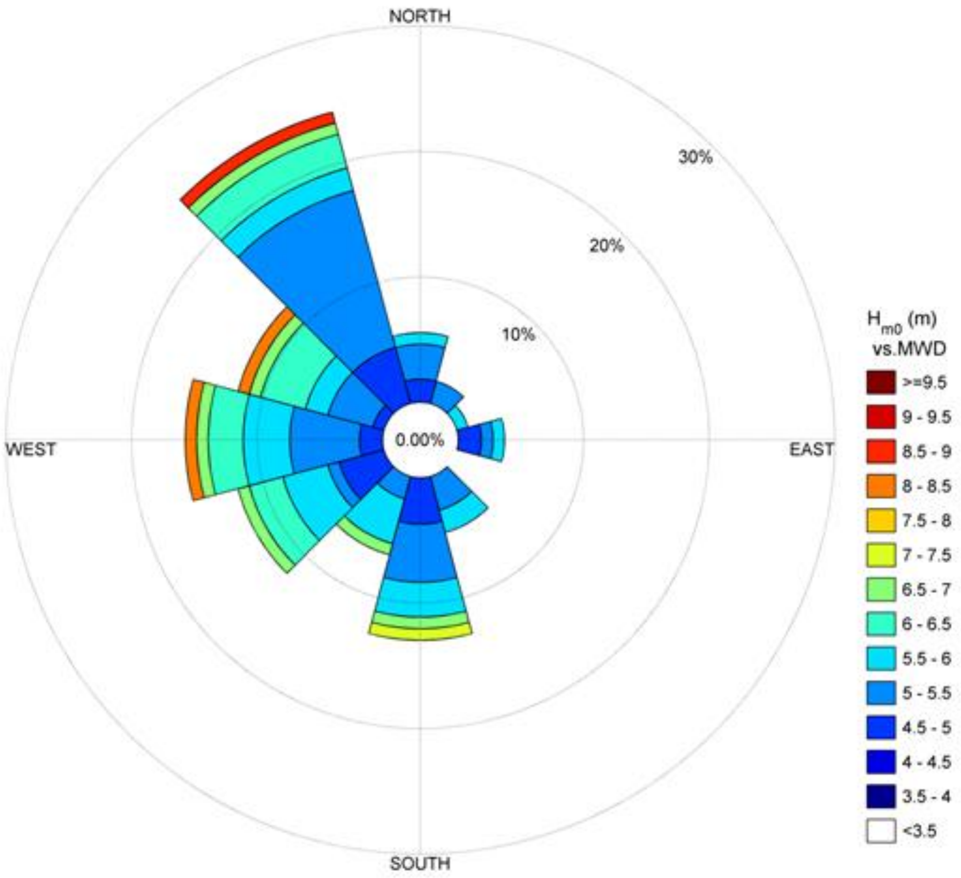


Figure 5.28 Directional distribution of storm peak wave heights H_{m0} for the 18-year simulation period, same data (black dots) as in Figure 5.27.

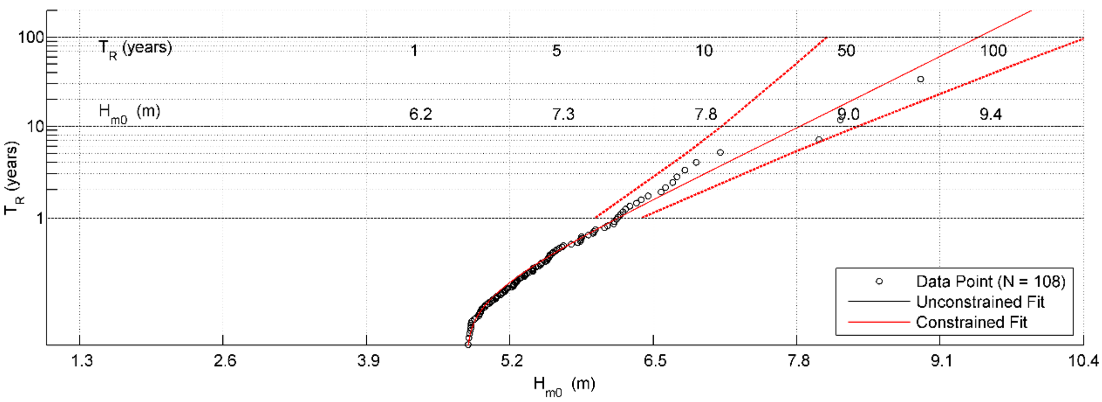


Figure 5.29 Extreme value analysis by Weibull distribution of peak over threshold extraction data for 18-year simulation period; same data as in Figure 5.27.

It is commonly agreed that extrapolation of wave data is allowed for a period which is approx. 2-3 times the period of the underlying sample. This is based on the work of Wang and Le Mehaute (1983) and further investigations by Fröhle (2000).

Figure 5.30 shows the relative standard deviation of extrapolated wave heights as a function of the period of the underlying wave data. It is obvious that a data base that covers a period of more than 10 to 20 years provides relatively accurate results and that data bases that cover a longer period do only slightly improve the extrapolation; data bases that cover shorter periods show significantly poorer results. This above is valid for statistical analysis of waves, which is typically a relatively ‘regular’ signal and therefore the required data period is relatively short.

However, it is different for analysis of storm surges because storm surge situations often have rare occurrences with irregular intervals between occurrences. Consequently, longer time series are required for extreme value analysis of storm surges.

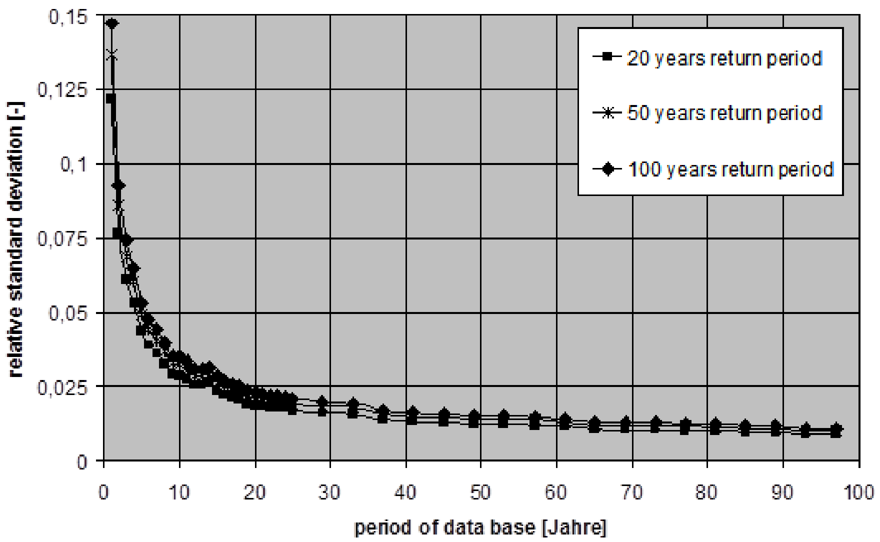


Figure 5.30 Relative standard deviation of extrapolated wave heights in the North Sea and the period covered by the data base (Fröhle 2000).

5.3.4 Wave climate classification according to wind climate

The different wind climates, which dominate different oceans and regions, cause correspondingly characteristic wave climates. These characteristic wave climates can be classified as follows:

- *Storm wave climate*. This is related to subtropical, temperate and arctic climates dominated by the passage of many depressions. At an exposed, open coast this climate is characterised by very variable wave conditions, both with respect to height, period and direction distributions. This type of climate often results in a wide littoral zone dominated by a sandy coastal profile with bars and a wide sandy beach backed by dunes.
- *Monsoon wave climate*. The monsoon climate is characterised by seasonal wind directions. During the summer, local depressions over tropical landmasses cause the wind to blow from the sea towards land. The Inter Tropical Convergence Zone intensifies these tropical summer depressions. In Southeast Asia the summer monsoon is referred to as the SW-monsoon. The summer monsoon is warm and humid. The winter monsoon, which is caused by local high pressure over land, blows from the land towards the sea. In Southeast Asia the winter monsoon is referred to as the NE-monsoon. The winter monsoon wind is relatively cold and dry. The monsoon wind climate is thus characterised by winds from the sea during the summer and winds from land during the winter. The above phenomenon is valid for major

continental landmasses only, whereas minor landmasses within the monsoon area can experience onshore winds during winter. An example of this is the East Coast of the Malaysian Peninsula, which is predominantly exposed during the NE-monsoon. Monsoon winds are relatively moderate and persistent for each monsoon season. This means that the corresponding wave climates are also seasonal and normally characterised by a relatively rough summer climate and a relatively calm winter climate. The summer climate can, in absolute terms, be characterised as moderate and relatively constant in direction and height. The monsoon climate typically results in a fairly narrow sandy inner littoral zone, shifting to a gently sloping outer part of the littoral zone dominated by finer sediments.

- *Tropical cyclone climate*. Tropical storms are called hurricanes near the American continents, typhoons near SE-Asia and Australia, and cyclones when occurring near India and Africa. Tropical storms are generated over tropical sea areas where the water temperature is higher than 27 degrees Celsius. They are normally generated between 5°N and 15°N and between 5°S and 15°S. From there they progress towards the W–NW in the Northern Hemisphere and towards the W–SW in the Southern Hemisphere. Cyclones do not penetrate the area between 5°N and 5°S, as wind circulation cannot occur so close to the equator. An average of 60 tropical cyclones is generated every year. Tropical cyclones are characterised by wind speeds exceeding 32 m/s and they give rise to very high waves, storm surge and cloudburst. Tropical cyclones occur as single events, peaking during September in the Northern Hemisphere and similarly peaking during January in the Southern Hemisphere. Tropical cyclones are rare and therefore recording programmes seldom document the resulting waves. A tropical storm will normally have great impact on the coastal morphology when it hits, but the coastal morphology will first and foremost be determined by the normal wave climate, which can be either monsoon or swell climates.

The above wave climates will be dominated by the limited geographical fetch if the wind climates are occurring in combination with confined waters.

- *Swell climate*. This typically occurs along coastlines near the equator, where the swell is generated by the so-called trade winds. Near the equator the heating of the air masses is particularly high. This causes the air masses to rise, which in turn generates a thermal depression near the surface. This depression causes winds to blow in from the north and from the south. The area where these winds meet is called the *Inter Tropical Convergence Zone* (ITCZ). The winds blowing towards the ITCZ are called *trade winds*. Due to the rotation of the earth, their directions are NE north of the ITCZ and SE south of the ITCZ. Near ITCZ the wind climate is predominantly calm; this area is called the *doldrums*. The trade winds mainly occur over the oceans as they are overruled by the monsoons near the continents. Trade winds are moderate and persistent. The wave climate generated by the trade winds is also moderate and persistent throughout the year. As it mainly occurs over oceans away from the coastlines, the associated wave climate along adjacent coastlines is mainly in the form of swell characterised by relatively small and long persistent waves travelling in a constant direction. A swell climate normally gives rise to a relatively narrow sandy littoral zone with an abrupt shift to a gently sloping outer part of the littoral zone dominated by finer sediments. Other swell climates occur in other areas. They are the result of extreme wind conditions in areas far from the coast, so that the swell climate is developed while the waves travel large distances. This is, for example, the case on the north-west coast of Mexico and the coast of California, where the swell wave climate dominates during the summer months with swells developing from tropical storms in the south and from waves originating in the southern hemisphere. This is an important wave climate from a coastal point of view since these waves tend to move sand from the shoreface onto the beach.

5.4 Long waves

The long waves are primarily second order phenomena of shallow water wave processes. The four main types of long waves are described in the following.

5.4.1 Surf beat

Natural waves often show a tendency to *wave grouping*, where a series of high waves follows a series of low waves. This is especially pronounced on open sea-coasts, where the incoming waves may be of different origin and will thus have a large spreading in wave height, wave direction, and wave period (or frequency). Wave grouping will cause oscillations in the wave set-up with a period corresponding to approx. 6 – 8 times the mean wave period; this phenomenon is called *surf-beats*. Surf-beats at a beach near a harbour entrances are very important in relation to mooring conditions and sedimentation in the harbour basins because the surf beat generates oscillation of the water in and out of the entrance, see Figure 5.31. Surf beat influence within a port is often caused by an inexpedient layout where a beach with shallow water is located close to the entrance. Shallow water adjacent to harbour entrances shall therefore be avoided.

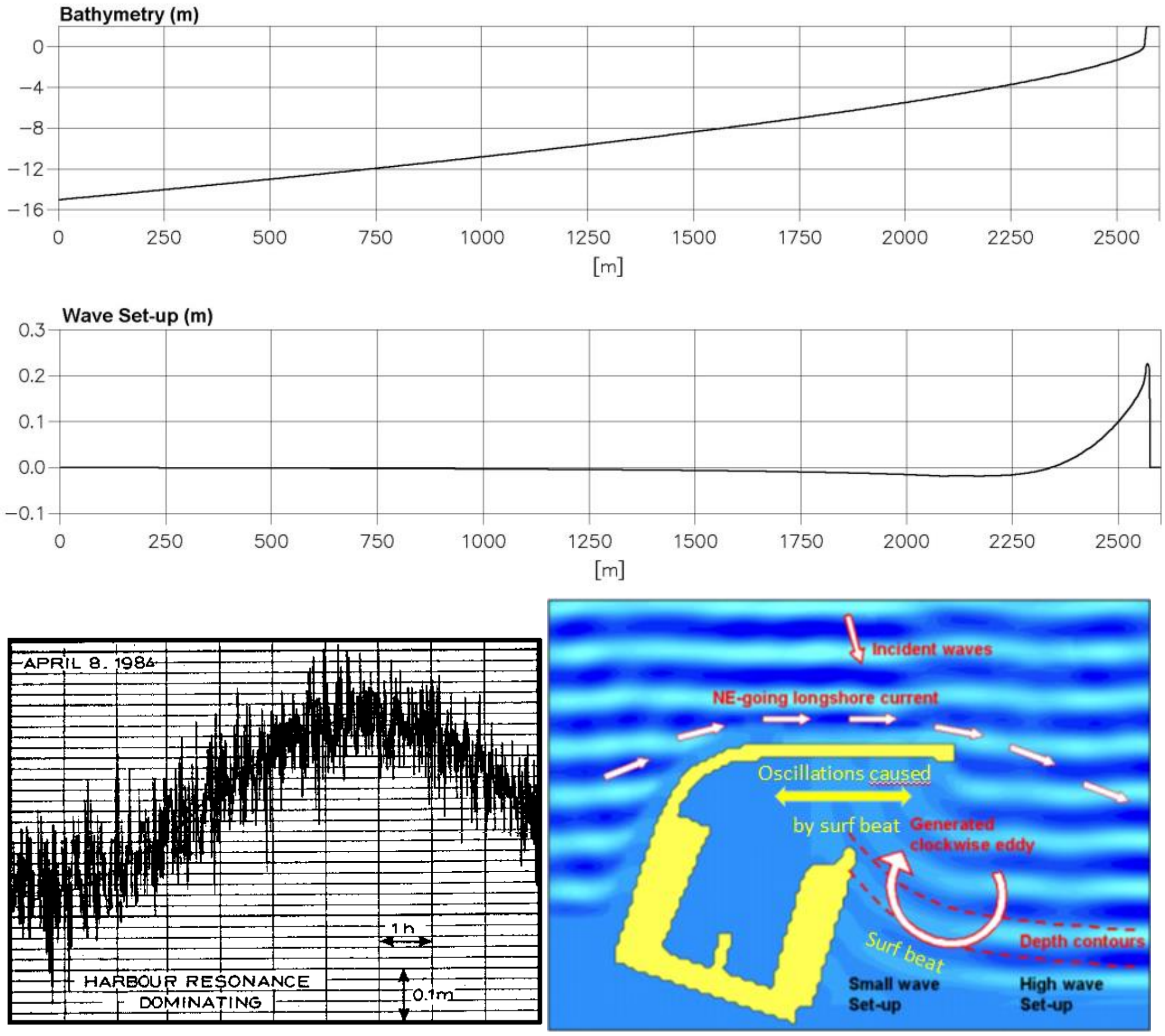


Figure 5.31 Wave set-up (upper), surf beat generated harbour resonance recorded with a tide gauge in a small port (lower left) and wave set-up, circulation caused by the gradient in the wave set-up, surf beat and oscillations caused by the surf beat (lower right).

5.4.2 Harbour resonance

Harbour resonance is forced oscillation of a confined water body (e.g. a harbour basin or a lagoon) connected to a larger water body (the sea). If long-period oscillations are present in the sea, e.g. due to wave grouping or surf beats or seiche, large oscillations at the natural frequency of the confined water body may occur. Oscillations at the first harmonic, which are the simplest mode of resonance, are often called the *pumping* or *Helmholz mode*.

Harbour resonance normally has periods in the range of 2 to 10 minutes. It is especially important in connection with the mooring conditions for large vessels, as their resonance period for the so-called surge motion is often close to that of the harbour resonance. In addition the associated water exchange may cause siltation.

5.4.3 Seiche

A seiche is the free oscillation of a water body, probably caused by rapid variations in the wind conditions. Seiche can occur in closed water areas, such as lakes or lagoons, and in semi-closed water bodies, such as bays. The period of the seiche oscillation is typically in the range of 2 to 40 minutes. Seiche can influence a port in the same manner as surf-beat, but the mechanisms of seiche and surf beat are different. Seiche is coming from deep water oscillation in the environment where the port is located whereas surf beat is associated with the layout of the port relative to adjacent beaches. It is therefore important to establish whether seiche is present in an area through field investigations, and if so, to take it into account in the layout of the port.

5.4.4 Tsunami

A tsunami is a single wave generated in deep oceans by extreme underwater disturbances such as earthquakes, landslides and submarine volcanic activities. The main generator of tsunamis is subsea earthquakes in deep oceans along the so-called subduction zones, which are special fault zones along the boundaries between the tectonic plates. Tsunami waves can travel long distances across the oceans. A tsunami wave moves as a shallow water wave even in the deep oceans which means that the speed is calculated as the square root of the product of the water depth and the acceleration of gravity, $v = (gh)^{1/2}$. Consequently, tsunamis travel very fast in the deep oceans. If the water depth is 4000 m, the speed will be about 200 m/s or more than 700 km/hour. The tsunami wave is normally not very high at the deep ocean, but when it approaches the coastline, refraction and especially the shoaling of the wave causes enormous high bore like waves near the coast. The wave height near the coast can reach more than 10 m. Most damages are caused by the run-up of the tsunami wave, which inundates wide areas of shallow land, and the return flow of water back to the ocean. The huge destruction capacity of a tsunami is evident from the picture in Figure 5.32.

Figure 5.32 Huge destruction by tsunami in Japan in March 2011.

The occurrence of tsunamis is associated to the occurrence of subsea earthquakes along the subduction zones, see Figure 5.33. The main subduction zones are located around the Pacific Ocean; this is also referred to as the “Ring of Fire”, see Figure 5.34. It is evident from the two figures that the main influence area for tsunamis are coastlines around the Pacific Ocean but there is also a subduction zone along the Sumatra west coast, which affected coastlines bordering the Bay of Bengal and the Indian Ocean/Arabian Sea. An example of such a tsunami was the December 2004 tsunami off the north-western part of the Sumatra coast. This tsunami affected coasts at Sumatra, Thailand, Sri Lanka, India, and the east coasts of the Somalia and Oman. Furthermore, there are minor subduction zones in the eastern Mediterranean, in the Caribbean Sea and along the south coast of Iran (the Makran fault).

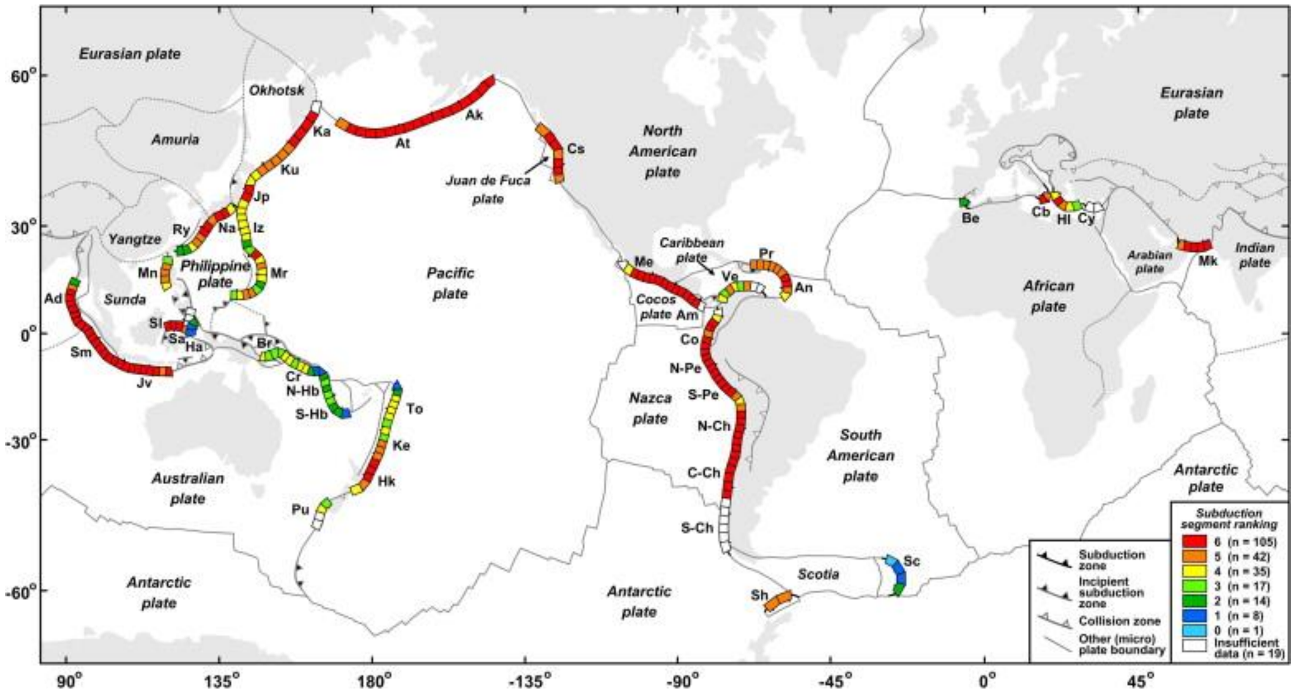


Figure 5.33 Global map of the active subduction zones, from Schellart, 2013

Compared to storm surges tsunamis are normally rare but when they hit a coastal community they can be very destructive and dangerous for the coastal population. Coastal protection is normally not designed for the impact of tsunamis. However, for very sensitive projects, such as nuclear power plants located in the coastal hinterland, and in densely populated areas the risk must be considered and taken into consideration in the planning and design of the protection of such projects/areas, or via warning systems or contingency plans.

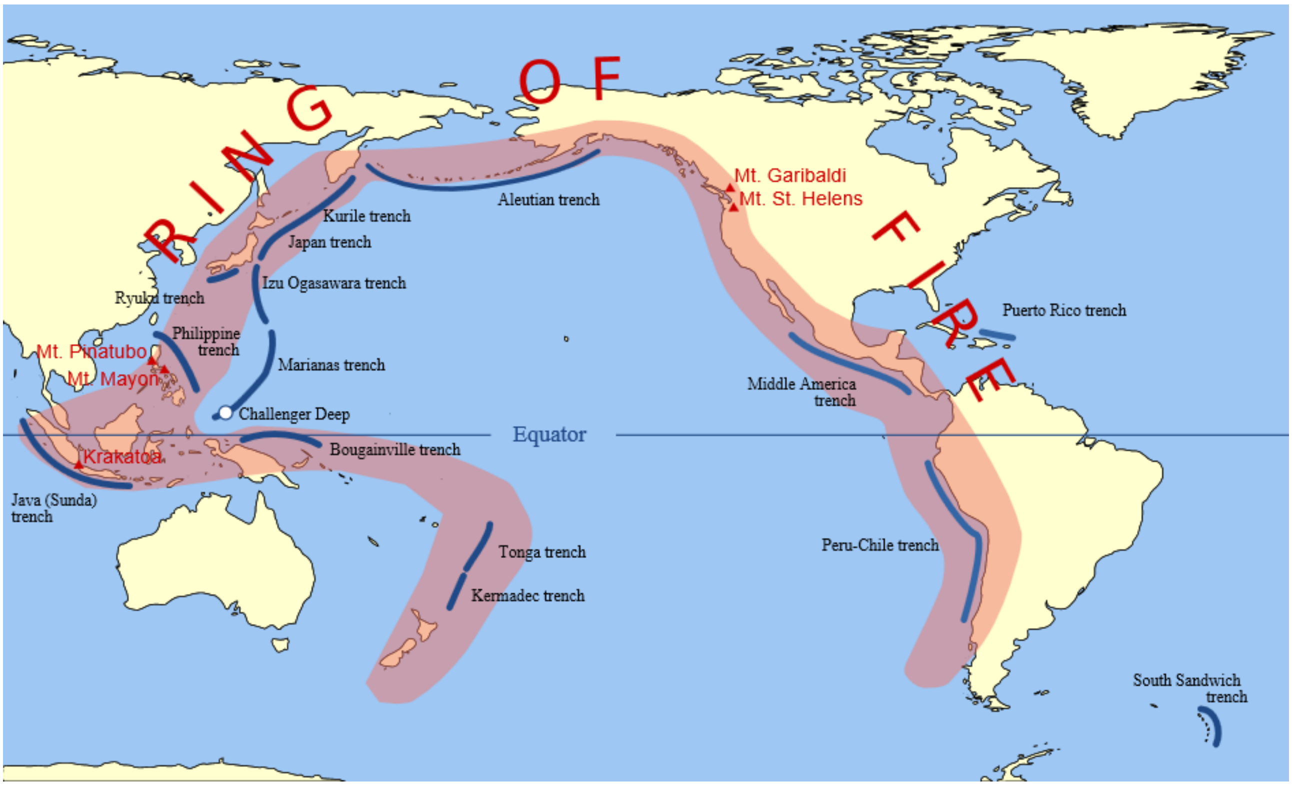


Figure 5.34 "Ring of Fire". From: http://en.wikipedia.org/wiki/Ring_of_Fire

5.5 Currents

Currents can be divided in ocean currents and nearshore currents, only the latter influence coastal processes. Consequently, only the nearshore currents will be described in detail whereas the ocean currents will only be briefly mentioned in this introduction.

The main types of currents are described in Table 5.4.

Table 5.4 Type of currents and their causes.

Main type	Current type	Driving forces	Influence on coastal processes
Ocean currents	Ocean circulation	Density gradients due to gradients in Temperature and Salinity	No
	Wind induced ocean currents	Wind patterns, cf. Figure 5.3 and Figure 5.4 Coriolis force	
	Tidal currents	Gravity forces from sun, moon and planets	Yes, see below
	Storm surge currents	Wind stress and barometric pressure gradients during storms	Yes, see below
Nearshore currents	Tidal currents	Gravity forces and interference with coasts, straits and inlets	Yes
	Storm surge currents	Wind stress, pressure gradients and interference with coasts, straits and inlets	
	Longshore currents	Waves Interaction with coast	
	Shore normal currents	Waves Interaction with coast	
	2D currents in the nearshore area	Waves Gravity forces Wind stress and pressure gradients Interaction with irregular seabed and with structures	

The various types of currents in the sea, which may be important to coastal processes in one way or another, are described in the following.

5.5.1 Nearshore currents

5.5.1.1 Tidal currents

Tidal currents are induced by the movement of the tidal wave around the earth's ocean surface. Under an undisturbed tidal wave the water particles are moving in the direction of the progressive tidal wave under the wave crest (high tide) and in opposite direction under the wave trough (low tide).

Near the coast, in straits, in estuaries and in tidal inlets, the tidal current is interacting with the land forms. These land and seabed forms forces the current to run shore parallel or through straits, estuaries or tidal inlets which may cause very high current velocities.

Effects of tidal currents

In coastal straits, extreme flow velocities of tidal currents can be well in the range of 5 kn (2.5 m/s) to 6 kn (3.0 m/s) and up to 10 kn (5 m/s) (Seymour Narrows, North America). However, such high currents do only occur in environments with a rigid (rocky) seabed.

Tidal currents are of great morphological importance in connection with estuaries, in tidal inlets and at river mouths. However, currents and morphological processes in estuaries will not be dealt with in this Guideline.

A tidal inlet is a channel that connects coastal lagoons with the sea, typically at barrier island coasts. They are subject to reversing tidal currents, and are conduits for the volume of water, the tidal prism, that flows in and out of the coastal lagoon through the tidal inlet during a tidal cycle. The tidal inlet is kept open by the shifting flood and ebb currents whereas a river mouth is kept open by a combination of the river discharge and the tidal exchange. There are typically also waves at the locations of tidal inlets and river mouths; the littoral transport generated by the waves will tend to close the inlet or the river mouth. The theory on stability of tidal inlets is a science in itself but this will not be treated in detail in this Guideline. The typical configuration of a tidal inlet is presented in Figure 5.35.

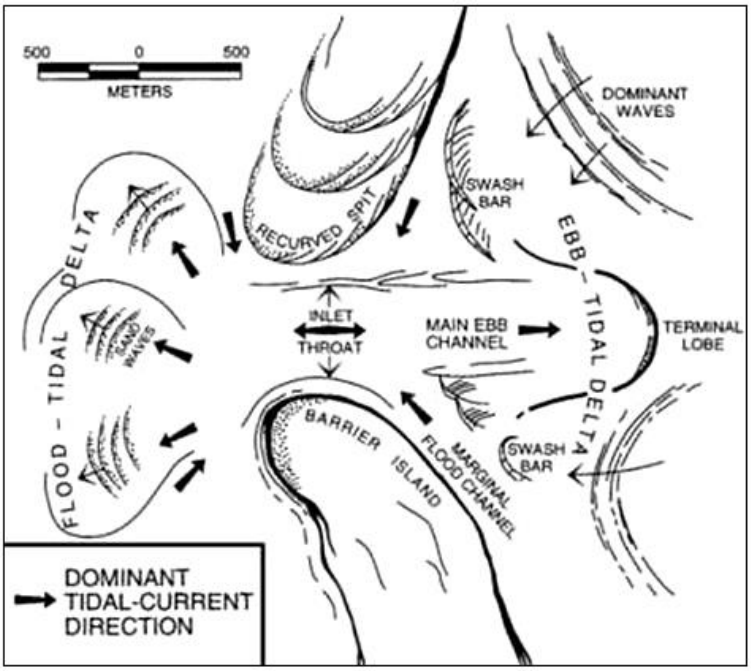


Figure 5.35 Tidal currents and morphological features in a tidal inlet.
http://www.state.nj.us/dep/srp/news/2000/0007_03.htm

It is evident that the current patterns and the associated sediment transport at such locations can be very complicated. Only a few general comments will be given in this overview of currents and their impacts.

There are often concentrated currents in the throat section of the inlet, but seawards of this area the current pattern expands and the current speed decreases. This is also the case landwards of the throat section in tidal inlets. The throat section is often deep and narrow, whereas the expanding currents on either side tend to form a shallow ebb tidal delta and irregular flood tidal delta shoals, respectively. The ebb tidal delta tends to form a dome-shaped bar on littoral transport shorelines, on which the littoral transport bypasses the mouth/inlet, see Figure 5.36.

Figure 5.36 Tidal inlet with dome shaped ebb delta shoal, river mouth east of Puri, Orissa State, India, 2006. Insert: Bypass mechanism, littoral transport bypassing on ebb delta. (Picture from Google Earth).

Many tidal inlets and river mouths are used for navigation. However, the shallow and ever-changing ebb tidal shoal constitutes a severe restriction on the navigation. Many tidal inlets are therefore protected by inlet jetties and dredged, which however, interrupts the littoral transport causing upstream sand accumulation and downstream coastal erosion. Furthermore, the regulated inlets are exposed to sedimentation. The management of tidal inlets is therefore a major challenge worldwide and the regulated inlets are a major cause for coastal erosion on sandy coasts.

The impact of tidal currents through at tidal inlet at a coast with a very mild wave climate is seen in Figure 5.37.

Figure 5.37 Ebb and flood shoals at tidal channel, Cay Calker, Belize. This area is mainly exposed to the tidal currents, whereas the wave climate is very mild.

5.5.1.2 Storm surge currents

Storm surge current is the current generated by the combined effect of the wind shear stress and the barometric pressure gradients over the entire area of water affected by a specific storm, and combined with the tidal currents. This type of current is similar to the tidal currents. The vertical current velocity follows a logarithmic distribution in the water column and has the same characteristics as the tidal current. It is strongest at large water depths away from the coastline and in confined areas, such as straits and tidal inlets. Whereas tidal currents are of regular oscillatory nature with typical periods around 6 and 12 hours the storm surge currents follow the time development of water level gradients caused by the storm surge.

In addition to tidal and storm surge currents, wave breaking generates currents near the coast, shore-parallel as well as shore-normal currents, respectively as described in the following.

5.5.1.3 Wave generated longshore currents

When waves are approaching obliquely to the shoreline and are finally breaking, a complex and highly turbulent long-shore current is initiated, the so-called longshore current, which is the dominant current in the nearshore zone. The longshore current is generated by the shore-parallel component of the stresses associated with the breaking process for the incoming waves, the so-called radiation stresses, and by the surplus water which is carried across the breaker-zone towards the coastline in the form of the mass transport and the surface roller drift (see later). This current has its maximum close to the breaker-line. During storms the longshore current can reach speeds exceeding 2.5 m/s. The longshore current carries sediment along the shoreline, the so-called littoral drift; this mechanism will be discussed further in Chapter 7.

The longshore current is generally parallel to the coastline and it varies in strength approximately proportional to the square root of the wave height and with $\sin 2\alpha_b$, where α_b is the wave incidence angle at breaking. As the position of the breaker-line constantly shifts due to the varying wave heights and since the distance to the breaker-line varies with the wave height, the distribution of the longshore current in the coastal profile will vary accordingly.

5.5.1.4 Wave generated shore normal currents

Rip currents

At certain intervals along the coastline, the longshore current may form a rip current. It is a local current directed away from the shore, bringing the surplus water carried over the bars in the breaking process back into deep water, see Figure 5.38.

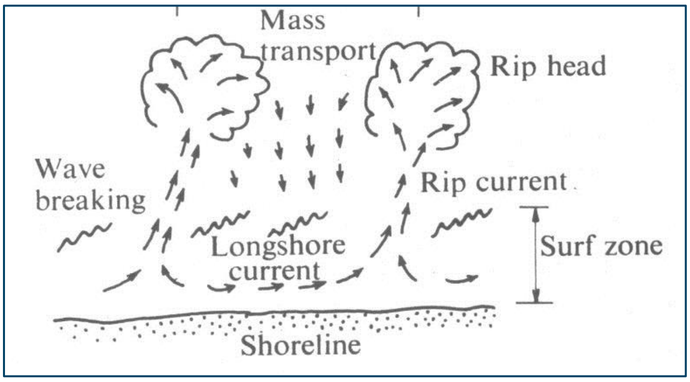


Figure 5.38 Principles of longshore currents and rip currents.

The rip gap in the bars will often form the lowest section of the coastal profile with less breaking than at adjacent locations, see Figure 5.39.

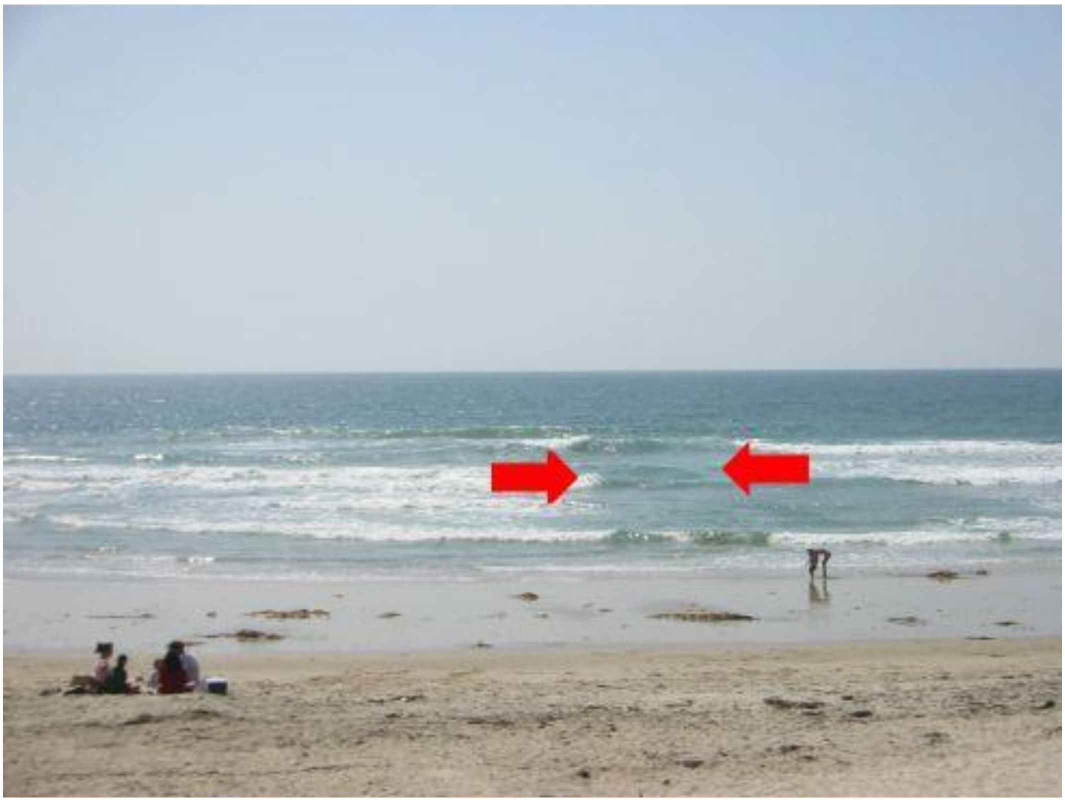


Figure 5.39 Reduced wave breaking at rip current gap in surf zone.
http://www.loving-long-island.com/rip-currents.html

A local setback in the shoreline is often seen opposite the rip opening. The rip opening travels slowly downstream. A numerical simulation of longshore currents and rip currents is presented in Figure 5.40.

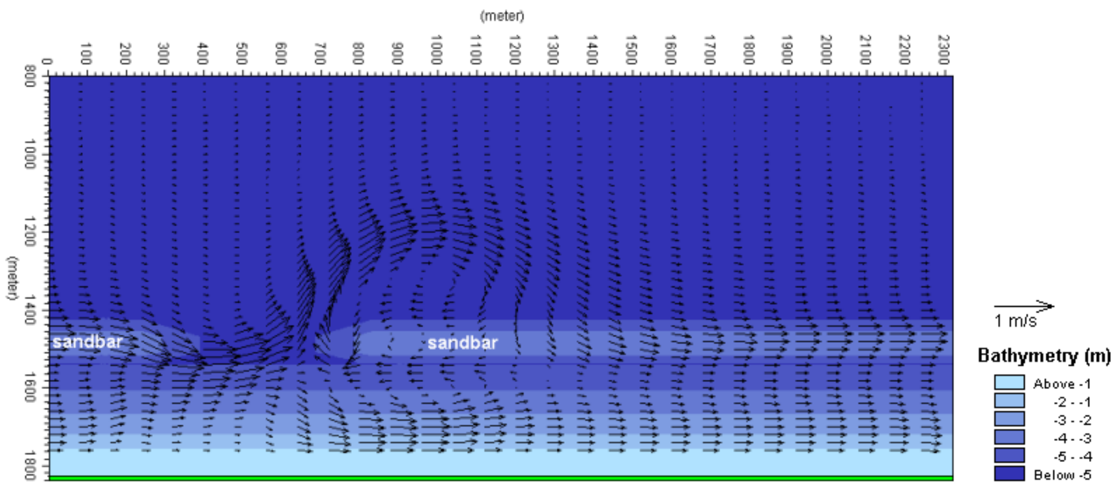


Figure 5.40 Distribution in longshore current in a coastal profile and rip current pattern.

Other shore-normal current contributions in the surf-zone on a straight coast are described in the following. These contributions balance in principal each other in combination with the rip currents.

- *Mass transport or wave drift*
  This is a phenomenon occurring during wave motion over both sloping and horizontal beds. Water particles near the surface will be transported in the direction of wave propagation when waves travel over an area. In the surf-zone the mass transport is directed towards the coast.

- *Surface roller drift*
  When the waves break, water is transported in the surface rollers towards the coast.

- *Undertow*
  In the surf-zone, the above two contributions are concentrated near the surface. As the net flow is zero, they are compensated for by a return flow in the offshore direction, which is concentrated near the bed. This is the so-called undertow. The undertow is important in the formation of bars.

5.5.1.5 Two-dimensional currents in the near shore zone

Along a straight shoreline, the above-mentioned shore-parallel and shore-normal current patterns dominate. The currents discussed in this sub-chapter are two-dimensional in the horizontal plane due to complex bathymetries and structures in the near shore zone.

Two-dimensional current patterns occur, especially in the following situations:

- *Irregular bathymetry*
  When the bathymetry is irregular and very different from the smooth shore-parallel pattern of depth contours characteristic of sandy shorelines, and also when the coastline is very irregular. This can, for example, be at partially rocky coastlines or along coastlines where coral reefs or other hard reefs are present. Irregular depth contours give rise to irregular wave patterns, which again can cause special current phenomena important to the understanding of the coastal morphology. Reefs provide partial protection against wave action. However, they also generate overtopping of water and compensation currents behind the reef. At low sections of the reef or in gaps in the reef, the surplus water returns to the sea in rip-like jets. This is the pattern for both submerged reefs and emerged reefs with overtopping during storms. Such current systems are of great importance to the morphology behind the reef. Changes in reef structure, natural or man-made, can cause great changes in the morphology.

- *In vicinity of coastal structures*
  Coastal structures, such as groynes, coastal breakwaters and port structures influence the current pattern in two principally different ways: by obstructing the shore-parallel current and by setting up secondary horizontal circulation currents.

Obstruction of shore-parallel current

The nature of the obstruction of the shore-parallel currents of course depends on the extension and shape of the coastal structure. If the structure is located *within the breaker-zone*, e.g. a groyne field, the obstruction leads to offshore-directed jet-like currents, which cause loss of beach material, see Figure 5.41.

Figure 5.41 Groyne field at Delfland, Holland. The groynes generate rip jets, which transport sand away from the littoral zone. From Terra et Aqua, Number 107, June 2007.

If the structure is a port, the current will follow the upstream breakwater and finally reach the entrance area. The currents in the entrance area will both influence the navigation conditions and cause sedimentation. The layout of the entrance must provide a smooth and predictable current pattern so its impact on navigation is acceptable, sedimentation must be minimised and the bypass of sand must be optimised. The answer is a smooth layout of the main and secondary breakwaters combined with a narrow entrance pointing towards the prevailing waves; this is referred to as a bypass harbour. This is further discussed in Subchapter 18.3.2.

Currents in sheltered areas

At the leeward side of coastal structures, special current patterns caused by the sheltering effect of the structure in the diffraction area can develop. Sheltered or partly sheltered areas may result in circulation currents along the inner shoreface as well as return currents leading to deep water. The reason for this is that the wave set-up in the sheltered areas is smaller than in the adjacent exposed areas and this generates a gradient in the water level towards the sheltered areas. These circulation currents in the sheltered areas can be dangerous for swimmers who are using the sheltered area for swimming during rough weather. Another problem is that the sheltered areas will be exposed to sedimentation and such areas must, therefore, be avoided when planning small ports. Examples of such wave generated circulation currents are presented in Figure 5.42.

If the structure extends *beyond the breaker-zone*, the shore-parallel current will be directed along the structure, where the increasing depth will decrease the speed. The current will deposit the sand in a shoal off the breaker-zone upstream of the structure. In the case of a major port, the longshore current will not reach the entrance area.

In the lee area of a major coastal structure, the effect of return currents towards the sheltered area will also be pronounced, but the current circulation pattern will be smoother and less dangerous for swimmers. The sheltered areas will act as a sedimentation area adding severely to effects of the lee side erosion outside the sheltered area of such structures. Consequently, sheltered areas should be avoided.

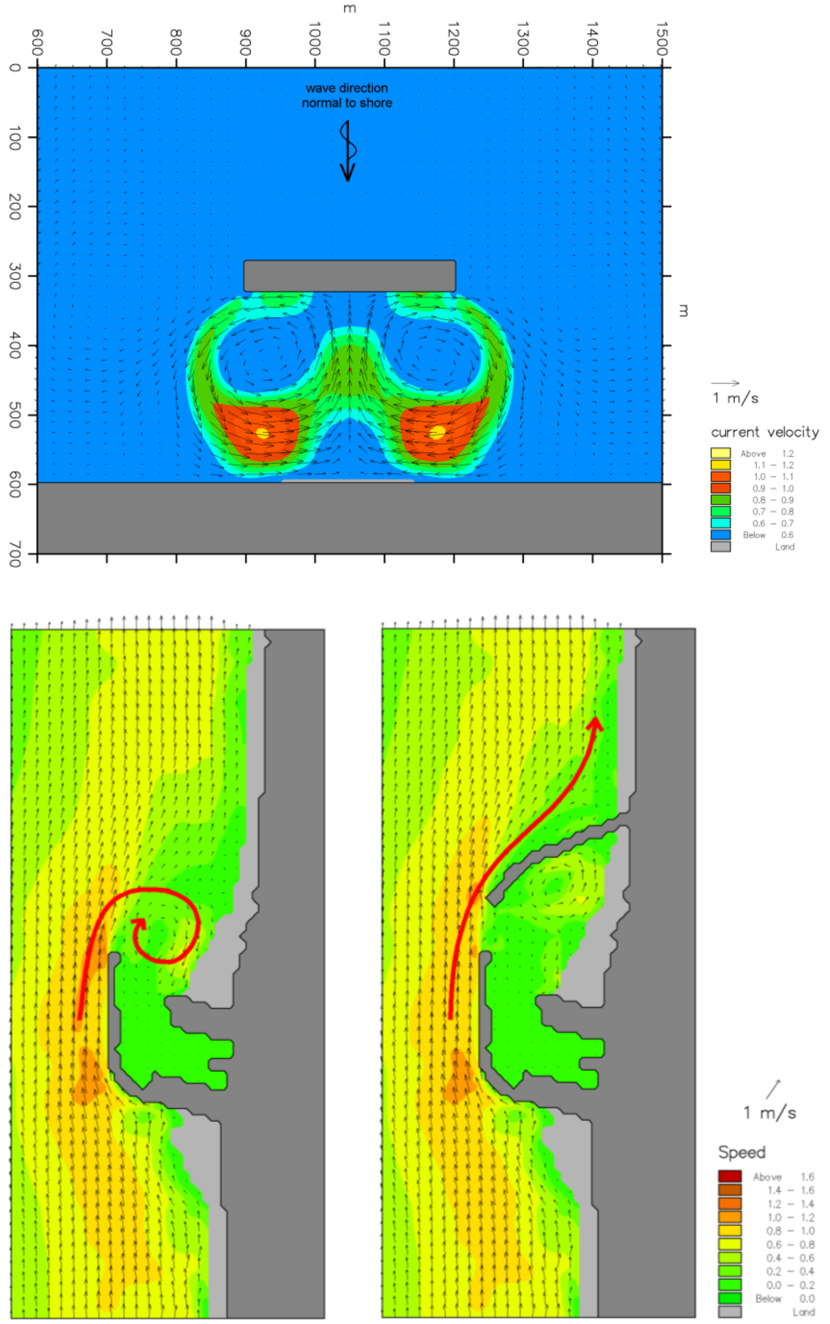


Figure 5.42 Circulation patterns in sheltered areas. Upper: a coastal breakwater. Lower: a small port. Left: original port with circulation current. Right: Optimised layout of the small port, avoiding the lee area provides optimal bypass and minimum sedimentation in the entrance.

5.6 Variations in water level

Variations in water level can be divided into the following types:

- Tides, which are regularly oscillating variations with periods from half days up to one year
- Non-regular variations with recurrence periods from days up to several years, mainly caused by meteorological conditions, e.g. storm surge, wind set-up, barometric pressure variations,

seasonal/yearly variations in weather conditions and climate changes (Sea Level Rise due to climate changes are discussed in Chapter 6.3)

Variations in water level – extreme as well as ordinary - are important because they lead to transport processes, which in turn lead to morphological changes. Flooding and design conditions for structures and reclamations are other important aspects of extreme water levels. Finally, water level oscillations are important for the formation and development of tidal inlets and estuaries.

5.6.1 Astronomical tide

The astronomical tide is generated by the rotation of the earth combined with the varying gravitational impact of the sun, the moon and the planets on the water. The rotation of the earth and the predictable movements of the sun and the planets govern the tide. These *tidal constituents* determine the tide at a given location. As the tide-generating forces per square metre are proportional to the depth, the tide is mainly generated in the deep oceans, from where the tide propagates to the coastal waters as a long wave.

The tidal wave height in deep water is normally less than 0.5 m. The tide in shallow coastal waters is modified by shoaling and friction, and in restricted waters by funnelling, so at certain locations the tide can be up to 15 m high.

An example for the huge influence of local tides on water level fluctuations can be seen in Figure 5.43 for the Bay of Fundy in Canada. Here, the differences between low tide and high tide are approx. 17 m.

Figure 5.43 Bay of Fundy (High Tide Water Level and Low Tide Water Level).

The astronomical tide at a specific location can be predicted and is published in *Tidal Tables*. The tidal conditions at a location vary mainly according to semi-diurnal and diurnal tidal constituents, the most important of which are called M_2, S_2, K_1 and O_1. If the semi-diurnal constituents dominate at a location, the tide is characterised as *semi-diurnal tide*, and if the diurnal constituents are predominant, it is characterised as *diurnal tide*. Mixed tides also occur. A semi-diurnal tide has two low waters and two high waters every day, whereas diurnal tides have only one of each every day.

Tide types may be classified by the amplitude ratio F:

$$F = (K_1 + O_1)/(M_2 + S_2)$$

as presented in Table 5.5.

Table 5.5 Classification of tides in semi-diurnal, mixed and diurnal tides (Defant 1961).

Amplitude ratio F	Classification
$F < 0.25$	Semi-diurnal
$0.25 \le F < 1.5$	Mixed, mainly semi-diurnal
$1.5 \le F < 3.0$	Mixed, mainly diurnal
$F \ge 3.0$	Diurnal

The time series of the tide at a specific site consists of the sum of the four dominant tidal constituents (plus a series of secondary constituents). The resulting tidal signal shows typical fortnightly variations (approx. 14.8 days), which cause the tide to be higher than average at full moon and at new moon, this is referred to as *spring tide*, and lower at the quarters, which is referred to as *neap tide*. This variation is caused by interplay of the different tidal constituents.

Typical types of tides, where semi-diurnal, mixed and diurnal tides as well at spring tides and neap tides are seen, are presented in Figure 5.44.

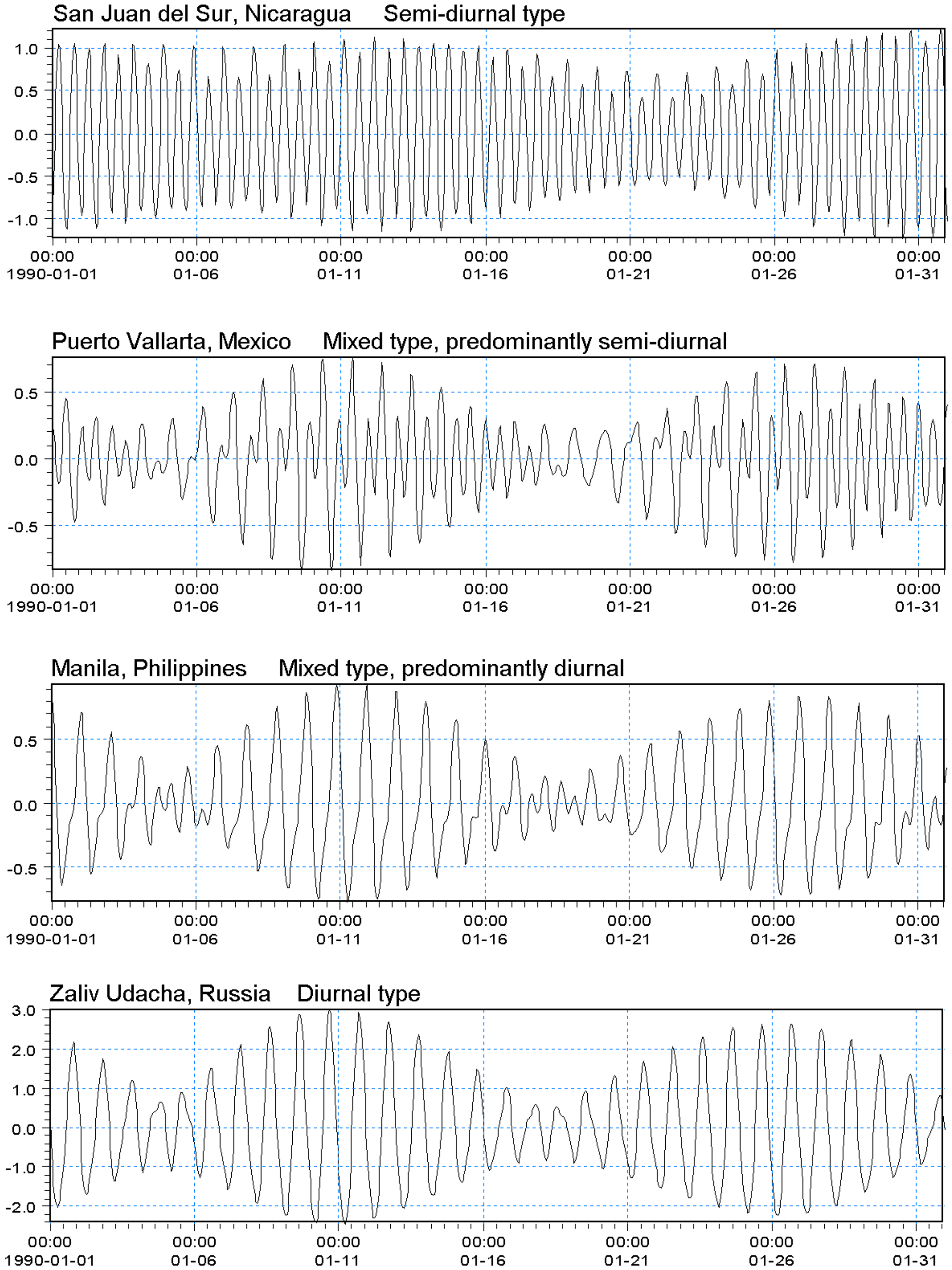


Figure 5.44 Different types of tides.

Astronomical tides are published in Tidal Tables and can be found for many locations world-wide via the internet or via local services. In addition, the free software WXTide32 can be used to generate tidal information for tide gauges worldwide. Normally, real time values or reduced values are available for selected locations. The most important reduced and characteristic tide levels are presented in Table 5.6.

Table 5.6 Characteristic tide levels.

Acronym	Name	Description	
		Semi diurnal or diurnal	Mixed tide
CD	Chart datum	The arbitrary level to which charted depths and tide heights are measured	
LPLW	Lowest Predicted Low Water	The level below which the tide seldom, if ever, falls below	
MLW	Mean Low Water	Used as a datum on the East coast of the USA.	
LAT	Lowest Astronomical Tide	The lowest tide that may occur under standard meteorological conditions	
MSL	Mean Sea Level	The mean level of the sea	
MHWS	Mean High Water Springs	The mean level of high water at springs	
MHW	Mean High Water	The average of all high water heights	
MHWN	Mean High Water Neaps	The mean level of high water at neaps	
MLWN	Mean Low Water Neaps	The mean level of low water at neaps	
MLW	Mean Low Water	The average of all low water heights	
MLWS	Mean Low Water Springs	The mean level of low water at springs	
MHHW	Mean Higher High Water		The mean height of the higher high water
MLHW	Mean Lower High Water		The mean height of the lower high water
MHLW	Mean Higher Low Water		The mean height of the higher low water
MLLW	Mean Lower Low Water		The mean height of the lower low water
Spring ML	Spring Mean Level	The average of MHWS and MLWS	
ISLW	Indian Spring Low Water	Chart datum used in India and the Persian Gulf	
MTL	Mean Tide Level	A datum located midway between MHW and MLW	
HAT	Highest Astronomical Tide	The highest tide that may occur under standard meteorological conditions	

In addition, tides are characterised using the tidal range which is the vertical distance between characteristic tidal levels:

Mean Spring Tidal Range MSTR:	MHWS - MLWS
Mean Tidal Range or Tidal Range MTR or TR:	MHW - MLW
Mean Neap Tidal Range MNTR:	MHWN - MLWN

The magnitude of the tide (Mean Tidal Range) at a site can be categorised as follows (Davies 1980):

Macro tidal regime:	Tidal Range > 4 m
Meso tidal regime:	Tidal Range 2 m – 4 m
Micro tidal regime:	Tidal Range < 2 m

A similar categorisation can be made for the storm surge conditions at a given site. The coastal morphology at sites with a macro tidal range, and a relatively mild wave climate, is normally greatly influenced by the tide and this is often reflected in wide tidal flats.

Figure 5.45 shows the distribution of tide types and tidal ranges along main coasts of the World.

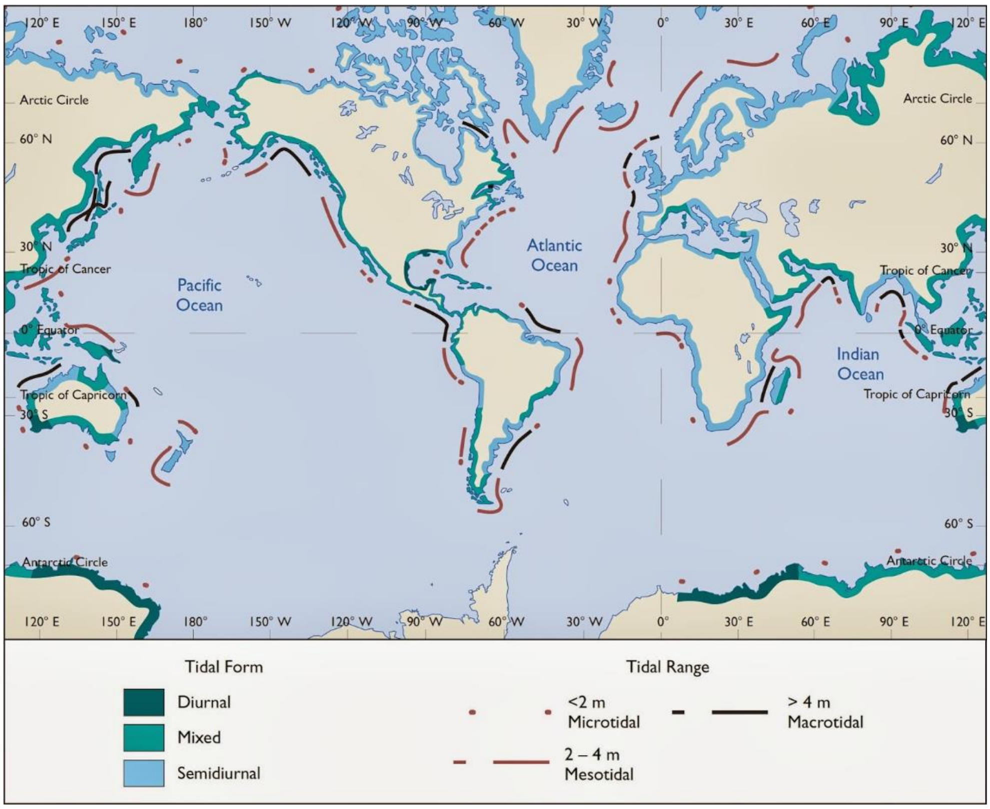


Figure 5.45 Distribution of type of tide and tidal range along main coasts of the World. From: Invitation to oceanography / Paul R. Pinet, 2009.

Sea charts contain information about the tidal levels MHWS, MHWN, MLWN and MLWS, whereas national and international tidal tables publish a more complete list of times for all high and low waters at selected ports. The reference level is of great importance for the correct use of the tidal information. In most areas, the reference level is close to MLWS or LAT, but a small deviation from one of these levels is not uncommon. In areas with only small tidal variations, the reference level is often close to MSL.

5.6.2 Seasonal variations

In some areas seasonal variations in wind and pressure systems, and in evaporation and precipitation, lead to seasonal variations in the water level. These seasonal changes in mean sea level are tabulated in the Admiralty Tide Tables.

5.6.3 Non-regular variations

5.6.3.1 Storm surges

As mentioned before, deviations from the astronomical tides can occur due to wind, storms, tropical cyclones/hurricanes and due to pressure fluctuations. Storm surge is defined as the rise of water above normal tidal water level on the open coast as a result of the combined effects of the action of wind stress on the water surface, the atmospheric pressure reduction, shallow water depths and the horizontal boundaries of the adjacent waters. The storm surge does theoretically not include the effect of the astronomical tide; however, the combined effect of astronomical and meteorological surges is often referred to as a tidal wave - the popular expression for an unusually high and destructive water level along a shore. However, in the general opinion storm surge is synonymous with tidal wave, which means the combined effect of astronomical and meteorological surges.

Winds generate shear stresses on the surface of the water and as a consequence, mass transport in local currents is generated. If the currents and consequently the mass transport are directed onto a coastal area (shallow water) or onto a bay, additional water fills the coastal area and as a consequence leads to wind set-up.

In theory, the wind set-up is proportional to the fetch length and to the wind velocity to the power of 2 and inversely proportional to the local water depth. However, these correlations are not applicable in practices as the form of the water body is also of major importance for the resulting storm surge. However, it is important to notice that storm surges are greatest in shallow water areas and in confined bays, such as in the SE part of the North Sea.

During storm surges water levels of 5 m to 10 m above the normal conditions may be reached.

Storm surges occurring in connection with the shifting tide and varying wind conditions

Storm surges, exclusive those generated by cyclones, are often analysed on basis of tidal gauges installed in ports and similar places. Many of these gauges have been in operation for several decades and this data therefore constitutes a sound basis for analysis of exceedance duration and for extreme event analysis. The exceedance duration analysis is typically performed on basis of hourly recordings whereas extreme event analysis typically is performed on basis of the highest recorded water level during individual independent storms above a certain threshold or on basis of yearly maximum recorded water levels. The result of such extreme event analyses are extreme water levels (design water levels) as function of the recurrence period T_d. An example of such analysis is presented in Figure 5.46.

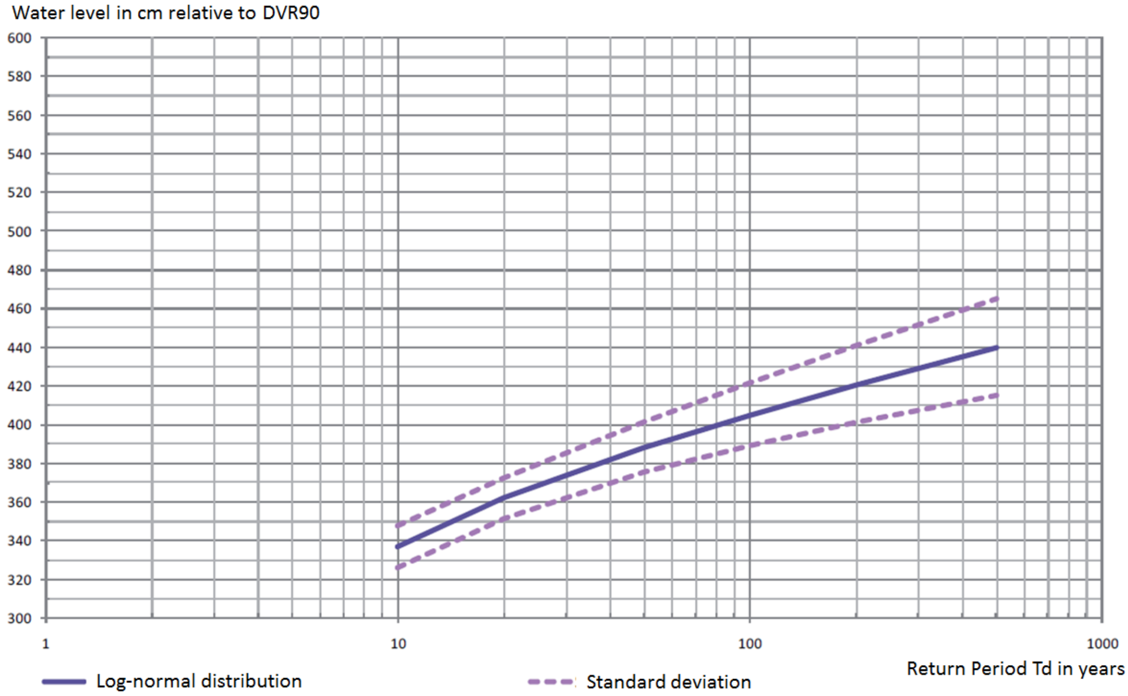


Figure 5.46 Extreme water level in cm relative to National vertical reference DVR90 as function of recurrence period T_d in years, for Esbjerg, Denmark. From: Extreme sea level statistics for Denmark, 2012, by Danish Coastal Authority.

Storm surges can also be analysed on basis of hindcast simulations in a hydrodynamic model covering the regional waters for a specific site, typically for a period of minimum 20 years however typically a longer period.

Storm surges related to cyclones require special cyclone analysis methodology because of the nature of cyclones in terms of characteristic cyclone tracks, their limited extension and their rare occurrence at a specific site.

5.6.3.2 Impacts of waves on the water level in the nearshore zone

Wave set-up occurs in the surf zone as a local effect. Wave set-up is the increase of the water level within the surf zone due to the transfer of wave-related momentum to the water column during wave-breaking (Dean & Walton, 2009), see also the description of wave set-up, etc. in Subchapter 5.3.2.6. As a consequence, the mean water level is locally higher in the nearshore zone than the still water level (SWL), see Figure 5.47. The Still Water Level (SWL) at a site for the design situation is the sum of the design storm surge and the Sea Level Rise. The wave impact on the water level in the nearshore zone is divided into a static component called the wave set-up and dynamic component called the wave uprush or the wave swash. The sum of the wave set-up and wave swash is denoted wave run-up. The sum of the SWL and the wave set-up constitutes the mean water level during the design event; this is also referred to as the Flooding Level (FL). The sum of the SWL and the wave run-up is called the Wave Impact Level (WIL).

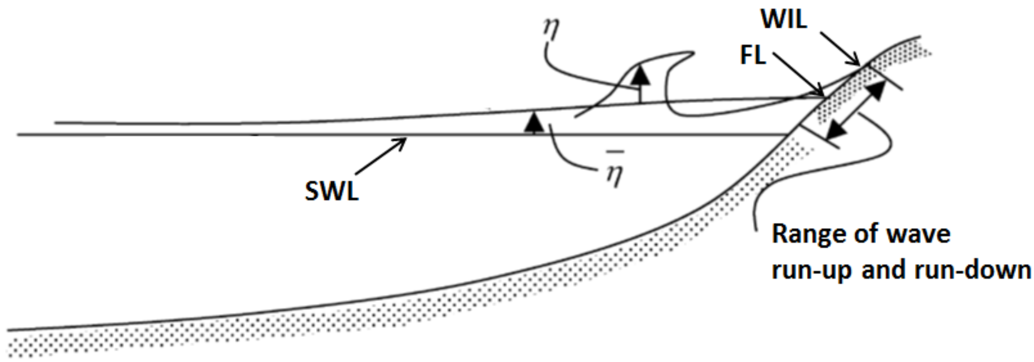


Figure 5.47 Illustration of differences between still water level (SWL) in the offshore area, flooding level (FL) in the nearshore zone and the run-up line on the beach or the wave impact level (WIL). Reference: Dean & Walton, 2009.

Wave set-up is more or less proportional to the wave height at breaking. As a rule of thumb, the wave set-up is of the order 20% of the offshore significant wave height. Of special importance are gradients in wave set-up, e.g. in partly sheltered shallow areas near port entrances, as such gradients will generate local circulation in the surf-zone towards the sheltered area thereby contributing to sedimentation in the entrance to the port. Additionally, oscillations in the wave set-up caused by wave grouping, called surf beats, in areas near a port entrance may cause oscillations in the water level in the port, which may introduce a pumping of water in and out of the port basin. This may introduce heavy siltation in the basin, see Subchapter 5.4.1.

5.6.3.3 Joint probability of waves and storm surges

Storm surges and high waves often occur simultaneously during the passage of a storm. However, there are situations where storm surges and high waves are not positively correlated. This is e.g. the case for coasts facing towards east in the Inner Danish Waters, where storm surge is closely related to the connection of the inner waters to the North Sea and to the Baltic Sea and to the high hydraulic resistance through the narrow straits. Storm surges in the northern Inner Danish Waters occur when water is pressed into these waters from the North Sea combined with regional wind setup, consequently storm surges occur for regional strong winds between west and North, also for coasts facing east, see Figure 5.48. Lack of correlation between onshore winds and high waters may also occur in areas where the water levels are dominated by non-storm components, for instance by astronomical tide. In these cases it is required to perform joint probability analyses of water levels and wave heights to assess the relevant design conditions.

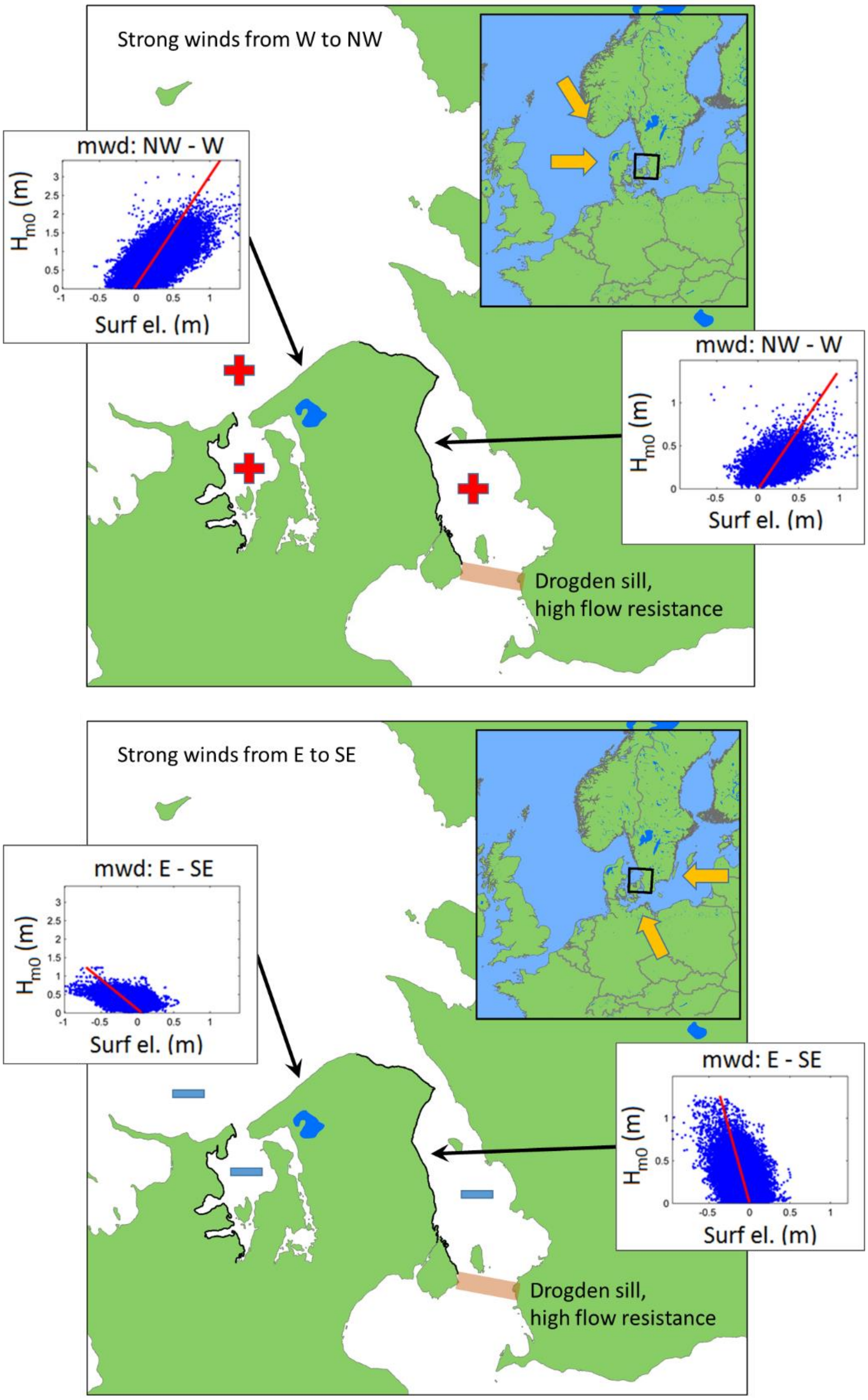


Figure 5.48 Surge levels along some inner Danish coastlines are exemplified with plus/minus for a case with westerly/northerly winds (top) and for a case with easterly/southerly winds (bottom). The coastlines highlighted in black will have a negative correlation between storm surges and H_{m0} (for onshore waves) as indicated by the scatter plots.

6 Climate Changes

The following description of climate changes summarises available scientific information on climate changes as background for the discussion of impacts of the climate changes on the coast and of climate adaptation measurers. It is noted that climate changes are subject to constant research and that the presently forecasted climate changes most probably will change in the future, but there seems to be consensus about the following statements:

- climate changes will certainly occur but the magnitude of the changes is for discussion
- it is recommendable to include adaptation to climate changes in future planning in coastal areas

The present Guideline will only briefly cover the causes for the climate changes and will not cover possible remedial measures for reduction of the climate changes but solely discuss the impact of and adaptation to the forecasted climate changes under the assumption that the forecasted climate changes are taking place.

6.1 Historical climate changes

Historical trends in temperature, sea level and snow cover have been widely documented for many areas; cf. Figure 6.1, Figure 6.2 and Figure 6.3.

Data from the publication:

> IPCC SPM 2013: Working Group 1 Contribution to the IPCC Fifth Assessment Report (AR5), Climate Change 2013: The Physical Science Basis, Summary for Policymakers

is the main source of information used in the following but also other sources are used.

Historical sea level rise is discussed further in the following. A (moderate) rise of the mean sea level ("secular sea level rise") has been monitored since more than a century at many water level gauges all over the world, (see e.g. Gauge Warnemünde, Baltic Sea in Figure 6.2). The long term rates of the local sea level rise are in the range between 1 and 2 mm/year. Altimeter data from satellites has been analysed for many parts of the world by NOAA (Figure 6.3). NOAA calculated an average sea level rise for the world of 2.8 mm/year for the last 20 years and IPCC 2013 describes it as likely that the mean global rate of sea level rise was 3.2 mm/year between 1993 and 2010. These rates are significantly higher than the average rate of the past century.

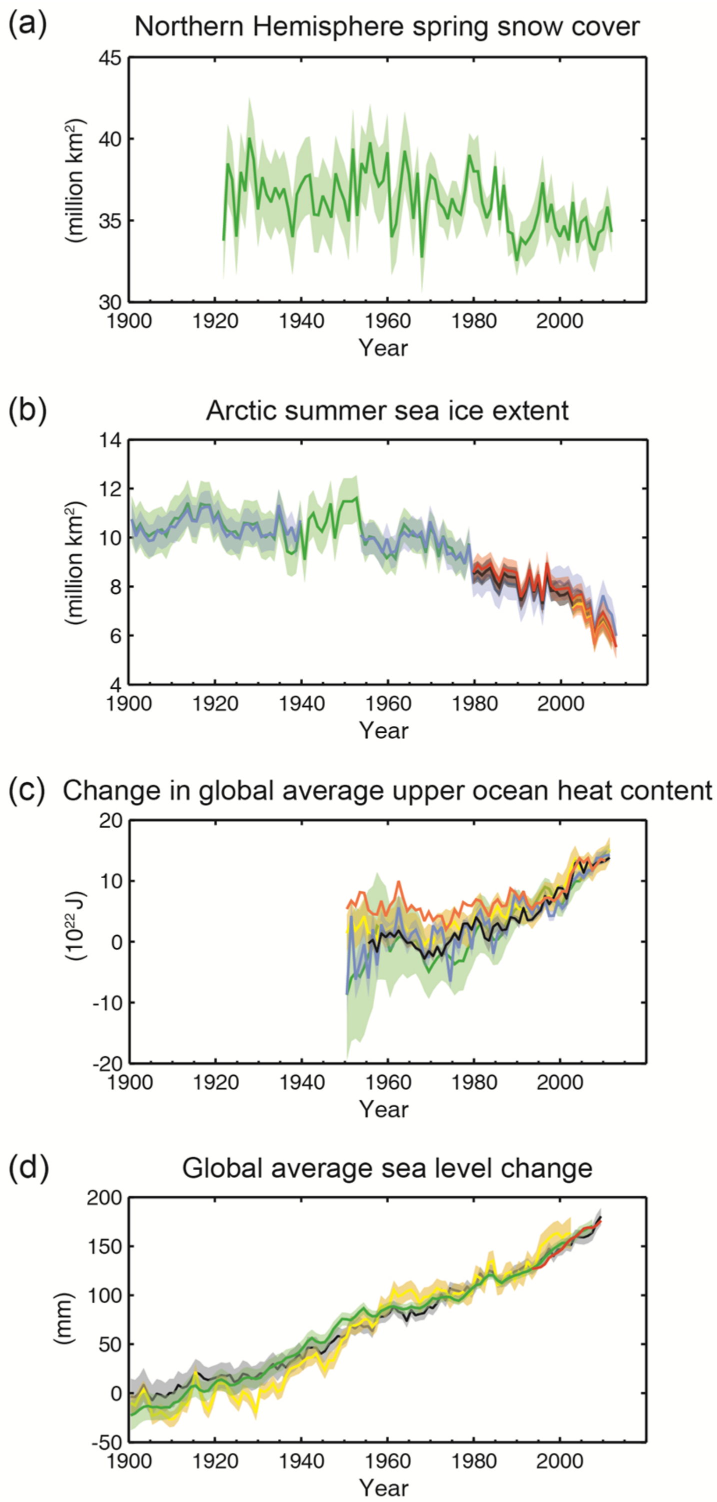


Figure 6.1 Copy of Figure SPM.3 from IPCC SPM 2013. Multiple observed indicators of a changing global climate. (a) extent of Northern Hemisphere March-April average snow cover, (b) extent of Arctic summer average sea ice, (c) change in global mean upper ocean (0 – 700 m) heat content relative to mean of all datasets for 1971 and (d) global mean sea level relative to the 1900 – 1905 mean with all datasets aligned to have the same value.

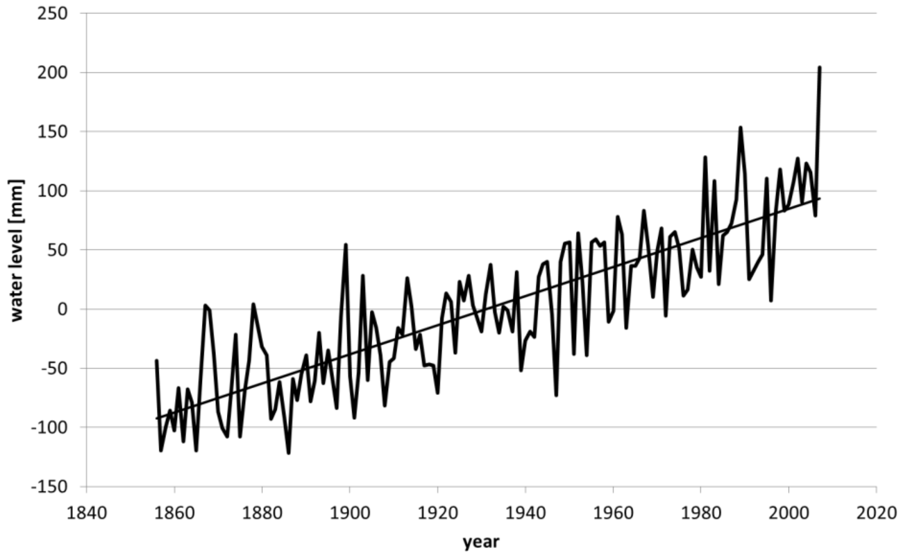


Figure 6.2 Sea level changes gauge Warnemünde, Baltic Sea, (data source: PSMSL data, www.psmsl.org , average sea level rise approx. 1.23 mm/year), Fröhle et al. 2011.

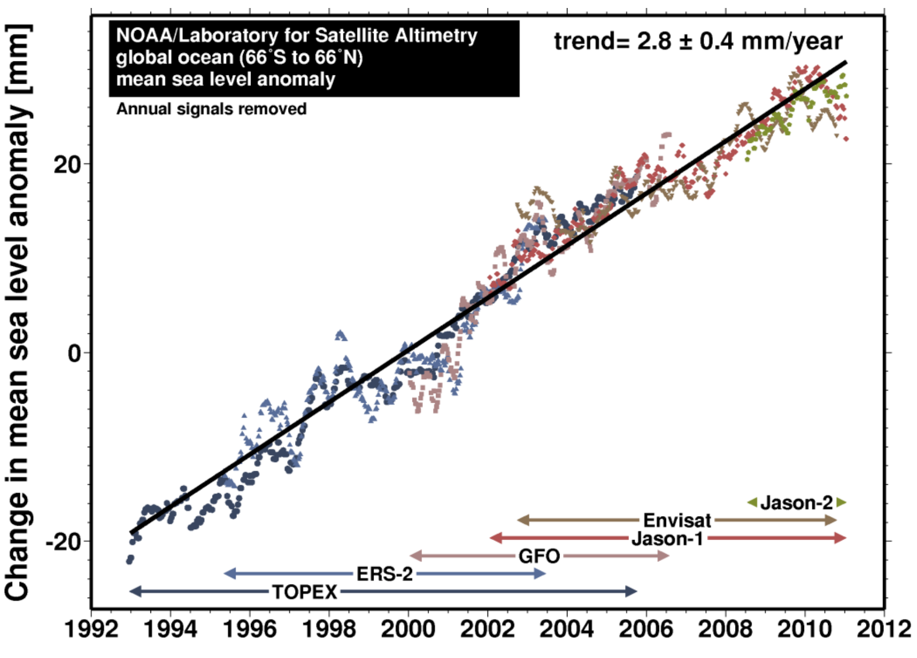


Figure 6.3 Sea level time series for the Global mean sea level (annual signals removed) measured by altimeter Satellite (NOAA Laboratory for Satellite Altimetry, Data for other areas can be found at http://ibis.grdl.noaa.gov/SAT/SeaLevelRise/LSA_SLR_timeseries_regional.php)

Basically, the absolute changes of the mean sea level are divided into eustatic and isostatic changes, where *isostatic* changes result from the loading/unloading of the earth crust caused by the ice caps, by tectonic movement of the earth crust by subduction or earthquakes, or by subsurface extraction of water, gas, oil, coal, etc. from the ground.

The *eustatic* changes result mainly from the sea temperature effects of climate change and are therefore directly related to global warming. The relative changes, which are ultimately decisive for coastal erosion and coastal flooding, result from the addition of the local isostatic and eustatic changes as illustrated in Figure 6.4.

The trend in the relative in sea level will show a considerable regional variation. The change in land level is local or regional. It may be caused by isostatic rebound after the last glaciation, subsidence due to extraction of ground water or hydrocarbons and compaction of delta deposits. The sea level rise is also expected to vary over the globe. For example, melting of ice from an ice sheet will cause a significant change in in the local mass distribution, which will give a subtle change in the Earth's gravity field. The result is that the gravitational pull from the ice sheet is reduced and the adjacent water level may even be reduced due to the melting while the increase further away will be even larger than if the melted water had been evenly distributed over the oceans. More details on this subject can be found in the technical reports from IPCC and in the specialist literature; a recent and comprehensive presentation is given by: Church et al. (2010).

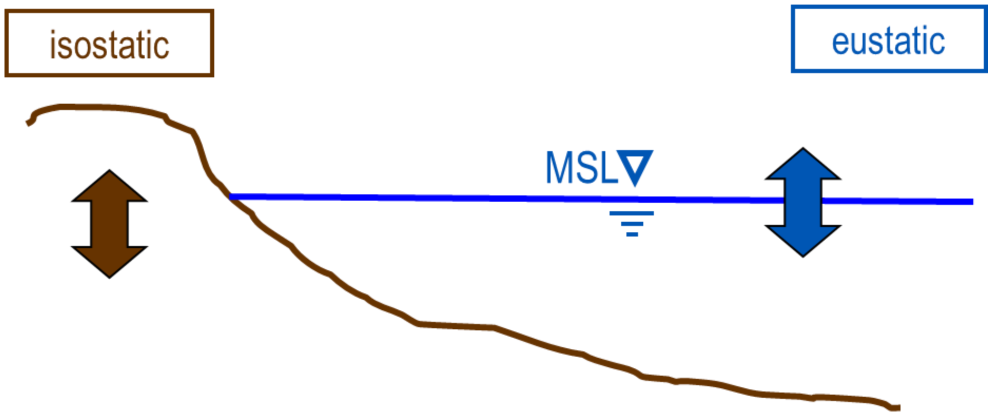


Figure 6.4 Isostatic and eustatic effects on the local relative mean sea level.

For shoreline management there is naturally an interest in the wave climate and surge levels, which both are directly related to the wind climate. It is difficult to determine trends in the wind climate, reference is made to Weisse and von Storch (2009) for a thorough treatment of the subject. First, the wind conditions show a considerable variability of a time scale of several decades. For example, the storm activity in the North Sea has been rather weak in the 1960s, high around 1990 and show a strong decrease into the decade after 2000. Second, it is difficult to obtain reliable measurements over a long period, the instrumentation has changed as well as the environment around the weather stations. The observational techniques have also developed rapidly. As an example the number of observed cyclones show a strong increase as satellite data has become available. This effect is most drastic on the southern hemisphere where surface stations are more sparse. Instead time series covering a century or more are obtained from proxy data such as atmospheric pressure from a single station or pressure differences between stations. The latter makes it possible to estimate trends in the wind velocity by assuming geostrophic conditions. A study by Bärring and von Storch (2004)) showed no long term (over centuries) trend in storminess based on Swedish barometric data.

IPCC concludes that after accounting for changes in observation capabilities there is a low confidence for long term changes in tropical cyclone activity. It is virtually certain that the storm frequency and intensity in the North Atlantic has increased since the 1970s, but the underlying reason is uncertain. It is likely that the extreme high water levels have increased since the 1970s, but most of the rise can be attributed to an increasing mean sea level.

6.2 Expected impacts due to climate changes

Recent scientific climate research and observations of global climatic conditions have made it clear that many future climate conditions will differ from historic and current trends. This change in climate conditions in general, change in sea level rise, changes in storm patterns and ocean acidification in particular, will likely present the biggest planning and engineering challenges for current and future protection of coastal areas.

Over the last few decades, there has been increased global awareness of the effects of anthropogenic climate change. Not a day goes by where the public is not warned that the continuation of our fossil-fuel powered lifestyles will lead to increased global temperatures, increased sea level rise, decreased ocean pH levels, and changes to precipitation and storm patterns. These changes will have many consequences for the world society. Global Climate Models (GCMs) show positive links between increasing atmospheric concentrations of carbon dioxide (CO2) and increasing global temperature, scientists are more and more convinced that human activities have and will continue to influence these changes. As more and more research identifies harbingers of change – from earlier blooming of springtime plants to ice-free summers in the arctic, scientists and the public are more and more concerned about the consequences of climate change. IPCC SPM 2013 expresses the likelihood of human impact as shown in the box below and in Figure 6.5.

> Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes (Figure SPM.6 and Table SPM.1). This evidence for human influence has grown since AR4. It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century. {10.3–10.6, 10.9}

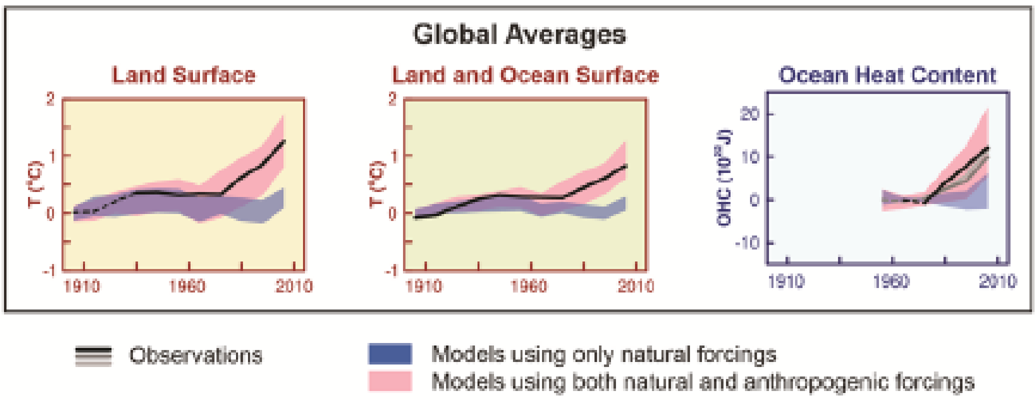


Figure 6.5 Copy of part of Figure SPM.6 from IPCC SPM 2013. Comparison of observed and simulated global average climate change indicators: Change in the continental land surface air temperatures, change in the land and ocean surface air temperatures and change in upper ocean heat content.

The climate changes are expected to vary between different regions of the world; however, scientists are predicting increasing temperatures in most parts of the planet. Increasing global temperatures will have consequences that ripple through many sectors, as outlined by the Intergovernmental Panel on Climate Change, see Figure 6.6.

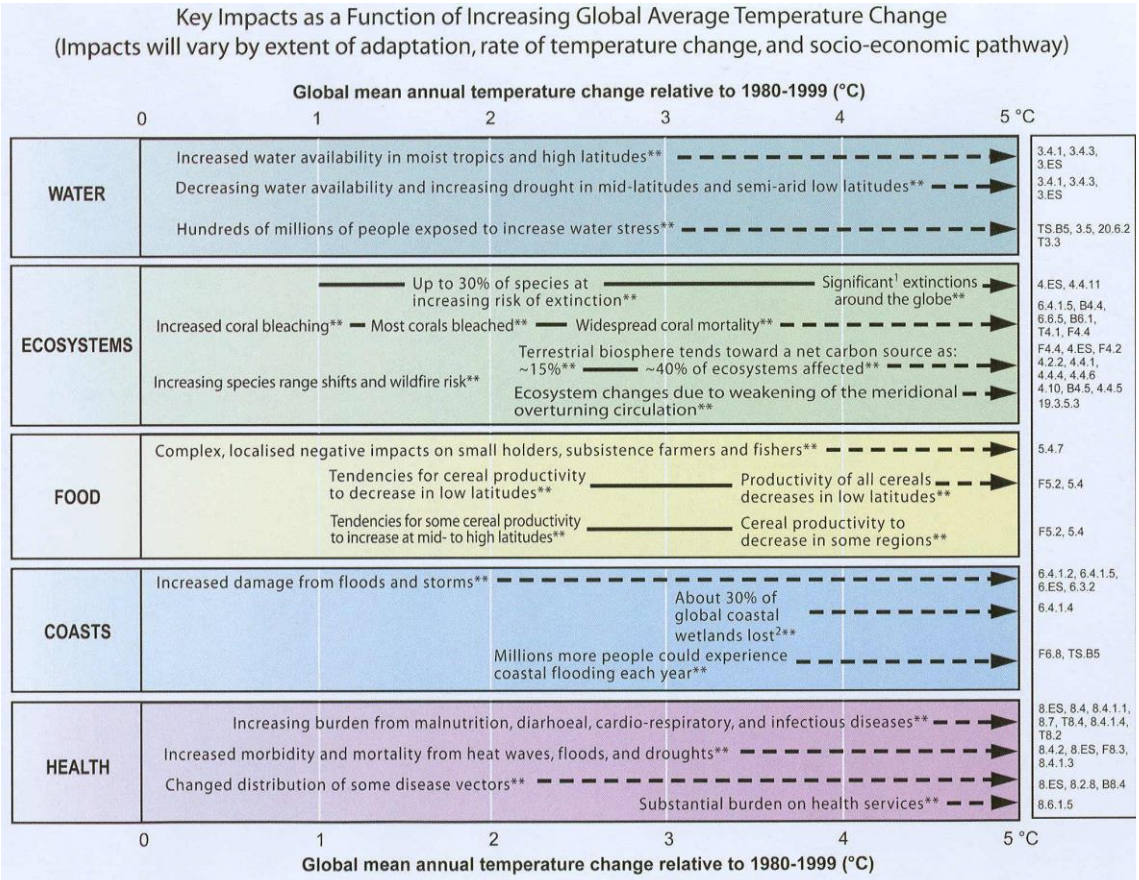


Figure 6.6 Predicted impacts from different temperature increases (IPCC 2007).

6.2.1 Impact of climate changes in coastal areas

The following climate changes cause the main physical and biological impacts within the coastal zone:

- Rise in sea water temperature
- Sea level rise
- Changed wind pattern (increased storminess)
- Changed precipitation
- Increased acidification

The direct or indirect impacts in the coastal zone caused by these climate changes are outlined in Table 6.1.

It is noticed that the climate changes have direct impacts on the coastal zone as well as impacts via secondary effects. The most important climate change element for the coastal zone is “Sea level rise” (SLR) as described further in Subchapter 6.3.

Table 6.1 Summary of climate changes impacting coastal areas, their secondary effects and their impacts.

Climate changes impacting coastal area		Secondary effects		Impacts: Type	Impacts: Nature
Increase in sea water temperature		Sea level rise		See below	
		Risk of coral bleaching		Coral reef degradation and coastal erosion	Gradual
Sea level rise		Landward movement of the water/land interface Elevated coastal groundwater levels Reduced gradient of coastal rivers and streams Vertical and lateral expansion of the zone of tidal influence in coastal rivers and streams		Coastal flooding of protected low lying areas	Catastrophic, impacting large areas
				Coastal flooding of low lying areas	Gradual
				Change coastal wetlands	Gradual loss of existing wetlands and generation of new wetlands
				Backwater problems, increased salinity and sluice practice	Gradual
				Shoreline retreat (coastal erosion)	Gradual, along the shoreline
Changed wind pattern (increased storminess)		Higher storm surge		Coastal flooding of low lying areas and shoreline retreat	Acute events
		Higher waves	Higher littoral transport	Shoreline retreat or Shoreline accretion	Gradual, along the coast
		Changed directional characteristics of winds and waves	Changed littoral transport		
Changed precipitation	Higher	Increased supply of sediments to the coast		Shoreline accretion	Gradual
		Increased supply of nutrients to coastal waters		Euthrophication	Gradual
				Backwater problems	Gradual
	Lower	Decreased supply of sediments to the coast		Shoreline retreat	Gradual
Increased acidification		Stressing of marine flora and fauna		Changes in marine flora and fauna such a coral reefs	Gradual

6.3 Sea level rise due to climate changes

Sea level rise is one of the most direct links to global temperature. Sea level is driven by many different factors, as listed below:

- Increasing sea temperature which causes thermal expansion of the oceans
- Melting of the Arctic/Antarctic ice caps and glaciers worldwide
- Rapid reduction in area of arctic sea ice during the summer, which causes increased absorption of heat in the ocean
- The reduction in the gravitational force from the Arctic/Antarctic ice caps as they are reduced in volume due to melting will change the regional mean sea level in areas "adjacent" to the ice sheets

Many factors affect the local sea level along the coasts. The Intergovernmental Panel on Climate Change (IPCC) has highlighted research and policy insight at the sub-national (regional) scale as an important and unexplored geographic and political arena for analysing the impacts of, and responses to sea-level rise. Historical trends in temperature, sea level and snow cover have been widely documented for many areas, see Figure 6.1, Figure 6.2 and Figure 6.3 , but the predictions of the rate of sea level rise into the future and even the utility of local historic trends in predicting future conditions have remained a contentious and debatable issue. There is a critical need, not only to understand sea-level change and its impacts around the world, but more particularly the situation as it pertains to coastal cities in the mega deltas around the world but especially in Countries in Transition due to in the near absence of data/research in these locations.

Projected sea level rise resulting from simulations of the different scenarios from the work undertaken by the IPCC yields a range of projected increases. In the IPCC, SPM 2013 the projected increases from 1986-2005 to 2081–2100 was given in the range of +0.26 - +0.82 m, cf. Table 6.2, which presents the main results of the simulations related to surface warming and sea level rise.

Table 6.2 Copy of table SPM.2 from IPCC, SPM, 2013, Projected change in globally mean surface air temperature and sea level rise for the mid- and late 21st century relative to the reference period 1986 – 2005.

		2046–2065		**2081–2100**	
Variable	**Scenario**	mean	*likely* range [c]	mean	*likely* range [c]
Global Mean Surface Temperature Change (°C) [a]	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8
		mean	*likely* range [d]	mean	*likely* range [d]
Global Mean Sea Level Rise (m) [b]	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

There is some variation in the forecasts for the various Representative Concentration Parthways (RCPs). However, it is evident that a mean sea level rise in the range of 0.40 to 0.63 m, i.e. in the order of 0.50 m in 2081-2100 is expected as an average of all the modelling results reported in IPCC 2013.

The above referred IPCC 2013 scenarios do include the possible acceleration of ice melting from the arctic ice sheets and the projected sea level rise however, this was not the case with the IPCC 2007 scenarios. The IPCC 2013 projections are therefore considered more reliable than the previous estimates.

At present there are two major techniques to project future sea level rise. A hierarchy of climate models (simple to comprehensive climate models, IPCC 2013) and semi-empirical models. The IPCC 2013 climate model simulations used a new set of scenarios, the Representative Concentration Parthways (RCPs) for the projections for temperature, precipitation and sea level rise. Semi-empirical models, the most regularly discussed being the work by Rahmstorf (2007), develops a relationship between historic temperature and sea level rise to project future sea level rise based upon the GCM temperature projections. Since Rahmstorf's initial study, several other semi-empirical projections have been developed, as shown in Figure 6.7.

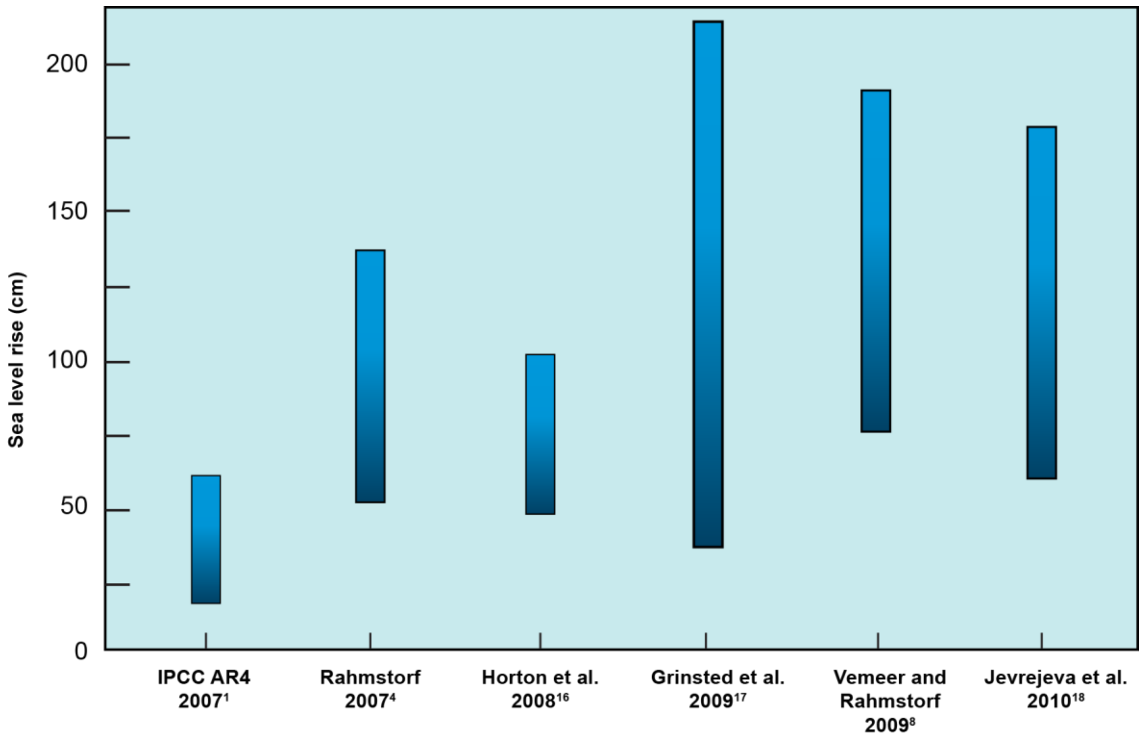


Figure 6.7 Estimates for twenty-first century sea level rise from semi-empirical models as compared to the 2007 IPCC Fourth Assessment Report (AR4). For exact definitions of the time periods and emissions scenarios considered, see the original references (IPCC (2007); Rahmstorf (2007); Horton et al. (2008); Grinsted et al. (2009); Vemeer and Rahmstorf (20109; Jevrejeva et al. (2010))

Many of these studies recommend projections for SLR which are considerably higher than the projections provided in the IPCC report 2013. Other research and international institutions have also published climate projections which are higher than those proposed by IPCC, an example is the report: Synthesis Report, Climate Change, Global Risks, Challenges & Decisions, Copenhagen 2009, 10 – 12 March, published by International Alliance of Research Universities:

Quote from Climate Change, Copenhagen 2009:

> *"These revised estimates show that the ocean has warmed significantly in recent years. Current estimates indicate that ocean warming is about 50% greater than had been previously reported by the IPCC. -- The rate of sea level rise has increased in the period from 1993 to the present, largely due to the growing contribution of ice loss from Greenland. However, models of the behaviour of these polar ice sheets are still in their infancy, so projections of sea level rise to 2100 based on such "process models" are highly uncertain. An alternative approach is to base projections on the observed relationship between global average temperature rise and sea level rise over the past 120 years, assuming that this observed relationship will continue into the future. New estimates based on this approach suggest a sea level rise of around a metre or more by 2100. Sea level rise will not stop in 2100. Changes in ocean heat content will continue to affect sea level rise for several centuries at least. Melting and dynamic ice loss in Antarctica and Greenland will also continue for centuries into the future. Thus, the changes current generations initiate in the climate will directly influence our descendants long into the future. In fact, global average surface temperature will hardly drop in the first thousand years after greenhouse gas emissions are cut to zero."*

Future changes in wind- and wave climate and storm surge levels have been predicted by down scaling of long term simulations by global climate models for the last part of the 20th and all of the 21st century for different emission scenarios (or RCPs). The global climate model is then used to generate boundary conditions for a more detailed regional model covering for example the Eastern part of the North Atlantic and the North Sea. This regional model is typically run for two time slices of 20-30 years, one covering the present conditions and one in the future at the end of the 21st century. The detailed results from the regional climate model can then be used to force a hydrodynamic model simulating the tide and surge and a wave model. For more details see Weisse and von Storch (2009). These models simulate the behaviour of complex weather systems and an extensive statistical analysis of the results is required to determine the predicted trends in the climatic conditions. In order to be consistent and compensate for at least some of the model errors the comparison is made for results from the same model complex for the late 20th and the late 21st century. The studies involve different combinations of RCP, global climate model and regional climate model, which may show the considerable uncertainty associated with our understanding of and ability to model the processes affecting the changing climate and the resulting weather conditions.

Tropical cyclones are formed over warm water bodies with a surface temperature above 26.60˚ C and derive their energy from latent heat through evaporation from the sea surface. According to IPCC it is likely that the frequency of tropical cyclones will decrease or remain unchanged but that the maximum wind speeds in the cyclones will increase.

Extratropical cyclones, wind fields at the mid-latitudes such as in the North Sea and North Atlantic, are in the west wind belt. These are associated with travelling low pressure systems formed at the boundary between warm and cold air masses and can produce strong winds. It has proven difficult to predict trends for these weather systems. It is considered unlikely that the number of extratropical cyclones will decrease significantly. It is likely that the storm tracks will shift poleward on the southern hemisphere and in the North Pacific while the North Atlantic predictions are more complex.

It is very likely that there will be a significant increase in the occurrence of sea level extremes, but this increase will primarily be the result of an increase in the mean sea level.

6.3.1 Examples of local practice

Rising sea levels will impact directly on coastal cities, towns and subsistence communities mainly through coastal flooding and through coastal erosion. The sea level rise recommendations, guidelines or requirements used by different governments or agencies are provided below as examples of the different approaches used around the world.

United Kingdom: The sea level projections developed by Defra for the coast of Great Britain is such an example. The main tools used by the United Kingdom for coastal management are Shoreline Management Plans (SMP), revised Shoreline Management Plans (SMP2), Defra SMP, and a new Coastal Change Policy, Defra (2010). The UK anticipates that with whatever policies are put into place now to address climate change, that their country will experience at least 30 to 40 years of rising temperatures and 100 years of rising sea level. The UK coast has experienced an average historic sea level rise of 1 mm/yr, or 0.1 m per century. In anticipation of increased future sea level rise, new engineering projects with a 100-year design lifetime **are required to include up to 1 m of sea level rise**. The plan provides recommended rates of sea level rise for various time periods (Table 6.3), recognising that the rate of rise is expected to be larger at the end of the 21st century than at the beginning of the century.

Table 6.3 UK Recommended Net Sea level rise rates and cumulative amounts, relative to 1990.

Time Period	Low Rate (mm/yr)/ cumulative SLR since 1990 (m) at end of period	Moderate Rate (mm/yr)/ cumulative SLR since 1990 (m) at end of period	High Rate (mm/yr)/ cumulative SLR since 1990 (m) at end of period
1990 – 2025	2.5/0.09	3.5/0.12	4.0/0.14
2025 – 2055	7.0/0.30	8.0/0.36	8.5/0.40
2055 – 2085	10.0/0.60	11.5/0.71	12/0.75
2085 – 2115	13.0/0.99	14.5/1.14	15/1.21

SOURCE: Defra 2010

The Netherlands: The Netherlands has had a long tradition of reliance upon dykes and engineered structures for flood protection and had undertaken a very pro-active approach for national flood protection. After the 1953 North Sea floods, the country initiated a major effort to upgrade its protective works and most major urban areas now have sea protection designed for recurrence periods that range from 2,000 to 10,000 years for coastal flooding, and from 250 to 1,250 years for river flooding. Work by Stefan Rahmstorf (projecting up to a 1.4 m rise in sea level from 1990 to 2100 through a semi-empirical method that correlates global sea level rise and global temperature) has informed much of the recent work by the Delta Commission. The major recommendations for future flood protection include heightening and strengthening existing engineering protection, identifying overflow area for flood events that exceed the capacity of existing and future flood structures. Advanced beach and dune nourishment projects to buffer the coastlands from erosion and flooding and provide for ecosystem enhancement has already been implemented, referred to as “Ecoshape Projects” or “Building with Nature” (Sand motor with 22 million m^3 and The Hondsboscche Zeewering with about 40 million m^3).

South Africa: In South Africa, recommendations for sea level rise to use in projects are based on the project type and significance. Table 6.4shows the breakdown of project types and recommended sea level rises.

Table 6.4 Sea level rise Amounts for Different Types of Infrastructure, South Africa, from Mather (2010).

Value of infrastructure	Life of infrastructure	Impacts of failure of the infrastructure	Planned amount of sea level rise
Low (Up to R2 million) I.e. Recreational facilities, car parks, board walks, temp beach facilities	Short term Less than 20 years	Low Minor inconvenience, alternative facilities in close proximity, short rebuild times	0.3m
Medium (R2 million to R20 million) Tidal pools, piers, recreational facilities, sewerage pump stations.	Short to Medium Term Between 20 and 50 years	Medium Local impacts, loss of infrastructure and property	0.6m
High (R20 million to R200 million) Beachfronts, small craft harbours, Residential homes, sewerage treatment works.	Medium to Long Term Between 50 and 100 years	High Regional impacts, loss of significant infrastructure and property	1.0m
Very High (Greater than R200 million) Ports, desalination plants, nuclear power stations	Long term In excess of 100 years	Very High Major disruption to the regional and national economy, failure of key national infrastructure	2.0m

California, Oregon, and Washington. The US National Academy of Science/National Research Council has in 2012 issued the following report:

Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future, NRC 2012

The recommendations from this report are presented in Table 6.5.

Table 6.5 Regional Sea Level Rise projections (in cm) relative to year 2000 for Seattle, Newport, San Francisco and Los Angeles, Table 5.3 from NRC 2012.

	2030		2050		2100	
Component	Projection	Range	Projection	Range	Projection	Range
Steric and dynamic ocean[a]	3.6 ± 2.5	0.0–9.3 (B1–A1FI)	7.8 ± 3.7	2.2–16.1 (B1–A1FI)	20.9 ± 7.7	9.9–37.1 (B1–A1FI)
Non-Alaska glaciers and ice caps[b]	2.4 ± 0.2		4.4 ± 0.3		11.4 ± 1.0	
Alaska, Greenland, and Antarctica with sea-level fingerprint effect[c]						
Seattle, WA	7.1	5.4–9.5	16.0	11.1–22.1	52.7	32.7–74.9
Newport, OR	7.4	5.6–9.5	16.6	11.7–22.2	54.5	34.1–75.3
San Francisco, CA	7.8	6.1–9.6	17.6	12.7–22.3	57.6	37.3–76.1
Los Angeles, CA	8.0	6.3–9.6	17.9	13.0–22.3	58.5	38.6–76.4
Vertical land motion[d]						
North of Cape Mendocino	-3.0	-7.5–1.5	-5.0	-12.5–2.5	-10.0	-25.0–5.0
South of Cape Mendocino	4.5	0.6–8.4	7.5	1.0–14.0	15.0	2.0–28.0
Sum of all contributions						
Seattle	6.6 ± 5.6	-3.7–22.5	16.6 ± 10.5	-2.5–47.8	61.8 ± 29.3	10.0–143.0
Newport	6.8 ± 5.6	-3.5–22.7	17.2 ± 10.3	-2.1–48.1	63.3 ± 28.3	11.7–142.4
San Francisco	14.4 ± 5.0	4.3–29.7	28.0 ± 9.2	12.3–60.8	91.9 ± 25.5	42.4–166.4
Los Angeles	14.7 ± 5.0	4.6–30.0	28.4 ± 9.0	12.7–60.8	93.1 ± 24.9	44.2–166.5

It is seen that average SLR projections for year 2100 range between 62 and 93 cm ±27 cm.

6.3.2 Concluding remarks

It is evident from the scientific sources quoted above that consensus on the magnitude of future sea level rise that the world society will experience in the future has not been reached. The highest projections available in the scientific literature should not be treated as likely increases in 21st century sea level, but they are useful for vulnerability tests against flooding in regions where there is a large risk aversion to flooding, or the consequences of flooding are particularly catastrophic. Different SLR-scenarios are typically used dependent of the consequences of the flooding or erosion.

A practical recommendation is to use central estimates of sea level rise from different sources and to perform sensitivity analyses reflecting the range of variability in the estimates. **A likely scenario to use seems to be that the sea level rise in year 2100 will be in the range of 0.5 m to 1.0 m however with a risk of being about 50% higher and that the sea level will continue rising also after year 2100**.

6.4 Impacts of climate changes in coastal areas

6.4.1 Coastal flooding

Sea level rise will increase the risk for coastal flooding of low lying coastal areas through the rise of extreme storm surge levels. The sea level rise in itself will normally not cause flooding but the raised sea level will increase the extreme water levels caused by storm surges, or in other words, the sea level rise will decrease the recurrence interval of storm surge events, see Figure 6.8 and Figure 6.9.

The impact of a sea level rise can be quite different within relatively short distances dependent of the slope of the exceedance curve for storm surges for different locations. The forecasted SLR for Denmark in year 2100 is presented in Figure 6.10. It is seen that the a SLR of 0.8 m is expected in Esbjerg (at the SW coast of Denmark) and a SLR of 0.7 m is expected in Copenhagen (at the eastern part of Denmark)

The examples shows that a rise in the sea level of 0.8 m in Esbjerg decreases the recurrence period from 100 years to 2.5 years for flooding of a dike, which is designed for a water level of 4.05 m. The shift in recurrence period is dependent of the slope of the extreme water level exceedance curve, and a flatter slope will introduce even more drastic reductions in the recurrence period for design events. This is evident from the similar example from Copenhagen in Figure 6.9, where a 0.7 m rise in sea level introduces a decrease in the recurrence period from 100 years to about 4 months for exceedance of the water level 1.50 cm.

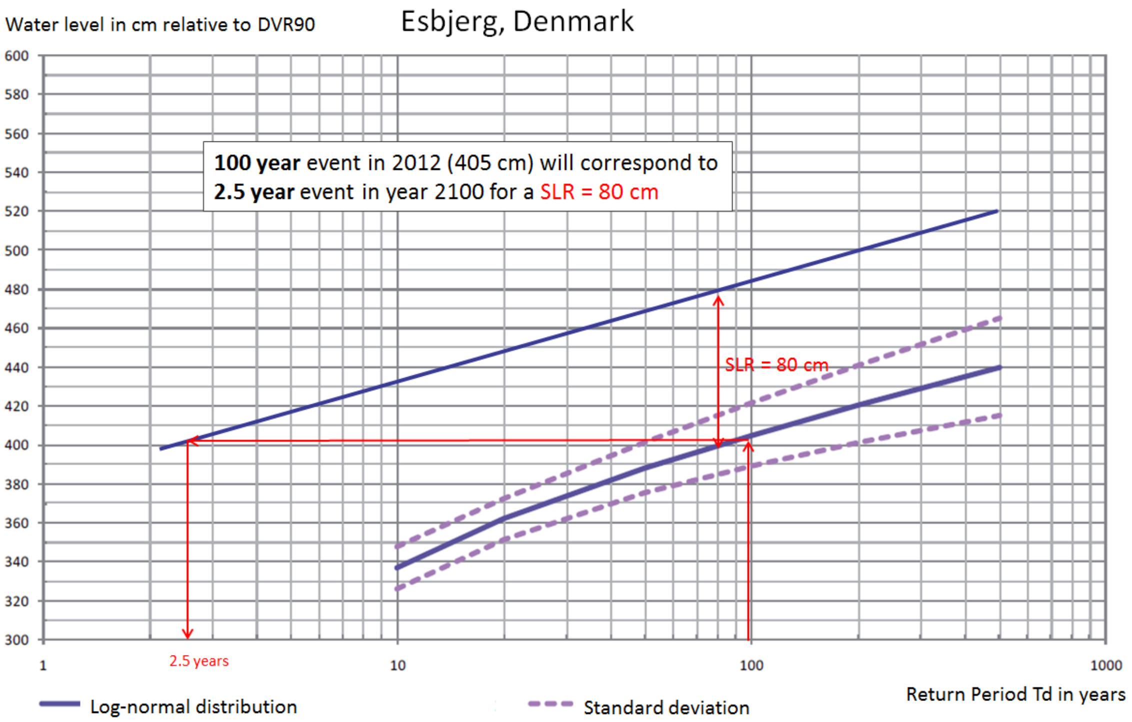


Figure 6.8 Example of extreme water level analysis, flooding levels vs. recurrence period in years for Esbjerg, a town at the Danish West Coast. The influence of a 0.80 m rise in sea level is shown.

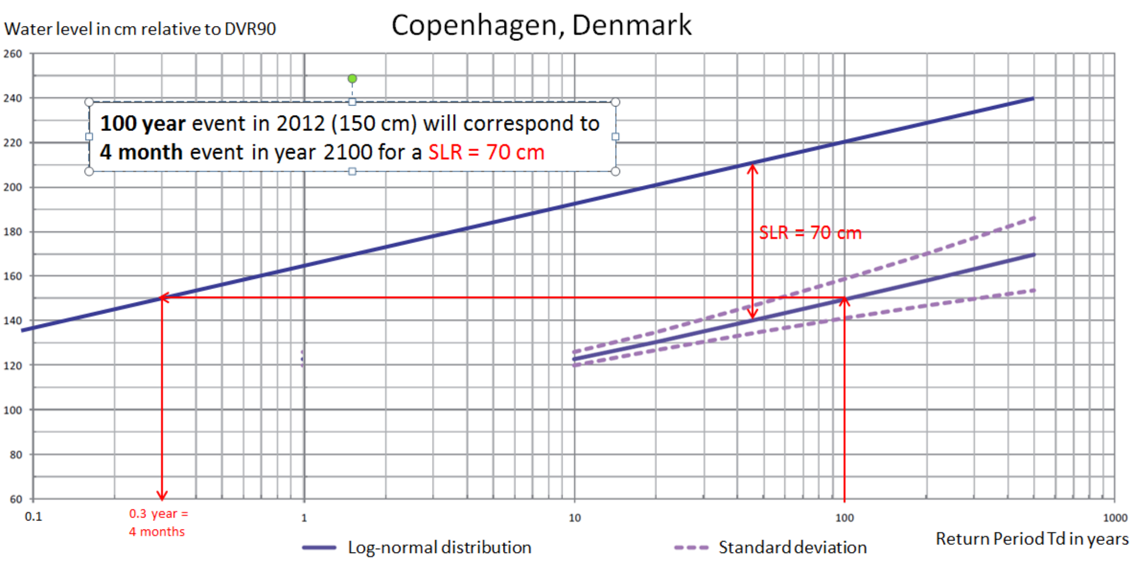


Figure 6.9 Example of extreme water level analysis, flooding levels vs. recurrence period in years for Copenhagen, Denmark. The influence of a 0.70 m rise in sea level is shown.

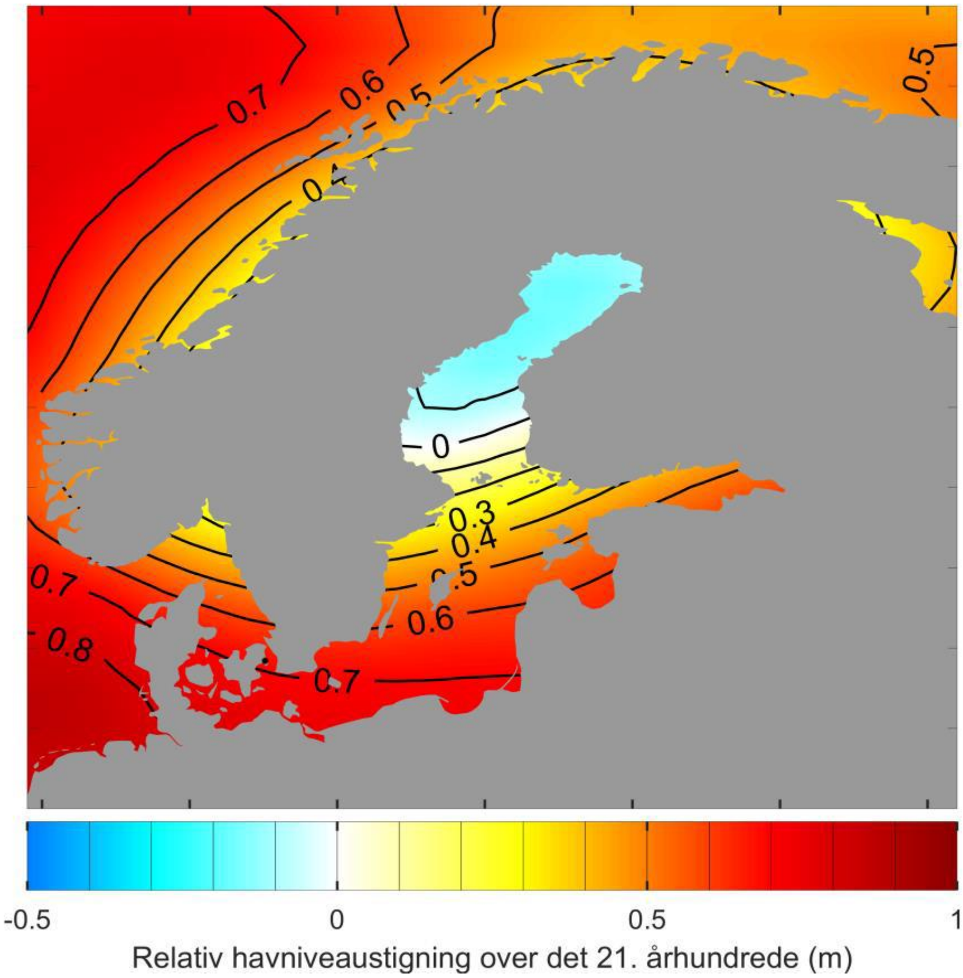


Figure 6.10 Relative sea level rise in Scandinavia in year 2100, including impacts of isostatic rebound movements.

It is thus seen that the impact of the expected year 2100 sea level rise in Denmark of between 0.7 m and 0.8 m for the eastern and western part, respectively, has great importance for the risk of flooding of low lying coastal areas, and the impact is relatively higher at locations which have a mild storm surge climate at present. The exceedance of design conditions may lead to overflow or breaching of sea defence structures (dikes), which is a catastrophic event as the protected low hinterland will suddenly be flooded. Proper adaptation measures shall consequently be implemented in a timely manner. Furthermore, the rise in sea level will increase the risk for coastal flooding in low lying areas, which are presently not protected. This is an important planning issue for low lying areas. Wetlands, dune systems and beaches will be drowned and while new wetlands or dunes may eventually develop further inland, this will only be possible if the inland locations are not already covered with shore protection, roads, or other “permanent” assets. The impacts of sea level rise will of course be most significant in low lying areas, such as deltas, along barrier islands and at atoll islands. There are special challenges in planning for sea level rise in coastal towns as it is not straight forward to implement sea defence structures along a city frontage.

6.4.2 Shoreline retreat

Sea level rise will introduce shoreline retreat. According to Bruun's rule (Bruns 1962) a sandy beach with a slope of the active coastal profile of s (typically s = 1/50 to 1/100) exposed to a sea level rise of h_{slr} will experience a shoreline retreat R = h_{slr}/s. Thus, a coastal profile with a slope s = 1/100 exposed to a sea level rise h_{slr} = 1.0 m will experience a shoreline retreat of R = 1/(1/100) = 100 m, which corresponds to a SLR generated erosion rate of ER_{SLR} = 1 m/year. This is a relatively small erosion rate on an exposed coast but a relatively high erosion rate at a moderately exposed coast. A typical natural erosion rates for an exposed coast is $ER_{N,E}$ = 3 m/year and for a moderately protected coast it is $ER_{N,P}$ = 0.3 m/year. The relative erosion rate is defined as R_{ER} = ER_{SLR}/$ER_{N.}$ This means that the relative erosion rate for an exposed coast will be in the order of R_{ER} ~ 0.3 and for a moderately exposed coast R_{ER} ~ 3. This indicates clearly that the relative severity of the increased erosion rate due to SLR will differ widely from site to site.

Shoreline retreat, also referred to as coastal erosion, caused by sea level rise is a gradual process and it can consequently be mitigated gradually as the sea level rises. However, it is of course advised to incorporate the increased coastal erosion in the planning for coastal areas.

6.4.3 Increased storminess

An increasing frequency of more extreme storms and cyclones is predicted for the 21st Century. The IPCC considers it *likely* that future cyclones will be strengthened by higher tropical sea surface temperatures resulting in more intense events with higher wind speeds and heavier rainfall, and maybe covering areas of higher latitudes (IPCC 2007). Some regions are likely to experience an increase in average wind speed throughout the year caused by stronger prevailing winds. The effect of just a 10% increase in wind speed on the coastal environment creates an order of magnitude increase of other coastal processes. A 10% increase in wind speed is predicted to result in about 26% increase in wave heights and potential increasing longshore transport rates by between 40% and 100% (Theron 2007). Actual changes will be co-determined by many other factors such as changes in wind directions, sediment availability, wave transformation, higher sea level, etc. These impacts are likely to affect the shoreline particularly in areas weakened by previous erosion or in low lying coastal areas.

6.4.4 Ocean warming and acidification

Increasing water temperature and decreasing ocean pH (termed ocean acidification) are two other consequences of climate change. Decreased coral calcification and decreased coral growth have already been observed on the Great Barrier Reef of Australia (Hoegh-Guldberg et al. 2007) as a result of recorded temperature and dissolved CO2 increases and these changes can be expected to continue with greater increases in warming and CO2 concentrations (Anthony, et al. 2008). At some point, the decrease in calcification may cause not just decreased coral growth but a decline in coral volume. Healthy coral reefs are of vital importance to the tropical habitats and also to the stability of tropical beaches. Most directly, the reefs dissipate wave energy, protecting the inland beaches from direct wave attack. In addition, carbonate beaches get their sand from the erosion of the coral reefs. Decreased coral calcification, loss of reef volume and sea level rise will increase wave energy on the beach and a decrease in available beach sand – all of which will have an adverse effect on the protective ability of the carbonate beaches.

7 Transport and Morphological Processes

7.1 General on sediment transport and other types of transport

The previous chapters explained how the waves are transformed over a coastal profile and how this generates wave set-up and longshore currents in the coastal profile. These hydrodynamic conditions or processes will result in movement and transport of the sediments (e.g. sand) in the profile. This is referred to as *littoral transport processes* and is the main subject of this chapter.

There are two types of sediment transport related to the stability of the beach, namely the longshore transport and the cross-shore transport.

The *longshore transport* is the wave generated transport of sand parallel to the shoreline in the littoral zone. The longshore transport is also called the littoral transport or the littoral drift. A gradient in the littoral drift along a coastal section will result in morphological changes, such as coastal erosion or sand accumulation, or if related to the shoreline, shoreline retreat or shoreline accretion. This type of erosion is referred to as chronic erosion.

Other items, which influence the morphology along a coast, are the presence of different coastal structures and other factors influencing the transport conditions, such as:

- Groynes and coastal breakwaters trap sand upstream and causes downstream erosion
- Revetments fixes the coast thereby hinders erosion of the coast but the beach and the nearshore zone will continue eroding
- Other coastal structures, such as ports, coastal reclamations, tidal inlet jetties and all other kinds of structures on the coast or in the nearshore zone
- Offshore structures, offshore development schemes or artificial reefs may impact the nearshore wave conditions thereby also impacting the littoral transport and the shoreline stability
- Sources and sinks of sediment such as, eroding coasts, Aeolian transport of sand, river mouths, tidal inlets and canyons in the seabed connected to the nearshore zone

The *cross-shore transport* in the coastal profile is composed of onshore and offshore transport components generated by the varying wave and water level conditions in the near shore area. These cross-shore transport components in a coastal profile normally result in an equilibrium shape of the coastal profile, the so-called equilibrium profile. The equilibrium profile is associated with normal to rough wave and tide/surge conditions. However, when an equilibrium coastal profile is exposed to extreme conditions in the form of large waves and high storm surges, sand will be moved offshore in the profile resulting in (temporary) coastal erosion or shoreline retreat. This is referred to as acute erosion. Similarly, a general rise in sea level, which is forecasted as part of the climate changes, will also cause (permanent) coastal erosion.

When analysing the causes and mechanisms of coastal instability (coastal erosion) it is therefore relevant first of all to study the littoral transport conditions. Relevant parameters for the description of the littoral drift are the following:

- The wave conditions at the site and the possible variations over the site plus the adjoining areas
- The longshore current as well as the variations of this over the area. Other types of current (tidal and storm surge generated and general circulation currents) are of less importance in

the nearshore zone and these are normally not taken into consideration when computing the littoral transport along sandy coast. However, all types of currents shall be taken into consideration when transport conditions in more complex areas are considered

- The water level conditions, i.e. tide, storm surge and wave set-up. The water level contributions from outside the littoral zone, i.e. tide and storm surge, decides where in the profile the littoral transport takes place. Variations in the wave set-up are responsible for special current and sediment transport conditions in semi sheltered areas

- The bathymetry (the depth variations) in the area

- The sediment characteristics in the nearshore zone

- Sources and sinks of sediment, such as rivers, eroding coasts or tidal inlets.

In order to assess the stability of a certain coastal cell it is consequently necessary to obtain information about the following main issues:

- Wind conditions, normal and extreme
- Wave conditions, normal and extreme
- Water level conditions (tide and storm surge), normal and extreme conditions
- Extreme combinations or waves and storm surges
- Sea level rise
- The bathymetry of the area
- Sediment characteristics and general geology of the area
- Sediment sinks and sources, and
- Historical information on coastal structures and shoreline movements

It should be mentioned that the conditions in the nature are often more complicated than described above due to e.g. the presence of bars and rip current gaps in the near shore area, due to natural irregularities in the bathymetry caused by the geological conditions and due to variations in the sediment composition over the area, etc. This is evident from the conditions shown in Figure 7.1.

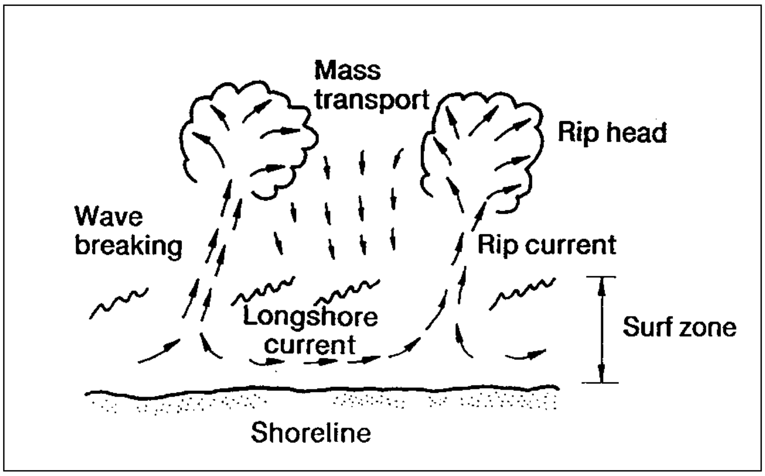


Figure 7.1 Nearshore wave, current and transport processes (after CERC, 1984).

For practical engineering purposes the overall coastal sediment transport is often subdivided in longshore sediment transport and cross-shore sediment transport. Hence, two more or less one-dimensional processes are the basis for the assessment of the morphological development of beaches. If a coastal area is more complicated due to an irregular coastal bathymetry or due to presence of coastal structures or complicated morphological elements, a two-dimensional approach has to be utilised.

Transport of fine sediments and of seaweed is also discussed briefly in Subchapters 7.6 and 7.7.

7.2 Littoral transport

Littoral transport is the term used for the transport of non-cohesive sediments, i.e. mainly sand, in the littoral zone along a shoreline mainly due to the action of breaking waves. The littoral transport is also called the longshore transport or the *littoral drift*. Littoral transport is often described under the assumption that the shoreline is long and nearly straight with nearly parallel depth contours. This assumption is very often valid, especially if the section of the shore is not too short and if a gradual transition between such sections can be assumed. The littoral transport process under such circumstances is briefly described in the following.

When waves approach the shoreline obliquely, refraction tends to turn the wave fronts so that they are almost parallel to the shoreline. At the same time, when approaching the breaker-zone, they undergo shoaling, which means that they become steeper and higher. Finally, the waves break. During the breaking process, the associated turbulence causes some of the seabed sediments to be brought into suspension. Further, the breaking waves deliver momentum to the water column and drive a littoral current along the shoreline. The suspended sediment, plus some of the sediment on the seabed, are then carried along the shoreline by the longshore current, which has its maximum near the breaker-line. The two transport modes are referred to as suspended transport and bed load, respectively. The sum of these is the littoral drift.

7.2.1 Variation of the littoral drift with forcing parameters

The littoral transport is dependent of a series of parameters as discussed above and further detailed in the following. The expressions for the longshore sediment transport (Fredsøe and Deigaard 1992) can be collected to give the rather complicated expression:

$$Q_l = 0.3\ \frac{H_0^{3.8}}{T}\ \sqrt{\tan\beta}\ d^{-0.8} \exp\left(-6.1\frac{w_s}{\sqrt{gd}}\right) \cdot sin^{5/2}(2\alpha_0)$$

Where H_0 and T are the offshore significant wave height and period respectively and α_0 is the offshore wave direction relative to the coast, $\tan\beta$ is the slope of the beach/shoreface, d is the median grain size of the beach sediment and w_s is the settling velocity. Inserting relevant values for quarts sand for grain sizes between 0.1 mm and 1.0 mm the above expression can be approximated with the following expression:

$$Q_l = 2 \cdot 10^{-12} \cdot \frac{H_0^{3.8}}{T} \cdot \sqrt{\tan\beta} \cdot d^{-3.54} \cdot \sin^{5/2}(2\alpha_0)$$

In these expressions the wave height and period are given in m and s respectively, grain size is given in m (N.B. not mm), w_s is given in m/s, g in m/s^2 and wave direction is given in degrees. The longshore transport rate (Q_l) comes out in m^3/s.

It is seen that that the magnitude of the littoral transport or drift Q depends on the various parameters as summarised below:

- *Wave height*. The littoral drift is proportional to the wave height to the power of ~ 3.8
- *Wave period*: The littoral drift is inversely proportional to the wave period
- *Grain size*. The littoral drift is inversely proportional to the grain size to the power of approximately 3.5
- *Wave incidence angle*. The littoral drift is proportional to $\sin^{5/2}(2\alpha_0)$. This gives increasing transport for incidence angles from 0° and 45° and decreasing transport from 45° to 90°

- *Beach/shoreface slope*: Increasing transport with steeper slope

The principal variation of the littoral drift as function of wave exposure and wave incidence angle is presented in Figure 7.2 and the variation of the transport in the profile in presented in Figure 7.3.

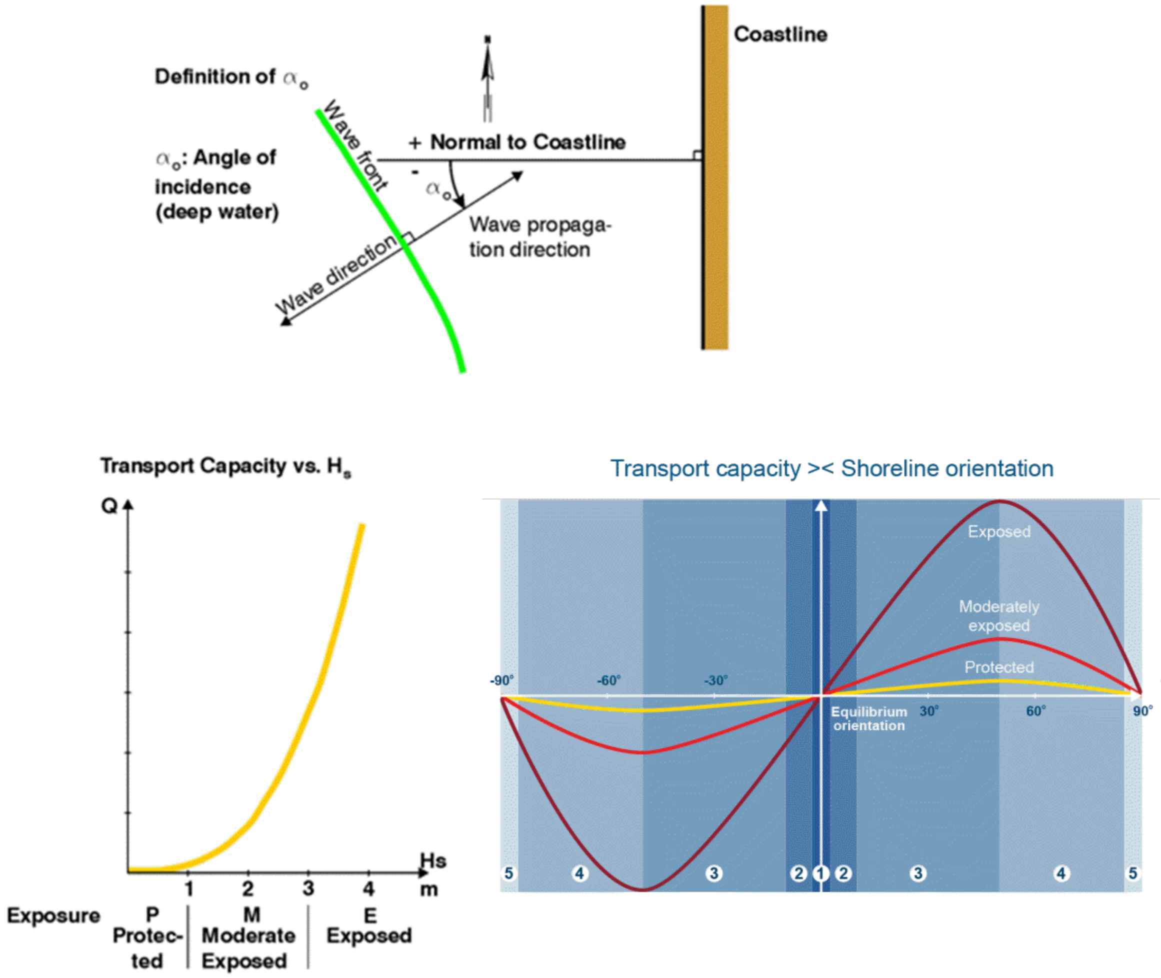


Figure 7.2 Variation in littoral transport with wave exposure and wave incidence angle.

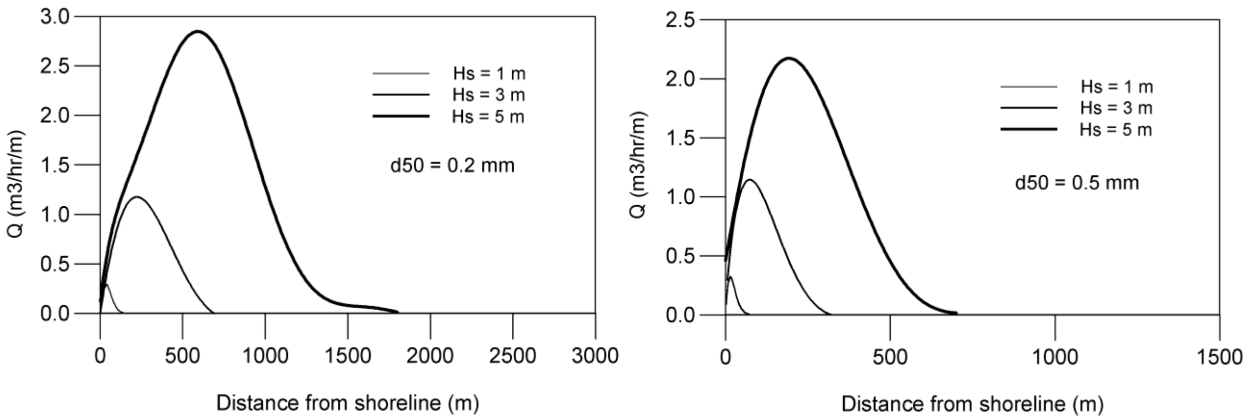


Figure 7.3 Distribution of the littoral transport over a coastal profile for grain sizes D_{50} = 0.2 mm (left) and 0.5 mm (right) and for the wave heights H_S = 1.0 m, 3.0 m and 5.0 m. Equilibrium profiles corresponding to the grain sizes have been used, cf. Figure 7.6. Angle of incidence: α = 30°. Calculated by LITPACK.

It is noted that the transport covers different widths and depths of the coastal profile depending on the grain size as well as the wave height.

The great variability of the transport for many of the parameters indicates the importance of high quality data when dealing with littoral transport computations.

7.2.2 Littoral drift budget

An annual littoral drift budget for a coastal profile is the sum of littoral transport contributions caused by all the occurring combinations of wave heights and directions, as well as tide and storm surge.

Consider, for example, a coastline oriented north-south with the sea to the west. All wave components from south to west will yield northward littoral drift contributions, and all wave components from west to north will yield southward littoral drift contributions. The sum of the northward drift contributions is called the northward littoral drift, and similarly is the sum of the southward drift contributions referred to as the southward littoral drift. The difference between the northward and the southward littoral drifts is called the *net littoral drift* or *dominant littoral drift*, which is associated with a *net littoral drift direction*. The nominal sum of the northward drift and the southward drift rates is called the *gross littoral drift*, which has no direction. As indicators of the net or dominant littoral drift one can mention: a) the direction of migration of a river mouth along the coast; b) the side of a groyne where the sand accrete, indicates that the net littoral drift direction is from the upstream coast towards the accretion area.

An overview of the magnitude of littoral drift Q is provided in the following Table 7.1 as a function of the following parameters:

- The significant wave heights H_s
- The angle of incidence at 'deep water' α_0 (20 m has been used as 'deep water')
- A duration of 24 hours
- Beach sand with d_{50} = 0.25 mm

Calculations performed by LITPACK on the equilibrium profile corresponding to d_{50} = 0.25 mm. LITPACK is DHI's numerical model for LITtoral Processes And Coastline Kinetics, see http://www.mikepoweredbydhi.com/products/litpack

Table 7.1 Littoral transport rates **Q** as a function of H_s and angle of incidence α_0 at deep water (20 m). Calculated by LITPACK.

Q [m^3/24hrs]		α_0[°]					
		5	**15**	**30**	**45**	**60**	**75**
H_s [m]	**1.0**	50	100	300	350	300	150
	2.0	400	1,000	2,000	3,000	2,500	1,000
	3.0	1,500	4,000	10,000	15,000	10,000	5,000
	4.0	4,000	10,000	30,000	40,000	35,000	15,000
	5.0	8,000	25,000	65,000	100,000	85,000	35,000

Note: D_{50}=0.25mm, H and MWD at 20 m water depth

Note the huge variation in the transport rate with the wave height as well as with the angle of incidence.

An important parameter in relation to the littoral drift conditions is the variation of the net transport with varying orientation of the coastline. If e.g. a groyne is constructed, this will initially block the transport resulting in net zero transport at this location. This means that the sand will accrete upstream of the groyne forming a coastline with the orientation, which gives zero transport, the so-called *equilibrium orientation*.

The concept of the equilibrium orientation is illustrated in Figure 7.4.

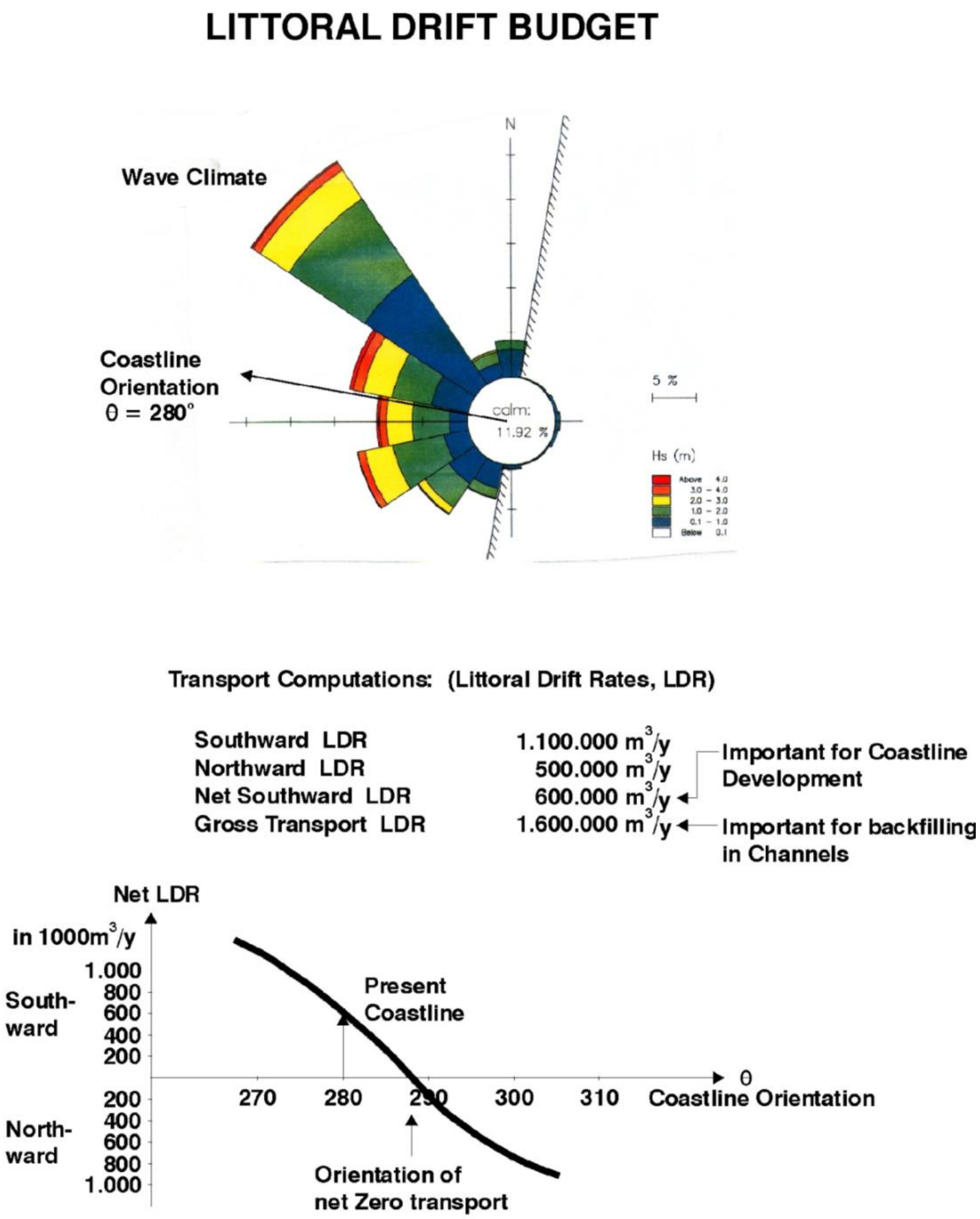


Figure 7.4 Example of a littoral drift budget from the Danish North Sea Coast and the relation between net littoral drift and coastline orientation.

The efficiency of the groyne depends very much on the angle between the present orientation of the coastline and the orientation of net zero transport. If this angle is small, the groyne will be efficient, as it will be able to hold a long sand filet. If the angle is large, which is the case with a very oblique wave exposure, the groyne will only be able to hold a very short sand filet, which means that a groyne will not be an applicable type of coast protection in this case. The concept of equilibrium orientation is also important for the design of artificial beaches as these shall be designed in the equilibrium orientation in order to be stable.

When discussing the littoral transport along a coastline in general, it is always the net littoral drift that is referred to unless otherwise specified. Gradients in the net littoral drift along a section of coast lead to *coastline erosion* or *accretion*. The gross littoral drift is important for backfilling of channels/trenches across the littoral drift zone, as all littoral drift situations lead to backfilling of the channel/trench.

The littoral drift also depends on the sea current, although to a much smaller extent than it depends on the longshore current. This means that the most important hydraulic parameter for the littoral transport is the wave condition.

The water level mainly determines where in the coastal profile the transport will take place, but the water level only influences the magnitude of the littoral drift to a lesser extent. However, the tide may have significant influence on the transport conditions for macro-tidal environments. Positive or negative correlation between the waves and the water level variations may be of importance for sedimentation patterns near large structures.

At many locations there is a considerable variation in the grain size depending on the distance from the coastline. Typically the sediments become finer with increasing distance from the coastline. This will, to some extent, blur the picture of the littoral drift given above.

The fine cohesive sediments, which may be present in the outer part of the profile, will be in suspension over the entire water column and will also tend to spread over the entire coastal profile during strong wave exposure. The transport which this gives rise to is normally not considered a part of the littoral drift, as this only takes the non-cohesive sediments into consideration. The transport of the cohesive sediments thus only plays an indirect role in the stability of the coastal profile. The existence of this transport of fine suspended sediments will, however, be of importance in relation to sedimentation in ports and in trenches.

The longshore transport is, as already mentioned, characterised by a combination of sediment moved along the seabed, the so-called *bed load transport,* and of sediment in suspension, the so-called *suspended load*. Even when the sand is in suspension it is still relatively close to the seabed because of the relatively high *fall velocity* of sand grains. This means that any change in the hydrodynamics or bathymetric conditions will almost "immediately" result in a corresponding change in the transport capacity and therefore also in the morphological response. This results for instance in the typical accumulation of sand behind even a relatively short, detached, coastal breakwater, as the accumulation of sand reflects the “immediate” response on the attenuated transport capacity behind the breakwater. It is not possible to guide the sand between the coastal breakwater and the shoreline if the breakwater has a length of more than around 0.5 times the distance from the shoreline. If the length of the breakwater is more than approximately 0.8 times the distance from the shoreline, so much sand will be trapped that the breakwater will be connected to land by a tombolo formation, see example in Figure 7.5. This will be discussed further in Subchapter 17.5.2. This immediate morphological response to even small changes in the littoral transport is also the reason why many attempts to construct island-ports with zero impact on the shoreline have failed. Most of them have been connected to land by tombolo formations.

Figure 7.5 Tombolo formation behind coastal breakwater, Hyllingebjerg, North coast of Zealand, Denmark.

7.3 Cross shore transport and equilibrium coastal profile

Varying wave conditions result in varying onshore and offshore transports over the coastal profile. These transports are, to some extent, reversible and therefore non critical in terms of long term coastal stability. However, extreme storm surge and wave exposure result in coastal erosion.

When the coastal profile is exposed to extreme waves and storm surge, the sediments near the shoreline will be transported offshore and typically be deposited in a bar resulting in an overall flattening of the slope of the shoreface. However, the inner part of the shoreface as well as the foreshore will become steeper in this process, and the shoreline will recede. During the following periods of smaller waves, swell and normal water level conditions, the bar will travel very slowly towards the coastline again, practically rebuilding the original coastal profile.

During such a sequence of profile erosion and rebuilding, certain parts of the coastal profile may experience temporary erosion. This may not be recorded in profile surveys, because some rebuilding will already have taken place before it is possible to carry out surveys after the storm. It is important to take such temporary profile fluctuations into account when designing structures in the coastal zone. It is particularly important to have a sufficiently wide beach so that the temporary erosion will not cause damages to facilities located near the coastline.

This onshore and offshore transport is closely related to the form of the coastal profile. Several investigations have revealed that a coastal profile possesses an average, characteristic form, which is referred to as the theoretical *equilibrium profile*. The equilibrium profile has been defined as “a statistical average profile, which maintains its form apart from small fluctuations, including seasonal fluctuations.” The depth d [meters] in the equilibrium profile increases with the distance x from the shoreline according to the equation (Dean, 1987)):

$$d = A\, x^m \quad [x \text{ and } d \text{ in meters}]$$

where A is the dimensionless steepness parameter and m is a dimensionless exponent. Based on fitting to natural upper shoreface profiles, Dean has suggested an average value of *m = 0.67.* However the value of m is subject to large variability dependent of the beach type expressed by the *dimensionless fall velocity* $\Omega = H_0/w_sT$, where H_0 is the deep water wave height, T is the wave period and w_s is the sediment fall velocity. The value of m varies typically between m ~ 0.4 for reflective beaches ($\Omega < 1.5$) and m ~ 0.8 for dissipative beaches ($\Omega > 5.5$). (Cowell et al. (1999), and Masselink and Huges (2003)).

The steepness parameter A has empirically been related (Dean, 1987) to the sediment fall velocity w_s as follows:

$$A = 0.067 w_s^{0.44} \quad [w_s \text{ in cm s}^{-1}]$$

Values for A as a function of the mean grain size d_{50} are shown in Table 7.2.

Table 7.2 Correlation between mean grain size d_{50} in mm and the constant A in Dean's equilibrium profile equation (Dean, 2002).

d_{50}	0.10	0.15	0.20	0.25	0.30	0.50	1.00
A	0.063	0.084	0.100	0.115	0.125	0.161	0.210

It is seen that the equilibrium profile becomes steeper with increasing grain size.

It is seen that the equilibrium profile does not depend on the wave height. The reason for this is that the water depth limits the wave height inside the breaker zone. However, the wave height decides the width of the littoral zone, within which the equilibrium shoreface concept is valid. Thus, the equilibrium profile is only valid for the littoral zone, i.e. out to the Closure Depth d_l (Hallemeyer, 1981):

$$d_l = 2.28 H_{S,12h/y} - 68.5 \frac{H^2_{S,12h/y}}{gT_s^2}$$

where d_l is the closure depth relative to mean low water level, $H_{S,12\,h/y}$ is the near shore significant wave height exceeded 12 hours per year, and T_S is the corresponding significant wave period. This definition is valid for "normal" sandy coastal profiles.

The width of the littoral zone and the slope of the shoreface thus depend on the mean grain size as well as on the wave conditions.

The equilibrium profile becomes increasingly steeper with increasing grain size. Typical equilibrium profiles for different grain size characteristics are presented in Figure 7.6. It is noted that the equilibrium profile is valid only out to the Closure Depth.

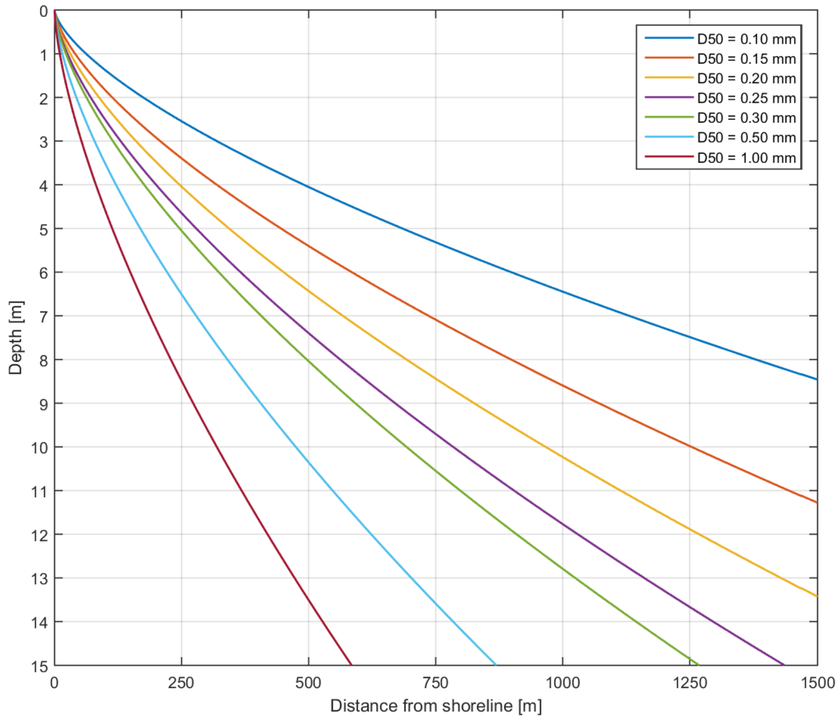


Figure 7.6 Equilibrium profiles for grain sizes 0.10, 0.15, 0.20, 0.25, 0.3, 0.5 and 1.0 mm.

The width of the littoral zone as a function of the mean grain size and for different wave climates, represented by $H_{S,\ 12\ h/y}$, is presented in Figure 7.7.

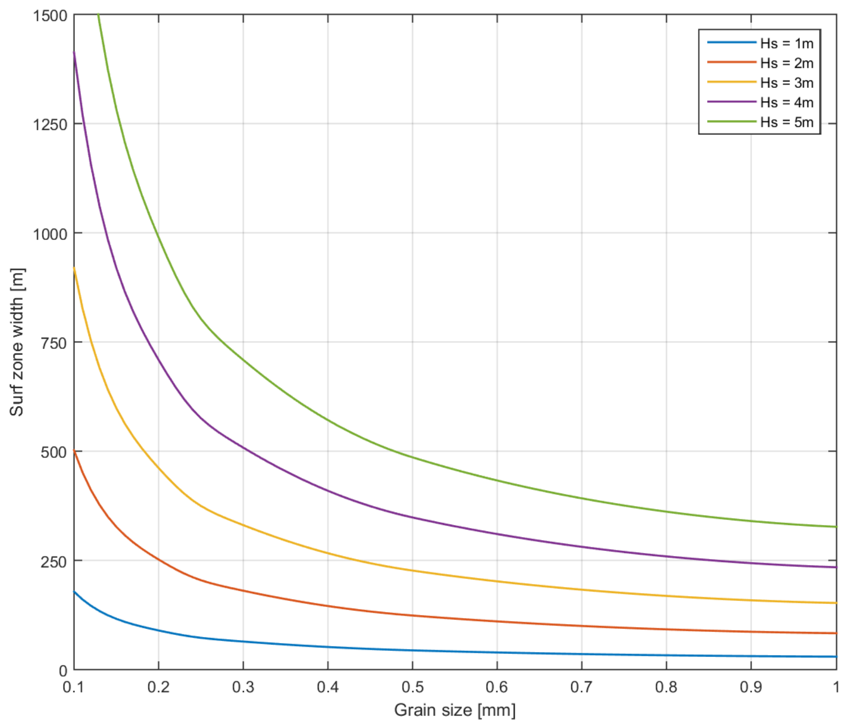


Figure 7.7 Width of littoral zone as a function of the mean grain size for various wave climates represented by $H_{S,12\ h/y}$.

These figures can be used in preliminary design considerations for artificial beaches and reclamation areas fronted by sand beaches.

Due to the hydrodynamic and turbulence conditions over the coastal profile, the coarser sediments tend to be transported onshore whereas the finer sediments are transported offshore. Thus, for a given wave condition, the sediment of a given diameter has a position of equilibrium over the beach profile. In this way, if sediment is deposited shoreward of its position of equilibrium, e.g. if fine sand is nourished on top of coarser natural sand, the nourished sand will be transported offshore by the natural hydrodynamic forces. On the other hand, if coarse sand is deposited on top of finer natural sand, i.e. if it is deposited offshore of its equilibrium position but still in an active littoral zone, the nourished coarse sand will be transported shoreward until it reaches its equilibrium position.

Some beaches are composed of very coarse sediments, pebbles or small to medium-sized cobbles, the so-called shingle beaches. Typically, the grain composition vary between 20 to 100 - 200 mm. Shingle beaches are typically very steep with slopes as steep as 1:5. They are very stable because the waves easily percolate through the coarse porous surface of the beach, decreasing the effect of backwash erosion and favouring the formation of a steeply sloping beach.

It is evident from these correlations between grain size, equilibrium profile and wave conditions that it is very important in beach nourishment to use materials as coarse as or coarser than the native material. Otherwise the nourished sand will immediately be transported offshore in nature's attempt to form the new and flatter equilibrium profile, which fits the finer sand, see also Subchapter 17.6.2.

The concept of equilibrium profiles is a rather crude representation of the coastal profile conditions since it neither includes nor explains the occurrence of bar formations, etc. However, the concept of the equilibrium profile is a rather practical "tool" for the analysis of coastal conditions and for design considerations in relation to beach nourishment and construction of artificial beaches.

If the geological coastal profile at a location is flatter than the calculated equilibrium profile, the wave action in the profile will tend to form the equilibrium profile, which means that material will be moved towards the shore. However, at a certain location towards the shore, there is not sufficient wave energy to move the sand any further and a barrier with a corresponding lagoon is formed.

The equilibrium concept can also explain why shore and coast erosion take place at locations where the equilibrium profile is already established, when such profiles are exposed to the combined action of storm waves and storm surge (tidal wave). With the increased water level the actual profile will be too steep compared to the equilibrium profile. At a certain distance from the shoreline the water will consequently be too deep relative to the equilibrium depth. Nature will compensate by transporting sand from the beach towards the sea in an attempt to re-establish the equilibrium profile, which fits the temporary high water level. This will result in retreat of the shoreline; however, if the beach is not sufficiently wide for this adjustment, the sediment will be taken from the cliff or dunes. The amount of erosion during a storm thus depends primarily upon the magnitude of the storm surge and its duration. It is evident from this description that a wide beach is a precondition for a stable coastline. Coast protection can thus be established by providing a wide beach through beach or foreshore nourishment. After the storm, the material, which was brought offshore during the storm surge conditions, will to a great extent be transported slowly back to the beach; however extreme storm surge/wave events will result in a permanent offshore loss of material. It is also evident from the equilibrium profile concept that sea level rise will cause retreat of the shoreline and eventually also of the coastline.

7.4 Transport conditions in tidal inlets

Most of the transport of non-cohesive sediments (sand) takes place in wave-dominated environments. There are, however, locations where the transport of sand is mainly dominated by the current. In relation to coastal morphology the *tidal inlet* is the most important. A tidal inlet is the connection between the sea and a lagoon, which is exposed to shifting tidal currents.

Flood tide causes the tidal current to run from the sea into the lagoon and ebb tide goes in the opposite direction. The exchanged water mass during a tidal cycle is called the *tidal volume*. This can roughly be calculated as the surface area of the lagoon times the tidal range.

The tidal current in a tidal inlet on a coastline is responsible for the exchange of sand between the littoral zone and the lagoon. This sand transport typically results in varying depths and shifting locations of the inlets and in the formation of lagoon shoals (*flood shoals*) and offshore shoals (*ebb shoal*s), as seen in Figure 5.37. At the same time the longshore transport interferes in these processes resulting in curved bar formations crossing the inlet as well as the formation of sand spits and possible shifting of the tidal inlet along the shore, see Figure 5.36. All in all, tidal inlets and associated morphological elements, are very dynamic features. Consequently, great care and thorough investigations are required in connection with designing of inlet regulation works and in connection with any kind of development adjacent to tidal inlets.

Tidal inlets are very often regulated and fixed by inlet jetties and they are frequently dredged to allow navigation. An important aspect in relation to regulated tidal inlets on littoral transport coastlines is that the jetties constitute a blockage of the littoral transport. This results in sand accumulation on the updrift side and lee side erosion along the downdrift coastline, unless special bypass precautions are taken. When the sand accumulation on the updrift side reaches the tip of the jetty, the sand will start to bypass and this will cause sedimentation in the inlet. Normally the sand does not pass the dredged channel and therefore it does not nourish the lee side beach.

The above description of tidal inlets is greatly simplified and presents only the mechanisms in a very broad outline. The hydrodynamic and sediment transport conditions in tidal inlets are very complicated, as a tidal inlet always constitutes a delicate balance between the “forces” which keep it open, namely the tidal exchange, and the “forces” which tend to close it, namely the littoral transport processes. It adds to the complexity of tidal inlets that many different time scales are involved, the most important of which are outlined below:

- Semi-diurnal and diurnal tidal components
- Neap and spring with fortnightly periods
- Seasonal variations in water level, storm surge and wave conditions
- Very wide time scales for the wave conditions: from seconds for single waves to days for storm duration to seasons for variations in general wave climate to years for the recurrence of extreme wave events

Tidal inlet studies can be performed at many levels, from

- a parametric empirical stability analysis involving only the main parameters such as the tidal parameters, the cross section area of the inlet and the wave energy

or

- a complete study involving numerical modelling of hydrodynamics, waves, sediment transport and morphological evolution

7.5 Mechanisms causing changes in shoreline position

The evolution of shorelines and coastlines is of major concern to coastal communities. The shoreline retreat leads to the loss of the beach and consequently to a setback of the coastline, which may threaten the coastal communities. It is important to understand the causes of the erosion in order to be able to forecast the long-term development and thereby take appropriate measures.

Changes in the position of the shoreline as observed by people visiting a beach may be caused by three main mechanisms:

- changes in the shape of the coastal profile typically occurring as a result of the combined effect of storm surge and storm waves, this is referred to as *acute erosion,*
- changes in volume of the active coastal profile (beach volume) typically occurring as a result of a gradient in the littoral drift, this is referred to as *chronic erosion* (volume erosion)
- sea level rise causes a general setback of the shoreline position occurring as a result of adaptation of the coastal profile to a new equilibrium shape under the higher mean sea level, this is similar acute erosion but of chronic nature

A change in the shape of the coastal profile can happen without a change in the volume of the beach, this is illustrated in Figure 7.8 where it is seen that flattening of the profile leads to erosion on the shoreline for the same beach volume. Similarly a change in the volume of the beach can happen without changing the shape of the profile. The setback of the shoreline position due to relative sea level rise can also happen independently from the two other mechanisms, and usually happens on a much longer time scale, this mechanism is described in Subchapter 6.4.

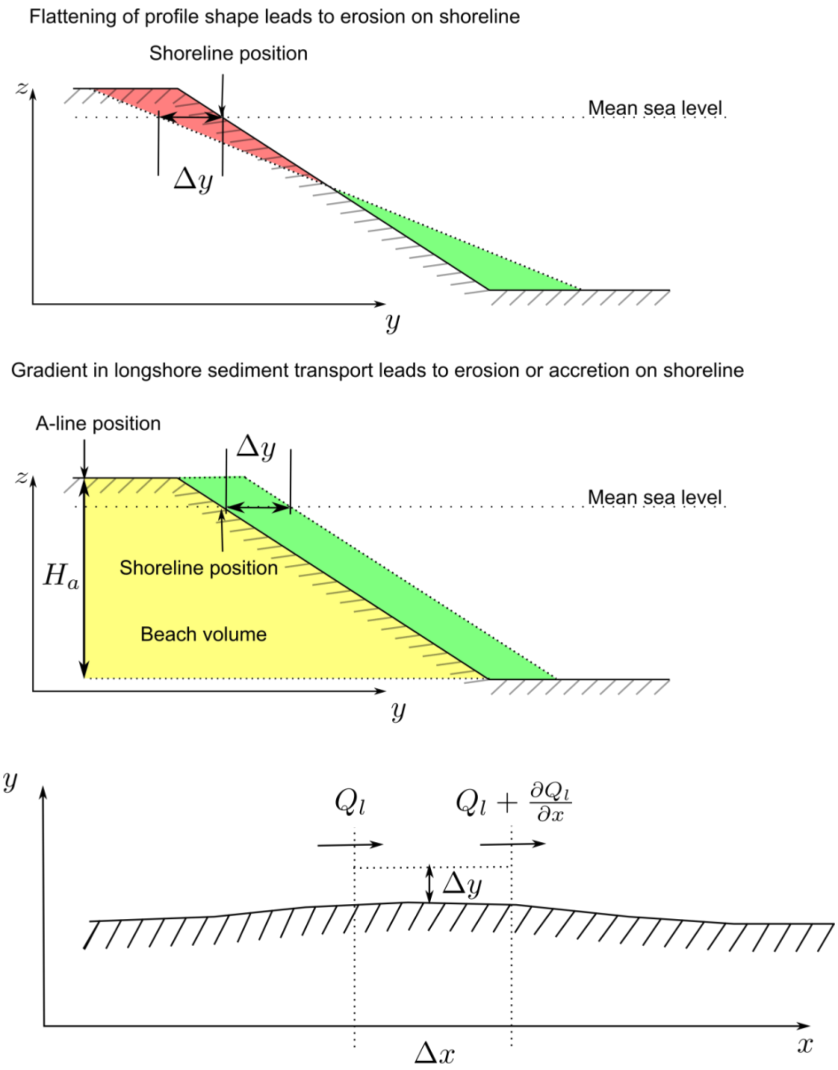


Figure 7.8 Sketch showing the two causes of changes in the shoreline position: Changes in shape of coastal profile and changes in beach volume.

Most of the time a combination of the three processes is responsible for an observed change in the position of the shoreline.

A change in the volume of the beach is caused by a gradient in the littoral transport over a coastal stretch. If, for example, a certain stretch has an increasing transport in the direction of the net transport, this will result in less sediment being transported into a given section of the coastal area than is transported out of the same section, which will result in coastal erosion. This will be seen in two ways, erosion of the seabed and coastal erosion, i.e. shoreline setback and possibly coastline setback. It is therefore fundamental to a discussion of the stability of shores and coasts to first describe the sediment transport processes and the sediment budget of the area.

Changes in the shape of the coastal profile typically happen during extreme events where storm surge and waves cause a strong off-shore transport of sediment, often leading to the formation of an off-shore breaker bar. In this process the coastal profiles becomes flatter in the inner surf-zone, leading to erosion on the beach and a land-ward shift in the position of the shoreline. This type of erosion is termed *acute erosion*. During subsequent normal weather conditions, most of the sand deposited off-shore will return to the beach as the beach profile becomes steeper again.

An example of the off-shore sediment movement during storm conditions and on-shore movement during calmer conditions is shown in Figure 7.9 which shows a measured coastal profile on Palm Beach, Queensland, Australia before and after the East Coast Low (storm) event in May 2009 as well as a full year after the storm. Extensive erosion is observed on the shoreline and dune system during the storm, but a year later much of the erosion on the beach has been reversed by onshore movement of the sediments. The flattening of the profile by the storm and the steepening during calmer conditions is clearly seen in the figure.

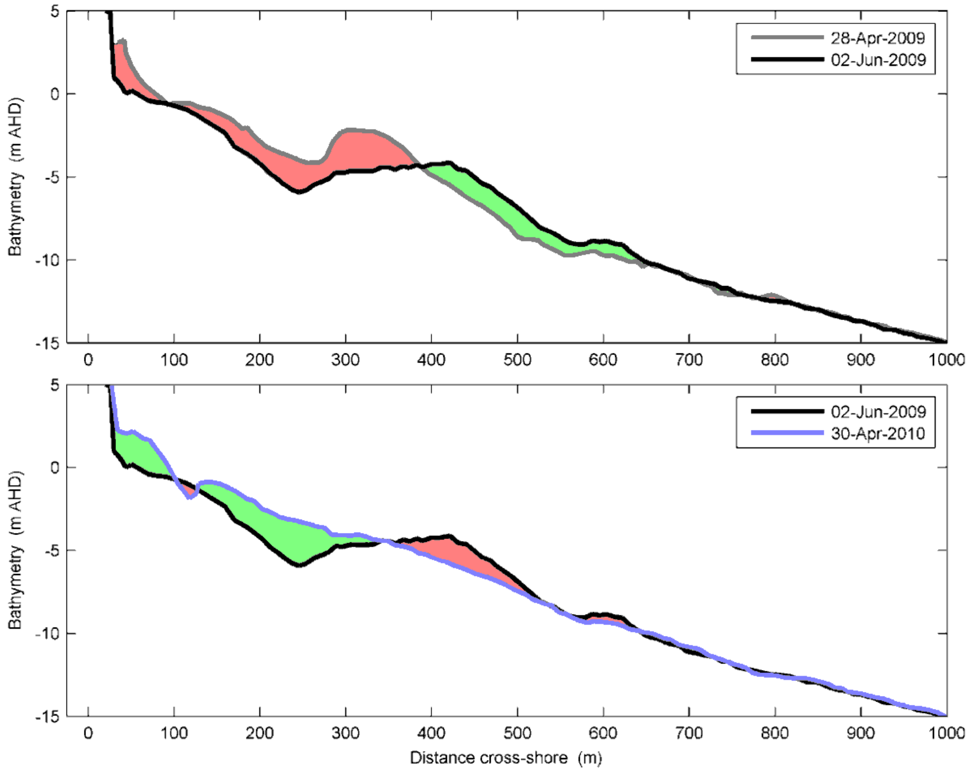


Figure 7.9 Example from Palm Beach, Queensland, Australia showing variations in the shoreline position due to changes in the shape of the coastal profile. Upper: impact of storm in May 2009. Lower: Beach restoration due to on-shore movements of sediments following the storm.

Shoreline erosion caused by changes in the shape of the coastal profile is usually less severe for the vulnerability of the beach than erosion caused by a loss of beach volume. This is because there is a natural limit to the amount of erosion which can be caused by the change in beach profile shape. The flatter the beach profile, the more resistant it will be to erosion caused by change of profile shape. This is simply because there is a limit to how flat the profile can become before all wave energy is dissipated prior to reaching the shoreline; in which case the flattening process and therefore the erosion on the shoreline will stop. Right after a storm the beach may be narrow and seem vulnerable, but because the profile is relatively flat, the beach is more resistant to further erosion because wave breaking will occur further offshore. The beach will furthermore be re-built by onshore transport during the mild wave conditions that follow the storm as was indicated in Figure 11.2 However during *extreme events* the eroded sediment can be located so far off-shore that it never returns to the beach, or only returns very slowly. This means that the offshore loss during such events is an important aspect of coastal erosion and has to be taken into account in the design of shoreline management measures

Erosion caused by a gradient in the littoral transport will persist as long as the gradient in the longshore transport persists and there is sand available for erosion. This type of erosion is termed *chronic erosion*, and is only reversed if additional sediment is supplied from upstream; furthermore a beach which has recently undergone severe erosion due to longshore gradients in the littoral drift has not increased its resistance to erosion because the eroded sediment has been completely removed from the beach profile. During extreme events the gradient in the littoral transport can become very large and cause major changes and losses in the beach volume; this can especially happen when the waves during the extreme event come from a different direction than the prevailing waves. The prevailing wave climate could, for example, be a monsoon climate, whereas the extreme climate could be dominated by cyclones. Even if the extreme conditions are correctly represented statistically in the normal wave climate the frequency of occurrence will be very small, which means that it will only play a minor role in the sediment budget. However, on the day the extreme event occurs, there will be very large littoral transport rates and gradients, which in turn may cause great changes to the shoreline and coastline.

The above description shows that it is important to study “normal” as well as extreme events in relation to shoreline evolution and coastal erosion.

The longshore and the on-offshore processes are normally analysed separately, although this is not entirely correct, but considering the tools available it has been the only possibility, this is discussed in detail in Chapter 21.

The main hydraulic parameters responsible for shoreline evolution and coastal erosion are wave and storm surge conditions and their possible correlation. Given wave and surge conditions, combined with the coastal profile and seabed sediments, define the transport conditions along a certain stretch of shoreline. The shoreline evolution at a given site depends on the interaction of the above processes with the geological setting, the sediment supply to the cell and any coastal structure in the area. All these conditions may result in a great variety of shoreline forms and features which are discussed in Chapters 8 and 9.

7.6 Transport of fine suspended sediments

The transport of fine suspended sediments, often referred to as mud, has already been mentioned briefly, but specific details with relevance for coastal engineering will be briefly discussed in the following.

The fall velocity of the transported sediment grains is the major difference between the non-cohesive and the cohesive sediment environments. However, another marked difference is the cohesion forces between the single sediment grains, which is characteristic for the cohesive sediments, but this will not be discussed further here. The fall velocity of sand grains is relatively high whereas the fall velocity of the mud particles is relatively low even when many individual particles aggregate to form flocs. This implies that the fine sediments are suspended nearly evenly over the entire water column, whereas the suspended sand is only found very close to the seabed. If the bathymetry or the hydrodynamic conditions change, the sand transport will react on this immediately. This will, for example, lead to backfilling on the upstream slope of a navigation channel in a sandy environment, see Figure 7.10.

The opposite is the case for the transport of fine sediments. If the bathymetric or the hydrodynamic conditions change the transport will only react slowly. This is the so-called space lag and time lag effects. The transport of fine sediments will thus react on such changes in a completely different way than what has been explained for sand. For example, backfilling of fine sediments in a navigation channel will occur as an evenly distributed sedimentation over the entire width of the channel. The sedimentation will be smaller than the difference between the transport capacities at the side of the channel and inside the channel due to the space and time lag effects. Typical backfilling patterns for medium and very fine sand are presented in Figure 7.10.

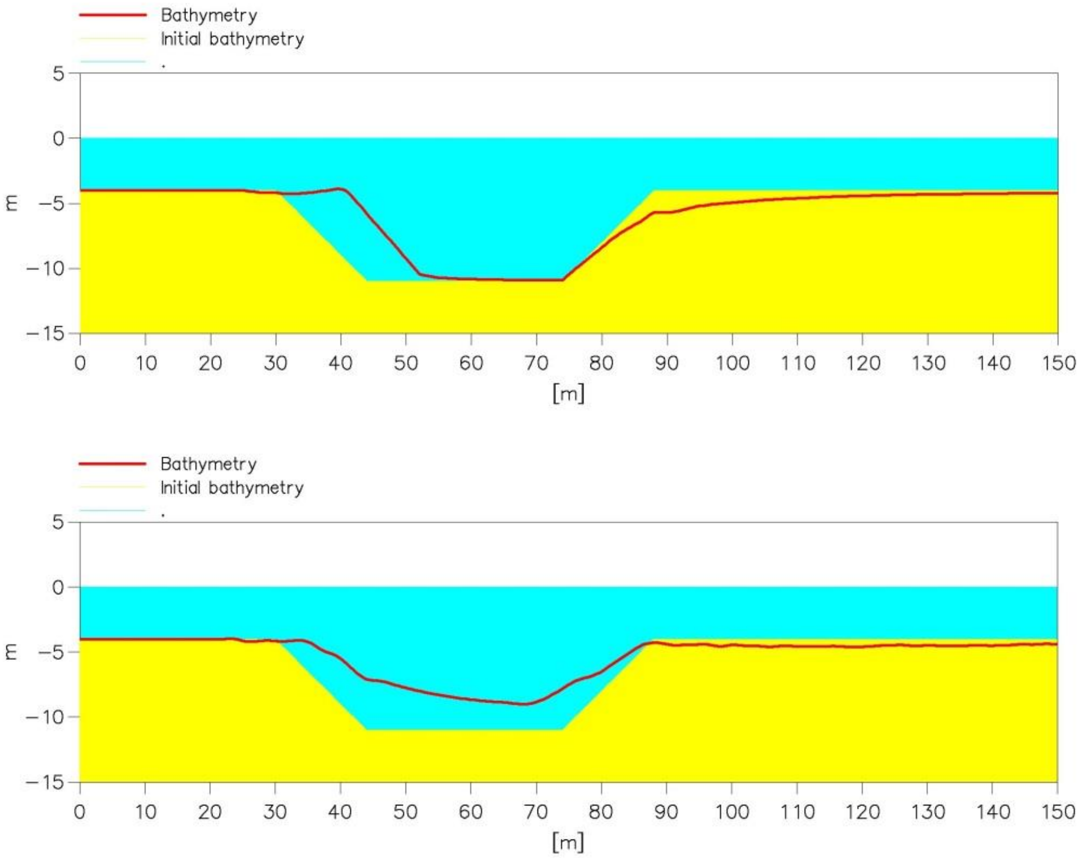


Figure 7.10 Backfilling patterns in a 30 m wide and 7 m deep channel at a water depth of 4 m exposed to H_s = 2 m waves and a current, u_b = 1.0 m/s, perpendicular to the channel. The top figure is for medium sand (d_{50} = 0.23 mm) and the bottom figure is for very fine sand (d_{50} = 0.10 mm). Computations performed by the TRENCH module of LITPACK.

In the case of a coastal breakwater constructed in an environment where both littoral transport and mud transport mechanisms are active, the breakwater will normally mainly trap sand, whereas there may be hardly sufficient shelter or space for major accumulation of mud.

Ports, constructed in environments where the transport of fine sediments takes place, will be exposed to siltation due to the entrainment of water with suspended fine sediments. The siltation is proportional to the water exchange, which is composed of the following contributions:

- *Tidal exchange*, which is proportional to the tidal volume (tidal range x area of harbour basin). Sedimentation due to tidal exchange cannot be avoided unless the entrance is closed
- *Eddy exchange*, which is proportional to the velocity of the passing currents and the area of the entrance opening. The siltation can be minimised by a smooth and narrow port entrance
- *Density exchange,* which is due water exchange caused by density gradients. This typically occurs for ports located in tidal zones of rivers
- *Water exchange due to different types of oscillations* in the port basin, of which *surf beat* generated oscillations are the most important. Such oscillations can be avoided by ensuring that the entrance is located at relatively deep seaward of the surf-zone well separated from nearby beach sections. Semi-sheltered entrances for small ports tend to form beaches right up to the entrance, which can generate surf beat and harbour resonance and thereby siltation. Such layouts should therefore be avoided, see also Subchapter 5.4.1

Sand can form a stable coastal profile and a stable beach in a wave-dominated environment, which is not the case with mud. Muddy coastlines are therefore only found in environments that are fairly calm with respect to wave conditions or in environments where there is an abundant supply of fine sediments. Such muddy coastlines are often vegetated, e.g. in the form of mangroves and are normally fronted by very flat slopes or tidal flats. Mixed environments with wave-exposed sand shores or sandy tidal flats alternating with mud-dominated tidal flats and deeper muddy areas are seen quite often. Such environments need special consideration in relation to shoreline management projects.

7.7 Transport and deposition of seaweed

There are many types of seaweed, the main types are:

- Makroalgae, which grows on hard bottom, such as rock and stones and boulders. Makroalgae exists in many variants and sizes
- Sea grass, which is a flowering plant that mainly grow in sandy environments. Sea grass shed the leaves regularly

The shedded sea grass leaves and leaves from sea grasses and makro algae that are torn off due to impact form currents and waves will initially float in the surface because they have a density lower than sea water however, when they start decaying they will increase in density and be suspended in the water column.

The freshly shedded and torn off seaweed leaves will consequently float in the surface and drift under the impact of wind and surface currents. If the seaweed is floating towards the coast it will finally be deposited on the beach in the form of seaweed berms or it may be deposited on revetments and similar structures. It the wind is oblique towards the coast the seaweed will partly be floating along the coast and partly be deposited on the beach as described above. The part of the seaweed floating along the coast driven by wind, wind driven currents and longshore currents may be trapped in corners between coastal structures and the coastline and may penetrate into harbour basins and into surface seawater intakes, etc.

The decayed seaweed leaves will float suspended in the water column and will therefore follow the prevailing current. The decayed seaweed will settle in calm areas, it may be in deep waters or in sheltered areas but it may also penetrate into coastal lagoons due to tidal exchange and into harbour basins due to eddy exchange, tidal exchange and exchange caused by surf beats. Furthermore, suspended seaweed may penetrate into seawater intakes.

The risk of trapping seaweed shall be taken into consideration during the planning and design of interventions in the coastal zone in order to minimise the risk of trapping of seaweed. A list of the type of interventions or facilities where seaweed accumulation may occur, the mode of seaweed accumulation, the impacts of the accumulation and possible measures to minimise seaweed accumulation is presented in Table 7.3.

Table 7.3 Areas with risk for seaweed accumulation, impacts and measures to minimise accumulation.

Type of intervention or facilities	**Mode of seaweed accumulation**	**Impacts**	**Measures**
Groyne	Accumulation on both side of groyne	Disturbs recreational activities	Make groynes as rounded headlands and avoid sharp corners
Coastal breakwater	Trapping of seaweed in protected area, together with sand		Do not use coastal breakwaters in waters with large amounts of seaweed
Terminal structure at artificial beach section	Trapping of seaweed in corner		Make the terminal structure with an abtuse angle to the coastline
Major coastal structures (harbours, inlet jetties, etc.)	Trapping of seaweed in sheltered corners		Avoid sheltered corners, make smooth transition between structure and coastline
Shallow sheltered water areas	Seaweed is trapped in shallow water and starts putrefying	The anoxic fermenting (eutrophication) produces unpleasant odeur, initiates ozygen depletion and initiates bottom turnover	Avoid shallow sheltered areas connected to open waters with seaweed
Inside harbour basins	Seaweed is trapped in harbour basins due to eddy exchange, due to exchange of water by tide or by surf beats, or due to wind drift		Make bypass harbour layout and avoid shallow areas near the entrance. Avoid making additional flushing by introducing extra openings
Seawater intake	Import of seaweed by the inflow water	Clocks up filters and disturbs utilisation of the seawater for cooling or other purposes	Make a deep-water intake or protect the intake from direct inflow of seaweed, make filters with automatic cleaning
Low seawall protecting artificial beach reclamation	Seaweed is accumulating at beach with overtopping waves	Disturbs recreational activities	Avoid such low seawalls
Beaches	Seaweed accumulation in the form of seaweed berms on the beach	Disturbs recreational activities	Mechanical removal of the seaweed berms

Examples of seaweed accumulations are presented in Figure 7.11.

Figure 7.11 Examples of seaweed accumulations. Upper left: Seaweed accumulation north of Rungsted Marina, Denmark, on shallow water and as berms on the beach. Upper right: Seaweed accumulation in Sejerø Bay, Denmark, foreground on beach section which has recently been cleaned, background old seaweed beams overgrown with weeds Lower: Smygehamn, Sweden, bottom turnover and seaweed in basin.

8 Classification of Coastal Profiles

8.1 General about classification of coasts

The development of coastal profiles and coastlines mainly depends on the local wave conditions (cf. Subchapters 5.2 and 5.3), the tidal regime (Subchapter 5.6.1) and storm surge conditions (Subchapter 5.6.3.1), the type of sediments available in the area (Chapter 4) as well as on geological and biological factors. Further, the coastline is influenced specifically by directional characteristics of the wave climate.

A comprehensive coastal classification and multi-hazard-assessment/management system for "Managing climate change in coastal areas – The Coastal Hazards Wheel system" has been developed by UNDP, cf. Appelquist (2016). *"The CHW is developed as a universal coastal classification system that can be used in areas with limited data availability and can therefore be used in both developed and developing countries. The CHW constitutes a key for classifying a particular coastal location, determining its hazard profile, identifying relevant management options and communicating coastal information. The system can be used to support coastal management at local to national level and covers all the main coastal hazards, hereunder the hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding. As the CHW incorporates climate change effects in the hazard evaluations, it is especially relevant for climate change adaptation"*. Quoted from Introduction in Appelquist (2016).

This system is mainly a screening system, a more engineering oriented approach for sandy coasts is described in the present Chapter 8, which provides an approximate classification of coastal profiles, and in Chapter 9, which describes a classification of coastlines.

Sandy coasts provide attractive recreational beaches, but due to their dynamic morphology they also often cause problems in the form of shore degradation, coastal erosion and sand accumulation, etc. Profiles and coastlines will be treated separately, although they do of course interact.

8.2 Classification of coastal profiles

The discussion will be limited to coastal profiles consisting of sedimentary deposits or similar materials.

The theoretical equilibrium profile (see Subchapter 7.3) is often recognised in real coastal profiles, but deviations often occur due to variations in the seabed material, and the presence of bars and due to the influence of tide, etc. Another reason for deviations from the theoretical equilibrium profile is that the forcing is not stationary over time. The actual profile is constantly changing due to the constant variation in waves, tides and surges, to which the profile is adopting, whereas the theoretical equilibrium profile is representative for the long-term average coastal profile. As an example, the coastal profile at many locations changes with the season, which means that the coastal system reaches a new dynamic equilibrium every season. It is important to be aware that such deviations are present in measured coastal profiles which complicates direct comparison with the theoretical equilibrium coastal profiles.

8.2.1 Exposed littoral dune or cliff coast

The exposed littoral coast is characterised by a wide sandy beach and a wide shoreface with up to three bars; the dry part of the beach can be bordered by dunes or cliffs.

Remnants of former geomorphologic environments, like glacial till, boulders or sandstones may be exposed to some extent in the coastal profile. There are for instance many shorelines where a coastal section is eroding and shapes a coastal cliff of till/sandstone, see Figure 4.4. In such cases, the coast can be characterised as an *Exposed Littoral Cliff Coast,* as opposed to an *Exposed Littoral Dune Coast* where the dunes dominate. There is often a gradual transition between these two types of coasts.

These exposed coastal types typically occur in connection with coastlines bordering medium large to large water bodies with dimensions from 100 km and upwards. They have storm wave climates with $H_{s,12h/y}$ larger than 3 m, micro to moderate tidal regimes, and meso to macro storm surge regimes. There is often a positive correlation between onshore wind speeds/wave heights and storm surge. The annual gross littoral transport will be large, from 50,000 m^3 per year up to more than 1 million m^3 per year. The littoral zone will be wide, typically from 300 m and up to more than 1 km.

The exposed coasts are characterised by highly dynamic morphological conditions and consequently the associated problems can also be severe. Management of such shorelines requires great care.

Typical examples of exposed coastal profiles are found along the European coasts bordering the North Sea, the Atlantic Ocean and to some extent the Mediterranean, the North- and the South American coasts bordering the Atlantic and Pacific Oceans, as well as the coasts in Africa and Asia bordering the Indian Ocean, the Persian (Arabian) Gulf, the Arabian Sea, the Bay of Bengal and the South China Sea, etc. A typical exposed coast and the associated exceedance curve for waves is presented in Figure 8.1.

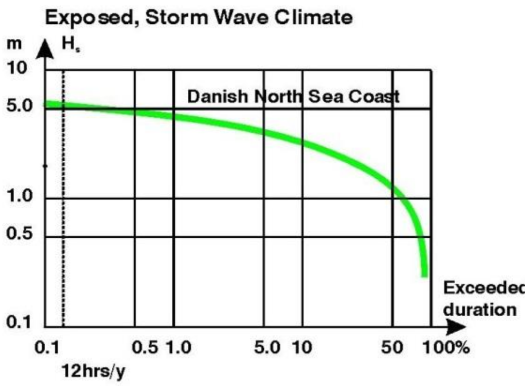


Figure 8.1 Typical exposed littoral dune coast, the Danish North Sea Coast, and the corresponding wave height exceedance distribution.

8.2.2 Moderately exposed littoral dune or cliff coast

The moderately exposed littoral coast will be characterised by a narrow beach and shoreface, normally with only one or no bars; the coast can consist of small dunes or cliffs.

This type of coast is normally seen in connection with coastlines facing relatively small bodies of water with typical dimensions from 10 to 100 km, storm wave climates with $H_{s\ 12h/y}$ between 1 and 3 m, micro to moderate tidal regimes and up to macro storm surge regimes with a positive correlation between surge and onshore winds/waves. The gross littoral transport will be relatively small, in the order of a few thousand and up to 50,000 m^3 per year. The littoral zone will be relatively narrow, typically 50 to 300 m.

A typical moderately exposed coast and the associated exceedance curve for waves are presented in Figure 8.2.

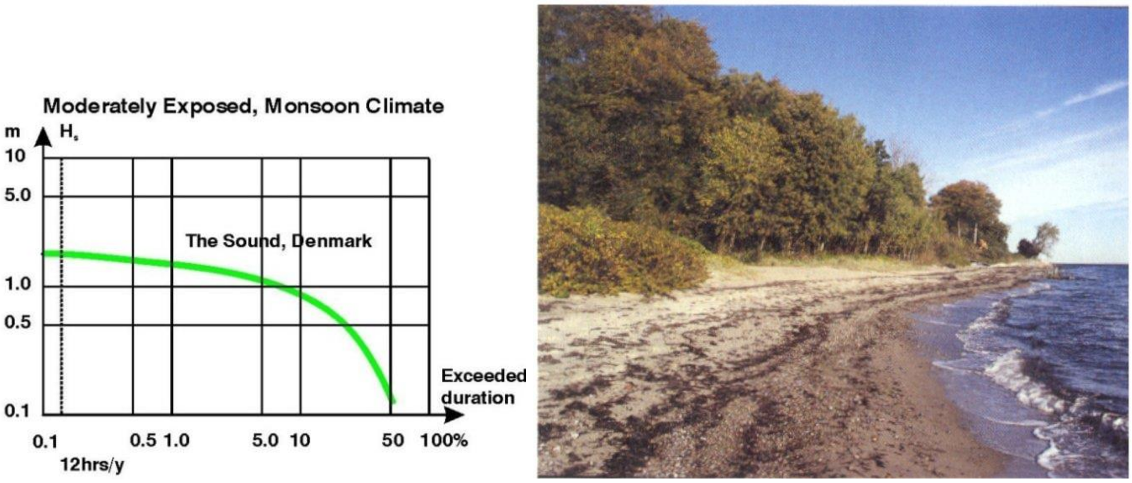


Figure 8.2 Typical moderately exposed littoral cliff coast, the Danish coast at the Sound, and the corresponding wave height exceedance distribution.

8.2.3 Protected or marshy coast

The protected coast will be characterised by a narrow beach or the complete lack of a sandy beach. The shoreface is narrow and without any bars; the coast is often covered with vegetation right out to the beach and sometimes it is marshy with only very low cliff-like scars in the coastal formations. This type of coast occurs under arctic, temperate and subtropical conditions.

This type of coast is normally seen in connection with semi-enclosed and small water bodies, for example fjords, estuaries and lagoons with typical dimensions of less than 10 km. However, such coasts can also occur in front of larger water bodies if one or more of the following conditions are fulfilled:

- The winds are relatively weak and wave climate is protected
- The geology of the area has provided a semi-enclosed water body with a very shallow nearshore zone, which protects the shore against severe wave action
- Strong onshore winds are correlated with low water (negative surge)

This type of coast can occur under micro to moderate tidal regimes and up to macro storm surge regimes. The littoral transport will be less than 5,000 m^3 per year and there will be hardly any littoral zone.

The protected coast will normally not erode, but it can be exposed to flooding. Protected coasts will normally have a poor recreational value, but are often of great environmental value, see examples in Figure 8.3 and Figure 8.4 in temperate and desert climates, respectively.

Figure 8.3 Typical protected coast in a temperate climate, Rødby Lagoon, Denmark.

Figure 8.4 Protected mangrove vegetated coast in desert climate, coastal lagoon in the Arabian Gulf.

8.2.4 Tidal flat coast

Tidal flat coasts are characterised by a very wide and mildly sloping foreshore, the so-called tidal flats. This type of coastal profile develops when tidal processes dominate over wave processes and is often found in semi-enclosed water bodies. The relative importance of the tide and the wave regime can be expressed by the *relative tide range RTR,* which is defined as (Masselink and Huges, 2003):

$$RTR = MSR/H_b$$

where MSR is the mean spring tidal range and H_b is the breaker wave height.

As a rule of thumb a tidal flat will develop when RTR = $MSR/H_b > 15$, where the yearly average significant wave height is inserted for H_b.

This definition does not account for the influence of storm surge, however tidal flats often occur for combined macro-tidal and macro-surge conditions. Negative correlation between storm surge and wave conditions may lead to the formation of a very flat shoreface similar to a tidal flat. The width and character of the backshore on tidal flat coasts will mainly depend on the storm surge conditions and the general geology and morphology of the area. If the coast is low-lying, it will often be exposed to flooding during combined high tide and storm surge. In this case sea defences, such as dikes will often have been constructed to protect the hinterland. If the coast is high, there will often be a sandy backshore and cliffs will back the coastline.

Tidal flat coasts are most frequently found in connection with moderately exposed to protected conditions combined with non-tropical climates. Under tropical conditions, the tidal flat will often be vegetated by mangrove, which changes the character of the tidal flat, see below.

The tidal flat will often consist of fine sand and mud under protected conditions, such as in estuaries, see Figure 8.5, and mainly consist of sand under more exposed wave conditions. However, many variations of tidal flat coasts exist. The specific characteristics strongly depend on the type and amount of sediments supplied from nearby rivers or from adjacent water bodies.

Figure 8.5 Tidal flat coast, the Danish Wadden Sea south of Manø.

The sediment transport processes on tidal flats are complicated as they are influenced by tidal currents and by waves. This means that there are considerable longshore as well as cross-shore transport processes. Furthermore, the tidal flats are separated in sections by tidal channels and creeks of different dimensions. The transport processes are further complicated by both non-cohesive as well as cohesive sediments as well as by the role of micro-fauna and vegetation.

These types of coasts are rarely used for traditional beach recreation because they don't provide attractive beaches. However, the tidal flats often constitute important habitats. Coastal erosion is normally modest, whereas flooding can be a major problem. However, sea defence structures, such as dikes constructed to prevent flooding, can be exposed to erosion.

8.2.5 Monsoon coast or swell coast

Monsoon wave climates and swell wave climates are characterised by persistent wave exposure with relatively modest waves. The average wave heights are typically in the order of H_s = 1-2 m, and extreme waves are less than H_s = 3 m. This provides a persistent and uniform exposure of the seabed up to water depths of 3 – 4 m, and hardly any exposure beyond that depth. Areas with monsoon wave climates and swell wave climates often occur in tropical environments with an abundant supply of sand as well as of fine sediment from rivers to the coast.

The combination of a large availability of mixed sediments and a fairly constant wave climate results in a very pronounced sorting of these sediments. This leads to the formation of a narrow sandy beach and a sandy shoreface out to a water depth of 3 – 4 m. The width of the shoreface is often less than 2-300 m. An example of typical monsoon wave conditions and associated sandy beach is presented in Figure 8.6.

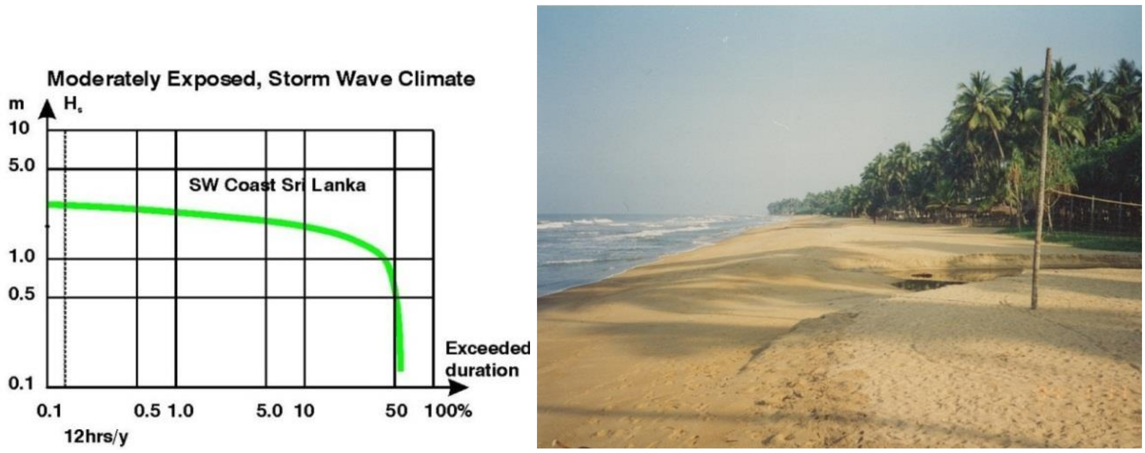


Figure 8.6 Monsoon coastline, SW coast of Sri Lanka, and the corresponding wave height exceedence distribution.

The beach and upper-shoreface often consists of well-sorted medium sand and the bed material often shifts abruptly further offshore to silt or mud and the slope of the profile becomes considerably is flatter. The fine offshore bed material is only suspended and transported during the more energetic part of the monsoon period.

Under these conditions, there is both littoral transport of sand as well as considerable transport of fine material.

The monsoon wave climate is seasonal in contrast to most of the swell climates. The monsoon coasts are normally only used for recreation in the calm period. The waves are simply too energetic in the monsoon period and the water is too turbid.

Monsoon and swell coastlines are often exposed to erosion if there is not sufficient supply of sand to the coast. Other typical problems are sedimentation in ports and the closure of river mouths due to the seasonal pattern of precipitation and wave conditions.

8.2.6 Muddy coast with mangrove vegetation

This type of coast is characterised by a muddy shoreface, sometimes in the form of muddy tidal flats, and the lack of a sandy shore. The area exposed to the tidal variation, or part of it, is vegetated by mangrove.

This type of coastline occurs in tropical climates, where rivers supply abundant fine material to the coastal zone, see example in

Figure 8.7. Normally the wave exposure is low to moderate and the tidal regime can be any type.

The coast in connection with this coastal profile is often low wetland exposed to flooding. Dikes are often built in such areas.

The mangrove constitutes an important part of such a profile, both biologically and with respect to the stability of the coastal profile. Cutting of the mangrove and utilisation of the mangrove areas for shrimp aquaculture, salt pans and agriculture constitutes a threat for such a coast due to decrease in bio-diversity as well as decrease in the resistance against erosion and flooding.

Figure 8.7 Mangrove coast, Port Klang, west coast of Malaysia. Left: Overview, Right top: Mangrove, Right bottom: Fishing village on stilts.

8.2.7 Coral coast

Corals exist both in temperate and tropical waters, but shallow-water reefs only form in a zone extending from 30°N to 30°S of the equator. Tropical corals do not grow at depths of over 50 m. The optimum temperature for most coral reefs is 26–27 C and few reefs exist in waters below 18 C. Most shallow-water corals live within the boundary of the 20°C isotherm, see Figure 8.8.

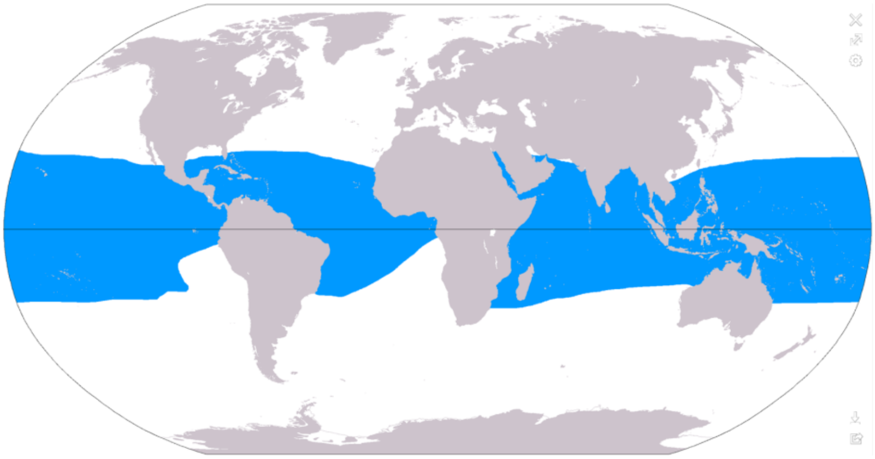


Figure 8.8 Boundary for 20°C isotherms. Note the cooler waters caused by upwelling on the southwest coast of Africa and off the coast of Peru.
From: http://en.wikipedia.org/wiki/Coral_reef#Zones

The global distribution of coral reefs is shown in Figure 8.9 including, as an example of available data, a zoom in on the area around the Arabian Sea.

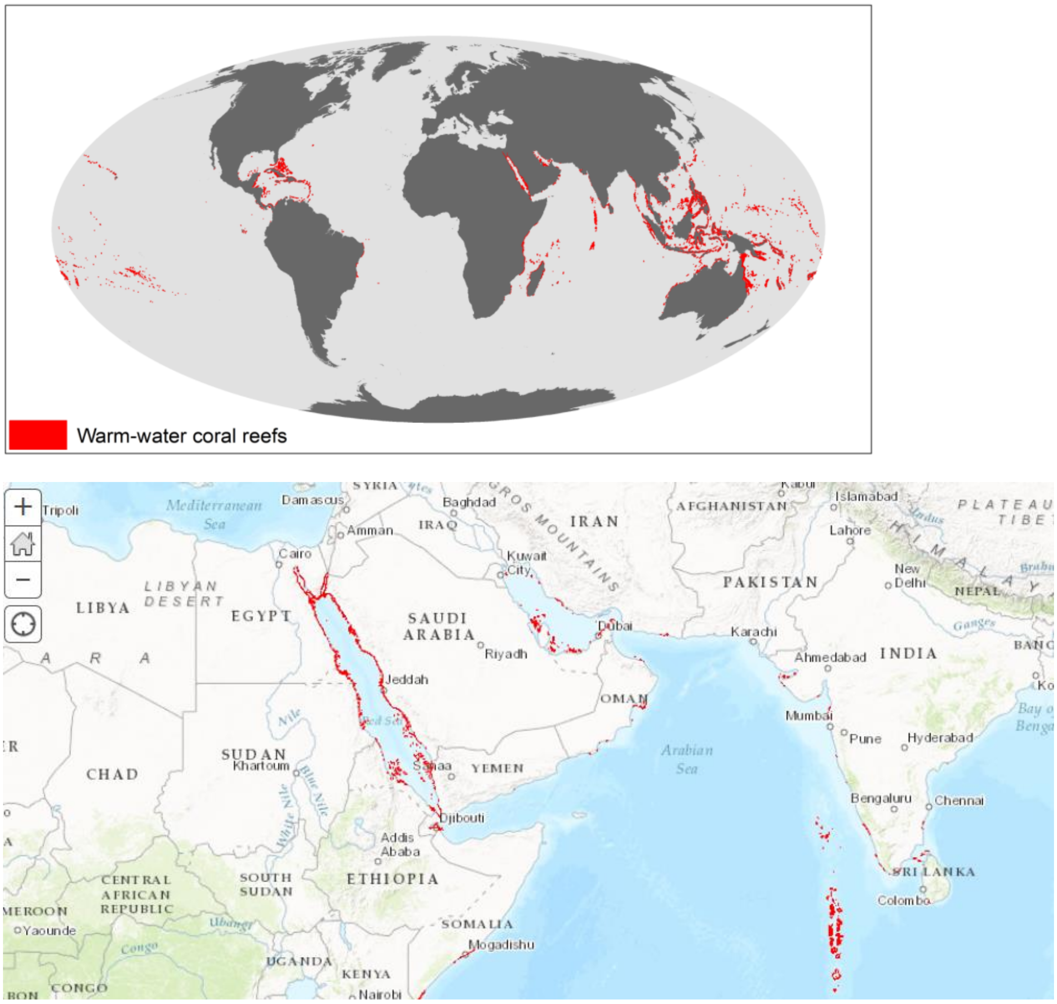


Figure 8.9 Top: Overview of global distribution of coral reefs. Bottom: Zoom in on coral reefs around the Arabian Sea.
From UNEP-WCMC global coral reef database: http://data.unep-wcmc.org/datasets/1

There are three main types of coral reefs: fringing reefs, barrier reefs, and atoll reefs. Fringing reefs grow directly from a shore and there is typically a reef flat or a relatively shallow lagoon between the reef edge and the shore. Barrier reefs are reefs located parallel to a shore and well separated from the shore by a lagoon. An atoll is a roughly circular oceanic reef surrounding a large deep central lagoon. The reef types are illustrated in Figure 8.10.

Figure 8.10 Types of coral reefs, from left: fringing reef, barrier reef and atoll. From: http://www.coral-reef-info.com/types-of-coral-reefs.html

Coral coastlines and carbonate beaches are mainly associated with fringing reefs.

Corals are small animals, which produce a hard skeleton composed of carbonate. The continued growth of these skeletons, on top of the old skeletons, produces the coral reef, which is illustrated in Figure 8.11 for a fringing reef. The coral reefs and related features are very fragile, as they are composed of the skeletal remains of living coral animals, which means that their survival are dependent on both physical and biological conditions. The growth of shallow water corals not only requires high temperatures, but also sunlight, clear and clean shallow ocean water. These conditions are often associated with nutrient-poor water, which is especially found in arid climates. The requirement to clear water also implies that the water shall be without suspended material. Furthermore, the corals require a firm seabed, to which they can adhere.

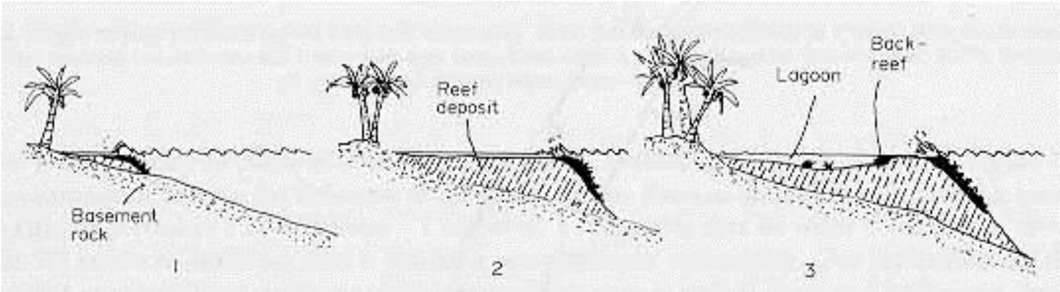


Figure 8.11 Fringing reef along the Egyptian Red Sea or Gulf coasts. Typical evolution stages 1) Early stage with little carbonate accumulation, 2) Stage with shallow reef flat, 3) Late stage with lagoon and back-reef developed. Heavy dark areas show good coral growth. Adopted from Mergner H, Schuhmacher H (1974).

The coral coasts will produce coral debris and coral sand, whereby originally hard coastlines over time are converted into sandy beaches fronted by the fringing coral reefs. In this way they enter into a category of sandy coasts, the so-called carbonate beaches. A typical carbonate beach is seen on the photo in Figure 8.12.

Figure 8.12 Coral coast with carbonate beach, Mexico.

The coral coast normally occurs in originally rocky areas in the tropics. This can be in rainforest climates on small islands, where there is no supply of fine sediments to the nearshore zone, see Figure 8.13, or in arid climates like the desert climates of the Red Sea, the Arabian/Persian Gulf and the southern part of the Mexican Gulf.

The shoreline will hardly be exposed to waves due to the presence of the reef. Waves break on the reef edge. This result in a narrow and not very attractive beach, which is not suitable for bathing, as it is fronted by the shallow reef flat, see example from the Red Sea coast in Figure 8.14

Figure 8.13 East coast of Malaysia at Marang: Sandy coast with turbid water at the mainland and coral coast and relatively clear water at island (Pulau Kapas) 5 km from coast.

Figure 8.14 Breaking waves at reef edge south of Safaga, Red Sea. The site is exposed but the beach is protected by the shallow reef resulting in a narrow beach fronted by a shallow reef flat.

The typical situation for a fringing coral reef coastline along the Red Sea coast is presented in Figure 8.15. (RSSTI guidelines, 2004).In a hot arid climate like at the Red Sea coast, river beds are normally dry and called a *wadi.* However, during the rare but violent thunder showers in the mountains, the wadies are transformed into violent rivers carrying lots of sediments. This sediment discharge prevents corals from growing locally around the outlet of the wadi and a small semi-protected bay may be formed, a so-called *sharm* or *marsa,* see Figure 8.15.

Such locations are very attractive locations for local fishermen, as they provide partly protected natural harbours, where boats can be moored and landed safely. Furthermore, these locations are very attractive from a recreational point of view. They provide attractive semi-protected beaches and sufficient water for swimming. The beaches around the wadi outlets often consist of sand carried to the coast by the wadies, see example from the Red Sea in Figure 8.16. Sediments in coastal profiles along the Red Sea coast are therefore influenced by the fringing coral reefs producing carbonate sand as well as the sediments supplied by the wadies.

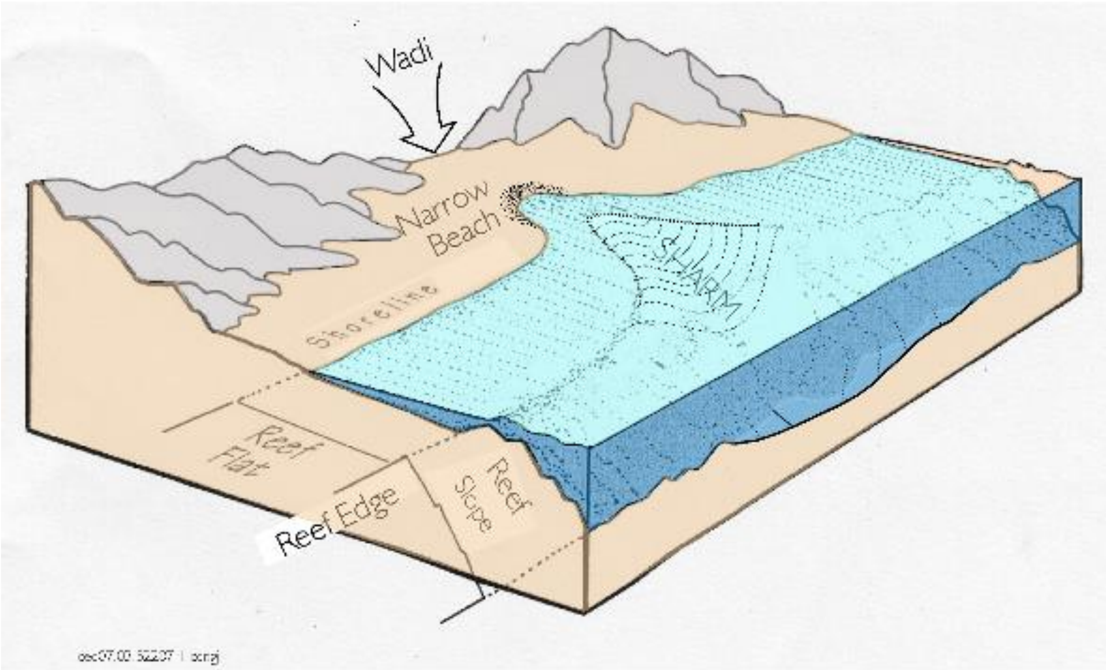


Figure 8.15 Diagram showing a fringing reef along the Red Sea Coast. A dry river, a Wadi, and a local bay, a sharm is also shown.

Figure 8.16 Attractive natural Red Sea beach at sharm location near Utobia Beach Resort in Bir Assal Center area.

9 Classification of Coastlines

The general principles for the classification of coastal profiles were presented in the previous chapter. However, the type of coastal profile is not sufficient to characterise the coastal morphology or to evaluate the stability of the coastlines, as these conditions also depend highly on the longshore processes and the coastal geomorphology. The interaction between the processes and the given coastal geology or geomorphology will result in the formation of different types of coastlines and coastal features. Therefore, it is relevant to describe and summarise the formation of various coastline features with the purpose of being able to make an overall evaluation of coastal processes and features at a certain site in relation to shoreline management activities. The main coastal processes of relevance for nearly straight sections of coastlines and for special coastal features, such as deltas, barrier islands, spits, etc. are described. The nearly straight coastlines are subdivided into categories dependent on wave exposure and on the angle of incidence of the prevailing waves. Typical problems related to the various types of coastline are mentioned.

9.1 Nearly straight coastlines

A coastline classification for nearly straight coastline sections is presented in this chapter. The classification provides a good link to typical coastal landforms and a connection to typical problems and a guideline to possible/feasible shoreline management measures. Only sedimentary coastlines, which are characterised by the presence of loose sediments on the shoreface and on the beach, will be included in the following classification.

The coastline has been divided in five main types defined by the off-shore angle of incidence of the prevailing waves.

1. *Perpendicular wave approach*, off-shore angle of incidence close to zero
2. *Nearly perpendicular wave approach*, off-shore angle of incidence 1° - 10°, net transport small to moderate
3. *Moderate oblique wave approach*, off-shore angle of incidence 10° - 50°, large net transport
4. *Very oblique wave approach*, off-shore angle of incidence 50° - 85°, large net transport
5. *Nearly coast-parallel wave approach*, off-shore angle of incidence >85°, net transport near zero

The off-shore angle of incidence is measured with respect to the normal to the coastline, i.e. the coastline orientation. The angle of incidence can also be expressed by the angle between the present coastline orientation and the coastline orientation of net zero transport, see Figure 9.1 and Figure 9.2.

The difference between the off-shore and nearshore angle of incidence is caused by wave refraction as discussed in Subchapter 5.3.2; therefore nearshore wave angles only seldom exceed 45 degrees. The classification of coastlines has been further subdivided according to wave exposure:

P *Protected*, the “once per year event” having $H_{s,\ 12h/y} < 1$ m
M *Moderately exposed*, the “once per year event” having 1 m < $H_{s,\ 12h/y}$ <3m
E *Exposed*, the “once per year event” having $H_{s,\ 12h/y} > 3$ m

Protected, moderately exposed and exposed can also be referred to as *low, moderate and high exposure*.The wave height $H_{s,\ 12h/y}$ is the offshore significant wave height exceeded 12 hours per year.

The coastline classification according to the above rules is, of course, not completely straightforward, as there can be seasonal variations, etc. to take into account. The littoral transport conditions for these coastlines are schematically presented in Figure 9.1 and Figure 9.2.

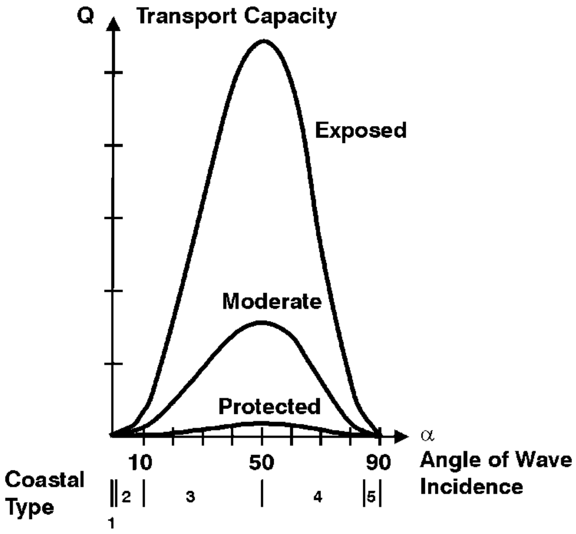


Figure 9.1 Littoral transport Q as a function of the off-shore angle of wave incidence and wave exposure.

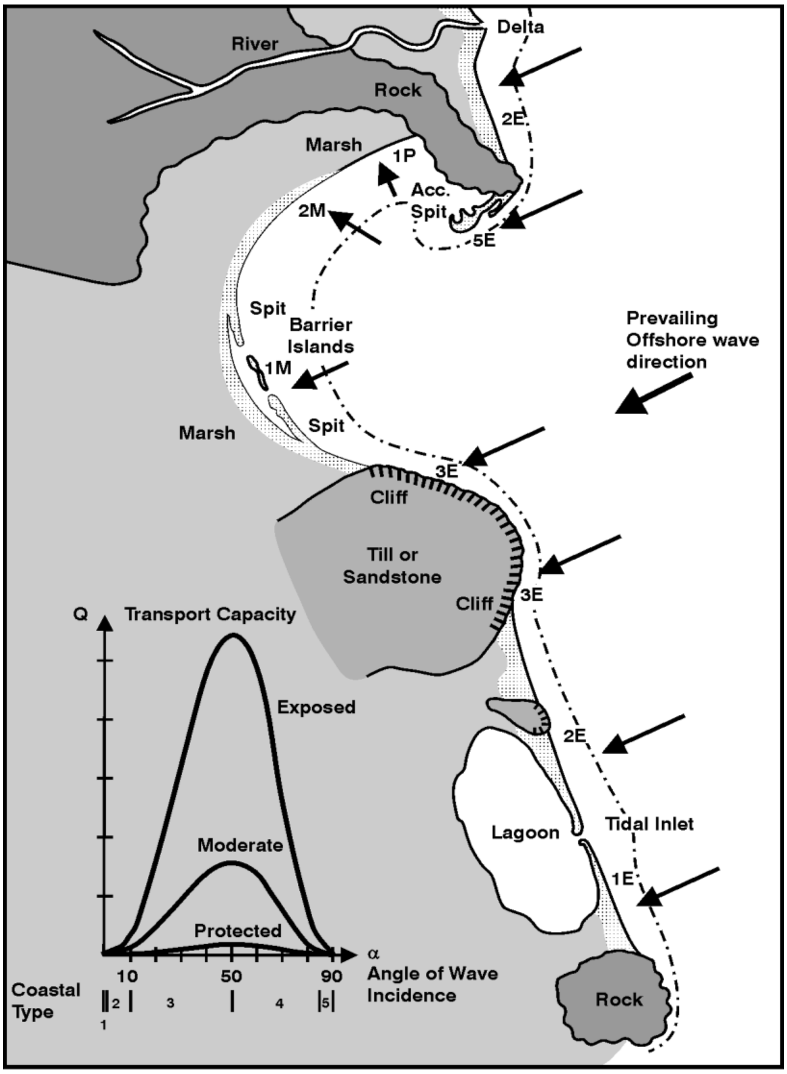


Figure 9.2 A classification of coastlines and a presentation of morphological features.

Table 9.1 presents examples of the main coastal characteristics for the different coastal types given above. It is based on a simplified classification of coastal landforms in relation to geological features. It is evident that there is a close relationship between the resulting morphological landforms and the type of coast classified by wave exposure and angle of incidence.

Table 9.1 Coastal classification as a function of the angle of incidence and wave exposure for littoral coasts and link to typical coastal landforms in relation to geological features.

Coastal Type	Angle of Incidence (0° = shore normal)	Exposure	Main Coastal Characteristics
1P	0°	Protected	Marsh
1M		Moderate	Narrow stable sand beach, barrier island, spits
1E		Exposed	Wide stable sand beach, barrier island, spits
2P	1°- 10°	Protected	Marsh
2M		Moderate	Narrow stable sand beach, barrier island, spits
2E		Exposed	Wide stable sand beach, barrier island, spits
3P	10° – 50°	Protected	Marsh
3M		Moderate	Narrow sand/shingle beach of varying stability, cliff or dunes
3E		Exposed	Wide sand/shingle beach of varying stability, cliff or dunes
4P	50° – 85°	Protected	Marsh
4M		Moderate	Narrow unstable sand/shingle beach, cliff or dunes, salients
4E		Exposed	Wide unstable sand/shingle beach, cliff or dunes, salients
5P	85° – 90°	Protected	Marsh
5M		Moderate	Sandy beach, accumulative land forms, spits
5E		Exposed	Sandy beach, accumulative land forms, spits

The above given classification is a simplification of the real world. Other parameters, such as the sediment supply from the neighbouring areas, as well as seasonal variations in wave climate, tides and storm surges, are sometimes also important.

The specific type of coastline at a certain location defines what kind of shoreline management measure can be recommended. Different types of coastlines within the group of nearly straight coastlines react differently on the same shoreline management measure. Typical problems and recommended shoreline management measures for the various coastlines will be dealt with in Chapter 17.

9.2 Other coastal form elements

Coastal morphology is more than sandy shorelines. The following types of special coastal form elements need careful and thorough analysis in connection with shoreline management initiatives.

9.2.1 Deltas

Deltas are formed when a river supplies abundant amounts of sediments into the sea. The shape of the delta is defined by the relative strength of the transport processes originating from the river discharge, the tidal currents and the waves. Deltas can be classified according to Galloway's classification, cf. Galloway 1975:

- Fluvial-dominated deltas are characterised by large catchment rivers discharging into relatively protected seas with minimal near shore wave energy and a relatively small tidal range. (Example: Mississippi)
- Wave-dominated deltas are characterised by relatively high exposure by waves and/or swell, so that the wave generated transport is larger than the transport generated by river discharge and tidal exchange. (Examples: Kelantan, San Francisco, Rhone and The Nile)
- Tide-dominated deltas are found in tidal environments, where the transport of material by the tidal exchange dominates over the transport generated by waves and river discharge. (Example: Ganges-Brahmaputra)

The different types of deltas are illustrated in Figure 9.3.

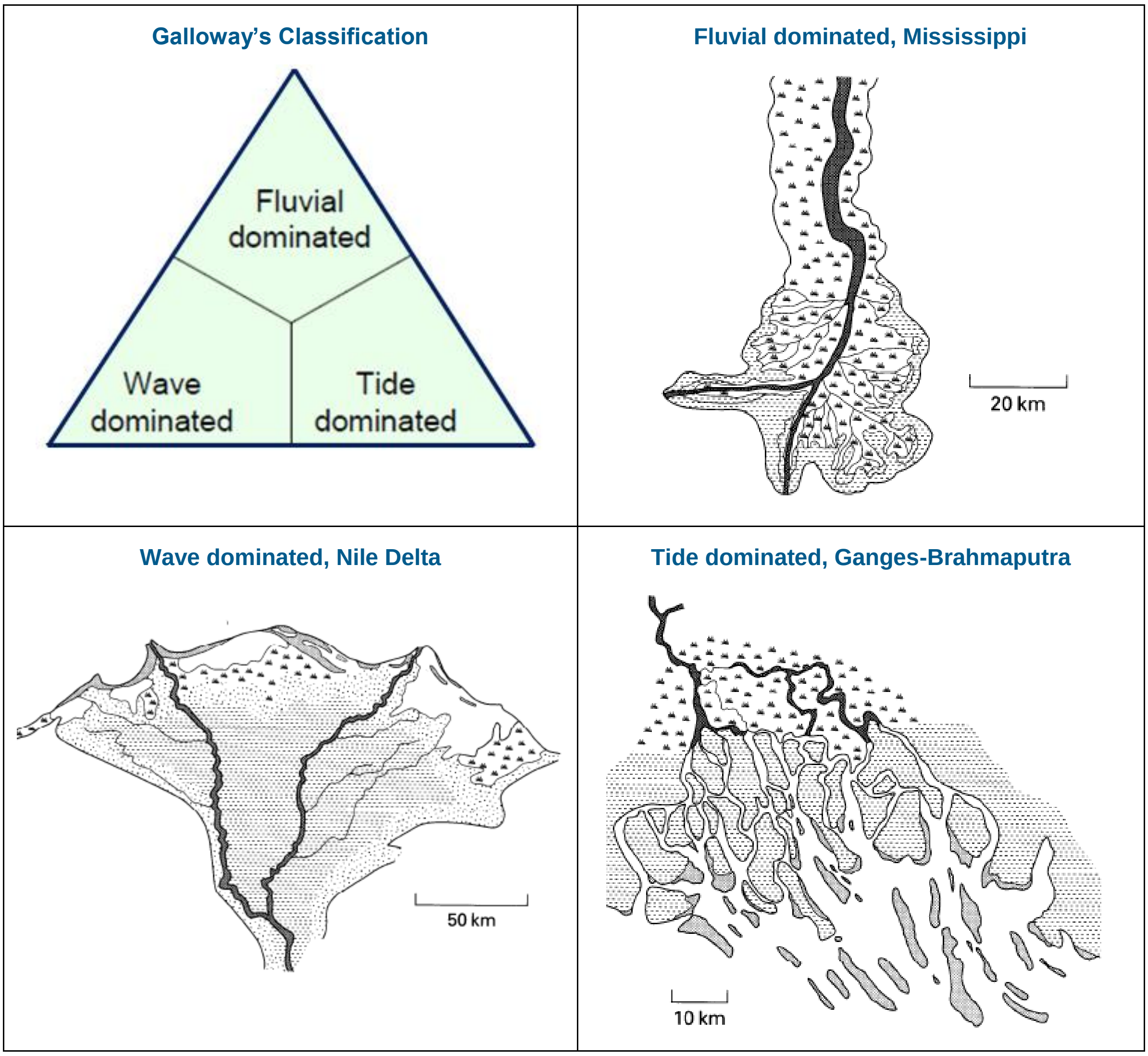


Figure 9.3 Galloway's delta classification and examples, from Galloway 1975.

There are many intermediate types. The coastal type within a delta often changes depending on its proximity to the river mouth, for which reason the classification above refers to specific sections of the delta. The stability of delta coastlines is highly dependent on the supply of material from the river. Regulation works or sand mining in the rivers will often cause a deficit in the supply of material to the coastlines, for which reason delta coastlines are often exposed to severe erosion. Development initiatives along delta coastlines should therefore be subject to careful investigations of the stability of the coastline. Such investigations have to include all activities in the associated river, such as dam and reservoir constructions, irrigation schemes, sand mining and river mouth improvement works, since all these works tend to decrease the supply of sand to the coast. Besides it has to include the normal influence of coastal works on the stability on adjacent coastlines.

9.2.2 Spits

There are two different types of sand spits, those with nearly perpendicular wave approach (Class 1M to 2E termed *Barrier Island, Spit*) and those with very oblique wave approach (Class 4-5M to 4-5E termed *Accumulating Spit*), see Figure 9.2.

9.2.2.1 Barrier islands and spits

This type of sand spit can have its origin in two types of mechanisms, by longshore supply of sand from an adjacent shore or by shoreward supply of sand from offshore as explained under Barrier Islands and tidal inlets in Subchapter 9.2.3 below. They occur on shoreline in Class 1M to 2E, see Figure 9.2. These sand spits are very morphologically active formations and may be exposed to breaching when exposed to extreme wave and storm surge conditions. Consequently, developments should be avoided at such locations and at adjacent stretches.

9.2.2.2 Accumulating spit

This type of coastal feature most often occurs at the end point of a coast with very oblique wave approach, where the littoral drift rate is decreasing resulting in deposition of sand, corresponding to Class 4-5M/E see Figure 9.2. However, for very oblique wave attack, the coastline development is often unstable and shows a tendency to form coast-parallel features at some distance from the coastline. A characteristic of this separated spit formation is that the coastline downstream of the spit has no supply of sediments, and consequently will be exposed to erosion. The construction of coastal structures which protrude into deep water or the shoreface area, may initiate the development of a coast-parallel shoal, for which reason such structures should be avoided at class 4 and 5 coastlines. Development close to such a coastline should be avoided as it is very difficult to predict how such a coastline will change.

9.2.3 Barrier islands and tidal inlets

Barrier islands are parallel to the shore, separated from the mainland shoreline by a lagoon. Barrier formations normally occur along coasts, where the slope of the original shoreface is flatter than the slope corresponding to the equilibrium profile, which corresponds to the actual conditions at the site. Under these conditions the waves on the shoreface will primarily transport sand towards the shore in an attempt to build up the equilibrium profile. Simultaneously, the waves lose their energy when travelling over the gentle shoreface, which means that there is not enough energy to transport the sand all the way to the shoreline. The deposition of sand some distance from the shoreline is a consequence of these mechanisms and this will eventually develop into a barrier island, or a series of barrier islands separated by tidal inlets, see Figure 9.4.

The above described mechanisms only consider cross-shore transport processes. However, sand is also brought into the area by longshore transport and this will add to the barrier formation processes. Under such conditions the island formation can be a mixture of spit and barrier island evolution. Barrier and spit formations of this kind are normally formed under coastal type 1 or 2 conditions.

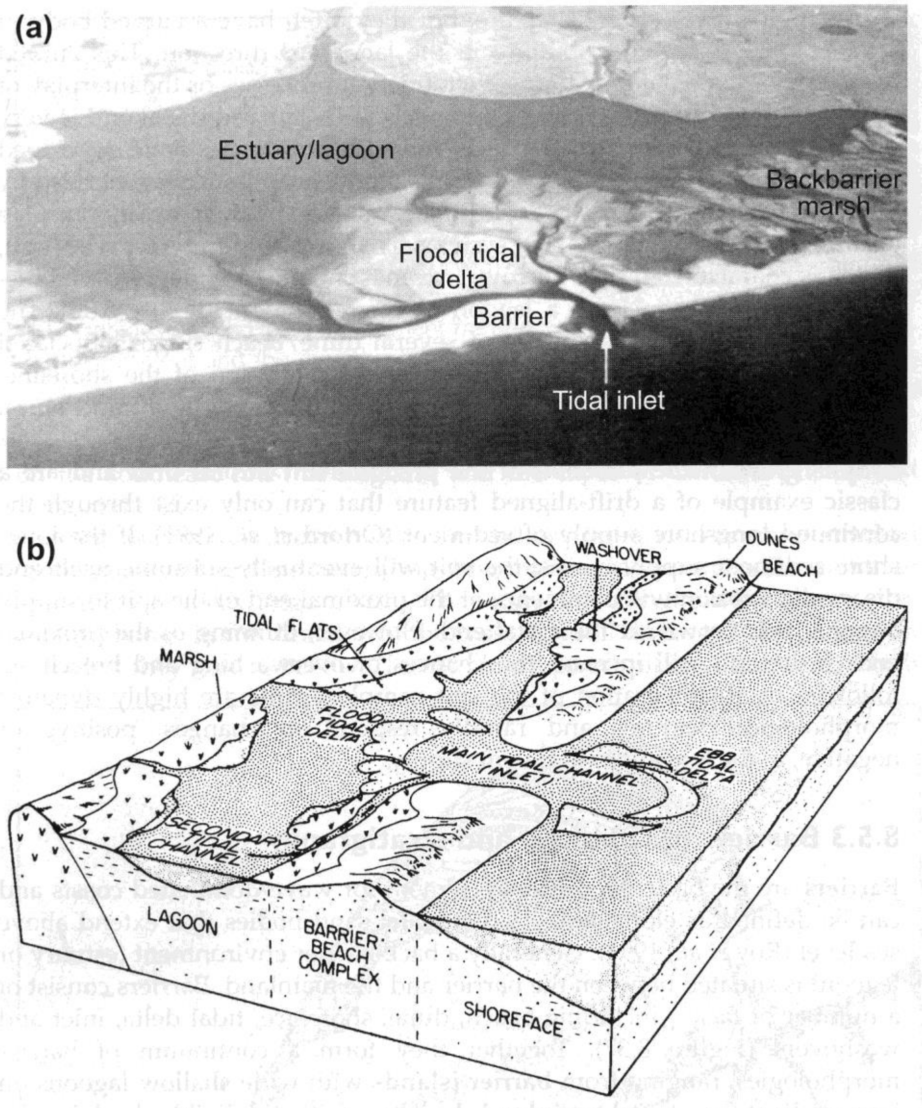


Figure 9.4 Barrier Island. (a) Oblique aerial view of barrier island system. (b) Block diagram illustrating the various sub-environments in a barrier island system. From, Masselink and Huges, 2003.

The barrier island is characterised by the following morphological form elements.

- The seaward side of the barrier has often a normal beach with dunes behind the coastline. The dune growth tends to stabilise the barrier formation.
- The back-barrier side is faced towards the lagoon and is typically dominated by marshes and adjacent tidal flats.

9.2.4 Overwash fans

The barrier islands and dune rows may be breached during extreme wave and surge conditions causing sand to be washed over the island forming overwash fans, see Figure 9.5. This situation will cause the transfer of sand from the front of the barrier to the back-barrier. This sand is not lost from the barrier island system but just moved to the back of the barrier. This means that the sand volume in the barrier is maintained and the breached section can recover itself by natural processes in the post-storm phase. However, the breaching will result in a general recession of the shoreline before a new equilibrium situation is reached. This is often seen on transgressive barrier islands.

Figure 9.5 Over-wash fans at Skallingen, southern part of the Danish North Sea coast.

9.2.5 Tidal inlet

The gap between two adjacent barrier islands is called a tidal inlet. Normally, there are two forms associated with the tidal inlet, a flood tidal shoal at the tidal basin side and an ebb tidal shoal at the side of the open sea. The lengths of the islands, or the distances between the tidal inlets, are dependent on the tidal volume. The distance between the inlets will be relatively short if the tidal volume is large and vice versa. The dimensions of the tidal inlets are dependent on the tidal volume as well as the littoral transport conditions.

Many tidal inlets are regulated by jetties and dredging. This will normally lead to loss of sand from the barrier system, either in an upstream accumulation, by offshore loss or by dumping of dredged material offshore or elsewhere outside the system. The regulation of tidal inlets is one of the most common causes of the destabilisation of downstream barrier island beaches. Well-known examples of this are the regulated tidal inlets along the American East Coast and the West Coast of Florida.

9.2.6 Lagoon/Coastal lagoon

The area between the barrier island and the mainland coast forms a lagoon. The barrier islands are active systems and may naturally move in a landward direction as a transgressive barrier island. However, this backward movement can no longer be accepted when a barrier island has been occupied by housing and other development. This situation, combined with the above-mentioned inlet problems, causes many severe erosion problems along barrier island shorelines. If it is not already too late, *development should be avoided* close to the coastline at barrier islands.

9.2.7 Coastlines close to river mouths and to tidal inlets

Such locations are very morphologically active formations as they are formed by the interaction between several hydrodynamic processes such as littoral processes, river discharge and tidal currents. Furthermore, river mouths and tidal inlets are often used for navigation and they are natural locations for towns and cities. There will often be a port of some kind, and the channels are often regulated by dredging and inlet structures. Furthermore, there can be stratification and associated additional sedimentation. Consequently, these types of coastal areas are often suffering from a series of interrelated problems, such as coastal erosion, flooding, sedimentation and navigation constraints. *New coastal development should not be allowed close to natural river mouths and tidal inlets*; the solution of specific problems *requires thorough investigations.*

9.2.8 Headland and bay beaches

9.2.8.1 Crescent bay

Rocky headlands with sandy bay beaches in between are typical for many coasts. The sandy bays will typically take the form of an asymmetrical crescent shaped bay when such a coastal stretch is exposed to oblique waves, see example in Figure 9.6. The shape and stability of such a bay is dependent of the wave climate and the supply of sand to the bay from the upstream bay and from rivers.

Figure 9.6 Crescent shaped bay, east coast of peninsula Malaysia at Tanjung Balau.

9.2.8.2

A pocket beach is a relatively short re-entrant beach between two headlands or littoral barriers, or with other words a beach enclosed between two (rocky) headlands. A pocket beach is independent of adjacent sediment cells since the headlands block all alongshore sediment exchange. An example of a pocket beach is presented in Figure 9.7.

Figure 9.7 Pocket beach at south coast of Mallorca, at Porto Cristo Novo. The length of this beach is about 50 m.

PART 2: Guidelines

10 Introduction

PART 2 of the *Shoreline Management Guidelines* contains the actual guidelines for shoreline management, whereas PART 1 describes the physical and coastal processes, which form the necessary basis for optimal participation in the management process.

PART 2, Guidelines, contains:

Chapter 11: Causes of Coastal Erosion and Coastal Flooding incl. Impact of Climate Changes

Chapter 12: Vulnerability and Risk Classification for Erosion

Chapter 13: Vulnerability and Risk Classification for Flooding

Chapter 14 Planning Concept in the Coastal Zone

Chapter 15: Coastal Projects

Chapter 16 Design Philosophy incl. Adaptation to Climate Changes

Chapter 17: Shore Protection, Coast Protection and Sea Defence Methods with Special Emphasis on Coastal Adaptation to Climate Changes

It is hoped that these *Guidelines* will assist the reader, whether an engineer or a planner, in formulating a suitable strategy for the problem in hand and in selecting realistic and sustainable solutions. This part of the book can either be read entirely or be used as a reference book.

11 Causes of Coastal Erosion and Coastal Flooding incl. Impact of Climate Changes

Coastal erosion, natural as well as erosion caused by human activities, has conventionally to be accepted as permanent as the cause of the erosion cannot be removed. However, it is often useful to distinguish between **chronic erosion** and **acute erosion**.

Chronic or long term erosion - is due to a deficit between supply of sand and loss of sand in a coastal cell along the coast. An increasing transport in the direction of the net transport will cause coastal erosion over the entire active coastal profile, see Figure 11.1. The gradient in the littoral transport along a coastal stretch is typically occurring as a result of changes in the orientation of the shoreline, as a result of changing wave conditions along the coast or blockage of the transport by a coastal structure. Chronic erosion is typically developing progressively and steady over long periods and is consequently not only associated with extreme storms.

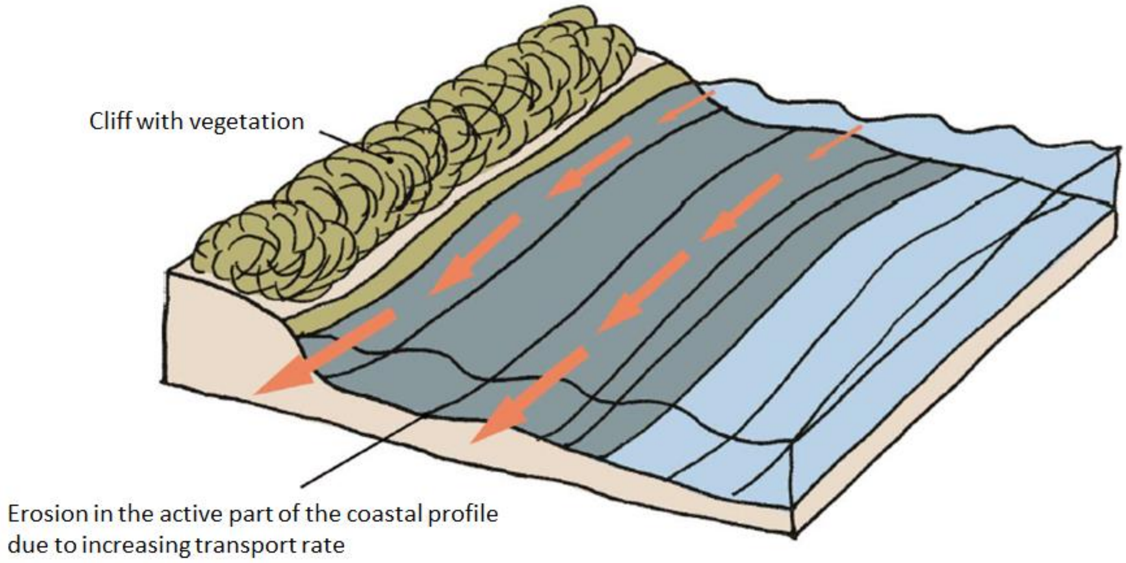


Figure 11.1 Chronic erosion on active coastal profile resulting from an increasing gradient in the net littoral drift in the direction of the net littoral drift.

Protection measures should be considered to protect coastal facilities against chronic erosion if the coastal facilities are in risk of being damaged by erosion within a certain number of years, say 20 years.

Acute erosion – is typically occurring during extreme events where the coast is exposed simultaneously to high waves and storm surges. Such an exposure will result in offshore transport of sand from the upper part of the profile, which results in coastal erosion. This type of erosion will typically attack all over a coastal stretch resulting in almost evenly distributed cliff erosion along the stretch, see typical example in Figure 11.2.

Figure 11.2 Example on acute cliff erosion NE of Liseleje following the extreme storm “Bodil” hitting the North Zealand coast in Denmark in Dec. 2013 with a storm surge of 1.9 m.

An extreme event, such as an extreme depression storm at the northern latitudes or a hurricane/typhoon/cyclone at lower latitudes, may also result in flooding of low laying coastal areas.

Acute erosion is often a reversible processes and is therefore often temporary in nature as the coastal profile may recover fully or partially after the storm. Acute erosion can also occur in part of a littoral cell due to longshore processes caused by an extreme and atypical storm with different directional characteristics than the predominant waves, or a combination of both. Seasonal variations in the location of the shoreline are also characterised as acute erosion.

Whether protection measures are recommended is dependent of the width of the buffer zone relative to the expected erosion occurring during a storm event or during a season and thereby whether coastal facilities are threatened.

The risk of damages caused by coastal erosion is related to the morphological process of coastal erosion, and the risk associated with coastal flooding of the hinterland is related to the storm surge water level exceeding a certain threshold, namely the level of a possible sea defence, dune field or the level of the hinterland, or a combination of both. The following three cases are considered:

Small risk of coastal flooding - The hinterland is higher than the design water level and the area may be protected by a dike/seawall with a top level higher than the design water level. There is only a risk of overrun of the hinterland due to wave overtopping. Furthermore, there is a very small risk of flooding for the very extreme event with a storm surge level higher than the design water level and higher than the level of the dike/seawall.

Moderate risk of coastal flooding - The hinterland is lower than the design water level but the hinterland is protected by a dike/seawall with a top level higher than the design water level. There is a risk of minor flooding due to wave overtopping of the dike but there is a moderate risk of flooding if the dike/seawall is breached.

Major risk of coastal flooding - The hinterland and the dike/seawall are both lower than the design water level. There is a major risk of flooding during the design event because the protection and the hinterland are both lower than the design water level. The area will in this case be inundated.

Tsunamis can cause severe flooding and destruction of the coastal hinterland but a tsunami will not necessarily result in acute erosion.

There is a morphological element in the evaluation of flooding risks in the event that a dike or a seawall is breached. These conditions are taken into account in assessing risk in connection with coastal erosion and coastal flooding.

11.1 Natural causes of coastal erosion

The description of natural causes of coastal erosion is given for *chronic erosion* and *acute erosion,* respectively.

11.1.1 Natural chronic erosion

Natural chronic coastal erosion can be due to a variety of reasons as discussed in the following:

- An increasing gradient in the littoral drift in the direction of the net transport is the main course for chronic erosion. The reason for chronic erosion along such a stretch is that more sand is transported out of a coastal section than is transported into the same section, as illustrated in Figure 11.1

  This can be due to gradients in the wave conditions at certain stretches, a curved coastline, or special bathymetric conditions. An example of this kind of coastal condition is the West Coast of Jutland, Denmark. The varying wave conditions and varying shoreline orientation along this coast results in a littoral drift budget, which varies in magnitude as well as in direction along this coast as presented in Figure 11.3. The gradients in the net littoral drift are responsible for the ongoing erosion and deposition along the coastline as also indicated in Figure 11.3.
- The loss of sand into canyons. If there is a deep canyon close to a littoral transport coastline, sand may be lost into the canyon.
- The loss of sand to an accumulative beach at the tip of a spit and into deep water at the leeward of the tip of a Spit at the termination point of a littoral cell. Sand lost in this way causes accumulative shore and shoal features in the deposition areas, but the upstream coastline has lost the sand. An example of this is the Skaw Spit, see Figure 11.4.
- The loss of material from a protruding area to one or two sides. This typically happens at till/sandstone headlands and at the apex of deltas, which do not receive sufficient material from the river due to reduced sediment load or a natural shifting of the river alignment. Delta erosion can also be caused by human impact, which will be discussed later. It also occurs along semi-hard (glacial till) convex-shaped sections of coastline. The natural state of such a coastline is erosion and straightening; the straightened coastline is referred to as a simplified coast, see Figure 11.5.

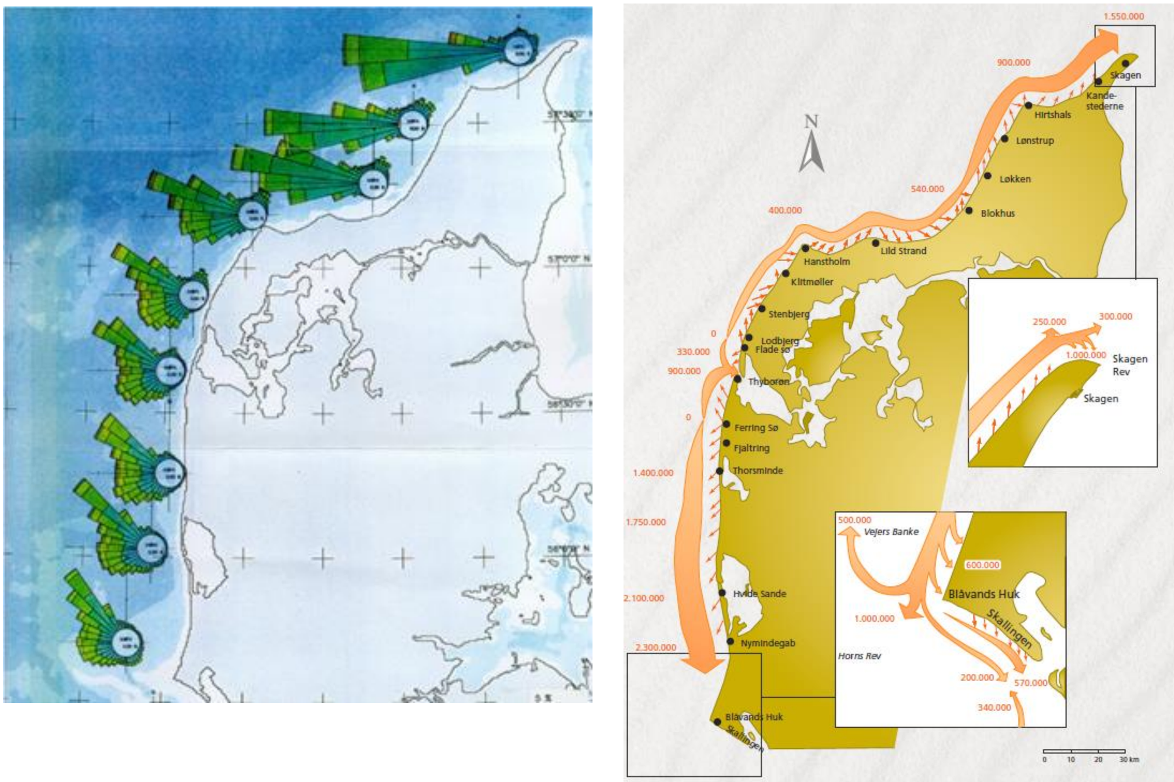


Figure 11.3 Wave conditions along the West Coast of Jutland, Denmark and net littoral drift budget as well as coastal erosion and accretion, Danish Coastal Authority (2001).

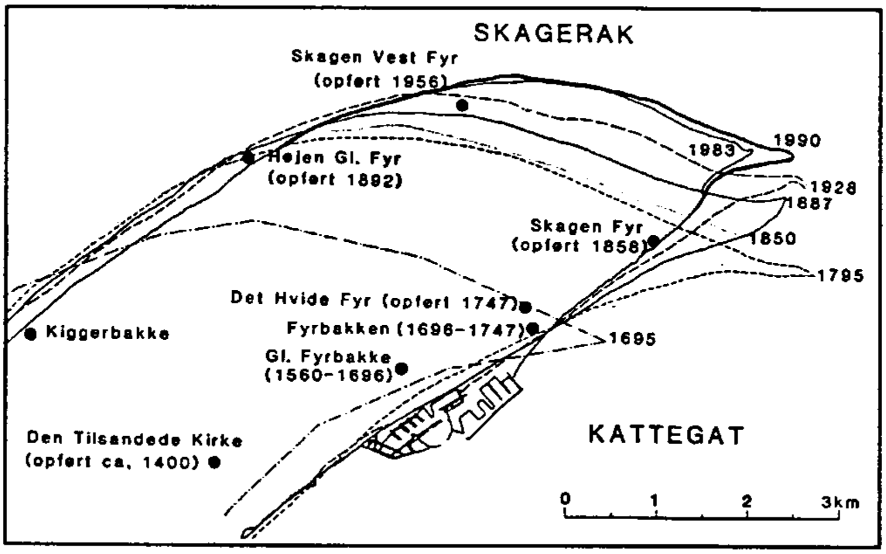


Figure 11.4 Sand deposition at the north beach at Skaw Spit and corresponding loss of sand from the upstream beach.

- The erosion of marine deposit shorelines suspended between sections of protruding semi-hard sections of the coastline, such as till or sandstone. The hard sections have historically provided material for building up the sedimentary shorelines. The shape of these shorelines is consequently dependent on the presence of the semi-hard sections and the wave climate. However, as the semi-hard sections continue to erode, the sedimentary shorelines will follow suit despite the fact that they were originally accumulative forms. This development is part of the simplified coast, see Figure 11.5.

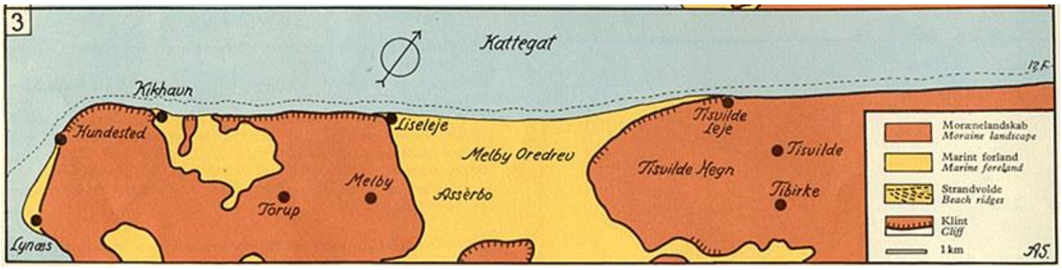


Figure 11.5 The NW coast of North Zealand, Denmark, an example of a simplified coast; the moraine landscape (red) has been cut back to a nearly straight line, marine platforms (yellow) has been formed in between.

- The erosion downstream of accumulative forms at coastlines with very oblique wave approach, coast types 4M, 4E, 5M and 5E cf. Subchapter 9.1. Along such coastlines there is a tendency for the natural formation of spit formations parallel to the coast. They accumulate the sand and shift the sand supply offshore, which means that the downstream coastline is starved and begins to erode, see Figure 11.6.

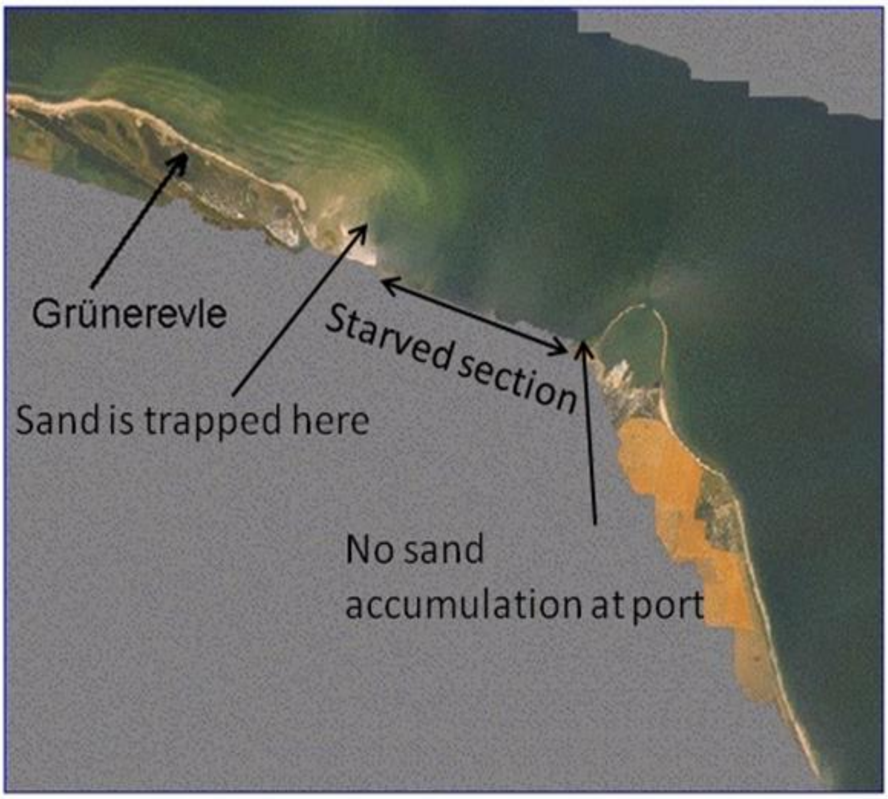


Figure 11.6 Grünerevle at the north coast of Fehmarn Island, Germany, an example of the formation of a sand spit formation parallel to the coast, which starves the downstream coastline. Note that there is no sand accumulation west of the port because the sand is trapped in the sand spit further upstream.

- Sea level rise. A global sea level rise is a phenomenon, which has been discussed for decades. A global sea level rise of 0.1 to 0.25 m was recorded over the last century. The forecast for the global sea level rise for the next century varies considerably; however, a likely scenario to use seems to be that the sea level rise in year 2100 will be in the range of 0.5 m to 1.0 m however with a risk of being about 50% higher and that the sea level will continue rising also after year 2100, see Subchapter 6.3. It can be discussed whether sea level rise is natural or caused by human activities, however,in this context it has been classified as natural. An increasing sea level will cause a shoreline setback, which is approximately equal to the sea level rise divided by the slope of the active coastal profile, when considering equilibrium profiles. Consider, for example, a sea level rise of 0.8 m and an equilibrium coastal profile with a slope of the shoreface and the shore of 1/100. The setback caused by such a sea level rise will be 80 m. Littoral coasts consisting of fine sediments will be exposed to higher setbacks than coasts consisting of coarser sediments.

- Subsidence lowers the surface in a specific region. Subsidence is a local/regional phenomenon in contrast to the sea level rise, which is global. Subsidence can be caused by many different phenomena, natural as well as human. Natural causes can be the settling of soft sediments, tectonic activity and different kinds of rebound processes (whereas human causes can be the extraction of groundwater, oil or gas in the coastal area). Subsidence acts in the same way as sea level rise in relation to shore erosion apart from the fact that a sea level rise will always be a gradual and slow process, whereas subsidence may occur rapidly depending on its cause.

11.1.2 Natural acute erosion

Examples of acute natural erosion are presented in the following.

- The most important type of acute erosion is the offshore movement of sand in the coastal profile during extreme wave and storm surge conditions causing erosion of the shoreline. However, the coastal profile and the shoreline will slowly re-establish themselves during less severe conditions provided that:
  - Breaching of the berm/dune did not occur during the acute event
  - The temporary erosion did neither reach the cliff nor any fixed coastal facilities

In addition, there are other types of acute erosion as discussed in the following:

- Breaches in barrier islands leading to the formation of a new tidal inlet will cause erosion along adjacent coastlines because sand is trapped in the ebb and flood shoals of the tidal inlet. This is initially acute erosion but may develop into chronic erosion.

- Inland sand loss due to over-washing of a barrier island will cause acute erosion of the shoreline. This kind of sand loss takes, for example, place along the exposed coast of Skallingen barrier island on the southern part of the Danish North Sea Coast, see Figure 9.5.

- The natural variation in the supply of sand to a coastline from a river. Droughts in large river basins can result in periods with decreasing supplies of sand to the shoreline, leading to acute coastal erosion. The historic large variations in the shorelines of the Nile delta were partly due to this situation, whereas the more recent erosion (since the construction of the High Aswan Dam in 1962) is mainly the result of human interventions along the Nile, see Subchapter 11.2.5 ; this erosion must be classified as chronic.

- The shoreline in a small littoral cell will tend to stabilise in the equilibrium orientation. Short term variations in the wave climate, such as during storm events, or variations with longer periods, such as seasonal variations, will result in temporary variations in the position of the shoreline, typically erosion in one end of the cell and accretion in the other end of the cell.

11.2 Human causes of coastal erosion

Although there are many natural causes of coastal erosion, most of the causes affecting coastal communities are due to human intervention in the transport processes along the coastlines and/or reductions in the supply of sand to the shorelines.

It should be noted that:

Most human causes of coastal erosion are classified as chronic erosion, only the erosion caused by wake waves is classified as acute erosion.

11.2.1 Coastal structures interfering actively with the littoral transport

Coastal structures interfering with the littoral transport are the most common cause of coastal erosion. The presence of the structure has a series of effects:

- Trapping of sand on the upstream side of the structure takes sand out of the sediment budget, thus causing shore erosion along adjacent shorelines. Mostly, of course, on the lee side, but large structures may also cause (initial) erosion on the upstream side

- Loss of sand to deep water

- Trapping of sand in entrance channels and outer harbours. The sand is often deposited in deep water after being removed by dredging.

The structures, which may cause this type of erosion, are:

- Groynes and similar structures perpendicular to the shore
- Ports
- Inlet jetties at tidal inlets and river mouths
- Detached breakwaters
- Coastal reclamations

The accumulation and erosion patterns adjacent to coastal structures depend among other things on:

- The classification of coastline, i.e. the wave climate and the orientation of the shoreline
- The extent of the structure relative to the width of the surf-zone
- The detailed shape of the coastal structure

The typical impact on the coastal processes and related shore erosion problems for different types of structures will be discussed briefly in the following. A more comprehensive description of the structures and their function will be given in Chapter 17.

11.2.1.1 Groynes and similar structures perpendicular to the shore

Groynes are normally built perpendicular to the shoreline with the purpose of protecting a section of the shoreline by blocking (part) of the littoral transport, whereby sand is accumulated on the upstream side of the groyne. However, the trapping of the sand causes a deficit in the littoral drift budget, and this kind of coast protection is always associated with corresponding erosion on the lee side of the structure. In other words, a groyne just shifts the erosion problem to the downstream area. This is the reason for groynes often to be built in long series along the shoreline, a so-called groyne field. In an attempt to compensate for the effect of the upstream groyne(s), new downstream groynes are built, which shift the lee side erosion problem even further downstream.

The efficiency of a groyne field as a protection measure depends on the length of the groynes relative to the width of the littoral zone and the number and spacing of the groynes. The more efficient the groyne field is protecting the shoreline within the groyne field, the more lee side erosion will be experienced downstream.

These effects of groynes were not fully understood and realised at the beginning of the last century when many major groyne fields were constructed. Nowadays, this mechanism is understood and can be modelled and therefore groynes can be selected -if suitable- and designed to fulfil their purpose optimally.

Apart from being beneficial to compensate erosion in a local area, groynes do not add to the beauty of the landscape, and they generate dangerous rip currents.

Examples of coastline development for different types of groyne schemes for different types of coast are presented in Subchapter 17.5.1.

11.2.1.2 Ports

The primary purpose of a port is to provide safe mooring and navigation for the calling vessels but when built on the shoreline it interferes with the littoral drift budget and the results are sedimentation and shoreline impact.

Like a groyne, the port acts as a blockage of the littoral transport, as it causes trapping of sand on the upstream side in the form of an accumulating sand filet, and the possible bypass causes sedimentation at the entrance and in dredged approach channels. The sedimentation requires maintenance dredging and deposition of the dredged sand. The result is a deficit in the littoral drift budget, which causes lee side erosion along the adjacent shoreline. The layout of a port on a littoral transport coast must consequently be designed to minimise sedimentation and coastal impact. Attention has not always been paid to these requirements. The result is that many ports trap large amounts of sand and suffer from severe sedimentation and cause severe downdrift erosion.

The principal shoreline development on littoral transport coasts with slightly oblique wave approach and very oblique wave approach, coast types 2-3M/E and 4M/E respectively, will be discussed.

Accumulation and erosion for 2-3M/E coasts (angle of incidence less than ~40°)

The coastal structure in this example is a large port with an extension greater than the width of the surf-zone, but the structure could also be a set of tidal inlet jetties or a long groyne. We consider an E-W directed shoreline, with a net eastward littoral drift rate (LDR) of 5, which is composed of an eastward LDR of 10 and a westward LDR of 5 (the LDR is presented here without any unit, the specific numbers are used to illustrate the principles only). Prevailing waves from the NW and secondary waves from NE, as shown in Figure 11.7, generate this transport climate.

Initially, there will be an eastward LDR of 10 close to the port on the upstream west side of the port, as this area is sheltered from the easterly waves by the structure there will be no westward LDR-component in this sheltered area. Outside the lee zone west of the structure, there will be a net eastward LDR of 5. This means that the transition section between these two areas will receive 5, but 10 will leave this section, which means a deficit of 5 in supply to this local area. The transition area will therefore initially be exposed to a sediment deficit of 5, whereas the area close to the structure will receive 10. This will cause initial erosion as well as sand accumulation on the upstream side of the structure. However, considering the entire upstream side as one unit, this unit will receive a surplus of 5 until bypass of sediment starts.

Close to the structure on the lee east side, there will be a westward LDR of 5, as this area is sheltered from the westerly waves by the structure. This will result in a short accumulation of sand immediately east of the port. Outside the lee zone east of the port, there will be a net eastward LDR of 5. Initially no sediment will bypass the port. The area east of the port will consequently, considered as one unit, have a deficit of 5. This is the so-called lee side erosion. However, there will be an area in the transition zone close to the port, which will have a deficit of 10, but this is only temporary, as the local reversed transport towards the structure will cease when the local coastline has adjusted to the conditions.

The above sediment budget is applicable for the "initial" situation immediately after the construction of the port. Initial is a relative concept. The duration of the initial period depends on the magnitude of the port and on the area and volume of the sheltered areas compared to the littoral drift rates. The sediment budgets for the initial situation, as well as for a situation when the bypass of sediments has started, are both presented in Figure 11.7.

The development of accumulation and erosion on the upstream and downstream sides of the port is sketched in Figure 11.7. As long as the transport is completely blocked by the port, the accumulation will take place as a seaward movement of the coastline adjacent to the breakwater parallel with the direction of the coastline corresponding to zero transport, i.e. perpendicular to the direction of the resulting incoming waves.

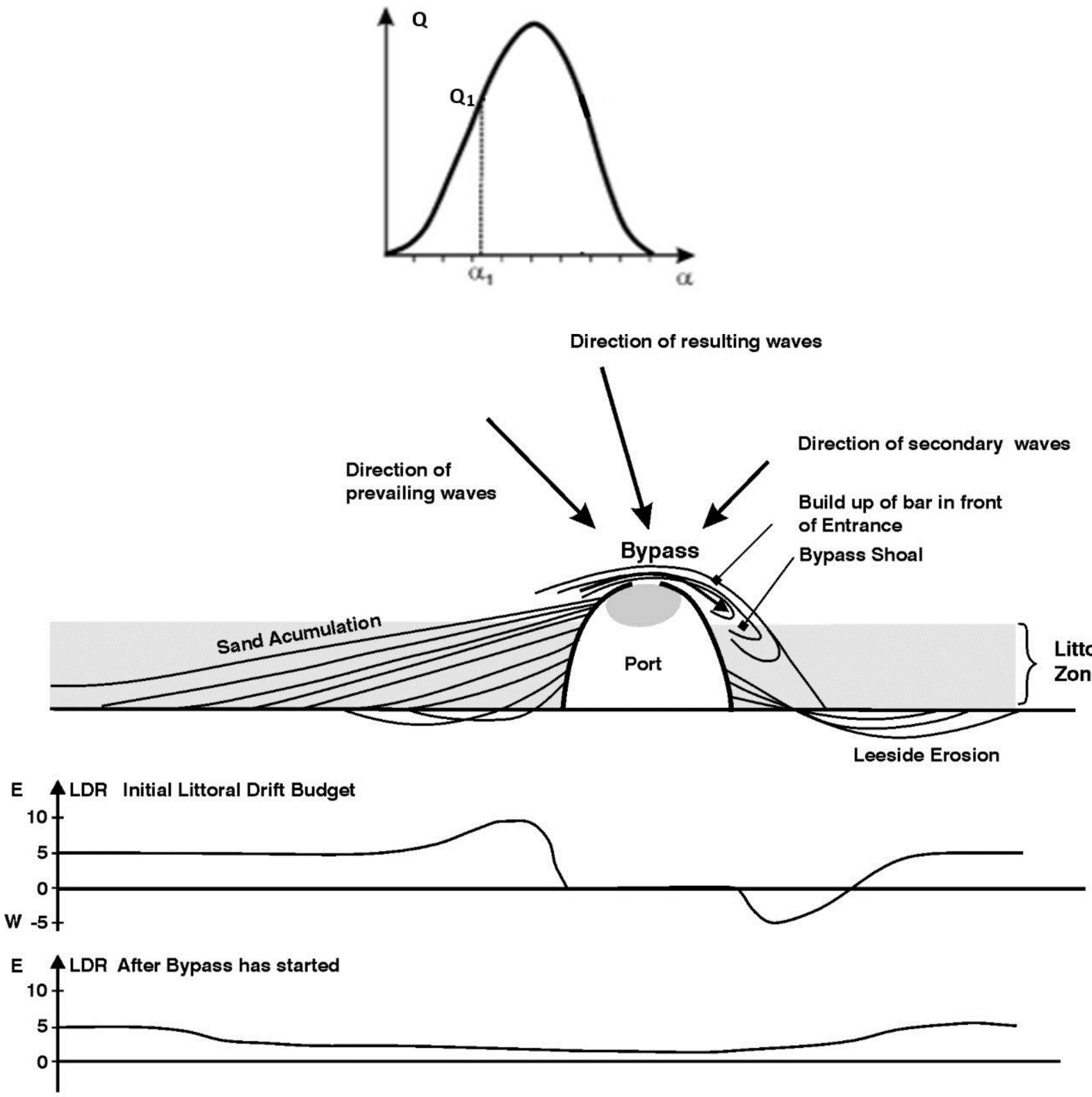


Figure 11.7 Upper: Relation between transport and predominant angle of incidence. Lower: Schematic shoreline development, morphological development and net littoral drift budgets for a port at a coast with a slightly oblique resulting wave attack.

When the bypass starts, a bar will build up in front of the entrance, and the accreting coastline will gradually turn towards the original direction concurrently with a gradual increase in the bypass. This bypass causes a gradual increase in the sedimentation of the port entrance and/or the navigation channel. The part of the bypassing material, which is not trapped in the entrance, will be transported past the port, building a shoal at the lee side of the port. The downdrift shoreline will suffer from erosion until this shoal reaches the shore. Even then, the downdrift shore will not receive the same amount of material as it originally received from the updrift shore, as this would require that the accreting coastline attained an orientation parallel with the original coastline. This would require a sand filet of infinite length, which is not possible. Furthermore, it would require that there was no loss of sand in connection with the bypass of the port, which is also unrealistic. This explains why the downdrift shoreline will forever suffer from erosion as a result of the port construction, or another similar coastal structure, unless artificial nourishment/bypass is introduced.

This situation is thus characterised by a long slowly developing sand filet at the upstream side of the port and the formation of a fairly short narrow shoal downdrift of the port, as well as shoreline erosion relatively close to the port along the downdrift shoreline. However, there will, in most cases, also be a very short accumulation zone immediately leeward of the port. Sedimentation in the entrance will develop slowly. It is worth noting that as soon as a coastal structure of an extension comparable to the width of the surf-zone has been built along such a shoreline, the downstream shoreline will forever suffer from erosion.

In addition to the phenomena described above, a non-optimal layout of the protective structures can result in additional trapping of sand. This typically happens in the sheltered area generated by port layouts, which consist of a main breakwater overlapping a secondary breakwater. This kind of layout will act as a sediment trap, which is filled concurrently with the maintenance dredging. This will cause additional lee side erosion depending on where the sand is deposited. This phenomenon is explained in further detail in Subchapters 5.4.1 and 5.5.1.

Accumulation and erosion for 4M/E coasts (angle of incidence α_2 greater than ~60°):

When the angle of incidence of the resulting waves is larger than 50º, the shoreline development and corresponding morphological changes are quite different from the situation described above, see Figure 11.8.

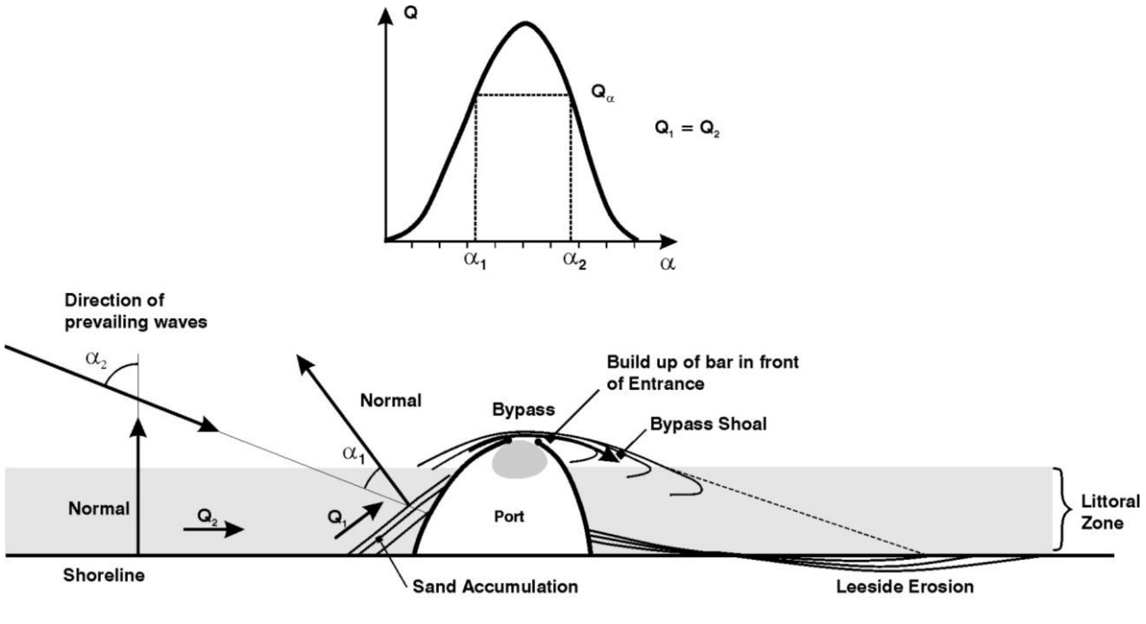


Figure 11.8 Upper: Relation between transport and angle of incidence. Lower: schematic shoreline development and morphological development for a port at a coastline with very oblique wave attack.

The angle of incidence of the waves with the original shoreline is denoted as $\alpha_{2,}$ which corresponds to the transport Q_2, see Fig 10.7 upper part. There is, however, another smaller angle of incidence α_1 which gives the same transport, $Q_2 = Q_1$. This means that the shoreline in the accumulation area upstream of the port will immediately switch to the position corresponding to the angle of incidence $\alpha_{1.}$ This provides a minor accumulation, which will very quickly develop into a situation with full bypass equal to Q_2, and the corresponding build-up of a bar past the entrance.

The bypassing sand will, due to the very oblique wave attack, develop into a bypass shoal nearly parallel with the coastline, i.e. a very long shoal.

This situation is thus characterised by a short and quickly developing accretion zone and a fairly long, slowly developing bypass shoal downdrift of the port. Another effect is a gentle shoreline erosion over a fairly long distance from the port along the downdrift shoreline. Sedimentation in the entrance will develop quickly.

11.2.1.3 Inlet jetties at tidal inlets and river mouths

Tidal inlets and river mouths are often by nature shallow and variable in location, which affects the neighbouring coasts and makes them unsuitable for navigation. In order to improve navigation conditions and, to some extent, flushing conditions, many tidal inlets and river inlets have regulated mouths. The regulation may consist of jetties, possibly combined with maintenance dredging programmes. If the tidal inlets and the river mouths are located on littoral transport shorelines, they are often in a natural equilibrium with respect to bypassing of the littoral drift, which normally occurs on a shallow bar across the inlet. If the inlet/mouth is upgraded to accommodate navigation, this bar is normally cut off by the jetties or dredged.

For the above reasons, regulated inlets are normally obstructions to the littoral transport which means upstream sand accumulation along the upstream jetty, loss of sand due to sedimentation in the deepened channel and the associated maintenance dredging. All in all, regulated inlets will very often cause lee side erosion problems. Modern legislation requiring mitigation measures, such as artificial sand bypass does not always work ideally. At many such locations the mitigation measures have never been introduced or are severely delayed.

In conclusion, past and present regulations of tidal inlets and river mouths are responsible for major erosion along many coastlines throughout the world.

11.2.1.4 Detached breakwaters

Detached breakwaters are used as shore and coast protection measures and have also been used to provide protected landing places for fishing boats and bathing. In general terms, a detached breakwater is a coast-parallel structure located inside or close to the surf-zone. Breakwater schemes have many variables, which determine the impact on the shoreline. The variable parameters are outlined in the following:

- Emerged, submerged or floating
- Distance from shoreline and location relative to the surf-zone
- Length and orientation
- Single or segmented
- Special shapes

A complete description of combinations of all these parameters falls outside the scope of this chapter but there are further descriptions in Chapter 17.5.2.

A shoreline management breakwater serves two purposes:

1. To provide shelter from the waves

2. Through this shelter, to manipulate the littoral transport conditions and thereby to trap some sand

Some breakwaters, offshore breakwaters, are constructed in deep water as a special type of port, providing shelter for a piled berth connected to the coast by a piled jetty. This kind of port is normally used when the slope of the coastal profile is very gentle, which makes the construction of a traditional port very costly. The philosophy is that the distance to the shoreline behind this kind of port will minimise the impact on the shoreline. However, in practice, it is very difficult to construct such a zero impact breakwater port.

A detached breakwater has the following impact on the hydrodynamic conditions in the adjacent area:

- The breakwater shelters partly from the waves; however, as the waves diffract into the sheltered area, a complete shelter cannot be obtained. The longer the breakwater, the better the shelter. Submerged and floating breakwaters provide less shelter.
- Wave-overtopping of submerged or low breakwaters will cause an additional supply of water in the area behind the breakwater, and consequently some compensation currents running out the sheltered area.
- The wave set-up on the foreshore is less in the sheltered area than outside, which generates local currents towards the sheltered area along the foreshore from both sides of the breakwater so that two eddies develop. These eddies also develop in the case of perpendicular wave approach, see Figure 11.9.

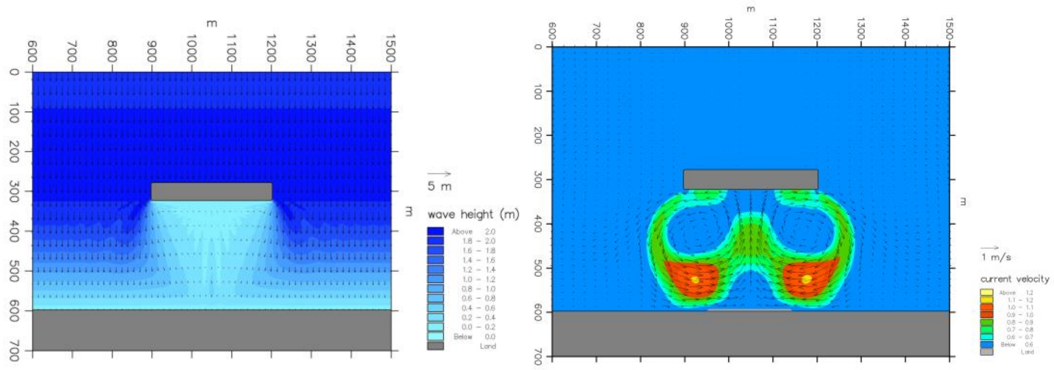


Figure 11.9 Wave and current conditions at a detached breakwater with a perpendicular wave approach.

- The longshore current is partially blocked by the circulation currents; this causes some of the longshore currents to be diverted outside the breakwater.
- Furthermore, a detached breakwater has the following impact on the morphological conditions, see Figure 11.10.
- The littoral transport in lee of the breakwater decreases due to the attenuated wave and longshore currents in the area sheltered by the breakwater. This causes the trapping of sand behind the breakwater depending on the conditions. As a rule-of- thumb, the trapping of sand will develop into a tombolo formation connecting the breakwater and the shore by sand deposits, if the length of the breakwater is equal to or longer than 0.8 times the distance between the shore and the breakwater. For shorter breakwaters, only a salient in the shoreline will develop.

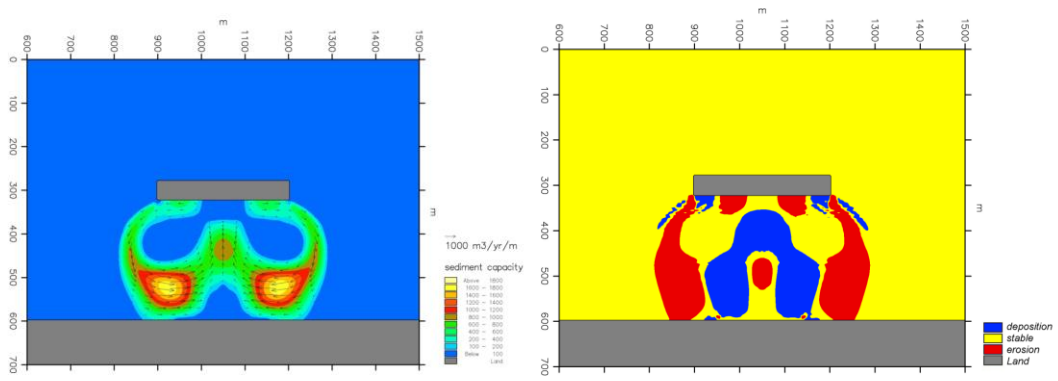


Figure 11.10 Initial sediment transport pattern and initial morphological impact caused by a detached breakwater for perpendicular wave approach.

- The diversion of the longshore currents will cause the development of local erosion close to the heads of the breakwater.
- The trapping of sand, especially if a tombolo has developed, will cause lee side erosion downstream of the breakwater. This downstream erosion is very similar to what is developed for groynes. However, there are more parameters involved in breakwaters, so it is possible to manipulate the transport in a more refined manner.
- A breakwater traps sand under all circumstances, even if the net transport is zero. This means also that there will be a coastal impact in any case.

When several breakwaters are constructed in a row, the system is referred to as a segmented breakwater. A segmented breakwater is used to protect long sections of shoreline; the downstream coastal impact will be correspondingly larger than for a single breakwater.

Other impacts of breakwaters are:

If segmented breakwaters are constructed with too small gaps, the water exchange in the embayments between the breakwaters may be poor.

Breakwaters normally obstruct part of the view over the sea, which means that the visual impact can be unacceptable.

Bathers may feel tempted to use the sheltered area behind detached breakwaters for swimming, but the circulation currents can be dangerous.

11.2.2 Passive coastal protection structures

Other types of coastal protection that do not protrude into the sea will, however, also cause increased coastal erosion. Seawalls and revetments are typically constructed at the coastline along coastal sections to provide protection of the coast.

An eroding shore/coast supplies material to the littoral transport budget if the erosion is allowed to continue. When the erosion is stopped at certain sections by the construction of seawalls or revetments, the supply of sand from this section of the shoreline to the sediment budget along the adjacent sections of shorelines will stop, whereby these adjacent shorelines will be exposed to increased erosion. The active trapping structures, such as groynes and breakwaters, will also act in this way in addition to their more direct coastal impact as discussed above.

The erosion of high cliffs often appears to be very drastic, which is why they have, in many cases, been the first to be protected in an area. However, before their protection they were the main suppliers of sediments to the littoral cell in question. Consequently, their protection leads to increased erosion at adjacent lower sections of the coastline. The result is that the erosion has been shifted to less resistant areas resulting in higher area losses per year.

11.2.3 Major reclamation projects

Major reclamation projects will have an impact on the hydrodynamic conditions along the adjacent coastal areas. There are in principle two types of reclamation schemes, coastal reclamations connected to the coast and detached reclamation/offshore development schemes, which are not connected to the shore.

The coastal reclamation schemes act in the same way as described under the other coastal structures above, however, with the additional effect of occupying some shoreline.

Offshore development schemes affect the coast through the impact on the wave conditions along the coast behind the scheme, provided of course that the scheme is located near the coast. As the wave climate is affected by such a scheme this implies that the littoral transport and shoreline morphology are also changed, which may lead to:

- Variations in the transport regime along the affected section of coast, in the transport rate as well as in the transport direction
- New accumulation and erosion patterns behind the scheme
- Large schemes may provide so much shelter that the beach quality degrades from a good quality exposed beach to a poor quality lagoon beach

Such impacts are described in Mangor 2008, COPEDEC.

11.2.4 Erosion of crescent-shaped bays

In areas where the coastal landscape is formed by an interaction between rocky headlands and a littoral transport regime, the shoreline configuration will often be in the form of crescent-shaped or spiral-shaped bay, see Figure 11.11.

The form and stability of these bays mainly depend on two factors:

1. The wave climate, which is considered stable
2. The supply of sand to the bay from the upstream bay, Q_B, and from a possible river, Q_R

The overall transport mechanisms in a crescent-shaped or spiral-shaped bay are a balance between the contributions:

- The supply of sand from the upstream bay Q_B will pass the headland and cross the bay via a bar.
- If, as shown in Figure 11.11, a river also contributes Q_R to the littoral budget, this material will be transported downdrift into the bay, partly along the shoreline and partly onto the bar. These transport processes are fairly complicated and two-dimensional in nature, but they result in the supply of $Q_B + Q_R$ to the straight downdrift section of the crescent-shaped shoreline of the bay.
- The orientation of this straight section is governed by the wave climate in such a way that the littoral drift Q_{S1} fulfils the balance: $Q_{S1} = Q_B + Q_R$ according to the transport correlation between incident wave direction α_1 and the transport $Q_{S1,}$ which is also shown in Figure 11.11.

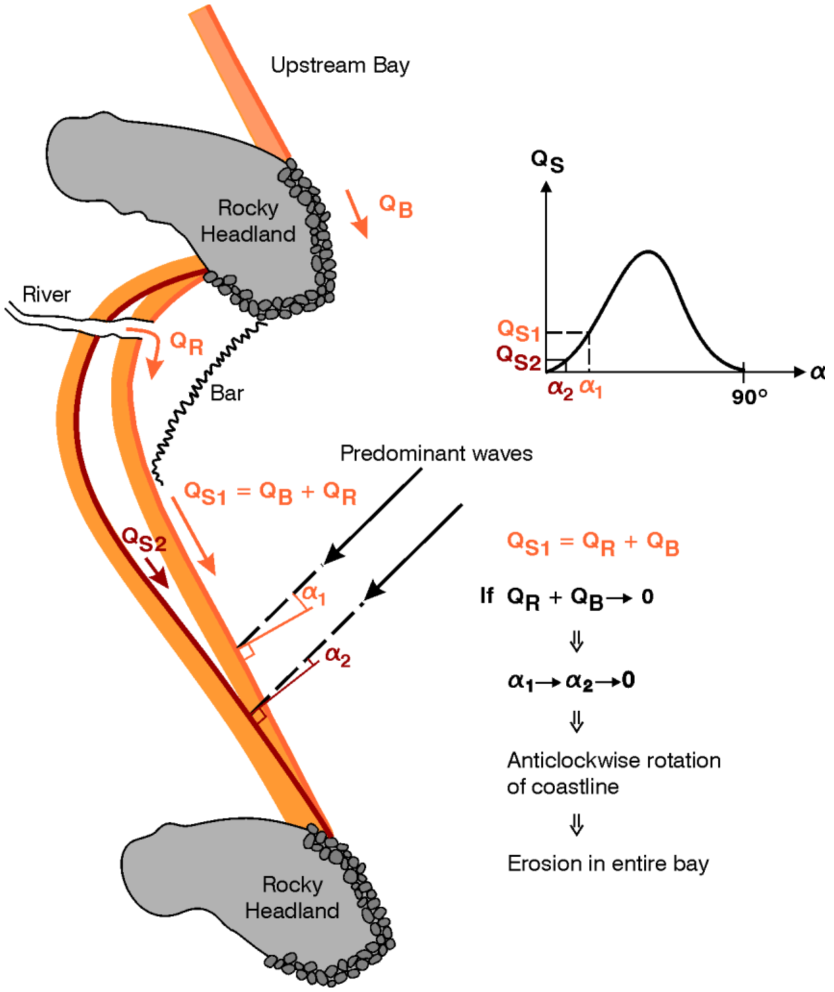


Figure 11.11 The correlation between the shape of a crescent-shaped bay and the transport supply to the bay.

The shape of the crescent-shaped bay is stable, apart from seasonal variations, as long as the supply of material to the bay $Q_{S1} = Q_B + Q_R$ is not changed. However, if the supply of material to the bay is reduced, typically by reduction in the supply from the upstream bay or from the river, the overall shape of the bay will also change, as the direction of the straight section will adjust to the new sum Q_2, where $Q_2 < Q_1$, leading to erosion in the entire bay, as sketched in the figure.

This means that changes in one bay will gradually penetrate into the downstream bays, so crescent-shaped bays, although they appear fairly stable, are actually very sensitive to changes in the supply of sand.

11.2.5 River regulation works and sand mining in rivers

A decrease in the supply of sediments to a shoreline, due to the regulation of rivers, which previously supplied material to the shoreline, is a very common cause of coastal erosion. The river regulation works can be the construction of dams for power production and irrigation purposes, or the deepening of navigation channels and sand mining, but all of them cause less supply of sediment to the shoreline. Perhaps the best-known example of this is the trapping of the sediments of the Nile River by the construction of the High Aswan Dam in the 1960´s, see Figure 11.12.

The promontory propagated until the early 1900's and then began to erode. The reasons for the erosion of 42 m/year during the period 1909-1971 were mainly a reduction in the river discharge and the construction of the Low Aswan Dam, whereas the drastically increased erosion rate of 129 m/year after 1971 was caused by the construction of the High Aswan Dam.

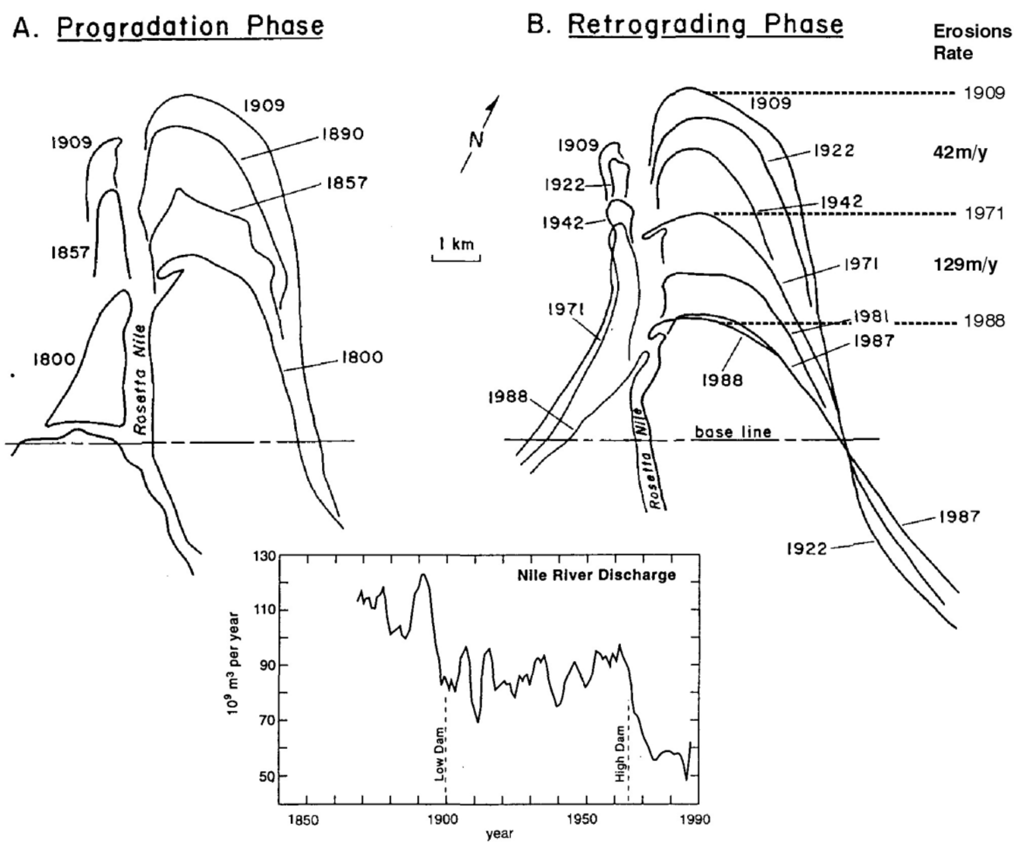


Figure 11.12 Natural delta accretion (left) and coastal erosion (right) of the Rosetta Promontory of the Nile delta caused mainly by the construction of the Low and the High Aswan Dam in 1900 and in the 1960´s, respectively.

Sand mining in rivers is a major cause of coastal erosion in many countries, such as Sri Lanka. The supply of sand to the coast Q_{coa} from a river depends of many parameters and there is no simple correlation between sand mining and decrease in supply to the coast. However, in general there are five components in the sediment balance for a degrading river section, cf. the illustration in Figure 11.13.

The components are:

- Sources
  - Sand supply from the catchment, $\mathbf{Q_{cat}}$
  - Degradation of the river bed, $\mathbf{Q_{bed}}$
  - Bank erosion, $\mathbf{Q_{ban}}$
- Sinks
  - Sand extraction (sand mining), $\mathbf{Q_{min}}$
  - Sand discharge to the coast, $\mathbf{Q_{coa}}$

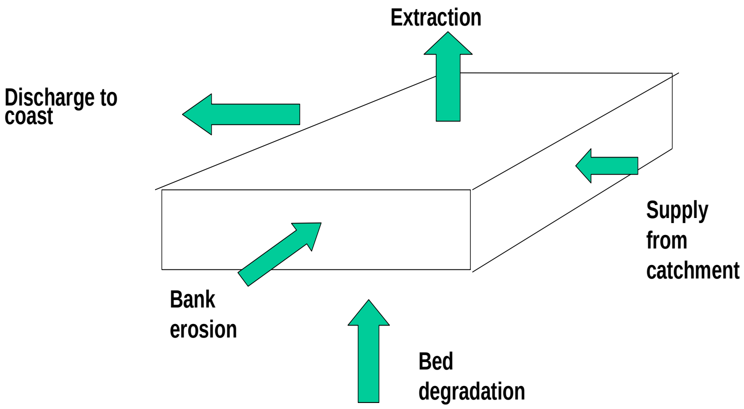


Figure 11.13 Sediment balance for a river segment.

The following equation must be fulfilled for a given segment of the river:

$$Q_{cat} + Q_{bed} + Q_{ban} = Q_{min} + Q_{coa}$$

Sand mining in a river lowers its bottom, causes bank erosion and reduces the supply of sand to the coast. Dependent of the circumstances sand mining in a river may cause a drastic or moderate drop in supply to the coast. Many rivers consist of a steep upper part, the mountain part, and a gently sloping lower part, where the river crosses the coastal plain. Sand mining in the two parts of the river has very different impacts on the supply of sand to the coast. River morphology modelling for Sri Lankan rivers has shown the following pattern (Mangor, 2002):

- Sand extraction in the upper part of the river causes a parallel translation (lowering) of the bed and of the water surface in the river, hence no changes in the sediment transport capacity. Thus the sand extraction in the upper part of the river is almost entirely balanced by local bed degradation, and has hardly any immediate impact on the supply of sand to the coast.
- Sand mining in the landward lower part of the river (far away from the mouth) will cause a local lowering of the river bed, but not a lowering of the water surface. This will cause a local decrease in the flow velocity and in the sediment transport capacity. This depression in the river bed will gradually be filled in from upstream supply, however dependent of the ratio between mining and catchment supply. The depression in the river bed will gradually travel towards the coast, however it may take many years before the impact, in the form of reduced sediment supply to the coast, is felt at the coast. But when the impact finally reaches the coast there may be an accumulated deficit in available river bed material corresponding to several decades sediment supply from the catchment. This means that an immediate halt in the sand mining will have hardly any remedial effect on the supply of sand to the coast, as the entire river bed has to be rebuilt before the original supply is re-established. In the case of the Kelani River in Sri Lanka, it was calculated that it will take more than 70 years for the original river bed and the supply to the coast to recover following a complete stop in the sand mining
- Sand mining close to the river mouth will only cause a local lowering of the river bed and an immediate decrease in the supply of sand to the coast. Halt of the sand mining in this situation will relative quickly cause recovery of the supply of sand to the coast.

Sand mining in rivers can cause other severe impacts along the river basin, which also have to be taken into consideration in order to find an overall sustainable solution. An integrated approach taking into account all the impacts has to be applied. This requires close collaboration between river authorities and coastal authorities. The main river related impacts are the following:

- Tide penetrates deeper into rivers and estuaries, which may cause increased saline intrusion in river estuaries, especially during the dry season, creating trouble for water intakes and for irrigation and causing changes to the estuarine habitats
- Increased flooding originating from the sea
- Lowering of the bed in a river also causes lowering of the water level in the rivers, which affects the ground water table in the flood plains. This may have impact on the agriculture especially during the dry period. This also causes problems for intakes to older irrigation schemes as they are now above the water level in the river
- Reduction of flood levels for small and medium sized floods as the deepened river bed and the low water level provides more volume between the river banks. However, the extreme floods will still spread over the flood plains. The absence of regular "small" inundations is likely to enhance man's encroachment on to the flood plain, thus causing increased "flooding problems" when the real large floods occur.

11.2.6 Sand and coral mining, and maintenance dredging

The mining of sand and gravel along beaches and in the surf-zone will cause erosion by depleting the shore of its sediment resources.

In connection with maintenance dredging of tidal inlets, harbours, and navigation channels, sand is very often lost from the littoral budget because the sand, unless otherwise regulated by legislation, is normally dumped at deep water. Suitable mitigating measures in terms of optimal layout of the port for the minimisation of sedimentation and bypassing techniques are discussed further in Chapter 19.

Coral mining and other means of spoiling the protective coral reefs, for example, fishing by the use of explosives or pollution, will also cause coastal erosion and beach degradation. The protective function of the reef disappears and the production of carbonate sand stops.

11.2.7 Wake from fast ferries, classified as acute erosion

The wake generated by fast ferries is special and is characterised by a series of approximately 10 relatively low waves (H_S in the order of magnitude maximum 1 m), but relatively long waves. These wake waves are very similar to swell waves and they are subject to considerable shoaling when approaching the coast. They often break as plunging breakers.

If a fast ferry navigates through protected waters, the wake waves are very different from the natural waves along the navigation route. The wake waves caused by fast ferries may influence the coastal conditions in the following ways:

- by higher wave uprush than that produced by normal waves
- by changing the coastal morphological processes in the area. This can result in erosion as well as the formation of a large beach berm by cross-shore processes. Consequently this type of erosion is classified as acute erosion
- by breaking unexpectedly and violently, the waves can be dangerous for small dinghies and for bathers

A precondition for approval of a new fast ferry route is therefore to perform an environmental impact assessment study. This will often result in navigation restrictions for certain parts of the route. An example of the impact of such waves is presented in Figure 11.14, where breaking waves in a local bay caused by a passing fast ferry generate violent breaking and associated turbid water and rip currents in an otherwise relatively protected environment in Tory Channel, Queen Charlotte Sound, New Zealand.

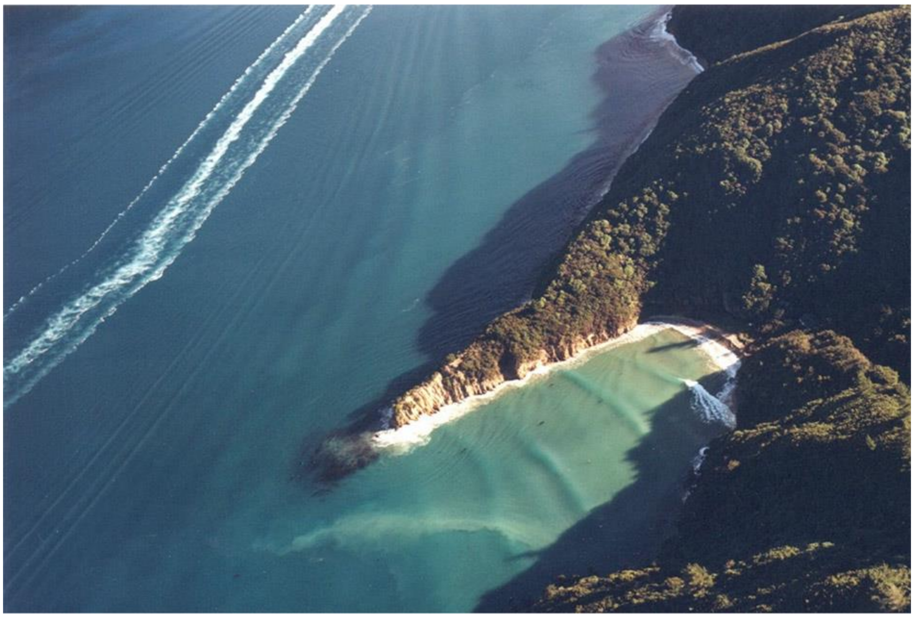


Figure 11.14 Wake waves from a fast ferry in Tory Channel, Queen Charlotte Sound, New Zealand. Note the violent breaking, turbid water and rip currents. (Copyright: Marlborough District Council, photographer: Graeme Matthews).

11.2.8 Concluding remarks

In conclusion, it can be seen that nearly every type of development and coastal protection along a littoral shoreline or along rivers will result in erosion of the adjacent shores and coasts.

An overview over sediment sources and losses to the littoral zone is presented in Figure 11.15.

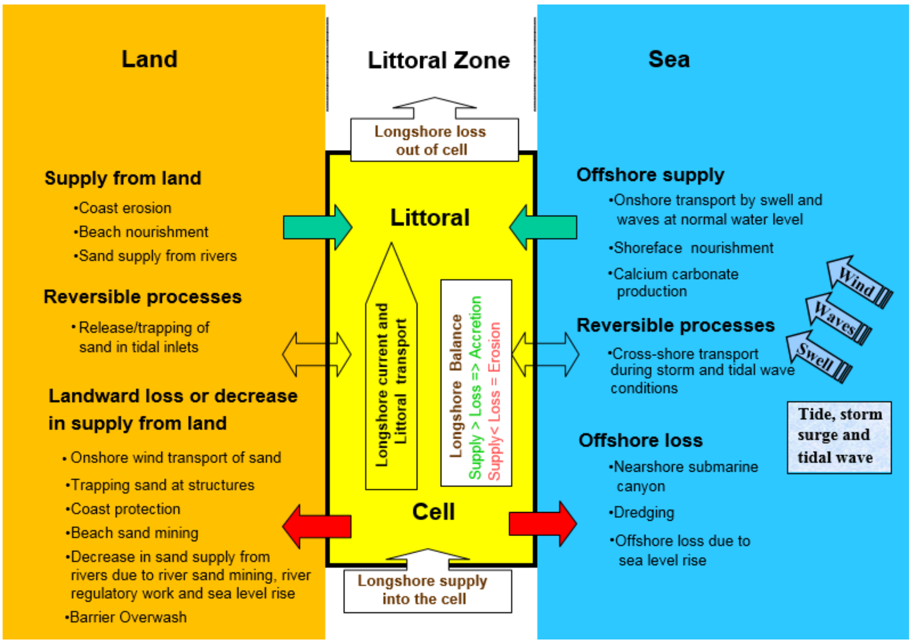


Figure 11.15 Overview over sediment sources and losses to the littoral zone.

11.3 Causes of flooding

Only coastal flooding caused by flooding from the sea is considered in this Guideline, but flooding caused by flash floods in connection with heavy rainfall and river floods are also very important.

The analogies and differences between coastal erosion and coastal flooding is discussed in the following. Flooding is occurring suddenly as a result of an extreme storm surge event which can be catastrophic in nature, especially if it occurs as a result of overtopping/breaching of a natural or manmade sea defence as such an event may affect large low lying areas in the hinterland. Flooding of low-lying coastal areas is thus similar in nature to acute erosion as both phenomena occur suddenly as a result of an extreme storm surge event. Chronic erosion is different in nature as this develops gradually over years due to a progressing process along the coastline over decades.

While coastal flooding is caused by the same type of events as acute coastal erosion flooding only occurs in areas where the coast and the coastal hinterland are low relative to extreme water levels whereas erosion occurs along low as well as high coasts.

Analysis of extreme water levels was in the past performed on basis of statistical analysis of historical extreme events, either based on analysis of recorded data or based on statistical analysis of data established from hindcast simulations, combined with the influence of historical local isostatic and eustatic changes. However, long term trends in sea level data, such as the forecasted sea level rise due to climate changes, have also to be taken into account in assessing future design water levels as the SLR constitutes an important trend compared to the relatively static statistical nature of historical data. Analysis of extreme water levels in relation to assessment of future risks for flooding shall therefore take these two types of statistical nature of water level data into account.

- Extreme events: the combined effect of tide and storm surge together with the action of waves. This applies for all types of wind and wave climates and associated tides and storm surges
- Long-term trends: sea level rise, subsidence and tectonic processes may give an increased risk of flooding combined with the extreme events

Extreme flooding and destruction of the hinterland will also take place when an area is hit by tsunami waves, but the nature and statistics of this phenomenon are different from those of storm surges and risks from tsunamis are treated separately.

11.3.1 Natural causes of flooding

Flooding can have the following natural causes:

11.3.1.1 Recurring events

Flooding of coastal areas will normally occur as the result of combinations of the following components:

- Extreme tides, i.e. High Water Spring or even the Highest Astronomical Tide
- Seasonal variations
- Meteorologically generated storm surge. Storm surges generated by cyclones, hurricanes and typhoons are especially dangerous, but also severe storm depressions at the higher latitudes are causing severe storm surges. Areas especially prone to high storm surge are wide shallow sea areas, e.g. the North Sea, the Gulf of Mexico, and large coastal estuaries

- Flood waves caused by under-water earthquakes, so-called tsunami, can cause very severe flooding and destruction of coastal areas

The methods used for analysing of the various types of events are different, as they follow different statistical distributions. Depending on the analyses for a given site, the flooding conditions will normally be described in the form of recurrence periods (in years) versus extreme water levels, see examples in Figure 6.8 and Figure 6.9.

11.3.1.2 Long-term trends

The long-term sea level rise will normally not cause flooding but the sea level rise will increase the flood level during extreme events, or in other words, the recurrence interval of the certain fixed water level will decrease, see e.g. Figure 6.8, which shows the present and future forecasted extreme water levels for Esbjerg, Denmark. It is seen that an increase in the sea level of 80 cm decreases the recurrence period from 100 years to 7 years for flooding of a dike, which is designed for a water level of 4.05 m.

A summary of the natural causes of changes in the long term trends of flooding is presented below:

- Natural subsidence in coastal areas is often seen in delta areas, where the present delta coast is located on earlier deposits of fine sediments. Subsidence can also be caused by earthquakes and tectonic movements
- Isostatic changes resulting from the loading/unloading of the earth crust caused by the ice ages in some parts of the world
- Sea level rise has both natural causes and human causes, and it is a world-wide phenomenon, which has to be taken into account in assessment of the risk for coastal erosion and coastal flooding

11.3.2 Causes of flooding due to human activities

Flooding can be caused, or the risk of flooding can be increased, by the following human activities.

11.3.2.1 Recurring events

Human activities can influence the risk of flooding in areas prone to naturally recurring flooding events. Examples are given in the following:

- Regulation works in a tidal inlet can change the flood levels in the lagoon
- Reclamation works in a lagoon can change the flood levels in the lagoon
- The construction of dikes can decrease the storage capacity in certain areas, which can increase the flood levels
- The felling of extensive mangrove areas can change the flood conditions in the hinterland

11.3.2.2 Long-term trends

Human activities can influence the long-term trends in sea level and subsidence, and this will increase the flooding risk in areas prone to naturally recurring flood events. Examples are given in the following:

- Subsidence in coastal areas can be caused by the extraction of groundwater, oil or gas. Subsidence can have very different time developments depending on the cause of the subsidence. A famous example of subsidence caused by groundwater extraction is Venice, where high groundwater extraction in the industrial area caused considerable subsidence of the entire town. However, the extraction was stopped when the interaction was realised in 1969, after which date the subsidence stopped and even a minor rebound occurred. The subsidence/sea level rise of most of the town since the beginning of the century was approximately 0.23 m in 1980, approximately half of which was due to groundwater extraction. The result is that today Venice suffers from very frequent flooding. This is now being remedied by the MOSES project, where storm surge gates are installed in the three openings to Venice Lagoon.

- Sea level rise has both natural and human causes, which are difficult to distinguish. Sea level rise is under all circumstances a world-wide phenomenon, which has to be taken into account in low-lying areas when designing sea defences and planning land utilisation. It is internationally believed that the Greenhouse effect will cause a sea level rise through general warming of the sea water and ice cap melting; see Subchapter 6.3.

12 Vulnerability and Risk Classification for Erosion

12.1 Background

When the erosion problem, or the combined erosion and coastal flooding problem, has initially been identified by studying available data as described in the previous subchapters, a vulnerability and risk assessment can be performed with the purpose of deciding the appropriate type of mitigation measure. The risk assessment for areas vulnerable to erosion operates with the two main types of erosion, namely *acute erosion* and *chronic erosion*. Acute erosion is typically caused by cross shore processes occurring as a result of exposure to a combination of extreme storm surges and high waves or by local shoreline retreat typically in a sediment cell due to an extreme storm with an uncharacteristic wind direction. Acute erosion is sometimes referred to as "unexpected" erosion. Chronic Erosion is typically caused by gradients in the littoral transport as explained in Subchapter 11.1.1. Both types are subdivided such that we have four main types of erosion:

- *Reversible (temporary) acute erosion* – Reversible erosion of the beach with no permanent loss of sand and no damages to non-recoverable coastal features or to , coastal assets. The beach will normally recover again and this type of erosion will not require any remedial measures other than securing a sufficiently wide beach to allow the shoreline fluctuations
- *Non-reversible (permanent) acute erosion* – Acute erosion, which has caused permanent loss of sand, damages to non-recoverable coastal features, such as cliffs, damages of coastal assets or caused breaching of barrier islands. This type of erosion will typically require some kind of immediate repair and coastal protection to avoid similar damages in the future
- *Immediate chronic erosion* – Chronic erosion which has progressed so far that coastal facilities are threatened within a time horizon of a few years consequently requires immediate protection in order to avoid damage. This type of erosion will typically require immediate (emergency) protection
- *Long-term chronic erosion* - Chronic erosion which has not progressed so far that coastal facilities are threatened in the near future but coastal facilities are threatened over a time horizon of say 20 years. This type of erosion leaves time for planning and design of optimised protection schemes or other interventions

The different classifications and protection measures are described in the following:

Acute erosion – Areas under threat of acute erosion may or may not require mitigation measures depending on the type and magnitude of damage caused by the erosion. The distance from the coastline to the cliff/dune or to fixed facilities on the coast, the buffer distance, is of importance. The coastline retreat for potential acute erosion events shall be evaluated and compared to the width of the buffer distance. Furthermore, the height of the coast is of importance in the evaluation of the risk for breaching of sand spits or dunes. Mitigation measures shall be implemented if the buffer distance is smaller than the potential coastline retreat and if valuable coastal features or assets are in risk of being damaged; otherwise no mitigation measures are required.

Immediate chronic erosion – Areas undergoing rapidly chronic erosion where coastal resources or coastal facilities are under risk of being damaged require urgent action in order to prevent immediate damages.

There are in principal the following types of emergency interventions:

- Temporary measures

- Land based nourishment can be applied in minor scale until more permanent schemes can be designed and implemented.
- Emergency protection in the form of stone dumping or alternatives such as sand filled geotextile units. It is assumed that the emergency structure is later upgraded to a properly designed scheme
- Permanent measures
- A properly designed protection scheme

Long-term chronic erosion - Areas which are under long-term chronic erosion leading to loss of beach resources or to damage of coastal facilities and assets (housing, infrastructure, etc.) within a time frame of about 20 years, require coastal stabilisation measures providing long-term stable and sustainable solutions. The proposed solutions also have to fit with the management and financial capabilities of the executing agency. The type of proposed solutions will typically be a combination of structures and beach filling, or a large scale nourishment depending on the management and financial capabilities of the executing agent. Large scale nourishment are usually preferred if the financial and organisational requirements for such a scheme are in place.

12.2 Vulnerability and risk classification, and proposed interventions

The vulnerability and risk classification is used for eroding coasts only, and it is useful for identifying if a certain area requires implementation of protection against acute erosion (reversible or non-reversible), immediate chronic erosion (emergency protection), long term chronic erosion or if no protection is needed. The type of protection, which is applicable in a certain area, will furthermore depend on the following issues:

- Type of coast (coastal classification)
- Land use
- Beach use (boat landing, recreational)
- Resources (management and design skills, equipment and materials)
- Available funds
- Environmental impact (maintaining the beach and the coastal landscape)
- Beach safety considerations for recreational beaches

An overview over type of proposed protection intervention as function of risk classification, land use and protection status of eroding coasts is presented in Table 12.1.

It is noted that the proposed risk categories are related to two main themes:

1. The risk of damage to coastal facilities in case of critical erosion if the area is not protected
2. The risk of losing the beach in case of critical erosion in areas which are protected by some kind of hard protection.

When the vulnerability and risk classification has been performed on the basis of existing data, and the areas requiring some kind of action thereby have been identified, the type of applicable technical protection measures which can solve the problems can then be identified. If the further analyses cover, for example modelling of future shoreline development, the results of these can be utilised to make a more refined vulnerability and risk assessment as described above.

Table 12.1 Overview over type of proposed protection intervention as function of risk classification, land use and protection status of eroding coasts.

Type of erosion	Situation	Erosion status	Land use	Present Protection status	Risk category	Type of intervention, see further details in Chapter 17
Acute	Reversible (Temporary)	Acute retreat less than buffer width	Rural	Not protected	Vulnerable to erosion but not critical for coastal facilities	Sand filling or beach drain to maintain wide beach. Impose static setback line
			Urban Dwellings	Protected or not		
	Non-reversible, (Permanent)	Acute retreat larger than buffer width	Rural	Not protected	Not critical presently	Impose static setback line, see Subchap. 17.8
			Urban Dwellings	Not protected	Critical to damage on fixed facilities	Sand filling, revetment (buried) or mixed protection
				Protected and exposed	Critical as beach is lost	Sand filling can be considered to regain sandy beach, however, no action required to protect coastal facilities
				Buried protection	Critical to loss of beach	Sand filling can be considered
Chronic	Immediate erosion	Not critical within 2 years	Rural	Not protected	Vulnerable to erosion but not critical	None
			Urban Dwellings	Protected or not		
		Critical within 2 years	Rural	Not protected	Not critical presently	Impose (dynamic) setback line
			Urban Dewllings	Not protected	Critical to damage on fixed facilities	Nourishment, emergency protection (temporary) or revetment
				Protected and exposed	Critical as beach is lost	Nourishment can be considered to regain sandy beach, however, no action required to protect coastal facilities
				Buried protection	Critical to loss of beach	Nourishment can be considered
	Long- term erosion	Not critical within 20 years	Rural	Not protected	Vulnerable to erosion but not critical	Impose (dynamic) setback line, see Subchap. 17.8
			Urban Dwellings	Protected or not		
		Critical within 20 years	Rural	Not protected	Not critical	Impose(dynamic) setback line
			Urban Dwellings	Not protected	Critical to damage on fixed facilities	Coastal stabilisation required
				Protected and exposed	Critical as beach is lost	Beach rehabilitation required
				Buried protection	Critical to loss of beach	Beach rehabilitation required

13 Vulnerability and Risk Classification for Flooding

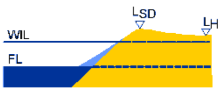
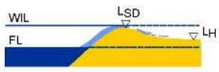
13.1 Vulnerability and risk classification for flooding caused by storm surges

The vulnerability and risk classification for flooding takes the following items into account:

- The level of the hinterland (L_H) relative to the Flooding Level (FL)
- The protection status of the section, i.e. the level of the sea defence/beach berm relative to the FL and to the Wave Impact Level (WIL)
- The type of the hinterland, rural or developed
- The size of the immediate hinterland areas, which are lower than the FL:
  - Small
  - Large

The vulnerability and risk classification for flooding is presented in Table 13.1.

Table 13.1 Vulnerability and risk classification for flooding.

Level of hinterland: L_H		**Protection status and level of sea defence (SD)*: L_{SD}**	**Illustration of situation**	**Occupation/ size of low-lying hinterland**	**Risk category and marking**	
L_H >FL	L_H > WIL	L_{SD} > WIL		All types	No risk	
	L_H < WIL	Low protection FL < L_{SD} < WIL		All types	No risk of flooding, vulnerable to wetting of hinterland	
L_H < FL		Low protection FL < L_{SD} < WIL		Rural/all sizes	Risk of moderate flooding if sea defence is stable, risk of major flooding if sea defence is breached	Not critical as flooding of backland is a natural process
				Urban/small		Moderately critical as potential flooded area is small
				Urban/large		Critical as major area may be flooded in case of breach of sea defence, check status of sea defence
		No protection L_{SD} < FL		Rural	Not critical, vulnerable to major flooding, impose dev. restrictions	
				Urban/small	Critical to flooding damage, introduce sea defence according of potential damage	
				Urban/large		

Note: *A sea defence could be a beach berm, a dike or a seawall. For the computation of the WIL, a natural beach profile has been assumed, which corresponds to the presence of a beach berm in term of sea defence type.*

During the first screening/assessment of a flooding risk and vulnerability, the established FL and WIL should be compared with a representative digital terrain model for the area of interest; thereby possible low lying areas behind natural or man-made sea-defences can be easily established. This will form the basis for more detailed studies as described in Chapter 21.

If the established FL and WIL are combined with projected sea-level rise, the future flooding risk and vulnerability can be established for future scenarios.

The United States Geological Survey (USGS) has developed a storm regime classification where they use the combination of water levels (tide, wind set-up, wave set-up and wave run-up) and morphology (toe of the dune and top of the dune) to estimate if a coastal area is under the impact of overwash or inundation under the passage of a hurricane.

13.2 Tsunami warning

The FL and the WIL do normally not include contributions from tsunamis because the nature and risk of occurrence of tsunamis are completely different from the nature and risk of occurrence of storm surges and wave run-up for storm waves. Consequently, the risk for flooding and destruction due to tsunamis should be evaluated as a separate item. The risk for a tsunami is at most locations very small but there are also coasts which are frequently hit by tsunamis, such as the east coast of Japan. It is neither possible nor practice to design normal coastal infrastructure for the impact of tsunamis, only very critical infrastructure such as nuclear power plants, high density populated areas and similarly critical areas take such risk into account. Ten metre high tsunami protection seawalls have been constructed at several locations in Japan; experience shows varying success of such seawalls dependent on design assumptions and local conditions, if not properly designed they may provide a false feeling of safety. A comprehensive analysis of Disaster Risk Reduction can be found in Sendai, 2015. An example of a Japanese tsunami seawall is shown in Figure 13.1.

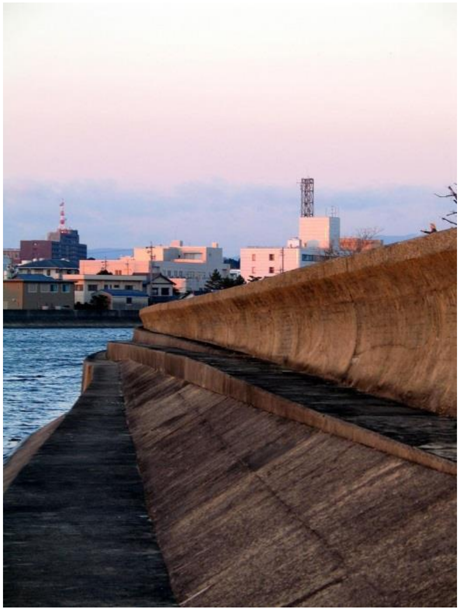


Figure 13.1 Tsunami seawall in Tsu, Japan.

Japan is considering (2016) constructing a 400 km long seawall for protection against tsunamis following the Great Tohoku earthquake on the 11th march 2011, which caused about 29,000 dead or missing persons and severe damages to the Fokushima Daiichi Nuclear Power Plant, cf. Kimberly, 2016.

The most common tsunami precaution system is a **Tsunami Warning System** (**TWS**) which detects tsunami waves at offshore stations and issues warnings to threatened coastal areas to prevent loss of life and damage. It is made up of two equally important components: a network of offshore sensors to detect tsunami waves and a communications infrastructure to issue timely alarms to permit evacuation of the coastal areas. Data from observed sea level height, either shore-based tide gauges or DART buoys (**D**eep-ocean **A**ssessment and **R**eporting of **T**sunamis), are used to verify the existence of a tsunami. The DART system is illustrated in Figure 13.2.

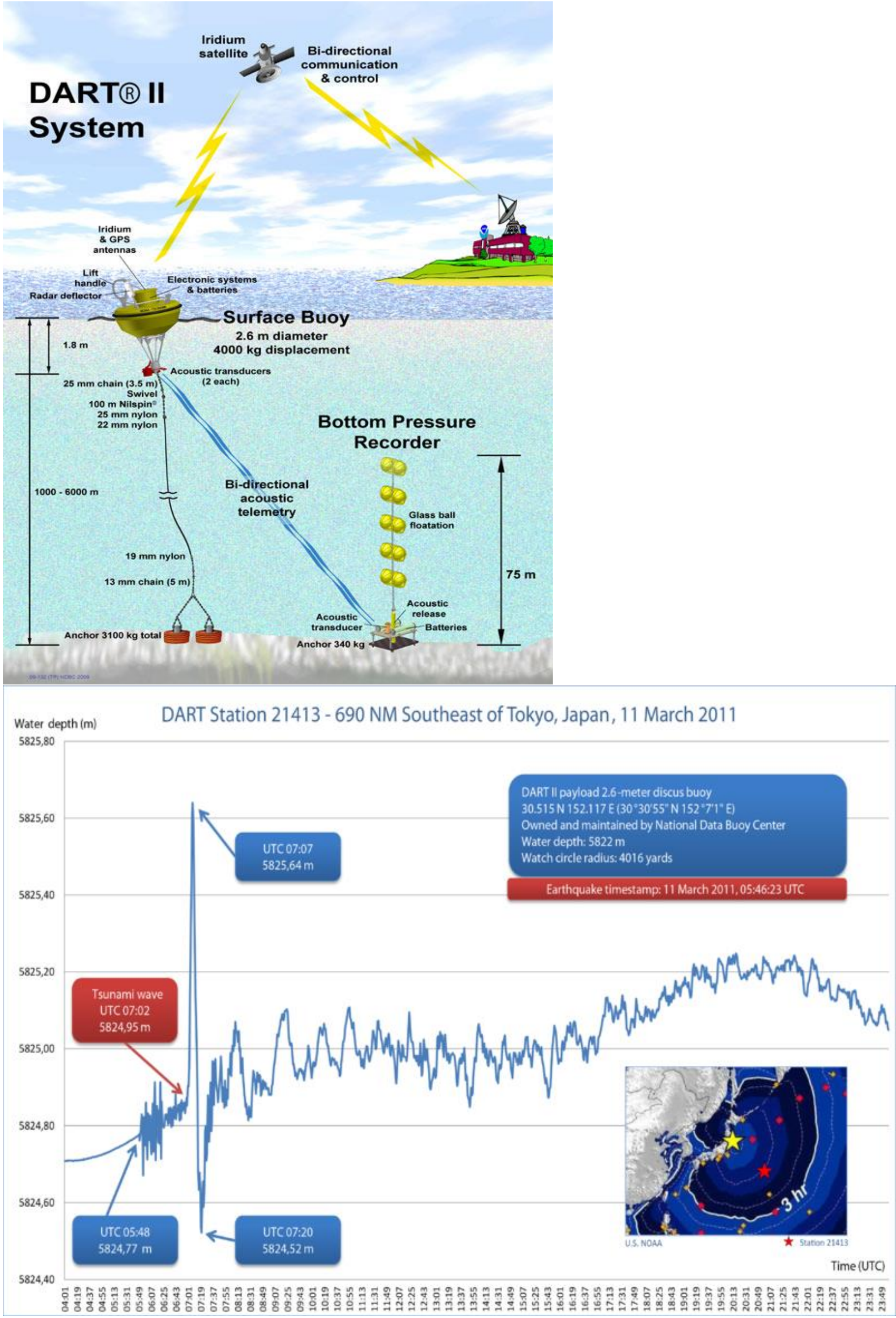


Figure 13.2 DART bouy (upper) and signal (lower) form the buoy (Water column height on 11 March 2011 (Tōhoku earthquake and tsunami) at DART buoy 21413, 690 NM Southeast of Tokyo).

Several international warning systems are in operation or are under construction:

- Pacific Tsunami Warning Center (PTWC), operated by the United States NOAA in Ewa Beach, Hawaii (since 1949)
- NOAA's National Tsunami Warning Center (NTWC) in Palmer, Alaska issues warnings for Canada, Puerto Rico, the Virgin Islands, and all U.S. coastal states, with the exception of Hawaii (since 1967).
- Indian Ocean Tsunami Warning system
- After the 2004 Indian Ocean Tsunami, which killed almost 250,000 people, a United Nations conference was held in January 2005 in Kobe, Japan, and decided that as an initial step towards an International Early Warning Programme, the UN should establish an **I**ndian **O**cean **T**sunami **W**arning **S**ystem. The system became active in late June 2006 following the leadership of UNESCO. It consists of 25 seismographic stations, relaying information to 26 national tsunami information centres, as well as 6 DART buoys
- The Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North-eastern Atlantic, the Mediterranean and connected seas (ICG/NEAMTWS) was formed in response to the tragic tsunami on 26 December 2004

Warning systems are often supplemented with siren warnings, signs and with the construction of high elevation shelters in low laying areas. Examples of tsunami warning signs are presented in Figure 13.3 and a tsunami shelter in Figure 13.4.

Figure 13.3 Examples of tsunami warning signs.

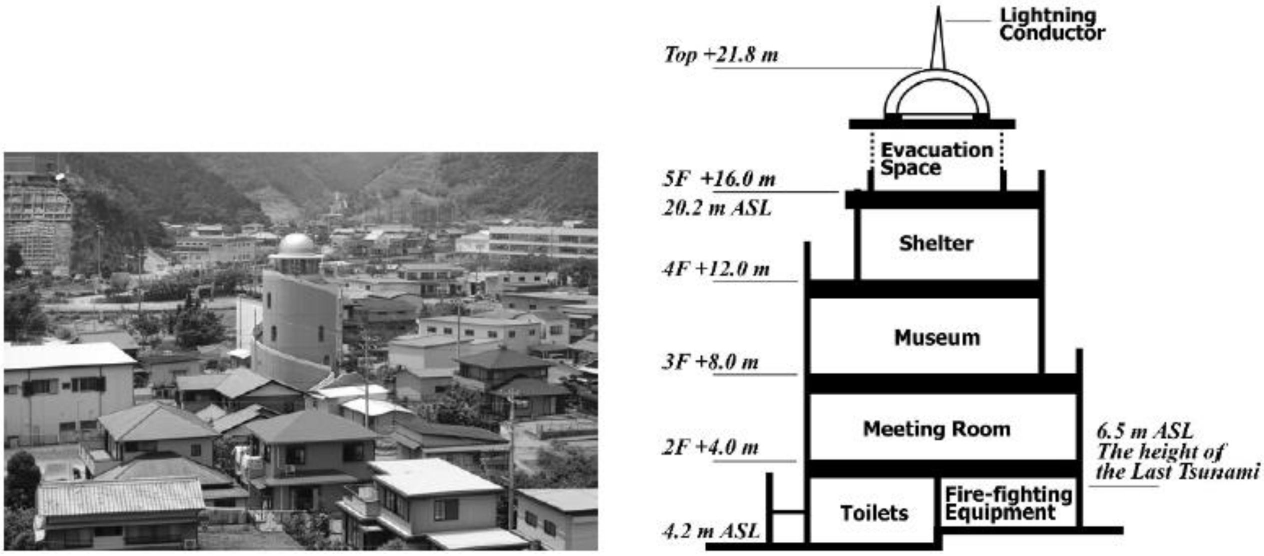


Figure 13.4 Tsunami shelter in Japan: Nishiki Tower and its cross- section, from Nakaseko, 2008.

14 Planning Concepts in the Coastal Zone

14.1 General

About 75% of the world's population live close to the coast and these people use the coastal areas for many purposes. There is also an increasing pressure on the coastal zone from numerous user groups, all of which require some kind of utilisation of the coastal resources. Consequently, a comprehensive planning effort is required in order to secure a balanced and sustainable development taking all demands and restrictions into account.

The prerequisites of planning in the coastal area are:

- To identify and describe the natural resources, such as coastal landscapes, beaches and coastal habitats thereby providing a basis for the evaluation of their sustainable utilisation;
- To identify the requirements for utilisation of the resources, now and in the future;

The objective is to make an optimal plan for utilisation where negative consequences of interactions are avoided or minimised between:

- The various activities;
- The activities and the natural resources/the natural processes.

The utilisation of the coastal resources can be divided in three different categories as shown in Table 14.1.

Table 14.1 Utilisation categories for coastal resources.

Type of utilisation	Examples of utilisation
Non-Extractive	Use of the beach for limited fishing activities Limited recreational activities and tourism Marine life
Transformative	All types of construction activities, such as houses, infrastructure, hotels and marine structures Moderate grazing Agriculture, plantation and aquaculture
Extractive	Mining of sand in rivers and on the beach Coastal protection leading to loss of the beach Major fishing activities leading to depletion of stock Major grazing leading to loss of sand by wind transport

The extractive utilisation is clearly damaging the coastal area, but the transformative activities can also exhaust the coastal resources to some extent. Only the non-extractive utilisation does normally hardly harm the natural coastal resources. It requires planning and regulation to avoid or minimise the conflicts between the various utilisations.

The planning is preferable directed towards sustainable solutions where the preservation of the natural resources is secured and where future generations do not inherite the handling of conflicts resulting from non-sustainable activities in the coastal area.

In most modern legislation and administration there are requirements for sustainable development and preservation of natural resources. Sustainable development has become the most important goal in planning and management of the coastal zone, which is the basis for development of the concept of *Integrated Coastal Zone Management (ICZM).* Similarly the concept of *Integrated Water Resources Management (IWRM)* is used for planning and management of river basins. In the past there has been a tendency to practice ICZM and IRBM separately, which has often left the coastal zone to suffer from downstream effects of works and regulations in the river basins. Some of these examples are:

- Changes in flow caused by irrigation, hydropower and water supply in the river have changed salinity in estuaries and lagoons and influenced the sediment supply to the coast
- Deforestation and intensive agriculture have increased the loads of sediments, nutrients, toxic chemicals and pesticides to coastal waters
- Discharge of household and industrial wastewater into the rivers have deteriorated the water quality and adversely impacted the ecosystems in the rivers as well as in connecting coastal waters
- Sand mining in rivers has caused drastic decrease in the supply of sand to the coast, which causes severe erosion at the river mouth and in the adjacent coasts.

The solution to such problems can only be derived with integrated approaches. A management concept which links IWRM and ICZM is referred to as: *I*ntegrated *C*oastal *A*rea and *R*iver Basin *M*anagement: *ICARM*.

The concepts of ICZM, IWRM and ICARM are integrated planning concepts, which are used in parallel with the traditional concepts of *Spatial Planning* and *Sector Planning.*

Spatial planning is basically a geographical concept that optimises the use of land and sea for specific development activities.

Sector planning deals with regulation of sector interests, typically represented by the interests of various ministries with a sector responsibility, such as Ministry for the Environment, Ministry for Traffic, etc. through the issue of laws, acts and planning regulations.

Planning of development in the Coastal Area is special because the coastal area is attractive for many kinds of development activities, such as tourism and recreation, fishing, sea and land transport, etc. and because the coastal area is environmentally valuable and morphologically dynamic. The dynamic nature is expressed in terms of coastal erosion and accretion, in terms of the morphological mobility of dune areas, sand spits, river mouths and tidal inlets, and in terms of the risk of flooding. This book especially deals with the sustainable management of the Coastal Area taking the above mentioned issues into account. This discipline is called *Shoreline Management*.

Shoreline Management can be regarded as the part of Coastal Zone Management, which is dealing with existing and planned development in the coastal area and its relation to actual and potential coast erosion and flooding, and to the planning of coastal engineering measures, coastal protection - and sea defence schemes.

The objectives of Shoreline Management are to ensure that:

- development activities in the coastal area follow existing spatial plans and sector requirements
- development activities in the coastal area does not contribute to or enhance erosion
- development activities do not occur in areas vulnerable to erosion or flooding

- erosion control techniques are cost effective and socially and environmentally acceptable

Shoreline Management is often locally executed and has to follow the plans, acts and restrictions described by higher governmental levels. So it normally has to fit in existing ICZM Plans, spatial plans and by the sector laws and guidelines.

All these planning concepts are briefly described in the following subchapters.

14.2 Spatial planning

Spatial planning is basically regulating the use of a geographical area for specific development activities.

The structure of spatial planning is normally following the governmental structure and is based on decentralised responsibilities. The typical spatial planning system is presented in Table 14.2.

The lowest levels of the spatial planning boundaries are typically the county or municipality boundaries. In many countries the spatial planning is restricted to the land activities. However, some countries in the EU (Denmark, The Netherlands) also include a circa 1 km wide coastal zone, or the entire shoreface, in planning activities (Sweden, Finland). The limited inclusion of the coastal area in front of the land in many planning activities is often regarded as one of the major problems in ICZM. Quite often, the spatial planning stops at the beach and many sector responsibilities are dealt with by other ministries.

The spatial planning system usually involves co-ordination and public participation. Public participation is normally mandatory on regional, local and project development level and is based on public involvement in the preplanning phase and when a plan proposal is published. In some cases the public involvement also involves formalised consultation and co-operation with recognised NGOs.

Table 14.2 Typical Spatial Planning levels and administrative bodies (applicable for Europe).

Spatial Planning Levels	Administrative Body	Product and Activities
International level	For example: European Union	Directives
National level	Government Administration	National guidelines and control of regional plans
Regional level	County Council or Governorate	Regional plan – presented on maps and binding for plans at local level
Local level	Municipalities	Municipal land use plans - presented on maps and binding for plans at project level
Project Development	Municipalities or Developers	Detailed local area master/development plans -District Plans

Major projects, which require an Environmental Impact Assessment (EIA), can normally not be implemented until directives in the regional plan regarding location and layout of the project, and the associated EIA report have been produced and approved. The implementation of a project will require a change/addition to the regional plan for the area. Similarly, such a project will in general also require a change/addition to the municipality land use plan.

The District Plans cover specific development areas, which usually are minor fractions of municipalities. District Plans are typically produced in connection with development plans for specific areas. The District Plans are utilised to inform the public about the development plans and are thus the basis for public hearings, which in many countries form part of the approval procedure for the District Plans.

The system for securing that the various spatial plans and District Plans are followed is normally regulated with planning and building permissions given by the local authority. New structures, e.g. coast protection structures or buildings, demolition of structures/buildings or changes in the use of the buildings/areas require permissions from the local authorities, which have issued the plans.

14.3 Sector planning – the national policy and strategy

14.3.1 Laws, acts and planning regulations

Sector planning is the responsibility of sector ministries, such as the Ministry for the Environment, the Ministry for Water Resources and Irrigation, the Ministry for Traffic, the Ministry for Tourism, the Ministry for Fishery, the Ministry for Housing and Development, etc. The ministries announce and execute their policies and strategies through the issue of laws, acts and planning regulations. These acts and plans cover the areas of responsibility of the various ministries, i.e. their sector. In general such acts are not restricted to specific areas of the country, but are applicable in all areas of the country as relevant. This means that there will be many laws and acts, which are to be taken into account in the coastal zone. The sector planning is often also inspired by different directives and acts that are coming from a federal or international level.

The sector planning and management aspects are in most countries placed at a central level in sector ministries/departments, and/or in state agencies, sometimes with regional directorates. Sector planning in the coastal zone could cover the following issues (the list is not exhaustive):

- Housing and Development
- Tourism and recreation
- Trade and industry
- Defence (military)
- Coast protection
- Resource utilisation (oil, gas, groundwater, minerals)
- Protection of nature, wildlife and natural habitats
- Water environment
- Protection of the landscape and securing public access
- Sea transport

The most important types of acts in relation to the policy for the coastal zone are the following:

- Coast Protection Act
- Environmental Protection Act
- Marine Environment Protection Act

However, there can also be other laws/acts/treaties, which are applicable in the coastal zone, such as:

- Sea Sovereignty Treaty
- Raw Material Act
- Nature Protection Act
- Planning Act
- River Regulation Act
- Forestry Act
- and others.

The typical distribution of sector responsibilities concerning the Coastal Zone is given in the following Table 14.3. However, the actual distribution of responsibilities varies from country to country.

Table 14.3 Sector responsibility in the Coastal Zone (typical).

Sector planning	Land	Sea
National level	Coastal protection Sea defence Nature Protection Exploitation of resources Military	Fishing Shipping Exploitation of resources Military
Regional level	Nature protection Water Quality Water catchment planning Culture heritage Aquaculture	Local fishing planning Dredging and disposal Oil-spill contingency planning Monitoring water quality
Local level	Waste collection Water supply Wastewater treatment Technical and env. adm. Local culture heritage Social administration	Port planning and administration

Sector acts are normally issued on government level and public participation is usually not a legal requirement.

14.3.2 Control of adherence to sector legislation

Any development or construction activity in the coastal area, such as a coastal protection project, will typically require a permit from the relevant sector ministry/directorate. In the case of a coast protection project, adherence to the Coast Protection Act will be checked by the Coastal Directorate/Regional Authority, who will also initiate call for the opinion of other relevant sector bodies. Based on this evaluation and hearing procedure, a construction permission will be given/rejected.

The Coastal Directorate/Regional Authority will also decide if the project comes under the requirement for performance of an Environmental Impact Assessment, i.e. if the project is a so-called Prescribed Activity. For further details see Subchapter 19.2.1.

The control, that the requirements to prescribed activities by sector acts are fulfilled, such as the Coast Conservation Act, the Environmental Protection Act or the Marine Environment Protection Act, is regulated by the requirement to performance and consequent approval of Environmental Impact Assessment (EIA) studies. In the case of a full EIA study the term "environment" covers all aspects within the following main categories:

- Physical/chemical
- Biological/ecological
- Sociological/cultural
- Economic/operational

A special type of an EIA study used in shoreline management projects is the so-called Shoreline Impact Assessment (SIA) study or Morphological Impact Assessment (MIA) study, which especially deals with the physical impact of an intervention in the coastal area. The MIA is thus considered part of the full EIA, however in many cases the MIA is the most important part of the EIA for shoreline management projects, which is the reason that this has got a special identification. The concepts of EIA and MIA are described in detail in Chapter 19.

In principle it is the responsibility of the developer of a project to perform the EIA/MIA study, however in some countries (e.g. in Denmark) this responsibility has formally been transferred to the local authorities. The main reasons for this are the following:

- It is believed that the impact assessments will be more realistic and less biased when they are performed by an authority, which has no direct interest in the actual development

- The regional authority is in a good position to introduce regional planning considerations into the assessments

The project developer will normally be requested to deliver specific impact assessment studies to the regional authority. These studies are hereafter, together with other studies and data available to the regional authority, used as basis for preparation of the official EIA report. The regional authority will typically co-ordinate the elaboration of the EIA with other sector authorities, if the project comes under their resort areas. This could typically be Coastal and Fishery Authorities in case the project occupies some of the sea territory. In the case that the developer produces the EIA report, it is delivered to the regional authority. The regional authority, which handles the EIA procedure, is normally the same authority that issues the regional spatial plans and additions to these, and handles the permit procedure in relation to the District Plans.

The regional authority uses the EIA report as basis for the public hearing process, which is generally part of the EIA procedure. It is also part of the hearing process that the regional authority shall circulate the EIA report among relevant sector authorities for consideration. In some cases the EIA report will also be circulated among recognised NGOs for consideration. The authorities and organisations entitled to be heard will hereafter submit their statement on the EIA report to the regional authority. On this basis the regional authority will finally decide the conditions for the proposed development and issue the approval of the EIA study accordingly.

The above described permit procedures for new developments in relation to Land Use Plans/District Plans and approval of impact assessment in relation to sector requirements, including public participation, are complicated and time consuming. It is important that sufficient time is allocated for these procedures in the planning stage for a project in the coastal area. Furthermore, it can be difficult for a private landowner to fulfil the environmental and sustainability requirements dictated by the sector agencies, as these requirements tend to make the projects more costly. If the objectives of the developer/landowner and those given in the spatial plans and in the sector acts cannot be secured solely through the private sector, then emphasis must be put on public-private partnerships in order to obtain sustainable solutions. Another tool in protecting nature in the development process is subsidies to landowners, when restrictions are made on privately owned nature areas

14.4 Implementation of sustainable development

The general land use planning system and the sector acts/guidelines provide no guarantee for implementation of sustainable development. Land use plans and sector guidelines tend to indicate only restrictions on future development or use of an area. This means that decisions on implementation of development projects are often separated from the planning policy decisions, as implementation of desired development is often based on private initiatives or initiatives by municipalities. These initiatives are driven by demands, such as private/public economic development (e.g. ports), public recreational facilities (e.g. beach parks) or public/private protection against erosion and/or flooding (e.g. coast protection and sea defence schemes).

The responsibility for performing and funding coastal protection and sea defence projects differ widely from country to country. However, most countries have a mixed system, where there is a shared contribution between government, regional authorities, local authorities and private landowners. The distribution between the various contributors may depend on the land use and the exposure to flooding and erosion. A generally applicable priority list for public funding does not exist, however, the list in Table 14.4 provides a typical priority for public funding of protection works and coastal rehabilitation works.

Land acquisition is normally used only for infrastructure projects, however, it is getting more common for governments to acquire land for preservation or rehabilitation of natural resources, e.g. for new natural reserves, etc. Such areas can be owned and managed by state agencies or by voluntary organisations subsidised by the government. But the general rule is that development depends on private initiatives or funding from other authorities than those responsible for the spatial planning.

Most countries have a Coastal Authority, which is normally organised as an administration under a resort ministry. The responsibility of the Coastal Authorities varies from country to country. However, in general a Coastal Authority will have the following, or some of the following responsibilities:

- To monitor the coast and possibly also tide and wave conditions
- To plan and execute coast protection and sea defence works to the extent that the execution of these are the responsibility of the Government
- To maintain the state owned coastal protection and sea defence works
- To construct and maintain tidal inlet regulation structures, navigation channels and port entrances
- To approve plans for private projects in the coastal area, especially coast protection and sea defence projects
- To support the regional planning authorities in their handling of coastal planning (shoreline management) and coastal projects and in their approval of Environmental Impact Assessment and Morphological Impact Assessment reports for coastal projects
- To represent the Government in matters in relation to enforcement of the States sovereignty over the Sea Territory
- To execute flood warning

Table 14.4 Typical priority ranking for funding of coast protection, sea defence and coastal rehabilitation works.

Facilities under risk for erosion, flooding or degradation	Type of protection	Land use	Funding body and priority				
			Govern-ment	Regional Authority	Local Authority	Public Utility	Private
Low laying areas	Sea defence	Public and private land and property	H	H	H	H	H
Power plants and other public utilities	Coast protection or sea defence	Public utilities	H	H	H	H	NA
Roads, railways, bridges/tunnels and outlets	Coast protection or sea defence	Public infrastructure	H	H	H	NA	NA
Towns and villages	Coast- or Shore protectionor Sea Defence	Areas of socioeconomic importance	H	H	H	NA	NA
Private buildings	Coast- or Shore protection	Private houses	L	L	L	NA	H
Public recreational beaches and beach parks	Coastal rehabilitation	Recreation and tourism	M	H	H	NA	NA
Archaeological and religious sites	Coast protection or sea defence	Protected sites	H	H	H	NA	NA
Protected nature areas	No protection, natural development	Nature preservation	SB	SB	NA	NA	NA
Land without infrastructure or buildings exposed to erosion	Coast and shore protection allowed only if buildings are threatened	Rural, forest og farming	L	L	L	NA	M

Note: Priority ranking for implementation of protection:
H: High
M: Medium
L: Low
SB: Impose Development Restriction, Set Back
NA: Non Applicable

There is a general requirement in most countries that all development shall be sustainable. This also applies for the developments in the coastal area. Here, there will typically be a conflict between development projects and coast protection projects on one side and preservation of natural resources on the other side. The conflict arises because such projects tend to impose restrictions on the natural morphological processes, which directly influence the coastal evolution of the area. Careful control of development in the coastal area is needed to protect nature and the environment while seeking high quality conditions for human living and activities.

The following aspects are normally considered of high importance:

- Protection of the undeveloped coast against development and to maintain high biodiversity, i.e. protection, enhancement and development of ecology and nature
- Maintain recreational areas of high quality, attractive places to live and work
- Increasing the quality of existing urban and recreational sites instead of expanding in new undeveloped areas
- Development in the coastal area shall be restricted to such types of development, which is dependent on the coastal location. Undeveloped coastal areas are supposed to be used for new development only if there is a strong justification for it
- Protection of cultural heritage and landscape
- Maintain or re-establish good coastal water quality by minimising discharge of pollutants and nutrients
- Coastal protection and sea defence is of high importance in low laying exposed areas, however, coastal protection should respect valuable natural habitats. In order to obtain sustainable protection it is important to utilise the natural coastal processes whenever possible, i.e. work with the processes instead of against the processes. Establish understanding of the coastal processes is therefore compulsive before shoreline management projects are implemented.

The integration of sector (horizontal) and spatial (vertical) requirements in the development of the coastal zone requires great co-ordination efforts from all involved authorities and stakeholders. However, distinguishing between horizontal and vertical planning aspects are not very well defined as e.g. the governmental structure is both horizontal (different ministries/sectors) and vertical (municipality, region, state, EU). Experience has shown that this is a difficult exercise without additional planning concepts. This is the background for the concept *Integrated Coastal Zone Management* (ICZM) and *Shoreline Management*. These concepts will be briefly discussed in the following.

14.5 Coastal Zone Management

There are indispensable requirements for sustainable development and preservation of natural resources in the coastal zone. There are many examples that unplanned, uncoordinated and uncontrolled development in the fragile coastal zone has led to destruction of natural resources as well as to unsuccessful development. This is the background for the development of the concept of *Integrated Coastal Zone Management* (ICZM).

ICZM integrates the demands for development and protection of the coast and the environment according to given sector acts/guidelines and according to spatial plans. The ICZM-process is normally expressed in the form of a Coastal Zone Management Plan (CZMP) covering an entire country.

There are many definitions of ICZM, The World Bank Guidelines 1996 quote Integrated Coastal Zone Management (ICZM) as:

'A process of governance that consists of the legal and institutional framework necessary to ensure that development and management plans for coastal zones are integrated with environmental (including social) goals and are made with the participation of those affected. The purpose of ICZM is to maximise the benefits provided by the coastal zone and to minimise the conflicts and harmful effects of activities upon each other, on resources and on the environment'.

The concept of ICZM is thus a structured co-ordination of the various activities and resource demands that occur in the coastal zone in order to achieve economically, environmentally and socially sustainable development in compliance with adopted relevant local, regional, or international goals.

The typical content of a CZMP is listed in Table 14.5. The content of such plans varies considerably, dependent of the actual natural conditions, the extent and type of development, the impacts of the historic development and legal and administrative conditions for the specific country. However, it always follows a traditional spatial planning cycle concept: inventory of the natural system, the users and the governmental system, inventory of potential conflicts, creation of different alternatives using decision support systems, and selection of the preferred solution.

Table 14.5 Typical generic List of Content for a CZMP.

Subject	Content
Preface	The context
Introduction	The background, special needs and subjects for the plan, reference to earlier plans
Executive summary	Presentation of main recommendations
Framework of ICZM	Presentation of framework • Institutional set-up • Legal set-up (Laws, acts, guidelines and plans) • Funding practice
Chapters for selected subjects • Coastal erosion and flooding • Resource utilisation (Mining, fishing, aquaculture, recreation and tourism) • Coastal habitats • Coastal pollution • Protected sites • Etc.	Each subject to be described under the following headings: • Current status of subject • Main threats • Current management practice, strengths and weaknesses
Recommended management actions	Management actions to be described for each subject area in terms of: • Policies • Strategies • Proposed actions • Timing and funding • Description of update procedures for the CZMP

The CZMP thus provides a sectorial and spatially integrated description of policies, strategies and proposed actions required for the sustainable development of activities in the coastal zone.

14.6 Shoreline Management

The fact that a CZMP has been developed does not secure that the development will actually take place, as already mentioned in relation to the spatial planning. The actual implementation of possible coastal development projects, major infrastructure projects or coast protection projects can start after political approval and the projects have to be implemented according to more specific management plans, development plans or master plans.

The initiative to such plans will typically come from developers, landowners, government sector authorities, concessionary companies, or central, regional or local authorities. These plans can be divided into shoreline management plans, master plans and sector development plans as presented in Table 14.6.

Table 14.6 Main types of management plans, master plans and development plans in the coastal zone.

<table>
<tr><th colspan="2">Type of plan</th><th>Mission of plan</th><th>Responsible body</th></tr>
<tr><td colspan="2">Shoreline Management Plan (SMP)</td><td>Strategy for sustainable protection and development of the coast</td><td>Coastal Authority or Regional Authority</td></tr>
<tr><td rowspan="5">Master Plan (MasP)</td><td>Shoreline Master Plan</td><td>Master plan for sustainable protection of the coast in a Management Unit</td><td>Local land owners, Coastal Authority or Regional Authority</td></tr>
<tr><td>Master Plan for infrastructure project</td><td>Master plan for infrastructure project, such as a fixed link (bridge, embankment or tunnel)</td><td>Government or Government Partnership</td></tr>
<tr><td>Master Plan for major plant</td><td>Master plan for a power plant, offshore windmill park or desalination plant, etc.</td><td>Concessionary Company</td></tr>
<tr><td>Master Plan for development project</td><td>Master plan for a specific development project, such as a reclamation project, a beach park, a marina or similar</td><td>Local Partnership or Stakeholder Organisation/Club</td></tr>
<tr><td>Regional DP</td><td>Plan for sustainable development of tourism facilities in a region</td><td>Planning or Tourism Development Authority</td></tr>
<tr><td>Sector Develop-ment Plan</td><td>Local Master Plan</td><td>Master Plan for local development area</td><td>Planning or Tourism Development Authority</td></tr>
</table>

Shoreline Management Planning and Shoreline Master Planning are described in detail in the following chapters.

14.6.1 Shoreline Management Planning

The purpose of Shoreline Management Planning is to identify the resources and assets in the coastal area now and in the future and through that minimise negative consequences from the interaction between the various interests, i.e. tourist and economic development, coastal protection, natural dynamics, etc. As such, it is a type of spatial planning.

Shoreline Management Planning is the part of the Integrated Coastal Zone Management that deals with the interaction between the actual and potential coastal evolution and the existing and planned activities in the coastal area.

The aim of a *Shoreline Management Plan* (SMP) is to provide the basis for the implementation of overall sustainable shoreline management policies and strategies – a management strategy - for a well-defined region and to set the framework for the future management of conflicts in the coastal area.

A Shoreline Management Plan is a strategy document that delivers a broad-brush assessment of the coastal resources, conflicts, opportunities and constraints. The plan must therefore contain reference to the adopted policies and to the adopted regulatory system as well as to a possible Coastal Zone Management Plan.

The SMP shall address, in broad terms, whether to defend, or continue to defend, assets with coastal defences or manage the risks through other means. The plan shall be based on a strategic assessment of conditions within the plan area rather than detailed studies of individual sites.

A Shoreline Management Plan normally covers an area along the coast described as a *Sediment Cell*. A sediment cell is a chapter of the coastline in which the physical processes are relatively independent from processes operating in adjacent sediment cells. The boundary of a sediment cell generally coincides with larger estuaries or prominent headlands. An example from the UK is presented in Figure 14.1.

In many cases, however, sub-cells or groups of sub-cells provide a more practical basis for the production of plans because they have a more manageable size. The boundaries of sub-cells, also shown in Figure 14.1, are not definitive; they are based on the best available knowledge of large-scale processes, and may need to be revised as further information becomes available. In many countries, the local municipalities have to create local municipality plans that include all activities in the coastal zone.

Shoreline Management Planning has become increasingly important with the accelerated development pressure in the coastal areas and the relatively strict sector requirements for preservation and restoration of the natural resources, which have been implemented in the legislation in most countries over the last decades. The challenge in this context is to combine the following interests:

- *Public interests*: Shore protection, resource preservation, development of infrastructure and public utilities, etc.
- *Private interests*: Development of projects and coast protection
- *Industry interests*: Industrial development, navigation, raw material utilisation, etc.

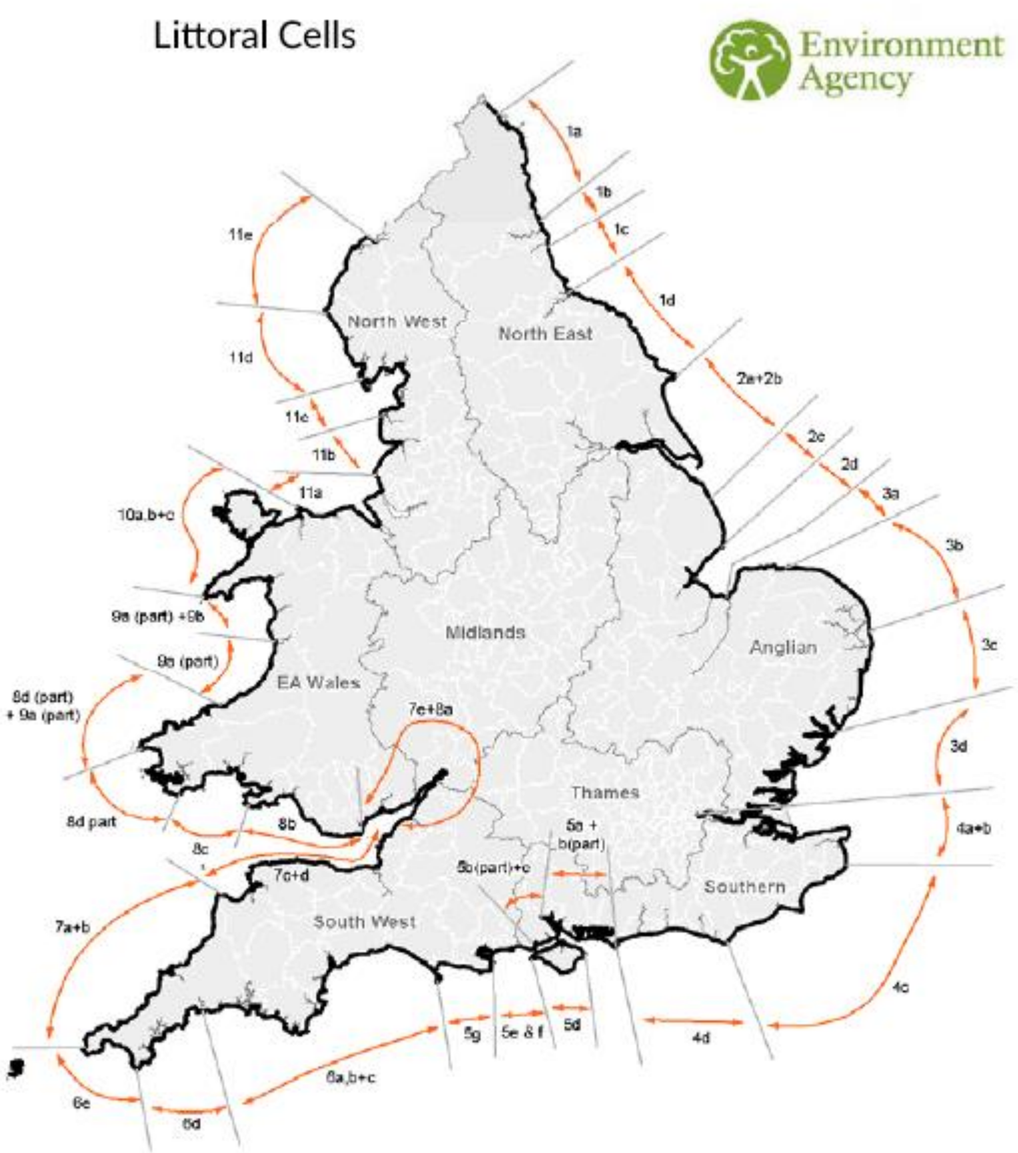


Figure 14.1 Littoral Cell location map, Rev. 2, 27.04.2010. From UK Environment Agency (2010).

There are often inherent conflicts of interests in e.g. coast protection projects, both with respect to the objectives and with respect to the sharing of the costs. Resolving these planning matters is often as difficult as it is to find a suitable technical solution. The following aspects are equally important in this planning process:

- Openness through public participation via dissemination of the planning concepts and public hearings
- Balanced weighting of conflicting interests, such as requirements for sustainable development, environmental protection and preservation of the natural coastal landscape versus requirements to protection, etc. This can be implemented through well planned optimised projects

- Fair distribution of cost between all involved parties. The main two types of parties and their interests are:
  - Landowners, who directly benefit from the project, e.g. in form of obtaining protection of property, and
  - Sector Authorities, who introduce requirements to sustainability and nature preservation, which often diverts a coast protection project in the direction of a coastal rehabilitation scheme with application of nourishment instead of hard coastal protection. This also implies the need for regular maintenance in the form of re-nourishment, which can be difficult to handle for a minor group of landowners

It is normally the responsibility of the regional authority or a sector authority as part of a ministry, such as the Coastal Authority, to develop Shoreline Management Plans. It is important that experts in the fields of coastal morphology, coastal engineering, landscape architecture and planning, and environmental management participate in the elaboration of the Shoreline Management Plan.

In the following, the overall content of a **Shoreline Management Plan** (SMP) is listed and described. The administrative procedures in connection with the planning process are also included in the description.

1. *Reference to related plans and to the legal and institutional framework*
   a. Summary of planning requirements for the Sediment Cell from existing regional and local spatial plans. Discussion of possible requirements for amendments to these plans in order to make room for possible new development
   b. Summary of sector requirements for the Sediment Cell from existing sector acts and from a possible Coastal Zone Management Plan
   c. Description of the institutional set-up and procedures in relation to elaboration and approval of the SMP

2. *Historically updated information about the coastal area*
   a. Description of the shore- and coastline development based on historic data (old surveys, aerial photographs, satellite images, charts, maps and other local/national information)
   b. Description of existing coastal and harbour structures (and how they have changed through time), including maintenance dredging. In relation to the above-mentioned the impact on the coastal development should be deduced
   c. Metocean conditions (wave climate, currents, wind, temperature, and water levels). If wave and water level data are not available it will be possible through numerical modelling to generate useable information
   d. Analysis of climate changes especially related to sea level rise, but also changes in temperature, precipitation and wind conditions. Define the life time, or planning horizon, for the SMP. This defines the time horizon for the climate changes to be taken into account
   e. Bathymetric and topographic information
   f. Geological and morphological information. Description of coastal landscape and recent development. Information on existing marine sand layers onshore and matching grain size distribution, which is required for calculation of the littoral drift budget
   g. Mapping of existing land use: Housing and habitation areas, agriculture, industry, major infrastructure and nature areas (forests, bare land, recreational areas)
   h. Biodiversity, nature conservation and environmental aspects
   i. Historic environment (important local or national historic locations, archaeology remains, historic buildings, parks, gardens, landscapes)
   j. Landscape issues (landscapes designated for their importance, national parks and world heritage)

3. *Establish the littoral drift budget, classify the shoreline and categorise sections of shoreline for sensitivity*
    a. Collection of necessary additional data
    b. Establish the littoral drift budget for the Sediment Cell by numerical modelling and by analysis of historic shoreline development data. The littoral drift budget is decisive for the erosion or accretion of the natural coast and for understanding impacts from man-made structures, existing or planned
    c. Analyse impact of climate changes on coastal erosion and coastal flooding
    d. Establish shoreline classification. This is important for understanding of morphological features and for evaluation of suitable protection measures
    e. Categorise sections of shoreline for sensitivity to acute/chronic erosion and accretion based on the sediment budget and correlation between storm surges and wave impact
4. *Identification of bindings (natural or man-made) in the coastal area, present and future*
    a. Description of present and future shoreline development including impact of climate changes
    b. Description of land use in a broad sense (present and future (planned development)). Land use in characteristic categories: Habitation, industry, major infrastructure, recreation and nature protected areas
    c. Analysing conflicts between shoreline development, land use and environmental requirements
5. *Strategy developed and accepted by stakeholders*
    a. Establish draft sustainable shoreline management strategy for future development and protection, e.g. where can development be accepted and whether to defend, or continue to defend, assets with coast protection or shore protection measures or manage the risks through other means
    b. Part of the management strategy is the establishment of a cost sharing distribution for different types of developments and protection principles
    c. Publish the draft shoreline management strategy and circulate among relevant authorities for consideration and carry through public hearing process
    d. Establish consensus via the circulation and public hearing processes, formulate the agreed shoreline management plan and publish
6. *Identification of Management Units*
    a. Identify Management Units within the plan area – the Sediment Cell or the Sediment Sub-Cell. Management Units represent a practical subdivision of the Sediment Cell into lengths that follow sediment cell principles and represent sections of homogeneous land use. Management Units are suitably sized sections of coasts to form the basis for Master Plans for conceptual design of shore development/protection schemes, the so-called Shoreline Master Plan (SMasP). An illustration of the relationship between Management Units and Sediment (Sub) Cells is shown in Figure 14.2.
7. *Establish a Monitoring Plan and a Database*
    a. Identified data gaps shall be filled by surveys, samplings and recordings as required to ensure that future plans will make use of the best and newest information.
    b. The development in the area shall be monitored through a monitoring programme, which can contain the following types of activities:
        - Monitoring of shoreline development and coastal profiles by regular surveys
        - Monitoring of hydrographic data, such as water levels and waves
        - Registration of coastal structures, nourishment and maintenance dredging, etc.
    c. Establish a GIS based data base for storing and easy access to all relevant data

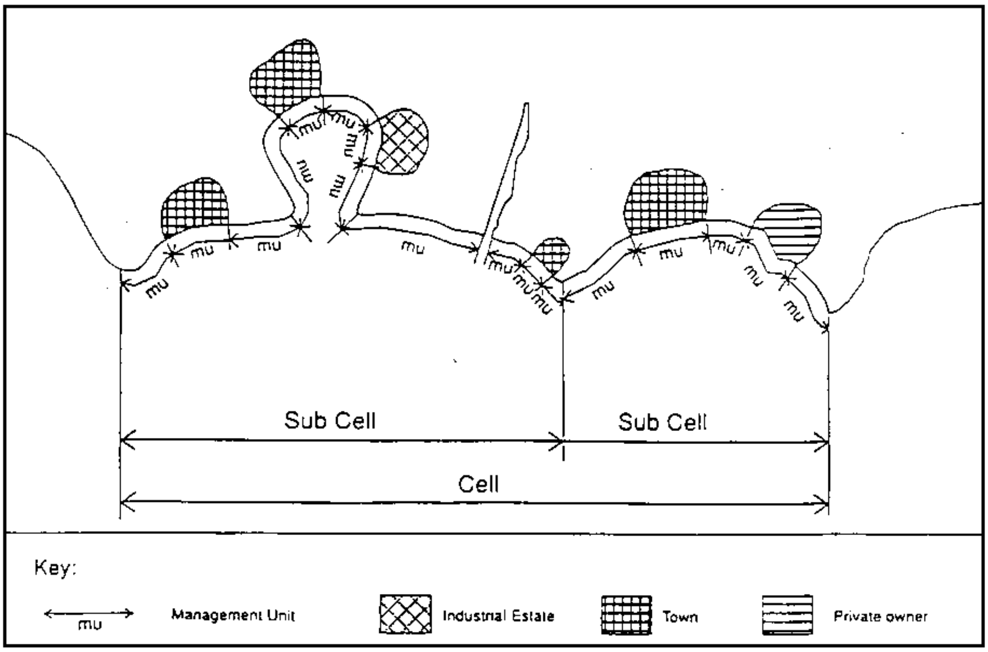


Figure 14.2 Example of Sediment Cell, Sediment Sub-cells and Management Units.

The Shoreline Management Plan thus provides the decision-makers with the necessary information about consequences in deciding on the future development and identifies manageable units (Management Units) within the Shoreline Management Plan area.

Knowing that a Shoreline Management Plan has a limited life span due to fast development of society and possible change in preference and to ensure that all relevant aspects always are included, it is advisable to revise the plan on a regularly basis.

The interval between plan revisions should be co-ordinated with the other involved/concerned planning authorities with respect to when they revise their plans (a suggestion is every 4 -5 years).

14.6.2 Shoreline Master Planning

The aim of the Shoreline Master Plan (SMasP) is to describe appropriate schemes as required by landowners following the policies set by the CZMP and the strategies set by the Shoreline Management Plan.

The Shoreline Management Plan provides the decision-makers with the necessary information about consequences in deciding on the future development. The Shoreline Master Plan delivers the preferred scheme type including economic and environmental decisions. The SMasP describes the type of scheme e.g. shoreline management scheme (beach nourishment, seawall, revetments, groynes, breakwaters, beach fill, etc.), waterfront development scheme or other types of coastal schemes.

The detailed design of the schemes is not a part of the Shoreline Master Plan and the actual choosing between preferred scheme type and project details is done by the developers.

The Shoreline Master Plan is applied on specific Management Units within the Shoreline Management Plan area, but can - if preferred - be applied to the entire Shoreline Management Planning area, i.e. the Sediment Cell.

An actual Shoreline Master Plan might not be very detailed.

The Shoreline Master Plan is based on the Shoreline Management Plan and the data collected for that plan is central and forms a basis.

It is normally the responsibility of the Coastal Authority or the Regional Authority to carry out the Shoreline Master Planning, although it may also be the responsibility of the land owner/developer. However, in many cases the responsible authority will not prepare the SMasP itself, but establish a project organisation typically consisting of:

- *A consulting team:* This should as a minimum include the following professionals: coastal morphologist, coastal design engineer, master planner, landscape architect and environmentalist.
- *A steering committee:* County, Municipality, Coastal Authority and representatives of the landowners and other groups involved (NGOs).

A typical **Shoreline Master Plan** has the following content:

1. *Detailed registration of the natural resources and assets (infrastructure e.g.) in the Master Plan area*
   a. Extracting data from the Shoreline Management Plan
   b. Additional information collection (common Database)
   c. Mapping of infrastructure and natural and environmental resources, based on aerial photos, locally available data, stakeholder information, etc.
2. *Detailed description of the metocean conditions*
   a. Extracting data from the Shoreline Management Plan.
   b. Additional information collection through field surveys and detailed numerical modelling e.g. meteorological information, wave, currents and water levels, etc. This includes assessment of climate changes, recommendation of planning horizon and of acceptable risk during the planning horizon.
3. *Detailed morphological description of the shoreline development*
   a. Extracting data from the Shoreline Management Plan
   b. Additional information collection through field surveys and existing data on: topography, bathymetry, geological and sediment information and visual reporting (vegetation, etc.).
   c. Description of the historical shoreline development
   d. Numerical modelling of the local littoral drift budget and forecast of the future shoreline development assuming no new protection measures
4. *Alternative measures for sustaining the shoreline identified*
   Obtained through:
   a. Identify conflicts between planned development and forecasted shoreline development assuming no new protection measures
   b. Propose alternative protection measures to solve conflicts in accordance with strategy set out in the SMP. The various stakeholders shall be involved in setting the goals.
   c. Forecast the future shoreline development for the alternative protection measures
   d. Identify conflicts between the future shoreline development and planned assets, optimise protection scheme accordingly. Environmental Impact Assessment (EIA) is the relevant instrument for this optimisation process. The following aspects shall be included in these assessments:
      - Preservation of the natural coastal landscape, perform aesthetic optimisation
      - Secure access along the coastline and secure public access from the hinterland
      - Secure bathing safety and good bathing water quality

   e. Feasibility analysis of the identified alternative measures. The various stakeholders shall be involved in the process of selecting the preferred scheme. Procedures separating technical evaluations and stakeholders' opinions are recommended. Agreement on the cost sharing shall be established

5. *Shoreline Master Plan document finalised, approved and published*
   Obtained through:
   a. Drafting the SMasP
   b. The plan must be according to the common policy set by the CZMP and according to the strategy set forth in the Shoreline Management Plan
   c. The SMasP shall be approved by the various involved authorities and the associated MIA/EIA shall also be approved according to relevant procedures
   d. The SMasP shall be published and made accessible to involved stakeholders
   e. The Shoreline Master Plan shall be revised on regularly basis to ensure that the optimum solutions always are met.
   f. The main output of the Shoreline Master Plan is a well-documented conceptual design of a shore development/protection scheme documented and balanced with respect to morphological impacts, environmental impact and other considerations. The SMasP thus forms the basis for possible implementation of the recommended scheme via detailed design, tendering for construction and construction.

14.7 Climate Adaptation Plans

14.7.1 Background

In many parts of the world there are international, e.g. EU directives for the European countries, and national directives for the issuing of national and regional climate adaptation plans.

The European Union issued a Flood Directive with guidelines to deal with flooding from rivers and the sea. This directive is subsequently implemented in all member countries. According to the Floods Directive all member states shall:

- Identify competent authorities and units of management
- Perform preliminary flood risk assessment for all types of floods
- Produce flood hazard maps and flood risk maps
- Issue flood risk management plans

In the United States the National Climate Assessment (NCA) are conducted under the auspices of the Global Change Research Act (GCRA) of 1990. The GCRA requires a report to the President and the Congress every four years that integrates, evaluates, and interprets the findings of the U.S. Global Change Research Program (USGCRP); analyses the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and analyses current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years, cf. Burkett (2012).

Similar directives exist for other countries and regions of the world.

The above directives are mainly implemented on national level in the national laws and acts. On a regional or local level there are typically requirements for issuing Climate Adaptation Plans for regional and local areas. The areas for the plans could either be selected by physical characteristics, such are water catchment areas or coastal cells, or by administrative boundaries, such as counties/provinces or municipalities.

14.7.2 Climate Adaptation Plans

A broad collaboration, dialog and involvement among authorities, organisations, companies and citizens is required to handle the challenges to our society that are induced by climate change.

In Denmark it is a requirement that the municipalities shall develop Climate Adaptation Plans, which shall be part of the Municipality Plans or as an attachment to such plans.

This has the following advantages:

- The Climate Adaptation Plans will be part of the broad and open public debate, which has been developed by the municipalities in their elaboration of municipality plans
- Overall considerations and synergy are incorporated in the climate solutions by integration with city planning, recreation and nature rehabilitation
- Climate adaptation plans are coupled to the regular updating of Municipality Plans
- Interaction will take place between the planning on government level and on regional/local level such as updating of regional development plans
- The means of operation of the planning law, such as administration of sector laws will be utilised

A **Municipality Climate Adaptation Plan** shall contain the following elements:

1. *Background and assumptions*
   A description of the normal and climate related pressures in the municipality and which issues that are consequently focused on in the plan. This could typically be flooding risk due to extreme precipitation which causes direct flooding in low lying areas, flooding from rivers and from overflowing sewage systems as well as flooding risks from storm surges combined with Sea Level Rise. Data for this analysis will typically be available from central authorities and from IPCC. This is often supplemented with description of extreme historical climate events. The description can also contain other considerations related to the effect of the climate events, such as town development, nature preservation and handling of sewage and interaction between business community, citizens and property owners
2. *Risk pattern*
   Maps showing potential flooding areas, so-called flooding maps, in risk of being flooded from the sea, rivers, groundwater, precipitation and sewage systems shall be produced. Value maps showing the value and importance of buildings and facilities, such as important/vulnerable institutions and cultural heritage that are threatened by flooding. Finally risk maps can be elaborated by combining the risk of flooding with the values that will be lost during the flooding events.

15 Coastal Projects

Coastal projects range from small harbour expansions to mega nourishments where millions cubic meters of sand is nourished to a beach. In the present chapter the following coastal projects will be discussed:

- Shoreline Management Scheme
  - Shore protection scheme, combined structures and sand fill or nourishment
- Coastal Development Scheme or Waterfront Development Scheme
  - Beach Park Scheme
- Coast Protection Scheme
  - Revetments
  - Breakwaters
  - Groynes
- Sea Defence Scheme
  - Dikes
  - Seawall
  - Reinforced dune
- Public Infrastructure, Utility Projects and Industrial Plants
  - Port or harbour projects
  - Pipelines, cables and utility/industrial projects (intake/outfall)
  - Regulation of tidal inlet
  - Fixed links such as bridges or tunnels

The objective of the various projects is different: Some projects are development schemes which are built mainly for housing and tourism development reasons (Coastal Development Schemes), whereas other projects are built to mitigate different types of problems (Shoreline Management Schemes, Coast Protection Schemes, Sea Defence Scheme) or to facilitate transport of goods, people (ports, harbours and fixed links) or energy (pipelines or harbours). A summary describing the different projects, the objective/characteristics of the projects, the hydraulic issues within the project, and typical impacts of the project is presented in Table 15.1.

Table 15.1 Summary of types of schemes and their relation to problems, objectives, characteristics, hydraulic and environmental issues and impact of the scheme.

Type of scheme	Reason for implementation	Objective	Key characteristics	Hydraulic and environmental issues	Impact of scheme	Cf. chapter
Shoreline Management Schemes	• Mainly coastal erosion in coastal cell, natural or caused by construction of other coastal projects	• Mitigation of erosion problem • Developmen t of recreational public beach	• Beach fill for new artificial beach • Coastal structures to support new beaches	• New beach shall be exposed to waves.	• Mostly minor and local impacts. Possible intermediate impact on adjacent littoral cells.	15.1.1
Coastal Development Schemes or Waterfront Development Scheme	• Lack of development area. • Lack of beach space and lagoon areas for development	• Economic development • Enhanceme nt of landscape quality in development area	• Beach parks: minor land reclamation and introduction of new beaches and excavation of new lagoons • New marinas	• Beach stability • Flushing • Water quality • Beach quality	• Env. impact of dredging and reclamation • Possible impact on adjacent beaches	15.1.2
Coast Protection Schemes	• Coastal erosion risk	• Coast protection (not beach preservation)	• Typically rubble revetment	• Beach will be lost	• The scheme protects coastal facilities, however, the beach will be lost	15.2
Sea Defence Schemes	• Flooding risk	• Coastal flooding protection	• Seawall, dike or reinforced foreshore and dune	• Beach may be lost if combined with coastal erosion	• Should not be used in rural areas as this may impact wetlands	15.3
Public Infrastructure Schemes	• Need for public infrastructure	• Build or expand existing port, harbour, pipeline, etc.	• Jetties, breakwaters submerged structures	• Possible impact on adjacent beaches. Mitigation measures can be implemented	• Dredging of navigation channels, pipeline trenches • Impact on adjacent littoral cells	15.4

Each of the coastal projects is briefly discussed in the following.

15.1 Shoreline Management/Coastal Development Schemes

Shoreline Management Schemes and Coastal Development Schemes are very similar, the main difference being the financing (public vs. private) and the driver for the scheme (management of erosion vs. development of the coastal area to attract tourists or residents).

15.1.1 Shoreline Management Scheme

A shoreline management scheme (SMS) is typically a publicly financed or mixed publicly/privately financed scheme, dependent of the legislation in the country, built to compensate an eroding shoreline and to rehabilitate and expand the beach and marine elements in an area. A Shoreline Management Scheme typically consists of the following marine elements:

- Beach fill or nourishment for stabilisation of the beaches
- Structures to support stabilisation of beach fill, typically by realigning an existing beach to fit the equilibrium orientation. The supporting structures thus minimise loss from the filled beaches. The supporting structures may typically be combined with marinas

The main challenge in developing successful Shoreline Management Schemes is to utilise the possibilities in an area so that:

- Coastal erosion problems are solved either by nourishment which, however, requires regular maintenance or by permanently solving the problems by building new beaches in the equilibrium orientation supported by coastal structures. Intermediate solutions between the above two are also used, where the structures support a beach which is close to the equilibrium orientation but still allowing some bypass of sand through the scheme
- The requirements for coastal structures are combined with meeting other demands in the area such as plans for expanding marinas, the need for viewing and promenading facilities, etc. In most areas around the world, it is important to use the concept of multi-functional facilities for the development of new coastal schemes
- The concept of “Building with Nature” is used, e.g. by utilising the existing marine forces as a basis for the future development rather than trying to protect the beach against the forces

There are in principal two main marine issues to consider: The internal functionality of the scheme and the requirement for minimising impact along adjacent coastal stretches (sustainable development).

15.1.2 Coastal Development Scheme or Waterfront Development Scheme

A Coastal Development Scheme/Waterfront Development Scheme (CDS/WDS) is very similar to a shoreline management scheme but the objective is mainly to enhance development potential of an area whereas it is only a secondary objective to stabilise the existing beach in the area. A CDS it is typically financed by a private or public development company. A coastal development scheme typically consists of the following marine elements:

- Artificial beaches and beach reclamations, typically by expansion and reshaping existing beaches
- Terminal structures to prevent loss from the artificial beaches, possibly combined with marinas or lagoon openings
- Artificial lagoons, either built into the sea in connection with beach reclamations or excavated into the mainland

- Lagoon openings, possibly navigable
- Marinas

A CDS consisting of the above elements is often referred to as a Beach Park Scheme. See Subchapter 17.7.2 for further description of the beach park concept.

The main challenge in developing successful CDS is to utilise the possibilities in an area so that:

- New artificial beaches are stable, which is obtained by aligning them in the equilibrium orientation and by supporting the beaches by terminal structures
- The beaches are moderately exposed to waves to obtain safe beaches and to obtain high quality beaches
- The requirements for coastal structures are combined with other demands in the area such as plans for expanding marinas, the need for new lagoon openings or the need for viewing and promenading facilities, etc. In most areas around the world, it is important to use the concept of multi-functional facilities for the development of new coastal structures
- The concept of “Building with Nature” is used, e.g. by utilising the existing marine forces as basis for the future development rather than trying to protect the beach against the forces

A coastal development scheme is typically built to attract tourists or new residents to an area; such a scheme is primarily built for development and recreational reasons and normally not as a reaction to coastal erosion but rather as a reaction to a poor beach quality.

15.1.3 Functionality of Shoreline Development – and Coastal Development Schemes

15.1.3.1 Rehabilitated beach sections or artificial beaches

Attractive and safe recreational beaches are always characterised by being exposed to moderate wave conditions, micro - to moderate tidal range, clean and transparent water, no or limited rock outcrops, well sorted medium sand and minimum amounts of natural and artificial debris. The wave climate at the new beach should not be too severe as this will make it dangerous to swim at the beach, this means that artificial beaches at locations with rough wave climates may require partial protection whereas artificial beaches at locations with limited wave activity should be designed to obtain maximum wave exposure to secure a good beach quality.

The orientation of an artificial beach should always be built in the equilibrium orientation such that erosion following construction is avoided; this means that the beach must face the predominant wave direction. Rehabilitated beaches may be designed to allow some of the natural littoral drift to pass through the scheme, in this case the beach orientation is turned towards the equilibrium orientation but in an orientation allowing some bypass of sand through the scheme.

Terminal structures are usually needed in order to secure an artificial beach from loss of sand. These structures may be made as multi-functional structures which also accommodate a recreational function, i.e. as sunset viewing platform, for promenading or for sporting facilities.

Sheltered corners behind structures should be avoided as these may introduce dangerous rip currents and trapping of sand, seaweed and debris. The structures should be made as streamlined as possible and the angle between the beach and the structure should be well above 90° to avoid “deep” corners.

The beach profiles should be constructed according to the equilibrium shape as discussed in Subchapter 7.3.

Only clean well sorted marine sand should be used whereas sand of terrestrial origin, such as desert sand, should be avoided because such sand typically contains too large amounts of fine fractions.

15.1.3.2 Artificial lagoons

Good water quality in the lagoon is of paramount importance for the recreational value of the lagoon. This leads to the following requirements:

- A good flushing of the lagoon shall be secured. This may require several openings to the sea and maybe forcing. It is important to optimise the flushing through detailed investigations
- Discharge of pollutants and nutrients into the lagoon and into adjacent waters shall be avoided or limited
- The water quality in the adjacent water areas shall be excellent

The waterfront perimeters inside the lagoon shall be selected to provide the best possible recreational facilities, whereas protection is only a secondary requirement inside the lagoon. There are the following types of perimeter structures:

- Rubble mound slopes or revetments which, however, may not be attractive from a recreational and visual point of view
- Vertical walls and bulkheads, which are suitable along promenades and in marinas, etc.
- Stepped slopes, which are suitable along promenades and private property
- Piled decks and piers in concrete or wood, which are suitable long promenades, private property and in marinas
- Floating piers, which are suitable along promenades, at private property and in marinas
- Sandy beaches, which are suitable along public areas, in parks and at private property. However, it is a problem to obtain a good quality beach in a lagoon environment due to limited wave exposure. Consequently, sandy beaches inside lagoons should be carefully considered

15.1.3.3 Sustainable development of Shoreline Development – and Coastal Development Schemes

Securing sustainability of a development scheme requires integration of sector and spatial requirements. This highlights the importance of sufficient coordination between all involved authorities and stakeholders, especially for projects in the coastal zone.

Consequently the following procedures shall be strictly adhered to:

- EIA procedures for the construction phase as well as for the operation phase
- Other approval procedures
- Sound design practice, which includes the following stages:
- Project conception
- EIA scoping
- Preliminary design and project optimisation
- Detailed EIA
- Detailed design
- Environmental monitoring during construction and operation
- Obtain permission for possible mining of fill sand for the scheme
- Obtain approved addition to the regional/structure plan for the area as required

The general marine requirements for obtaining sustainability are:

- Secure that the scheme has good hydraulic and coastal functionality
- Secure that the scheme has minimum impact on flushing and water quality in the adjacent area, both during construction and during the operation phase. Optimise and propose mitigating measures as required
- Secure that the scheme has a minimum impact on coastal conditions on the adjacent coast in respect of coastal stability and beach degradation. Optimise the layout for minimising the impact, and propose and implement mitigating measures as required. This especially relates to the possible impact of major coastal structures such as expanded marinas and lagoon openings, as they may have impacts in the cell at both sides of the structure and not only to the side, where it is part of the overall scheme

15.2 Coast Protection Scheme

The objective of coast protection is to protect infrastructure built on the coast or the coast itself if the amenity of the coast is important to an area. The best type of coast protection depends on the location and utility of the coast which is to be protected. A division can be made between public recreational beaches, where the beach amenity is important, and beaches in front of industrial plants or public utilities, where the beach itself is less important.

Therefore, coast protection can be divided in two types:

- *Coast protection.* The objectives of coast protection are to protect facilities and property on the coast against recession of the coastline (coast erosion). This applies for all kinds of beaches where private or public facilities on the coast are threatened by coast erosion
- *Shore Protection.* The objectives of shore protection are to maintain, rehabilitate, stabilise and expand eroding beaches, thereby securing and enhancing the recreational possibilities and the environmental conditions most possible as well as protecting against coastline retreat. Such beaches could be in front of public recreational areas or in front of private habitation areas. Shore protection is covered under the discussion of Shoreline Management Schemes

The philosophy of shore protection is governed by the requirement to protecting the sandy beaches and the natural beach environment in contrast to coast protection by traditional hard protection measures, which will normally result in the loss of the beach. Protection against erosion in industrial areas only has the requirement to protect, not to preserve the sandy beaches. However, there can be requirements from coastal and environmental authorities to securing the beach environment also in industrial and similar areas in order to maintain the integrity of the coastal environment in the area

See Subchapters 17.4, 17.5 and 17.6 for more details on specific types of shore protection and coast protection.

15.3 Sea Defence Scheme

A sea defence structure has the purpose of protecting low-laying land against coastal flooding. Seen from a nature preservation point of view protection by sea defence should be minimised and only used when there is risk of loss of infrastructure or human life. In other areas, such as area with farm land or land used for grazing, flooding is a natural part of the ecosystem and it should be considered if flooding shall be accepted or even promoted.

In many places there is need for both shoreline management schemes and sea defence schemes, in these cases it is obvious to try and combine those needs into a combined shoreline management and sea defence scheme.

The following types of sea defence schemes are used:

- Dikes
- Seawalls
- Artificial dunes
- Maintenance and restoration of marsh/mangrove forelands

These different types are discussed in detail in Chapter 17.

15.4 Public infrastructure, utility projects and industry projects

Public infrastructure projects in the coastal area are mostly projects related to transportation of people, goods or energy, typically projects such as ports, bridges/tunnels and pipelines. Public utility projects include power, desalination and sewage treatment plants which need port facilities as well as cooling water intakes/outfalls or storm water drainage outfalls. Industry projects include heavy industry plants, which need port facilities and seawater intakes/outfalls but also fishing or aqua-culture projects.

These projects share the common feature that some structure must cross the surf zone and therefore fully or partly block the littoral drift along the shoreline. This often has negative impacts on the surrounding shoreline which need to be mitigated. In the following a very brief description of the different types of projects is given together with examples.

15.4.1 Port and harbour projects

Ports and harbour projects are constructed in order to bring people or goods on board a vessel to be transported somewhere. The size of the harbour and the depth of the navigation channels determine the maximum size and draft of the vessels which can enter the harbour.

As vessel sizes and drafts increase, the size of the ports and the depth of the navigation channels also need to be increased to accommodate the larger vessels.

Increasing the size of a harbour in the coastal zone can significantly alter the way the harbour interacts with the littoral drift therefore very careful studies must always be completed before such a project is undertaken.

Examples of harbours on the Danish west coast are shown in Figure 15.1 and Figure 15.2.

Figure 15.1 A photo of Hanstholm Harbour in the Northwest of Denmark. (Picture from Google Earth).

Figure 15.2 Example of a combined tidal inlet and harbour mouth. Hvide Sande, Denmark.

One of the most extreme cases of increasing navigation channel depth, is the navigation channel to the Port of Rotterdam which is 23 m deep and starts more than 50 km off-shore, a sketch of this channel, known as the Eurogeul, is shown in Figure 15.3.

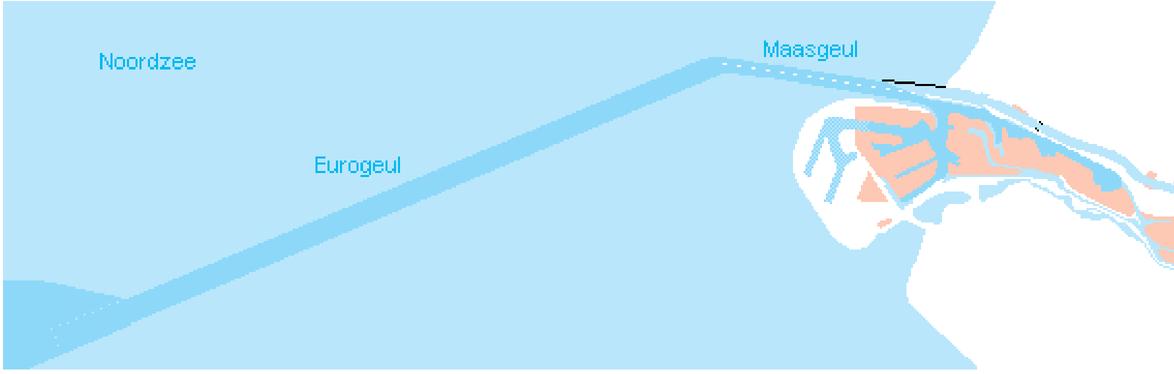


Figure 15.3 A sketch of the navigation channel to the Port of Rotterdam.

The breakwaters, jetties and navigation channels, which make up coastal ports and harbours, interact with the natural processes on the shoreline by affecting the littoral drift directly through blocking or partial blocking and indirectly by sheltering/altering the wave conditions along the adjacent coasts. Under special conditions navigation channels can block/reflect the incoming waves causing changes to the wave climate on adjacent shorelines.

Mitigation measures for ports and harbours are discussed in detail in Subchapter 19.3.2.

15.4.2 Pipelines, cables and utility/industrial projects (intake/outfall)

15.4.2.1 Pipelines and cables

Pipelines and cables crossing the shoreline will normally not have any impact on the coastal conditions in the operation phase as a requirement for such installations will be that they are sufficiently buried so that they are never exposed in their lifetime. There can be temporary coastal impacts during installation of pipelines and cables and the coastal processes may impact the installation procedure.

Determination of burial requirements and design of burial works require coastal analyses.

15.4.2.2 Intakes and outfalls

Cooling water intakes and outfalls are industrial structures built in connection with power plants or industrial plans which need cooling water to operate. Cool water is pumped in at the intake and warmer water is disposed at the outfall.

The intake structures must be long enough such that the concentration of sediment in the intake water is at an acceptable level not to damage the cooling system. Furthermore the intake and outfall must be far enough apart that recirculation of the warmer disposed water is avoided.

Therefore, the intake structure can become quite large and impact the shoreline both by blocking the littoral drift and by sheltering the incoming waves.

Mitigation measures for the impacts from these structures are given in Subchapter 19.3.4.

15.4.3 Regulation of tidal inlet or river mouths

Tidal inlets and river mouths are very morphologically active in their natural state. The morphological activity is not very easy to accommodate when building infrastructure on or around such places and it is difficult to secure safe navigation by vessels in the inlet or river mouth. Therefore most inlets and rivers mouths in developed areas are regulated by jetties to control the position of the inlet or river mouth. An example of a regulated river mouth in New South Wales, Australia is shown in Figure 15.4.

The fixation of the tidal inlet or river mouth clearly obstructs the natural state of the system and interacts with the coastal processes by blocking the littoral drift, often reducing sedimentation in the inlet, but also reducing the bypass of sediment past the inlet. For the case of the Tweed River inlet shown in Figure 15.4, approximately 500,000 m^3/yr of sediment is artificially bypassed the inlet using a mechanical pumping system. The intake jetty of this system is seen in the figure south of the inlet.

Mitigation measured for regulated tidal inlets or river mouths are given in Subchapter 19.3.3.

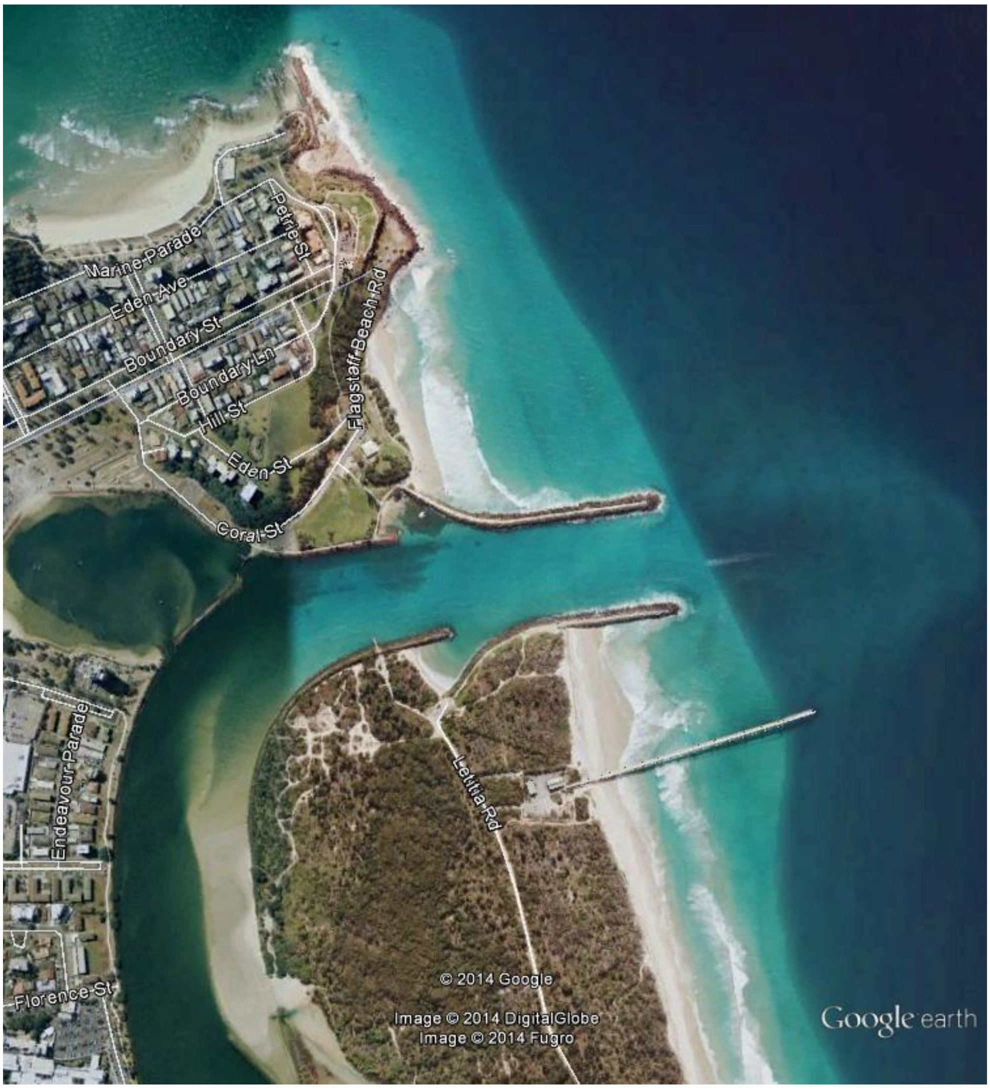


Figure 15.4 Example of a regulated tidal inlet/river mouth. Tweed River, New South Wales, Australia. (Picture from Google Earth).

15.4.4 Fixed links: Bridges or tunnels

Fixed links such as bridges or tunnels are built across smaller enclosed water bodies such as bays, fjords or straits.

These fixed links are built to allow fast passage of cars, trucks and trains across the water body. They impact the surrounding shorelines by both blocking the littoral drift due to landfall structures crossing the surf-zone and by changing the wave and current climate by interfering with the waves and currents.

An example of a fixed link is the Great Belt Fixed Link connecting Zealand with Funen in Denmark, shown in Figure 15.5.

The link consists of the following elements:

- Across the Eastern Channel:
  - A high suspension bridge for road traffic
  - A bored tunnel for rail traffic
- Transition between Eastern Channel and Western Channel:
  - A partly artificial island providing support for road ramps and for the tunnel portal
- Across the Western Channel:
  - A low bridge for road traffic
  - A low bridge for rail traffic

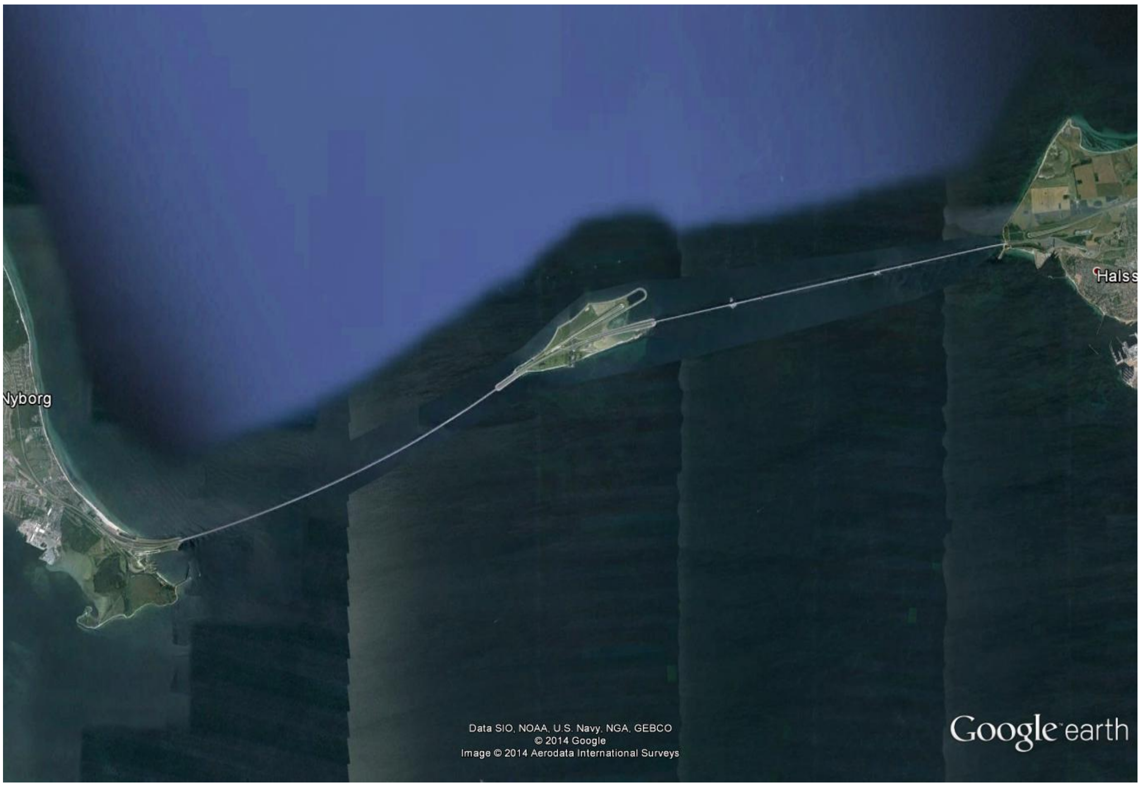


Figure 15.5 The Great Belt Fixed Link connecting Zealand with Funen in Denmark. (Picture from Google Earth).

16 Design Philosophy including Adaptation to Climate Changes

16.1 General design considerations

When wave and storm surge data are used for design of coastal protection and sea defence structures it is important to decide on to the following parameters:

- The probability of occurrence of design event also referred to as the acceptable risk **R**, that the structure may fail within the considered lifetime **L**
- Lifetime, L, of the project/structure. The lifetime can also be considered as the planning horizon for the project
- The design recurrence period, $\mathbf{T_d}$, for the design event

The recurrence period T_d to be used for the design of sea defence structures and other coastal structures e.g. for determination of the relevant design storm surge level and wave height is a function of the lifetime L of the project and the acceptable risk R during the lifetime according the equation:

$$R = 1 – (1 – 1/T_d)^L$$

The acceptable risk *R* as function of the life time L and the recurrence period is presented in Table 16.1.

Table 16.1 The probability of occurrence of the design event **R** [%] as function of the of the life time **L** [years] and the recurrence period $\mathbf{T_d}$ [years].

Life Time (*L*) in years	**Recurrence Period (Td) in years**							
	5	**10**	**30**	**50**	**100**	**500**	**1,000**	**10,000**
1	20	10	3	2	1	0	0	0
5	67	41	16	10	5	1	0	0
10	89	65	29	18	10	2	1	0
30	100	96	64	45	26	6	3	0
50	100	99	82	64	39	10	5	0
100	100	100	97	87	63	18	10	1
200	100	100	100	98	87	33	18	2
500	100	100	100	100	99	63	39	5

If we are considering designing a sea defence structure protecting an area against flooding we have to decide on the recurrence period T_d in order to be able to determine the design flood level and the design wave height on basis of the established extreme value curves for these parameters. It is seen from the table that if a project has a lifetime of e.g. *L* = 50 years and it is designed for a recurrence period of T_d = 50 years, then there is a probability *R* = 64% that the design event will occur within the lifetime. The acceptable probability of occurrence and life time for the project is dependent on the type of facilities to be protected and size of the area. A probability of R = 64%

could be acceptable if we are considering a relatively small area of farm land because the consequence of failure is moderate.

However, if the potential flooded area is large and intensively used for habitation and infrastructure, the acceptable probability of occurrence of the desing event would need to be very low, say *R* = 1 %. As we are considering a large area of highly developed land a lifetime or 100 years is proposed. These conditions lead to a required design recurrence period of approximately T_d = 10,000 years.

The criteria presented in Table 16.1 can also be presented graphically, see e.g. Figure 16.1.

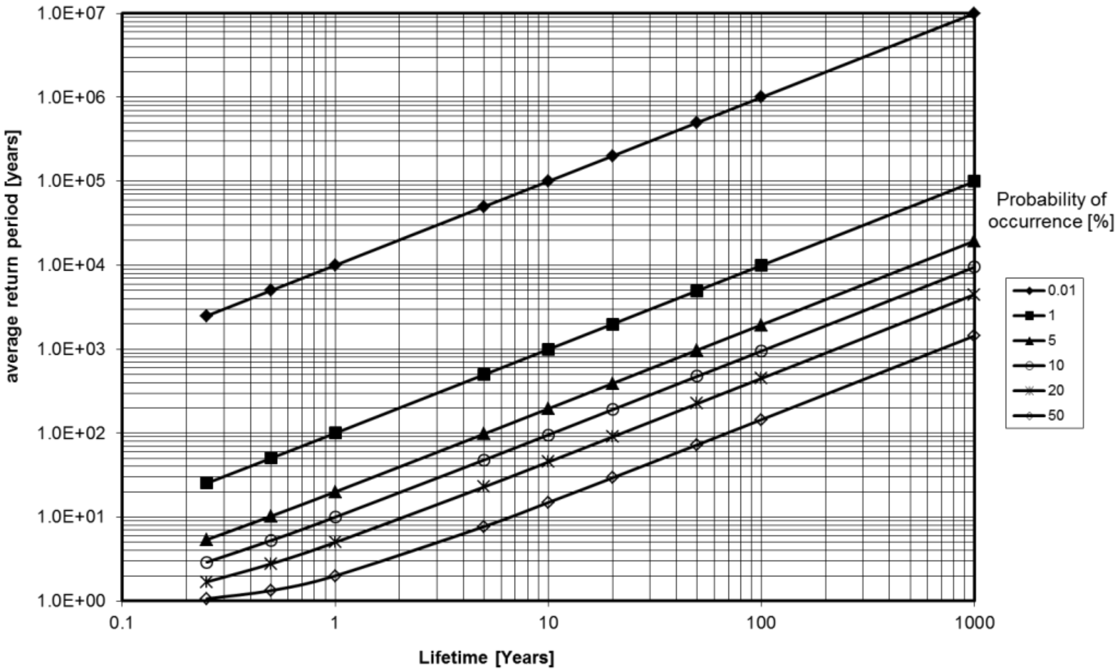


Figure 16.1 Probability of occurrence for given mean return periods and given lifetime (Fröhle 2000).

Tropical cyclones (typhoons, hurricanes) and tsunamis are episodic events, which require special design considerations. These phenomena are described in the chapters on wind, waves, and water levels in the Chapter 5.

16.2 Climate change considerations

The most severe type of climate changes in the coastal area is Sea Level Rise, see description in Chapter 6. SLR will cause increased risk of flooding, coastal erosion and salt intrusion etc. The great concern related to these impacts is the fact that the coastal zone is heavily occupied by human activities, such as coastal towns, ports, infrastructure, industry, public utilities, tourist developments and fishing communities etc. The most severe impact is probably the increased risk of flooding, especially in the world's densely populated major deltas and low lying island communities, such as atoll islands although increased erosion may be significant as well.

Many mega cities are located in low lying delta areas where storm water and coastal flooding already a recurrent problem will be further aggravated with rising sea level. Present day planning is already including sea level rise for development of new areas, but how are we protecting already developed low lying areas against flooding due to rising sea level? Inspiration for handling this problem can be borrowed from Holland, Venice, Hamburg, London and St. Petersburg etc. where major sea defence works have been constructed to protect large low lying areas.

Many coastal communities in developing countries have built a lifestyle in symbiosis with the coastline. Many people have their dwellings immediately behind the coastline and they use the beach for boat landing, for beach seine fishing and as a general area for stay, work and recreation. Their lives are directly related to beach and sea activities and they rely on the sea and the beach for income and to provide food for their families. Coastal protection at such locations needs to respect their use of the beach. Another important beach activity is international beach tourism. Global foreign tourism's direct spend was estimated at about US$ 1.03 trillion in 2011 with a significant portion of this on beach tourism. Rising sea levels will lead to reduced beach widths, damage tourism infrastructure, and may be the single biggest factor in the shrinkage and/or collapse of the beach tourism industry in especially fragile areas. Again, possible coastal protection in areas used for recreation and beach tourism needs to be designed in such a way that the attractiveness of the beach is not lost but rather enhanced.

Ports and harbours have long been part of the preferred logistical transport network for nations to trade. The majority of international imports and exports are moved by sea transport because this method of transport is, compared to road, rail and air transport, by far the cheapest. This makes the long-term viability of ports and harbours a key element in a country's economic survival into the next century. Port and harbour development is hugely expensive and the developers of this infrastructure expect to use it for extended periods, i.e. for centuries. Rising sea levels are therefore a potential threat to the viability of world ports and therefore we need to plan them carefully, fully informed about potential impacts from sea level changes.

The problems associated with global warming and the associated sea level rise can principally be addressed in two ways, by mitigation of the climate changes and by adaptation to the changes.

- *Mitigation* of the climate changes - Actions that eliminate or reduce the climate changes, e.g. through greenhouse gas (GHG) emission initiatives. However, climate change mitigation measures, while of critical importance for stemming future climate change, are not an applicable tool for particular countries or local authorities for reducing the risks associated with the unavoidable climate changes, such as sea level rise.
- *Adaptation* - Action which reduces the impact of the forecasted greenhouse effects, such as sea level rise, coastal flooding and coastal erosion etc. Adaptation is a method which can be applied for a specific country, for a region or locally to compensate for the impacts of the local effects of climate changes. Adaptation thus accepts that certain changes in sea level and coastal forcing may occur and takes that into account in the planning of future coastal initiatives and in the risk assessment for a possible protection of present and future coastal activities and facilities. The additional risk for coastal flooding and coastal erosion etc. imposed by the climate changes are taken into account via risk assessment for a specific site, in parallel to other types of risks, such as by adjusting design water levels for coastal flooding risk assessment and by adding potential shoreline retreat.

16.3 Design philosophy and risk assessment for adaptation to sea level rise

Many low-lying areas, which by nature are flooded regularly, have been protected by sea defence structures and are developed for agriculture, infrastructure and habitation. With the expected sea level rise caused by the climate changes there will be a need for strengthening of these defence structures.

The following chapters discuss the design parameters further and provide examples of possible values for both acceptable risk and lifetime. Specific projects should determine these parameters, based upon national or regional directives, direction from appropriate funding entities, community standards and professional judgment. Since the assumptions for risk and project life are integral to the project design, they need to be adopted and explained by the design engineers and they need to be understood and accepted by the project owner.

16.3.1.1 Acceptable risk R

The acceptable risk for an area being flooded, or in general terms for a design event being exceeded, is dependent of the size of the protected area and the type/value of the protected facilities. Acceptable risk can vary due to differences in demographic conditions, availability of replacement facilities, economic condition, community values and coastal culture; therefore what may be an acceptable risk for one community may be unacceptable for another community. Consequently, the acceptable risk needs to be carefully considered as one of the initial project steps.

16.3.1.2 Lifetime L of sea defence/coastal project

The lifetime of a sea defence structure or a coastal project is a concept used in the design of projects exposed to natural forces, which can be described by statistical models. Defining the lifetime has taken on a new dimension with the increase in design parameters with time due to climate change. This makes it even more important during a design process to decide on the lifetime of a project. It is necessary to define the lifetime as part of the statistical design process and to define the acceptable risk during the lifetime. The design lifetime of a project is dependent of the type of the project, the size of the protected area and the type of the protected facility.

16.3.1.3 Design recurrence period T_d

The recurrence period T_d to be used for the design of sea defence structures and other coastal structures e.g. for determination of the relevant design storm surge level, is a function of the lifetime L of the project and the acceptable risk R during the lifetime according to the equation for a parameter following a binomial distribution:

$$R = 1 - (1 - 1/T_d)^L$$

The correlation between R and T_d as function of L was already presented in Table 16.1.

The procedure on how to utilise the correlation between lifetime, recurrence period and acceptable risk for the combined effects of storm surges and sea level rise is discussed in the following step by step methodology, with sample values provided to aid the understanding.

16.3.1.4 Step 1: Exceedance statistics for storm surges based on historical recordings

Many coastal authorities have typically recorded water levels for selected stations over decades. This data can be analysed for exceedance of certain water levels which results in an exceedance curve for water levels presenting the water levels exceeded as a function of the recurrence period. Such curves reflect an extrapolation of historical data and do thus not include the trend in the water levels due to climate change effects, at least only to a very limited extent. An example of such a curve from Copenhagen in Denmark is presented in Figure 16.2. Such exceedance curves will typically be available at selected locations in most countries around the world. Exceedance curves for storm surges can also be established based in hydrodynamic simulations (hindcasting) following statistical analysis.

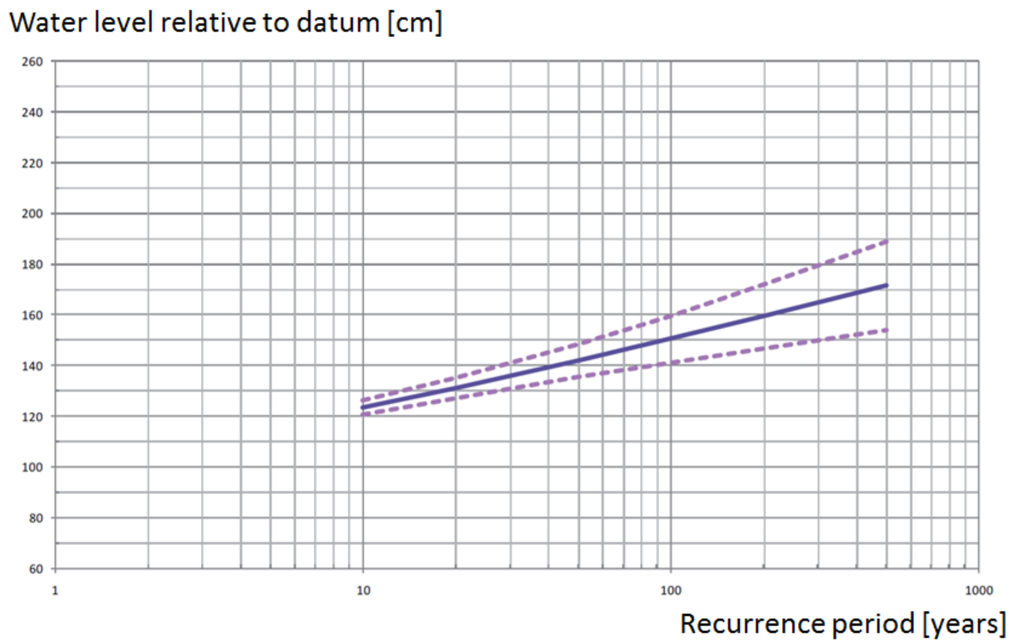


Figure 16.2 Storm surge water level in Copenhagen relative to yearly MSL (trend-free) as function of recurrence period, based on data from 124 years.
From: http://borgere.kyst.dk/hoejvandsstatistikker.html

16.3.1.5 Step 2: Determination of project lifetime L

The lifetime of a project needs to be determined, using the recommendations in Table 16.2 as a guide; however, specific countries, regions, communities and funding entities may have their own preferred methodologies for deciding the lifetime. The lifetime is used as basis for determination of recurrence period, when the acceptable risk has been defined. Proposed lifetimes L in years as function of type of project, size of protected area and type of the protected facility are presented in Table 16.2.

Table 16.2 Possible lifetimes L in years as function of type of project, size of protected area and type of the protected facility.

Type of project	Size of protected area	Type of facility protected	Lifetime L in years
Flexible: Soft sea defense (dike or dune) or beach fill	Small	Farm land and recreational facilities	~20
		Habitation and infrastructure	~30
	Large	Farm land and recreational facilities	~50
		Habitation and infrastructure	~100
Unflexible: Hard sea defense (seawall or dike protected by revetment) or reclamation	Small	Farm land and recreational facilities	~50
		Habitation and infrastructure	~100
	Large	Farm land and recreational facilities	50 - 100
		Habitation, infrastructure and public utilities	>100

16.3.1.6 Step 3: Selection of scenario for sea level rise

The future rise in the sea level shall be taken into account when designing a project for a storm surge level. There are two principle contributions:

- The design water levels predicted on the basis of extrapolation of historical records of water levels
- The additional increase in the storm surge due to the sea level rise caused by the climate changes

There are many approaches for determining an appropriate sea level rise scenario. The problem is that nobody can predict exactly how the future sea levels will develop. Consequently various authorities have developed different approaches. A common approach is that the relevant authorities describe different scenarios and that the recommended sea level rise is selected as a function of the following criteria:

- The lifetime L of the project
- The severity of impact of failure due to exceedance of the design water level

The lifetime of the project - If the lifetime is 50 years, the project shall be designed for the sea level rise, which is predicted 50 years from the time the project can be completed. The design water level should be determined from exceedance curves. The rise in sea level, plus a contribution due to increased storminess as relevant, should be added to the design water level to develop the design conditions for the project.

The severity of impact of failure - The scenario for sea level rise shall be selected according to the severity of the impact of failure, see Table 16.3. For a specific project, the national, regional or funding entity recommendations should be consulted.

Table 16.3 Example of scenario for sea level rise as function of type of infrastructure impacted by the design event.

Type of infrastructure	**Severity and Failure**	**Typical sea level rise [m] in year**			
		2030	**2050**	**2100**	**Later than 2100**
Farmland and recreational facilities	Low	0.1 – 0.2	0.2 -0.4	0.5 -1.0	Up to 1.2
Habitation and infrastructure	Medium	0.15 – 0.3	0.3 – 0.6	1.0 – 1.2	Up to 1.5
Major habitation, infrastructure and public utilities	High	0.2 – 0.4	0.4 – 0.8	1.1 – 1.5	Up to 2.0 or higher

16.3.1.7 Step 4: Determination of acceptable risk R

The acceptable risk for the size and type of project is determined on basis of the national, regional, local or agency guidance, cf. guidelines in Table 16.4.

Table 16.4 An example of acceptable risk of failure R [%], i.e. risk of flooding, during life time of project as function of size of the protected area and type of protected facility.

Size of protected area	Type of facility protected	Acceptable risk of failure R [%] during life time of project
Small	Farmland and recreational facilities	50 – 80
	Habitation and infrastructure	10 – 20
Large	Farmland and recreational facilities	25 – 40
	Habitation, infrastructure and public utilities	0.1 – 5

16.3.1.8 Step 5: Determine the recurrence period T_d

The recurrence period T_d is determined on the basis of the lifetime L and the risk R, based on national, regional, local or agency guidance for appropriate risk and lifetime. See the values in Table 16.1.

16.3.1.9 Step 6: Determine the design water level

The design water level without the impact of climate changes is determined on the basis of a storm surge exceedance curve similar to the one presented in Figure 16.2.

16.3.1.10 Step 7: Determine the future design water level including the impact of sea level rise

A first approximation for the future design water level including the impact of sea level rise is determined as the sum of the design water level obtained in step 6 with the sea level rise decided in step 3. It is noted that this is an approximation as the surge depends on the water depth and the water depth will change with sea level rise, consequently storm surge and sea level rise are only additive as a first approximation. Two examples of how to decide the future design water level including the impact of sea level rise are presented in Table 16.5.

Table 16.5 Examples of design procedure for approximation of design water level under the impact of Climate Changes, storm surge exceedance curve for Copenhagen has been used, see Figure 16.2.

Steps	Type of Project	
	Farm land protected by dike	Small infrastructure build on reclaimed land
1. Exceedance Curve	Exceedance Curve	
2. Life time L	20 years	100 years
3. SLR scenario and SLR value	Low, 0.15 m	Medium, 1.1 m
4. Acceptable risk R in %	65%	15%
5. Recurrence period T_d	20 years	500 years
6. Design water level excl. SLR	1.3 m	1.7 m
7. Design water level incl. SLR	1.45 m	2.8 m

It is seen that there is a considerable difference in the design water levels for the two different types of projects.

It is recommended to perform sensitivity analysis when designing actual projects where the influence of the following parameters is tested:

- Choice of lifetime *L*
- Definition of type of project
- Choice of *SLR* scenario and selected *SLR* value
- Choice of acceptable risk *R*
- Impact of increased storminess on storm surge

The following contributions have to be added to the future design water level in order to arrive at the habitable level, e.g. for a reclamation:

- The wave run-up can either be accommodated by introduction of a seawall or the run-up contribution can be added to the level of the reclamation.
- A safety margin to take into account the uncertainty especially in the prediction of sea level rise.

16.4 Considerations about adaptation measures for climate changes

The above mentioned impacts of climate changes indicate that it is necessary to consider more sustainable and flexible solutions in relation to coastal protection and sea/river defence techniques as traditional solutions (revetments, seawalls and dikes) are very inflexible and often counteract natural mechanisms, such as gradual retreat of the coastline and associated shoreward movement of the dune system in the case of coastal erosion, and flooding of the river plains in the case of river dikes. Furthermore, traditional protection solutions have often been introduced as remedial measures to compensate for negative impacts of other interventions, which is a reactive approach.

But now, with the increasing impact of climate changes in the coastal zone, there is a good reason for shifting to a more proactive approach by implementing a sustainable development by taking into account all the needs and requirements in the coastal zone by implementing integrated shoreline management projects. An example of an integrated shoreline management project could be a scheme which rehabilitates a coastal section by removing hard protection measures, providing new beaches for recreation and fishing activities, providing protection against erosion and flooding and providing new space for development. Such a scheme will typically be soft and flexible and will require comprehensive dredging, filling and reclamation activities. An old example of such a type of project, which has proved to work very well, is the Køge Bay Beach Park located south of Copenhagen. Before the implementation of the project this site was characterised by a shallow shoreface with some barrier islands and a low lying hinterland, which suffered from frequent flooding. The shallow coast was not suitable for recreation for which there was a huge demand as the backland is heavily populated. An integrated scheme was developed, combining construction of artificial beaches on top of the barrier islands for recreation, construction of four new marinas, and excavation of new lagoons between the beach islands and the coast and introduction of a dike throughout the entire stretch, which secured the low lying backland against flooding. The project is shown in Figure 16.3.

Figure 16.3 Køge Bay Beach Park south of Copenhagen, inaugurated in 1980.
Left: Natural conditions. Right Upper: Aerial photo. Right Lower: Satellite image with the alignment of the dike shown as a red line.

17 Shore Protection, Coast Protection and Sea Defence Methods with Special Emphasis on Coastal Adaptation to Climate Changes

17.1 General considerations

A precondition for a successful shoreline restoration project is that all the parties involved have some understanding of the coastal morphological processes. They are then in a position to understand why the present situation has developed and why certain solutions will work and others will not.

The following should be considered in connection with shoreline management projects:

- Consider the coastal area as a dynamic natural landscape. Make only interventions in the coastal processes and in the coastal landscape if the interests of the society are more important than preserving the natural coastal resource.
- Appoint special sections of the coast for natural development.
- Demolish inexpedient old protection schemes and re-establish the natural coastal landscape where possible.
- Minimise the use of coastal protection schemes, give high priority to the quality of the coast resource, and concentrate on shore protection. Preserve the natural variation in the coastal landscapes.
- Restrict new development/housing close to the coastline in the open uninhabited coastal landscape. Allow only such facilities, which require access to the sea.
- Maintain and improve the public access to and along the beach, legally as well as in practice.
- Reduce pollution and enhance sustainable utilisation of coastal waters.

This leads to the following practical guidelines in connection with coast protection, shore protection and shore restoration projects:

- Work with nature, for instance by re-establishing a starved coastal profile by nourishment and by utilising site-specific features, such as strengthening semi-hard promontories.
- Select a solution which fits the type of coastline and which fulfils as many of the goals set by the stakeholders and the authorities as possible. It is quite often impossible to fulfil all goals, as they are often conflicting and because of budget limitations. It should be made clear to all parties, which goals are fulfilled and which are not. The consultant must make it completely clear what the client can expect from the selected solution; this is especially important if the project has been adjusted to fit the available funds.
- Propose a funding distribution, which reflects the fulfilment of the various goals, set by the parties involved.
- Manipulate the littoral drift rate and - gradient by use of a minimum number of structures. Preserve sections of untouched dynamic landscape where possible. Allow protection measures only if valuable buildings/infrastructure are threatened. This policy will preserve the natural coastal resources and the neighbouring sections will receive material as a result of erosion in the unprotected area.

- Secure passage to and along the beach.
- Enhance the aesthetic appearance, e.g. by minimising the number of structures. Few and larger structures is normally better than a lot of small structures. Preferably allow only projects which deal with an entire management unit/sediment cell and which have maximum shore protection. Individual projects tend to concentrate on coast protection.
- Minimise maintenance requirements to a level, which the owner(s) of the scheme is able to manage. A stand-alone nourishment solution may at first glance appear ideal, but it will normally not be ideal for the landowners, as recharge will be required at short intervals.
- Secure good local water quality and minimise the risk of trapping debris and seaweed.
- Secure safety for swimmers by avoiding structures that generate dangerous rip currents. Avoid making semi protected coastal areas at exposed locations by constructing detached breakwaters and the like as such areas will most often be exposed to rip currents, which may dangerous for poor swimmers. The partial protection against wave action thus gives a false impression of safety due the rip currents. Protected areas in direct connection to adjacent beaches at exposed sites also tend to suffer from sand accumulation. If the water is too rough for swimming, a swimming pool, possibly in the form of a tidal pool, is a good solution.
- Provide good beach quality by securing that the beaches are exposed to waves, as the waves maintain the attractive sandy beaches. This will of course limit the time when swimming is possible, but protected beaches often lead to safety hazards, poor beach quality and poor water quality.
- Be realistic and pragmatic, keeping in mind that the natural untouched coastline is utopia in highly developed areas. Create small attractive locations at otherwise strongly protected stretches if this is the only realistic possibility.

17.2 Requirements for sustainable solutions

Coastal authorities typically develop strategies for coastal protection with increasing emphasis on sustainability. Sustainable development in general is defined as follows by the Bruntland Commission:

> *"**Sustainable development** is a pattern of resource use that aims to meet human needs while preserving the environment so that these needs can be met not only in the present, but also for future generations"*

Sustainable and holistic development serves the requirements of our society in terms of development needs and economic growth so that we get most possible out of the resources at the same time as we respect the environment.

In terms of coastal protection the Danish Coastal Authority has developed a strategy with the vision:

> *"Develop more beautiful coasts for the benefit of all"*

The objectives for obtaining a sustainable protection are the following

- Coastal protection operates in the cross field between the need for protection of infrastructure assets and the need for protection of nature- and landscape values. Consequently, coastal protection shall be optimised, shall serve long term needs and shall be executed as overall solutions covering longer sections of coast and no more protection than necessary shall be performed

- Clean up of inappropriate, ineffective and worn-out protection shall be part of any new coastal protection
- Soft solutions are to be preferred to hard solutions. Compensation for loss of release of sand by natural erosion caused by hard protection shall be part of the project when hard solutions are applied
- Protection shall be performed at the right time, i.e. not until required to avoid damager to valuable infrastructure within a time horizon of about 20 years and not so late that damages to infrastructure in taking place
- The lifetime for coastal protection shall fit to the lifetime of what is going to be protected, flexible solutions are recommended for longer lifetimes in order to be able to adjust the protection to climate changes
- Coastal protection must as a whole not have negative consequences

17.3 Overview of types of coast protection, shore protection and sea defence

Protection of the coast and the shore against the erosive forces of waves, currents and storm surges can be performed in many ways, and protection of the coast and the hinterland against flooding adds even more types to the protection defence measures.

The choice of the measure in a given situation depends on the three primary conditions:

1. The problem (coast erosion, beach degradation or flooding)
2. The morphological conditions (the type of coastal profile and the type of coastline)
3. The land use (infrastructure/habitation, recreation, agriculture etc.)

A summary of the various types of protection and management measures is given in the following. The measures are divided into the following main categories:

- Coast protection
- Shore protection
- Beach construction
- Management solution
- Sea defence

An overview of the content of this chapter is presented in the following in order to facilitate its use.

Content of the remaining part of Chapter 17:

- Coast protection:
  - Seawall
  - Revetment
  - Emergency protection
  - Bulkhead

- Mixed coast/shore protection by structures and beach fill:
  - Groynes
  - Detached breakwaters
  - Headlands or modified breakwater
  - Perched beach
  - Cove and artificial pocket beach

- Shore protection:

  - Regulation of the coastal landscape
  - Nourishment
  - Beach de-watering or beach drain

- Artificial beaches and beach parks:
  - Artificial beach
  - Beach parks and beach reclamation

- Land use restrictions

- Sea defence:
  - Dike
  - Artificial dune
  - Marsh/Mangrove platform restoration

- A Summary of the applicability and the function of coastal protection and shore protection, and sea defence measures

Some of the measures have both a wanted function but also an unwanted negative impact, which e.g. is the case for a revetment. It protects the coast against erosion, but aggravates shore erosion. Beach nourishment, on the other hand, protects against coast erosion as well as against shore erosion.

17.4 Coast protection

Coast protection may be defined as follows:

COAST PROTECTION: Measures aimed at protecting the coast against coastline retreat, thus protecting housing, infrastructure, the coast and the hinterland from erosion often at the expense of losing the beach and the dynamic coastal landscape. Coast protection often consists of hard structures such as revetments or groynes.

17.4.1 Seawall

Definition:

A seawall is defined as a structure separating land and water areas. It is designed to prevent coastal erosion and other damage due to wave action and storm surge, such as flooding. Seawalls are normally very massive structures because they are designed to resist the full force of waves and storm surge. In practice, seawalls and revetments are synonyms.

Method:

A seawall is constructed at the coastline, at the foot of possible cliffs or dunes. A seawall is typically a sloping concrete structure; it can be smooth, stepped-faced or curved-faced. A seawall can also be built as a rubble-mound structure, as a block seawall, or as a steel or wooden structure. The common characteristic is that the structure is designed to withstand severe wave action and storm surge. A rubble-mound revetment often protects the foot of such non-flexible seawalls. A rubble-mound seawall bears a great similarity to a rubble-mound revetment; however a revetment is often used as a supplement to a seawall or as a stand-alone structure at less exposed locations. An exposed dike, which has been strengthened to resist wave action, is sometimes referred to as a seawall.

A seawall is usually a fixed unflexible structure and therefore future sea level rise must be fully accounted for during the design phase as described in Chapter 16.

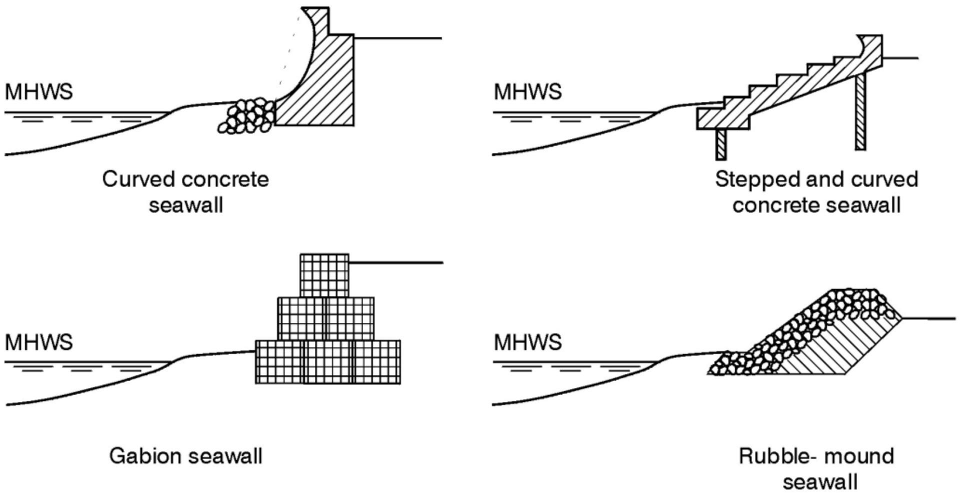


Figure 17.1 Examples of seawall structures.

Functional characteristic:

The nearly vertical seawall, which was mainly used in the past, had the unfortunate function of reflecting some of the wave energy, whereby the erosion was aggravated, resulting in accelerated disappearance of the beach. However, all kinds of seawalls involve beach degradation as they are used at locations where the coast is exposed to erosion. The seawall will fix the location of the coastline, but it will not arrest the ongoing erosion in the coastal profile. On the contrary, it will to a varying degree, accelerate the erosion. It is quite normal that the beach disappears in front of a seawall, and it will most often be necessary, after some years, to strengthen the foot of the seawall with a rubble revetment.

A seawall will decrease the release of sediments from the section it protects and will have a negative impact on the sediment budget along adjacent shorelines.

Seawalls can be used to protect locations against sea-level rise but the negative impacts from seawalls will be aggravated. Those sea-walls which have managed to retain some beach in front of the seawall will most likely lose this beach in the future due to the rising sea level. Furthermore, the lack of flexibility of the seawall makes it unattractive taking into consideration the uncertainty regarding future sea level rise. If a seawall must be used, it is advised to think some future flexibility into the design such that changes in sea-level rise may be accommodated.

Applicability:

A seawall is a passive structure, which protects the coast against erosion and flooding. Seawalls were (are) often used at locations off exposed city fronts, where good protection was needed and where space was scarce, see example in Figure 17.2.

Figure 17.2 Seawall/revetment in front of Corniche in Alexandria.

Promenades have often been constructed on top of such seawalls.

Seawalls are also used along other, less inhabited coasts, where combined coast protection and sea defence is urgently needed, e.g. to protect a coastal road against the action of tidal wave conditions, see example in Figure 17.3.

Figure 17.3 Rubble mound seawall protecting the coastal road at Madampagama, SW coast of Sri Lanka.

Seawalls are applicable against chronic as well as acute erosion, and against SLR.

17.4.2 Revetment

Definition:

A revetment is a facing of stone, concrete units or slabs, etc., built to protect a scarp, the foot of a cliff or a dune, a dike, or a seawall against erosion by wave action, storm surge and currents. This definition is very similar to the definition of a seawall, however a revetment does not protect against flooding. Furthermore, a revetment is often a supplement to other types of protection such as seawalls and dikes.

Method:

Revetments can be an exposed structure as well as a buried structure.

Exposed revetments:

Traditional sloping revetments
Revetments are always made as sloping structures and are very often constructed as permeable structures using natural stones or concrete blocks, thereby enhancing wave energy absorption and minimising reflection and wave run-up.

However, revetments can also consist of different kinds of concrete slabs, some of them permeable and interlocking. In this way their functionality is increased in terms of absorption and strength. An example of a permeable and interlocking concrete slab is the so-called Flex Slab.

Net mesh stone-filled mattresses, such as Gabions, are also used; however, they are only recommended for use at fairly protected locations.

Revetments can also consist of sand-filled geotextile fabric bags, mattresses and tubes. Such structures must be protected against UV-light to avoid weathering of the fabric. Sand-bagging is often used as emergency protection. Geotextile fabric revetments are fragile and sensitive to mechanical impact and vandalism, and their appearance is not natural.

A revetment is a more flexible structure than a sea-wall as is as such easier to modify in the face of changes to future sea-level rise.

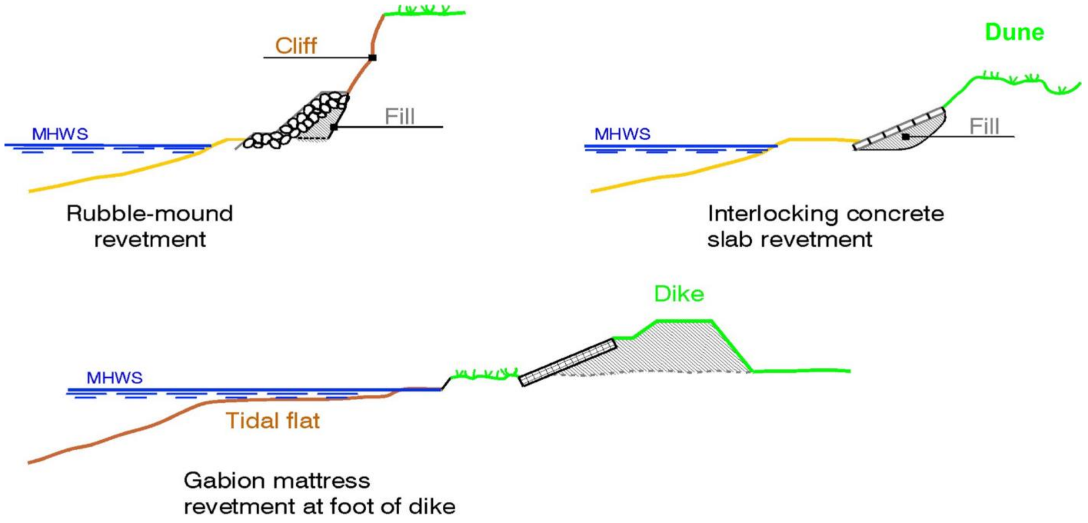


Figure 17.4 Examples of revetments.

Special types of revetments
Interlocking concrete units are potentially cost-saving by providing a high degree of structural stability for a low volume of concrete through the interlocking capabilities. The trade-off is a risk of rapid deterioration of the entire structure under severe climatic conditions if a few units are damaged and thereby compromise other units. Experience from Malaysia shows that there have been many failures of revetments constructed by interlocking concrete slabs at coastal locations exposed to waves, see example in Figure 17.5.

Figure 17.5 Damaged Flex Slab revetment south of Merang in Terengganu, Malaysia.

However, Flex Slabs are reasonable stable as slope protection along river banks, where there is no wave exposure, see Figure 17.6.

Figure 17.6 Flex Slab revetment along river bank, Labuan, Malaysia.

Another type of revetment consists of specially designed concrete blocks, which is widely used in Malaysia, see example in Figure 17.7.

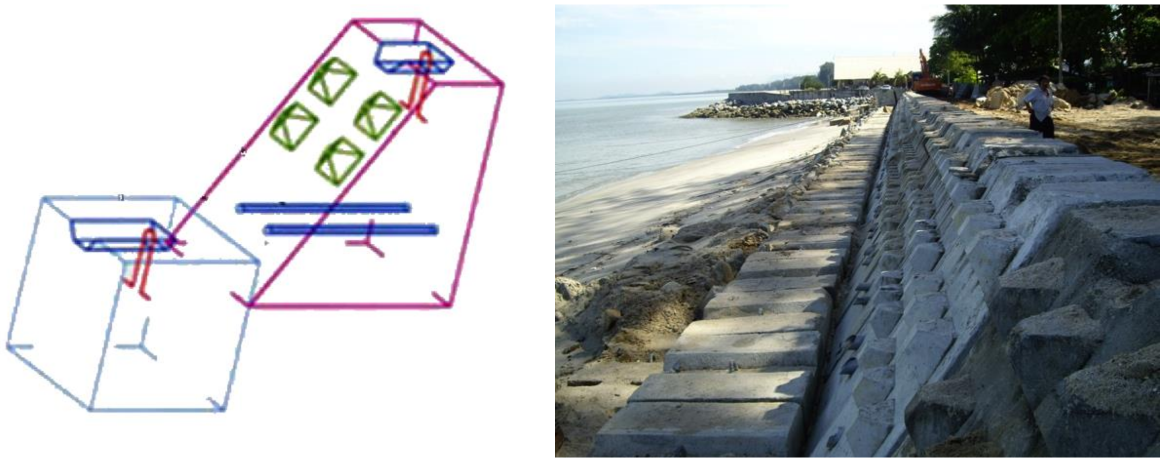


Figure 17.7 Sketch of concrete block revetment (Labuan blocks) (left) and photo of installed units (right).

This type of revetment consists of gravity type units where the stability of the units relies on gravity. The toe units are often initially secured by being buried in the beach, but may be fully exposed through scouring as erosion proceeds. The individual blocks are not interlocking. The total height of the structure is generally limited by the height of the main units, since the units are not stacked to form higher structures.

Experience has shown that this type of concrete block revetment is highly susceptible to failures due to scouring at the toe and or foundation, leading the blocks being shifted and the overall protection scheme losing its integrity, or they are damaged by overtopping, see examples in Figure 17.8.

Figure 17.8 Examples on failures of concrete block revetments in Malaysia. Left: By scouring of the toe (Penang), Right: By overtopping (Labuan).

Net mesh stone-filled mattresses, such as Gabions, are commonly used for minor revetments because they can be established by the use of relatively small stones and without the use of heavy equipment. It is important that the used stone material consists of durable and resistant rock material. However, experience shows that Gabion revetments exposed to heavy wave action are often damaged, see example in Figure 17.9.

Figure 17.9 Damaged Gabion revetment at Lumsås, Denmark. Damages occurred during the extreme storm ”Bodil” on 6th December 2013.

Consequently, Gabion revetments are only recommended for use at fairly protected locations.

Revetments can also consist of sand-filled geotextile fabric bags, mattresses and tubes. Such structures must be protected against UV-light to avoid weathering of the fabric. Major advantages of this type of structure are that it does not require the use of rock and it can be constructed by labour intensive methods and the use of simple equipment. However, generally geotextile fabric revetments are fragile against hydraulic and mechanical impact as well as against vandalism, which often results in limited life; furthermore their appearance is not natural. An example of a revetment constructed by sand tubes is presented in Figure 17.10.

Figure 17.10 Revetment constructed by geotextile sand tubes, note partly collapsed tubes and unnatural appearance. Marine Drive, Cox's Basar, Bangladesh.

Sand-bagging using easily available sand bags, such as grain bags, is often used as emergency protection. However, such bags are not durable which results in quick failure as seen in Figure 17.11.

Figure 17.11 Emergency protection using grain bags and piles, Odissa, India.

Revetments can also consist of a combination of a sheet pile wall (wood or concrete) possibly protected by a rubble mound revetment to minimise reflection, see example in Figure 5.8, or of a low sheet pile wall supporting the foot of a rubble mound revetment.

Figure 17.12 Small wooden wall supported by stone revetment in front, and piled groynes protecting artificial beach at Bellevue, Denmark. (Constructed in the 1930ties but now replaced by a natural beach).

Buried revetments:
A buried revetment can be constructed as part of a soft protection, e.g. as a hard emergency protection built into a strengthened dune which acts as shore protection and/or sea defence. However this makes the dune system static; as the dune system will no longer be able to retreat under the impact of sea level rise, a loss of the dune can be expected under this scenario.

Figure 17.13 An example of a buried revetment constructed in concrete blocks, the revetment will later be buried into an artificial dune. (Danish Coastal Authority).

Functional characteristics:

All types of revetments have the inherent function of beach degradation as they are used at locations where the coast is exposed to erosion. A revetment will fix the location of the coastline, but it will not arrest the ongoing erosion in the coastal profile, and the beach in front of the revetment will gradually disappear. However, as a revetment is often made as a permeable, sloping structure, it will normally not accelerate the erosion, as did seawalls; on the contrary, rubble revetments are often used as reinforcement for seawalls which have been exposed due to the disappearance of the beach. Such reinforcement protects the foot of the seawall and minimises the reflection.

A revetment, like a seawall, will decrease the release of sediments from the section it protects, for which reason it will have a negative impact on the sediment budget along adjacent shorelines. There may also be flanking effects at the terminal points of a revetment, which may undermine the structure unless properly addressed.

Applicability:

A revetment is a passive structure, which protects against erosion caused by wave action, storm surge and currents. The main difference in the function of a seawall and a revetment is that a seawall protects against erosion and flooding, whereas a revetment only protects against erosion. A revetment is thus a passive coastal protection measure and is used at locations exposed to erosion or as a supplement to seawalls or dikes at locations exposed to both erosion and flooding. Revetments are used on all types of coasts.

Revetments are applicable against chronic erosion as well as acute erosion, and against SLR.

Rubble revetments and similar structures have a permeable and fairly steep slope; normally a 1:2 slope is used. Such a rubble revetment is neither suitable at beaches used for recreation nor for beaches used for landing or hauling of small fishing boats. For such locations, other types of protection measures must be considered, but if a revetment is required, a more gently sloping structure with a smooth surface is recommended.

17.4.3 Emergency protection

Definition:

Emergency protection is a quick installation of a temporary revetment-type structure made by available material as response to "unexpected" coastal erosion. It is normally applied for securing buildings or infrastructure against unexpected erosion.

Method:

Emergency protection measures are by nature quickly built and not well designed measures. Typical building methods and materials are the following:

- Rock dumping. Without filter layers, often too steep and low, without proper toe protection, which means that they are unstable
- Sand bagging, sometimes supported by wooden piles. Often too low and without toe protection etc. The fabric is not durable, which means that such protection will collapse after a very short period
- Dumping of other kinds of material easily at hand, such as different kinds of concrete pieces, building materials, old tires, etc., see Figure 17.14

Figure 17.14 Emergency revetment constructed by concrete rubble, Dubai.

Functional characteristics:

Emergency protection measures are typically having the following characteristics:

- They are unstable and thus not providing proper protection
- They need constant maintenance and supply of new materials
- They are always passive, and promote further loss of beach
- They are spoiling the natural beauty of the beach
- They prevent passage along the beach
- They pollute the beach with unnatural elements, such concrete debris, bricks, rubber and plastic

Applicability:

Private and public land owners are sometimes forced to "construct" emergency protection at locations where "unexpected" erosion occurs. The emergency protection is installed in order to prevent further damage to coastal installations. "Unexpected" can have different causes as discussed in the following:

- Unexpected can be in the form of a rare of extreme event, such as a tidal wave situation or the passage of cyclone, which causes acute erosion
- Unexpected can be the development of ongoing chronic erosion at locations where it has not been possible to provide funds for a proper and timely protection

- Unexpected can be due to lack of knowledge to coastal processes and/or data, whereby chronic or acute erosion seems to be unexpected despite the fact that it could have been foreseen if proper monitoring and coastal investigations had been practised

Emergency protection can to a great extent be avoided by proper monitoring, planning and funding.

Emergency protection is not applicable against sea level rise.

Emergency protection is used to protect against chronic as well as acute erosion, however emergency erosion is not the recommendable solution to any erosion problem.

17.4.4 Bulkhead

Definition:

A bulkhead is a structure or partition used to retain or prevent sliding of the land. A secondary purpose is to protect the coast against damage from wave action. Bulkheads are normally smaller than seawalls, as their primary function is to retain fill at locations with only limited wave action, and not to resist coastal erosion. A bulkhead must, of course, be designed to resist erosion caused by the mild to moderate wave climate at a specific site.

A bulkhead cannot really be characterised as a coast protection structure; it is rather a structure that is used to retain fills along the water perimeter of reclaimed areas and in port basins.

Method:

Bulkheads are normally constructed in the form of a vertical wall built in concrete, stone, steel or timber. The concrete, steel or timber walls can be piled and anchored walls, whereas the concrete and stone walls can also be constructed as gravity walls. Special mesh boxes containing stones, e.g. the Gabion type, are also used.

Figure 17.15 Example of bulkhead structure constructed by Gabion mesh boxes.

Functional characteristic:

The function of a bulkhead is, in protected environments, to retain or prevent the sliding of land at the transition between the land, filled or natural, and the sea.

Future sea level rise will normally not impact the design of the bulk head directly, but should be taken into account when designing the vertical level of the land which the bulk head is protecting as described in Chapter 16.

Applicability:

Bulkheads function well as a separation between land and sea in marina basins, and along protected shorelines. They are used along natural shorelines and along filled areas, where a well-defined separation between land and sea is required.

Bulkheads are not used to protect against erosion.

Bulkheads can be used against sea level rise if adjusted in height and if the area is still protected against waves despite the sea level rise.

17.5 Mixed coast/shore protection by structures and beach fill

Mixed coastal protection and shore protection measures are schemes, which combine structures and initial nourishment, which is called beach fill. These schemes are an attempt to find a solution that combines the ability of the structures to directly protect a section of the coast with the ability of the structures to support and maintain beach filling/nourishment. The result is protection of the beach and protection of the coast behind the beach. The advantage of this combination is that it minimises the requirements for regular recharging of the fill/nourishment. The relevant structures in connection with this have characteristics that make use of the littoral processes, either the longshore littoral drift and/or the cross-shore transport. The relevant structures are:

- **Groynes**, which are normally straight structures perpendicular to the shoreline. They work by blocking (part of) the littoral drift, whereby they trap/maintain sand on their upstream side. Groynes can have special shapes; they can be emerged, sloping or submerged, and they can be single or arrenged in groups, the so-called groyne fields.

- **Detached breakwaters**, which are straight shore-parallel structures, which partly provide shelter in their lee thus protecting the coast and decreasing the littoral transport between the structure and the shoreline. This decrease of transport results in trapping of sand in the lee zone and some distance upstream. Breakwaters can also deviate from the straight and shore-parallel layout, they can be emerged and submerged, and they can be single or arranged in groups, the so-called segmented breakwaters.

- **Headlands**, which are smooth structures built from the coastline over the beach and some distance out on the shoreface. They work by blocking (part of) the littoral transport. A headland combines the effects of groynes and detached breakwaters and at the same time, minimises some of the disadvantages of groynes and breakwaters.

- **Ports or marinas**, which may act as headlands at the same time as they serve their primary purpose of servicing vessels.

- **Perched beaches**, which are natural or nourished beaches at locations with a steep shoreface. They are supported at their lower part by a submerged structure.

- **A cove**, which is a semi-protected sandy bay, formed by two curved shore-connected breakwaters at a coastline, which is otherwise protected by revetments.

17.5.1 Groynes

Definition:

Groynes are normally straight structures perpendicular to the shoreline. They work by blocking (part of) the littoral drift, whereby they trap/maintain sand on their upstream side. Groynes can have special shapes and they can be emerged, sloping or submerged, they can be constructed as single structures or as groyne fields. Groynes are normally built as rubble mound structures, but they can also be constructed in other materials, such as cast concrete or concrete units, timber, geo-tubes filled with sand or concrete. Examples on groyne fields are presented in Figure 17.16 and Figure 17.17.

Figure 17.16 Left: Groyne field at the south coast of Beira, Mozambique. Old concrete groynes to the left and one rebuilt rubble mound groyne to the right. (Picture from Google Earth).
Right: A rebuilt sloping rubble mound groyne.

Figure 17.17 An old groyne field protection at the Danish North Sea Coast, constructed in concrete blocks.

The following subchapter on groynes is fairly comprehensive. The reason for this is not a special preference for groyne solutions but rather because groynes are well suited to explain various basic morphological responses including lee side erosion effects.

Method:

Groynes are normally constructed from the coastline, over the beach and some distance into the shoreface. Their effectiveness in trapping sand from the littoral drift depends on their extension or, in other words, how big a part of the littoral drift they block. The sand accumulation and lee side erosion depend on the coastal type and are very similar to what was discussed in Subchapter 11.2.1.2, Figure 11.7 and Figure 11.8, in relation to a port. However, this comparison is only valid for very long groynes. Groynes are normally designed to cover only part of the surf-zone. As the littoral drift varies greatly over the coastal profile, see Figure 17.18, it is important to know the transport characteristics so as to be able to predict the shoreline response. A groyne functions by trapping sand on the upstream side, and in this way the coast behind the sand filet is protected. Precisely how protected depends on the stability of this sand filet under extreme conditions. The groyne must, therefore, cover the entire beach, so that it is not back-cut during situations with storm surges and high waves and under future impact of sea level rise. This means that the landward end of the groyne must be constructed covering the backshore right up to the coastline at the foot of the cliff/dunes and that its height at the landward end is not lower than the top of the backshore. The height of the groyne further seawards can be lower, depending on the requirements for bypass, etc.

Functional characteristics:

Coastal type 2: Slightly oblique wave attack and gradient in the transport, which means an eroding shoreline:

Simulating the shoreline impact of two types of groynes; a long and a short one demonstrate the function of single groynes and groyne fields on an eroding shoreline, respectively. The function of spacing between the groynes in the groyne fields, for the same two types of groynes, is also demonstrated.

This demonstration covers the influence of the following parameters:

- The length of the groyne relative to the width of the surf-zone
- The spacing of the groynes relative to the length of the groynes

The demonstrations are performed on an E-W oriented shoreline, which is exposed to prevailing waves from the NW and secondary waves from the NE, resulting in a net littoral drift towards the east. There is also increasing transport towards the east, which means that the shore is eroding. The direction of the normal to the shoreline with zero net littoral drift is calculated at 350°.

The demonstrations are performed using DHI's LITPACK software. The module for the calculation of the littoral drift, LITDRIFT, and the one-line shoreline evolution module, LITLINE, are applied.

The coastal profile and distribution of the littoral drift in the coastal profile are presented in Figure 17.18.

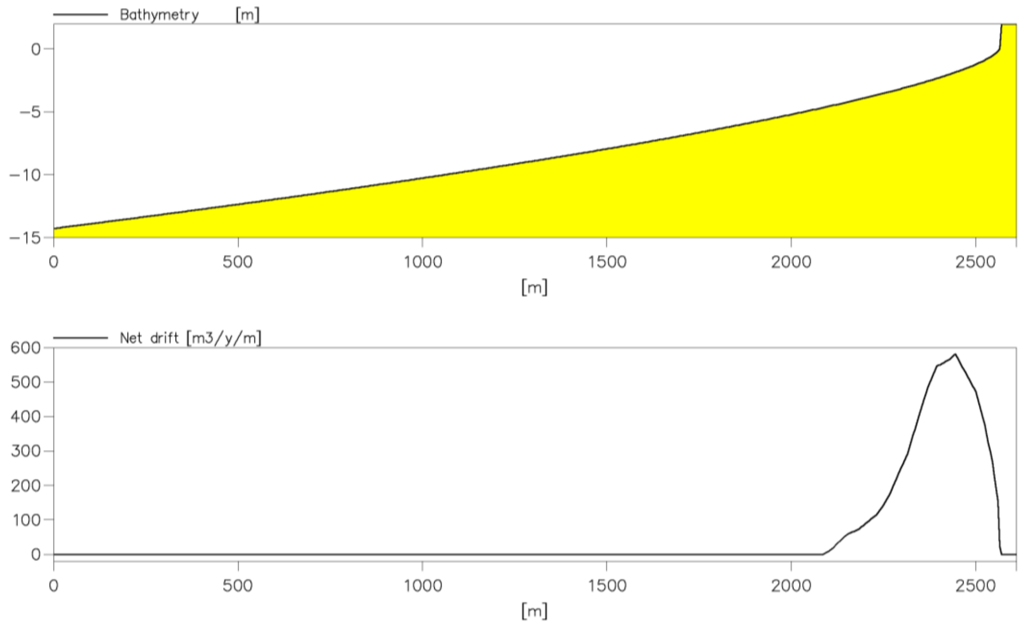


Figure 17.18 Coastal profile and distribution of the littoral drift in the coastal profile.

The width of the surf-zone is approximately 400m.

Case 1: Type 2 coast, protection by single groynes, long and short
The first shoreline simulation shows the development of the shoreline without any structures, see Figure 17.19 upper part. The shoreline is exposed to a uniform shore erosion over the entire stretch.

The second simulation shows the shoreline response for a single groyne with the same length as the width of the surf-zone. The shoreline responds in the same way as in the case of the port in Figure 11.7, i.e. a sand filet with constant orientation accumulates on the upstream side. There is also some initial small and local upstream erosion. As bypass has not started, severe lee side erosion has developed and is continuing to develop.

The third simulation shows the shoreline response for a single, but short groyne. The sand filet accumulation has stopped at the tip of the groyne but is developing slowly along the upstream shoreline tending towards being parallel to the original shoreline. At the present stage of the development, the short groyne actually protects a longer section than the long groyne. This is because the long groyne traps most of the sand close to the structure. The lee side erosion is also large, but the erosion rate is decreasing due to the increasing bypass.

In both cases, the erosion problem is solved only on the upstream side of the groyne for a length, which depends on the length of the groyne for the given wave climate, but lee side erosion is extensive, unavoidable and everlasting. Introduction of the groyne has resulted in a drastic response far from the gentle evenly distributed erosion, which persisted before the intervention.

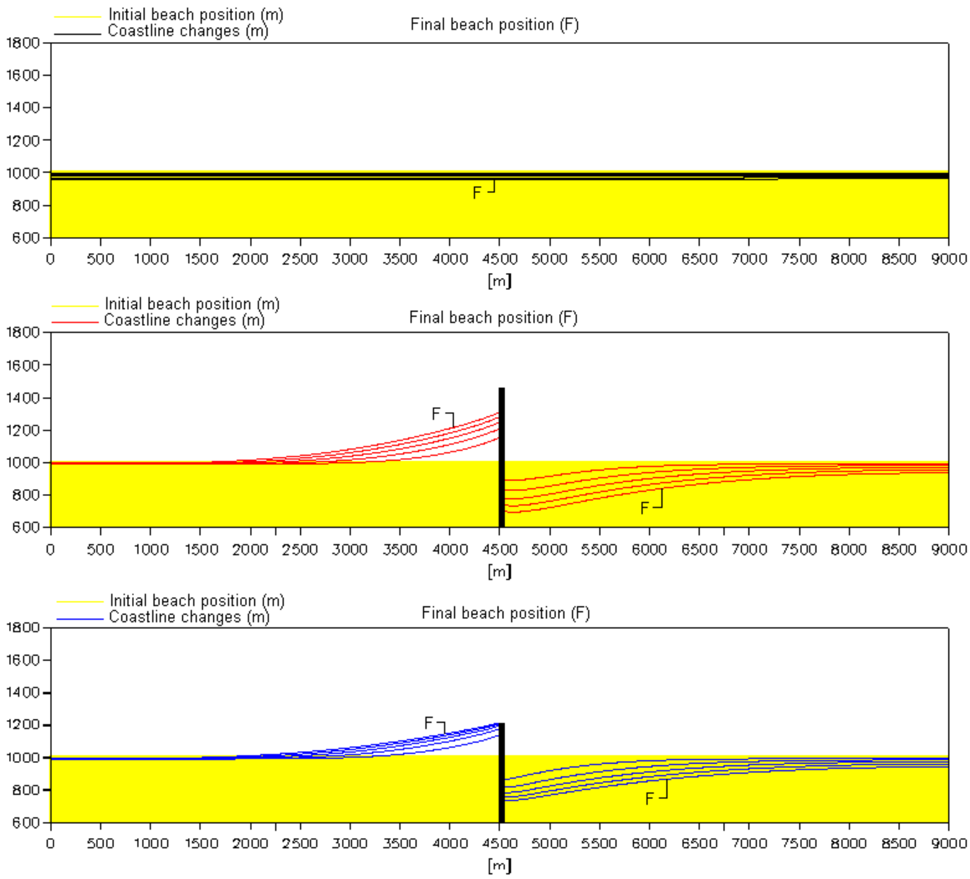


Figure 17.19 Shoreline development for a situation with a slightly oblique wave climate with increasing transport in the direction of the transport. Upper: Shoreline without any structures. Middle: For a single long groyne. Bottom: For a single short groyne.

Case 2: Type 2 coast, protection using groyne fields, short and long groynes

A single groyne, long or short, on a shoreline exposed to a slightly oblique wave climate causes downstream erosion (Figure 17.19). In order to extend the length of the protected area, and to compensate for the lee side erosion, it has been normal practice to construct several groynes along the shoreline, a so-called groyne field. Figure 17.20 demonstrates the shoreline development for the following groyne fields:

- Three long groynes with a spacing of 600 m, i.e. 1.5 times the length of the groynes
- Three long groynes with spacing equal to 1200 m, i.e. 3 times the length of the groynes
- Three short groynes with a spacing of 600 m
- Three short groynes with a spacing of 1200 m

The ability of the groyne field to protect a certain section of a shoreline depends on many parameters discussed in the following.

It was seen for the single groyne that the wave climate and the length of the groyne together determine the length of the section, which a single groyne can protect. However, both the spacing and the time are important parameters for groyne fields, as it takes a relatively long time to fill a groyne field with sand. Until this has been done, there will be temporary erosion between the groynes; longer spacing increases the temporary erosion. In the two cases of the long groynes, bypass of the first groyne did not start within the simulation time. This means that the only development, which takes place between the groynes, is an initial turning of the shoreline to the orientation of zero transport. The erosion downstream of the groyne field is identical to the erosion caused by the single groyne; however, this will only be the case initially, as bypass has not started in any of the situations. Later, when bypass starts, the erosion will slow down for the single groyne, as seen for the short groyne in Figure 17.19, whereas major erosion will continue in the groyne field, until the two gaps between the groynes have been filled. This means that in the long run a groyne field will give higher lee side erosion than a single groyne.

In the case of the two short groynes, the initial development in the gaps is very similar to the development seen for the long groynes, i.e. a turning of the local shorelines to the direction of zero transport. However, the influence of the bypass can be seen in the first gap, which is gradually being filled with the bypassed material. The lee side erosion for the groyne field is larger than for the single groyne because bypass of the groyne field did not start at the end of the simulation period.

The design of a groyne field requires great care in order to avoid temporary erosion within the field. It must also be remembered, that the protection provided by a groyne field is always at the expense of lee side erosion.

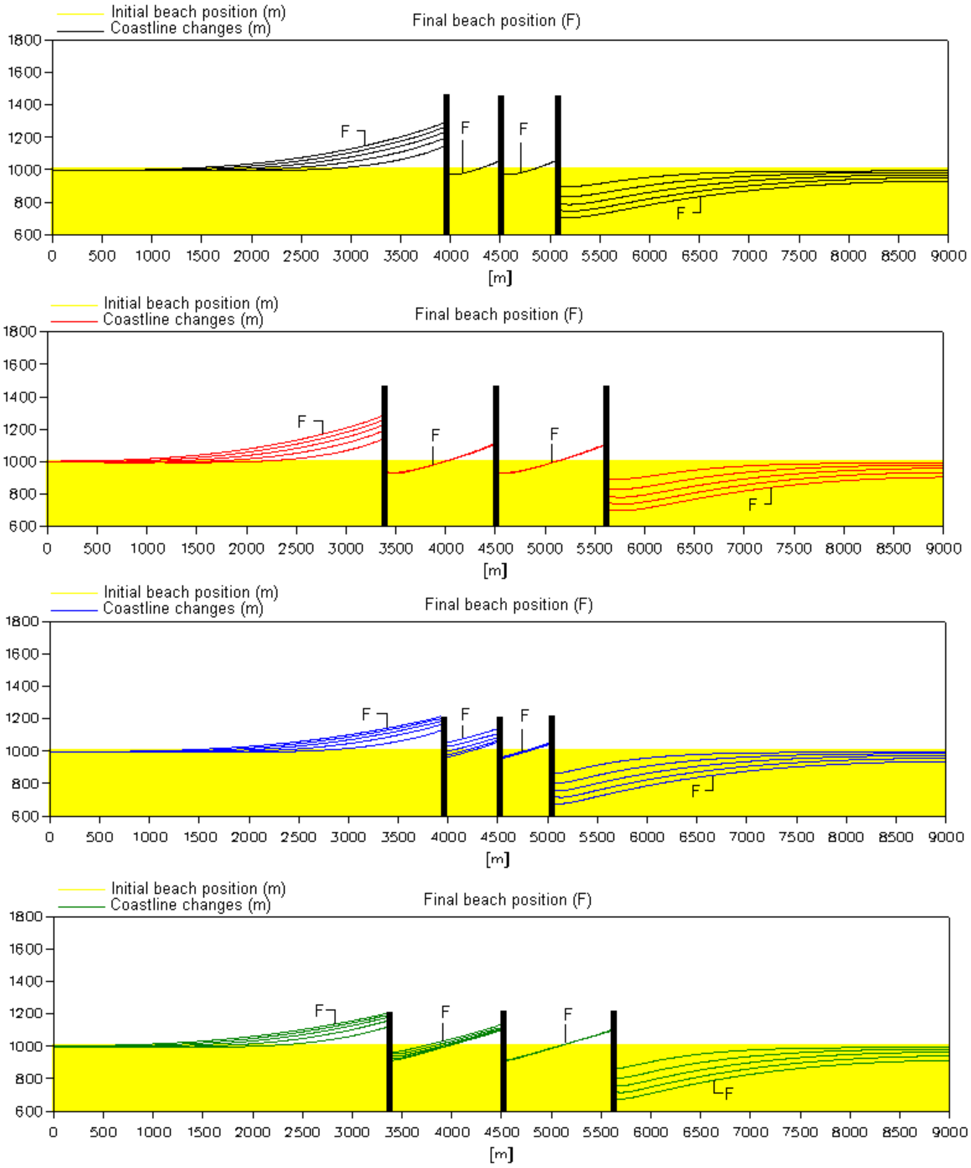


Figure 17.20 Shoreline development for groyne fields for long and short groynes for a slightly oblique wave climate.

The obvious disadvantages of groynes mean that they are used less today than previously. If, for one reason or another, they are used in new protection schemes, it will normally be part of the project to fill sand artificially into the groyne system in order to avoid temporary erosion. Figure 17.21 shows how one of the groyne fields tested above was filled initially with sand and how this influences the shoreline development.

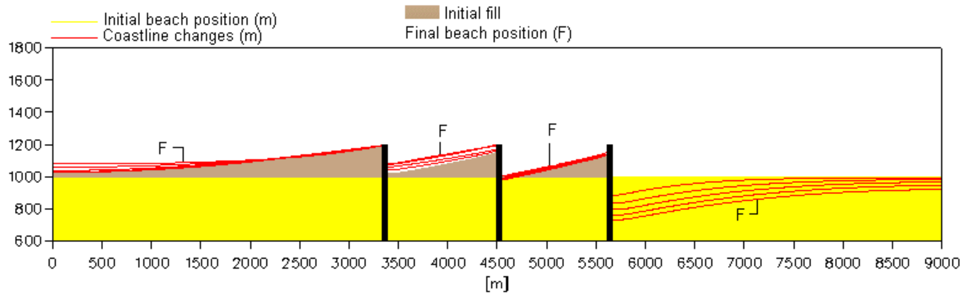


Figure 17.21 Shoreline development for a groyne field consisting of three short groynes at a shoreline with a slightly oblique wave climate. The groyne field was initially filled with sand.

It is seen from the shoreline development of the filled groyne field, when comparing this with the similar shoreline development for the non-filled field, (see Figure 17.20 lower part), that temporary erosion is avoided and that lee-side erosion is slightly smaller.

Other wave climates

The influence of the different wave climate has not been demonstrated in the above simulations, but this influence is demonstrated in the following for a shoreline with zero net transport and for a shoreline with a very oblique wave climate, respectively.

Coastal Type 1: Perpendicular wave approach in a nodal area, eroding shoreline

The natural development of a slightly curved shoreline, with a zero net transport in the middle part and with small gradients in the transport away from the middle section, is shown in the upper part of Figure 17.22. It is seen that there is erosion in the central part of the section despite the fact that the net transport here is zero. The reason is that it is a (negative) nodal point, from which sediment escapes in both directions.

The figure in the middle shows the shoreline development in a situation, where the central section has been isolated by the introduction of two long groynes. The two groynes practically secure the central section of the shoreline against erosion by preventing loss of sand to the adjacent sections. In this situation the erosion a small distance away from the groynes is slightly larger than the erosion in the situation without groynes; the reason for this is that the two groynes trap sand and prevent loss from thecentral section. This trapped and non-eroded sand is consequently causing sediment deficit along the adjacent sections.

The lower part of Figure 17.22 shows the shoreline development for one long groyne in the centre of the nodal section. The influence of the groyne is reflected in local accumulation on both sides close to the groyne and erosion at adjacent sections, which is a little larger than the erosion without a groyne.

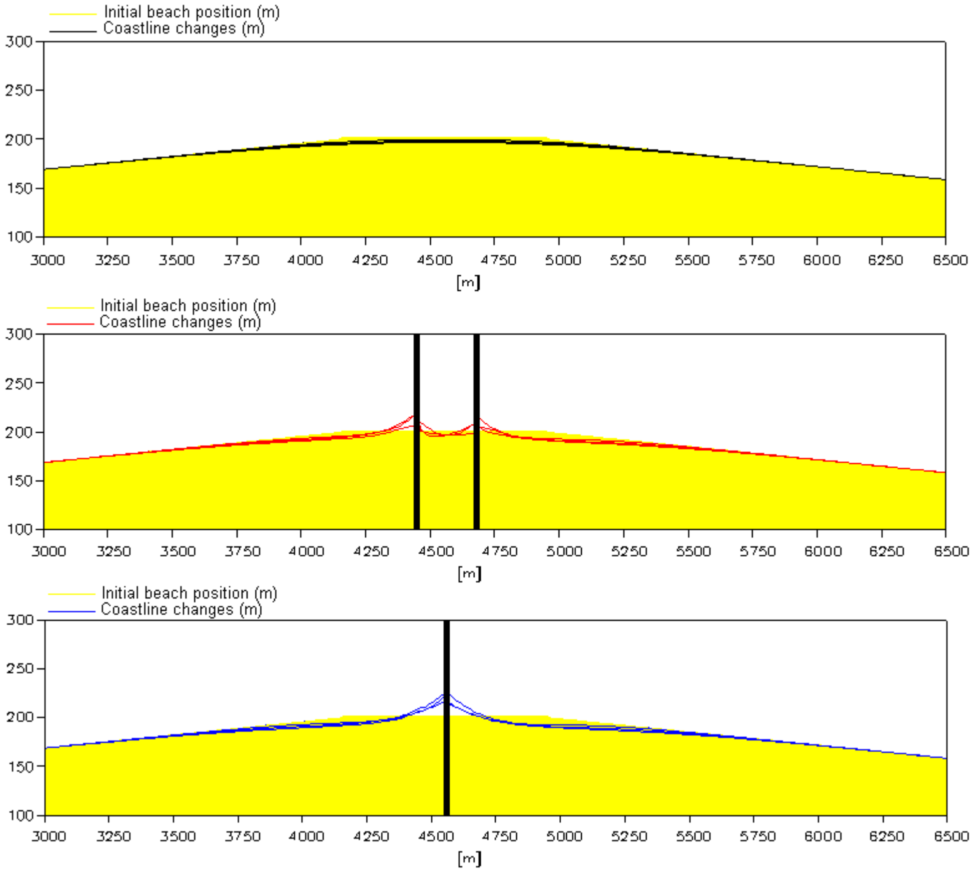


Figure 17.22 Shoreline development for an eroding shoreline with zero net transport; natural development and the development under the influence of two long groynes and a single long groyne.

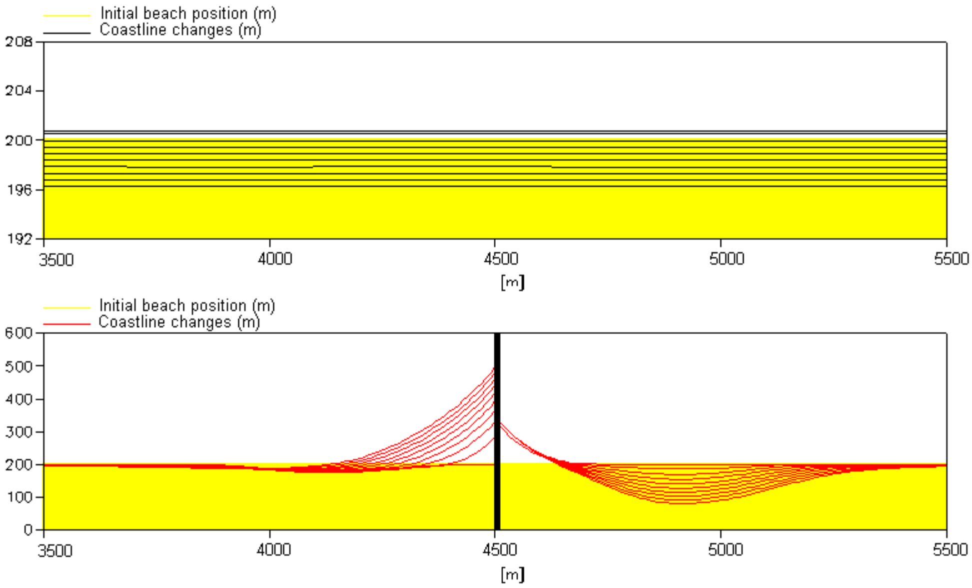


Figure 17.23 Shoreline development for an eroding shoreline with moderate to very oblique wave approach and increasing littoral drift in the direction of the net transport. The natural development and the development under the influence of a long groyne. (Note different cross-shore scales)

Coastal Type 3/4: Moderate to very oblique wave approach, eroding shoreline
The upper part of Figure 17.23 demonstrates the natural shoreline development for a shoreline exposed to moderate to very oblique incident waves, with increasing transport in the direction of the net drift. The result is that the shore is exposed to uniform erosion along the entire section.

The long groyne causes the development of only a relatively short sand filet, and there is an upstream erosion area, which is only filled in slowly. A relatively long stretch of downstream coastline is exposed to severe erosion. When bypass starts, the sand will be deposited in a shoal east of the head of the groyne, which means that it will not contribute to the sediment budget for the downstream shoreline. This assumption will be correct for the first (many) years, see the discussion in Subchapter 11.2.1.2, Figure 11.8, where the influence of a port in a similar position was discussed. Here there is only a positive influence of the groyne in the form of a short sand filet upstream of the groyne over a length comparable to the length of the groyne itself, whereas the erosion downstream has increased considerably compared to the situation without protection. It is seen that the section protected by the sand accumulation is considerable shorter than the similar section for the slightly oblique wave climate as presented in Figure 17.19. This example shows that groynes are not suitable as shore protection for wave climates dominated by very oblique incident waves.

Discussion of 2D and 3D effects and long-term profile changes
The above shoreline developments for various groyne schemes are somewhat simplified as they do not include 2D or 3D effects or long-term profile changes. Such effects do, however, occur in connection with groyne schemes.

2D effects
A groyne redirects the longshore current, as it is constructed perpendicular to the longshore current direction. The groyne thus directs the current seawards along the structure, whereby an offshore-directed jet is generated. A long groyne with approximately the same length as the width of the surf zone, will generate a strong jet as the entire longshore current is blocked. A shorter groyne will generate a smaller jet more or less parallel to the shore due to the interference with the outer uninterrupted part of the longshore current. Groynes with lengths similar to or shorter than the width of the surf zone will under all circumstances gererate rip current jets, which will cause loss of sand to deeper water. Furthermore the rip current jets may be dangerous for swimmers. The offshore directed jets cease in strength along groynes or similar structures, which are longer than the width of the surf zone.

The contraction of the current near the head of the groyne will also cause local seabed erosion upstream and off the groyne head, which may damage the head and which may be dangerous for bathers.

In the lee zone of the groyne, the diffraction of the waves, and the decrease in wave set-up on the foreshore towards the structure, will generate an eddy with the outward-directed current running along the lee side of the structure. This eddy adds to the offshore sand loss and local seabed erosion and it is also dangerous for swimmers during rough weather conditions.

3D effects
When waves and current pass the breakwater head, 3D current eddies will be formed, which will generate scour in the seabed in addition to the local seabed erosion caused by the 2D current contraction. The scour is especially pronounced for structures, which cause abrupt current changes.

Long-term erosion in the coastal profile
A groyne field which has been constructed at an eroding shoreline, and which does not cover the entire width of the littoral zone, will only secure the inner part of the coastal profile against erosion. The outer part of the coastal profile will continue to erode and the coastal profile will gradually become steeper. This will destabilise the outer part of the groynes and eventually the groyne heads

will collapse unless they are strengthened considerably. A groyne field, which covers the entire littoral zone, will not be exposed to this phenomenon, but groynes are seldom made that long.

Function of groynes related to sea-level rise

The shoreline sections currently protected by groynes will also be protected if the sea level rises, provided that the sand trapping capabilities of the groynes are not impacted by the sea-level rise. This will require that the crest height of the groynes is high enough and the groynes are not back-cut on the beach.

The downstream erosion caused by the groynes will be increased due to sea level rise because the rising sea level will cause additional sand to be trapped by the groynes, this sand will then cause sediment deficit along the down-drift shoreline sections.

Consequently, future sea level rise should be taken into account in the design phase, both in terms of the future minimal crest height of the groyne as well as in terms of additional lee-side erosion. However it is noted that groynes usually have a limited design lifetime of 20-30 years; the projected sea level rise during this period is relatively small and therefore the above effect will be limited.

Applicability:

It is evident from the above that groynes are able to protect sections of shoreline, but it is also evident that groynes have many disadvantages. Furthermore, it has been demonstrated that the function of groynes depends on the type of coast.

Groynes are generally applicable against chronic erosion as groynes are active when there is a net longshore transport. Groynes are not applicable against acute erosion as demonstrated in the photo in Figure 17.24. Groynes will retain their protective capability on the upstream coast during SLR provided that they are high enough and that they are not backcut but the leeside erosion will increase.

Figure 17.24 Acute erosion of beach and cliff despite groyne protection. Villingebæk, North Sealand, Danmark following the extreme storm “Bodil” on 6th December 2013. Yellow line indicates estimated beach profile before storm.

The applicability of groynes on different types of coasts is discussed in the following, where advantages and disadvantages have been highlighted:

Type 1 coasts
Groyne fields can be used on type 1M and 1E coasts in order to prevent loss of sand to adjacent sections. As there is no net transport in this situation, only local sand is trapped close to the groyne, and hardly any lee side erosion occurs. However, minor additional erosion does occur in neighbouring sections due to the lack of the supply of sand from the protected section.

Type 2 and most perpendicular part of type 3 coasts
Groynes are applicable on coasts of types 2M and 2E and on the parts of the 3M and 3E coasts, which have an angle of incidence close to the type 2 coast. The groynes accumulate sand on their upstream side at the expense of lee side erosion on the downstream side.

Groyne fields will be exposed to initial erosion inside the protected area if they are not nourished as part of the construction schedule.

Local erosion and scour will occur near the groyne heads, and the outer part of the coastal profile will continue to erode. Groynes will eventually collapse if their heads are not strengthened.

The negative effects of the groyne fields, lee side erosion and profile steepening, can be mitigated by regular nourishment. The advantage of the combined solution of groyne fields and nourishment is that well-designed groynes prevent or decrease erosion of the beach. However, groynes do not protect against acute erosion during high storm surge; under such circumstances groynes only reduce the amount of erosion due to the buffer effect caused by that sand volume trapped along the upstream side of the the groynes. Consequently, groynes are only effective against acute erosion if combined with sufficient nourishment or if combined with a revetment.

Type 3, 4 and 5 coasts
As the sand filet accumulation for these types of coasts is very short, groynes cannot be recommended as a protective measure.

In addition, a groyne on a type 4 or 5 coast may lead to the development of a sand formation detached from the coastline. This will deprive the downstream shoreline of supply of sediment. Erosion will follow, and an undesired lagoon may develop in the area sheltered by the sand spit. Groynes on these types of shorelines may initiate uncontrollable shoreline development.

General comments
Groynes tend to trap seaweed and floating debris on the upstream side as well as on the lee side.

Groynes obstruct passage along the beach.

Groynes are often dangerous to walk on; however, if they are built to allow passage on the top, they are popular for promenading and fishing.

The lee zone eddy as well as the upstream rip current can be dangerous for bathers.

Groynes constitute a foreign element in the coastal landscape due to their unnatural appearance perpendicular to the shoreline.

Lee-side erosion will be aggravated by future sea-level rise.

17.5.2 Detached breakwaters

17.5.2.1 Emerged breakwaters

Definition:

A detached breakwater is a structure parallel, or close to parallel, to the coast, built inside or outside the surf-zone. Detached breakwaters are mainly built with two purposes, either to protect a ship wharf from wave action or as a coast/shore protection measure.

A detached breakwater can be characterised by several parameters as shown in Figure 17.25.

The most important parameters are:

- L_B Length of the breakwater
- x Breakwater distance to shoreline
- x_{80} Surf-zone width, approximately 80 % of the littoral transport takes place landwards of this line

Dimensionless length and distance:

- $L_B^* = L_B/x$ Breakwater length relative to breakwater distance to shoreline
- $x^* = x/x_{80}$ Breakwater distance relative to surf-zone width

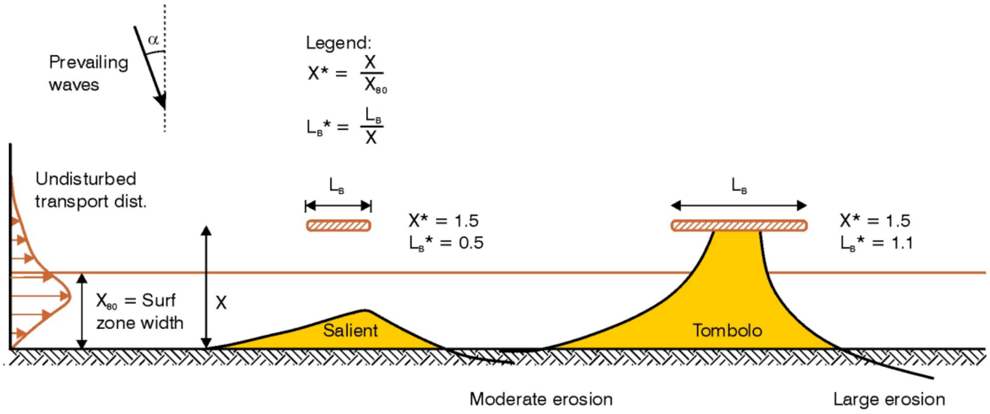


Figure 17.25 Definition of parameters characterising detached breakwaters and accumulation forms.

Accumulation forms:

- Salient: When the dimensionless breakwater length L_B^* is less than approx. 0.6 to 0.7, a bell-shaped salient in the shoreline will form in the lee of the breakwater. However, parameters other than the breakwater length and distance also influence the accumulation pattern.
- Tombolo: When the dimensionless breakwater length L_B^* is greater than approx. 0.9 to 1.0, the sand accumulation behind the breakwater will connect the beach to the breakwater in a tombolo formation. However, the accumulation pattern adjacent to breakwaters is also dependent of other parameters than the breakwater length and distance.

If there are several breakwaters in a series, then this is referred to as a *segmented breakwater*, where the length of the gap between the breakwaters is denoted:

- L_G: Length of gap between breakwaters in a segmented breakwater

Functional characteristic of emerged detached single breakwaters:

A detached breakwater provides shelter from the waves, whereby the littoral transport behind the breakwater is decreased and the transport pattern adjacent to the breakwater is modified. These characteristics of a breakwater are utilised in different ways for various types of breakwaters by varying relevant parameters. There are three different types of breakwaters as presented in Figure 17.26.

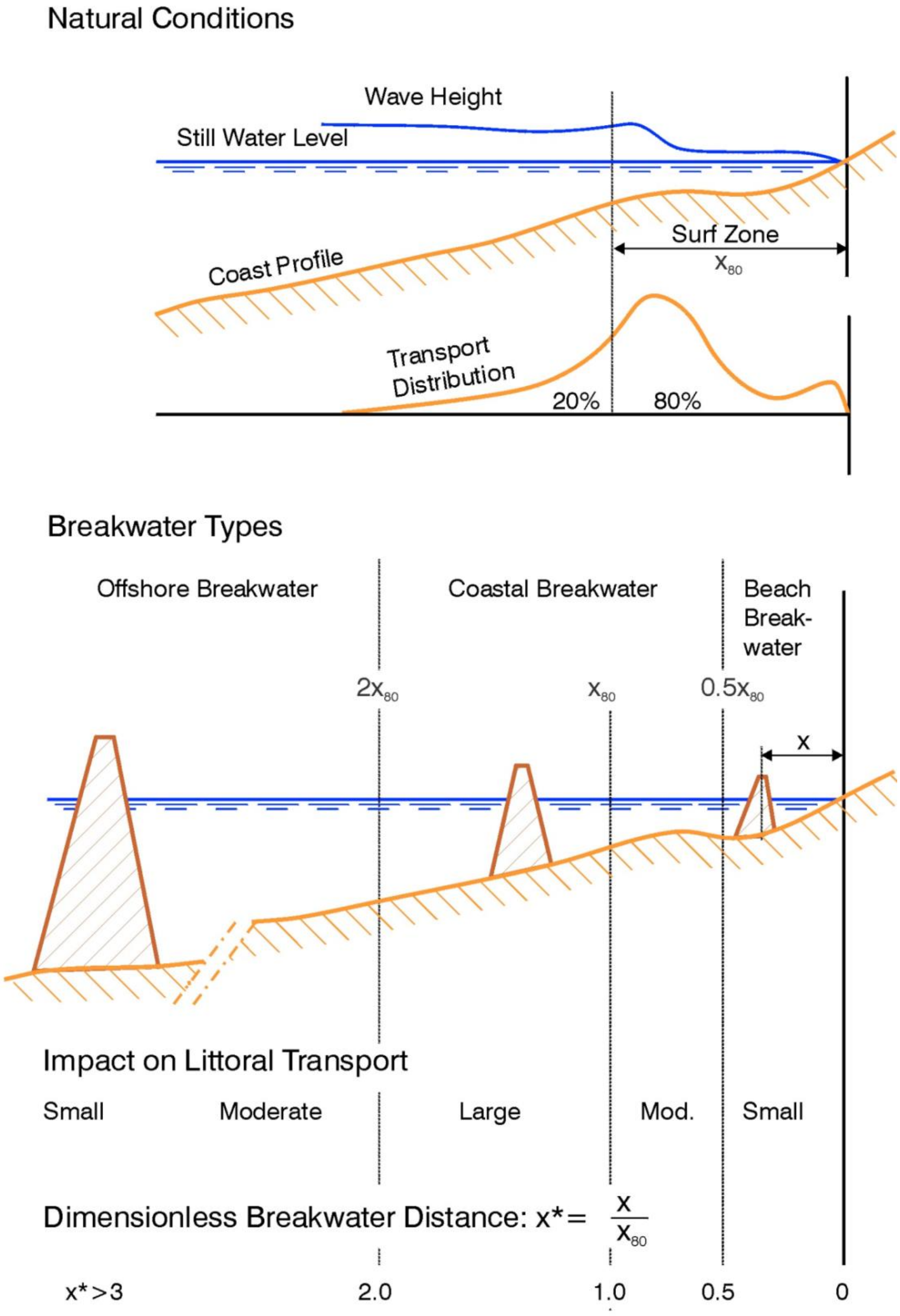


Figure 17.26 Types of detached breakwaters.

- *Offshore breakwaters* are located relatively far outside the surf-zone, $x^* > 3$. The purpose of an offshore breakwater is normally to protect an offshore ship wharf against wave action, which means that an offshore breakwater is a special type of port. The offshore breakwater type of port is used when the coastal profile is very flat. At such locations, a traditional port would have to extend far from the shoreline or extensive dredging works would have to be carried out to provide access to the port. In order to minimise the works and to avoid the associated coastal impact, an offshore breakwater may be the answer. The offshore breakwater is normally located at a slightly greater water depth than is required for navigation, thus avoiding/minimising capital dredging and minimising sedimentation. The philosophy is thus threefold: First, to provide shelter for a mooring pier, secondly, to minimise sedimentation and thirdly, to minimise the impact on the coast. The idea behind an offshore breakwater, in relation to its influence on transport conditions, is thus to place it as far away from the surf-zone as possible and make it as short as possible so that its impact on the coastal morphology is negligible. However, this is usually very difficult to obtain in practice; offshore-detached breakwaters often cause accumulation in their lee zone resulting in erosion effects in adjacent areas. It is thus important that the coastal impact of offshore breakwaters is taken into account when carrying out an environmental impact assessment for this type of port. Offshore breakwaters will not be treated further in these Guidelines as offshore breakwaters are not used as shoreline management structures.

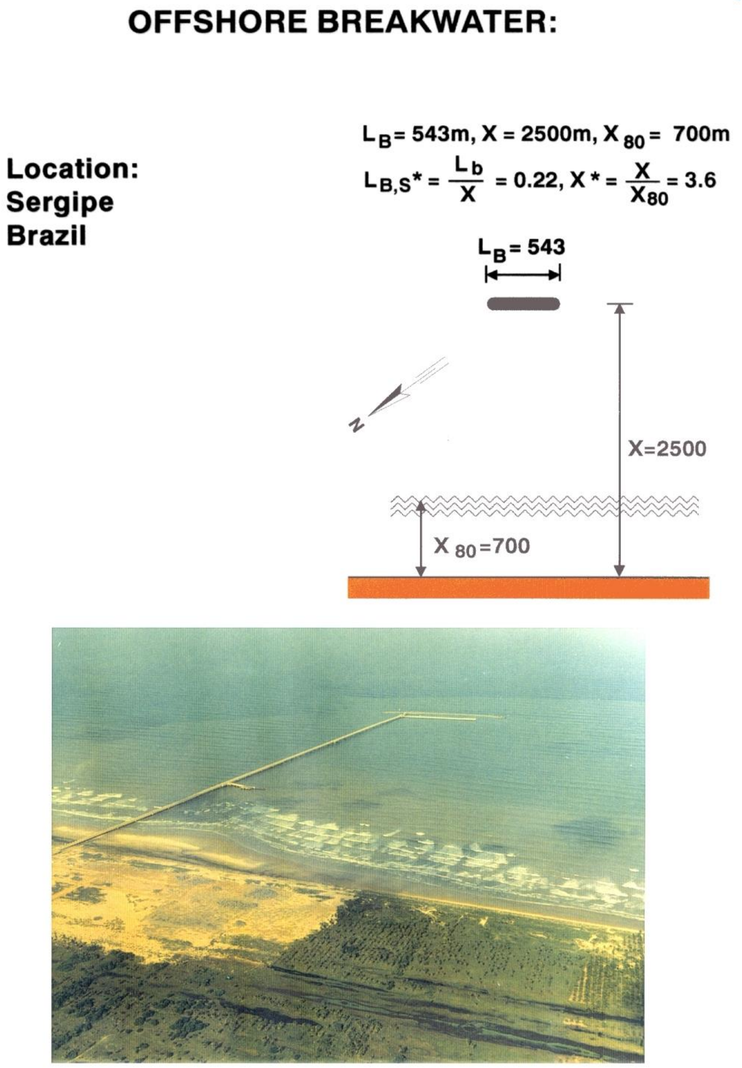


Figure 17.27 Sand accumulation forming a salient in the shoreline behind an offshore breakwater, Sergipe, Brazil. $L_B^* = 0.22$, $X^* = 3.6$.

The following two types of breakwaters are mainly used for shoreline management, where the inherent capability of a breakwater to manipulate the littoral transport is utilised.

- *Coastal breakwaters* are located within a distance from the shoreline of half the width of the surf-zone, up to twice the width of the surf-zone, $2 > x^* > 0.5$. Such breakwaters trap sand within the part of the littoral zone they cover, thus securing that part of the coastal profile against erosion. An example of a coastal breakwater, which has a length .$L_B^* = 0.8$ in the transition between the salient and the tombolo phase, is presented in Figure 17.28.

Figure 17.28 Coastal breakwater, which has formed (an unstable) tombolo, Covis Place, Sri Lanka. $L_B^* = 0.8$, $X^* = 1.0$.

- *Beach breakwaters* are located within less than half the width of the surf-zone from the shoreline, $x^* < 0.5$. Beach breakwaters trap sand on the foreshore without interfering significantly with the overall transport pattern. An example of a segmented beach breakwater scheme with $L_B^* = 1.0$ is presented in Figure 17.29.

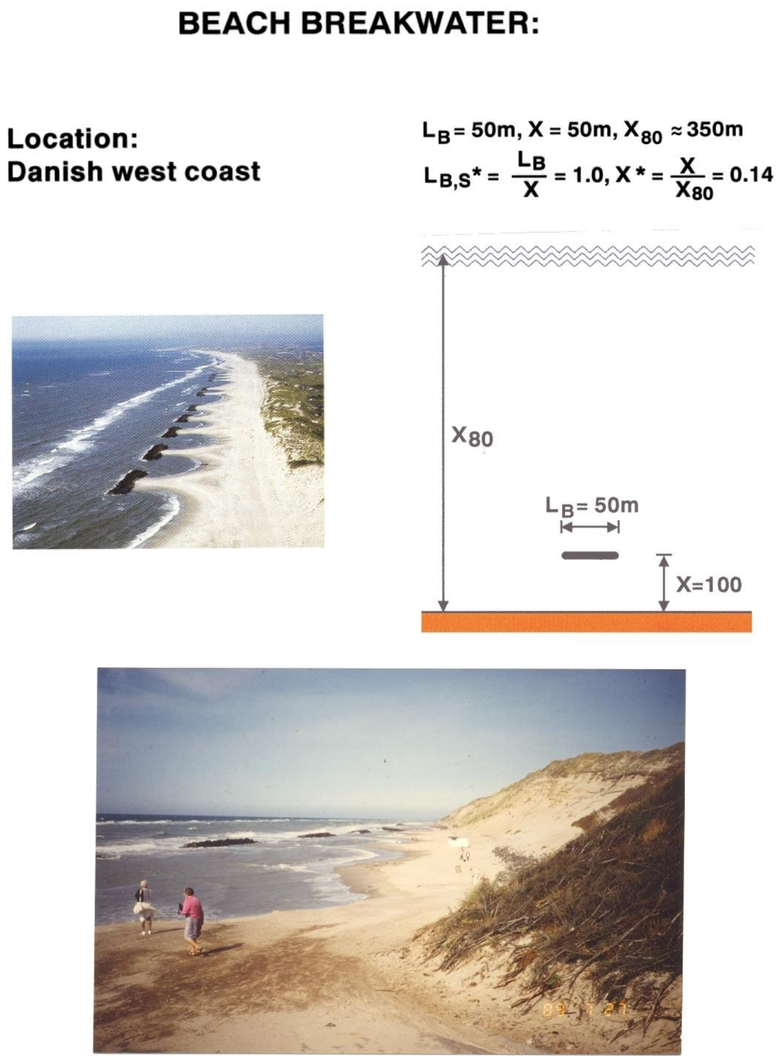


Figure 17.29 Beach breakwaters, The Danish West Coast. $L_B^* = 1.0$, $X^* = 0.14$.

The philosophy behind coastal and beach breakwaters is as follows:

- To partly provide wave shelter for a certain part of the shore and the coast
- To modify the littoral transport in a predictable way, so that the combined shore-restoration and coastal protection function can be properly designed. The extent of the sand trapping, or the ability to establish the desired sand accumulation pattern, is mainly regulated by choosing the length of the breakwater L_B and the breakwater distance to the shoreline taking into consideration also the dimensionless length and distance: $L_B^* = L_B/x$ and $x^* = x/x_{80}$. Furthermore, for segmented breakwaters, the number of single breakwaters and the length of the gaps.
- The advantage of a breakwater in comparison to a groyne is that it is possible to modify the littoral transport in a smoother manner than for a groyne. In this way there may be less lee

side erosion on the downstream shoreline. This applies especially to breakwaters, which are so short that a permanent tombolo does not develop.

- Another advantage of a breakwater compared to a groyne is that the detached breakwater does not obstruct access along the beach. A disadvantage could be reduced beach quality due to its sheltering effect on waves and trapping of floating seaweed.

Sometimes coastal breakwaters are planned so as to provide shelter for the beach landing of small fishing boats or sheltered water for swimming. This is difficult as sufficient shelter for the boats and the swimmers requires such a long breakwater that a tombolo develops. When the tombolo has developed there is no sheltered water area left for boat landing and swimming, only a semi-protected bay downstream of the tombolo is left. This bay may be suitable for landing small boats, but it is certainly not suitable for swimming during rough wave conditions due to the eddy, which will always be present during such conditions.

Sand will be trapped behind a breakwater if initial sand fill is not performed. The trapped sand comes from the adjacent beaches, which will cause sediment deficit along both the upstream and downstream beach, which will result in erosion during the development of a salient or a tombolo. When a tombolo has been formed, the adjacent beaches are influenced in a way similar to that of a groyne with upstream accretion and lee side erosion. The influence of a salient will be smoother.

The influence of various coastal breakwaters on the flow pattern of the longshore current is discussed in the following. Two breakwaters, one relatively long and the other one relatively short, are considered. Immediately after the construction of the breakwaters, the flow pattern is simulated by applying DHI's numerical model system MIKE 21.

The dimensions of the breakwaters are:

	L_B	x	x_{80}	L_B*	x*
Long breakwater	312 m	240 m	250 m	1.3	0.96
Short breakwater	144 m	240 m	250 m	0.6	0.96

The bathymetry was a plane beach with constant slope of 1:50

Irregular and directional waves with: Hs = 2.8 m, Ts = 8.0 s and α_0 = 12° were used.

The flow patterns for these two breakwaters are presented in Figure 17.30.

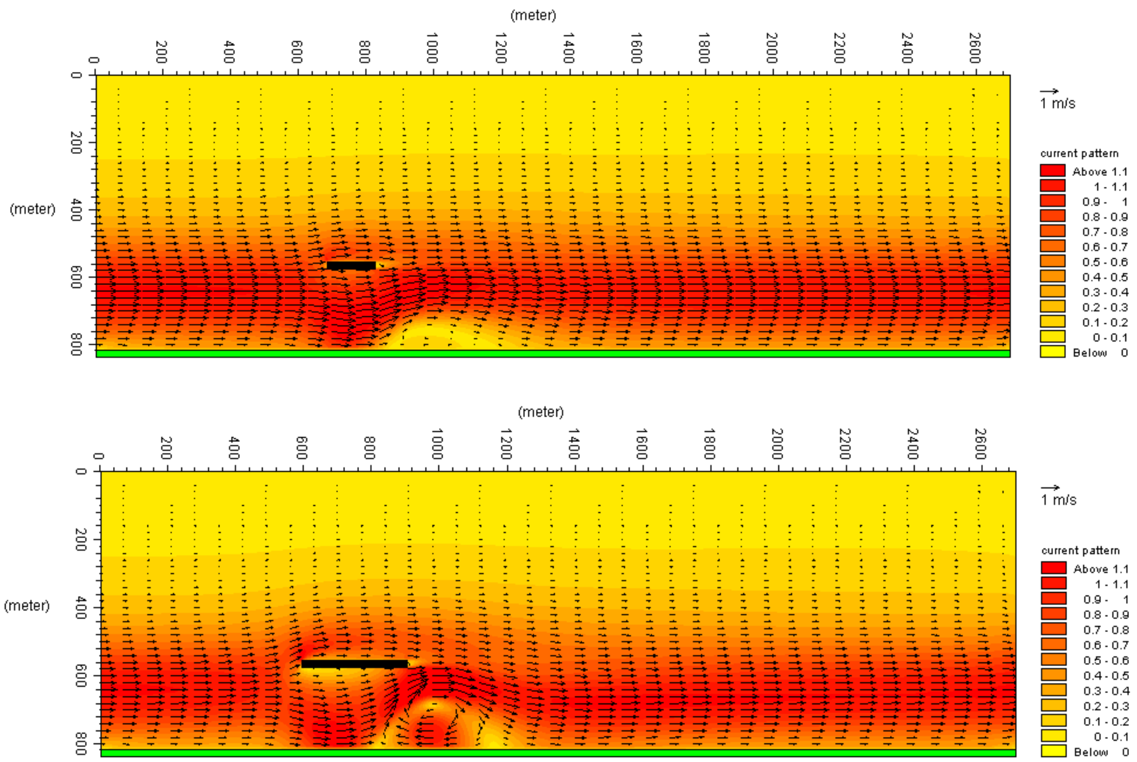


Figure 17.30 Flow pattern for a "short" and a "long" breakwater, L_B^* =0.6 and L_B^* =1.3, respectively, for slightly oblique incoming waves.

The long breakwater causes major changes in the flow pattern. The current speed was found to increase towards the lee zone and close to the breakwater heads. Furthermore, a circulation pattern was observed near the downstream end of the lee zone. This current pattern and the corresponding sediment transport pattern cause the formation of a tombolo (Figure 17.25). There will also be local scour close to the breakwater heads. The eddy in the lee zone will remain, even after the tombolo has formed, and the current around the upstream head of the breakwater will increase and will develop an offshore directed component. The current eddy and the scour holes will be dangerous for bathers, and the jet directed offshore will cause loss of sand and decreased sediment bypass, resulting in relatively large lee side erosion. The local lee bay will tend to collect seaweed and debris. Furthermore, the tombolo provides easy access to the breakwater, which is not practical, as walking on the structure and jumping from it can be dangerous.

The flow pattern will be quite different if the breakwater is fairly short, as seen in the above figure. There will be no high currents at the breakwater heads; there will be only a minor tendency for eddy formation and there will be only slight changes in the general pattern of the longshore current. The morphological response to such a breakwater will be a smooth salient in the shoreline; a tombolo will not form and there will be no scour holes at the end of the breakwater heads. There will be no offshore loss of material, and the lee side erosion will be mild. These are all positive effects; the negative effect is that the protection, provided by a short breakwater, is limited. It will secure a wider beach locally, but it will not be able to stabilise a long section of shoreline by a stable sand filet. If the sand filet consists of nourished sand, frequent re-nourishment will be necessary.

The optimal solution is probably somewhere between a long and a short breakwater. It must form a solid salient, but not a tombolo. This solution is balanced between the requirements for coast and shore protection, the minimisation of downstream impacts and seaweed trapping, and the optimisation of safety. Other modifications to the breakwater can also be considered. This will be discussed under the heading: Modified breakwaters and headlands.

Functional characteristics of emerged detached segmented breakwaters:

The above discussion was related to single breakwaters, but shoreline management schemes often utilise segmented breakwaters. A segmented breakwater scheme provides many possibilities, ranging from total coastal protection to mild shore protection. Figure 17.31 shows the characteristic shoreline development, which can be obtained with segmented breakwaters with various combinations of breakwater lengths and gap widths.

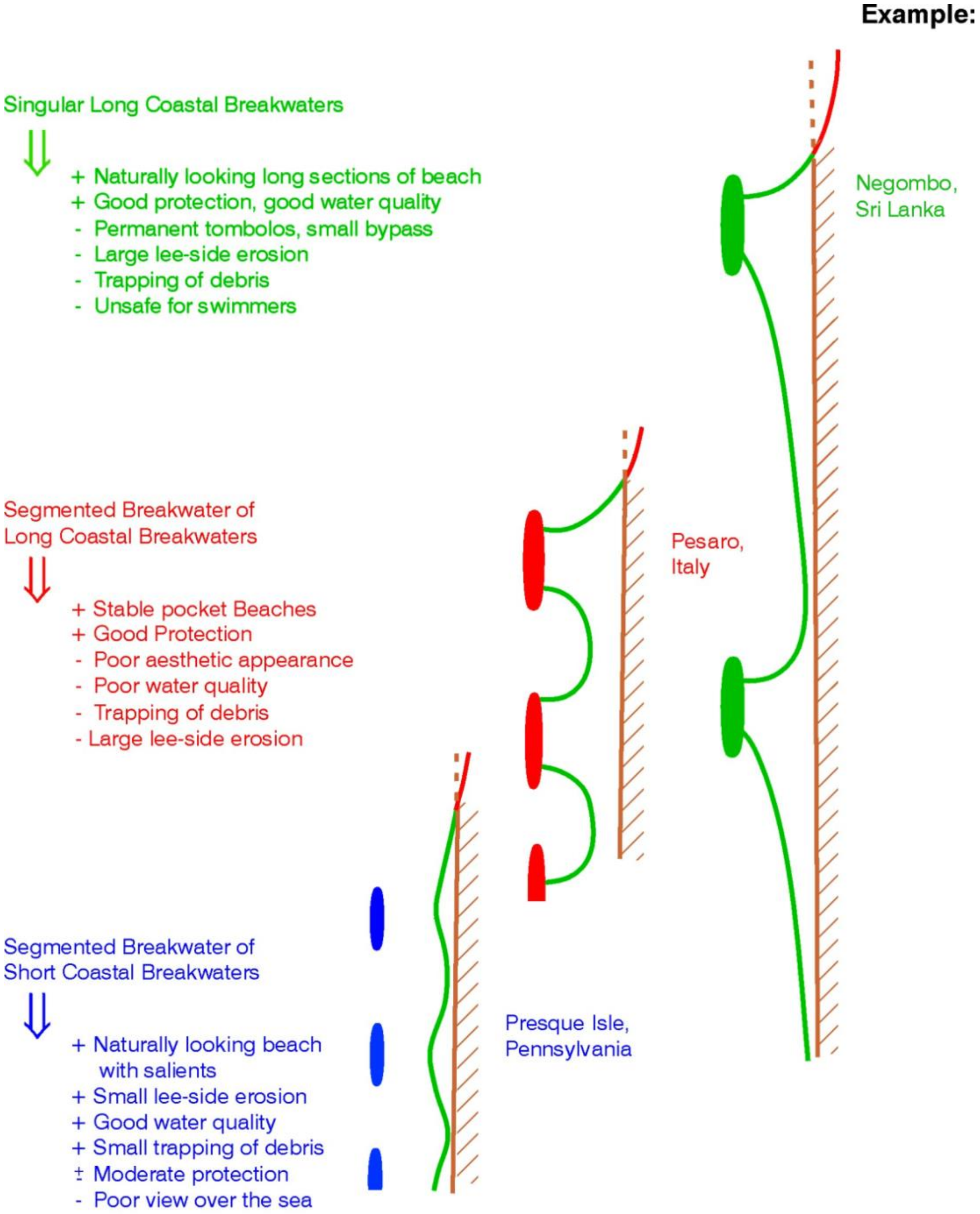


Figure 17.31 Characteristics for various segmented breakwater schemes.

A mixture of seawalls, revetments, groynes and breakwaters has, in the past, often been used in densely populated areas as coastal protection against chronic erosion. In some places the protection was co-ordinated, but most often it was everybody's individual fight against the sea. Such areas are characterised by lost beaches, poor passage along the coastline and poor aesthetic appearance. The natural beauty of the coastal landscape is lost due to coastal protection measures and erosion continues. Such areas require an urgent upgrade to secure the values behind the coastline, as required by the landowners, and to re-establish the shore to the highest possible level, as required by the public and the authorities. This calls for a well-co-ordinated shoreline management scheme. With modern techniques and sufficient funds, it will be possible to upgrade the spoiled coastline to a nearly natural condition. However, it is almost impossible to re-establish the active coastal cliff, which is also a valuable coastal resource. The only way to achieve this is to allow the natural coastal erosion to continue. However, this requires that the authorities purchase the coastal land and allow it to develop naturally. In most cases this is unrealistic, but one solution may be to leave public-owned sections without protection, provided they are of a suitable length.

In such heavily populated and mostly privately owned areas, it is normally difficult to obtain wide support for a solution using nourishment as a standalone measure. This is because land owners prioritize protection of their property rather than reestablishment of a natural sandy beach. Furthermore, landowners feel that nourishment will not provide sufficient safety against coastal erosion and nourishment also requires regular maintenance. In this case a scheme of segmented breakwaters is a good choice, and it can be tailored to suit the requirements agreed upon by the interested parties. However, practice (already the practice in Denmark) develops in the direction that authorities do not allow the construction of hard coastal protection and if permission for hard protection is given then it is usually required to combine it with nourishment which compensates for the loss of sand supply caused by the hard protection. The argument is that the protection hinders erosion of the coast whereas an unprotected coast would contribute sand to the littoral budget by release of eroded material. A pure nourishment solution normally requires overall planning along a longer section as well as regular maintenance, therefore such solutions are in most cases managed by associations of land owners and/or by public authorities.

The numerous possibilities are illustrated by the three very different schemes sketched in Figure 17.31. It is evident that nearly all combinations of requirements can be met. The most difficult aspect of such projects is often the public and political process, which has to be carried through to reach consensus. The importance of this process must not be underestimated in the planning process.

Applicability:

It is evident from the above that breakwaters are able to protect sections of shoreline in a more diversified and less harmful way than groynes, but some of the disadvantages of groyne schemes also characterise breakwater schemes. It has been demonstrated that, on some types of coast, breakwaters function differently to groynes. A breakwater can, for example, trap sand on a coastline with a perpendicular wave approach, which is hardly the case for a groyne. The applicability of breakwaters to different types of coasts is discussed in the following:

Type 1 coasts

Breakwaters can be used on 1M and 1E type coasts in a way similar to groynes, namely to prevent the loss of sand to adjacent sections. When groynes are used in this way, they will hardly trap any sand and there will hardly be any lee-side erosion. When breakwaters are used on type 1 coasts, they will trap sand in their lee areas, which causes local erosion on both sides of the breakwaters. This can be avoided if the sheltered areas behind the breakwaters are filled in as part of the project. In addition to this local erosion, adjacent to the breakwaters, a little additional erosion occurs on either side of the protected section, due to the lack of sand supply from the protected section.

Single breakwaters or segmented breakwaters can both be used as direct protection of specific sections against shore erosion and against coast erosion if they are combined with initial sand fill.

Breakwaters are generally applicable against chronic erosion on type 1 coasts but breakwaters do only provide very local protection against acute erosion.

Breakwaters are not applicable as a stand-alone measure against erosion caused by Sea Level Rise.

Type 2 and the most perpendicular part of type 3 coasts
Like groynes, breakwaters are applicable on coasts of type 2M and 2E and on the parts of the 3M and 3E coasts, which have an angle of incidence close to that of the type 2 coast. The breakwaters accumulate sand both on their upstream side and in their sheltered zones as a tombolo or as a salient, depending on their characteristics. The upstream accumulation will be very similar to that of a groyne if the breakwater is so long that it forms a tombolo. If this is not the case, the upstream accumulation will be smaller. Both the sand accumulation in the sheltered zone and the upstream accumulation will take place at the expense of lee side erosion on the downstream side of the breakwater scheme. In order to minimise the downstream erosion within the scheme, it is important to include the initial filling of the scheme in the construction project.

Local erosion and scour will occur near the breakwater heads, and the outer part of the coastal profile will continue to erode unless the breakwaters cover the entire littoral zone. Beach breakwaters will consequently eventually collapse if they are not strengthened, whereas coastal breakwaters constructed at a distance greater than approximately $x^*>1.2$ may not be exposed to an eroding seabed.

Lee side erosion and profile steepening occurring in areas protected by segmented breakwater schemes can be mitigated by regular nourishment. However, regulating the length of the individual breakwaters in the scheme can also partly mitigate the extent of the lee side erosion. The combined use of segmented breakwaters and nourishment secures mainly against chronic erosion whereas acute erosion may occur within a segmented breakwater scheme, especially along the beach in the gaps. This means that a segmented breakwater scheme combined with nourishment has to be further supplemented with revetment protection in the gaps in order to provide complete coastal protection. This is also relevant in relation to protection against sea level rise.

It is recommended to use few large structures instead of many small structures in order to enhance the aesthetic appearance of a segmented breakwater scheme. This is especially true for type 2 coasts, as the individual breakwaters are capable of supporting long upstream sand filets as shown in the Liseleje breakwater shoreline management scheme presented in Figure 17.32. The Liseleje area is characterised by the old breakwater in the NE-ern part of the area, which supports a tombolo and a long sand fillet, but the beach has been lost SW of the sand fillet and the area was dominated by many individual protection schemes, such as revetments and very small beach breakwaters. The rehabilitation scheme consists of a series of coastal breakwaters with relatively long spacing in between combined with initial sand filling.

Figure 17.32 Breakwater protection scheme, Liseleje, Denmark. Upper panel: Situation before scheme. Middle panel: Aerial photo 12 years after construction in 1999. Lower panel: Situation in the middle of the scheme in June 2010. Project and photos by COWI. References: Helledie, C. (2011) and COWI (2012).

Another example of a segmented coastal breakwater scheme is the protection scheme in Negombo, Sri Lanka, as presented in Figure 17.33. This scheme consists of 4 coastal breakwaters with a length of 160 m and spaced about 800m to allow for long beach sections suitable for recreation and beach fishing activities; only two of the breakwaters are seen in Figure 17.33. The scheme included sand filling between the breakwaters. This type of scheme was designed to protect the beach section against chronic erosion caused by the prevailing SW-monsoon waves. The scheme was not designed for acute erosion caused by cyclones because cyclones are very rare at this location. However, a cyclone passed the site in November 1992 and caused the shoreline response as shown with a red line in the figure.

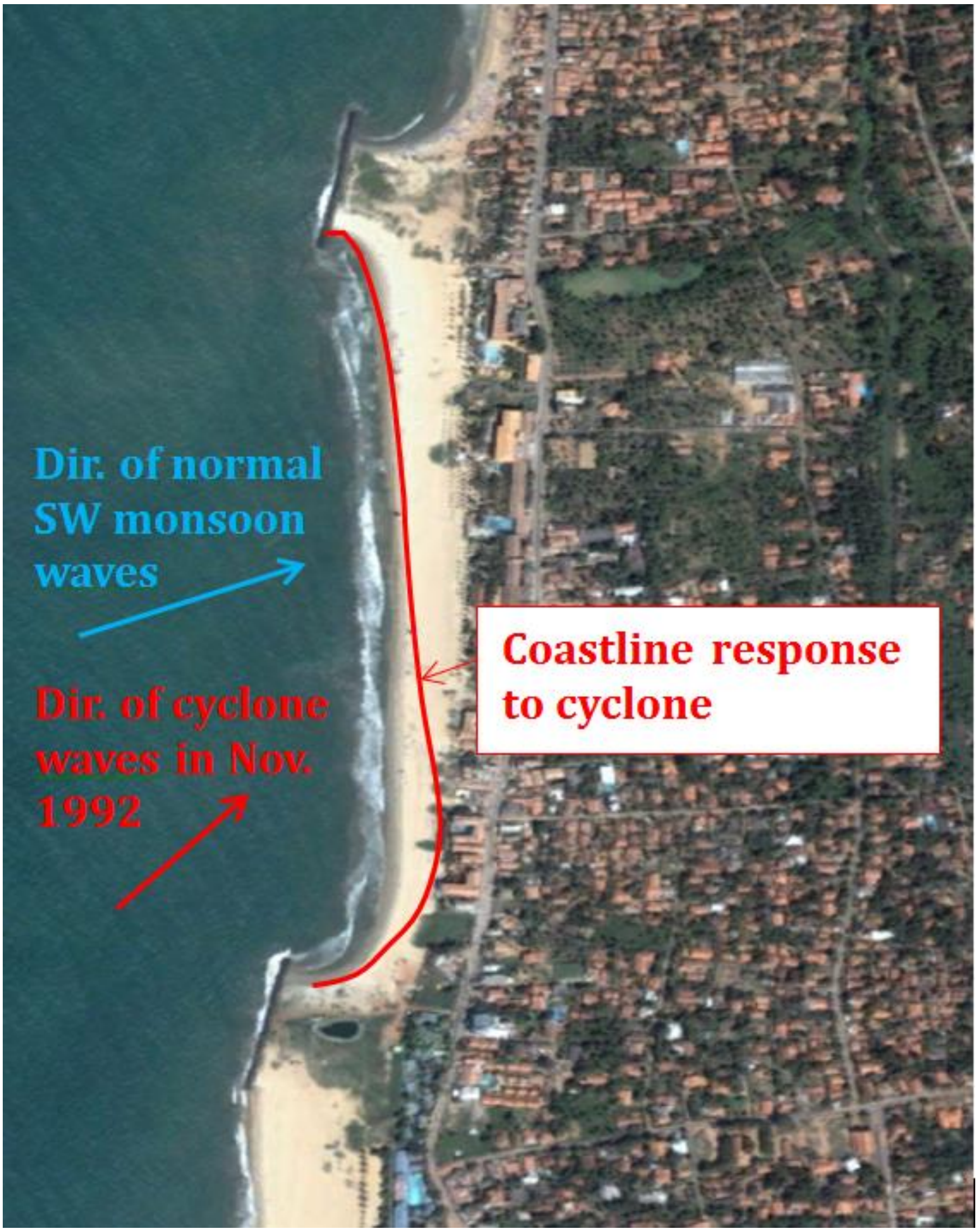


Figure 17.33 Segmented breakwater scheme in Negombo, Sri Lanka including coastline response to cyclone in November 1992.

The normal position of the shoreline is represented by the shoreline seen in the figure, whereas the response of the shoreline to the Nov. 92 cyclone, which generated waves with a more southerly direction than the normal SW monsoon waves, is sketched with a red line. The acute erosion eroded away the beach in the southern part of the beach section but only small damages occurred to fixed assets and after some months the shoreline was back to its normal position. The mixed scheme was consequently able to resist the reversible acute erosion during the cyclone but the coastal assets would have been safer if additional protection measures had been installed in the form of a buried revetment in the southern part of the cell between the two breakwaters.

When designing such protection schemes it is therefore important also to test for extreme events which may cause reversible acute erosion.

Type 4 and 5 coasts and the most oblique part of type 3 coasts
A single structure parallel to the coast is not very efficient when the waves aproach the shoreline under a fairly oblique angle, as the effective length of the structure perpendicular to the wave direction is relatively small in this case. For this reason and because the sand filet accumulation for these types of coasts is very short, single breakwaters cannot be recommended.

Segmented breakwater schemes with relatively short gaps can be used as a combined shore and coastal protection measure on all types of coasts because the formation of pocket beaches in the gaps does not depend very much on the wave direction when the gaps are small.

General comments on emerged breakwaters
Breakwaters tend to trap seaweed and floating debris in the bays, which are formed on the upstream side as well as on the lee side.

A breakwater does not constitute an obstruction for the passage along the beach.

Breakwaters are dangerous to walk on and should be constructed so that only a salient is formed.

The lee zone eddies are dangerous for bathers.

Breakwaters constitute a foreign element in the coastal landscape as they obscure the view of the sea, but if their number is kept at a minimum, and they are built relatively far from land, this problem is minimised.

The disadvantages of breakwaters and groynes can, to some extent, be avoided by optimising the shape of the structures. This is the subject of the next section.

Function of emerged breakwaters in relation to sea-level rise
In the case of sea level rise, a general setback of the shoreline is likely to occur as explained in section 6.4.2. This setback will result in breakwaters being located relatively farther seaward, thus offering a smoother passage of the littoral drift and less protection than before the sea level rise. The increasing sea level will also cause the crest level to be relatively lower. This may result in increased overtopping of the breakwaters, which may lead to less protection efficiency and to structural instability..

It is noted that coastal breakwaters usually have a limited design lifetime of 20-30 years; the projected sea level rise during this period is relatively small and therefore the above effects will also be limited for a short time horizon.

Applicability of emerged breakwaters in relation to chronic and acute erosion
Breakwaters are generally applicable against chronic erosion as breakwaters are active whenever there is a longshore sediment transport, also in cases where the net annual littoral drift is zero.

Breakwater schemes are generally not applicable to halt acute erosion but a segmented breakwater scheme provides some protection over the stretch covered by the scheme. However, there may be erosion spots in the open bays between the individual breakwaters. Breakwaters are generally not applicable against SLR.

Other types of breakwaters
All the above-mentioned detached breakwaters were assumed to be emerged structures exposed to only insignificant overtopping. This is the most common type of breakwater. However, many other types of breakwaters exist:

- Submerged or low-crested breakwaters
- Floating breakwaters
- Special type breakwaters

These types of breakwaters are described briefly in the following.

17.5.2.2 Submerged or low-crested breakwaters

Submerged or low-crested breakwaters function by provoking wave-breaking and by allowing some wave transmission so that a milder wave climate is obtained in lee of the submerged structure, although it is not as mild as if the structure was emerged. The sediment transport capacity behind the breakwater will also decrease, which means that sand will accumulate in a manner similar to an emerged structure with a slightly smaller length. The wave-breaking and overtopping also mean mass transport of water over the structure. There is a close relationship between, on one hand, wave transmission and mass transport over the structure and reduction in the sand transport and, on the other hand, crest freeboard, crest width and wave height and steepness. The reasons for selecting a submerged/low breakwater could be:

- The visual impact of a submerged/low structure is less dominating
- A submerged or low-crested structure is less expensive
- The impact on the transport climate and on the sand accumulation is smoother
- The overtopping water generates good water circulation behind the breakwater
- Submerged breakwaters are very similar to natural reefs. They attract fish and are therefore popular among fishermen
- Submerged breakwaters can be designed to promote surfable waves, which are attractive to surfers

However, there are also severe disadvantages to submerged/low breakwaters:

- A submerged structure can be dangerous for small craft navigation
- The overtopping water initiates local currents, which can be dangerous for swimmers
- A submerged or low-crested structure provides only partial attenuation of the wave action as well as partial shore protection and coast protection
- The efficiency of a submerged structure with respect to the attenuation of both waves and littoral transport and with respect to shore protection very much depends on the crest freeboard of the structure. If there is considerable tide and storm surge at the location in the design situation, even a submerged or low crested structure relative to the design water level will end up being rather high relative to the normal water level. This means that one of the advantages of a low-crested structure, namely that it is not visible most of the time, cannot be obtained
- The design is very difficult and challenging because the proper function of a submerged or low-crested structure depends on both water level and wave conditions as well as on the structure characteristics
- A submerged breakwater, which is placed relatively close to the shoreline, may result in erosion instead of accretion shoreward of the breakwater due to the mass transport of water across the submerged breakwater
- Sea level rise will decrease the effectiveness of submerged breakwaters due to increased water depth over the breakwater crest

17.5.2.3 Floating breakwaters

Floating breakwaters work by dissipating and reflecting part of the wave energy. No surplus water is brought into the sheltered area in this situation.

Floating breakwaters are normally used as piers in marinas, but they are also used as protective structures for marinas in semi-protected areas. They are especially suited for areas where the tidal range is high, as they follow the water level. Floating breakwaters are seldom used as shoreline management structures because they are not suitable for installation in the open sea.

The wave transmission coefficient H_t/H_i, i.e. the ratio between the height of the transmitted wave and the height of the incoming wave, depends very much on the ratio L/w between the wavelength L and the width of the floating structure w. As a rule-of-thumb the transmission varies between H_t/H_i = 0.3 for L/w = 3 and H_t/H_i = 0.9 – 1.0 for L/w = 8, see Figure 17.34.

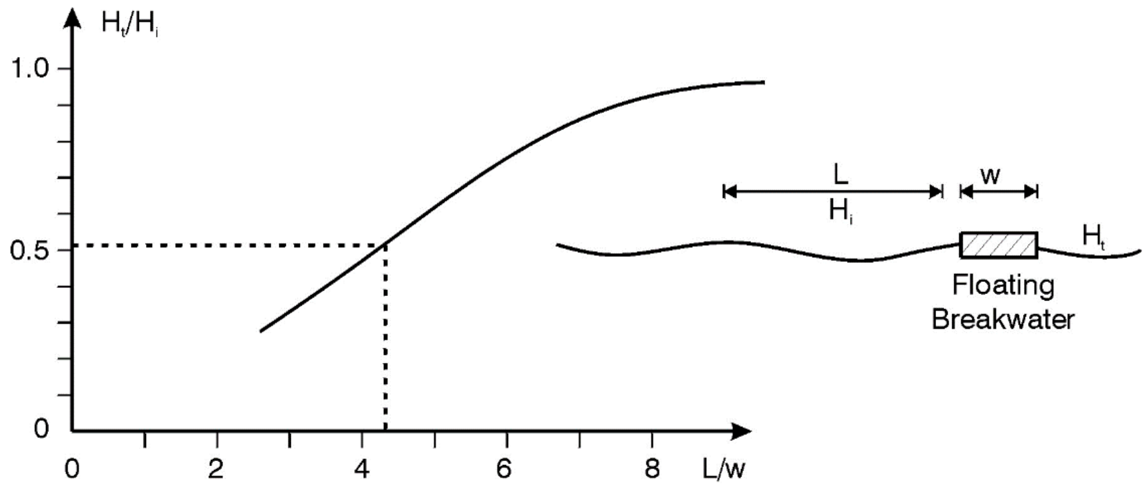


Figure 17.34 Rough relation between the transmission coefficient H_t/H_i and the ratio L/w between the wavelength L and the width of the floating structure w.

Consider the example of a pontoon width of w = 3 m, and a requirement of a wave transmission of min. H_t/H_i = 0.5. In this case the wavelength should be smaller than L < 4.2w = 12.6 m, which corresponds to an approximate wave period of T = 2.9 seconds. Consequently, floating breakwaters can only be used for wave protection in waters of very limited fetch.

Consequently, floating breakwaters can generally not be used as shoreline management structures at moderately exposed and exposed locations.

Floating breakwaters will not be impacted by sea level rise, as they follow the rising sea level.

17.5.2.4 Special type of breakwaters

Various specially designed concrete element type submerged and permeable breakwaters and flexible tube breakwaters have been introduced onto the market. Examples of such structures are presented in the following:

The Beachsaver® Reef consists of intersecting concrete elements. It is a submerged breakwater for reducing wave energy along shores and nourished shore sections and it has been reported to reduce incoming wave energy by approx. 30% by reflection and dissipation under typical conditions. The patented element is shown in Figure 17.35.

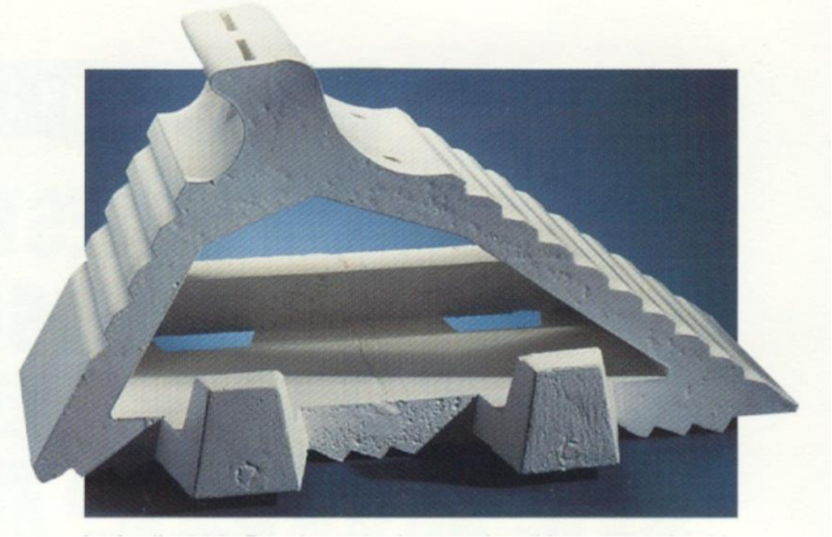


Figure 17.35 The Beachsaver® Reef.

The Beachsaver® Reef elements are rigid and their interlocking device is only able to resist minor settlements and scour. Therefore they must be placed on suitable filter material. Knowledge of the seasonal variations of the coastal profile is critical to the performance of the structure and it is evaluated that these elements will not be suitable for coastal profiles with large seasonal or long-term changes.

Flexible sand-filled geotextile tubes can be used for the construction of submerged and low-crested breakwaters, as well as for revetment, bulkhead and groyne structures. The tubes are made of geotextile fabric up to 150 m long and with diameters of up to approximately 4.0 m. They are installed empty at the location and then filled hydraulically.

Figure 17.36 An example of a protection scheme at the mouth of the Po River, Italy, consisting of bulkheads and submerged breakwaters (photo taken at low tide).

Their function is similar to other types of structures of similar dimensions, but they require special installation equipment and foundations.

There is still some controversy with respect to the durability of these structures especially when used as breakwaters or submerged breakwaters. There are many reports of structures which have failed and although the producers of the geotextile containers claim to be using more durable materials it is not advisable to use these systems for long term projects at location with rough wave conditions. See also Subchapter 17.4.2.

17.5.3 Headlands or modified breakwater

Background:

The supporting structures for coastal restoration schemes have, in the preceding discussions, mainly been traditional groynes and breakwaters. Various unwanted effects associated with these structures have also been highlighted. This subchapter discusses possible modifications to the layout of traditional structures to minimise these unwanted effects, see Figure 17.37.

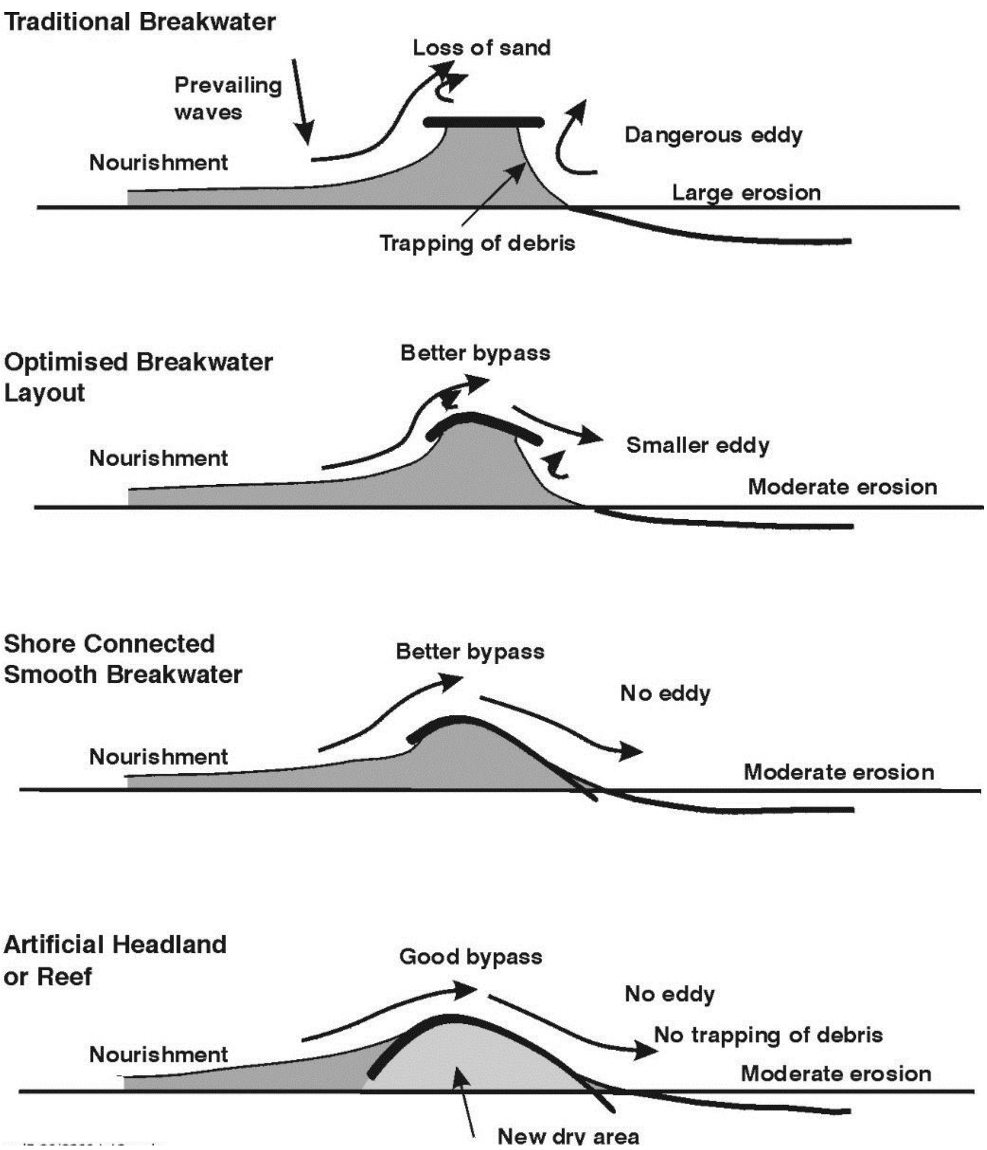


Figure 17.37 Optimisation of coastal breakwater to artificial headland, applicable for moderately exposed to exposed coasts for small angles of incidence.

The philosophy behind the optimisation of the traditional, coast-parallel breakwater into an artificial headland (Figure 17.37) is as follows:

a. To improve the bypass and to minimise offshore loss as well as lee side erosion
b. To eliminate dangerous rip currents as well as lee areas, which may otherwise trap debris or sea-weed
c. To enhance the aesthetic appearance and to gain some useful land.

Functional characteristics:

The initial current patterns for these structures are illustrated in Figure 17.38.

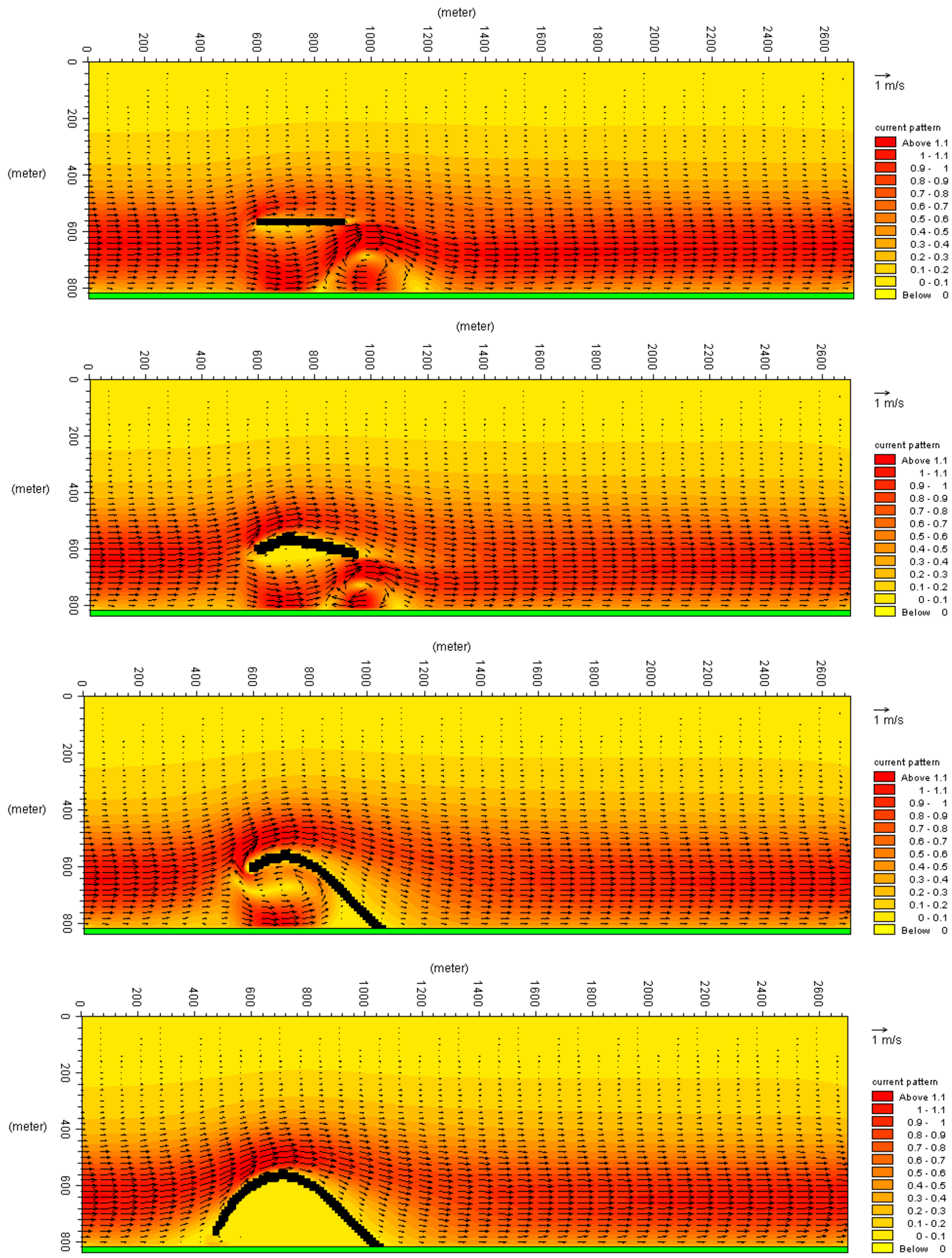


Figure 17.38 Initial current patterns for: a) A coast-parallel breakwater, b) A curved optimised breakwater, c) A Shore-connected smooth breakwater and d) An artificial headland.

These current patterns only show the initial situation without nourishment so they are not fully applicable in evaluating the conditions after initial fill or trapping of sand has taken place. However, they are useful as indicators of how the different schemes will function. The following characteristic conditions are important:

- Comparing a and b: The curved breakwater guides a larger amount of longshore current (and the littoral transport) around the structure on the offshore side, but turning the flow slightly towards the shore, it provides better bypass and less lee side erosion. The eddy in the lee area downstream of the structure is smaller for the curved structure, but it is still there. The scour hole at the lee end is evaluated to be smaller.
- Comparing b and c: The breakwater connected to the shore provides a very smooth passage for the longshore current (and the littoral transport) around the structure, thereby providing optimal bypass and less lee side erosion. The eddy at the downstream side no longer exists, which improves the safety for swimmers and reduces the trapping of seaweed and debris. The internal current pattern of the area sheltered by the structure is not relevant because this area will be filled with sand. This sandy area will become very attractive for recreational activities.
- Comparing c and d: The headland acts more or less like the breakwater connected to the shore; the only difference is a smoother transition of the longshore current (and the littoral transport) at the upstream end of the structure. This is due to the smooth transition between the coast and the structure in the case of the headland. The transition will be even more smooth if sand fill is introduced upstream of the headland. There is no eddy at the downstream side, which improves the safety for swimmers and reduces the trapping of seaweed and debris. If the reclaimed area is sufficiently elevated, it can be used for permanent recreational installations.

The headland can also be partly submerged, whereby it will act as a headland continuing into a reef. Careful design will make this type of headland appear almost natural.

Applicability:

The curved breakwater, the breakwater connected to the shore and the headland are useful substitutes for traditional groynes and breakwaters on coastal types 1 and 2.

The curved breakwater can be used for all types of coasts, where traditional breakwaters can be used, see above.

Neither the breakwater connected to the shore nor the headland can be used as replacements for traditional segmented breakwaters with small gaps and pocket beaches.

The impact from sea level rise on the curved breakwater is the same as for the traditional breakwater, whereas the impact from sea level rise on the shore-connected breakwater and the headland is the same as for a groyne.

Headlands are generally applicable against chronic erosion as headlands are active when there is a net longshore transport. Headlands are only effective against acute erosion along the stretch occupied by the structure but they provide no protection along adjacent stretches.

An example of the use of coastal headlands is shown in Figure 17.39 showing a series of semi-circular artificial headlands supporting a beach filled area at Marataizes, Brazil. Results from the hydrodynamic simulations show wave generated currents for the dominating wave conditions; it is seen that no offshore directed rip currents are generated due to the smooth layout of the headlands.

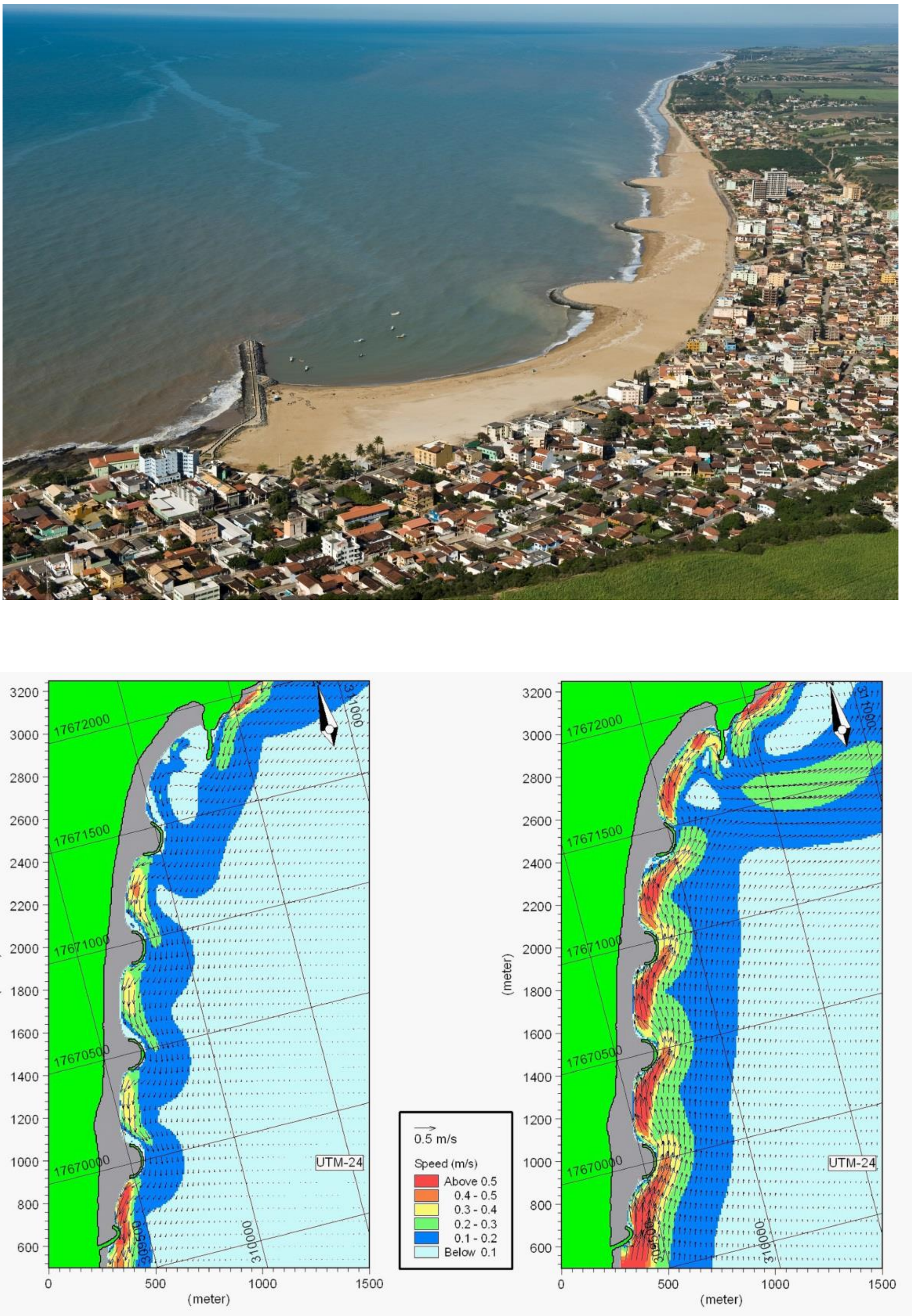


Figure 17.39 Artificial rounded headlands supporting a new artificial beach in Marataizes, Brazil. Upper: Aerial Photo. Lower: Simulated wave generated currents for dominating wave situations.

17.5.4 Perched beach

Definition:

A perched beach is a beach retained above the otherwise normal profile level by a submerged structure parallel to the coast, se Figure 17.40.

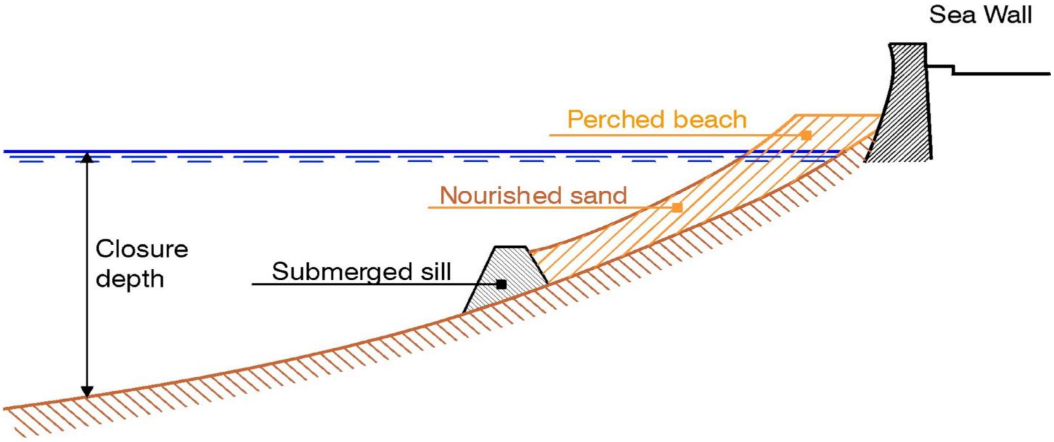


Figure 17.40 A sketch of a perched beach consisting of a beach fill (nourished sand) supported by a submerged sill.

Method:

A perched beach provides a wider beach at locations where the natural beach has become too narrow and low due to the erosion of the coastal profile at a location, where the coastline is fixed. Assuming the situation is that a wider beach shall be provided by beach fill and that the available borrow sand is of the same quality as or slightly finer than the natural sand. In this case the sand shall be filled out to the closure depth in order to be stable. This will require large amounts of fill. To avoid this, the submerged sill is introduced as a substitute for the seaward part of the profile as seen Figure 17.40.

Functional characteristics:

The perched beach concept is, in principle, very simple; the submerged sill substitutes the outer part of the active equilibrium coastal profile. However, under extreme wave conditions and storm surge, the perched beach profile may adjust to the extreme conditions by moving sand from the upper part of the profile to deeper water, i.e. over the sill. This will be a reversible process for a normal beach profile, but for a perched beach, the process will lead to permanent loss of sand over the sill.

High waves combined with low tide would lead to wave-breaking over the sill and hence mass transport of water over the sill. An undertow would compensate for this landward transport of water but would also lead to a loss of sand from the perched beach profile.

If the sill is made very high in order to minimise the sand loss, extreme conditions may lead to undesirable wave-breaking and a mass transport of water over the sill. This will result in current circulation and undertow currents, both of which are dangerous and difficult to control. In calmer conditions, the high sill may result in stagnant water and poor water quality.

The conclusion is that a perched beach should not be designed with an extra high sill to minimise sand loss. A further consequence is that a perched beach may require some maintenance.

Applicability:

The perched beach concept is applicable on coasts of Type 1M and 1E at locations with a steep and eroded coastal profile. It shall be noted that it is not applicable on coasts with oblique wave attack and at locations with a macro tidal regime. In general, a perched beach shall be carefully designed in order to avoid dangerous currents and loss of sand.

A perched beach is only applicable against mild chronic erosion where the net littoral drift is very small due to nearly perpendicular wave approach. Perched beaches are not applicable against acute erosion.

Sea level rise will increase the volume of sand needed for re-nourishing the perched beach. Generally a perched beach is not applicable against SLR

17.5.5 Cove and artificial pocket beach

Definition:

A cove is a small pocket beach suspended between two minor (inside the littoral zone) oblique coastal structures, see Figure 17.41, whereas an artificial pocket beach is typically a larger beach suspended between two oblique major coastal structures reaching beyond the littoral zone, see example in Figure 17.42. This latter type of artificial beach serves more as beach improvement rather than shore protection.

Figure 17.41 Layout of a cove (upper) and photo of a cove (lower) constructed at the SW coast of Sri Lanka.

Figure 17.42 Major artificial pocket beach at San Stefano, Alexandria, Egypt.

Method:

The pocket beach will form by itself as soon as the structures have been built, however it is recommended to include initial beach fill in the design whereas an artificial pocket beach is normally independent of the littoral processes along adjacent stretches. The offshore extension of the cove structures are normally less than the width of the littoral zone whereas the extension of the structures supporting a pocket beach is larger than the width of the littoral zone.

Functional characteristics:

The shape of the beach in a cove and in a pocket beach is fairly independent of the directional characteristics of the wave climate due to the relatively narrow opening, which makes diffraction the most important factor for the shape of the beaches. The distance from the coastline to the head of the structures is important for the current conditions in the bay, as short distance introduces currents near the structures whereas longer distances minimises currents in the bay. This distance is normally relatively short in a cove implying that there can be strong currents, which makes coves unsuitable for recreational use. The dimensions of artificial pocket beaches are normally relatively large implying that strong currents near the beach will normally not be generated. This makes large artificial pocket beaches suitable for recreational use.

Applicability:

The Cove

The cove concept is especially suited for coasts with a very oblique wave attack, i.e. type 3M and 3E coasts, and for locations with steep coastal profiles. This type of coast has a large littoral transport potential and is often exposed to erosion and will therefore in many cases already have been protected, typically by a revetment. This type of coast is normally unsuitable for artificial nourishment as a stand-alone measure, as this will result in large maintenance requirements. Nor will beach fill in connection with structures work, as the structures can only hold a short beach section due to the oblique wave exposure.

The small cove shown in Figure 17.41 may convert a small coastal section protected by a revetment into a semi protected beach environment. A cove is consequently especially suited as a combined coast protection and beach landing arrangement at sections otherwise protected by revetments.

Although the cove concept is the optimal solution for type 3 coasts, the concept can also be used for all other types of coasts.

The opening to the cove should not be made too narrow, as this will cause the bay to be completely filled by sedimentation.

The cove may trap seaweed and debris, but the smooth shape of the structures will normally reduce this problem.

Provided the crest level of the breakwaters is sufficiently high, sea level rise will only result in a general setback of the beach in the cove equal to the general setback in the shoreline position as calculated in Subchapter 6.4.2.

The cove solution is suitable in connection with chronic erosion but is only partially applicable against acute erosion.

Artificial pocket beach
An artificial pocket beach is used as a recreational facility providing a semi protected beach lagoon at locations which are too exposed for bathing or where there is no recreational beach. An artificial pocket beach may also be part of a coast protection scheme as in the case of the San Stefano pocket beach.

Pocket beaches are best suited for coast of types moderately to exposed with perpendicular to moderate oblique wave approach (1M and 1E to 3M and 3E).

The shoreline in a pocket beach will recede according to Bruun's rule when exposed to Sea Level Rise.

17.6 Shore protection

Shore protection is defined as follows:

SHORE PROTECTION: Measures aiming at protecting, preserving or restoring the shore and the dynamic coastal landscape as well as protecting against coastline retreat to the extent possible.

17.6.1 Regulation of the coastal landscape

17.6.1.1 Dune stabilisation

Background:
Dunes are a natural coastal feature on moderately exposed and exposed coasts. Dunes are formed by the sand, which blows inland from the beach and is deposited in the area behind the coastline. The presence of dunes is thus mainly a function of the presence of a wide beach with suitably fine sand and prevailing onshore winds. During storm surge events, the foot of the dunes can be eroded, but the dunes act as a very flexible buffer zone, which protects the hinterland from erosion and flooding. The eroded material supplies material to the littoral budget minimising the general erosion along the entire section of shoreline. During the storm and also during more normal events, sand will be transported inland, sometimes in connection with the formation of wind alleys in the dune row. After the storm, the damaged dune will gradually be built up again, maybe slightly more inland. This means that a dune acts as a natural flexible coast protection and sea defence measures. The dune formation moves backwards simultaneously with the eroding coastline and at the same time it maintains its form and volume as well as a wide beach. This is a natural quasi-equilibrium situation.

However, the natural balance will shift if the dune vegetation is damaged by grazing or if beach-users generate too much traffic or if the dune vegetation is stressed by extraction of groundwater etc. Such stress factors may cause the dunes to degrade resulting in loss of the coast protection provided by the natural dunes. At the same time the sand blowing inland causes various kinds of damage. Consequently, authorities normally tend to protect dunes by protection of the vegetation, regulating grazing and traffic and by avoidance of other stress factors.

In some cases authorities have been very eager to protect the dunes by planting marram grass and placing fascines in the wind alleys to trap the sand. (Fascines are the placing of pine or spruce branches as a wind fence). This has, in some cases, resulted in a complete fixing of the dune position and an unnatural growth in height. Consequently, the flexibility of the natural dune is lost resulting in a gradual disappearance of the dune when erosion progresses, whereby the protection provided by the natural dynamic dune system is lost.

The impact of sea-level rise on a flexible dune system will be the gradual land-ward movement of the entire dune system, provided the rise in sea-level happens slow enough and there is space for the dune system to retreat landward. Therefore the enhancement of a flexible dune system is very well suited for coastal protection when considering the impacts from future sea-level rise.

Method:

Planting marram grass and setting up spruce fascines for trapping of sand and enhancement of dune build up. Larger wind alleys can also be filled artificially prior to planting. However, as mentioned above, the protection should not be so comprehensive that it completely fixes the dunes.

Figure 17.43 Marram planting and the placing of spruce fascines in wind alleys (Danish Coastal Authority).

Restrictions for their use can also protect the dunes. Grazing in dune areas is prohibited in most countries, and authorities often limit public access. Such restrictions may regulate the traffic in the dunes, e.g. by prohibiting different kinds of traffic such as riding, mountain biking and motor traffic, and arranging paved walking passages in areas near parking lots and fencing fragile newly planted areas.

Functional characteristic:

Dune stabilisation is a sustainable protection measure, enhancing the natural protection ability of dune areas. Stabilised dunes protect against wave and storm surge attack to a certain extent and at the same time it preserves the natural coastal landscape, if performed moderately. Dune stabilisation requires a planned and co-ordinated effort.

Applicability:

Dune stabilisation is applicable on all coastal types where natural dunes occur. This is especially the case on moderately exposed to exposed sandy coasts with perpendicular to very oblique wave (wind) attacks, types 1M to 4M and 1E to 4E.

The flexibility of dune systems makes well maintained dune systems well suited to accommodate future sea-level rise, however it is important to notice that some setback of the shoreline and of the coastline will occur in connection with sea-level rise. Dune stabilisation has to be supplemented with nourishment if such setbacks are not acceptable in connection with sea-level rise.

Dune stabilisation is applicable against chronic erosion as well as against acute erosion.

Artificial dunes are also used as a sea defence measure. This will be further discussed under sea defences.

17.6.1.2 Cliff stabilisation

Background:

Coastal cliffs can be unstable due to the combined effect of several factors, such as:

1. Erosion of the foot of the cliff caused by wave action and storm surge
2. Cliff erosion occurs as a consequence of chronic erosion as well as acute erosion
3. Sliding or weathering of the slope due to geo-technical instability. The erosion of the foot of the cliff normally initiates geotechnical instability, but the sliding/collapse can be of different nature depending on the geo-technical conditions of the slope. There are basically three different situations:
   - If the cliff material is non-cohesive material (sand), the sliding of the cliff will normally occur shortly after or simultaneously with the erosion of the foot of the cliff as a talus formation, which is the collection of fallen material forming a slope at the foot of the cliff.
   - If the material is a mixture of clay, silt, sand and boulders, such as in the case of moraine till, the slope can be very steep for a longer period due to the cohesive forces, but the slope will eventually collapse. Smaller or bigger fractions of the cliff will fall in connection with groundwater pressure, frost impact or general weathering, or by sliding. Sliding will especially occur in connection with groundwater pressure.
   - If the material consists of plastic clay or silty clay, the collapse of the cliff will be in the form of slides, which can go far behind the top of the cliff.
4. Erosion of the cliff by wind transport of sand away from the open cliff frontage. Obviously, this will be most pronounced if the cliff material is sand.
5. Future sea level rise can increase the rate of erosion of coastal cliffs.

Method:

The basic cause of cliff instability is normally the marine erosion of the foot of the cliff.This erosion can be mitigated using a revetment. Establishment of the revetment will halt further erosion of the foot, but at that stage the slope of the cliff may very well be so steep that weathering and sliding may still occur. This can be counteracted by the following means:

- Artificial smoothing of the slope, if there is enough space at the foot as well as at top of the cliff for this. This will counteract future uncontrolled weathering and sliding.
- Smoothing of the slope by filling with granular material at the foot of the cliff. This requires that there is sufficient space at the foot of the cliff for the filling.
- Establish a vegetation cover on the cliff. This can best be done by following the above-mentioned smoothing of the slope. Good vegetation protects against weathering and groundwater seepage, and thereby to some extent against sliding

- Drainage of groundwater. This can be used if the cliff suffers from sliding due to high groundwater pressure and poor drainage conditions. Horizontal and vertical drains can be used as well as the regulation of the surface runoff.

Cliff slopes are often “protected” by dumping various types of rubbish, such as garden refuse etc., over the cliff. This is an inappropriate “solution” because the dumped material spoils the vegetation and thereby increases the risk of instability of the slope.

Functional characteristic:

Cliff stabilisation presupposes that the foot of the cliff has been stabilised. Stabilisation counteracts the natural behaviour of cliffs to slide and weather. However, an active cliff is part of the dynamic coastal landscape and should therefore in principle be maintained as an integrated part of this landscape.

Applicability:

Cliff stabilisation can be applied at all moderately exposed to exposed coasts where the foot of the cliff has been protected; however, in order to preserve the dynamic coastal landscape cliff stabilisation should only be used sparingly. Preserving the active cliff at densely built-on coasts is normally not acceptable because the presence of an active cliff implies setback of the coastline, which is not acceptable in such areas. Cliff stabilisation by smoothing of the slope can only be used when there is sufficient space at the foot of the cliff or in the hinterland for the smoothing. In other cases stabilisation has to be performed by vegetation or by drainage.

Accommodating sea-level rise requires strengthening of the foot of the cliff by reinforcement of e.g. an existing revetment. In this case the same cliff stabilisation measures as described above can be applied.

Cliff stabilisation can be used to counteract chronic as well as acute erosion under the condition that the foot of the cliff is protected by e.g. a revetment.

17.6.1.3 Beach scraping

Definition:

Beach scraping is recovering material from the berm at the foreshore and placing it on the backshore at the foot of the dunes or the cliff.

Method:

A beach berm consisting of coarse sand or gravel is sometimes formed during relatively mild summer wave conditions, which tend to transport seabed material towards the beach. Beach scraping is normally performed using front loaders where the coarse materials in the beach berm are excavated and deposited at the backshore.

Functional characteristics:

The purpose of beach scraping is to strengthen the upper part of the beach profile and the foot of the dune/cliff. The material is placed in a position that reduces the erosion occurring during storm surge conditions, i.e. during situations with acute erosion.

Applicability:

This method can be used for beaches, which are mainly exposed to seasonal erosion or the acute erosion during extreme events, whereas it is probably not feasible for locations, which are exposed to chronic erosion. One disadvantage of the method is that the material used for strengthening the upper part of the beach profile is taken from the lower part of the same profile, which means that the method only contributes insignificantly to the overall stability of the beach profile. Another issue is that the scraping operation, which is typically performed late summer, may disturb recreational activities.

Scraping is not applicable against erosion caused by sea-level rise.

17.6.1.4 Managed retreat

Definition:

The natural and free development of a coastline, be it erosion or accretion, should ideally be the overall objective for all coastlines. In rural areas, this happens without any problems. Developed areas exposed to erosion have, in many cases, been protected by different kinds of coastal protection structures, preventing the natural coastal morphological processes. With time, this may result in a situation, where the coastline appears as a completely engineered feature, with a complete loss of the resources, which the natural coast constitutes. This situation will be further aggravated if/when sea level rise occurs.

In such situations one may consider relaxing the requirements for fixing the coastline in a certain position and allow a managed retreat. The rate of this allowed retreat will typically be less than the natural no-interventions retreat rate.

Method:

A managed retreat is normally obtained through a combination of methods. First of all, the acceptable retreat rate will depend on the land use. If housing or infrastructure facilities are very close to the coastline, managed retreat is only possible if these facilities are abandoned or moved landward. However, this will generally not be feasible. In densely populated areas authorities might require the re-establishment of the natural coastline, or sections of it, to enhance the environmental and recreational quality of the area. In such cases the authorities can expropriate or buy the property with a view to demolishing the buildings and infrastructure and thereby give the coast back to natural processes.

If publicly owned rural land has been protected against coastal erosion in the past, the shift to a managed retreat is less complicated. The authorities may wish to demolish the old coastal protection structures and leave the coast exposed to natural development, provided this is acceptable. If this natural development will result in an unacceptable situation, for example, the breach of a sand spit, the threatening of an isolated building or similar, the removal of the hard structures has to be combined with some nourishment or other environmentally acceptable intervention.

The managed retreat normally means a combination of demolishing worn out coastal protection structures and the execution of soft shoreline management interventions, possibly supplemented with very few environmentally optimised structures. The required amount of soft shoreline management interventions will vary, but it will typically consist of well-planned beach fill or beach nourishment, whereby the development of the shoreline can be managed to suit the set objectives for the management unit. In such a case the managed retreat switches gradually over in a shoreline management scheme which typically contains elements of beach fill supported by a few coastal structures.

Functional characteristic:

The managed retreat is simply to remove the restrictions on the natural coastal development and to leave the coast for natural development. In case the natural erosion rate is unacceptable, it can be necessary to supplement the demolition of coastal structures with soft engineering interventions to obtain an acceptable coastline retreat rate. Soft engineering solutions reintroduce the natural coastal processes as the dominating development factor.

The **advantages** of a managed retreat are:

In areas protected by coastal protection structures:

- A reduction in cost for coastal protection maintenance

- The re-establishment of the natural coast in the form of a less steep natural coastal profile, the re-appearance of a sandy beach and the possible re-appearance of an active cliff
- A positive impact on adjacent stretches through the supply of littoral material
- The re-establishment of the shore as a natural coastal defence allowing the natural shore to function as a buffer
- The re-establishment of the natural coastal habitat
- The enhancement of the beauty of the natural coastline
- Better recreational/touristic value of the shore
- Increased safety for swimming

In low lying areas protected by combined coastal protection and sea defence structures. As above, plus the following:

- The re-establishment of a wide wetland previously protected by the sea defence is an important environmental and ecological improvement
- Enhancement of natural sedimentation processes on the new wetland.

The **disadvantages** of a managed retreat are mainly:

- Expensive, especially if private land has to be taken over by the public
- Coastal land area will be lost unless combined with nourishment
- Coastal land may be exposed to flooding if the managed retreat philosophy is applied where sea defence structures are removed or moved backwards

Applicability:

The managed retreat is an option in areas exposed to coastal erosion and in areas exposed to combined coastal erosion and flooding if the above disadvantages can be accepted. Normally the authorities will have to take lead in this kind of shoreline management. It should be noted that it would normally not be economically feasible to protect rural/agricultural land. It can, for example, be mentioned that in Denmark it is the policy of the authorities not to allow coastal protection in rural areas, and this is valid for both publicly-owned and privately-owned land.

Managed retreat can be used in areas exposed to chronic as well as to acute erosion.

The expected sea level rise will impose increased pressure on all types of coasts both increased risk for coastal erosion and increased risk for coastal flooding. This increases the need for maintenance, reinforcement and rehabilitation of existing coastal protection and sea defence schemes but it also increases the risk for further degradation of the beach environment in these protected areas. This can sometimes be used as an argument for a change in the protection practice used hitherto along the lines of re-establishment of the natural beaches and coastal landscape.

17.6.2 Nourishment

Background and general considerations:

Nourishment can be divided into five types: Dune nourishment, Backshore nourishment, Beach or Foreshore nourishment, Shoreface nourishment and Profile nourishment. Nourishment as part of a shoreline management project, which combines structures and initial nourishment, also referred to as Beach Fill, will not be discussed in this chapter; however, the general considerations regarding nourishment, as discussed in the following, also apply for beach fill combined with structures.

Nourishment can be regarded as a very natural way of combating coastal erosion and shore erosion as it artificially replaces a deficit in the sediment budget over a certain stretch with a corresponding volume of sand. However, as the cause of the erosion is not eliminated, erosion will continue along the nourished beach section. It is thus inherent in the nourishment concept that the nourished sand is gradually sacrificed. This means that nourishment as a stand-alone method normally requires a long-term maintenance effort.

It is important to note that traditional nourishment, where the sand is distributed evenly along a coastal section, is only suited for relatively long sections of shoreline; otherwise the loss of sand to neighbouring sections will be too large. Dean (2002) says that the durability of a nourishment varies as the square of the length of the nourishment section, thus if a nourishment over a 1 km long section loses 50% of its material from the section over where it was placed over a period of one year then the same nourishment in terms of volume per unit length of beach over a 2 km long section would be expected to lose 50% of its material in a period of 2^2 x 1 years = 4 years. The presence of a background erosion would alter these results. These conditions are illustrated in the results from morphological simulations performed by DHI as presented in Figure 17.44.

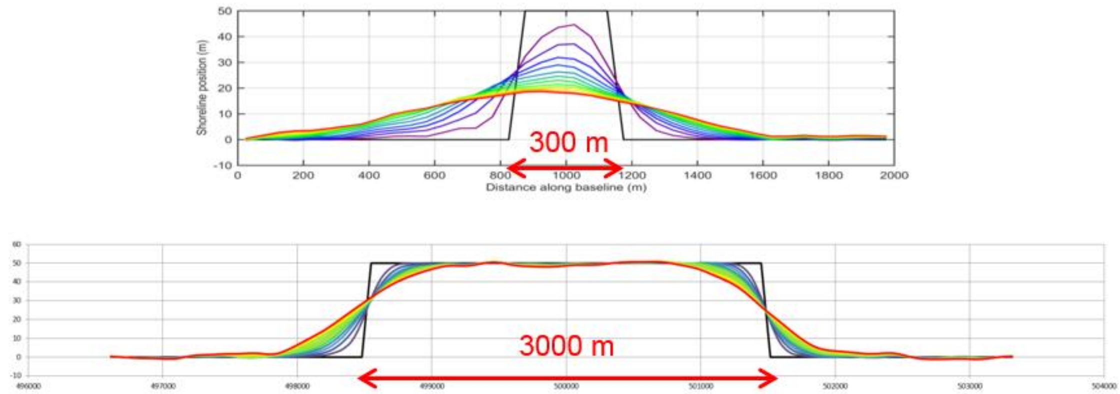


Figure 17.44 Monthly shoreline evolutions over a year from morphological simulations of 50 m wide nourishments for 300 m (upper) and 3,000 m (lower) long sections, respectively. Exposed to H_S = 1 m, angle of incidence at deep water: 10 deg., d_{50} = 0.2 mm. NOTE: different scales.

It is evident from the simulation results that the durability of the long nourishment is considerably better than that of the short nourishment.

Regular nourishment over long stretches requires a permanent well-functioning organisation, which makes nourishment as a stand-alone solution unsuitable for privately owned short sections of coasts unless the stakeholders join their efforts for longer sections of shoreline and are able to organise the regular maintenance nourishment campaigns. Public involvement/administration of nourishment projects is a considerable advantage.

The success of a nourishment scheme depends very much on the grain size of the nourished sand, the so-called borrow material, relative to the grain size of the native sand. As described in Subchapter 7.3, the characteristics of the sand determine the overall shape of the coastal profile expressed in the equilibrium profile concept. Furthermore, in nature the hydrodynamic processes tend to sort the sediments in the profile so that the grain size decreases with increasing water depth.

When borrow sand is deployed in a coastal profile, neither the profile nor the grain size distribution will normally match the equilibrium conditions. Nature will attempt to re-establish a new equilibrium profile so changes will always occur in the nourished profile. There will also be changes caused by the continued long-term erosion trend and the profile response to individual events. This means that in practice it is neither possible to perform a short-term nor a long-term stable nourishment at an eroding coast. It is inherently unstable on eroding shorelines. These are the basic realities, which the public, the politicians and those who fund the projects, have to accept. On the other hand, as environmental concerns and requirements for sustainability are gaining in importance, nourishment has gradually increased its share of shoreline management schemes over the last decades.

As mentioned above, the performance of a nourishment scheme very much depends on the grain size of the borrow material relative to the grain size of the native material, see the discussion of equilibrium profiles in Subchapter 7.3 and Figure 7.6.

If the borrow sand is finer than the native sand, it will tend to form a flatter profile than the natural one. The equilibrium reshaping of the nourished sand will reach out to the closure depth. If the objective of the nourishment is to obtain a wider beach, this will require very large volumes of sand, as illustrated in the upper part of Figure 17.45.

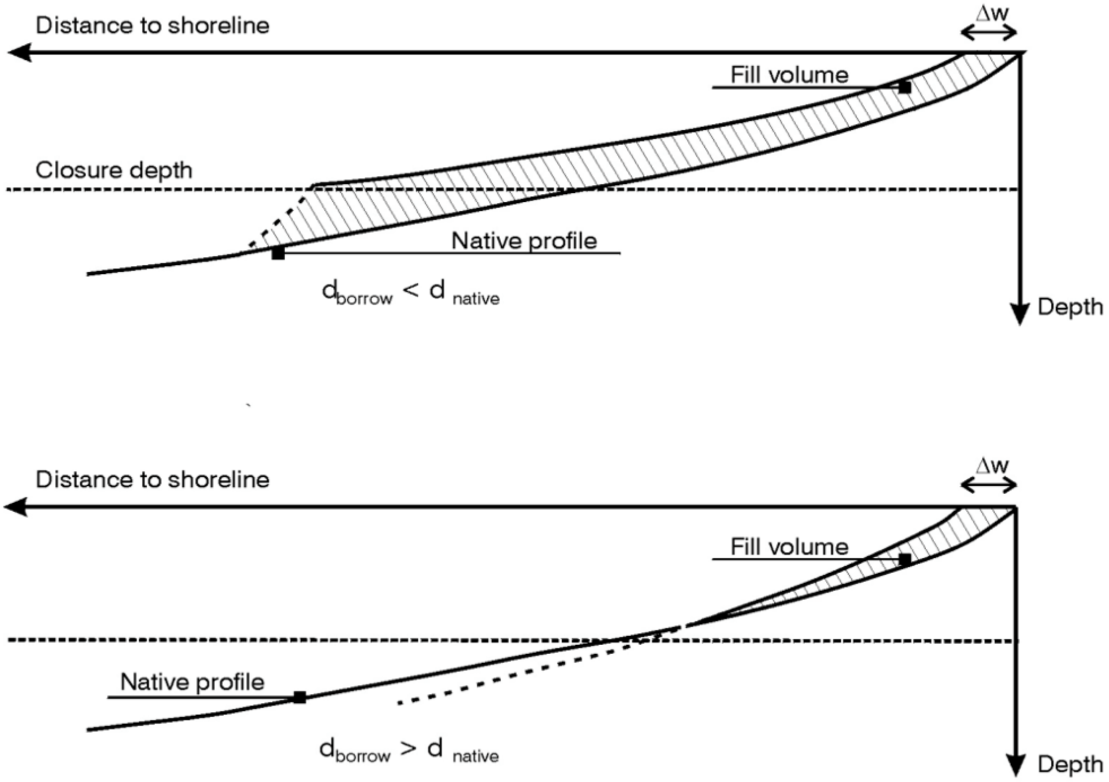


Figure 17.45 Equilibrium conditions for nourished beaches required to obtain an additional beach width of Δw with borrow sand, which is finer and coarser than the native sand (upper and lower, respectively).

It is evident that the volume of sand needed to obtain a certain beach width increases drastically with the decreasing grain size of the nourished sand. Most coastal authorities realise this and some of them have introduced special bonuses for their nourishment contractors when they provide coarse sand.

It is evident from this figure that if borrow sand with a larger grain size than that of the native sand is nourished into a coastal profile, it will tend to form a steeper profile than the natural profile. This means that a wider beach will tend to be formed using coarser sand for the same nourishment volume, see Figure 17.45 lower part. Furthermore, coarser sand will be more stable in terms of longshore loss.

The characteristics of nourished sand can also affect safety or have other impacts as discussed in the following. If, for example a nourishment is performed with relatively coarse or too graded material compared to the native sand, the action of the waves in the nourished profile may result in the formation of a submerged beach scarp, a so-called beach step, immediately seaward of the shoreline, which can be dangerous for bathers as a beach step can be up to over a meter in height. Other morphological phenomena may cause difficulties in using the beach as well as aesthetic impacts; this applies especially for backshore and beach nourishment, which can generate a very steep scarp due to the imbalance in the coastal profile caused by the nourishment, see Figure 17.46. Mitigating measures for such kinds of impacts are a better design of the nourishment scheme.

Figure 17.46 Beach scarp at recently nourished beach, Jumeirah, Dubai.

Areas, which for a long time have been protected by hard coastal protection structures, have often lost their beaches and developed steepened coastal profiles. Such areas are far from their cross-shore equilibrium form. If nourishment is introduced in such areas it will require major volumes of sand to restore the profile to the equilibrium profile, which is required to re-establish a sandy beach and to release the pressure on existing coast protection structures. In such cases, it is very important to find borrow sand that is coarser than the native sand. However, biological factors point towards using sand with the same grain size distribution as the native sand, see discussion below.

Nourishment is a very flexible method and therefore well suited to accommodate future sea level rise as the re-nourishment volumes or intervals can easily be adjusted in the future if needed due to sea level rise.

Nourishment with shingle

Nourishment is normally performed using sand; however, nourishment can also be performed using shingle. This is normally only practiced by reinforcing already existing shingle beaches, which needs some extra beach material to the stable. This is similar to a berm breakwater, which is constructed in quarry run, which is reshaped when exposed to high waves. A shingle nourishment of an existing shingle beach can therefore be considered as a kind of soft revetment or berm revetment, which acts as a reinforcement of the natural beach. Natural shingle beaches sometimes acts as a kind of natural seawall as they form berms separating the beach from low laying hinterland, see Figure 17.47. Reinforcement of such a formation can be considered as a kind of soft seawall.

Figure 17.47 Shingle beach with beach berm forming natural defence of low-lying hinterland.

Environmental considerations:

There are environmental impacts when sand is deployed in a coastal profile. The main impacts are the following:

1. Spill of suspended fine sediments to the ambient marine environment
2. Disturbance of recreational activities
3. Impact on the marine micro fauna in the sandy seabed and on the marine flora

Ad 1:

Spill of suspended sediment is normally not an important issue under the assumption that the borrow sand is clean sand of marine origin and of a good quality with only negligible contents of fine sediments. A considerable “washing” of the sand is normally taking place in the sand mining process especially if the sand is mined by suction dredging. This means that there may be some spill of suspended sediments at the borrow site but less spill at the deployment location. However, these issues are normally covered in the EIA process for major nourishment projects.

Ad. 2:

The nourishment process may result in noise and in restrictions in access to the nourishment site for safety reasons as the nourishment process typically involve activities by heavy equipment for installation of pipelines (bulldozers) and for distribution of sand (bulldozers and dumpers) etc. Therefore a general recommendation is that nourishment shall preferably be performed off the recreational season. Again, these issues are normally covered in the EIA process for major nourishment projects.

Ad. 3:

Nourishment is normally performed at locations with sandy beaches and shorefaces. However, at eroding coasts, where the backland consist of e.g. moraine till, there may be sections of the beach and the shoreface which are covered with stones and boulders and where the sandy beach has been lost due to passive coast protection. At such locations there may be marine flora in the form of macro algae attached to the stones and marine fauna adapted to this environment. Nourishment at such locations will change the conditions drastically, which has to be taken into consideration in the EIA process.

Nourishment in a sandy coastal profile, which is the normal case, has also some environmental implications.

Sandy beach faces normally house a rich intertidal macroinvertebrate species community, such as Bathyporeia pylosa. These small invertebrates live in the sand surface layer and are present in huge numbers. They feed by eating algae attached to the sand grains and different species are characteristic for different types of sand. These invertebrates swim during the night, where they are feeding source for many fish larvae during the summer months. They are consequently important for the natural production of fish stocks.

Sandy shores are hosts for a great number of these invertebrate communities, which are of great importance as feeding basis for fish larvae. The general pattern for these communities is that they reside in deeper water during the winter (typically on the outer bar) whereas they move to the shallow part of the beach face during summer.

Nourishment on a beach will cover a great number of the invertebrates, but the general opinion is that they will recolonise within less than a year. But if nourishment is performed e.g. in the spring, the feeding basis for the fish larvae will be reduced the following summer.

Tomme (2013) proposes the following recommendations for beach nourishment in relation to minimising the impact on the beach environment:

> *To mitigate the impact of beach nourishments on intertidal sandy beaches and to assure a swift recolonization of the nourished beach by the original sandy beach community, the use of sediment that resembles the initial beach sediment, is therefore strongly encouraged. The use of coarse sediments is likely to have a negative effect on some of the dominant macrobenthic species of the high-intertidal on fine-grained beaches. Therefore, both technical as well as ecological aspects of the sandy beach ecosystem should be considered in beach nourishment programmes to assure its highly valuable ecosystem role.*

Another environmental mitigation measure to consider in relation to minimising the impact of nourishment is to perform the nourishment during the winter time and to perform the nourishment on the upper part of the beach profile as these two measures will secure minimal impact on the coastal fauna.

Traditionally, nourishment has been performed evenly distributed over longer sections, referred to as “section nourishment” however; from a marine environmental point of view this is not ideal because the marine fauna will be disturbed over the entire nourishment section. This is the background for the alternative concept of “stockpile nourishment”, where all the nourishment material is stockpiled within a limited area from where it is distributed along the coast by wave action. The environmental advantage of this method is that the marine fauna is only disturbed at the limited nourishment location, outside this area the sediments are distributed by natural littoral transport processes which does not disturb the marine fauna. The technical conditions for stockpile nourishment are described in the following.

Methods, functional characteristics and applicability:

There are two principally different nourishment methods as described above, namely:

- Section nourishment, i.e. nourishment distributed uniformly along the shoreline in the project area, and
- Stockpile nourishment, i.e. nourishment of a large amount of sand in a stockpile limited to a short fraction of the shoreline in the project area

These methods are described in the following.

17.6.2.1 Section nourishment

Section nourishment can principally be performed in five different ways as discussed briefly in the following and as illustrated in Figure 17.48.

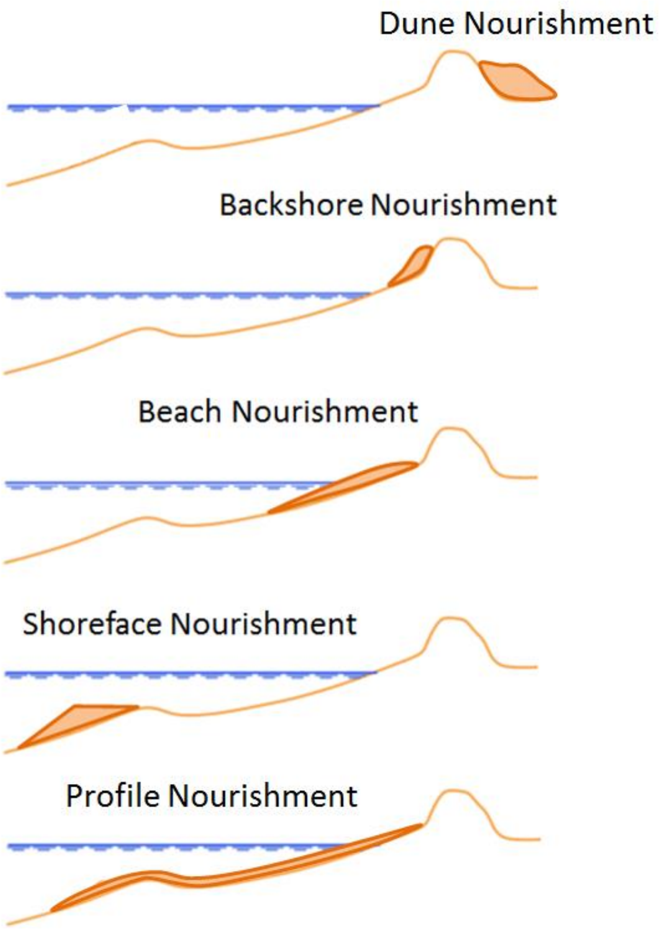


Figure 17.48 Principles in dune nourishment, backshore nourishment, beach/foreshore nourishment, shoreface nourishment and profile nourishment.

Dune nourishment is the supply of sand to the dune system with the purpose of increasing the strength of the dune against breaching during acute erosion events rather than increasing the strength against coastline setback due to chronic erosion. This is used at stretches where the dune row acts as a natural defence against flooding of low laying hinterland or, when the dune is located at a sand spit separating the sea from a coastal lagoon, against flooding of the coastal lagoon and surrounding low laying land areas.

Dune nourishment is thus a reinforcement of the dune against breaching during storm surge conditions. Research during the COADAPT project has shown that it is most effective to increase the width of the dune rather than increasing the height of the dune in such cases. An example of such a dune nourishment is presented in Figure 17.49.

Figure 17.49 Dune nourishment at Kryle at the Danish North Sea Coast. Left: photo; Right: satellite image.

Backshore nourishment is the strengthening of the upper part of the beach by placing nourishment on the backshore or at the foot of the dunes.

The main objective of backshore nourishment is to strengthen the backshore/dune against erosion and breaching during extreme events. The material is stockpiled in front of the dunes and acts as a buffer, which is sacrificed during extreme events where acute erosion is taking place. This kind of nourishment works more by volume than by trying to restore the natural wide beach. The loss is normally large during extreme events, whereby steep scarps are formed. Backshore nourishment can be characterised as a kind of emergency measure against dune setback/breach; consequently, backshore nourishment is recommended as a tool against acute erosion but it is not the recommended method for compensating chronic erosion.

Backshore nourishment can be performed by hydraulic pumping through pipes discharging at the foot of the dunes and later adjusted using a bulldozer. The sand source can be either an offshore supply via a cross-profile pipeline, floating or buried, or it can be supplied along the shore from, for example, a sand bypassing plant. The sand can also be supplied via land transport by dumpers.

Beach nourishment or Foreshore nourishment is the supply of sand to the shore to increase the recreational value and/or to secure the beach against mainly chronic coast erosion by feeding sand on the active part of the beach however, backshore and beach nourishment is also applicable against acute erosion. Beach nourishment is not a coastal protection measure, as the beach will normally be flooded during extreme events allowing erosion of the coast (coastal cliff/dune front), but it will support possible coastal protection measures. When performing beach nourishment, the borrow sand must be similar to the native sand to adjust smoothly to the natural profile. It may be an advantage to use slightly coarser sand than the natural beach sand, as this will enhance the stability of the resulting slightly steeper profile, however also the ecological impacts of coarser sand shall be considered as discussed under “Environmental considerations” in Subchapter 17.6.2. Finer sand will very quickly be transported to deeper water and will thus not contribute directly to a wider beach.

The experience of the Danish Coastal Authority related to numerous beach/foreshore nourishment projects is that the nourished sand is partially transported downstream and partially transported offshore and that the nourishment contributes to building up the bar system. The distribution of the nourished sand between being transported downstream by the longshore transport and being transported offshore by the cross- shore transport depends on the local conditions, such as the shape of the coastal profile and correlation between high water and wave action. However, it can be concluded that the sand does normally not “disappear” into deep water but the nourished sand increases the volume of sand available for the transport capacity and it strengthens the coastal profile.

Shoreface nourishment, also referred to af bar nourishment, is the supply of sand to the outer part of the coastal profile, typically on the seaside of the bar. It will strengthen the coastal profile and add sediment to the littoral budget in general. This type of nourishment is used in areas where coastal protection measures have steepened the coastal profile or in areas exposed to chronic erosion.

Shoreface nourishment is often performed using split barges. The unloading is fast and the unit price therefore low. Shoreface nourishment can profitably be used in connection with large beach nourishment schemes, in which finer borrow material, which does not fulfil the requirements for beach nourishment, can be used in the outer part of the profile where it naturally belongs.

Stand-alone shoreface nourishment acts indirectly as a shore protection measure through slightly decreased wave exposure and as a shore restoration measure. Results of tests with shoreface nourishments performed by the Danish Coastal Authority have shown that this type of nourishment is relatively stable and that it acts as a large submerged breakwater initiating trapping of sand on the foreshore and on the beach/dune face in the nourished area. It was also found that shoreface nourishment more than counteracted the autonomous beach erosion along the nourished section and strengthened the bar systems further downstream but also caused downstream beach erosion.

Both a long bar nourishment (3.5 km) and segmented bar nourishments (3 segments of 750 m spaced 2 km) were tested as part of the NOURTECH project. The experience was that segmented bar nourishments extend the positive effects of the nourishment over a longer section. Segmented bar nourishment also causes leeside erosion.

Shoreface nourishment can with advantage be combined with beach/foreshore nourishment to achieve a cost optimised nourishment strategy. This leads to profile nourishment as discussed in the following.

17.6.2.2 Profile nourishment

Excessive use of passive coastal protection over long stretches often lead to a residual seabed in the coastal profile, where most of the mobile sand has been transported away. This will often result in a situation where the sandy beach is lost and the coastal profile is steepened. Rehabilitation of a sandy wide beach at such locations requires that the entire active coastal profile shall be re-established; it is not enough just to perform beach nourishment because the outer part of the profile is far from the equilibrium shape. In such situations it may be considered to perform nourishment in the entire active coastal profile. This is referred to as profile nourishment.

Traditional beach/nourishment will typically also be spread over the entire coastal profile when it is exposed to rough weather conditions, whereby beach nourishment will naturally develop into profile nourishment. This will be at the expense of faster erosion of the beach as compared to the situation where profile nourishment is performed.

Nourishment in the entire profile will cause higher environmental impact on the macrobenthic species in the coastal profile compared to beach and backshore nourishment.

Figure 17.50 Nourishment methods in practice by the Danish Coastal Authority. Upper: Beach nourishment by pipe discharge on the beach. Lower: Left: Foreshore nourishment by over the bow pumping and right: Shoreface nourishment by split barge. From: Rohde Nielsen.

Profile nourishment is applicable against chronic erosion but it also works against acute erosion.

Profile nourishment is well suited to counteract erosion caused by sea level rise.

General recommendations for section nourishment

The following general design recommendations for section nourishment have been developed during various research initiatives in Denmark:

- A solid knowledge to the littoral budget and coastal erosion is required
- The nourishment volume per meter along the beach per year shall be equal to the sediment budget deficit in order to obtain a stable shoreline
- Shoreface nourishment can be used in well planned long term nourishment campaigns to compensate for chronic erosion

- Foreshore/beach and dune face nourishments can be used to compensate for ongoing chronic erosion and to compensate for acute erosion as a kind of disaster management
- Dune nourishment, or dune strengthening, can be used mainly against acute erosion
- Foreshore/shoreface/profile nourishment disturbs the coastal marine fauna and flora

17.6.2.3 Stockpile nourishment

Stockpile nourishment is the supply of a large amount of sand in a stockpile limited to a short fraction of the shoreline in the project area. The philosophy is that the sand is hereafter distributed along the adjacent shoreline sections by the natural littoral transport mechanisms.

The main **advantages** of stockpile nourishments are:

- The main part of the shoreline is not directly influenced by the nourishment construction works
- The stockpiled sand will gradually be distributed over adjacent stretches by natural littoral processes, thus reducing the ecological stress on adjacent shorelines
- The initially large localised nourishment creates a hot spot for recreation and viewing of coastal processes
- Dependent of the type of coast and the shape of the stockpile nourishment, the natural processes may develop special coastal form elements, such as sand spits and coastal lagoons, which can enrich the diversity of the coastal landscape and attract additional wild-life in the short to medium term
- The price per m^3 nourished sand can be reduced due to less costs to distributing the sand over longer stretches

The main **disadvantages** of stockpile nourishments are:

- The protection does not provide equal level of beach stabilisation along the nourished section and adjacent sections
- The stockpile nourishment may initiate erosion along adjacent stretches if the stockpile has a relatively large extension into the sea and if the main waves are very oblique (have a large angle of incidence). This is the case for type 4 and 5 coastlines. In such cases sand spits and coastal lagoons will typically be formed. This means that the littoral transport will be detached from the downstream shoreline resulting in (initial) downstream erosion.
- Steep slopes may develop at the inner part and at the tip of sand spits, which may be dangerous for unexperienced swimmers
- Dangerous rip currents may be formed at abrupt changes in the shoreline orientation at the boundaries of the stockpile nourishment.

In the Netherlands, a pilot project involving a mega sand nourishment of 21.5 M m^3 of sand was completed in the autumn 2011. This is referred to as the “sand engine” or “zandmotor”, see Figure 17.51, which shows the development of the zandmotor over a 2½ years period. This mega nourishment is expected to be more efficient, economical and environmentally friendly than traditional beach and shoreface sand nourishments which are typically 1-3 M m^3 of sand nourished at 3-5 year intervals on this shoreline. The mega nourishment is anticipated to widen the beach on a 10-20 km stretch of shoreline for a period of 20 years or more.

05.09.2011. From: https://www.flickr.com/photos/zandmotor/6208058825/

10.01.2012. From https://www.flickr.com/photos/zandmotor/6678738365/

20.12.2013. From https://www.flickr.com/photos/zandmotor/11795767285/

Figure 17.51 The development of the Zandmotor mega nourishment. © Zandmotor.

The hooked spit shape was chosen in order to create an open as well as a closed coastal lagoon which can be used for recreation and which adds new types of coastal features to this location. The fast development of the initial nourishment shape and the diversity of the developed morphological coastal elements are clearly seen in Figure 17.51.

A comprehensive field measurement campaign was launched to monitor the morphological development of the sand engine. At the time of writing, the initial results from this campaign have started to be published; these results indicate that the sand engine is performing according to design, but it is still too early to say whether the design will last for the projected 20 years.

Stockpile nourishment is applicable in connection with chronic erosion, but it shall be taken into account that the protection provided by the developing stockpile is only gradually distributed along the downstream stretch and it is therefore only applicable if the situation is not critical along the project area. This means that stockpile nourishment is mainly applicable as maintenance nourishment in areas which are already well nourished and where breaching of the dune row is not immediately threatening.

Stockpile nourishment is applicable as a general maintenance measure to counteract chronic erosion and the additional erosion caused by SLR but it is probably too unevenly distributed to be used against acute erosion.

17.6.3 Beach de-watering or beach drain

Definition:

A beach de-watering system or beach drain, is a shore protection system working on the basis of a drain in the beach. The drain runs parallel to the shoreline in the wave up-rush zone. The beach drain increases the level of the beach near the installation line, thus also increasing the width of the beach. The beach drain method is patented worldwide by GEO, Denmark.

Method:

The drain consists of a permeable plastic pipe installed 1.0 to 2.0 m below the beach surface in the wave up-rush zone. If there is a significant tide, the drain must be installed close to the MHWS line, i.e. near the shoreline. The drain is connected to a pumping well from which the drain water is pumped, either into a lagoon or back into the sea. The only visible part of the drain installation is the pumping well and a small control house.

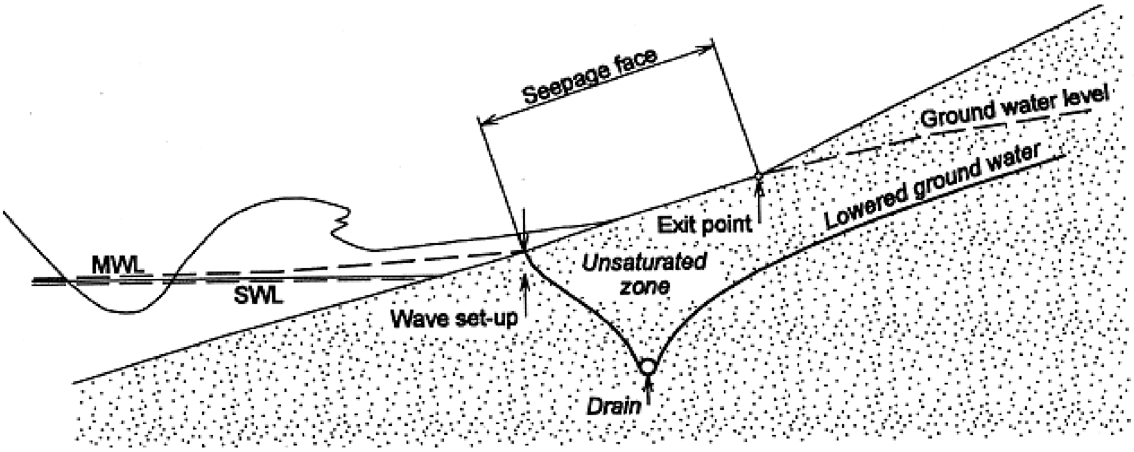


Figure 17.52 Principle of beach drain function.

Functional characteristics:

The conditions influencing the function of the drain are summarised in the following:

- The site must have a sandy beach. The beach material must be sand, preferably with a mean grain diameter in the range of 0.1 mm < d_{50} < 1.0 mm and preferably sorted to well sorted ($C_u = d_{60}/d_{10} < 3.5$). These conditions give the permeability that provides optimal functionality of the beach drain.

- The beach drain works by locally lowering the groundwater table in the uprush zone, which decreases the strength of the down-rush as a higher fraction of the water percolates into the beach. Furthermore, the physical strength properties of the beach sand is increased remarkably by the lowering of the water table in the wave up-rush zone thereby making the beach more resistant against erosion. The groundwater table in the beach is a function of several factors, the most important of which are: a) the groundwater table conditions in the coast and the hinterland, b) the groundwater table caused by tide and storm surge, and c) the groundwater table caused by waves.

- A high groundwater table in the coast and the hinterland influences beach stability and beach formation. The hinterland-based groundwater table saturates a large portion of the beach, causing groundwater seepage through the foreshore. This seepage tends to destabilise (fluidise) the foreshore. The beach drain locally lowers the groundwater table to the level of the drain and counteracts the destabilisation.

- The beach drain works well at locations with relatively high tide because the tide generates an elevated groundwater table in the beach, which can be lowered considerably by the drain. It can therefore be stated that the presence of high tide at a location enhances the functionality of the drain.

- The presence of high storm surges will affect the functionality of the drain by moving the uprush zone landwards away from the drain. The function of the drain during high surge conditions will mainly be indirect; the previously accumulated sand will act as a buffer for the erosion during the storm. When the storm surge falls, the elevated groundwater level in the beach will increase beach erosion if there is no beach drain to prevent it.

- Waves on a beach increase the height of the local groundwater table in the beach, partly due to the wave run-up on the foreshore and partly due to the locally elevated water level in the uprush zone called wave set-up. Once again, the beach drain counteracts this.

- The beach drain requires some wave activity on the beach as the drain works by manipulating the downrush conditions on the foreshore. Too small and too high waves make the beach drain inefficient. It works best on moderately exposed coasts.

- As the beach drain system functions only on the foreshore in the uprush zone, it does not directly protect the entire active profile against erosion. Consequently, it is best suited at locations with seasonal beach fluctuations or where the objective is a wider beach at an otherwise stable section of the shoreline. For locations that experience on-going recession of the entire active coastal profile, the beach drain is probably only suitable combined with other measures. The long-term capability of the beach drain under such circumstances remains to be tested.

Applicability:

The beach drain **is best suited** for the management of beaches with the following characteristics:

- Sandy beaches
- Moderately exposed to waves
- Exposed to tide
- Suffering from high groundwater table on the coast and on the beach
- Exposed to seasonal fluctuations of the shoreline

- Exposed to minor chronic beach erosion
- Locations with a narrow beach, where a wider beach is desired

The beach drain is, however, **not recommended** as a primary shore or coastal protection at locations with the following characteristics:

- Severely exposed locations
- Locations exposed to acute erosion
- Protected locations
- Locations exposed to severe chronic shore erosion and coast erosion
- Erosion caused by sea level rise

17.7 Artificial beaches and beach parks

17.7.1 Artificial beach

An *artificial beach* is the construction of a new beach profile by supply of sand, so-called *beach fill*. An artificial beach is often supported by structures for limiting the fill area, but it can also be performed without supporting structures if the natural conditions provides natural boundaries for the fill, e.g. in the form of natural headlands. An artificial beach shall be stable in plan and profile form, it can as such be considered as a kind of shore protection. The technical difference between an artificial beach and beach nourishment is that an artificial beach operates with a completely new stable beach profile following a stable plan form, whereas nourishment is strengthening of an existing eroding section. A nourishment is normally not stable, but is a substitute for a deficit in the littoral budget, and is as such sacrificed, for which reason considerable maintenance is normally required.

An artificial beach thus consists of a new coastal profile including a wider backshore, but not a new coast area. The establishment of an artificial beach by beach fill in connection with the construction of major coastal structures will minimise the impact at the adjacent sections of shore as the filled sand would otherwise have been taken out of the existing littoral budget. The inclusion of beach fill in connection with the construction of major coastal structures has therefore become a requirement as part of the mitigating measures dictated by the EIA for such projects.

17.7.2 Beach parks and beach reclamation

Definition:

A beach park expands and improves the quality of beach facilities in the area of the beach park, and includes stable sandy beaches and recreational facilities. Technically speaking, a beach park often consists of many elements, such as coastal structures, artificial beaches, artificial dunes, reclamation and dredging.

Reclamation is gaining of new land area by filling some part of the foreshore and the shoreface. If a beach fill has a component of reclamation it is referred to as *Beach Reclamation*. When reclamation is used on an open coast it can be considered as a kind of shore protection or coast protection measure provided that the reclamation perimeter, or part thereof, is constructed as an artificial beach. At the same time this type of protection expands/upgrades the coast by producing new land area suitable for development. If the reclamation perimeter is protected by a revetment, it is neither considered a coast protection nor a shore protection measure, but as a pure reclamation project. This latter type will not be further discussed.

There are two principally different types of beach parks:

- The purely recreational beach park, which is constructed in recreational or habitation areas requiring upgrading of the existing beach quality

- The beach reclamation type of beach park, which is normally only considered and permitted under the following conditions:
  - In congested urban areas, where the shore is highly degraded due to advanced erosion and worn down hard protection works
  - When the reclamation can contribute to development potential in respect of fulfilling new needs, which cannot be fulfilled in the present hinterland, such as providing space for new infrastructure, urban development and recreational facilities
  - When the reclamation is socially, environmentally and economically justified

Beach parks and beach reclamation very often include marina facilities.

Method for establishing an artificial beach:

The artificial beaches in a beach park or in a beach reclamation scheme must be stable in plan shape as well as in the cross-shore direction, as there will be no sources of material as replacement for possible losses. The plan shape stability is obtained by turning the artificial beaches in the direction of the shoreline with zero net transport. Curved stable beaches can be obtained by introducing artificial headlands, which divide the new shoreline into sections adjusted to different wave directions; however, too many sheltering structures must be avoided, as sheltered areas generate dangerous circulation currents and trap sea weed and debris as explained earlier.

The cross-shore stability is obtained by constructing the artificial beaches according to the equilibrium profile matching the available sand characteristics out to the closure depth. Beyond the closure depth, a steeper slope can be used.

The mechanism, which forms an attractive sandy beach, is the constant movement of the sand by the waves and the varying tide/surge. Artificial beaches must be exposed to a certain extent to appear attractive and clean. If they are not exposed to wave action, the beach and the seabed will gradually shift into a soft bed type by settlement of fine suspended matter, which is present in all marine environments. Such a beach environment is unsuitable for recreational activities.

The beach fill sand shall fulfil the following specifications:

- If the fill sand will be mixed with the native sand in the area, the fill sand shall have characteristics similar to those of the native sand in the area in terms of geological composition, colour and grain size characteristics, however as a rule slightly coarser than the native sand

- Preferably sand of marine origin

- A medium grain size d_{50} in the interval: 0.25 mm < d_{50} < 0.5 mm. This will provide a suitable slope of the shoreface and at the same time minimise the loss due to wind drift

- The sand shall be well sorted to sorted , i.e. $2.0 < u < 3.0$, where u is the uniformity ratio defined as: $u = d_{60}/d_{10}$

- Dry Weight of sand at sample location shall be 82% ± 2%
  - Higher DW indicates poor sorting and large content of coarse material, lower DW indicates material that is very well sorted (too steep grain size distribution curve)

- A minimum content of fines, i.e. a silt content less than 1-2 %. The use of medium well sorted sand with a low content of fines will promote a good drainage of the beach, whereby a constantly wet and swampy beach is avoided

- The content of organic matter in fill sand for artificial beaches shall have a smallest possible content of organic matter expresses through Loss of Ignition (LOI) and Total Organic Carbon (TOC) as follows:
  - LOI < 1% of Dry Weight
  - TOC < 0.5% of Dry Weight

- A minimum content of gravel and shells, i.e. less than 3 % material coarser than 2.0 mm, as the coarse fractions will otherwise be separated and deposited on the surface of the finer sand. This will be unpleasant to walk on

- The colour shall be white, light grey or yellow/golden

- The thickness of the beach sand layer shall not be less than 1.0 to 2.0 m dependent on the exposure and stability of the artificial beach. Note that artificial beaches are normally not constructed at very exposed locations

Artificial dunes are also used as landscape elements in beach parks; the sand should be the same type as natural dune sand, however slightly coarser in order to minimise the loss, but not too coarse, as this might prevent the natural reshaping of the dune.

Applicability:

Beach parks are constructed in areas requiring an upgrading of the existing beach facilities, or where developers find possibilities for resort development but inadequate natural conditions. Beach parks can be constructed in most wave climates; however it is a prerequisite that there is a certain minimum wave exposure, as this is required for maintaining an acceptable beach quality.

Insufficient wave exposure of a potential site for an artificial beach can have two principally different causes:

- The wave climate in the area is too mild due to a mild wind climate or due to small fetch. In this situation it is not possible to construct a high quality artificial beach.

- The wave climate at the site is mild due to a geologically shallow foreshore or because the mainland shore is protected by a barrier island or a reef. In these case it will be possible to construct a new better quality beach at a more exposed location. These principles are discussed further in the following.

Improving the beach for the barrier island case

An attractive exposed beach can be constructed in the case of a shallow shoreface by filling sand on the shallow shoreface thereby shifting the beach into deeper water resulting in a more exposed and attractive sandy beach with easy access to suitable bathing depth, see left situation in Figure 17.53.

If the barrier island is low, the associated lagoon is shallow, and the entire complex is relatively narrow, (distance from the mainland shoreline to the sea-shoreline of the barrier island less than approximately 500 m), it will be possible to convert the entire coastal area into an attractive beach and lagoon environment. This can be done in two principally different ways:

1. By filling the lagoon and moving the beach seawards thereby obtaining a more exposed and attractive beach with direct access to sufficiently deep bathing water

2. By dredging the lagoon and upgrading it to a recreational protected water area combined with reclamation on the island. The shoreline of the island is moved seaward to a more exposed location, which enhances the recreational quality of the beach. This principle is shown in right side of Figure 17.53. The Køge Bay Beach Park south of Copenhagen was constructed according to this principle, see Figure 17.54.

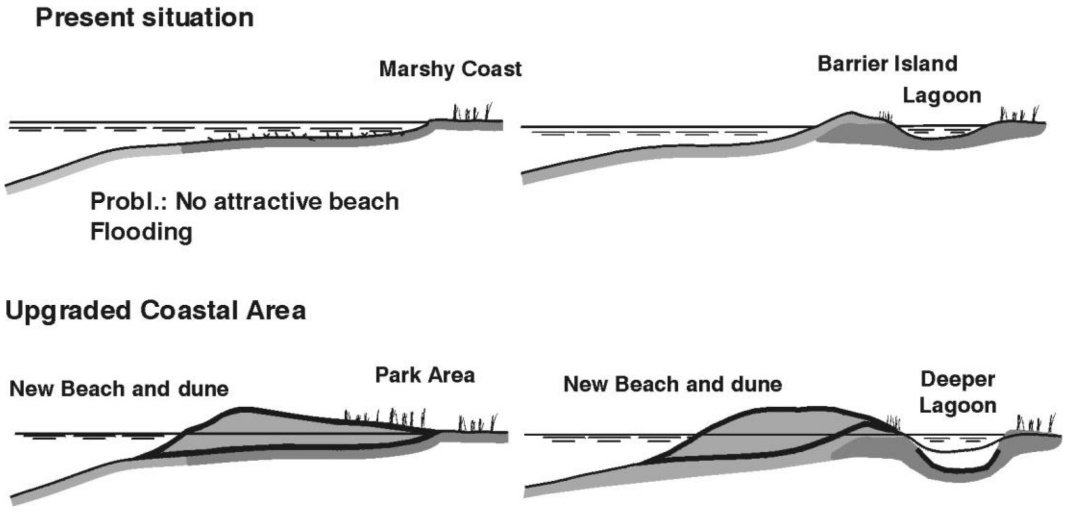


Figure 17.53 Upgrading of protected shores, where the protection is caused by a geological shallow shoreface (left) or by the presence of a barrier island (right).

Figure 17.54 An example of a beach park constructed on top of shallow barrier islands by moving the beaches out to deeper and more exposed water combined with a deepening of the lagoon, the construction of marinas, etc., Køge Bay Beach Park, Denmark.

Improving the beach for the shallow foreshore case:

It will be possible to move the shore to a deeper and more exposed position if a shore is protected either due to a geological shallow shoreface or due to correlation between wave exposure and low water. This can be done either by filling or by excavating for a recreational lagoon combined with filling a new beach at a more seaward location, as shown in Figure 17.53.

At the Amager Beach Park, also near Copenhagen, the existing coastal profile had a very gentle slope and the beach was moved seaward out to an exposed location and an artificial lagoon was excavated in the shallow area, see Figure 17.55. The new beach is divided in two sections, each facing its own dominant incoming wave direction reflecting waves coming from sectors north and south of the Saltholm Island located east of the scheme, respectively. The two wave climates are separated by the central pier.

Figure 17.55 At Amager Beach Park, the existing beach was moved seaward on a shallow profile out to an exposed location and an artificial lagoon was excavated. The new beach is divided in two sections each facing one of the two dominant wave directions at the site.

Future sea level rise will results in a general setback of the shoreline position in the beach park as discussed in Subchapter 6.4.2.

A complete description of the design considerations for a complete waterfront development scheme is presented in Chapter 18.

17.8 Land use restrictions

Definition:

Restrictions on the use of the coast and the coastal hinterland are part of the legislation in most countries. The philosophy behind the concept of a setback line is to avoid conflicts between anthropogenic developments in the Coastal Zone and the active morphology of the coastal area within a certain agreed time horizon. Construction or any anthropogenic development is not allowed on the seaside of these lines without special permission. Special restrictions governing land use can be relevant in the vicinity of very active morphological features such as river mouths, tidal inlets, sand spits and barrier islands.

Method:

The Danish regulation and permit system will be briefly described in the following as an example of how such a system can be set up.

The development is controlled through the right and duty of the municipal authorities to issue local plans and to grant building permits.

The planning system is based on the division of the coastal area in two zones:

- A planning zone: The "Coastal Proximity Zone" with a width of 3 km
- A prohibition zone: The "Coast Protection Line" or the "Coastal Setback Line" defines an up to 300 m wide coastal area where development is prohibited

The planning law operates with the "coastal proximity zone" with a width of 3 km, covering rural and recreational areas. This law secures that development or any change in land use, for purposes other than agriculture and forestry, are prohibited or subject to special permission from the regional authorities. This means that planning permission for inclusion of areas into the urban zone or for new developments in the rural zone is restricted to activities that in a planning or functional context require a location near the coast. It is also prohibited to lay out new summer house areas in this zone. Rural areas cover about 90 % of the country however probably less in the coastal area.

The Law for Protection of Coastal Areas, the so-called "Coast Law", which is part of the Nature Protection Law, provides protection of the coastal landscape in the immediate vicinity of the coastline defined by the "Coastal Setback Line".

Planning and zoning regulations govern the development possibilities, whereas building permits sanction construction works in accordance with adopted planning regulations and statutory land-use provisions.

The entire country is divided into three planning zones: urban zones, recreational zones and rural zones.

From the 1930s, a 100 m protection zone, or a 100 m Coastal Setback Line, has protected the Danish coastal area against new developments. This protection zone has recently been increased from 100 m to:

- 300 m in rural coastal areas
- 100 m in recreational areas occupied by summer cottages
- 0 – 300 m in urban areas

In the protected zone it is prohibited, with a few exceptions, to introduce new development including alteration of the appearance of the coast, erecting fences, parking of caravans and establishing new boundaries. The protection zone is administered by the municipalities with the exception of the North Sea Coast, where this duty is the responsibility of the Danish Coastal Authority.

The purpose with the coastal setback restrictions is to secure the near coastal area against any form of intervention that alters the present conditions or usage. This secures landscape, biological and recreational interests against pressure from development. In areas with dunes the interest is also to limit sand drift and to maintain the open coastal landscapes as an essential nature- and landscape resource.

The general goals for introducing a setback line can be defined as follows:

- To secure a fringe of coastal landscape against interventions that will change the present conditions and utilisation. This will secure a fringe where natural backshore processes can take place, such as dune formation and where natural coastal flora and fauna can develop without restrictions. This secures the overall goal of a setback line, namely to safeguards scenic, biological and recreational interests in the coastal hinterland
- To avoid conflicts between existing and new coastal developments and a receding shoreline or coastal flooding. This is especially relevant for areas which will be exposed to erosion/flooding in the future for any reason, including the impact of sea level rise. It shall be mentioned that the setback line will in many cases only provide a partial security against damages caused by chronic coastal erosion, provided this erosion is allowed to take place. Furthermore it is normally not feasible in the case of chronic erosion to introduce setback lines, which provide "full" security against coastal erosion especially in already developed areas where the space is limited
- To allow for a certain natural variability of the shoreline due to acute erosion caused by seasonal longshore and cross shore variations and extreme events
- Allowance for changes caused by coastal development in adjacent areas, such as the construction of ports or similar, which may be developed in the future
- There is an inherent conflict involved in introducing a setback line in an area which in the future will be exposed to chronic coastal erosion as the eroding shoreline will eventually reach the setback line if this is defined as a static line. Consequently two types of setback lines may be defined:
  - Dynamic setback line in areas with chronic erosion
  - Static setback line in areas with only reversible acute erosion

Of course, erosion problems can be mitigated by the construction of coast protection schemes. However, one of the intentions of introducing a setback line is to avoid reaching a situation where the construction of coast protection is required. This philosophy is related to the general development goal for the coastal area that "as much as possible of the coast shall be preserved as natural dynamic landscapes". The philosophy of how to protect the coastal area of course varies from country to country.

Sector regulations, such as setback lines, are only effective if they are respected by all stakeholders. Illegal development activities in the restricted zone may be a main cause for the conflicts between shoreline development and building activities near the coast. It is therefore recommended to enforce adherence to introduced setback restrictions. It is recommended that simple and easily understandable and manageable setback restrictions are introduced. It is also recommended that different setback distances are used dependent on the present land use. It is also important that the introduced setback restrictions are realistic and respect existing coastal facilities and infrastructure.

Furthermore, coastal facilities presently exposed to erosion have to be treated by introducing erosion mitigation measures, a setback restriction will not work in such a situation.

Functional characteristics:

Land use restrictions work by providing sufficient space for the natural coastal processes to take place and to preserve the natural coastal landscape. In the long-term this is the most feasible and sustainable solution.

When this setback policy is adhered to, problems in relation to coastal retreat will not occur in the near or far future, but this, of course, depends on the setback distance in relation to the rate of coastal erosion. However, in many cases development has already taken place close to the coastline because no regulations were in force at the time of construction, because no regulations existed or because regulations were not followed. Most of the problems relating to coastal erosion and shore degradation occur in areas, where it is too late to introduce land use restrictions.

However, if a house is lost due to coast erosion in such an area, the land use restrictions will typically not allow the construction of a new house on the lot, if there is not sufficient space according to the regulations in force. Land use restrictions thus prevent a repetition of the problem.

Discussion of static and dynamic setback lines for acute erosion
Static setback lines should theoretically only be used for areas which are exposed to reversible acute erosion whereas a static setback line is theoretically not applicable for areas with chronic erosion as discussed above. The required width of the setback zone can be calculated on the basis of the amount of acute erosion to be expected from various reasons, cf. Subchapter 11.1.2. However, the overall goal of the setback line, namely to safeguards scenic, biological and recreational interests in the coastal hinterland, should be remembered.

Discussion of static and dynamic setback lines for chronic erosion
Coasts with chronic erosion require in theory a dynamic setback line, which is moved inland at intervals at the same average rate as the coastal retreat. The alternative is a “static” setback line with either a very long setback distance applicable for a long time period or a small setback distance with applicable only for a short time period.

In areas with chronic erosion it can be considered to associate a lifetime with the various types of setback lines and land uses. Consequently, it may not be advisable to define a setback line only in metres, because the rate of erosion has to be taken into account. For this reason, it could be considered to define the setback line as a function of the rate of coastline regression. For example: "Development activities are forbidden in a zone likely to be threatened by the sea in the next 50 - 100 years". So in fact the width of the setback zone will be 50 times the yearly erosion rate and there should be no problems with houses being threatened by erosion in the next 50 – 100 years.

The decision on the 50 – 100 years erosion rate to be used as basis for the computation of the setback line distance from the existing coastline can be based, for example, upon the lifetime of a house. The idea is that after 50 - 100 years the house will have to be rebuilt anyway. So if all houses are built at a distance of 50 – 100 erosion-years away from the coastline, it will never within this time horizon be necessary to remove a house because of coastal erosion. A condition to build “near” the setback line at any time shall be supplemented with the conditions that the house owner must accept that his house is to be abandoned when the erosion reaches the house and that he is not allowed to build a new house. However, this approach is probably not realistic and it is neither realistic that the house owner loses the entire value of his property after 50 – 100 years.

It is evident that the concept of a dynamic setback line is very difficult to implement because it will result in a lot of conflicts as described above. In practice the society will in many cases not allow the chronic erosion to take place because the landowner/the coastal authority will try to maintain the position of the coastline by some of the applicable protection measures. This means that eroding coastlines in developed areas, in areas with a certain population density and in areas with economic interests generated by beach tourism, will normally be stabilised, whereby the coastline becomes more or less static. A dynamic setback line thereby also becomes static. The present trend in many countries is to stabilise eroding coastlines by nourishment programmes, which secures a stable coastline at the same time as the nature of the coast is maintained as nearly natural, whereby the natural landscapes and processes are maintained with minimal interference.

Furthermore, it is not possible in practice to use varying setback distance dependent of the specific erosion rate in specific areas and it will require major administrative efforts to shift the setback lines as future erosion progresses.

Recommended setback line policy

In practice it is not feasible to administrate dynamic setback lines. In many countries there is consequently a practice to protect the coastal landscape and the coastal facilities in a pragmatic and practical way, which combines the use of suitable protection measures with static setback lines of various categories, such as:

- Use no setback line in port and other industrial areas, where immediate proximity to the sea is a must
- Use existing building line in city and dwelling areas where the coastal area is already occupied with housing and infrastructure relatively close to the coastline. Allow protection of property and infrastructure following an application procedure. In this case emphasis is on protection of property rather than protection of the coastal landscape because the coastal landscape is already lost
- Use a reasonable setback distance, e.g. 100 m, in areas laid out for recreational activities, such as summer houses and hotels. It is important that the setback distance is acceptable and respected by all stakeholders. Use existing building line in cases where it is too late to implement the 100 m setback line. Here the emphasis is mixed, partly to avoid conflicts with receding coastlines and partly to preserve the environmental and scenic values of the coastal landscape. Coastal protection is only permitted if fixed facilities are threatened by coastal erosion within a time horizon of about 25 years. Coastal stabilisation via nourishment is often used in these areas which secures a stable coastline at the same time as the nature of the coast is maintained as nearly natural
- Use a large setback distance, e.g.. 300 m in open coastal areas, which are not occupied by any kind of fixed facilities, such as buildings and infrastructure. The purpose of this is to safeguard scenic, biological and recreational interests in the coastal hinterland. This strategy involves no effort to protect the land from erosion which means that coastal areas subject to erosion are left for natural development and it is accepted that such areas are eventually eroded away as part of the natural development at the location. The philosophy is that nature shall not be protected against the forces of nature. Coastal protection will not be permitted in this category of area
- Introduce an e.g. 3 km wide coastal planning zone covering rural and recreational areas. Planning permission within this zone for new developments shall only be given if there is a specific planning or functional reason for location near the coast

In principle the setback lines are fixed but authorities may revise the setback lines if significant shoreline changes have occurred.

To maintain the setback lines requires an authority to control illegal building in the setback zone, to control illegal removal of sand from beaches or foreshore, to control removal of essential vegetation and disposal of waste and wastewater.

Applicability:

Land use restrictions are applicable for all types of coasts but such restrictions are typically only effective in rural undeveloped areas protecting such areas from development too close to the shoreline and protecting the natural coastal landscape and processes. Land use restrictions used in developed areas should be adjusted to fit to the existing development combined with soft protection measures.

Land use restrictions shall take the risk of future sea level rise into account and the risk of SLR makes the implementation of land use restrictions even more relevant.

17.9 Sea defence

Sea defence is defined as follows:

SEA DEFENCE: Measures aiming at protecting low-lying coast and coastal hinterland against flooding caused by the combined effect of storm surge and extreme astronomical tides. Sea defence often consists of dikes or seawalls of some kind, or in the form of artificial dunes.

17.9.1 Dike

Definition:

A dike is a sea defence structure protecting low coasts and coastal hinterlands from being flooded as a result of high storm surge, high tide and wave run-up. Normally, the dike consists of sand with a layer of meadow soil with grass; however, severe wave action can make it necessary to protect the front of the dike with a revetment. In that case the defence structure can also be characterised as a seawall.

Method:

Dikes are often constructed in areas with tidal flats and where the coast consists of low meadows or mangroves, and where there is no erosion problem. Under such conditions the dike is most often constructed well above the mean high water-line, which means that the dike is fronted by a low-lying coastal platform. In such cases the dike will typically consist of sand covered with meadow soil planted with grass, see Figure 17.56.

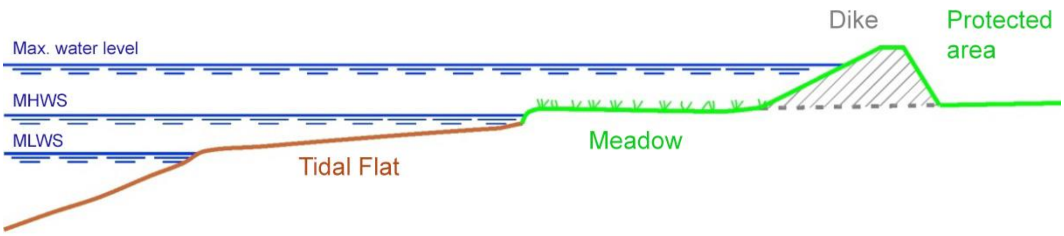


Figure 17.56 Traditional sand dike at a tidal flat coast. Dike built by sand with a surface of meadow soil planted with grass.

An example of such a dike is presented in Figure 17.57.

Figure 17.57 The dike in the Danish Wadden Sea, note that the dike is protected by a marshy foreland.

On a sandy eroding shore, where dunes form the natural protection of the low hinterland, a combined coastal protection and sea defence can be constructed. It can either be an exposed dike protected with a revetment in front of the dunes, see Figure 17.58, or an unprotected traditional dike constructed landwards of the dune row. The exposed dike can also be characterised as a seawall.

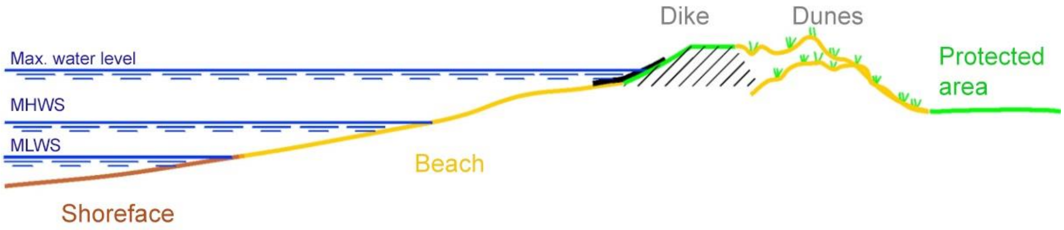


Figure 17.58 Exposed dike protected with revetment at sandy dune coast.

The combined sea defence and coast protection can also be performed as a strengthening of the natural dunes; this solution is discussed in the next subchapter.

Functional characteristics:

The main function of a dike is to prevent flooding of low coastal hinterland, which means that the height of the dike is a most important design parameter. However, the dike must also be able to resist the force of the waves during extreme water level conditions. Normally, the wide tidal flat and the coastal platform in front of the dike attenuate the wave action on a traditional dike. Furthermore, the exposure is rare and the duration is short. If the dike is constructed with a very gentle front slope, and the slope is vegetated with a dense and well-maintained grass cover, further reinforcement of the dike front is not required.

It is important that the platform, which normally consists of meadow and/or mangrove vegetation, is well maintained and sound as the platform is an integrated part of the defence scheme. Cutting of the mangroves has in many cases resulted in the erosion of the platform and thereby destabilisation of the dike.

If the above conditions are not fulfilled, or if coastal erosion takes place, the front of the dike has to be reinforced with a revetment.

Future sea level rise should be taken into consideration during design of the dike as described in Chapter 16.

Applicability:

Traditional dikes are used to protect low coastal land against the combined action of tide and storm surge. Reinforcement of the front of the dike is required if the platform is narrow and low and the dike is exposed to severe wave action and/or if acute coastal erosion takes place.

17.9.2 Artificial dune

Definition:

A natural dune is nature’s own flexible protection against coastal erosion and flooding. In areas with natural dunes, which suffer from wind and acute coastal erosion, beach degradation and flooding, artificial dunes are applicable as a combined protection measure. This can be done in different ways, and there is a gradual transition from dune restoration to artificial dunes. An artificial dune can also be categorised as a soft seawall, dune nourishment or backshore nourishment.

Method:

The two principal methods of constructing artificial dunes are:

1. To introduce measures on the backshore/coast, which trap sand, such as the planting of marram grass or the erection of spruce fences. A new dune will subsequently form automatically. However, this is a slow process and it is difficult to forecast the result. The method is useful for fighting coastal and dune erosion, whereas it is not suitable as protection against flooding

2. The natural dune can be reinforced by importing sand from outside the project area and filling this sand amalgamated to the existing dune, this is also referred to as an artificial dune. Recent research has shown that the most efficient way to reinforce a dune to be able to resist dune erosion (acute erosion) and thereby maintain its capability to act as a flexible measure against coastal flooding is to increase the dune width landwards. An example of such a dune reinforcement is presented in Figure 17.59. The reinforced dune area is normally planted with marram grass in order to stabilise the bare sand area. This type of artificial dune functions as a combined shore protection and sea defence measure.

Figure 17.59 Dune reinforcement by widening the dune landwards from the landwards slope of the existing dune, from the Danish North Sea Coast.

Functional characteristics:

The functions of an artificial dune are many; the main functions are listed in the following:

- An artificial dune enhances the natural dune growth processes and is an environmentally sound and sustainable protection method.

- An artificial dune provides flexible protection against coastal erosion As the dune is gradually eroded sand is released to the littoral processes, and the impact on adjacent beaches is therefore positive. The volume and quality of the nourished sand determines the durability of the protection.

- An artificial dune helps to maintain a wide sandy beach.
- A sufficiently high continuous artificial dune line protects against flooding against acute erosion and against breaching. However, if it is also eroded by longshore losses, it has to be maintained. The function therefore depends on the volume and quality of the sand as well as the distribution along the protected area and the level, to which the sand barrier is constructed. As a reinforced dune hinders breaching of the dune row and wash-over into the hinterland, it will, to some extent, prevent the natural stable recession of a dune formation. The sand will be lost along the shore and offshore when the dune has been reinforced in lieu of being washed inland.

Applicability:

This method is applicable as a flexible protection against acute and chronic coastal erosion and coastal flooding. It acts as a combined coastal protection, shore protection and sea defence measure on natural dune coasts and in areas where artificial beaches have been constructed. It is thus mainly applicable on moderately exposed and exposed coasts.

17.9.3 Marsh/Mangrove platform restoration

Definition:

On coasts with a low coastal platform, consisting either of marsh or a mangrove belt, the platform is an important stabilising element, which protects against coastal erosion and flooding. The stability of the coast and the safety against flooding will be threatened if the mangrove vegetation at the platform has been damaged. This situation can be remedied by restoration of the platform.

Method:

Mangrove platforms are restored by:

- Imposing restrictions against the cutting of the mangrove forest and against filling of the mangrove forest area
- Preventing pollution
- Re-establishment of the natural flow conditions in the mangrove area, for example, by the backwards displacement of dikes
- Planting new mangrove vegetation, see Figure 17.60
- Construction of permeable dams/groynes for enhancement of sediment accumulation, see Figure 17.61

These measures require a high level of management and active participation by the local coastal communities. Such programmes should, therefore, be associated with education and awareness campaigns.

Figure 17.60 Planting of mangrove.

Figure 17.61 Example of permeable groyne structure for enhancement of sediment accumulation, central Java coast, cf. Winterwerp (2016).

Marsh platforms can be restored by regulating possible overgrazing and/or by landward displacement of dikes. The natural growth of the platform can be enhanced by constructing siltation traps on the shallow tidal flat as shown in the photo below.

Figure 17.62 Siltation traps for the enhancement of natural platform growth.

Functional characteristics:

In many tropical countries the mangrove platform has been severely damaged by cutting the mangrove, by pollution, by filling or by preventing the natural flow of water, sediments and nutrients by dike construction, etc. This increases the risk of flooding of the hinterland, and the biological diversity of the mangrove forest is lost, which can severely affect the living conditions for the coastal population. Restoration of the mangrove platform is therefore a very important step towards better safety and living conditions for the coastal population.

Marshy areas can be worn down by too intense grazing, and the building of dikes can reduce the width of the platform. This reduction of the platform will influence the natural morphological processes and the biological diversity of the platform, thus reducing the width even further. Preservation and restoration of a marshy platform is therefore important in order to maintain/increase the safety level against flooding, to arrest the erosion of the platform and to preserve/enhance the biological diversity of the platform.

Applicability:

Restoration of coastal platforms is applicable along coasts with a low coastal platform consisting of either marsh formations or mangrove belts. If the platform has been damaged, it must be restored in order to obtain greater coastal stability, improved safety against flooding and in order to re-establish and enhance the natural morphology and bio-diversity.

The forecasted SLR will threaten the stability of coastal platforms and preservation of coastal platforms will therefore be more critical in the future.

17.10 A Summary of the applicability and the function of coastal protection and shore protection, and sea defence measures

In the following an overview is provided of the applicability and the function of the methods for coastal - and shore protection, and sea defence measures described in Chapter 17.

Table 17.1 summarises the types of protection measures and the protection/defence measures against the types of problems and the coastal types upon which they can be applied.

The choice of solution is dependent of many conditions, which can be divided in two main groups:

- The technical aspects
- The economical and capability aspects

The technical aspects are dependent on four main conditions:

- The problem to be solved, or the goal of the protection:
    - protect facilities against erosion (Coast protection)
    - protect facilities against erosion and flooding (Coast Protection/Sea Defence)
    - protect facilities and maintain the beach against beach erosion (Shore Protection)
    - protect coastal facilities against coastal flooding (Sea Defence)

- Suitability of different stabilisation measures related to the type of coast (coastal classification)

- The impact of the protection on adjacent stretches, e.g. in the form of sand accumulation and lee-side erosion

- The type of coastal erosion -- acute erosion or chronic erosion.

When a series of applicable protection measures have been selected they shall be checked for compatibility with the type of coast in the project area and for possible lee-side erosion, see summary in Table 17.1.The table is used by first defining the problems and identifying the type of coast in question. Finally, one can find applicable protection/defence measures and evaluate whether the protection measure will cause preservation of the beach and/or leeside erosion.

Table 17.1 The applicability of coast protection and sea defence measures.

Type of protection	Protection measure		Applicable for				Preser-ves beach	Coastal Type in terms of obliqueness of predominant waves					Leeside erosion	Comment
			Chronic Erosion	Acute Erosion	Flood-ing	SLR		Perpendi-cular $\alpha_0 \sim 0$	Sligthly oblique/ $0<\alpha_0<10$	Oblique $10<\alpha_0<50$	Very oblique $50<\alpha_0<85$	Shore parallel $\alpha_0 > 85$		
Soft	**Nourishment**	**Dune**	Yes	Yes	Yes	Yes	Yes	X	X	X	-	-	No	
		Beach	Yes	Yes	No	Yes	Yes	X	X	X	X	-	No	
		Stockpile	Yes*	No	No	Yes	Yes	X	X	X	-	-		*As maintenance
	Marsh/mangorve restoration		Yes	Yes	Yes	Yes	No	X	X	X	X	X	No	Only in marsh or mangrove areas
	Sand bypassing		Yes	No	No	No	Yes	-	X	X	X	X	No	
	Beach drain		Yes*	No	No	No								*Seasonal erosion
	Regulation of landscape	**Dune stab.**	Yes	Yes	(Yes)	Yes*		X	X	X	X	-		*Combined with nourishment
		Cliff stab.	Yes*	Yes*	No	Yes*		X	X	X	X	X	Yes	*Comb. with revetment
		Beach Scraping	No	Yes	No	No	Yes	X	X	X	X	X	No	
	Managed retreat (Removal of hard protection combined with nourishment)		Yes	Yes	Yes	Yes	Yes	X	X	X	X	X	No	Unaccpetable shoreline retreat may be regulated by nourishment
Hard	**Revetment**		Yes	Yes	No	Yes	No	X	X	X	X	X	Yes	
	Emergency protection		Yes	Yes	No	No	No	X	X	X	X	X	Yes	Shall be avoided
	Seawall		Yes	Yes	Yes	Yes	No	X	X	X	X	X	Yes	
	Dike		No	No	Yes	Yes	No	X	X	X	X	X	No	Can be armoured to resist wave impact
	Bulkhead		No	No	Yes	Yes	NA	X	X	X	X	X	No	Not against erosion
Mixed	**Groynes**		Yes	No	No	No	Yes	-	X	(X)	-	-	Yes	
	Detached breakwaters		Yes	No	No	No	Yes	X	X	X	-	-	Yes	
	Modified breakwaters and headlands		Yes	No	No	No	Yes	X	X	(X)	-	-	Yes	
	Perched beach		Yes	No	No	No	Yes	X	(x)	-	-	-	No	
	Cove or artificial pocket beach		Yes	No	No	No	Yes	X	X	X	X	(X)	Yes	
	Artificial beach/beach park		No	Yes	Yes	Yes	Yes	X	-	-	-	-	No	Use for creating dev. and recreation area
	Shoreline management scheme		Yes	Yes	Yes	Yes	Yes	X	X	(X)	-	-	No	
Land use restrictions	**Dynamic setback line**		Yes	Yes	Yes	Yes	Yes	X	X	X	X	X	No	Normaly not used
	Static setback line		No*	Yes	Yes	Yes	Yes	X	X	X	X	X	No	*Yes if combined with nourishment

The choice of solution among the technically feasible solutions are further discussed below. The proposed procedure for selecting the optimal technical protection measure, once the problems are identified, can be subdivided in three phases:

- Select an applicable protection measure that can solve the problem
- Select among the applicable protection measure a type of protection which works on the specific type of coast
- Check the protection measure for impacts

Finally, the alternative protection schemes shall be checked for economical as well as construction and management capability aspects; these conditions vary greatly dependent of the facilities to be protected and the organisation responsible for implementation of the protection. These conditions are especially related to the following conditions:

- Construction cost compared to available funding for construction
- Cost-benefit of the project
- Management/planning and administrative capabilities of organisation responsible for the protection scheme (private landowners or coastal authority)
- Construction capability in the area
- Capability of maintaining the protection works beyond the construction period in terms of monitoring and organisation of funds for the maintenance as well as implementation of the maintenance

Most of the solutions require consensus and well-coordinated Shoreline Management Planning and/or Integrated Coastal Zone Management Planning.

18 Waterfront Development Schemes

The present chapter is inspired by and partly copied from the two articles: Mangor, K., Brøker, I. and Hasløv, D. (2008) and Mangor et. al. (2012), which both describes Waterfront Developments in Harmony with Nature.

The main development theme in many coastal countries is to utilise the attractiveness of water in a broad context. Nowadays emphasis has shifted from coastal protection to shoreline management, which includes the construction of waterfront development schemes.

A waterfront development scheme can be considered as an artificial piece of new nature which consists of nature elements, such as artificial beaches and artificial lagoons, and of various kinds of landscaping, recreational and habitation facilities. The artificial beaches and lagoons, so to speak, do not know that they are artificial. Consequently, such landscape elements will follow the natural marine and coastal processes in the construction area. These parameters cannot be changed. It is therefore important to understand the prevailing natural processes responsible for creating attractive beach and lagoon environments as basis for the design of well-functioning artificial coastal and marine elements.

The focus of this chapter is to provide the reader with a basic understanding of how to create a well-functioning waterfront development scheme with regard to the important hydraulic elements - beaches and lagoons.

Design guidelines for artificial beaches and lagoons are presented as well as guidelines for landscape elements of waterfront developments. Examples include a popular new beach park in Copenhagen and a new type of offshore development scheme. Finally, investigation methodology for waterfront developments is presented.

18.1 Introduction

The art in developing waterfront projects is to utilise the possibilities provided at a specific site to the benefit of the project, i.e. to integrate the possibilities provided by the marine environment with the demands of the society. The art is to perceive the marine forces such as waves and tides, as external opportunities, which shall be used to maintain high-quality artificial beaches and lagoons, contrary to the traditional approach of perceiving these external forces as problem generators, against which protection is required.

The chapter is divided into the following subchapters:

- The characteristics of natural landscape elements
- Design guidelines for artificial beaches
- Design guidelines for artificial lagoons
- Landscape elements of waterfront developments
- An example of a successful beach park development
- New concept for an offshore development scheme
- Investigation methodology
- Conclusions and recommendations

18.2 The characteristics of natural landscape elements

18.2.1 Characteristics of natural beaches

Attractive and safe recreational beaches are always characterised as being exposed to moderate wave action, the tide is micro to moderate (tidal range < ~1.5 m), clean and transparent water, no rock outcrops, well sorted medium sand and minimal amounts of natural and artificial debris.

Examples of attractive natural beaches are presented in Figure 18.1.

Figure 18.1 Examples of attractive beaches. Upper: The Skaw Spit in Denmark. Lower left: NW-Mediterranean coast in Egypt. Lower right: Sunset Beach in Dubai.

These beaches are all characterised by being exposed to waves, the sand is clean beach sand and the water is clean. The type and colour of the sand is different, but all types are natural beach sand of great beauty and recreational value. The exposed beaches have a sandy and clean appearance due to the wave action which prevents settlement of fine sediments and organic matter. However, there are also many examples of good quality beaches along coasts where the water contains high amounts of suspended sediments, at least during the rainy season and/or during rough weather conditions. This is e.g. the situation along Malaysia's east coast and along Sri Lanka's coasts. The reason for the clean sandy beaches in these environments is that these beaches are exposed to waves.

Natural beaches appear differently when they are lacking wave exposure. This is clearly seen in the examples presented in Figure 18.2 and Figure 18.3.

Figure 18.2 Natural beaches lacking wave exposure. Left: Beach in a natural Lagoon in the UAE, which suffers from algae and deposition of fine sediments. Right: Muddy beaches in creek in the UAE.

Figure 18.3 Example of correlation between type of beach and wave exposure. Left: Location “Map”, North Beach in Doha, Qatar. Note that the southern part is protected by an island and associated reefs and has a muddy tidal flat type of beach (photo lower right), whereas the northern part is exposed and has a sandy beach (photo upper right).

It is evident from the above examples of exposed and protected natural beaches that the wave exposure is of paramount importance for the type of natural beach which develops in an area. Lack of wave exposure on an artificial beach will allow settlement of suspended matter on the seabed and on the beach, also in cases where the beaches have been built of clean beach sand. This will with time lead to the seabed of the shoreface being covered with a layer of soft sediments. Such a muddy seabed is unattractive for recreational purposes.

18.2.2 Characteristics of natural lagoons

Natural lagoons are attractive from a recreational point of view due mainly to the open water body they offer and not due to their beaches, which are often of poor quality. Coastal lagoons are characterised by the following elements:

- One or more so-called tidal inlets which connect the lagoon and the sea
- Tidal exchange of water between the lagoon and the sea known as the tidal prism or tidal volume
- Rich flora such as sea grass beds, mangroves and meadows
- Rich fauna such as mussel banks, nursery areas for many fish species and rich bird life
- The openings are sometimes stable and sometimes suffering from sedimentation, this is dependent of the balance between the tidal range and the wave exposure
- The lagoon environment is protected and is therefore often characterised by settlement of fines, which in many cases leads to the formation of a muddy seabed and mud flats

These natural conditions offer the following attractions:

- Protected water environment, which is traditionally used by coastal societies as a natural location for settlements based on natural harbour facilities
- Possibilities for a great number of commercial activities such as fishing, hunting, aquaculture, location for water intakes/outlets of different kinds, salt production, etc.
- Recreational activities such as water sports, navigation in protected waters, fishing, bird watching, etc.

However, settlements and the many associated activities in the lagoons imply on the other hand also the risk of many impacts on the lagoons such as:

- Pollution leading to degradation of the water quality and associated degradation of flora and fauna
- Installation of sluices leading to changes in the salinity, etc.
- Reclamations leading to changes in the tidal volume
- Regulation of inlets and dredging of navigation channels leading to changes in the tidal volume, which may lead to local erosion or general siltation
- Navigation possibly leading to pollution and erosion, etc.

An example of an attractive lagoon environment is the semi open Marsa Matruh lagoon located at the NW-Mediterranean coast of Egypt, see Figure 18.4. This lagoon offers attractive sandy beaches and good water quality due to the wide opening, which allows some wave penetration and good flushing.

Figure 18.4 Upper: Marsa Matruh Lagoon, NW-Mediterranean coast of Egypt, red dot is photo location for photos below. Lower left: Semi-exposed sandy beach towards NW. Lower right: semi-exposed beach towards SE.

18.3 Design guidelines for artificial beaches

The most important landscape elements in many waterfront developments are attractive sandy beaches. An artificial beach is the construction of a new beach by supply of sand, so-called beach fill. The design requirements to a good quality recreational beach are outlined in the following.

18.3.1 Exposure to waves

A beach shall be exposed to waves in order to obtain a good quality beach. However, a recreational beach shall not be too exposed, as this endangers bathing safety. This means that there are two opposing requirements:

1. There shall be a certain exposure to secure a self-cleaning beach
2. The exposure shall not be too large in order to secure safe bathing conditions

In order to safeguard an attractive sandy beach the yearly wave exposure shall be moderate to exposed, which means that the significant wave height ($H_{S,12h/y}$), which is exceeded 12 hours per year, shall be higher than approx. 1.0 m. It is the consistent movement of the sand by the wave action during rough conditions which maintains a nice sandy beach and shoreface through preventing settlement of the content of fines, which are often present in seawater. Furthermore, the wave exposure prevents sea grasses from growing on the shoreface.

The difference in attractiveness between two artificial beaches in a beach park in the UAE area is clearly seen in Figure 18.5. The first beach is exposed to waves and the second beach is a protected lagoon beach.

Figure 18.5 Left: Exposed artificial beach in the UAE, nice clean beach due to the wave exposure. Right: Artificial Beach in artificial lagoon in the UAE, note the muddy seabed, which is due to lack of wave exposure. The lack of freshness is clearly seen.

There exist no internationally agreed criteria related to wave height relative to safe bathing conditions. Bathing safety is mainly related to the occurrence and type of breaking waves and the wave-generated currents in the breaking zone. These conditions are discussed in the following.

Spilling breakers are often associated with the formation of bars and rip currents, which can carry both adults and children out into deep water. This situation is typical for strong wind and storm conditions at sandy (ocean) coasts. Plunging waves are dangerous because the violent breaking can hit a bathing person. Plunging breakers typically occur on ocean coasts with moderate wave conditions, such as under monsoon and trade wind conditions on coasts with relatively coarse sand. It is evident from the above that ocean coasts are the most dangerous. An upper limit for wave heights in relation to safe bathing conditions is estimated at: Hs < 0.8–1.2 m during the bathing season. The lower limit is valid for long-period waves (swell) and the upper limit is for steep waves (wind-waves).

This means that protective measures are required if a site is more exposed during the bathing season than given in the above rough criteria, e.g. in the form of specially designed coastal structures.

However, rip currents generated as a result of the presence of coastal structures can also be very dangerous. The condition which makes this situation dangerous is that during a storm situation there will be partial shelter for the waves behind the coastal structure, but in the same area there will be strong currents due to eddy formation, which can carry poor swimmers out into deep water. In conclusion, areas with partial shelter provided by coastal structures near the coast generate a false feeling of safety and such arrangements should consequently be avoided.

It is noted that especially small coastal structures with an extension less than the width of the littoral zone tend to generate dangerous rip currents around the head of the structure, which might be dangerous for unexperienced swimmers.

The principle of providing safe partial shelter and shoreline stability at an exposed coast is presented in Figure 18.6, which shows an optimised layout for an artificial beach and a marina in Alexandria, Egypt incorporating:

- Partial shelter provided by the large breakwaters
- A width of the opening to the open sea adjusted to provide suitable wave exposure to fulfil the requirements of moderate exposure for securing a good beach quality and semi-sheltered conditions for providing safe swimming conditions
- A stable beach under the resulting wave conditions
- Exclusion of dangerous rip currents due to the long distance between the head of the breakwaters and the beach and because of the equilibrium shape of the beach

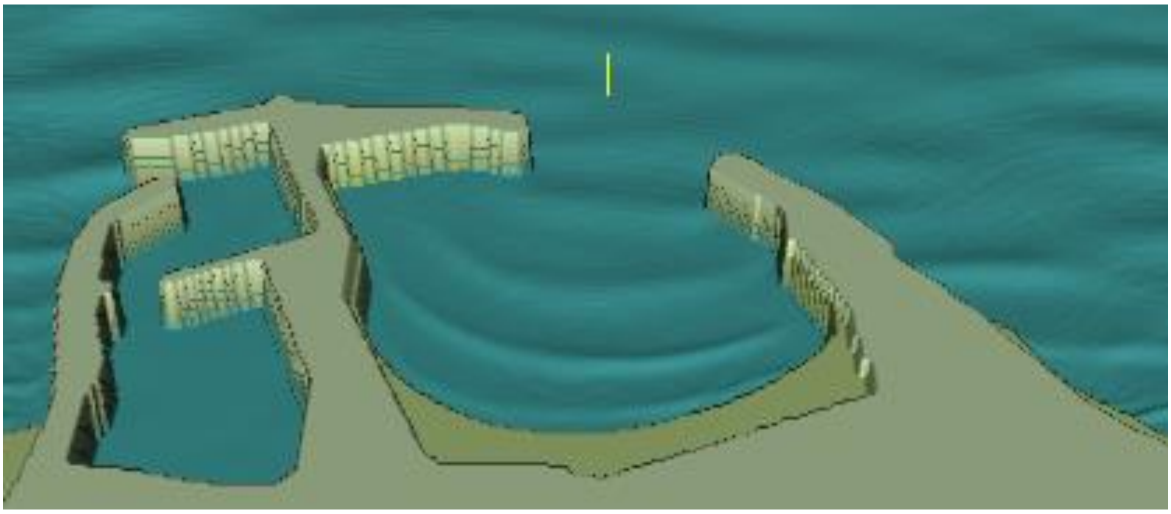


Figure 18.6 Artificial beach at Alexandria's exposed coast. Upper: Modelled wave conditions. Lower: Photo of newly constructed beach in 2009. Beach designed by DHI, Hasløv & Kjærsgaard and ECMA.

18.3.2 Minimum wave exposure

A recreational beach shall have an active profile out to a water depth of about 2.0 m relative to low tide. This recommendation of a depth of 2.0 m relative to low tide is caused by the requirement that bathers walking on the seabed shall experience an attractive clean sandy seabed without deposition of fines in the “walking zone” of the shoreface. The clean and active seabed is secured by the requirement that the active coastal profile shall extend out to a water depth of 2.0 m, i.e. closure depth $d_l \geq 2.0$ m or in terms of wave height: $H_{S,12h/y} \geq 1.0$ m. This means that the seabed out to this water depth will be exposed regularly to waves preventing fine sediments to settle on the shoreface. Furthermore, the growth of sea grasses will also be prevented.

If the natural shoreface does not allow these requirements to be fulfilled, e.g. if the shoreface is shallower than the equilibrium profile, then there are two possibilities to modify the beach slope so that these requirements are fulfilled:

- The beach is shifted seaward
- The existing coastal profile is excavated to accommodate the equilibrium profile

18.3.3 Exposure in relation to tidal range

A certain tidal range and storm surge activity will cause a wide beach. However, a tidal flat may develop if the tidal range is much larger than the yearly average wave height, cf. Subchapter 8.2.4. Furthermore, a high tidal range constitutes a major challenge for the layout of an artificial beach. Thus, a good quality recreational beach is normally characterised by a micro to moderate tidal regime, which means a tidal range smaller than approximately 1.5 m.

18.3.4 Beach plan form

The beach should be stable in plan form (horizontally) in order to secure minimum maintenance. This means that the orientation of the beach shall be perpendicular to the direction of the prevailing waves, or in other words, the orientation of the beach shall be in the equilibrium orientation, which is the orientation providing net zero littoral transport. This often leads to the requirement of supportive coastal structures for stabilising the beach in the equilibrium orientation, which is different from the existing orientation of the coastline in the project area. The equilibrium orientation is typically varying along the beach dependent of the varying shelter provided by the supportive coastal structures.

At beaches with oblique wave attack, the supportive coastal structures for an artificial beach shall be designed differently dependent of the wave exposure. In the case of an *exposed beach* which is so exposed that bathing security is threatened, the following conditions for the supportive structures shall be fulfilled:

- Provide support for a stable lateral shape of the beach following the equilibrium orientation

- Prevent or minimise loss of sand out of the artificial beach area, which means that the supportive coastal structures shall cover out to near the closure depth

- Provide partial protection against wave action so that suitable wave exposure is obtained. This is a compromise between the requirement for sufficient exposure to secure a good beach quality and for moderate exposure in order not to threaten bathing safety

- Secure that there are no dangerous currents along the beach and around the tip of the structure. This leads to the requirement of the structure to extend out to the closure depth

- All coastal structures should also have recreational functions

In the case of a *moderately exposed to protected beach,* the following conditions for the supportive structures shall be fulfilled:

- Provide support for a stable lateral shape of the beach following the equilibrium orientation
- Prevent or minimise loss of sand out of the artificial beach area, which means that the supportive coastal structures shall extend out to the closure depth
- The structures shall not provide shelter as this will compromise the requirements for sufficient wave exposure to secure a good quality beach
- The structures shall have a streamlined form to minimise trapping of floating debris and an obtuse angle between the shoreline and the structure is recommended (angle greater than 90 deg.)
- Ensure that there are no dangerous currents along the beach and around the tip of the structure. This leads to the requirement of the structure extending out to the closure depth
- All coastal structures should also have recreational functions

Changing wave conditions between seasons or years may lead to temporal changes in the equilibrium orientation and thus temporal variations in beach plan form. Assessment of shoreline variations will inform on requirements for a buffer in beach width or a need for revetment structures that may function as a last line of defence.

On one hand, a short beach section will respond more rapidly to changes in wave direction compared to a long beach section. On the other hand, a one degree change in orientation of a long beach section will lead to larger shoreline changes at the extremities of the beach section compared to a short beach section. Thus; reducing temporal variations in beach plan form will depend on the timescales of the changing wave directions compared to the response rate of the beach sections. Robust solutions shall be sought in order to minimise the impact of changes in wave conditions due to climate changes or due to inaccuracies in the design assumptions.

18.3.5 Beach profile form

The beach profile shall be stable, which means that a beach shall be built in the form of the equilibrium profile. A beach adjusts with time naturally to the equilibrium profile in the active littoral zone. The shape of the profile is mainly dependent of the grain size characteristics of the sand. The equilibrium shape, Dean's Equilibrium Profile, follows the shape $d = A\,x^{2/3}$, cf. the description of the equilibrium profile in Subchapter 7.3.

The equilibrium profile concept is valid only for the active littoral zone, i.e. out to the closure depth, d_l. As a rule of thumb $d_l \sim 2H_{S,12h/y}$ can be used for normal wind-waves.

18.3.6 Design level for coastal areas

The required design levels for various kinds of coastal land areas are mainly dependent on the following conditions:

- Land use
- Safety level
- Design water level

The land use and the recommended safety level are inter-dependent; the recommended criteria are presented in Table 18.1.

Table 18.1 Relation between type of land use and recommended return period for flooding (only for guidance).

Type of land use		Criteria	Recommended recurrence period in years
Waterfront Developments	Boat piers	Low vulnerability, access to boats important	½ - 1
	Park areas	Low vulnerability, proximity to water is important	1 to 10
	Inhabited and roads	Vulnerable to flooding, risk of damage to houses	50
Industrial/public utilities		Very vulnerable to flooding, risk of interruption in supplies	100
Low-lying inhabited areas		Extremely vulnerable to flooding, risk of losing lives	200 or higher dep. of size of area and density of population

The design level is dependent of the following conditions:

- Extreme still water level, which includes the effect of tides and storm surges, cf. Subchapter 5.6
- Allowance for the influence of future sea level rise due to Climate change
- Wave run-up on beaches, which is the sum of the wave set-up and the wave swash. As a rule of thumb the wave run-up is in the order of 36% of the design wave height, cf. Subchapter 5.3.2.8
- Wave overtopping on rubble mound structures and quay walls. The allowable wave overtopping varies greatly with the slope/type of the structure and the safety requirements. Typical requirements to the crest level of the structure are in the range $0.5H_S$ to $1.5H_S$
- Special phenomena such as the risk of tsunamis should be taken into account when relevant
- Safety margin

The difference in the recommended recurrence periods for the different types of land use categories opens for terraced layouts of the water edges as proposed and discussed in Subchapter 18.5.

In the planning of waterfront schemes there are sometimes several conditions to be taken into consideration such as improvement of the beaches and the need for sea defence. An example of a scheme where both these conditions have been built into a beach park project is the Køge Bay Beach Park south of Copenhagen, Denmark, where new exposed beaches were established and the dunes were designed as a sea defence structure safeguarding the low-lying built up area behind the scheme, see Figure 18.7.

Figure 18.7 Køge Bay Beach Park south of Copenhagen, Denmark. A dike, marked with a red line, is integrated in the dunes and runs behind the marinas thereby protecting the entire hinterland against flooding.

18.3.7 Beach fill material

Specifications for fill material for artificial beaches were discussed in Subchapter 17.7.2, the main fill specifications for supporting a high quality recreational beach are summarised in the following:

- The characteristics of the fill sand shall be similar to that of the natural sand in the area if the new artificial beach is connected to an existing beach, however, as a rule slightly coarser
- The sand shall be medium, i.e. 0.25 mm < d50 < 0.5 mm, preferably coarser than 0.3 mm, which minimises wind loss
- Minimum content of fines, i.e. silt content less than 1–2%
- Gravel and shell content less than 3%
- The sand shall be well sorted to sorted , i.e. 2.0 < u < 3.0, where u is the uniformity ratio defined as: u = d60/d10
- Colour shall be white, light grey or yellow/golden
- No content of organic matter
- The thickness of the beach sand layer shall not be less than 1.0 to 2.0 m dependent on the exposure and stability of the artificial beach

The reason for the requirement for the beach sand to be medium, well-sorted sand with minimum content of fines is discussed in the following. If this requirement is not fulfilled, i.e. if the sand is graded (the opposite of well-sorted) with some content of fines, the permeability will be low, which means that the beach will drain very slowly at falling tide. This implies that the beach will be wet at all times and it will have a tendency to be swampy, and thereby unpleasant to walk on. This criterion is especially important for artificial beaches built at protected locations as there will not be enough wave action to wash the fine sediments out of the beach. Furthermore, algae may start to grow on the beach which makes it greenish in colour and un-aesthetic. Finally in such environments the beach will be occupied by beach crabs and their pellets. It is especially important at protected sites to use clean sand with zero content of organic matter because the combination of lack of wave exposure and content of organic matter may lead to anoxic conditions resulting in formation of hydrogen sulphide, which causes a bad smell and dark colouring of the sand, see examples in Figure 18.8.

Figure 18.8 Examples of anoxic conditions and the formation of hydrogen sulphide at protected artificial beaches. Left: Dark substance suspended in the water when seabed at shallow water is disturbed, artificial beach in protected lagoon environment at the Egyptian NW coast. Right: Dark substance at beach in artificial lagoon in the Red Sea area.

The requirement to a small content of gravel and coarse fractions is important for the quality of the beach surface as the action of the waves will wash away the fine fractions leaving the beach armoured with the coarse fractions. Such a beach surface is unpleasant to walk on, see examples in Figure 18.9.

Figure 18.9 Artificial beaches with too much coarse material. Left: Beach Park in Copenhagen. Section with too high content of gravel and pebble. Right: Artificial beach in the UAE. Too high content of shells and coral debris.

It is evident from the above examples that it is of great importance to use very good quality fill sand for the construction of artificial recreational beaches.

18.4 Design guidelines for artificial lagoons

The most important landscape elements in many coastal development schemes are attractive tidal lagoons. Such lagoons provide an attractive protected marine environment — but also major technical challenges. Design guidelines for the hydraulic performance of artificial lagoons are discussed in the following.

18.4.1 Lagoon mouth and channel sections

The stability of tidal inlets is a science in itself, for which reason it shall not be discussed in detail here. It shall just be pointed out that the stability of tidal inlets is a major issue at littoral transport coasts. This means that careful studies are required to secure a stable tidal inlet which is not blocked by sedimentation. The required cross-sections of the inlet will depend on the tidal volume of the lagoon. No specific criteria can be given. However, the cross-section area of mouth and channel sections of artificial lagoons shall be so large that peak tidal current velocities are less than ~ 0.8 m/s. The width and depth shall also be designed according to guidelines for safe navigation if the lagoon is to accommodate navigation by motor and sailing yachts.

18.4.2 Open water body

The main purpose of introducing artificial lagoon and channel elements in a coastal development scheme is to add attractive water landscape elements adjacent to recreational or development areas. The lagoon may be designed to accommodate water sports, navigation, sport fishing and bathing, but bathing will never be as attractive in a lagoon as in the sea, see Figure 18.20. The most important function is to provide the inherent attraction of water to an area which does not have this in its native condition. The lagoon shall therefore be properly designed as an important landscape element.

A set of water quality objectives for the lagoon area has to be established in order to secure an appropriate water quality in the lagoon. This could e.g. be in the form of international bathing water quality standards, e.g. the EU Standard (Directive 2006) The water quality objectives reflect the designated use of the planned water body elements and specify sets of water quality criteria (transparency of the water, concentration of nutrients and pathological bacteria, etc.) that have to be met in order to secure the planned recreational uses of the water body.

The water quality in the lagoon has consequently to be planned and regulated to meet the established water quality objectives based on factors such as:

- Control of local sources of pollution such as point sources (rivers and sewage discharges) and diffuse sources (surface run-off and drainage waters)
- Degree of flushing of the lagoon with water from the sea and/or from rivers considering also the water quality in these

The retention time of the water in the lagoon and channels is often relatively long because the extension of these elements is maximised in order to facilitate the recreational use of the lagoon. Consequently, it is imperative to avoid or seriously reduce all point sources of pollution as well as to avoid or reduce the use of fertilisers or treated sewage water for irrigation of green areas in the proximity of the lagoon elements. There are two reasons for these requirements. Primarily: To avoid seepage of nutrients to the lagoon waters. Secondly: Fallen leaves and cut grass from these recreational areas are often mineralised locally to improve the quality of the soil, whereby all phosphorous and most of the nitrogen contained in the fertilisers or the treated sewage waters used for irrigation are eventually washed to the groundwater and further to the lagoon water. These supplies of nutrients to the lagoon waters may cause eutrophication unless controlled by increased flushing. As brackish waters are generally less diverse than freshwater or marine ecosystems, it is advisable to avoid bigger discharges from rivers in the lagoon.

The need for flushing with seawater is dependent on a number of factors such as:

- Flow and quality of river water discharged to the lagoon (control of salinity and water quality)
- Local discharges of nutrients and bacteria from point and diffuse sources as such discharges may cause eutrophication and reduced bathing water quality
- Water quality in the ambient seawater used for flushing (a high flushing with polluted water does not solve the problem)

The flushing can be expressed in terms of a characteristic “flushing time” T_{50}, which is the time it takes before 50% of the water in the lagoon system has been exchanged with “clean” water from the sea outside the lagoon during a design scenario. The design scenario shall be a calm and warm period, as this is most critical for flushing and water quality. There are no specific requirements for the flushing time. An acceptable flushing time for a natural lagoon with minimal local sources or freshwater supply, pathogenic bacteria and or nutrients will normally be 5–7 days, but the flushing time T_{50} for artificial recreational lagoons should preferably be shorter.

It will under many conditions be recommendable with more than one opening to accommodate sufficient flushing, but two openings do not necessarily provide sufficient flushing as this depends on the local tidal conditions. Consequently, it will sometimes be required to establish forced flushing by tidal gates or by additional pumping. Other rules of thumb are:

- Water depths shall not be larger than 3–4 m and shall not be less that ~ 2 m
- There must be no local depressions in the seabed
- There must be no discharge of pollutants to the lagoon such as sewage, storm water, brine, cooling water, pesticides and nutrients.

18.4.3 Perimeters

Normally it will be difficult to obtain a good quality beach inside a lagoon for the reasons discussed in the previous chapter. The following guidelines should be followed to obtain the best possible lagoon beaches if lagoon beaches are embarked on despite the above “warnings”:

- Use only high-standard beach sand as explained under the design guidelines for beaches
- Construct the desired beach profile from the beginning
- Build only beaches at exposed locations in “large” lagoons with dimensions preferably > 2–5 km and water depth not less than 2 m or select a beach site near the opening to the sea where some wave exposure is secured
- Build only beaches if the amount of suspended substances in the lagoon water is very small, say in the order of less than 5–10 mg/ℓ

It is strongly advised to consider other alternatives than beaches inside lagoons.

18.5 Landscape elements of waterfront developments

The recreational and landscaping requirements in relation to design of the marine elements of waterfront developments are discussed in the following. The characteristic elements are:

- Beaches
- Other types of water edge treatments
- Landscape behind the shoreline perimeter
- Lagoon areas

Far too many coastal projects are developed without a clear understanding and respect for the natural hydraulic and coastal processes which are decisive for the overall layout of the marine elements of a development. Consequently, many projects are developed without a clear idea of which layouts are feasible and of how the different elements can support each other. This may lead to unstable shoreline sections or to shoreline sections with a poor beach quality and consequently major expenses for maintenance – often resulting in poor results.

The planning process for a waterfront development shall consequently secure a balance between the objectives of the developer and the possibilities that the specific development site can offer in terms of artificial marine elements, and taking environmental impacts into consideration. The main objectives of the developer of a waterfront development, being a public authority or a private company are typically:

- Enhancement of economic development possibilities in an area
- Expansion of the length of water perimeter through establishment of artificial water bodies inland or by reclaiming land in the sea
- Development of attractive marine landscape elements combined with recreational facilities and service facilities, such as marinas
- Provide balanced public and private access
- Provision of attractive sandy beaches and other water edge treatments
- Establishing coastal structures combining technical requirements with recreational requirements
- Establish optimum internal functionality and minimum environmental impacts

These objectives shall be balanced against the possibilities and constraints offered by the natural conditions in the development area – where can beaches be located and how shall they be orientated, how can good flushing conditions and good water quality be secured in artificial lagoons, etc. These conditions are already discussed in the previous chapters where design guidelines for artificial beaches and artificial lagoons are presented.

In the design and planning process for marine landscape elements and coastal structures, it is especially important to secure that technical requirements are combined with recreational requirements, which means that most marine elements shall be designed as multifunctional facilities. Examples of such layouts are listed below and examples are presented in the following figures:

- A terminal structure designed as a viewing headland, see Figure 18.10
- Smooth transition between structures and beaches provided by an obtuse angle between beach and terminal structure, see Figure 18.10
- A headland structure designed as a recreational pier, see Figure 18.11

Figure 18.10 Amager Beach Park, Copenhagen with terminal structure as viewing headland.

Figure 18.11 Amager Beach Park, Copenhagen, headland designed as recreational pier.

- A marina designed as a terminal structure for a beach section, note the detached breakwater providing a soft transition, see Figure 18.12

Figure 18.12 Kalø Vig Marina, Denmark. Marina with detached breakwater providing soft transition between beach and marina.

- Artificial lagoons, canals, marinas and sea baths designed to provide a combination of the following assets: Attractive landscape elements, areas for water sports, navigation and mooring, viewing, promenading, bathing and provision of open space, see Figure 18.13 and Figure 18.14

Figure 18.13 Amager Beach Park, Copenhagen. Lagoon with water sport activity. Note: Non exposed beach of low quality.

Figure 18.14 Port of Copenhagen, recreational activities.

- A lagoon opening designed as a marina, see Figure 18.19 in the next subchapter

- Water edge perimeter structures designed to combine technical requirements with recreational requirements. Examples of structures could be: A) Water edge treatments with low-lying stepped promenades/ platforms providing close connection to the water and different safety levels against flooding, see Figure 18.15 and Figure 18.16. B) Revetments equipped with steps for access to the water etc., see Figure 18.17

Figure 18.15 Terraced water edge treatment providing close connection to the water with different safety levels against flooding.

Figure 18.16 Low platform providing possibility for water sport activity.

Figure 18.17 Malmø West Harbour, revetment equipped with steps and platforms for access to the water.

- A seawall designed as an integrated part of the beach furniture, see Figure 18.18.

Figure 18.18 Amager Beach Park, Copenhagen. Upper: Promenade separated from the beach by a seawall. Lower: Seawall along the southern beach section having multiple functions: Coast protection, separation between promenade and beach and sitting furniture.

Landscaping principles for layout of artificial beaches should focus on as long and uninterrupted beach sections as possible and minimisation of the number of structures as these principles will enhance the natural appearance of a beach section. Stabilising structures shall preferably reach out to the closure depth in order to minimise dangerous rip currents.

An integrated planning based on workable marine elements will make it possible for developers and planners to create unique and sustainable coastal developments where the possibilities and requirements of nature are combined with the economic and recreational requirements of the developing entity.

18.6 An example of a successful beach park development

A new beach park was recently built in Copenhagen using the principle of making the new beaches exposed by moving them out to deeper water thereby avoiding the shelter provided by the existing shallow shoreface. An aerial photo of the new beach park just after finalisation of the civil works is presented in Figure 18.19.

Figure 18.19 Aerial photo of Amager Beach Park (2005), which consists of the following main elements: Island with terminal structures north and south and a separating headland between northern and southern beaches and a lagoon. Designed by DHI, Hasløv and Kjærsgaard and NIRAS.

The main wave directions at the site are NE and SE, which have been utilised to create two sections of exposed beaches separated by a headland, one facing towards NE and one facing towards SE. Note the Y-shape of the headland structure providing a smooth transition between the structure and the beaches, which secures minimum trapping of floating seaweed and debris in the transition areas. The beaches have been constructed on a new island in order to obtain sufficient wave exposure and a new lagoon (excavated) has been built between the island and the old shoreline. There is always a good current just off the beach park as it is located in the Sound, the strait between Denmark and Sweden, where water exchange between the Baltic and the North Sea takes place. This results in a good flushing of the lagoon.

The beach park has been very well received by the citizens of Copenhagen and it has in an opinion poll been nominated as the best beach in the Copenhagen area. It has also received a reward from the “Society for the beautification of the Capital”, and people are enjoying all the facilities in the park all over the year, see picture in Figure 18.20.

Figure 18.20 Amager Beach Park, Copenhagen. Kite surfing on the Lagoon, the beach island in the background.

18.7 New concept for an offshore development scheme

A new concept for an offshore development scheme utilising the principles presented in this article has been developed by DHI and Hasløv & Kjærsgaard, Planners and Architects, Copenhagen. The scheme is universal in the way that it can be implemented at any location where there is a development need and where there is wave exposure. The scheme has been developed under the motto: "Work with Nature" understood in the way that the wave exposure at the site is considered as a valuable gift from nature, which is utilised for developing a superb recreational facility in the scheme, namely a high-quality exposed beach.

Figure 18.21 "The Universe" concept for an offshore development scheme, Artist's impression of the beach in "The Universe" and a possible concept for a marina. © DHI and Hasløv & Kjærsgaard. All rights reserved.

The jewel of the scheme is the unique half-moon shape ocean bay providing a superb sandy beach. The scheme thus offers the possibility for developing an extremely high-quality urban beach which can be equipped with an attractive cornice along which most of the important recreational and leisure functions of the new city can be developed such as: Promenades, retail down-town areas, advanced apartment schemes, hotels, marine sport facilities, entertainment facilities, parks, etc.

18.8 Investigation methodology

18.8.1 General requirements

The building of a waterfront development scheme in a coastal area imposes on one hand an impact on the marine and coastal conditions at the site and on the other hand it exposes the development to the marine and coastal processes at the site. The art of developing a successful and sustainable waterfront development is to minimise the negative impacts and at the same time to utilise the possibilities given by the natural conditions at the site such as flushing and wave exposure, for a successful development of the scheme. A successful scheme is often characterised by solving existing problems at a site such as coastal erosion and flooding, at the same time as it introduces new coastal and marine facilities to the area such as artificial beaches and lagoons, marinas, viewing points and sea promenades, etc.

It is required to obtain information on the natural conditions in the area. The types of relevant data to be collected are listed in the following:

- Geological data
- Topographic and bathymetric surveys and maps
- Historical and recent aerial photos and satellite images
- Shoreline development maps
- Sediment sources and sinks in the area
- History of coastal structures and nourishment
- Sedimentation and maintenance dredging in ports, navigation channels and tidal inlets
- Land use maps
- Meteo-marine data (winds, tides and storm surges, sea level rise, waves, currents and ice)

Studying this data will most probably provide a good understanding of the important processes in the area, the impact caused by the existing structures and the possible problems but the baseline study will also serve as guideline for future development possibilities in the area.

18.8.2 Hydraulic studies

The reliability of numerical models representing coastal processes has increased dramatically in recent years. This development is driven by the ever-increasing computer power, combined with research in and increased understanding of the physics (hydrodynamics, sediment transport and ecology), which is reflected in the development of numerical models, see also Chapter 21.

The models can provide detailed information of wave and flushing conditions and on littoral transport, shoreline development and coastal classification, which can provide insight into the cause of present problems and the consequences of different schemes for remedial action. The numerical models can also be used in functional analysis of waterfront development schemes and for layout optimisation as well as hydraulic design. Finally the models can be used for analysis and quantification of environmental impact. The relative ease of using such models, however, can be deceptive. The choice of the modelling methodology and the interpretation of the simulation results require a thorough understanding of phenomena treated, both the large-scale coastal morphology and the physical processes involved at a smaller scale. The numerical models are only useful when applied in combination with qualified engineering judgments. It can thus be concluded that predictions by numerical models can be extremely useful provided that the following conditions are fulfilled:

- The input data shall be of good quality

- Data shall be available for calibration, validation and production runs

- The models shall be of high scientific standard and cover the relevant subjects such as waves, hydrodynamics, sediment transport and ecology, etc. It is important to use a sufficiently fine grid size to secure that the important processes are resolved and to realise which assumptions have been introduced, what the model can represent and with which accuracy
- The scheme to be tested shall be defined on basis of an understanding of the physical processes. It is important to realise that even the most up-to-date numerical hydraulic model only provides documentation of the hydraulic/coastal characteristics of the scheme having been defined for testing; the model does not in itself provide the optimal scheme. It is up to the hydraulic engineer and the master planners to define a layout, which has near optimal functional characteristics. The model can then be used to document the actual functional characteristics of the tested scheme, on which basis further optimisation of the scheme can be introduced and tested. It is therefore of utmost importance that the definition of the hydraulic layout of a scheme is made on basis of a profound hydraulic knowledge and experience in order to secure an optimal outcome of its testing using numerical models. The important aspect for good functionality of coastal schemes is the subject of the previous subchapters in this chapter.

This subchapter summarises the capabilities and limitations of different modelling concepts, and provides some indication of the predictions that can be obtained by proper application of a given type of model. The emphasis is put on models describing sandy coasts and on models primarily based on a description of physical processes rather than on data-driven or rule-based models.

Specific modelling techniques such as single grid, multiple grids or flexible mesh techniques will not be addressed such issues are discussed in Chapter 21. A summary of the following characteristics for numerical models typically used for layout analysis and hydraulic design of coastal development schemes are presented in Table 18.2.

- Phenomena to be simulated
- Type of numerical model
- Model size
- Input data
- Typical results of the modelling

Physical scale models are generally mainly used in the detailed design phase for stability of armour layers, overtopping of structures and wave agitation in port basins and semi closed bays.

Table 18.2 Summary of characteristics and types of numerical models applicable for layout analysis and hydraulic optimisation of coastal development schemes.

Phenomenon to simulate	Type of model	Model size in m	Input data	Typical results
Wave transf. from offshore to nearshore	Spectral wind-Wave Propagation model (WP)	$> 10^3$	Bathymetry Offshore waves Wind over modelling area	Wave patterns Statistical distribution of waves Design wave conditions Input to HD, ST and LT models
Wave disturbance in ports and local bays etc.	Short Wave model (Boussinesq or similar)	$10^2 – 10^4$	Bathymetry Nearshore wave data	Wave height/direction distribution in port/bay area Wave reduction factor distribution
Tides, storm surges and currents	HydroDynamic model (HD), 2D or 3D	$> 10^2$	Bathymetry Tide Wind Radiation stress from wave model	Tidal analysis Storm surge design data Current patterns Input to Flushing model Input to ST models
Flushing, spreading and sedimentation of substances	Advection-Dispersion model (AD)	$10^3 – 10^5$	Hydrodynamics from HD model Source of substances	Flushing pattern and time Transport, dispersion, decay and sedimentation of dissolved and suspended substances
Water Quality	Ecological process model	$10^3 – 10^5$	Hydrodynamics from 3D HD model Source of substances WQ data	Distribution of: Ammonia, Nitrite and Nitrate, Total Nitrogen, Phosphate, Total Phosphorous, Chlorophyll a and Secchi Disk Depths, and others
Sediment Transport over an area	2D Sediment Transport model (ST) for sand (MT) for mud	$10^3 – 10^5$	Bathymetry Sediment charac. Input from HD and WP models	Transport fields for selected storms and "annual" situation Initial and annual sedimentation and erosion patterns
Morphological Development over an area	Morphological evolution model for sandy environments	$10^3 – 10^4$	Bathymetry Sediment charact. Boundary cond. on waves and hydrodynamics	Evolution of seabed during selected storm events
Littoral Transport	Annual Littoral Transport in a coastal profile (LT)	$10^2 – 10^3$	Bathymetry Sediment charac. Wave statistics or time series	Annual littoral transport in a profile Transport distribution in the profile Equilibrium orientation Closure depth
Shoreline Evolution	One-line shoreline evolution model	$10^2 – 10^5$	Initial shoreline and coastal structures Annual transport data from LT model	Present shoreline evolution Future shoreline evolution (without and with stabilisation scheme) Shoreline variability
Profile Evolution	Surf zone coastal profile model	$10^2 – 10^3$	Coastal profile Sediment characteristics Waves from WP	Profile evolution during storms

18.9 Conclusions and recommendations

It is concluded that it is crucial for a successful design of beach and lagoon elements in waterfront development schemes that the hydraulic, coastal and environmental aspects are included in the planning from the early planning stage. The reason for this is that the design of these elements has to follow the “rules of nature”, which impose certain restrictions on the design.

The main issues to observe are the following:

Artificial beaches:

- Good quality recreational beaches shall be moderately exposed to waves, they shall be orientated towards the direction of the prevailing waves to be stable and terminal structures shall be constructed to prevent loss
- Temporal variability in beach plan form (seasonal or yearly) should be evaluated to inform on requirements for a buffer in beach width or for protective structures
- Terminal structures shall have an obtuse angle with the shoreline and shall be designed so that no dangerous currents are generated
- Artificial beaches shall be constructed by good quality beach sand: medium, i.e. $0.25 \text{ mm} < d_{50} < 0.5 \text{ mm}$, well sorted, attractive colour, minimum content of fines and minimum content of coarse fractions and no content of organic matter

Artificial lagoons:

- High water quality standards shall be secured in recreational lagoons. The “flushing time” T_{50} shall be better than 5 to 7 days, which may require special precautions
- The lagoon mouths shall be stable and free of sedimentation
- Water depths shall be between 2 m and 4 m
- There must be no local depressions in the seabed
- There must be no discharge of pollutants to the lagoon such as sewage, storm water, brine, cooling water, pesticides and nutrients

Waterfront developments in general:

- A thoroughly planned location and layout of the urban elements integrating recreational demands with the natural dynamics of artificial beaches and lagoons are important. Coastal structures shall also have recreational functions.

19 Environmental Impact Assessment (EIA) and Morphological Impact Assessment (MIA)

19.1 Introduction and background to EIA and MIA

Environmental Impact Assessment (EIA) is a methodology/tool used in the planning of projects in relation to minimising possible negative impacts on the environment. In a broader context one can say that EIA aims to ensure that the development options under consideration are environmentally sound and sustainable.

The environmental impact assessment shall identify, describe and assess in an appropriate manner, in the light of each individual case the direct and indirect effects of a project on the following conditions:

a. Physical/chemical conditions
b. Biological/ecological conditions
c. Sociological/cultural conditions
d. Economic/operational conditions
e. The interaction between the conditions referred to in points a, b, c and d

Once alternative projects have been specified, environmental impact assessments could be conducted to ensure that the relevant environmental consequences of the various alternatives are recognised early in the project cycle and taken into account in selection, planning and design. In many countries it is mandatory to carry out the process of environmental impact assessment (EIA) for the application of permits related to specific projects, the type of projects requiring an EIA are discussed further in the following. The EIA procedure is an important project optimisation tool for developers, decision makers and the public whereby the environmental impact of a project can be minimised or mitigated. Therefore it is recommendable to conduct an EIA anyhow, also if it is not mandatory.

This guideline mainly deals with the physical conditions related to shoreline management projects, namely the impact of a shoreline management scheme on the morphological environment, referred to as Morphological Impact Assessment (MIA). As procedures for performing morphological impact assessments are a part of the general EIA procedures, these will be summarised as background for the following description of the MIA. The fact that this chapter mainly deals with MIA does not indicate that other aspects of EIA for a certain project are not relevant, but it is assumed that these aspects are covered by other studies, which will not be dealt with here.

ICZM (Integrated Coastal Zone Management) is the full planning and management process for the coastal zone involving economic, environmental and social aspects, whereas SM (Shoreline Management) concerns actual and potential coastal erosion and its relation to planned or existing development activities. Similarly, EIA is the planning tool used to ensure that development options are environmentally sound with respect to physical/chemical, biological/ecological, sociological/cultural and economic/operational aspects, whereas MIA deals with the impact of a project on the morphological conditions.

It is important to emphasise that the impact assessment process is an integrated part of the optimisation process and that the impact assessment should be used in all phases of a project as an interactive tool for the adjustment and optimisation of the project. It is better to optimise a certain project to avoid negative impacts instead of introducing mitigating measures to counteract possible impacts of a non-optimised project.

EIA has been adopted into the planning regulations for numerous countries over the last 30 years. The performance of a proper EIA is also a basic requirement for many regional and multilateral agencies, such as the World Bank, EU, European Bank for Reconstruction and Development (EBRD) and Danida, etc.

19.2 General EIA procedures

The procedures described in the following are applicable for EIA studies for marine projects. These procedures are, in principle, identical to those valid for an MIA study, the difference is that the number of relevant projects and study items for an MIA study is much less than for an EIA study.

19.2.1 Type of marine projects requiring Environmental Impact Assessment

The type of projects requiring Environmental Impact Assessment varies from country to country.

The normal practice is that projects are divided into two categories:

1. Prescribed activities, i.e. projects that must be made subject to EIA
2. Non-prescribed activities, i.e. projects that may be made subject to EIA

An EIA shall be performed for all prescribed activities, whereas it is up to the environmental authorities to evaluate whether an EIA should be performed for non-prescribed activities. This evaluation takes the following conditions into consideration:

- Project characteristics (dimension, cumulating with other projects, use of natural resources, production of waste, pollution, risk of accidents)
- Project location (present land use, the quality of natural resources and of the natural environment) with special attention on coastal areas, reserves, densely populated areas, historical and cultural monuments
- Characteristics of the possible impact (amount, character, complexity, occurrence, duration and reversibility)

A list of prescribed and non-prescribed coast related activities is given in the following; this list should only be seen as a typical list, as conditions will vary from country to country (the list is inspired from EU Directive 2011/92/EU). It should be mentioned that the European Community has introduced common conditions for the performance of EIA in all member countries not only to enhance the environmental conditions in all member countries, but also to secure equal competition between the different countries.

19.2.1.1 Prescribed activities

The specific numbers given in the following refer to EU-directives; they are thus not universally applicable, but they can be used as guidelines in countries, which have not established their own regulations. Characteristic coast related projects that must be made subject to EIA are listed below (inspired from EU Directive 2011/92/EU) (not exhaustive):

- Crude-oil refineries
- Major Shipyards
- Thermal power stations of more than 300 megawatts
- Nuclear power stations
- Plants for smelting of cast iron or steel

- Chemical factories and industrial plants for the production of pulp and paper (more than 200 t per day)
- Major infrastructure projects affecting the marine environment, such as bridges, reclamations, runways, tunnels and artificial islands
- Inland waterways and ports which permit traffic of vessels over 1350 tonnes
- Trading ports, piers for loading and unloading connected to land and outside ports (excluding ferry piers) which can take vessels of over 1350 tonnes
- Waste disposal installations for chemical substances
- Waste water treatment plants with a capacity exceeding 150000 population equivalent
- Pipelines with a diameter of more than 800 mm and a length of more than 40 km for transport of gas, oil or chemicals
- Mining of marine resources (sand and similar) when the mining takes place in protected area or when the volume is greater than 1 mio. m^3 per year or total 5 mio. m^3

19.2.1.2 Non-prescribed activities

Note that non-prescribed activities may be made subject to EIA. When an activity is referred to as minor in the following, it is referring to the corresponding figures “greater than” given under prescribed activities. Characteristic coast related projects that, following an assessment, may be made subject to EIA are listed below (inspired from EU Directive 2011/92/EU) (not exhaustive):

- Deforestation (mangroves) for the purpose of conversion to another type of land use, e.g. fish farming
- Intensive fish farming and mariculture
- Extraction of minor volumes of sand from the sea/beach or from rivers
- Thermal power stations (less than 300 megawatts) and desalination plants
- Shipyards
- Installation of wind power farms and wave power farms
- Fish-meal, fish-oil and canning factories
- Construction of harbours and port installations, inland waterway, fishing harbours and marinas (projects not included under prescribed activities)
- Minor infrastructure projects affecting the marine environment, such as bridges, embankments, runways, tunnels and artificial islands
- Pipelines for gas, oil or chemicals (not mentioned under prescribed activities)
- Coastal works to combat erosion and coastal flooding, such as revetments, seawalls, dykes, groynes, breakwaters and nourishment, excluding maintenance of such works
- Coastal, nearshore and offshore waterfront development projects capable of altering or impacting the coast
- Coastal holiday villages and hotel complexes outside urban areas

- Waste disposal installations and waste water treatment plants (not mentioned under prescribed projects)
- Sludge deposition sites

Whether the project shall be subject to EIA is decided by relevant authorities taking the selection criteria into consideration as listed in the following box.

If it is concluded that an EIA is not required, this should be announced publicly, thus making it possible to lodge complaints.

SELECTION CRITERIA (ANNEX III of Directive 2011/92/EU)

1. CHARACTERISTICS OF PROJECTS

The characteristics of projects must be considered having regard, in particular, to:

a. the size of the project;
b. the accumulation with other projects;
c. the use of natural resources;
d. the production of waste;
e. pollution and nuisances;
f. the risk of accidents, having regard in particular to substances or technologies used.

2. LOCATION OF PROJECTS

The environmental sensitivity of geographical areas likely to be affected by projects must be considered, having regard, in particular, to:

a. the existing land use;
b. the relative abundance, quality and regenerative capacity of natural resources in the area;
c. the absorption capacity of the natural environment, paying particular attention to the following areas:
    i. wetlands;
    ii. coastal zones;
    iii. mountain and forest areas;
    iv. nature reserves and parks;
    v. areas classified or protected under Member States' legislation; special protection areas designated by Member States pursuant to Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds (1) and to Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora (2);
    vi. areas in which the environmental quality standards laid down in Union legislation have already been exceeded;
    vii. densely populated areas;
    viii. landscapes of historical, cultural or archaeological significance.

3. CHARACTERISTICS OF THE POTENTIAL IMPACT

The potential significant effects of projects must be considered in relation to criteria set out in points 1 and 2, and having regard in particular to:

a. the extent of the impact (geographical area and size of the affected population);
b. the trans frontier nature of the impact;
c. the magnitude and complexity of the impact;
d. the probability of the impact;
e. the duration, frequency and reversibility of the impact.

19.2.2 The concept of a full Environmental Impact Assessment

In order to emphasise that morphological impact assessment is only part of the full EIA, the project optimisation procedure, objectives, components and study requirements for a complete detailed EIA are outlined briefly in the following. There can be specific requirements from country to country; the outline given in the following is general and fits most marine projects.

19.2.2.1 Overall project optimisation procedure

It is recommended that the progress of marine projects shall follow a fixed progression through the various project phases in order to ensure that the findings of the various EIA's are fully integrated with the final design and work plans during the implementation of the project. These phases are:

1. Project conception:

Here a concept design for the project is presented to the authorities. The developer is required to provide the following basic information:

- Project description
- Bathymetry survey
- Conceptual design and costing

2. Preliminary Environmental Impact Assessment:

Based upon approval of the concept design, a preliminary analysis of the possible impacts of the project upon the physical-chemical, biological-ecological, socio-cultural and economic-operational environment should be performed by a qualified EIA Consultant. The EIA is presented for the regional authority, see Subchapter 14.3.2

The Preliminary EIA is required as a minimum to address the following topics:

- Preliminary hydraulic impact assessment covering current, waves, sediment transport and morphology
- Marine habitat survey and impact assessment
- Socio-economic impact assessment

The Preliminary EIA may be performed using the Rapid Impact Assessment Matrix, the so-called RIAM method.

For large projects where detailed EIA is mandatory, the preliminary EIA shall be commissioned as an integral part of the detailed EIA.

3. Preliminary design:

Subject to approval, the results of the preliminary EIA must be integrated into the preliminary design of the project. Plans for project design and project implementation are elaborated.

4. Detailed Environmental Impact Assessment:

Depending upon the scale of the project and the findings of the preliminary EIA, a detailed EIA may be required. For large-scale marine projects, the performance of a detailed EIA is normally a prerequisite. The impacts of the preliminary design are analysed in a detailed Environmental Impact Assessment. Terms of reference, TOR, are specified in the following subchapters. At this level, all potential impacts are quantified and/or described and the suitability and effectiveness of the optimisation proposals, and of those mitigating measures identified in the preliminary EIA, are investigated.

5. Detailed design:

The mitigating actions emerging from the detailed Environmental Impact Assessment are built into the project to give a final design, minimising the possible environmental impacts.

6. Construction and monitoring:

Implementation of the project while carrying out an environmental monitoring programme, which includes a feedback mechanism and a possibility for mitigating unforeseen adverse impacts.

19.2.2.2 TOR for Detailed Environmental Impact Assessment

The Terms of Reference, TOR, for the detailed EIA presented in the following are only an example of how such terms can be put together. The terms have been developed on basis of practice in several international projects.

Objectives

The main objective of the detailed Environmental Impact Assessment is to analyse the project in order to evaluate the extent to which it complies with the goals of minimising negative impact to the environment and society, whilst attaining the goals of the developer with respect to the provision of the desired function of the project.

To this end, the detailed EIA should embrace the following:

- Describe the project
- Describe the existing physical-chemical conditions and identify the potential impact of the project on the physical-chemical environment
- Describe the existing biological-ecological conditions and identify the potential impact of the project on the biological-ecological environment
- Describe the existing socio-economic conditions and identify the potential impact of the project on the socio-economic conditions
- Describe and analyse the sustainability of the operation and maintenance of the project
- Recapitulate the optimisation and mitigation actions that have been taken, and those suggested to minimise negative impact
- Recommend the appropriate monitoring programme that enables control of compliance with the assumptions of the EIA, and compliance with possible environmental quality objectives for the project
- Recommend the appropriate audit programme

Components

The detailed Environmental Impact Assessment should be carried out using a widely-accepted analytical process. The analysis should include, but need not be limited to, the following elements:

Bounding:

The process of bounding is setting the limits of the study area. This area should cover any area - at land or at sea - which is influenced to any degree by the project.

Scoping:

The relevant problems for the study should be selected during the scoping procedure. A checklist of possible/potential impacts may be used as a basis. The scoping should include the definition of environmental quality objectives for the project. These include, but need not necessarily be limited to:

- A definition of primary and secondary impact zones
- A definition of the limits of acceptable change within these zones

These quality objectives may be updated throughout the course of the investigations.

Investigation:
In the investigation phase the necessary data and information for the assessment should be collected and assimilated into a baseline for the area.

Quantification:
A quantification of the specific environmental impact of the individual components is accomplished through the use of numerical models and other appropriate analytical techniques.

Participation:
Information is passed on to related authorities and the public for their commenting.

Analysis:
The phase where information is transferred into one or more reports that include the findings. The presentation should be in a form, in which the information is prepared for decision making.

Mitigation and environmental optimisation:
An analysis of the possible actions in the form of, for example, changes in design, protective works, special construction methods, cleaning techniques, etc. which can be introduced to mitigate the negative impact of the project.

Monitoring:
A plan for a monitoring programme, which can control compliance with quality objectives and check the predictions of the Environmental Impact Assessment. Provision of baseline data for the recommended variables to be included in the programme.

19.2.2.3 Study requirements

The detailed Environmental Impact Assessment of the marine project should contain, but need not be limited to, descriptions and assessments of the following items within the geographical area likely to be affected by the project. In the event that the Consultant chooses to exclude a specific item from the assessment, written justification for such exclusion must be provided.

Basic data should be provided for all items mentioned in the following subchapters. The data may be supplied from existing sources but should be supplemented with data from field surveys, recordings and numerical simulations as required. The basic data requirements are listed in the following subchapter.

a. Physical-chemical conditions

The following items should be covered:

- *Hydraulic circulation*:
  Description, assessment and simulation of the present and future prevailing current speeds and directions.
  It is necessary to use computerised hydrodynamic modelling for this analysis.
- *Wave conditions*:
  Description, assessment and simulation of the present and future prevailing wave heights and directions. The simulations should investigate the proposed scheme plus alternative schemes as relevant.

- *Coastal morphology*:
  Description, assessment and simulation of the present and future coastal morphology and the dominant coastal processes. The identification of littoral cells, sub-cells and management units within the EIA boundaries including quantification of the littoral sediment budget and its seasonal variation. The impact of the project upon regional and local morphological processes, including erosion and sedimentation of cohesive and non-cohesive material, as relevant. The coastal defence requirements, strategies, options and effectiveness. The impact of the project upon local sedimentation arising from rivers, storm drains and/or the sea with particular reference to maintenance requirements and drainage reserve of channels and basins within the development area.

- *Water quality*:
  Description and assessment of the present water quality, during the construction phase and after the completion of the project.

  It is normally necessary to use computerised water quality modelling for this analysis.

- *Persistent substances*:
  Description and assessment of the use and discharge of heavy metals and persistent organic compounds and their impact during the construction phase, and after the completion of the project.

  It is normally necessary to use computerised water quality modelling for this analysis.

- *Extreme events*:
  A description, assessment and simulation of the present and future actions of extreme waves and flooding.

  It is normally necessary to use computerised wave and hydrodynamic modelling for this analysis.

- *Drainage*:
  Hinterland drainage capacity if the project has any impact on drainage conditions.

  Computerised hydrodynamic modelling is normally necessary for this analysis.

- *Borrow materials*:
  Description of the place, type and amount (including estimates of net loss) of material and methods used for the extraction of borrow materials from the seabed, if these are part of the project. An assessment of the impact on the adjacent physical-chemical environment due to dredging and sand extraction at the dredging location and at adjacent areas.

  It is normally necessary to use computerised sediment plume modelling.

- *Reclamation works*:
  Description of the methods used for the reclamation fill. Assessment of the impact on the adjacent physical-chemical environment due to the spill of sediments from the reclamation works.

  It is normally necessary to use computerised sediment plume modelling.

b. Biological-ecological conditions

- *Coral reefs:*
  Description and an assessment of the present distribution, bio-diversity and living state, and of the impact of the project on the same parameters during the construction phase and after completion of the project.

The results of the above-mentioned computerised water quality, sediment spreading and sedimentation modelling may be used for this analysis.

- *Mangroves*:
  Description and an assessment of the present distribution and living state, and of the impact during the construction phase and after completion of the project.

  The results of the above-mentioned computerised sedimentation and wave modelling are normally used for this analysis.

- *Sea grass beds*:
  Description and an assessment of the present distribution and living state, and of the impact during the construction phase and after completion of the project.

  The results of the above-mentioned computerised sediment spreading and eutrophication modelling are normally used for this analysis.

- *Soft bottom macro zoobenthos*:
  Description and an assessment of the present distribution, species composition and richness, and of the impact during the construction phase including borrow areas, and after completion of the project. The analysis should embrace, but need not be limited to, areas and benthos community types, where it is assessed that soft bottom macrozoobenthos will disappear due to sand extraction, land reclamation or other impacts of the project.

  The above-mentioned computerised sediment spreading and eutrophication modelling results are normally used for this analysis.

- *Endangered species*:
  Description and assessment of the present occurrence of endangered species or commodities aimed at preserving endangered species or extraordinary natural resources.

- *Eutrophication*:
  Description of the present conditions concerning nutrient dynamics, algae blooms, and water turbidity (Secchi depth).

  Computerised eutrophication modelling is normally used for this analysis.

- *Terrestrial ecosystems*:
  Description and an assessment of the effect on adjacent, terrestrial ecosystems of utilising land materials for revetments, bridge and road construction, and for primary armour protection.

c. Socio-cultural conditions

- *Aesthetic and recreational value*:
  Description and an assessment of the effects of the project on resources valued by the people (i.e. the ecological assets or resources such as beaches, coral reefs, rain forest, fauna and flora, mangrove, natural trails, recreational areas and facilities, and lifestyle in general), and on the visual impression of the shoreline, its interference with scenery and amenities, which maintain the quality of life for the local population as well as the visiting tourists

- *Income*:
  Description and an assessment of the effects of the project on the generation of income for the coastal community.

- *Employment*:
  A description and an assessment of the effects of the project on the employment opportunities.

- *Fishery and aquaculture*:
  Fisheries and aquaculture are important resources along many coasts and careful consideration of the impacts in this field are required, both during the construction phase and after completion of the project. The position of present and planned aquaculture sites should be taken into consideration.

- *Quarries and earth borrow sites*:
  Description and an assessment of the supply of durable armour stones for revetments, headlands and breakwaters from quarries, their impact on the physical-chemical environment in the vicinity of the quarries and on the roads along possible transport routes.

- *Housing and urban development*:
  Description and an assessment of the present situation, the situation during the construction phase, and after completion of the project with respect to the demand for housing and the risk of spontaneous settlements both in the vicinity of the project and in the hinterland.

- *Cost of living*:
  Description and an assessment of the effect of the project on the cost of living for the local population, for example, property values, food prices.

- *Cultural heritage*:
  Description and an assessment of the effect of the project on the traditional, cultural and historical sites, items, etc.

- *Public health*:
  Description and an assessment of the effect of the project on community health and well-being as a result of activities during the construction phase and the competitive demand for social amenities.

  A computerised model for dust plume excursion should be utilised if major earthworks are part of the project.

- *Utilities*:
  Description and an assessment of the effect of the project on the accessibility to utilities, such as water, electricity, telephones etc., including increased competition with the demands from the tourist sector.

d. Economic and operational conditions

- *Infrastructure*:
  Description and an assessment of the impact of the project on the existing infrastructure during the construction phase and after completion of the project.

- *Utilities*:
  Description and an assessment of the impact of the project on the existing utilities during the construction phase and after completion of the project.

- *Maintenance*:
  Description of the need for special maintenance and an assessment of cost, sustainability and the impact of these project activities after completion of the project. The assessment should include, but need not be limited to: dredging for navigation or avoiding siltation, the restoration of revetments, nourishment and cleaning of beaches, etc.

- *Navigation*:
  Description and an assessment of the present and future navigation for merchant ships, ferries and fishing vessels.

- *Solid waste*:
  Description and an assessment of the production of solid waste during the construction phase, and after the completion of the project, and the impact of these operations.

- *Water supply*:
  Description and an assessment of the water supply systems during the construction phase and after the completion of the project and the impact on the freshwater resources and water supply in other areas.

- *Waste water treatment*:
  Description and an assessment of the present situation, the production of waste water during the construction phase and after completion of the project.

- *Customer base*:
  Description and an assessment of the effect of the project on future tourism in the region of the project location. Existing and future customer base.

- *Regional economy*:
  Description and an assessment of the effect of the project on the economy of the region.

19.2.2.4 Field survey requirements

It is recommended performing field surveys covering the subjects listed in the following, unless equivalent recent information is available from the site. This serves as documentation of the present conditions in the area, so-called baseline information.

- Bathymetry
- Measurements water levels, currents and waves
- Suspended solids
- Bottom sediments
- Water quality parameters
- Secchi depths
- Temperature
- Salinity
- Marine habitat surveys
- Vegetation survey
- Ornithological survey
- Visual survey

Part of the baseline investigation could be in the form of a pre-construction baseline monitoring programme.

19.2.2.5 Monitoring and control programme

The EIA consultant should specify an environmental monitoring programme, which should run during the construction phase and after completion of the project. This monitoring programme could be a continuation of a pre-construction monitoring programme run in connection with the baseline investigations. The consultant should provide adequate baseline data for the variables suggested in the monitoring programme. The programme must be designed for quick feed-back action. The monitoring programme should comply with the following demands:

- It should include variables, which monitor the ecological and environmental state of features potentially impacted by the project.

- It should include variables, which provide an immediate identification of situations, in which major environmental quality objectives are exceeded.

- It should include stations for the monitoring programme in areas, which are outside the impact area of the project, and which can act as a non-effect reference.

- It should include a selected number of variables, which can act as feedback variables during the construction phase, allowing a fast response to unforeseen negative effects of the project, i.e.:
  - variables, which are representative of the most important ecosystems
  - variables, for which a limit for transgression can be fixed prior to possible impact
  - variables showing a fast response time with respect to the impacts of the project, and
  - variables, for which analysis results can be “immediately” available or within a few days

- It should make use of tools, which can forecast potential impacts on selected variables (for example suspended sediment concentration and sedimentation) continuously throughout the construction period.

- It should provide baseline data for the monitoring and control programme collected before the initiation of the project in order to enable comparisons during the construction phase and after completion of the project.

19.2.2.6 Reporting

It is recommended that the deliverables of the detailed Environmental Impact Assessment should include:

- An inception report describing the detailed approach to the study. The approach should be accepted by the client and the approving authorities before commencing the main body of the study.

- A report describing the development project documenting:
  - Why the project has been approved at the concept and preliminary EIA stage
  - The overall design of the project, size and function.
  - The project location showing regional and local setting in a recognised co-ordinate system
  - A planar aerial photograph or high-resolution remote sensing image of the site showing the boundaries of the project and pertinent local features.
  - Shore- and inter island connections
  - Pre- and post-project bathymetry
  - Volume requirements for reclamation, types and sources
  - Perimeter protection design, material requirements, types and sources
  - Planned utilisation, type, number of employees, number of visitors, housing, etc.
  - Utilities: water supply, power supply, sewage treatment, solid waste disposal

- A report describing the results of the field campaign. All data must be recorded in digital form and transferred to a baseline environmental database. All spatial data must be presented in map form with an appropriate scale and a clearly marked co-ordinate system.

- A report describing the results of the calibration of the appropriate numerical models, including collected data and the existing conditions (baseline).

- A report describing the results of the Environmental Impact Assessment as outlined in the previous chapters. The report should include a description of the recommended optimisation/mitigation actions and revised plans whenever the need for optimisation/mitigation actions makes it essential.

- A report containing the necessary baseline data for the monitoring, which describes the monitoring programme that is considered necessary to ensure compliance with the environmental criteria during and after the accomplishment of the project.

- All reports should be provided with a short executive summary, which summarises the problems, the methods used, and the basic findings, conclusions and recommendations. The executive summary should be written in an easily accessible form.

19.3 Morphological Impact Assessment

The performance of a MIA study is thus only relevant for projects, which physically intervene, directly or indirectly, in the coastal hydrodynamics and sediment balance and thereby eventually lead to morphological impact. The concept of MIA is also referred to as Shoreline Impact Assessment (SIA).

19.3.1 Interventions leading to morphological impact

The most important physical interventions leading to morphological impacts are listed in the following. It should be noted that the most common impact is coastal erosion and sand accumulation, but morphological impacts may also occur at a distance from the littoral zone.

- Coastal structures of any kind, which by their nature directly impact the transport processes and thereby the coastal morphology. Such structures are typically:
  - Ports and marinas
  - Active coastal protection structures (groynes, coastal breakwaters, headlands and all other structures occupying part of the foreshore and/or the shoreface)
  - Passive coastal protection structures (revetments, seawalls and all other structures which fix the coastline)
  - Reclamations
  - Dikes
  - Inlet jetties at tidal inlets
  - Sea works at river mouths
  - Embankments for bridges and runways
  - Intake and outlet structures crossing the littoral zone

- Structures outside the littoral zone, which, by their impact on the hydraulic conditions, may impose coastal impacts or impacts off the littoral zone. Such structures are typically:
  - Offshore breakwaters
  - Island ports
  - Artificial reefs
  - Artificial islands
  - Offshore wind power farms
  - Bridge piers

- Soft interventions in the littoral zone
  - All types of nourishment
  - Beach sand mining

- Soft interventions off the littoral zone
  - Sand mining
  - Dumping of dredging material, e.g. from maintenance dredging in ports and tidal inlets

- Interventions in rivers and in the coastal hinterland
  - Sand mining
  - Deepening for navigation
  - Construction of dams
  - Drainage and irrigation schemes
  - Construction of river dikes

- Logging of forested areas
- Discharge of silty spill water from sand and gravel mining

- Extraction from the underground causing subsidence
  - Water
  - Oil or gas
  - Coal
- Others
  - Changed storm surge or tidal conditions due to regulations of lagoons
  - Effects of climate change: Sea level rise and change in storminess and storm patterns

The philosophy behind minimising impacts by project optimisation and recommendable mitigation measures will be discussed in the following, among other things by discussion of projects which cause severe impacts.

The first and most important guidance is that minimisation of the impacts shall be an integrated part of the planning and design procedure for all projects, as this provides the most sustainable and feasible solution. However, in many cases it must be realised that even an optimisation of the project is not enough to avoid negative impacts and mitigating measures must be implemented.

19.3.2 Discussion of impacts from and mitigating measures for ports

The coastal impact of a port located on a littoral drift coast depends mainly on the following conditions:

- The extension of the port relative to the width of the littoral zone
- The type of coast and the magnitude of the net littoral transport
- The layout of the port

Here, ports can be divided in three main types with respect to their ability to:

- Accommodate natural bypass
- Minimise sedimentation
- Minimise coastal impact

The three main port types used on littoral transport coasts are as follows, see also Figure 19.1:

- *Single main breakwater ports*, which are characterised by one main breakwater protecting against the prevailing waves and a secondary breakwater protecting against other waves, etc. The main philosophy behind this type of port is the provision of sheltered mooring and entrance conditions. The entrance in this type of port is directed away from the prevailing waves. The main breakwater thus provides a semi-protected area along the downstream coastline, which may cause secondary circulation, surf beats and harbour resonance, which again may lead to problems with regard to sedimentation, navigation and coastal impact, see Figure 5.31

- *Double breakwater ports*, which are characterised by two almost equally sized breakwaters providing an entrance pointing directly offshore (the line between breakwater heads parallel to the shoreline) or towards the prevailing waves. The main philosophy of this type of port is to minimise sedimentation and coastal impact and, at the same time, provide good mooring conditions through the establishment of an outer harbour and acceptable navigation conditions. The behaviour of such ports has been discussed in Subchapter 11.2.1.2 under the discussion of human causes of erosion.

- *Offshore breakwater ports*, which are ports, constructed a distance from the coastline well beyond the littoral zone. The mooring facilities often consist of a piled jetty protected by an offshore breakwater and connected to the coastline with a piled bridge. The main philosophy behind this type of port is to minimise dredging works, sedimentation and coastal impact. This type of port is used mainly on littoral coastlines with a very gentle slope of the coastal profile. An example of this type of port is presented in Figure 17.27 under the discussion of breakwater types.

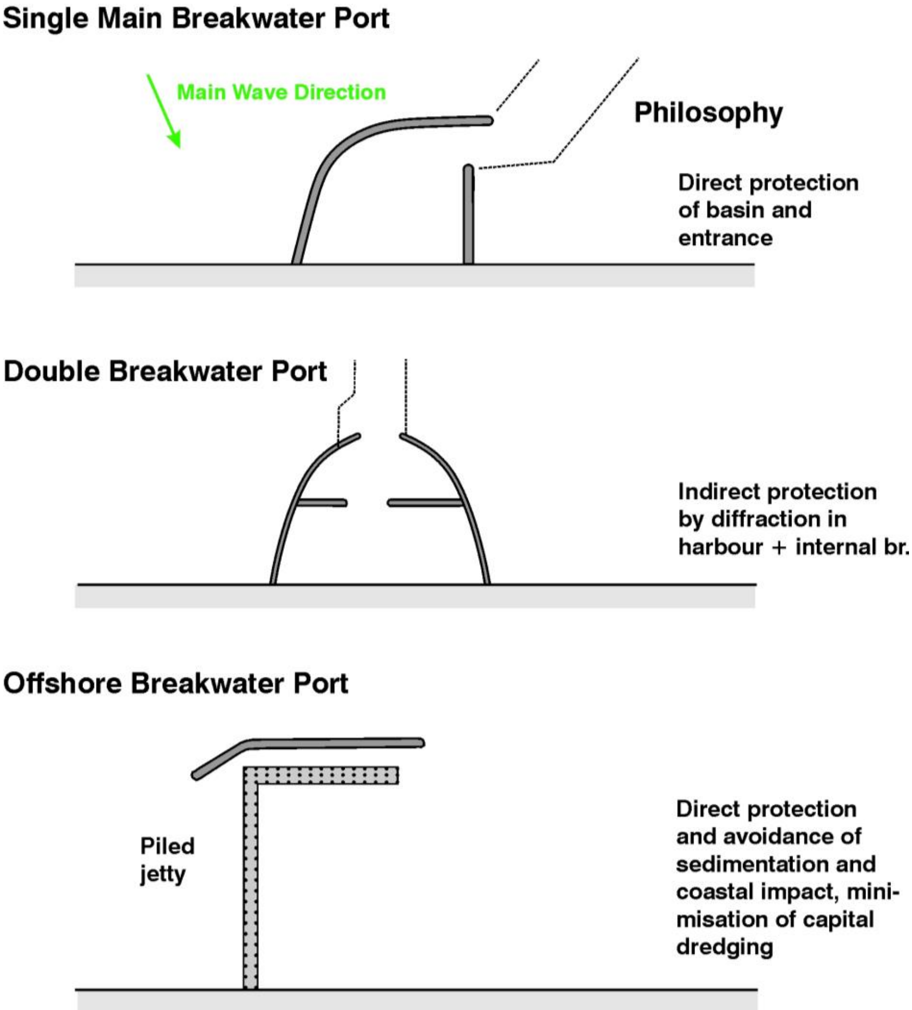


Figure 19.1 Sketch of three types of ports.

In connection with the construction of new ports, most countries require environmental impact assessment studies and proposals for optimisation/mitigation measures to compensate for shoreline impact. This may lead to an optimal layout, but many old ports, and unfortunately also some new ports, are not optimised properly with respect to the impact on adjacent shorelines.

For already existing ports there will, in many cases, be legislation which both requires permission to perform maintenance dredging and which also specifies that the sand must be deposited at the downstream shoreline to compensate for the sand trapped by the port, i.e. artificial bypass. However, this is difficult to impose efficiently, and under all circumstances, there will be a delay in the bypass of the sand, for which reason it is difficult to completely avoid lee side erosion. If a major port has been constructed at a shoreline with a moderate net littoral drift rate, it will take many years before sedimentation becomes an issue. During all these years, no mitigation measures will be imposed to compensate for the deficit in sand supply to the downstream shoreline caused by the trapping of sand by the port. Consequently, the downstream shoreline can be seriously eroded before mitigation measures are imposed in connection with the maintenance dredging.

19.3.2.1 Measures for optimising a port layout with respect to minimal coastal impact

The basic requirement for *minimising the coastal impact on the adjacent coastlines is* strongly connected to the sedimentation aspects at the entrance, for which reason these two aspects will be discussed in parallel in the following. The sedimentation and impact requirements are, to some extent, contradictory. Hence, a small impact on the coastline requires structures, which block the active littoral zone as little as possible, whereas minimum sedimentation requires structures, which extend well beyond the active littoral zone. Therefore a compromise has to be made. Important parameters for the optimal layout and management of a port entrance with respect to minimising sedimentation and shoreline impact are discussed in the following:

- *Provision of a smooth alignment of the breakwaters*. A streamlined layout of the breakwaters guides the current past the entrance with a minimum of eddy formation. The avoidance of eddy formation minimises the risk of sedimentation and at the same time maximises the natural bypass, whereby the coastal impact is minimised, but not eliminated. This calls for an alignment of the breakwater heads to be parallel to the coastline and the angle between the outer breakwater sections to be approximately 140^o. This angle secures optimal smooth current pattern and an optimal wave reflection away from the entrance route.

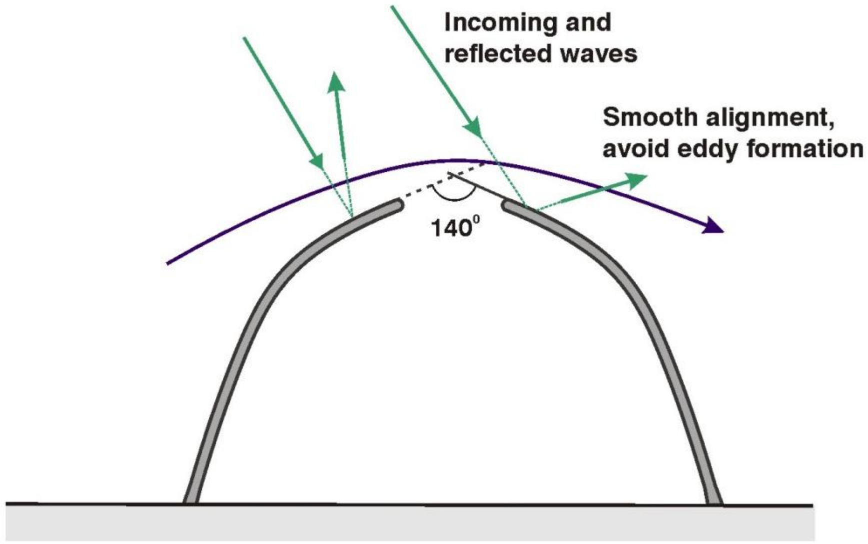


Figure 19.2 Optimal layout of port entrance.

- *Provision of a narrow entrance*. The sedimentation caused by the entrainment of sediments due to eddy formation is proportional to the width of the entrance. Minimum sedimentation also means minimum coastal impact.

- *Connection of the breakwater structures to the coastline.* The transition between breakwaters and the coast should be as smooth as possible on both sides of the port. A sheltered corner on the lee side will act as a sediment trap, and should therefore be avoided. A sharp angle between the coastline and the breakwater on the updrift side will lead to maximum sand accretion, and should therefore be avoided. The trapping of sediments in such corners will deprive the adjoining shorelines of the trapped sand and will consequently enhance coastal erosion.

- *Maintaining navigation depth (minimising sedimentation in front of the entrance) and optimised bypass.* This is achieved by exposing the entrance area to waves and converging currents. Furthermore, it may be considered using vertical reflecting breakwaters in order to maintain the sediments in suspension and thereby enhance bypass and avoid sedimentation. These objectives are best obtained with a double breakwater type of port. This type of harbour layout is called a **bypass harbour**, cf. Mangor 2010.

An example of an optimised smooth port entrance is presented in Figure 19.3, which shows the sediment transport pattern past the new layout of Hvide Sande Fishing Port on the West Coast of Denmark. The relatively high transport past the entrance secures maximum bypass to the downdrift coastline, thereby also minimising the coastal impact. The smaller transport rate off the entrance compared to the adjacent up- and down-stream locations are due to the presence of a deepened navigation channel, see also Subchapter 21.4.7.16.

It shall be mentioned that the bypass harbour concept is only applicable in the case where the extension of the harbour is less than the width of the littoral zone. This is typically the situation for small fishing ports, with moderate requirements to navigation depth, located at an exposed coast. The bypass concept is not possible to establish for e.g. a relatively large commercial port, which requires a considerable navigation depth, located at a littoral transport coast with moderate exposure, e.g. on a coast exposed to a monsoon or swell wave climate.

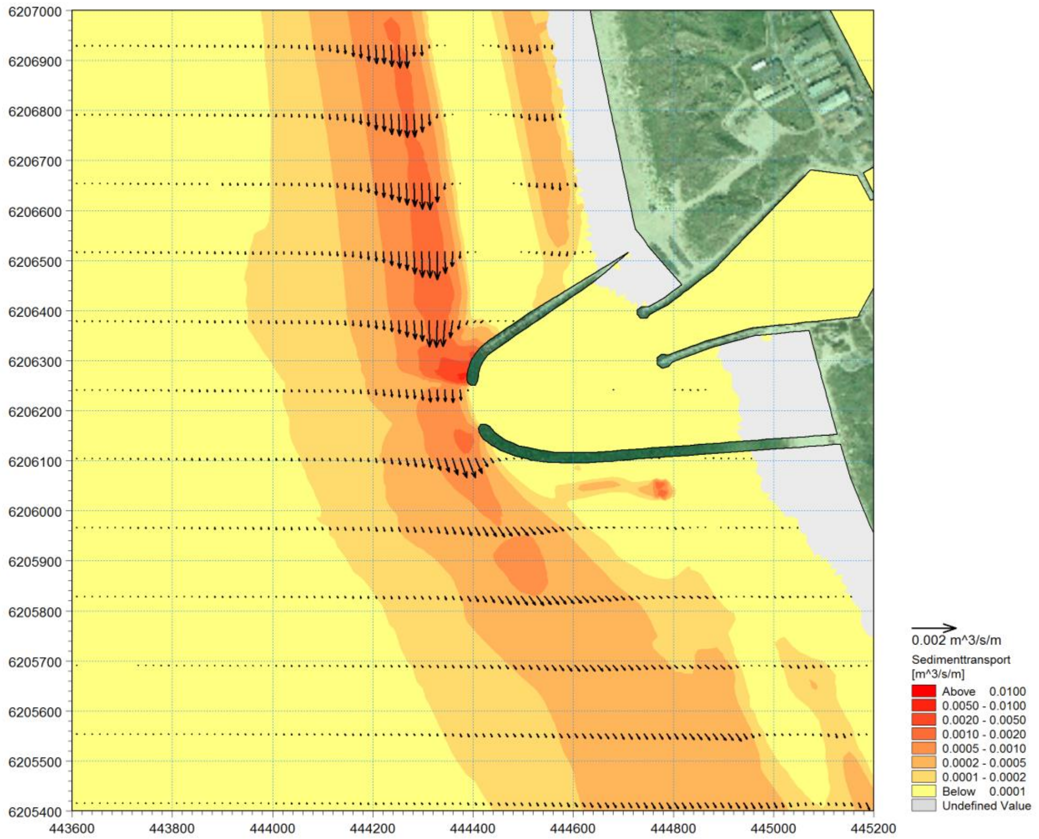


Figure 19.3 Sediment transport pattern past the entrance of Hvide Sande Fishing Port.

A sheltered entrance area, protected from wave and current exposure, as in the case of the single main breakwater type of port, tends to intensify the risk of sedimentation and shoreline erosion, see Figure 5.42. The mechanisms in the area sheltered by the main breakwater are the following. The diffracting waves in the sheltered area will reverse the local littoral transport close to the port so that sand is accumulated along the secondary breakwater. The secondary waves from the downstream directions will also cause an accumulation of sand in this area. Furthermore, there will be a gradient in the wave set-up along the coastline with the smallest set-up close to the port. This will drive a local current along the shoreline towards the port entrance, where an eddy will form, causing sedimentation in the entrance area. Finally, the surf beats along the beach adjacent to the entrance may cause oscillations in the harbour basin. The resulting water exchange in the port basin can be many times larger than the water exchange caused by the tidal exchange, see also the description given in Subchapter 5.4.1 and the surf beat generated oscillations presented in Figure 5.31. This surf beat generated water exchange may lead to severe siltation in the port basin if suspended fine sediments are present. All the sand which accumulate upstream of the main breakwater, adjacent to the secondary breakwater and which deposit in the entrance, is subtracted from “the littoral budget”, thereby causing downstream erosion. However, the trapping of fine sediments causing siltation in port basin, will not cause any impact on the adjacent shorelines.

All the above aspects, which should be considered to minimise the sedimentation, will also cause the largest possible bypass of sediments and thereby also minimise the impact on the downstream shoreline.

However, despite all the above optimisation efforts, sedimentation will often occur to some extent, as the optimisation can only minimise the sedimentation, but not prevent it. Consequently, sedimentation in port entrances often necessitates maintenance dredging in order to secure sufficient navigation depth. It is important that such maintenance dredging and subsequent disposal of the dredged sand is performed in a way that to the highest possible extent favours the downstream coast. Consequently, the dredged material, which belongs to the littoral budget of the adjacent shores, shall be disposed along the downstream shoreline. This is referred to as artificial bypass.

- *Maintenance dredging and artificial bypass*. Maintenance dredging requirements depend on many parameters as discussed above, but maintenance dredging can be divided into two different types:

    1. *Maintenance dredging off the entrance.* This is required when the natural depth in front of the entrance is less than the depth required for navigation. In this case a dredged navigation channel is required. The natural depth in front of the entrance is maximised by the methods explained above; however, this may not be sufficient. When a dredged navigation channel is constructed in a littoral transport environment, it will be exposed to sedimentation. The type of sedimentation mode is dependent on the type of sediment, depth, and width of the channel, wave and curret conditions as explained in Subchapter 7.6 and Figure 7.10. In order to maximise the interval between maintenance dredging campaigns, a sedimentation reservoir can be dredged. With coarse sand, this should entail widening the channel in the main transport zone towards the side, from which the net transport comes, and possibly a minor reservoir on the other side. With fine sand the reservoir should be in the form of over-deepening.

       In order to *minimise the impact on the downstream shoreline,* special precautions should be taken to deploy the sand along this shoreline, especially when frequent maintenance dredging is required, for example, for small ports in rough littoral climates. Under such circumstances dredging has to be performed immediately following a storm, also under fairly rough conditions. This is possible using a small trailing suction hopper dredger, although the sand cannot directly be deployed along the downstream beach under such conditions. In this case it may be a solution to construct a protected unloading pier inside the port, from which the dredger can connect to a permanently installed unloading pipe leading to discharge locations on the downstream beach. A booster station may be required. This arrangement has been used successfully by the Danish Coastal Authority for maintenance dredging at the combined harbour entrances and tidal inlets at Hvide Sande and Thorsminde on the Danish North Sea Coast. This principle is illustrated in Figure 19.4.

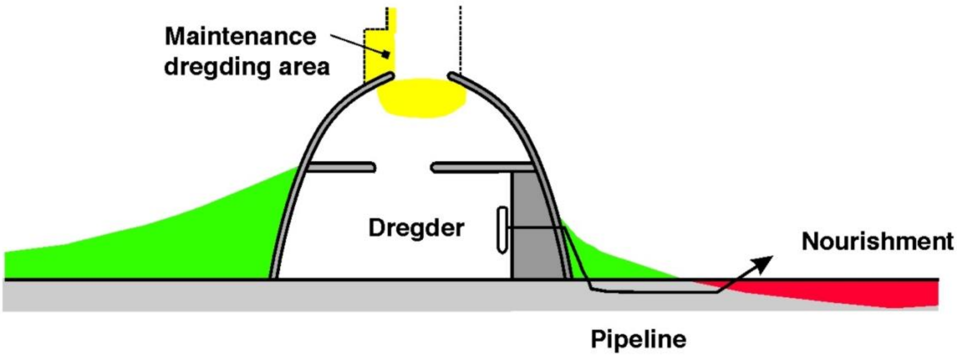
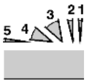
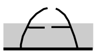
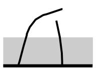
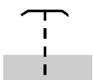


Figure 19.4 The principle of maintenance dredging and artificial bypass arrangement for a small port at a littoral transport coastline.

2. *Maintenance dredging in the outer harbour* is necessary for most ports where transport bypasses the entrance. Again, the time interval between dredging campaigns can be maximised by the introduction of a reservoir. However, reservoirs will always lead to increased total amounts to be dredged.

Table 19.1 shows the different port types, their characteristics with respect to sedimentation and coastal impact as well as possible mitigation measures at the port site as well as along the adjacent shoreline. It is often recommended using a combination of measures. Therefore it is recommended supplementing possible existing active coastal and shore protection measures, such as groynes and breakwaters, as well as passive coastal protection measures, such as revetments, with artificial bypass and nourishment in order to avoid transferring the leeside erosion problems downstream.

Table 19.1 Summary of sedimentation, coastal impact and mitigation measures for different port layouts as a function of the coastal type and the extension of the port relative to the width of the littoral zone

Type	Extension of Port relative to Width of Littoral Zone	Type of Coast 	Problems / Impact		Mitigation Measures				
			Sedimen-tation	Coastal Impact	Optimise Layout	Artificial Bypass	Nourish-ment	Active Coast or Shore Protec-tion	Passive Coast Protec-tion
Double Break-water	Less 	1M to 1E	Small	Small	No	No	No	No	Yes
		2M to 2E	Mod.	Mod.	No	Yes	Yes	Yes	Yes
		3M to 3E	Sign.	Mod.	No	Yes	Yes	Yes	Yes
		4M to 4E	Sign.	Mod	No	Yes	Yes	No	Yes
		5M to 5E	Mod.	Des.	No	No	No	No	Yes
	Wider 	1M to 1E	Small	Small	No	No	No	No	Yes
		2M to 2E	Small	Mod.	No	Yes	Yes	Yes	Yes
		3M to 3E	Mod.	Sign.	No	Yes	Yes	Yes	Yes
		4M to 4E	Mod.	Sign.	No	Yes	Yes	No	Yes
		5M to 5E	Small	Des.	No	No	No	No	Yes
Single Break-water	Less 	1M to 1E	Sign.	Mod.	Yes	No	No	Yes	Yes
		2M to 2E	Large	Mod.	Yes	No	No	Yes	Yes
		3M to 3E	Large	Sign.	Yes	No	No	Yes	Yes
		4M to 4E	Sign.	Sign.	Yes	Yes	Yes	No	Yes
		5M to 5E	Small	Des.	Yes	No	No	No	Yes
	Wider 	1M to 1E	Small	Mod.	No	No	No	No	Yes
		2M to 2E	Mod.	Mod.	No	Yes	Yes	Yes	Yes
		3M to 3E	Sign.	Large	No	Yes	Yes	Yes	Yes
		4M to 4E	Sign.	Large	No	Yes	Yes	No	Yes
		5M to 5E	Small	Des.	No	No	No	No	Yes
Off-Shore	Always Wider 	1M to 1E	Mod.**	Mod.**	Yes	No	No	Yes	Yes
		2M to 2E	Mod.**	Sign.**	No	Yes	Yes	Yes	Yes
		3M to 3E	Mod.**	Sign.**	No	Yes	Yes	Yes	Yes
		4M to 4E	Mod.**	Mod.**	No	Yes	Yes	No	Yes
		5M to 5E	Small	Des.	No	No	No	No	Yes

Legend:						
	Problem	Small	Moderate	Significant	Large	See * below
	Text	Small	Mod.	Sign.	Large	Des.

* Destabilisation of the downdrift coastline, see Subchapter 11.2.1.2.
** Functionality for the offshore breakwaters are sensitive to length and distance from the shore etc., see Subchapter 17.5.2.

19.3.3 Discussion of mitigation measures for tidal inlets

Natural tidal inlets have only a minor influence on sediment bypass past the inlet as the bypass takes place via a dome-shaped bar formed by nature, see Figure 5.35 and Figure 5.36. As discussed in Subchapter 7.4, the function of a tidal inlet is to accommodate the exchange of water between a coastal lagoon and the sea due to the tide. A natural tidal inlet is characterised by the tidal volume and the associated equilibrium cross section area of the inlet, which is required to accommodate the tidal exchange. As natural inlets are variable in location and often too shallow for navigation, many tidal inlets have been regulated by inlet jetties in order to fix the inlet location and have been deepened in order to provide sufficient navigation depth. It is important to be aware of the required equilibrium cross section area when designing regulation works for tidal inlets as the “correct” area is required in order for the inlet to be stable and for providing suitable cross section area for the tidal flow. Construction of inlet jetties result in interruption of the littoral transport, partly due to the physical obstruction by the jetties and partly due to the deepened channel, which traps most of the bypassing sand. Furthermore, sand is lost in connection with construction of inlet jetties due to building up of new flood and ebb shoals.

Examples of tidal inlets managed by four different methods are discussed in the following:

- An inlet controlled by relatively short inlet jetties and flexible maintenance dredging
- An inlet controlled by relatively short inlet jetties and a fixed bypass plant
- An inlet controlled by long inlet jetties
- An inlet controlled only by dredging

19.3.3.1 Tidal inlet managed by inlet jetties shorter than the width of the littoral zone and dredging:

An example of such an inlet is the Thorsminde Tidal Inlet, which suffers from considerable sedimentation, as well as navigation constraints. A bar develops across the entrance after each medium storm, which poses a major navigational constraint for the fishing fleet in the port. An aerial photo of the inlet (before re-design) is presented in Figure 19.5.

Figure 19.5 Aerial photo of Thorsminde Tidal Inlet (before re-desing) on the North Sea Coast of Denmark. The fishing port is an attachment to the channel on the seaside of the sluice; Part of Nissum Lagoon can be seen to the right.

DHI has investigated the possibilities for improvements, especially in relation to improvement in the bypass conditions. The main objective was to provide larger natural depths in front of the entrance, secondary objectives were to provide less maintenance dredging and less lee side erosion. The investigations were performed for and in close collaboration with the Danish Coastal Authority. Wave, current and sediment transport patterns for the old layout as well as for the new layout, which was implemented in 2004, are presented in Figure 19.6.

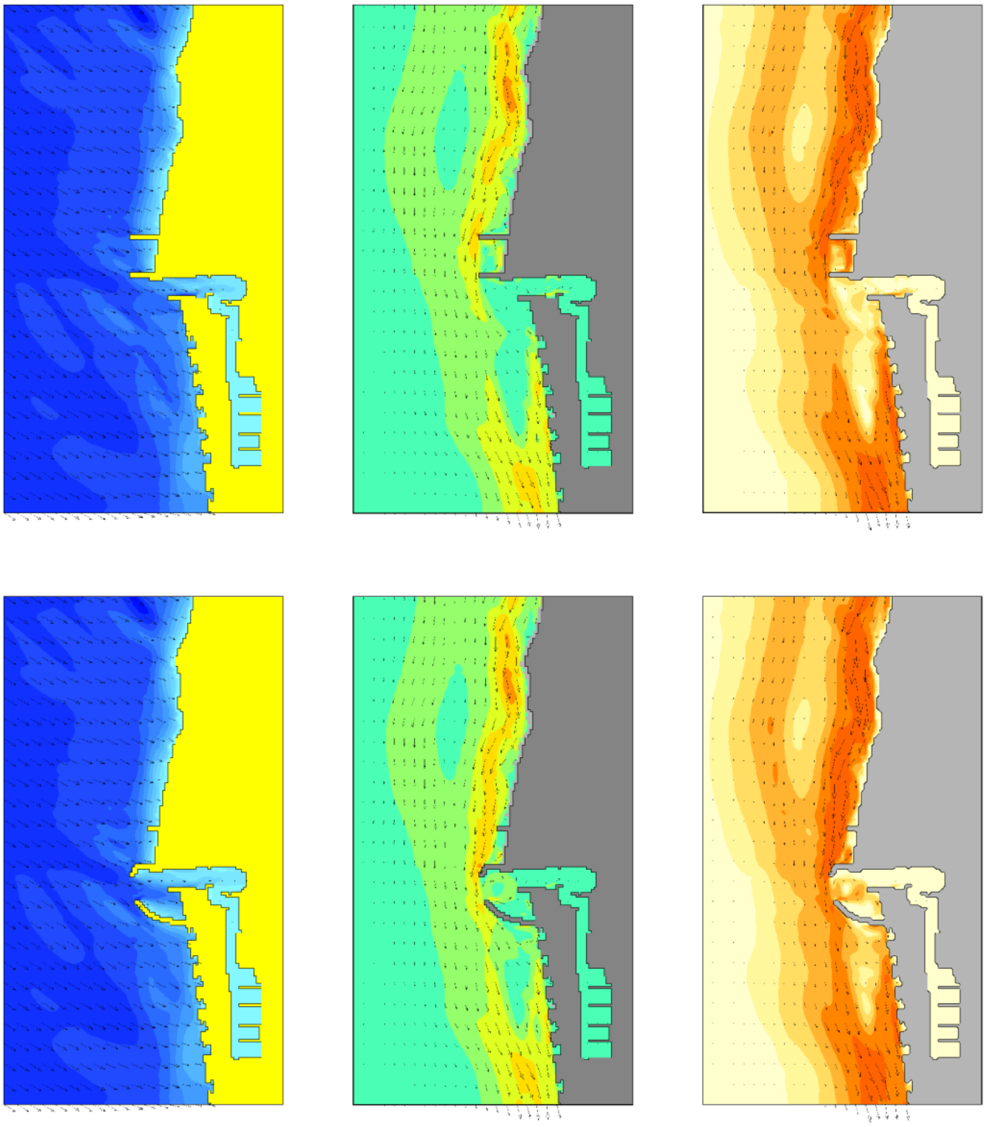


Figure 19.6 Thorsminde tidal inlet and port entrance. Upper part: Before 2004, lower part: After re-design in 2004. Left: northwesterly waves, middle: current pattern and right: sediment transport pattern. The tidal channel to the lagoon is closed by a sluice most of the time.

The conditions at the site before the new layout was implemented are as follows: There is a net southward transport of 350,000 m^3/year, which has resulted in a fully developed accumulation north of the inlet jetties. The full transport naturally bypasses the upstream jetty, resulting in maintenance dredging of approximately 100,000 m^3/year. The remaining material is transported further south forming a long shoal, with a large offset relative to the downstream coastline. This has resulted in severe lee side erosion. The lee side erosion is mitigated by beach breakwaters and artificial bypassing using a small trailing suction hopper dredger with a unloading facility in the sheltered outer basin, in principle as described in Figure 19.4. The artificial bypass is supplemented by nourishment. However, the main problem is the navigation constraints following each storm, where a bar forms across the entrance. The fishermen cannot use the port until maintenance dredging has been performed, which sometimes result in several weeks downtime. There are also navigation problems due the breaking waves and opposing currents for southwesterly waves. All in all, a typical tidal inlet/harbour entrance problem complex.

The old layout is characterised by a slightly offshore-directed bypass flow and a decreasing transport rate in the entrance area, which results in the bar formation across the entrance as described above. The bypassing transport does not join the lee shoreline.

New layout (implemented in 2004) with rearrangement of jetties:

The new layout consists of the following changes:

- Shortening of the northernmost groyne and bending of the inlet jetty towards the inlet, creating a smoother path for the current and the transport, which counteracts offshore setoff and eddy formation, and which provides larger natural depth at the entrance
- Adding a new curved jetty towards the south, which completes the smooth path for the current and the transport and minimises sedimentation and waves in the entrance during southwesterly storms.

These changes result in a smoother current and transport pattern with only a slight decrease in the transport rate in the entrance area, which means less sedimentation and not least larger natural depth. The transport pattern downstream approaches the shoreline slightly more than in the existing situation. In addition to this, the new southern jetty protects against waves and sedimentation in the entrance for southwesterly waves and protects a wide outer harbour, which greatly improves the navigation safety.

The sedimentation and the natural depth in front of the entrance were investigated by the use of a two-dimensional morphological model, which was calibrated on the existing situation. Results from this model is presented in Figure 19.7, cf. Brøker et al. (2007) and Mangor et al. (2010).

The upper row in Figure 19.7 shows the pre- and post-storm bathymetry. It can be seen that the sand shoal off the main breakwater was pushed to the south during the storm thereby partly blocking the entrance. This development is in perfect agreement with the results of the soundings.

Figure 19.7 lower row shows the result of a repetition of the simulation of the October 1997 storm with the new bypass layout. The left panel is the initial bathymetry and the right panel is the bathymetry after the storm. It appears that a water depth of about 3.5 m can be maintained in front of the entrance after the storm with the modified layout.

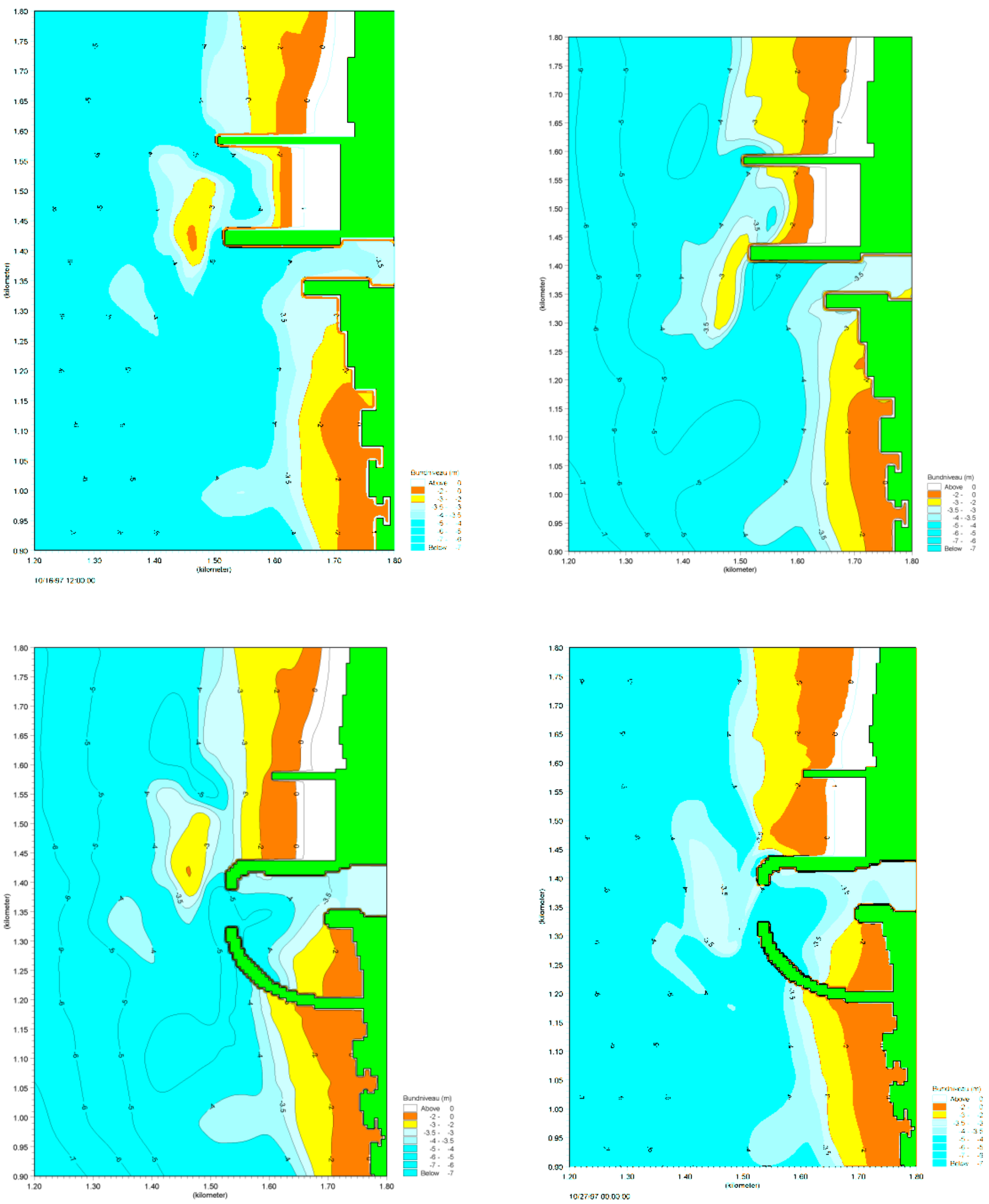


Figure 19.7 Thorsminde Harbour. Upper row: Simulated pre-storm and post-storm bathymetries for Oct. 1997 storm. Lower row: New layout. Morphological modelling of the October 1997 storm from Brøker et al (2007).

The simulations were also performed for southwesterly waves.

The short term morphological simulations showed considerable improvements in the natural bypass.

Development since implementation of new layout

The new breakwaters were finished in the autumn of 2004. The maintenance dredging volumes during the period 1999 through 2009 are presented in Figure 19.8. The first two winters indicate a reduction in maintenance dredging to about 40% of the amounts before the reconstruction. This improvement was so large that it was not necessary to have a permanent dredger stationed at the harbour to secure safe navigation. However, the maintenance dredging the following years has increased again up to the level before the new layout was implemented.

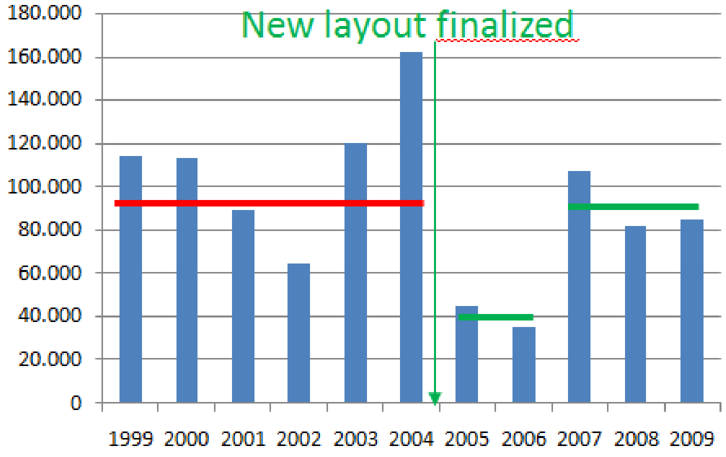


Figure 19.8 Annual maintenance dredging [m3/year] in front of Thorsminde Harbour in the period 1999 through 2009. The new layout of the breakwaters was implemented in late autumn 2004.

The results of the morphological model simulations indicate that the implementation of the new breakwater layout was able to reduce the maintenance dredging requirements and to improve the navigation conditions for about 2 years.

This improvement was due to two changes:

1. The slight increase in extension of the breakwaters
2. The more streamlined layout of the breakwater

After two years the updrift bathymetry had adjusted to the new layout. Maintenance of sufficient navigation depth requires dredging of similar amounts of sediment as before the change of layout. However, the natural bypass has been improved resulting in less erosion pressure on the downdrift coast and navigation safety has been improved. Further, the harbour is open for navigation with sufficient water depth a larger part of the time

19.3.3.2 Inlet managed by inlet jetties longer than the width of the littoral zone:

Many tidal inlets have been protected and managed by the construction inlet jetties, which are considerably longer than the width of the littoral zone. This has often been done in an attempt to obtain a fixed tidal inlet with sufficient depth for navigation and to protect against sedimentation in the new channel. If the cross-section area of the new channel is of the same order of magnitude as the original stable, but variable, natural inlet opening, it will be possible to obtain a practically maintenance-free stable, fixed, deep and narrow channel. However, this will be at the expense of a complete blockage of the littoral drift, which will have a severe impact on the adjacent shorelines. The severity of this impact will depend on the type of coast and the actual length and shape of the inlet jetties. In addition to the normal lee side erosion there will be additional impact due to the local accumulation of material in the sheltered areas adjacent to the structures. The duration of the period, when no bypass takes place, also depends on the above parameters. If the net littoral drift is not zero, natural bypass of the upstream jetty is sure to occur some time in the future. When this happens it will cause sedimentation in the inlet, but there will be no bypass to the downstream shoreline as the bypassed material will either be trapped in the channel or “lost” off the littoral zone.

Lido Tidal Inlet, Venice, Italy

An example of one such inlet is the Lido Inlet connecting Venice Lagoon to the Adriatic Sea. The 2 - 3 km long jetties were constructed at the beginning of the 20th century. They caused a complete blockage of the littoral transport for 80 to 90 years. The upstream jetty caused an enormous accumulation of sand along the upstream beach with a length of about 6 km and a width at the jetty of about 1.5 km, this is the present Cavallino Beach. Bypassing has now started, which has resulted in sedimentation in the channel in the order of magnitude of the littoral drift. At the downstream side a huge lee accumulation occurred along the lee-breakwater, in the northeastern end of the Lido Beach, see Figure 19.9, as well as a huge lee-side erosion of Lido Beach further south.

This example shows that navigation conditions were solved for many years at the expense of large upstream sand accumulation and a huge lee side erosion, but after about 90 years the bypass has increased considerably. The impact to the coast has been huge and it is questionable whether the large jetties have at all been feasible. Major remedial measures to re-establish the lost beaches have been implemented over the years in the form of a programme combining nourishment and supporting structures.

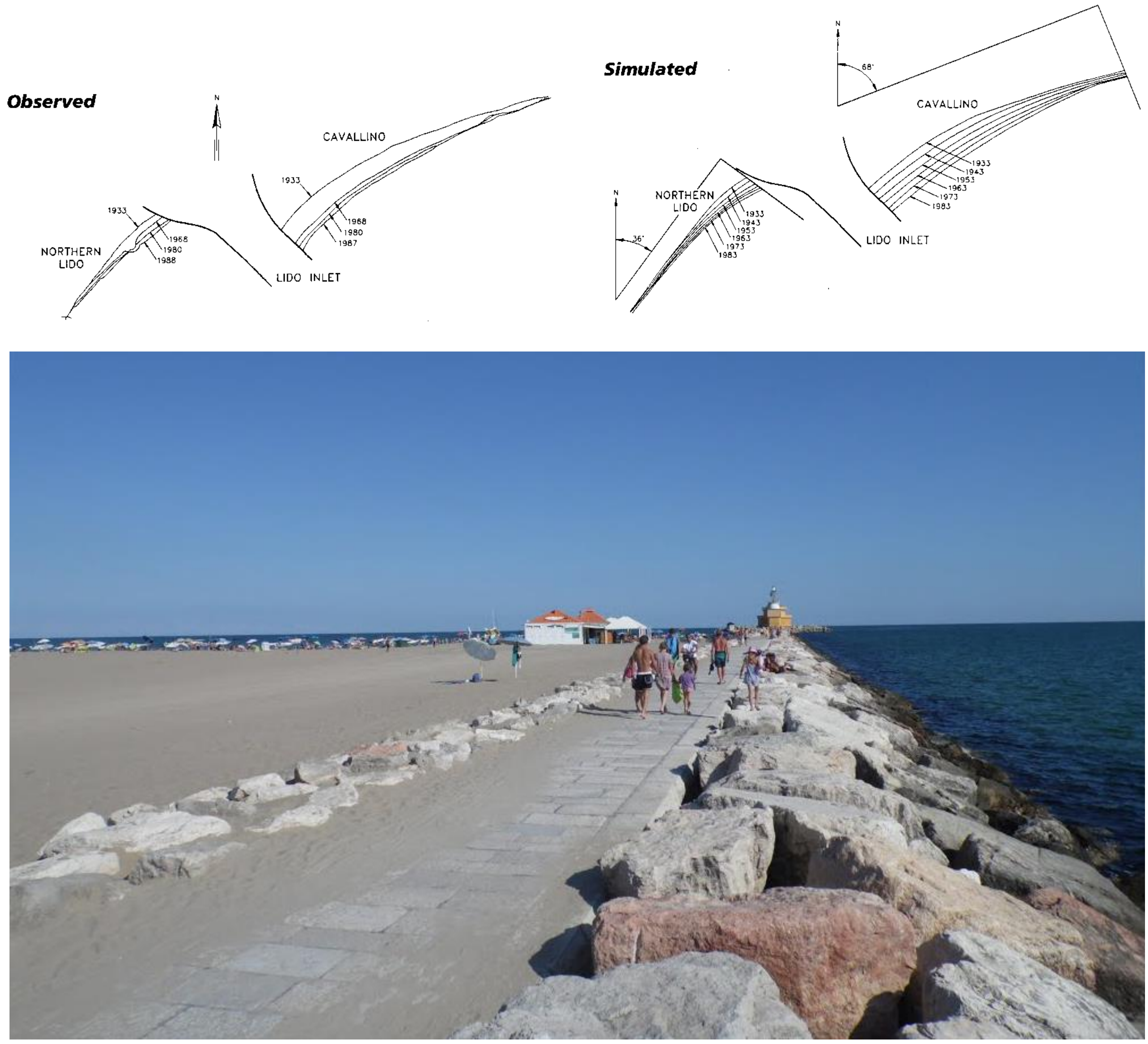


Figure 19.9 Top: Coastline evolution, observed and simulated, adjacent to Lido Inlet, Venice, Italy. Bottom: Cavallino Beach adjacent to upstream jetty.

Marang River Mouth and Tidal Inlet Improvement Project, East Coast of peninsula Malaysia

The Marang fishing village has, for many years, suffered from hazardous navigation conditions in the river mouth, which is very morphologically active with shifting channels traversing shallow shoals. The gross littoral transport at the location is moderate, but the net littoral transport is practically zero. This situation makes it possible to regulate the inlet with fixed structures with only marginal shoreline impact. A combination of curved outer inlet jetties and internal straight parallel inlet jetties marking the channel was proposed in order to obtain a balanced solution between the following requirements:

- Coastal impact
- Navigation and safety
- Sedimentation and wave disturbance
- Accommodation of tidal currents and river discharge

The recommended solution is presented in Figure 19.10, top right. The proposed improvement works have been constructed by the Department of Irrigation and Drainage, see satellite image of the scheme at bottom part of Figure 19.10. The scheme works according to the results of the numerical investigations providing safe navigation conditions, minimal sedimentation and minimal coastal impact.

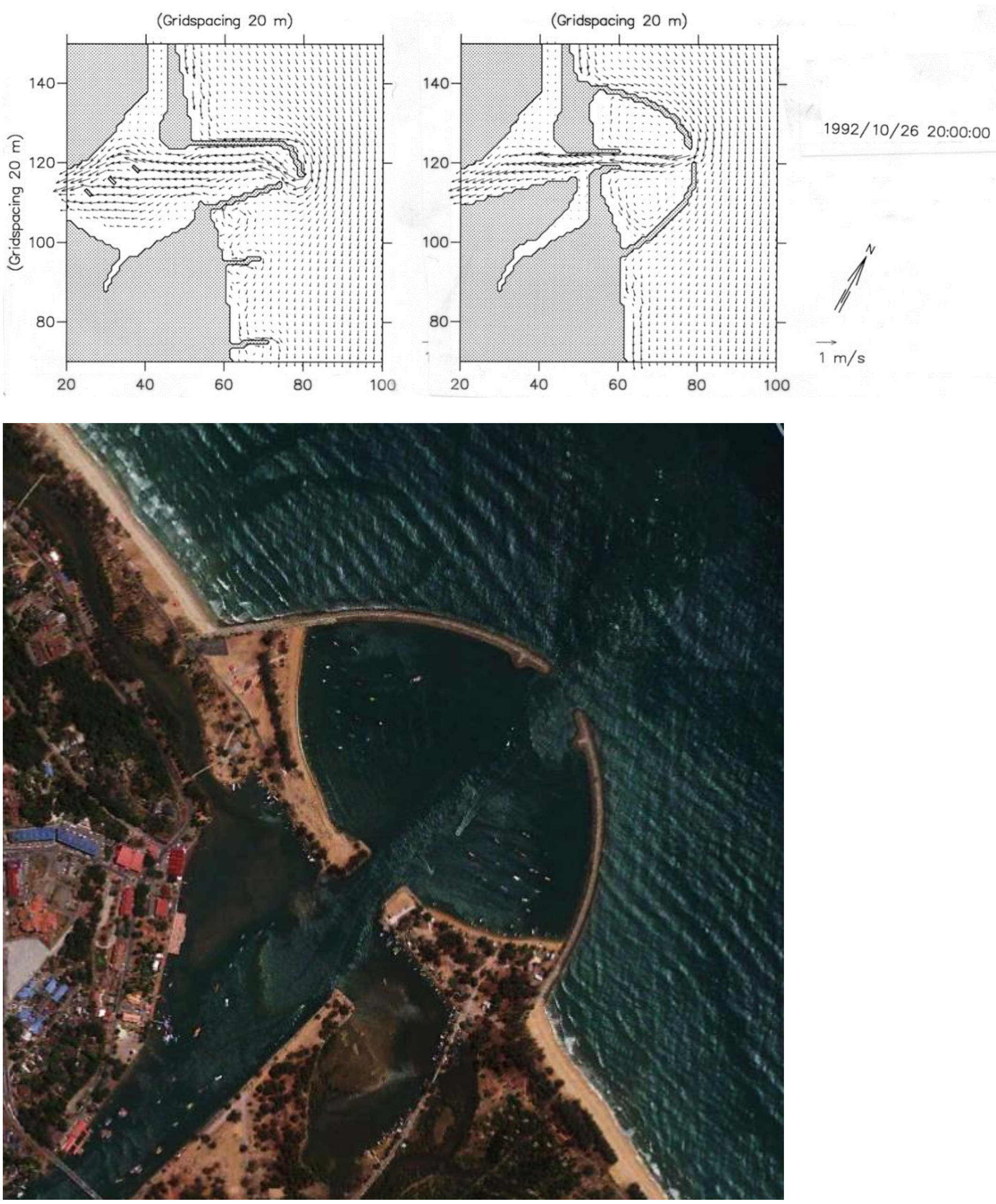


Figure 19.10 Improvement works at Marang River Mouth, Malaysia. Top left: Originally proposed layout, top right: Recommended layout, bottom: As implemented (Google Earth, 2016).

19.3.3.3 Inlet managed only by dredging

Rather few tidal inlets, which are used for navigation, are managed solely by maintenance dredging, as this requires a continuous dredging effort. An example of one such tidal inlet is Grådyb, which is one of the connections between the Danish part of the Wadden Sea and the North Sea. By nature this inlet was curved, fluctuating and shallow with a natural depth of approximately 4 m. Over the last century it has gradually been straightened and deepened to its present depth of about 10 m, see Figure 19.11.

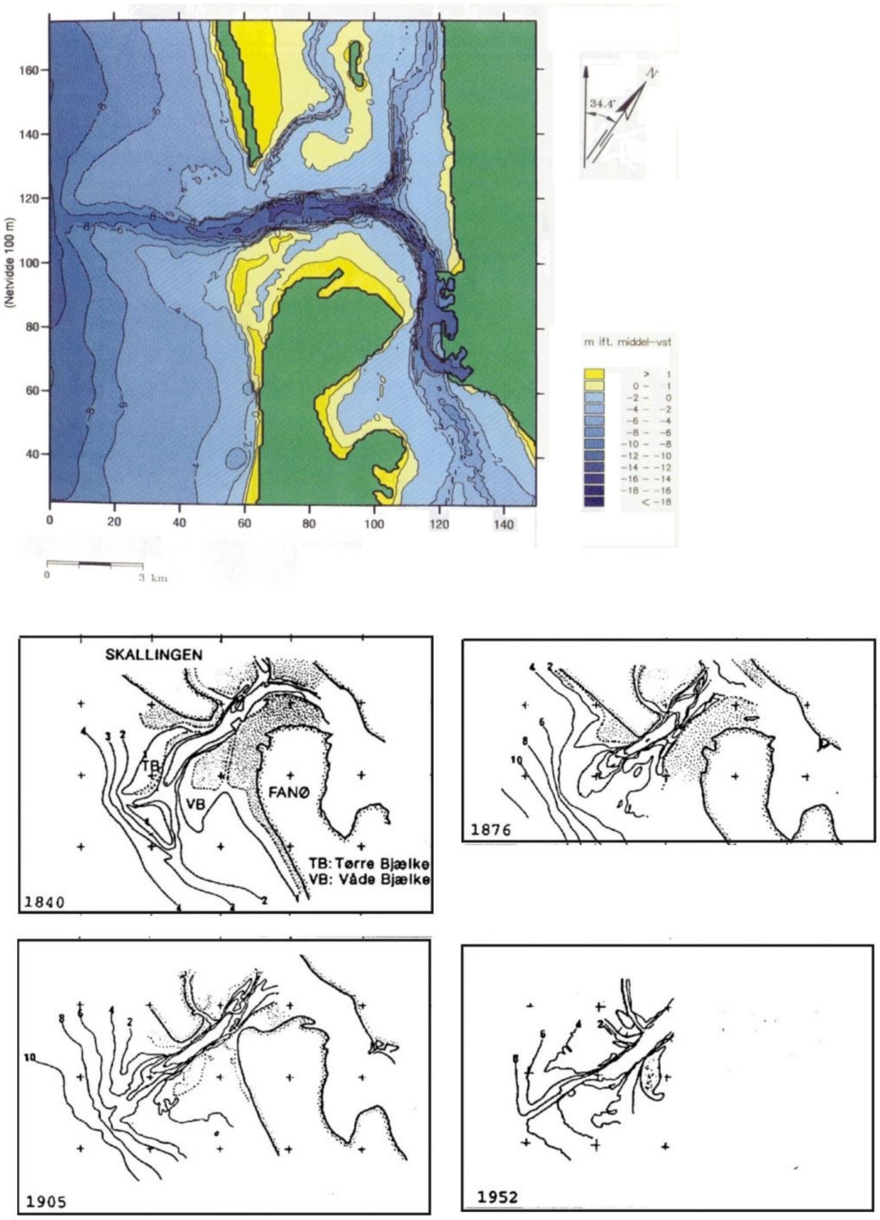


Figure 19.11 Top: Bathymetry (1992). Bottom: Four stages of Grådyb tidal inlet, which acts as the access channel to the port of Esbjerg, Denmark.

The maintenance of the inlet has always been carried out solely by dredging apart from a few groynes on the northern barrier formation Skallingen, these groynes have later been demolished. The present dredging operations are in the order of magnitude of 1 mio. m^3/year; the dredging is carried out using a trailing suction hopper dredger, which bypasses most of the material to the downstream part of the ebb shoal. The dredging has caused some erosion of the upstream part of the ebb shoal as well as some erosion of the upstream tip of Skallingen. There have been no negative downstream impacts.

The construction of major inlet structures has been considered. However, it has been evaluated that the mitigating measures required in order to compensate for the downstream morphological impacts will be as large as the present maintenance requirements. For this reason and also to be able to preserve the “natural” environment, such structures have been found neither feasible nor environmentally acceptable.

Numerical modelling investigations have been carried out in order to investigate if alternative layouts of the dredged channel would provide less dredging. It was concluded that the practised dredging and bypass management was equally good as any of the tested alternative layouts and that the present practise has been environmentally successful and economically feasible.

19.3.3.4 Other tidal inlet impact mitigation measures

There are also other possibilities for the management of bypass and mitigating measures of tidal inlets than those mentioned above.

Tidal inlets on littoral transport coasts regulated by inlet jetties is typically suffering from upstream accumulation, downstream erosion and sedimentation in the inlet. These problems can also be partly mitigated by land-based excavation in the upstream sand filet, and transport of the excavated sand to the downstream shore. This is referred to as *backpass.* However, backpass can normally not be used as a stand-alone solution because some sand will bypass the excavation area thus causing sedimentation in the inlet, which has to be handled by other measures.

Another method of bypass is the application of fixed jet-pumps, possibly supplemented with a fluidisation arrangement. This system is explained further in the following.

19.3.3.5 Inlet managed using jetties and a fixed bypass plant:

A fixed bypass plant can consist of a piled jetty constructed upstream of the upstream jetty and equipped with a series of jet-pumps, or a movable pumping arrangement. The pumps are connected to a discharge point on the downstream shoreline via a pipeline crossing the tidal channel. Such arrangements have been constructed at several locations, e.g. at Oceanside Harbour, California and at Gold Coast Seaways, Australia, partly as test arrangements, see Figure 19.12.

Figure 19.12 Gold Coast Seaways, Australia. Bypass arrangement. (Google Earth).

Such arrangements are operational, but they are expensive to construct and are not flexible. In order to function properly the fixed arrangement shall cover most of the littoral zone, otherwise sand will pass seawards and sedimentation will occur anyway. This means that it will be best suited for locations with relatively coarse sand which are exposed to monsoon or swell climates, as such conditions result in a narrow littoral zone, combined with inlet jetties covering the entire littoral zone. Furthermore, sedimentation may also occur for situations with waves from a secondary direction. This is actually the case for the Oceanside location, California, for which reason they have installed all the pumps on a hoist barge, which can be moved from one side of the inlet to the other. When in position it is jacked up on a pile cluster arrangement for the season, see Figure 19.13.

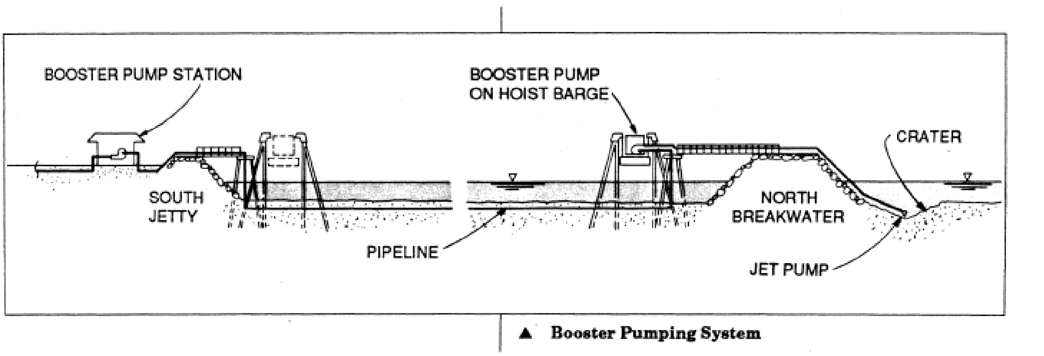


Figure 19.13 Semi-fixed bypass jet-pump plant at Oceanside Harbour, California.

The Oceanside jet-pumping arrangement was designed to work continuously, in order to avoid clogging the pumps. However, as its capacity is higher than the supply rate to the relatively narrow crater created by the jet-pumps, fluidisers have been added to widen the effective width of the craters. This further adds to the complexity of the system.

To conclude, a fixed bypass arrangement can help bypassing sand to the downstream side of an inlet, which is protected by jetties. In most cases it will be necessary to supplement this arrangement with normal maintenance dredging and bypass. It is not suited for coasts exposed to storm climates, as the littoral zones at such locations are too wide. Furthermore, the cost of the initial installation is very high compared to tradition measures, and the system is not flexible.

19.3.3.6 Mitigating measures along adjacent shorelines

The arrangements described above all concentrate on mitigating measures at the inlet proper, however mitigating measures can also be introduced along the shorelines, which are affected by the inlet works. It is good practice to try to carry out as many mitigating arrangements as possible at the source of the problems, namely the inlet, before measures along the adjacent shorelines are addressed.

The bypass arrangements can be considered as a double solution; they solve the sedimentation problem at the same time as they address the downstream shoreline impact directly where the impact occurs. However, the bypassing is normally not sufficient to compensate the shoreline impact, as there are several causes for this. The bypassing only compensates the part of the impact associated with sedimentation and dredging in the access channel whereas e.g. the accumulation of sand upstream of the port is not compensated by the bypass arrangement. Therefore, it is normally necessary to use a combination of methods to mitigate the shoreline impact. The following supplementary methods are available:

- Nourishment
- Application of active coastal protection and shore protection measures, such as groynes and detached breakwaters
- Application of passive coast protection measures, such as revetments and seawalls

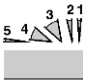
The application of these measures should follow the guidelines given in Chapter 17. However, when using these methods near a tidal inlet, which is not controlled by fixed structures, one should consider whether, for example, nourishment will affect sedimentation conditions in the inlet. In this case transport contributions from both directions, the difference of which constitutes the net transport, shall be considered.

19.3.3.7 Summary Tidal inlets

The application of the most common mitigation measures for the compensation of morphological impact caused by regulation of tidal inlets has been summarised in Table 19.2. The applicability of the various measures can be difficult to characterise in such a short form as this, and for this reason some of the judgements can be discussed. The table shall thus only be used as a rough guideline to managers, the exact weighting between different measures etc. still has to rely on detailed studies.

It is important to note that the summary of the morphological impact assumes that the inlet regulation are made so that the required equilibrium cross section area of the inlet is established.

Table 19.2 A summary of morphological impact and possible mitigation measures for tidal inlets with and without inlet jetties (assuming that equilibrium cross section area is established).

Present Inlet Manage-ment	Extension channel/ jetty relative to Width of Littoral Zone	Type of Coast 	Problems/Impact		Mitigation Measures to compensate Coastal Impact						
			Sedi-men-tation	Coastal Impact	Artificial bypass: Trail. Suct. Hopper	Artificial bypass: Fixed bypass	Nourish ment	*** Add short jetty	Optimise Struc-tures	Active Coast protect. or Shore protect.	Passive Coast Protec-tion
Tidal channel main-trained by dredging	Less 	1M to 1E	Small	Small	Rec	N rec	N req	App	N A	N rec	Rec
		2M to 2E	Mod	Mod	Rec	N rec	N rec	App	N A	Rec	Rec
		3M to 3E	Sign	Mod	Rec	N rec	Rec	App	N A	Rec	Rec
		4M to 4E	Sign	Mod	Rec	N rec	Rec	App	N A	N rec	Rec
		5M to 5E	Small	Small	Rec	N rec	Rec	App	N A	N rec	Rec
	Wider 	1M to 1E	Mod	Mod	Rec	N rec	N rec	App	N A	N rec	Rec
		2M to 2E	Mod	Mod	Rec	N rec	N rec	App	N A	Rec	Rec
		3M to 3E	Large	Sign	Rec	N rec	Rec	App	N A	Rec	Rec
		4M to 4E	Large	Sign	Rec	N rec	Rec	App	N A	N rec	Rec
		5M to 5E	Mod	Mod	Rec	N rec	Rec	App	N A	N rec	Rec
Inlet jetties	* Less 	1M to 1E	Small	Small	Rec	N rec	N req	N A	Rec	N rec	Rec
		2M to 2E	Mod	Small	Rec	N rec	N rec	N A	Rec	Rec	Rec
		3M to 3E	Sign	Mod	Rec	N rec	Rec	N A	Rec	Rec	Rec
		4M to 4E	Sign	Mod	Rec	N rec	Rec	N A	Rec	N rec	Rec
		5M to 5E	Small	Des	Rec	N rec	Rec	N A	Rec	N rec	Rec
	** Wider 	1M to 1E	Small	Small	N. req	App	N req	N A	App	N rec	Rec
		2M to 2E	Small	Mod.	Rec	App	Rec	N A	App	Rec	Rec
		3M to 3E	Small	Large	Rec	App	Rec	N A	App	Rec	Rec
		4M to 4E	Small	Large	Rec	App	Rec	N A	App	N rec	Rec
		5M to 5E	Small	Des	Rec	App	Rec	N A	App	N rec	Rec

Notes:
- * Assumes some natural bypass
- ** Assumes no natural bypass, however this may change with time
- *** Jetty will minimise loss of sand into inlet thereby help fixing the shoreline, but will make coastal impact worse due to upstream trapping of sand

Legend:	Problem	None to small	Moderate	Significant	Large
	Text	Small	Mod.	Sign.	Large

Abbreviation	Explanation
Rec	Recommendable
N rec	Not recommendable
N req	Not required
App	Applicable, but not sufficient as stand-alone measure
N A	Not applicable
Des	Destabilisation of the downdrift coastline, see Subchapter 11.2.1.

19.3.4 Mitigation measures for other actively occupying structures in the littoral zone

Mitigating measures for ports, tidal inlets and river mouths have now been discussed in detail. All the other kinds of actively occupying structures, such as coastal protection structures, reclamation works, dikes, embankments and intake and outlet structures etc. will not be discussed, as their impact can be treated following the same guidelines as discussed for ports and inlets.

19.3.5 Mitigation measures for structures outside the littoral zone

Projects off the littoral zone, which, by their impact on the hydraulic conditions, impose morphological impacts, can be of the following kind:

- Offshore breakwaters
- Island ports
- Artificial reefs
- Artificial islands
- Offshore wind power schemes
- Bridge piers

Offshore breakwaters and island ports are normally used in order to minimise impacts, and a design study of those will therefore inherently address the minimisation of the impacts. Supplementary traditional mitigation measures will normally be required on top of the optimal design. Offshore breakwaters have already been discussed in detail in Subchapter 17.5.2.

Artificial islands may have great morphological impacts. The impacts can be some of the following:

- Accretion and erosion along the adjacent shorelines
- Accretion and erosion of non-cohesive sediments on the seabed adjacent to and in lee of the island
- Accretion of cohesive sediments on the seabed in lee of the islands in regions, where suspended sediments are present in the ambient environment
- A change in the type of mainland coast due to changes in the wave conditions, both in terms of less wave exposure and changed equilibrium orientation
- Related environmental impacts

General guidelines for the minimisation of the impacts cannot be given as they require detailed numerical modelling for clarification of their impacts and testing of possible mitigating measures.

An example of changes in the equilibrium orientation along a coast sheltered for by a large offshore development scheme is presented in Figure 19.14.

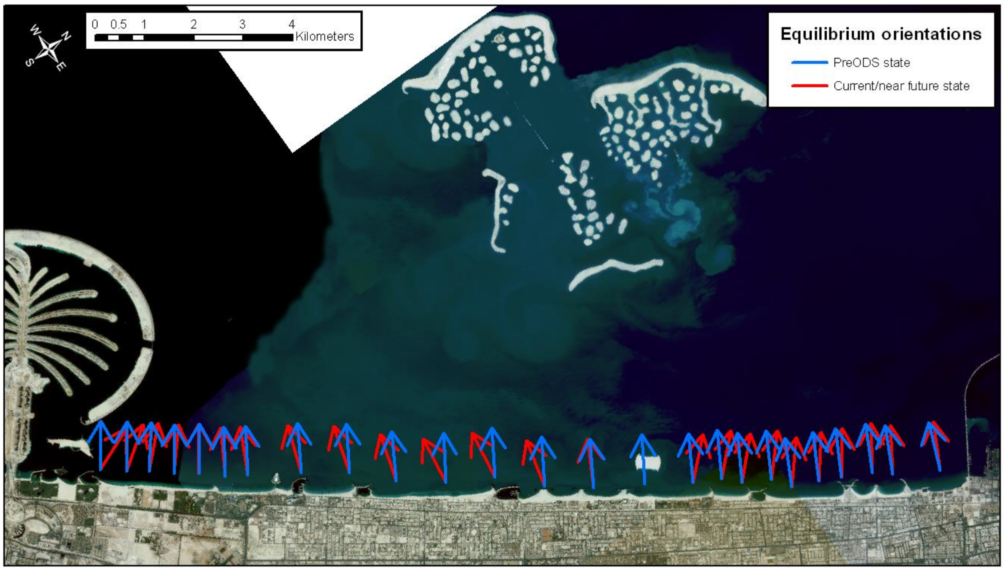


Figure 19.14 Estimated equilibrium shoreline orientations along the Jumeirah shoreline in Dubai due to impacts from Palm Jumeirah and The World Islands. Pre situation without the offshore developments (Blue arrows) and including these developments (Red arrows). Arrows indicate the normal to the equilibrium coastline. Reference: Mangor et. al. (2008).

It is seen that the equilibrium orientation changes significantly in the lee areas of the offshore developments. This results in a complete change in the shoreline development in the small sediment cells along the shoreline as seen in Figure 19.15.

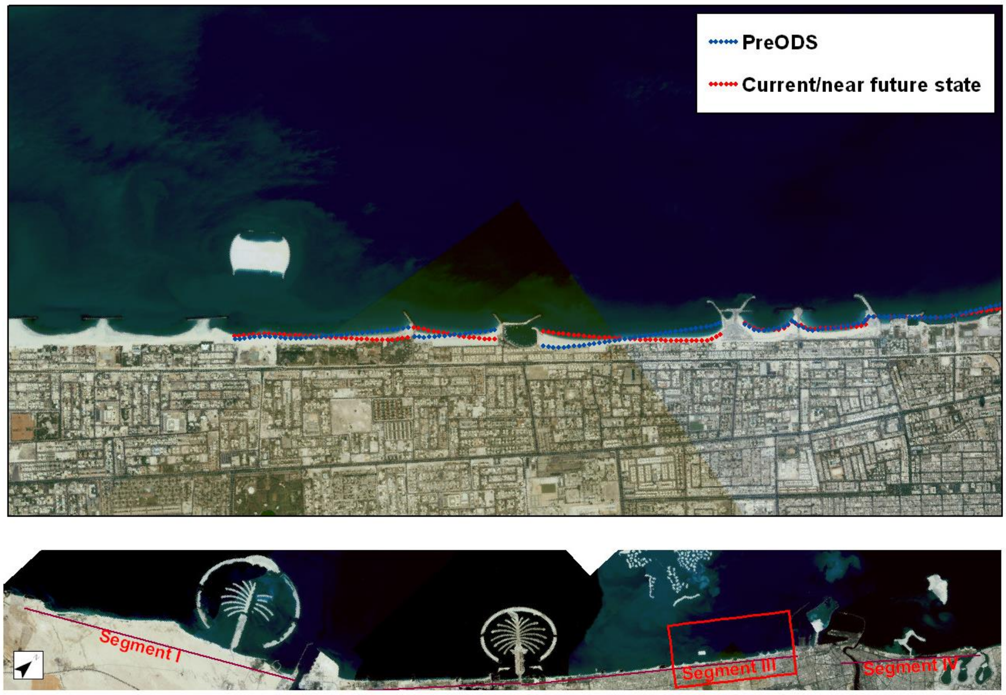


Figure 19.15 Predicted 20-year shoreline positions for Northern Part of the Jumeirah Shoreline for historic state and current/near future state. The impact of The World Islands are clearly seen. Reference: Mangor et. al. (2008).

Offshore wind power units and bridge piers are normally very small in dimension and far apart so the morphological impacts are often relatively small. However, if they are constructed in a vulnerable environment, detailed investigations are required to document the impacts and to test possible mitigation measures. There will also be local impacts in the form of scour, which shall be addressed as part of the structural design.

The elements of the morphological impact assessment for two offshore wind power schemes Rødsand I and II, constructed off the barrier formation of Rødsand in the Fehmarnbelt, Denmark, see Figure 19.16, followed the schedule shown in Table 19.3.

Figure 19.16 Rødsand I and II offshore wind power plants, off the Danish coast in Fehmarnbelt, Denmark. © Pavlo Dyban.

Table 19.3 Elements of a MIA for an offshore wind power scheme.

Type of investigation	Detail of investigation	Currents	Winds	Waves	Transport and Morphology
Baseline	Present conditions without scheme	Currents	Winds	Waves	Sediment transport
	Future development without scheme	Feedback from morphological change		Feedback from morphological change	Natural shoreline and morphological changes
Immediate impacts of scheme	Impact within scheme	Change in currents	Change in wind		
	Changes adjacent to scheme	Change in regional flow and in longshore currents	Change in wind climate	Change in waves due to changes in local wind climate and due to reflection	Change in littoral transport due to scheme
Morphological (long term) impacts of scheme	Changes within scheme	Feedback from seabed changes			Seabed changes
	Changes outside scheme				Shoreline and seabed changes

19.3.6 Mitigation measures for soft interventions in the littoral zone

Soft interventions in the form of nourishment in some cases require an EIA, cf. Subchapter 19.2.1.2. As the requirements for nature preservation increase, the need for documentation of both the morphological and the biological impact of nourishment projects will probably be a requirement in the future.

Optimisation of nourishment with respect to minimising the impact on the marine fauna may lead to nourishment techniques in favour of stockpile nourishment, optimisation in location of nourishment in the profile, timing of the nourishment and selection of suitable borrow sand which is similar to the native sand.

19.3.7 Mitigation measures for soft interventions off the littoral zone

Soft interventions off the littoral zone may be in the form of sand mining, possibly for nourishment in the same area but inside the littoral zone or for reclamation projects, or it could be in the form of dumping of dredged material, for example, from maintenance dredging in ports and tidal inlets.

Sand mining for nourishment, or for other purposes such as reclamation, requires a permit. The permit will normally secure that the mining takes place at sufficiently deep water in order to avoid disturbing the nearshore sediment balance and the allowed mining volume will be limited so that it will not cause significant changes in the coastal hydrodynamics and morphology. If the mining takes place in coral sand or coral debris, the permit should secure that live coral areas are not affected.

Sand mining areas in shallow coastal seas often features a variety of mobile sand waves and large-scale tidal ridges, typically perpendicular and parallel to the dominating currents, respectively. The variation in height, in sand characteristics and in hydrodynamic conditions near these formations, create a variety of habitats with a high biodiversity and productivity. These habitats are important for various fish, shellfish and worms species, cf. De Vriend (2012).

Nourishment sand is often dredged by a trailing suction hopper dredger, which leaves the seabed relatively smooth with only minor dredging tracks. This dredging method thus fulfilled the traditional requirements of leaving the seabed relatively smooth following the dredging process. However, a flat seascape does not encourage biodiversity, as described above. This recognition has lead to development of the concept *Seabed Landscaping,* which builds on the idea “that local seabed landscaping would help to speed up the process of recolonisation, and promote higher biodiversity and productivity”, citation from De Vriend (2012). Tests were performed with this concept of selective dredging leaving artificial sand ridges in the borrow areas. Results show that the seabed landscaping leads of more fish and more species, than outside the landscaped areas, cf. De Vriend (2012).

Sand mining is also performed by stationary suction dredgers. This dredging method may leave the seabed with big craters. Stagnant water may be generated in the craters causing oxygen depletion and anaerobic conditions and furthermore this type of seabed may cause disturbance for fishing activities. Consequently, this dredging methodology will often be associated with restrictions.

Finally, borrow sand for nourishment is also excavated by cutter suction dredgers in the cases where free sand deposits are not available. This type of dredging is typically performed in porous lime stone or in areas dominated by extinct corals. This kind of dredging may eradicate the marine flora and benthic fauna in the dredging area and may cause major spill of fine sediments. This type of dredging will often be subject to restrictions in order to minimise the environmental impact.

As the forecasted future sea level rise will result in an increased need for nourishment, it can be concluded that there will be an ever increasing need for suitable borrow material for nourishment. The cumulating impact on the seabed of this growing need for nourishment material should be taken into account in the planning of resource utilisation. This is the responsibility of the authorities.

Disposal of sand also requires a permit. In most countries legislation requires that suitable sand from the maintenance of port entrances and tidal inlets should be utilised to nourish the downstream shore. However, there will be cases where this is not required or where there are no such requirements. In these cases the sand will typically be disposed within a relatively short distance downstream of the dredging site some distance outside the littoral zone. In most cases this will have no impact on the coastal morphology and no mitigation measures are required.

The disposal of fine dredging material from harbour basin maintenance also requires a permit. The permit should, apart from securing that the material is not polluted, assure that the seabed in the disposal area has characteristics similar to those of the material to be disposed. This will secure a good acceptance and a negligible impact. Special precautions have to be taken in connection with the disposal of fine material from major ports in tidal lagoons and estuaries. Such areas have, by nature, a delicate balance between deposition and erosion, and the material trapped in the port basins can constitute a major drain in this balance. Disposal practice should, therefore, secure that material is delivered back to its natural environment; it should not be allowed to dispose such material outside the lagoon or estuary area. It would be good practice to dispose the material at flood tide. This will ensure that most of the material is carried back into the system, whilst still in suspension. The mitigation measures for avoiding negative morphological impacts when disposing this kind of material should thus take place through a sound and sustainable permit practice.

19.3.8 Mitigation measures for interventions in rivers and in the hinterland

Interventions in rivers such as:

- Sand mining
- Deepening for navigation
- Construction of dams
- Drainage and irrigation schemes

may all have an impact on the supply of material from the river to the littoral zone.

The impacts can be very drastic as discussed in Subchapter 11.2.5 under the discussion of human causes of coastal erosion. The main problems in relation to such impacts are the following:

- The authorities responsible for the administration of the rivers are not always aware of the impact and the damage that reiver works can cause along the coasts
- Different authorities may be responsible for the administration of rivers and the coast
- The impact may occur very far from where the intervention is taking place
- The impact on the coast may be delayed several years/decades

In most cases it will not be possible to undo the interventions causing the impact on the shoreline, as they are normally very important interventions for the society along the rivers. This is valid for deepening for navigation, dams and irrigation schemes, whereas sand mining can normally be stopped. If sand mining is stopped it may take many years before the supply of sand to the coast is re-established. It can thus be concluded that the impacts caused by projects implemented in the past have to be handled on the coast without the possibility of removing the cause of the problem. Possible future interventions in rivers have to be handled in a more holistic perspective through the performance of EIAs or MIAs, so that the impacts are forecasted and possible mitigation measures are proposed, tested and decided as part of the river intervention. This should be part of the ICZM planning process or rather part of the *I*ntegrated *C*oastal *A*rea and *R*iver Basin *M*anagement: *ICARM*.

Other types of interventions such as:

- Construction of river dikes
- Logging of forested areas
- Discharge of silty spill water from sand and gravel mining

may have the opposite effect, namely to increase the flow and the supply of sediments carried to the sea. The impact of this can be an accumulation along sandy shorelines and the formation of muddy shoals. It is difficult to avoid the impact of river dikes at the dike location, as dikes are very critical structures for the safety of the low land adjacent to the protected section of the river. However, the impact of logging and spill from mining can be mitigated by regulations of these activities. Again, in order to avoid such problems in the future, these kinds of activities should be regulated by carrying out specific MIA studies in connection with the permission process for such activities or, possibly as part of the ICARM process.

19.3.9 Mitigation measures for the extraction of resources from the underground

The extraction of water, oil or gas from the underground in coastal areas may impose subsidence, which will result in shoreline setback as discussed in Subchapter 11.1.1, under sea level rise and subsidence. Furthermore, if the coastal hinterland is low SLR/subsidance will result in an increased risk of flooding, as illustrated in Figure 6.8 and Figure 6.9. Mitigation measures may be in the form of the following interventions, which in most cases have to be combined:

a. Stop the extraction. This will only stop the subsidence and only a very little rebound can be expected, so the experienced subsidence will remain

b. Treat the shoreline setback as a normal coastal erosion problem where nourishment can be used to re-establish the coastal profile maybe combined with other coastal protection measures as required

c. Address the increased risk for flooding by adjusting dikes or any other sea defence measures, which have already been constructed or construct new sea defence measures as required.

19.3.10 Mitigation measures for sea level rise

The impact of a sea level rise on coastal stability and flooding can be mitigated as mentioned above for subsidence under items b) and c). However, the sea level rise is a global phenomenon, which means that the reduction in the rate of the sea level rise cannot be treated under a specific project. The efforts for reducing the rate of the sea level rise are co-ordinated internationally by the Intergovernmental Panel on Climate Change IPCC under the auspices of the United Nations.

The fact that the sea level rise is a global problem indicates that the need for nourishment in the future will increase drastically. This is illustrated with the following example. The Danish Coastal Authority nourishes the central part of the Danish North Sea Coast with approximately 3.5 mio m^3/per year, which is sufficient to balance the annual natural loss from this coastline. The length of the nourished coastline is approximately 120 km, which means that the present nourishment is in the order of 30 m^3/m/year.

Assuming an annual sea level rise in the future of 0.8 cm/year, and assuming an average slope of the coastal profile of 1:100, this results in an average coastline recession of 0.8 m/year. As the height of the active coastal profile along this coast is approximately 12 m; this corresponds to a volume loss of about 10 m^3/m/year caused by the sea level rise. It can thus be concluded that the need for nourishment will be increased by at about 10 m^3/m/year in the future if the impact of the sea level rise is to be compensated for by nourishment. This is an increase of approx. 33% relative to the present nourishment for the example above. This imposes increased demands for nourishment material, which may have an impact on the condition of the seabed in the borrow areas. This impact has to be addressed by the authorities, who issue permits for the extraction of seabed resources.

The sea level rise will have an impact on the hydraulic and the sedimentological processes and delicate balances in tidal areas and estuaries. There is a risk that the sedimentological balance, which, for example, at present results in a net sedimentation of fine material in the Wadden Sea, will be overruled by the sea level rise, resulting in an apparent net erosion. In the long run this will destabilise the area with an increased risk of coastal erosion and flooding. There are no obvious mitigation measures to directly counteract these processes; the mitigation measures have to concentrate on various coastal stabilisation and sea defence measures. Similarly, rivers presently supplying sand to the coast may be changed into sediment sinks by the sea level rise, which will add to the shoreline setback caused directly by the sea level rise. This calls for long term co-ordinated planning in the coastal zone to cope with these challenges.

PART 3: Hydraulic Study Methodology as Support for Shoreline Management

20 Data Collection and Field Investigations as Support for Shoreline Management

The present Chapter 19 and the two following Chapters 21 and 22 will briefly describe the hydraulic study methodology that are typically applied in connection with shoreline management activities, such as execution of Morphological Impact Assessment studies, Shoreline Management Plans, Shoreline Master Plans, Waterfront Development Projects and Coastal Protection Projects. Such studies can typically be divided in four different types as follows:

- Collection of existing data (Subchapter 20.1)
- Field investigations and surveys (Subchapter 20.2)
- Numerical modelling (Chapter 21)
- Physical modelling (Chapter 22)

The following descriptions will concentrate on the first three items, whereas physical modelling will only be very briefly described, as physical modelling is only rarely applied in connection with shoreline management activities.

20.1 Collection of existing data

The description of collection of basic data will concentrate on the type of data normally required as basis for performing the subsequent type of investigations, whereas the method of analysis of the data will not be given much attention however, this was briefly discussed in Chapter 5.

For all projects dealing with coastal morphology it will be relevant to initiate the investigation by collection of whatever data is available from various public and other available sources. The data shall serve the following purposes:

- As a first description of the site conditions and the history of the development at the site in terms of coastal structures (coast protection works, ports etc.), shoreline development and development of habitation and infrastructure

- As part of the basic description of the present conditions at the site, which is an important part of Shoreline Management studies and of possible EIA studies

- As basis for definition of the need for further data collection and data generation in the form of field investigations and hindcast studies, respectively

- As calibration basis for the numerical modelling

20.1.1 Listing of type of data and their relevance

The following types of data are often available in some form or the other. A shoreline management project will consequently often be initiated by collecting and analysing this type of data.

20.1.1.1 Geological data

Existing geological maps showing the surface geology of the coastal area will normally be sufficient for the performance of SMPs and SmasPs.

Subsidence of coastal areas is often a result of the geological history of the area, however it can also be caused by extraction of oil, gas or groundwater. Subsidence of coastal land will in all cases cause coastline retreat, which will be felt like coastal erosion. Consequently, information on possible subsidence is important for analysing the morphological development of an area.

20.1.1.2 Topographic Maps

Topographic maps are available in most countries in the form of new maps and varying series of historical maps. In many cases the recent maps are available in digital form. Such maps are normally useful for the performance of SMPs.

20.1.1.3 Bathymetric maps and special surveys

Bathymetric maps in the form of international and national Sea Charts are available for all sea areas of the world, however many of the Sea Charts are in a relatively large scale. Furthermore, they are often based on relatively old data and they are not very detailed at shallow water, as Sea Charts are mainly made as support for navigation. Sea Charts are often sufficient for the performance of SMPs.

Special bathymetric surveys may be available near port entrances and in tidal inlets, as sedimentation and maintenance dredging in these areas require frequent surveying.

20.1.1.4 Aerial photos

Aerial photos are available in most countries at their national survey authorities, at the counties and/or at the municipalities. Historical aerial photos are also often available. Aerial photos can be very informative for studying coastal features and shoreline development. Such easily available aerial photos are very useful for the performance of SMPs, SmasPs and MIA studies.

20.1.1.5 Satellite images

Satellite images are available in many different qualities and resolutions. The main advantages of satellite images are that they can be obtained back in time and that they cover large areas. With the recent advancements within satellite image market, there is an increasing amount of satellites and products available, resulting in lower prices and faster turnaround time. Google earth is a very powerfull tool for viewing high resolution satellite images free of charge. Even historical pictures dating 10 years back are available for free.

This makes satellite images applicable for investigations in remote and undeveloped areas where other data are scarce; however, satellite images are also very useful for developed areas.

Shoreline development and major coastal features can be studied in detail by taking advantage of combined information from the detailed spatial resolution of many panchromatic sensors, as well as the multispectral response that allows to differentiate between surface properties (e.g. dry vs. wet sand, vegetation lines etc.).

Satellite images are seen as a very useful and cost efficient tool for preparing SMPs and SMasPs, and for MIA studies. Another advantage of satellite images is that presence in the area is not required for obtaining the data. The main disadvantage is the coarse resolution of the older satellite images, say from before year 2000, where the spatial resolution can be relatively coarse compared to that of recent images. A summary of the historically and currently available satellites and characteristics are presented in the following Table 19.1.

Table 20.1 Overview of selected historically and currently available satellites (referenced to 2015) relevant for shoreline management activities and their characteristics.

Name of Satellite	Operational period	Spatial Resolution	Temporal resolution	Scan width	Comments
Sentinel 2	2015 -	10m	1-3 days	285 km	Modern spectral properties, free data
SPOT 6/7	2012 -	1.5m	1-3 days	60 km	Good balance between cost, resolution and coverage. Prices starting at 3 €/km^2
Pléiades	2012 -	0.5m	1-3 days	20 km	Fast turnaround time. Prices starting at 10 €/km^2
WorldView 1/2/3	2007 -	0.3-0.5m	1-3 days	13-16.5km	Fast turnaround time, very detailed images. Prices starting at 20 €/km^2
RapidEye	2008 -	5 m	1-3 days	77 km	Cost efficient, large coverage. . Prices below 1 €/km^2
QuickBird	2001 – 2015	0.6m	3.5 days	16.5km	Historical archive of detailed imagery. Prices starting at 15 €/km^2
Ikonos	1999 – 2015	1.0m	3 days	11km	Historical archive of detailed imagery. Prices starting at 10 €/km^2
SPOT 1 – 4 **SPOT 5**	1986 – 2013 2002 – 2015	10 & 20m 2.5 & 5m	3 days 1- 4 days	60km 60km	Good quality, long historical archive. Prices below 1 €/km^2
Landsat	1972 – 1999 1985 -	80m 15 & 30m	16 days 16 days	185km 185km	Free data, coarse resolution, consistently long time series
Old spy satellites	Back to 1965	Down to 3m	Varying	Varying	Historical images of varying quality, minimal costs

Satellite images are generally easy to rectify and they are well suited as basis for producing ortho photos and Digital Terrain Models. Orthophotos are very useful as background pictures for SMPs and SMasPs.

An example of a historical shoreline analysis is presented in Figure 20.1.

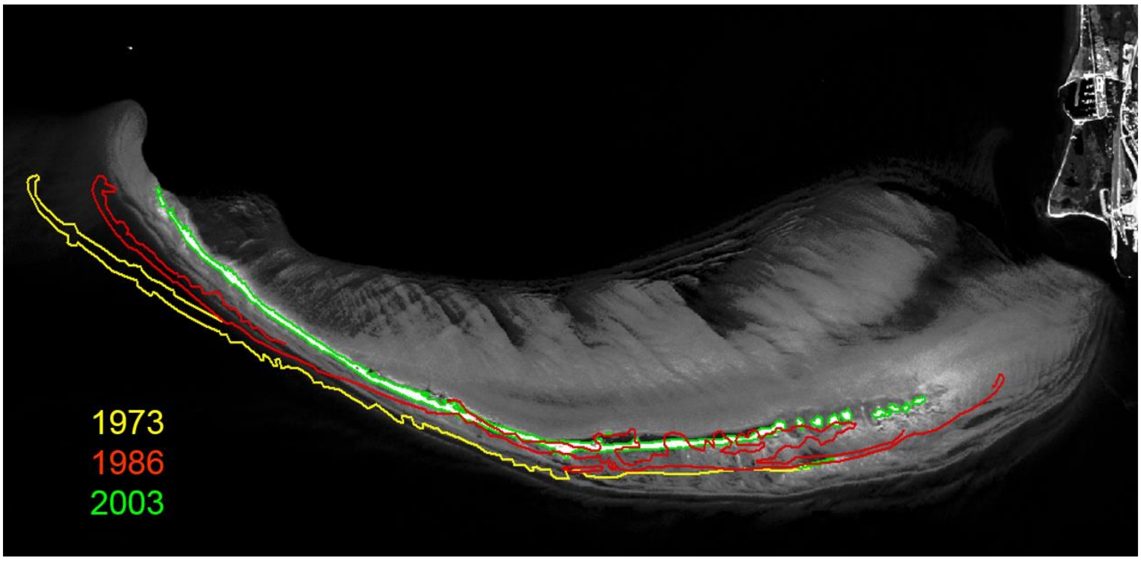


Figure 20.1 Shoreline evolution analysis for the eastern Rødsand barrier island formation, satellite data from USGS, DHI GRAS.

20.1.1.6 Shoreline development

The historical development of shorelines is often a very valuable tool for studying coastal morphological development in general and for overall calibration of the littoral transport budget modelling. Shoreline development can be extracted from historical maps and surveys, from aerial photos and from satellite images. Well defined shoreline accretion on the upstream side of coastal structures, such as groynes, inlet jetties at tidal inlets/river mouths and ports are especially suited as calibration basis for littoral drift and shoreline development modelling.

20.1.1.7 Sediment sources and sinks in the area

Quantitative information on sediment sources to a coastal section is of great importance for establishment of the littoral drift budget. The most important active source is supply of sand to the coast from rivers, however, nourishment can also be an important sand source. The sediments released from the coast in connection with especially chronic coastal erosion is also an important sediment source. The sediment supply from rivers is characterised by being heavily influenced by human interventions in the river basin as described in Subchapter 11.2.5, which means that the historical development in the supply from rivers is of great importance for the historical shoreline development. Nourishment is 100% controlled by human activity.

Sediment sinks are as important for the littoral drift budget as the sources are. Sediment sinks can be natural or caused by human interventions as listed in the following.

- *Natural sinks:* Nearshore submarine canyons and offshore loss during extreme events and due to sea level rise.
- *Sinks caused by human interventions:* Trapping sand at structures and in navigation channels, beach sand mining, trapping of sand in river mouths due to river sand mining and sea level rise.

The historical development in the sinks is as important to describe as that of the source.

20.1.1.8 Coastal structures and nourishment

The history of coastal structures and of nourishment is important to record, as these interventions intervene actively in the littoral drift budget by trapping sand, preventing erosion and supplying sand to the littoral budget.

20.1.1.9 Maintenance dredging at ports, tidal inlets and river mouths

Maintenance dredging at ports, tidal inlets and river mouths constitute a loss of sand from the littoral budget, unless it is bypassed back to the shoreline. Information on such maintenance dredging and mode of dumping is therefore important for establishing the littoral drift budget.

20.1.1.10 Land use maps

Land use maps provides a good basis for evaluating the need for protection as coastal protection shall only be allowed if valuable infrastructure, buildings or other installations are in danger of being lost. Consequently, land use maps are useful for shoreline management activities.

20.1.1.11 Metocean data

The metocean conditions in an area constitute the active "forces", which are driving the littoral drift and the morphological development. The types of relevant metocean data are the following:

- Winds and barometric pressure
- Tides and storm surge
- Sea level rise
- Waves
- Currents
- Ice

Available data on these subjects shall be collected as basis for description of the present conditions over the area of interest, and as basis for further analysis and numerical modelling, as described in Chapter 21. The typical type of available data and their use are described in the following:

Winds and barometric pressure

General description of the wind and pressure conditions in the area shall be collected. Long term wind data from nearby meteorological stations shall be collected and analysed if the site is located out to a relatively small water (fetch less than approx. 2 - 300 km). Waves can be modelled on basis of such data. If the site is located out to a major water (fetch greater than 300 km), it will be more accurate to base the wave modelling on time series of barometric pressure/wind fields over the relevant water. Such data can be purchased from international meteorological institutes, such as UKMO, and from private companies.

Winds caused by cyclones require special data and analysis, as cyclones are rare events relative to impact at a specific site. There exist data basis and atlases describing strengths, paths and frequency of tropical cyclones.

Tides and storm surge

Tides for an area can normally be described on basis of the tidal constituents, which are published in the Tide Tables. The Admiralty Tide Tables, published by the United Kingdom Hydrographic Office cover the entire world. In addition to these international tables, national tide data will generally also be available.

Analysed storm surge data may be available from public authorities, otherwise storm surge can be analysed from tide recordings. Consequently, it can be necessary to procure time series of tide recordings from nearby ports or hydrographic recording stations for analysis. Time series covering several years are required in order to analyse extreme storm surge conditions.

Storm surge caused by tropical cyclones requires special analysis, as they are relatively rare. This means that tide recordings normally cannot be used to analyse storm surge caused by cyclones. Analysis of extreme storm surge can be obtained by modelling of typical cyclone tracks based on standard cyclone parameters in a hydrodynamic model, followed by statistical analysis of the results.

Sea level rise

Sea level rise is analysed by many national hydrographic offices and by the Intergovernmental Panel on Climate Change (IPCC), from where forecasts for sea level rise can be obtained. It is of special relevance to include the influence of sea level rise in the design of dikes and other structures sensitive to flooding, as flooding of such structures may cause catastrophic conditions.

Waves

Wave data are of utmost importance for all shoreline management activities. Wave monitoring programmes or operational wave modelling programmes are operated by hydrographic or coastal authorities in many countries, from where data can be obtained. Such data may be useful if the recording location is close to the shoreline management site.

Wave data are also available from global wave models and from satellite monitoring, such data can be provided from virtually any location around the world. In general such data are provided from specific offshore locations. The transformation of such wave data to the coast may require numerical modelling.

Currents

Information on currents is important for most shoreline management projects however, the type of current which is of main importance for coastal projects is the wave generated longshore current. This type of current is strongest in the surf zone and at the shallow shoreface, and it is varying very much with location and time, dependent of the actual wave conditions. Recording of this type of current is in practice impossible to perform, which means that data on longshore currents are normally not available. Information on such currents is usually provided by numerical modelling.

Tidal currents can be very strong in straits and tidal inlets, data on such currents may be available in tidal stream atlases and are normally provided in sea charts and in pilots. Such data are provided as aid to navigation and will typically not be suitable as basis for shoreline management projects, however they provide useful information on the general current conditions in an area.

In rare occasions data on current recordings in straits etc. are available at hydrographic or coastal authorities. Such data may be useful as calibration data for numerical modelling.

In conclusion, relevant current data for a shoreline management project will normally not be available. Current data for shoreline management projects will usually be provided by numerical modelling of hydrodynamics, which take into account the following driving forces:

- Astronomical tide
- Wind stress and storm surge currents
- Barometric pressure
- Radiation stress gradients caused by wave breaking

Ice

Ice forces are important for design of certain coastal structures and for execution of works in temperate and arctic climates. Data on ice occurrence and thickness etc. are generally available at national hydrographic offices in countries where ice occurs.

20.2 Field investigations and surveys

The requirement to the type and extent of field investigations and surveys will primarily depend on two factors:

- The type of investigation, which requires the data
- The availability of existing data

The requirements to additional data provided through field surveys and recording will typically be of the same type as listed in the previous subchapter. A summary of typical types of field investigations and their relevance for different types of shoreline management activities are discussed in the following and summarised in Table 20.2. The various types of field investigations have been categorised in relation to their relevance for the following shoreline management activities:

- SMP, Shoreline Management Plan
- SMasP, Shoreline Master Plan including Coastal Protection Projects
- MIA, Morphological Impact Assessment
- DD, Detailed Design

The descriptions in the following concentrates on the type and scope of surveys and recordings, which are required for various types of projects, whereas types of recording instruments are not dealt with.

20.2.1 Listing of type and scope of surveys and recordings and their relevance

20.2.1.1 Surveys for provision of geological/geotechnical and seabed characteristics data

In addition to the geological maps, which are normally available, field data collection will be required for execution of SMasP, MIA and DD studies.

The type of field surveys required for SMasP, MIA and DD studies are typically the following:

- Sampling of seabed and beach samples and consequent description and sieving. Will typically be performed in lines perpendicular to the coastline covering the beach and the littoral zone
- Wash borings may be required to provide the thickness of the sand layer
- Sub bottom surveys in the form of seismic surveys and vibro-core borings may be required for projects, which involve foundation of major structures (bridge piers and port structures), burying of cables or pipelines, excavation or reclamation. Seismic surveys are also used for analysis of burial depth and backfilling coverage of pipelines and cables
- Seabed classification for identification of singular objects or provision of surface characteristics in terms of for example coverage of sand, seaweed meadows and mussel beds. This can be established by the combined use of different methods, such as side-scan survey (deeper water), digital image analysis of aerial photos or satellite images (shallow water), by underwater photos in a predefined grid or by paravane diving inspection. Special acoustic processing systems for interpretation of the seabed surface conditions based on echo sounder data has also been developed. The systems can distinguish different types of seabed based on analysis of seabed roughness and hardness

20.2.1.2 Topographic surveys

In addition to topographic maps, more detailed information will normally be required for the performance of SMasP, MIA and DD studies.

The type of field surveys required for establishing detailed topographic data for SMasP, MIA and DD studies are typically the following:

- Optical sensing: Traditional land surveys are used in general for establishing coastal profiles, digital terrain models and for recording of e.g. coastal structures. Using modern GPS based survey techniques makes this a much easier and faster task than before. Terrain models are often established using ATV (All Terrain Vehicles).

- Remote sensing
  - Aerial photography (aircraft or drone) is used as basis for establishment of detailed topographic maps (photogrammetry) and ortho photos are used for providing a clear visual impression of the area, where morphological features and coastal structures etc. can be studied
  - Satellite images for establishing illustrative image of the plan area and analysis of different themes by image analysis
  - The airborne system LIDAR (Light Detecting and Ranging) is a system with good horizontal and vertical accuracy for topographic and bathymetric surveys of large areas. Relatively low price drone based LIDAR systems are also available which makes surveying on dry land very fast and accurate. Several manufactures of these systems are also developing drone based LIDAR systems, which can measure bathymetry under water down to a water depth of 10 m to 15 m depending on the turbidity in the water column.

20.2.1.3 Bathymetric surveys

The standard Sea Charts are not detailed enough for the performance of SMasPs, MIA and DD studies. Additional surveys of the following types will usually be required for the performance of these activities as follows:

- Coastal profiling by echo sounding (digital) combined with a positioning system, such as optical (total station), DGPS (Differential Global Positioning System) or Real Time Kinematics GPS (RTK-GPS). The advantage of RTK-GPS is that reference to the water level is not required during the echo sounding. Coastal profiling can also be made using traditional Lead Line recordings. Echo sounding can only be performed for water depths greater than approximately 1.0 to 2.0 m, dependent of the type of equipment and survey vessel. However, as it is typically a requirement that the surveys cover the entire coastal area, or at least the shoreface and the shore, i.e. from the closure depth to the coastline, see Figure 3.1, it will normally be required to supplement the echo sounding with traditional land based surveying techniques to cover the section from 1.0 to 2.0 m water depth and up to the coastline.

- Bathymetric surveys:
  - Digital Echosounder combined with a positioning system (see above). The survey equipment can be mounted on a survey boat or on a "Hydrone", which is a remotely controlled hand portable catamaran platform suitable for surveys in protected and shallow waters.
  - Remote sensing by for example LADS (*L*aser *A*irborne *D*epth *S*ounder), which is a system with good horizontal and vertical accuracy for bathymetric surveys of large areas.
  - LIDAR, which stands for Light Detection and Ranging, is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. These light pulses - combined with other data recorded by the airborne system - generate precise, three-dimensional information about the shape of the Earth and its surface characteristics. A LIDAR instrument principally consists of a laser, a scanner, and a specialised GPS receiver. Airplanes, helicopters and drones are the most commonly

used platforms for acquiring LIDAR data over broad areas. Two types of LIDAR are topographic and bathymetric. Topographic LIDAR typically uses a near-infrared laser to map the land, while bathymetric LIDAR uses water-penetrating green light to also measure seafloor and riverbed elevations. It also referred to as Green Laser.

Repeated bathymetric surveys, often combined with topographic surveys and/or aerial photography, can be used to monitor the impact of coastal structures on the shoreline evolution and on the bathymetry adjacent to the structures, and for monitoring of backfilling in channels and trenches.

20.2.1.4 Surveying of morphological features in shallow water

Morphological features can to some extent be seen on geological, topographic and bathymetric maps, however they are normally much better presented on shallow water aerial photos and satellite images. Standard aerial photos and available satellite images are usually sufficient for SMP studies, whereas such standard products in general are not detailed enough as basis for SMasP, MIA and DD studies. Ortho photos produced from detailed aerial photos taken from low altitude or high-resolution satellite images are very useful for studying of morphological features as well as flora and fauna characteristics, such as sea grass beds and corals.

Aerial photos and satellite images from programmable satellites are also useful for monitoring of short term morphological development in shallow areas, or shoreline development, in connection with post construction monitoring of morphological impacts.

A good overview over longer sections of coastline can also be established by a video recording survey taken from a helicopter, a small plane or a drone equipped with a suitable positioning system.

20.2.1.5 Recording of metocean data

Analysis of metocean data is important in connection with all shoreline management studies, as the study of the littoral transport will always be an important part of such studies. A general description of the metocean conditions in an area is often established on basis of existing data as described above. The needs for additional recordings are especially related to the following requirements:

- As part of the documentation required for establishment of basic description of the area, which is part of the EIA for the specific project
- Establishment of basic design data in areas, where hardly any data are available. This will often be in combination with establishment of data as basis for numerical modelling of hydrodynamics and waves, see below
- Establishment of data as basis for numerical modelling of hydrodynamics and waves, as data for boundary conditions, calibration and verification
- Establishment of data in connection with intensive field campaigns, where metocean data are required as documentation of conditions during other types of field activities, such as bathymetric surveys (water level recordings) or collection of water samples for determination of content of suspended sediments (water level, current and waves) etc.
- Monitoring of critical parameters in connection with construction activities
- As monitoring of impact in connection with EIA studies

Typical requirements for recordings of metocean data (winds, tides and storm surges, sea level rise, waves, currents, sea temperature, salinity and turbidity) are discussed in the following and a summary for of typical recording requirements for different types of activities are presented in Table 20.2.

Winds

Long term wind data are typically available from nearby stations, which means that wind recordings are normally only required in connection with intensive field surveys. Wind recordings can also be relevant at locations where land- and sea breeze effects dominate the daily wind pattern, and thereby the local wave pattern, as this may not be represented in data from stations which are not located on the coast.

Tides and storm surge

Tidal recordings, or rather water level recordings, are relevant in the following situations:

- At sites located far from tidal prediction stations and at sites with a complicated bathymetry, which makes tidal prediction difficult. To be used as basis for calculation of tidal constituents. Two months of recordings are sufficient for this purpose.
- For establishment of characteristic correlations between wind conditions and surge. This requires a one year recording period as a minimum.
- Establishment of extreme water levels caused by storm surge requires decades of recordings. Such analyses are normally performed on basis of long term recording from existing recording stations, or from numerical hydrodynamic modelling of extreme events
- As reference for bathymetric surveys or other field investigations in the area
- Recordings at two locations for establishment of boundary conditions for hydrodynamic modelling of the area
- Recordings at one or more locations inside the modelling area for calibration and verification of hydrodynamic models
- Recordings as part of construction activities

Sea level rise and subsidence

Recordings of sea level rise and subsidence in general are not part of a specific shoreline management project, as this requires very long time series.

Waves

Waves are the most important parameter for shoreline management activities. Detailed information about waves in the project area is very often established by numerical modelling, which has reduced the need for wave recordings in connection with shoreline management projects over the last decades. However, recordings of waves are relevant in the following situations:

- To provide data for calibration and verification of numerical wave modelling. This will normally require recording at two stations for 3 to 6 months. This methodology is especially used in waters of limited size, say up to 3 - 500 km fetch, as wave modelling in such areas can be performed by simpler methods than for very lager waters (oceans)
- To provide background data for other field investigations in the area, such as sampling of water samples for analysis of concentration of suspended sediments or in connection with recordings of local current pattern by floats etc. This will generally require recordings for some months, maybe in two characteristic seasons
- Wave conditions at oceans coasts are difficult to simulate by local wave models as the wave characteristics are dependent of the history and variation of the wind over huge areas. Consequently it can be relevant to perform offshore wave recordings at such locations. Many years of recordings are required for establishment of reliable descriptions of the normal wave conditions and of design data. Such long recording series are generally performed by authorities, from where data can be acquired. A local wave climate can consequently be

established by numerical modelling, whereby the offshore conditions can be transferred to a specific site

- Shorter nearshore recording periods (6 to 12 months) are sufficient for confirmation of specific local wave characteristics at sites where the overall wave conditions have been determined by other means. This is especially applicable at sites dominated by regular wave climates, such as monsoon climates, trade wind climates and areas dominated by perennial swell
- Wave recordings can be relevant as reference parameter in connection with monitoring programmes performed as part of an EIA investigation
- Monitoring of waves can be relevant in connection with construction activities

Currents

Current is an important parameter as mentioned under the discussion of collection of existing data. Especially the longshore currents and current patterns in shallow areas close to coastal structures are important for shoreline management projects, however, such currents are not suitable for recording by stationary recorders. Recordings of currents are relevant in the following cases:

- Current recording at fixed locations by Recording Current Meters (RCM) for:
  - Provision basic information for planning or design
  - Recording inside project area but seawards of the nearshore zone, for which numerical hydrodynamic modelling is to be carried out. For calibration of the HD model
  - As documentation of currents in connection with water sampling for determination of content of suspended sediments
  - Monitoring before and after implementation of a certain project as documentation of impact
  - Monitoring of currents in straits and at ports for navigation purposes
- Current recording by ADCP (Acoustic Doppler Current Profiler):
  - Installed in a frame on the seabed: Provision of time series of current profiles, typically used for documentation of stratified flow in straits and estuaries
  - Installed in the bottom of a survey boat: Provision of current profiles across a strait or a major river. Can provide flux information by application of integration software, typically for calibration purposes.
- Current recording by floats for documentation of current pattern in an area with complicated 2D current pattern. Can be used as a calibration basis for numerical modelling in combination with recordings of currents at fixed locations by an RCM.

Temperature, salinity and turbidity

Temperature and salinity are often recorded together with recording of currents in connection with oceanographic investigations and in connection with major EIA investigations in areas with stratified flow etc.

A summary for of typical recording requirements for different types of activities are presented in Table 20.2.

Table 20.2 Typical requirements for field investigations for various planning, impact and design activities.

Type of field investigation	**Type of Plan/Activity**				
	SMP	**SMasP** **Coast protection**	**Morphological Impact Assessment**	**Environmental Impact Assessment**	**Design Project**
Geological and geotechnical	N	Y	Y	N	Y
Seabed characteristics	Y	Y	Y	Y	Y
Topographic survey	N	Y	Y	Y	Y
Bathymetric surveys	N	Y	Y	Y	Y
Morphological features	N	Y	Y	N	Y
Wind	Y	Y	N	N	N
Tide and storm surge	Y	Y	N	N	N
Waves	Y	Y	Y	Y	Y
Currents	N	Y	Y	Y	N
Temperature, salinity, turbidity	N	N	N	Y	N

Note: N: Not required, Y: Yes required

21 Numerical Models as Support for Shoreline Management

This chapter has been divided into four main chapters with different targets.

- *Numerical modelling principles* is a general introduction giving an overview over the different terms and principles involved in numerical modelling
- *Model application in projects* takes a broad overview over the role and impact of numerical modelling in applications and commercial project work
- *Coastal processes – modelling a complex environment* gives an overview over how the complex coastal phenomena can be simplified and represented in a model
- *Models for coastal processes* gives a more specific description of a selection of the most important models used within coastal and shoreline engineering, including examples of their capabilities

The reader is welcome to consult these parts in a sequence different from the one suggested here.

21.1 Numerical modelling principles

21.1.1 Introduction

Numerical models of coastal processes are powerful tools for quantifying a large range of technical questions which a coastal engineer or scientist encounters. The models can not only help analysing a given problem, it can also help analysing the effect of different mitigation and solution strategies designed to counteract the problem. However, no matter how strong the tools are, the numerical models cannot completely replace the coastal engineer's or scientist's knowledge, skills and physical intuition about the coastal system. In fact the models should be regarded more as a helping tool for the engineer – a complicated and relevant calculator, but a calculator still. Models should not be used "blindly", but regarded as a strong tool when carefully executed by an experienced user.

In the first parts of the present guideline we have presented definitions used in coastal engineering, natural physical phenomena, human interventions and possible problems that a coastal engineer may encounter. Furthermore a number of solution strategies and a number of different ways to mitigate the problems have been given. In the present part we focus on the modelling tools available for illustrating and quantifying the effects –both of the problems and their mitigation - giving guidelines and inspiration on how to work with models in order to quantify the processes correctly, i.e. to find the right balance between model capabilities and realistic application of the models within the limits of a given project.

As further inspiration one may imagine three aspects of advanced coastal engineering, which - if successfully absorbed - in combination represent a good coastal engineering team (or a very skilled single person), cf. Figure 21.1

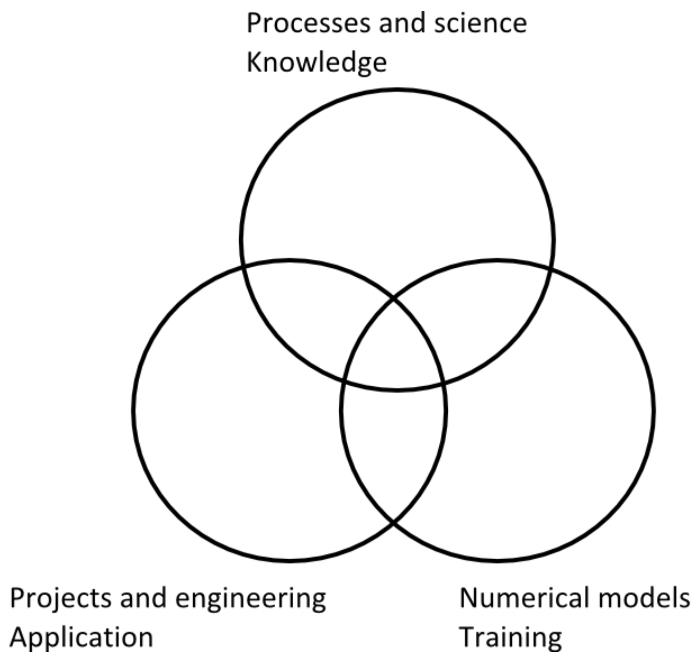


Figure 21.1 Three aspects of advanced marine engineering.

21.1.2 The basic idea of numerical models

21.1.2.1 Continuous solutions and discrete representation

Coastal flows – along with wave propagation, sediment transport and morphological evolution - can be described mathematically by partial differential equations formulated in variables such as velocity, pressure and surface elevation, and are continuous in space and time. Furthermore the boundaries - bathymetry, shoreline, inflow and outflow boundaries - are in real cases quite complex. These differential equations with their boundary conditions can in practice not be solved analytically.

Fortunately numerical techniques exist that can transform the general equations into numerical algorithms and by coding these algorithms into a computer program, a computer can produce a numerical solution to the equations. Such a numerical solution will be an approximation to the exact continuous solution. In most cases the details behind the exact computational method is not known by the user of the model. But an overview of the idea behind is good to have when trying to understand both the possibilities and limits of a given model.

When the continuous variables are to be represented in a numerical model the partial differential equations governing the flow are transformed to difference equations in the discrete variables. The translation of the continuous flow variable to the discrete representation happens by introducing a mesh with discrete points and/or cells, where the discrete values are located. The better resolution of the physical spatial and temporal domain and the better numerical methods we use, the closer the numerical solution will be to the real solutions (although at some rather extreme point, increasing the resolution will in fact not give better results). Increasing the resolution or refining the numerical method will however be at the cost of calculation time. Hence there are always two opposite directed factors to find a compromise between the two facts:

1. Better resolution gives better results
2. Better resolution requires more computational resources and takes more time

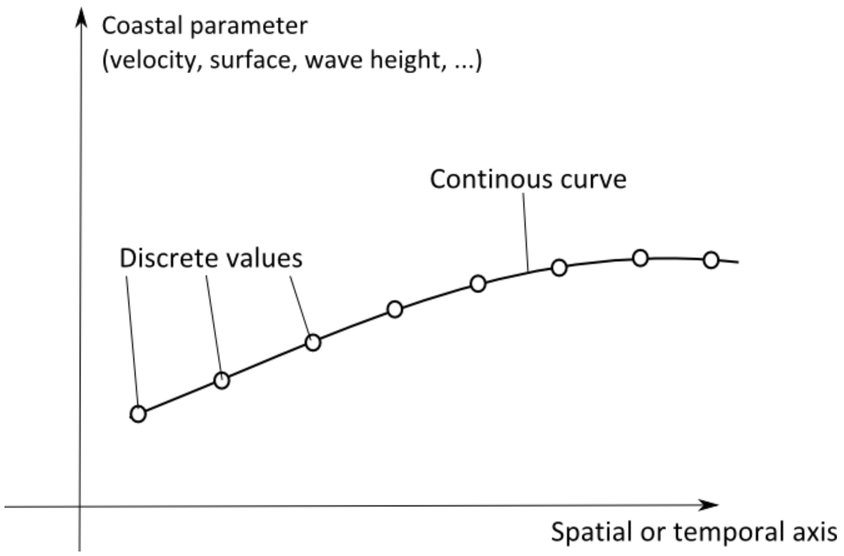


Figure 21.2 The continuous solution is approximated by a discrete number of points.

21.1.2.2 Mesh types

Three main types of meshes may be considered

- Rectangular meshes
- Curvilinear
- Flexible meshes

Rectangular

In rectangular meshes the discrete values are distributed evenly in a rectangular fashion as depicted in the example in Figure 21.3.

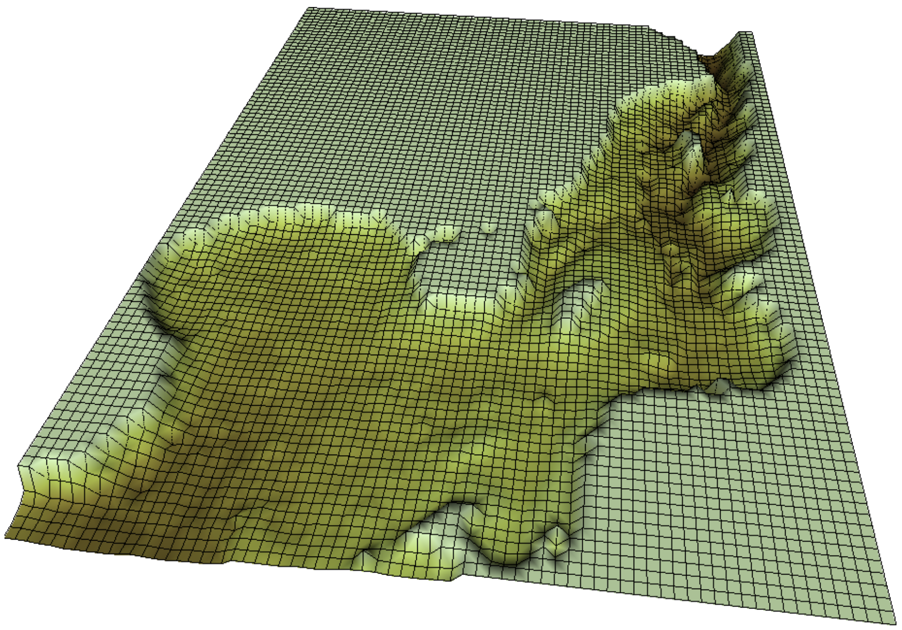


Figure 21.3 An example of a rectangular mesh representing a set of bathymetric data.

Curvilinear

The discrete values in curvilinear meshes are distributed along lines and lines normal to these lines, but the mesh can be stretched and curved. An example of this type of mesh is seen in Figure 21.4. This type of mesh is often used for situations with a predominant flow direction following a curved path, e.g. for river flow calculations.

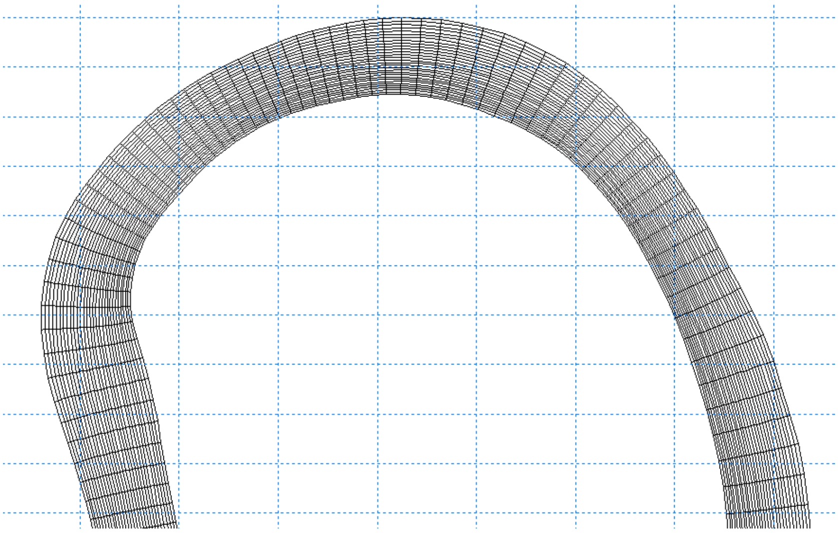


Figure 21.4 A curvilinear mesh for a river bend section.

Flexible mesh

More flexible ways of distributing the discrete values exists, e.g. in the case where the mesh is build up by triangles as is shown in Figure 21.5. A flexible mesh makes it possible to use elements of vary different size and a fine resolution can therefore be made freely in any area of interest or where strong gradients are expected. Cells can gradually be made much larger away from the areas of interest. The mesh can in this way be optimised to have a fine resolution with a manageable number of cells.

Figure 21.5 A triangular mesh, valuable for boundary fitting and for varying bathymetry.

21.1.2.3 Allocation

The variables (current, surface elevation, wave characteristics etc.) can be allocated in the mesh in different ways. For example, variables could be allocated at grid points, at the edges or in the middle of a computational cell, etc.

Here we consider two of the perhaps most used allocation used in coastal models:

- Staggered
- Collocated

Staggered – finite difference

Staggering of the variables means that the pressure (or surface elevation) and velocities (or fluxes) are not allocated at the same locations, but rather are allocated with the fluxes being defined between the points where the pressure is allocated as illustrated in Figure 21.6. Time staggering may also be used so that the different velocity components and the water level are calculated at different stages in each time step.

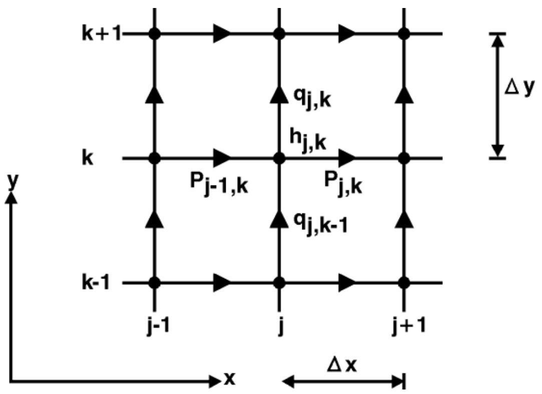


Figure 21.6 Staggered allocation of variables on structured grid.

Collocated – finite volume

Collocated variables mean that the pressure and velocities are located at the same locations. A good example of this is the case of the Finite Volume technique where the variables are all allocated in the cell centres, as illustrated in Figure 21.7. Here the flux between two cells is determined by interpolation between the velocities in the two cells.

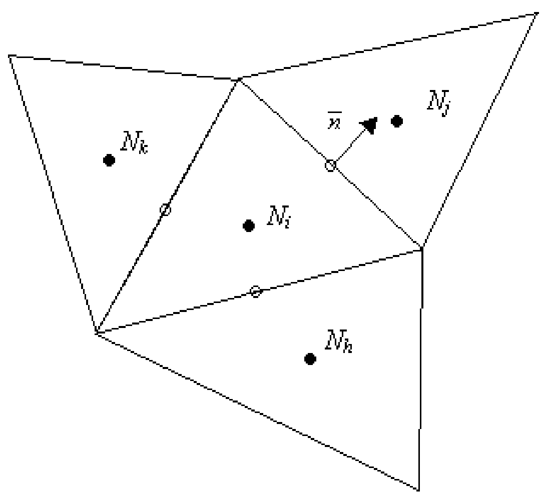


Figure 21.7 An example of a finite volume strategy where all variables are allocated in the cell centre, i.e. a collocated approach.

21.1.2.4 Mesh structures

Another concept used to describe the mesh and is the structuring. Two possibilities exist:

- Structured meshes
- Unstructured meshes

A structured mesh (rectangular or curvilinear) is a mesh where the location of each point can be ordered in a logical sequence, so that neighbouring points are easy to identify without a complicated book keeping system. A flexible mesh is unstructured, which means that for a given cell the location and properties of the neighbouring cells have to be found by use of a ‘connectivity table’.

21.1.2.5 Basic types of discretisation

A number of different strategies for formulating a numerical model of flows may be considered

- Finite difference
- Finite volume
- Galerkin method
- Finite element
- Smoothed-particle method

Finite difference is a discretisation strategy based on approximating the partial differential terms with finite difference terms, for example where a derivative is found as the slope of the line connecting two discrete values. The finite difference approach is most often seen in connection with structured grids.

Finite volume is defined from as mesh containing cells with boundaries (to the neighbour cells). It is a strategy based on the approximation that in every cell the quantity at hand (pressure, velocity, etc.) is fully mixed, i.e. has the same value at each location within the cell.

The Galerkin method is based on the idea that the spatial and temporal distribution of a given quantity can be approximated by the sum of a finite number of orthogonal functions. The Galerkin strategy is an example of a mesh-free method.

Finite element has characteristics that in some sense remind of finite volume as it builds on the idea of cells, but is based on introducing distribution functions (basis functions) for the variable inside each cell. The problem becomes unique when applying a variational method to optimise the distribution under the restriction of the transitions between cells is continuous. The method is not so often seen used for flow problem, but is widely used within solid state mechanics.

Smoothed particle method is a mesh-free method where the flow is represented by a large number of interacting particles. The method is hence Lagrangian (“moving reference frame”) opposed to the above methods that are Eulerian (fixed reference frame). The method has not yet been applied as an engineering model, but may be a relevant alternative in the future.

21.1.2.6 Order of accuracy

A term often used when speaking about the accuracy of the model is the order of accuracy.

Some sort of error is introduced whatever approximation is used when introducing a discretisation of the continuous set of differential equations. The discretisation error will scale with the size of the cell for the spatial gradient terms and the time step for approximations of the temporal gradients. For example for a “first order” accurate scheme, the error will grow linearly with increasing grid size, and for a “second order” accurate scheme, the error will grow parabolic, etc.

The higher the order, the more accurate the scheme is, but it will also tend to sometimes produce more spurious oscillations and be more unstable.

Some models have the possibility for the user to select different orders of the solution. As indicated it is not always trivial to choose as it is not certain that a higher order will produce the best result for a given mesh, but it will always require more computer time.

21.1.2.7 Time integration

The solution in a numerical model is obtained by marching forward in time. Step by step the solution for one time step is built from the conditions in the previous. Even a stationary solution can be obtained by making the model run until steady conditions have been reached, or by an iterative procedure acting as a modified time stepping.

The solution requires a start condition. In most simulations of coastal problems the interesting conditions are independent of the actual start conditions and the simulation is run until the flow or waves are determined by the forcing from the boundaries; it can be a tidal flow, a storm coming after a calm period, or a simulation over a period of several months or even years. A simulation may therefore start from rest and - if necessary - the forcing from the boundaries can be gradually increased from zero to the actual values during a 'warm-up period'. Another possibility is to make a 'hot start' starting from the point where a previous simulation ended.

Two different principles exist for the integration in time:

1. Explicit time integration
2. Implicit time integration

Explicit time integration means that the solution to the next time step in a given cell is found only from the solution from the previous time step. No extra solver techniques are needed. The explicit time stepping is limited by the criterion that the Courant number should be less than 1.

The Courant number is defined as

$$\boldsymbol{C} = \frac{V\Delta t}{\Delta x}$$

where V is a measure of the advection velocity and/or wave celerity, Δt the time step, Δx a measure of the size of the computational cell.

A courant number below 1 corresponds to flow information (i.e. a water particle or pressure) not travelling more than one cell at the time. This is also called the Courant-Frederichs-Lewy condition.

Implicit time integration means that the solution to the next time step is not only depending on the solution at the previous time step, but also on the solution in the neighbour cells for the next time step. All the values in the model for the new time step are thus determined simultaneously. To solve the equations demands a matrix equation solver. It is characteristic for implicit time integration that larger time steps can be chosen (i.e. not bound by the Courant criterion $\boldsymbol{C} < 1$), but the computational work is larger for a given time step compared with explicit schemes.

Many models use a combination explicit and implicit time stepping for different processes such as advection and diffusion.

It could be noted that for flows that are more dominated by the mixing than the typical coastal flows one should also sometimes consider a grid Peclet (or Reynolds) number condition. This is however a relatively special topic in this context which we will let the reader study by herself/himself, if needed.

21.1.2.8 Types of numerical errors

The order of accuracy is a local quantity, i.e. the error for the approximated gradients around a point or cell in the model. The overall solution will be a sum of the effect of all the errors.

- Numerical stability
- Numerical diffusion
- Erroneous oscillations

A numerically stable model is a model that produces a solution, independent of the quality and the accuracy of the solution. There can be different reasons for a model to be unstable, either the Courant or so called cell-Peclet criteria are not fulfilled (see time integration) or the solution is ill-defined because of a low mesh quality. Some numerical schemes become unstable for high flow velocities and supercritical flow conditions. Numerical instability will in most cases give results that are obviously wrong and cause the model to 'blow up' and stop.

Numerical diffusion is a phenomenon often seen for low order advection schemes and cell sizes that are large, i.e. coarse meshes. It leads to an artificially high diffusion, but may not be readily detected because the solution still appears realistic.

Erroneous oscillations may emerge due to higher order scheme, if they are not treated properly numerically in the model (i.e. a model or code issue).

21.1.2.9 Boundaries and boundary conditions

A flow simulation requires a complete and consistent set of boundary conditions.

It cannot be stressed enough that *the boundary conditions generate the solution inside the domain and the quality of the boundary conditions directly affects the solution.*

There are two fundamental types of boundaries in coastal flow problems: 1) the boundaries around the model domain and 2) the bed- and the water surface boundary.

The first category constitutes open boundaries towards adjacent water bodies and closed boundaries towards land or structures.

Open boundaries for a flow model are typically specified as water levels or water fluxes, although some mixed boundaries have been formulated consistent with waves propagating through the boundary. Wave models typically have the incoming waves and boundary condition combined with conditions which allow the waves to propagate out of the domain. The boundary conditions for a coastal model, which covers a limited local or regional domain, will often be taken from other global models for tides and surges or wave hindcast models.

Closed boundaries will have zero flux and may have slip or a no-slip condition for the flow parallel to it. The land/sea boundary is special. On gently sloping beaches and tidal flats it will often be formulated with a flood/dry condition allowing the domain to change as the water line passes through the computation cells.

When an open boundary crosses the shoreline the flood/dry boundary needs to be resolved sufficiently. This is often relatively easy for long coasts, but for more complicated geometries like for fjords or tidal inlets, etc., flexible meshing techniques are often needed.

The bed boundary is given by the bathymetry which is of course very important for coastal flows. In fact the quality of the bathymetric data used for constructing the bed geometry is of utmost importance for modelling the flow in the coastal region. The boundary condition used for the bed is kinematic as the bed is treated impermeable and no flow through the bed is allowed.

In the case of detailed calculations of the velocity profile in a three-dimensional model, the velocity at the bed is put to zero (complete adhesion at the non-moving bed). If the grid cells are needed to be large close to the bed, one often use a so-called wall-function to transfer this criterion to a distance above the bed often by assuming a logarithmic profile near the bed. In a depth integrated flow model, this degenerate to a bed shear stress formulation connecting the depth averaged flow with the bed shear stress. This implicitly corresponds to assuming a given velocity profile over depth (again often logarithmic).

At the surface a dynamic boundary condition is needed when wind is blowing, i.e. a surface shear stress is needed in that situation or energy transfer to the wave field.

21.1.2.10 Mesh quality

The way the continuous solution is represented by a discrete mesh is important for the quality of the solution. This points to the quality of the mesh. The better the mesh is, the closer the solution is to the real solution.

The mesh quality can be viewed from the following angles:

- Resolution of features
- Rounding errors
- Mesh alignment with flow
- Mesh angles and other quality measures
- Numerical scheme

Resolution: The more points that are used to resolve a given feature, the better results are obtained in the model. There is an optimal resolution for a given geometry and type of model, where adding more points do not improve the solution, but in practice this limit is rarely reached.

Rounding errors: In principle a numerical model with a given type of mesh, but where the number of numerical cells is gradually increased for each rerun, should converge to the real solution. However, at some stage rounding errors become dominant due to the limited number of digits in the number processed, after which further refinement will actually increase the error. In practice this limit is very rarely of significance in coastal modelling.

Mesh alignment with flow: Errors may accumulate in the solution if the mesh is badly aligned with the flow.

A mesh that has areas where the cells or point alignments are very skew with very obtuse-angles triangles the solution cannot be expected to be good. A measure of the mesh angle is hence a number that can be used to diagnose the mesh quality.

21.1.2.11 Working with the mesh

In order to obtain a high quality numerical solution, the flow should be resolved properly, etc. The optimal mesh is not independent of the solution and before defining the mesh the modeller needs to anticipate where in the numerical domain the flow is likely to occur. In most cases some sort of iteration procedure with a few test calculations is needed to optimise the resolution of the mesh before starting to make the actual production runs.

In marine applications the primary boundary is the bathymetry, which must be resolved in the mesh in a numerically sound way. This means that all features in the bathymetry that affect and/or control the flow have to be resolved sufficiently.

Some work is hence needed before using the mesh in the final calculations:

1. Anticipation of main flow patterns before defining the mesh
2. Resolution of features in the bathymetry relevant for the flow
3. Iteration: Define mesh, run test, re-define mesh, etc.

21.1.2.12 Parallel codes

For models with a large number of cells (say >> 10.000 calculation points).Run time on the computer will often be a limiting factor. And the possibility for parallel computing is therefore attractive. A number of ways exist to utilise the computers parallel processor capacities.

- OpenMP
- MPI
- GPU

In the OpenMP framework the calculations are performed by processes working in a parallel fashion but where the memory for processes is shared.

MPI is a fully parallel method utilising both parallelisation of memory and processing. In this method a "physical" division of the calculation is introduced in the beginning of the simulation and the computations are done in each domain followed by a communication step to transfer information between the domains.

GPU is a parallelisation method that uses graphical computational processing unit which has a large number of parallel processers (but not as high clock frequency as linear core CPUs).

21.1.2.13 Engineering models

Numerical models range from very simple ones based on the solutions of simple differential equations to very complex ones resolving very fine flow structures of turbulence etc., i.e. very time and memory consuming models. The simple models may not give very accurate results because the physics are simplified too much, on the other hand the very detailed model may resolve phenomena not of interest and are impossible to handle CPU- and memory wise in a real application. However, in the range between the too simple and too advanced models we may find a model that is in fact well-suited for being applied in an engineering context. We will therefore define what we mean by an engineering model:

Engineering model: A model that is optimal with regard to the following criteria:

- Pre- and post-processing time
- CPU time – calibration, validation and production runs
- Accuracy and detail of model results = accuracy and detail needed

21.1.2.14 Commercial and free products

The choice whether to use either freely available numerical codes or investing in a commercial product is a central question in the field of coastal engineering. The advantages of the two types of products are:

- Commercial product: Industry standard, quality control, optimised for the specific use, support, community, easy to use (pre- and post-processing tools), user friendly graphical interface, training, etc.

- Open software: No fee, community, broad spectrum of developers (typical universities) etc.

21.1.2.15 Pre-processing

It is important in engineering projects that the software for pre-processing is flexibility and that the methodology for working with the model set-up and meshing is as streamlined as possible. Pre-processing includes

- Preparing mesh – bathymetry data
- Preparing boundary conditions

- Setting up model – import mesh and set up boundary conditions

If e.g. the meshing tools are integrated in the software, this would often be seen as a benefit in this context.

21.1.2.16 Post-processing, interpretation and analysis

As for the pre-processing the flexibility and streamlining of the output is important and the analysis should be thorough, but should not take up unnecessary time.

- Output
- Analysis tools

Output should be in such a format that post processing tools can easily read the model result data and the post processing tools should have the capacity to make the right plots and most proper analyses, for the given project. Integration with other software programs for data analysis or plotting is a benefit in terms of flexibility and the possibility for making special case analyses.

Integration of modelling, model output and analysis in a single dedicated piece of software will in many cases be optimal.

21.1.2.17 Calibration and validation

The effort put into the calibration and validation of the model relies partly on the uncertainty of coastal process and sediment transport modelling and partly on the aim of the project in the context of accuracy. The level of accuracy needed may be divided into four levels:

1. Quantification, accurate absolute numbers
2. Quantification of changes or differences between scenarios
3. Trend analysis
4. System/process understanding

other important factors at play are:

- The availability of calibration and validation data
- The budget for obtaining these, relative to the risks connected with accuracy in the project
- The accuracy of the chosen model relative to the extra effort put into calibration and validation of the model

In the case of current and wave predictions it is expected that the models can be very accurate and therefore a correctly calibrated and validated model can produce very realistic numbers and hence be of great value e.g. for design.

In general models for sediment transport are less accurate, but the better input in the form of sediment characteristics, current and wave data and historical shoreline evolution etc. the better the sediment transport prediction is still expected to be.

All of these issues should be taken into account in order to decide the level of calibration and validation needed for the given exercise.

21.1.2.18 Model bias and errors

The error in a model result is the sum of model bias and error in the boundary conditions

Modelling error = model bias + data error

Data error

- Data missing or with insufficient resolution
- Measurement bias originating from the data source (measurements, hindcast etc.)

Model bias

- Insufficient model set up
- Biased process representation (lack of scientific knowledge)
- Introduction of simplifications giving bias

21.1.2.19 Model bias cancellation

The relative value of a given variable between two simulations will in most cases be more accurate than the absolute value of one of the results, because model bias will tend to be reduced if not – in some cases - completely cancelled out.

21.2 Model application in projects

21.2.1 Numerical modelling purpose

Numerical modelling has become less costly, fast and reliable and most Shoreline management projects will involve the use of numerical models. The purpose of the modelling may, however, be different depending on the objective of the project and the problem. In order to develop an optimal modelling strategy it is important to make the purpose of the modelling clear.

21.2.1.1 When, why and how do we use numerical models?

In a specific project the modelling part of the project would benefit from definition of a simple and precise objective that the model should help you to attain. The more accurate one can formulate the question, the easier it is to identify what type of model you are looking for.

Examples of problems addressed by modelling

Determination of design parameters. Find the wave- , water level- or the current condition with a specific return period. Often this will be obtained by acquiring boundary conditions from a regional or even global model, which has been run in hindcast mode for a period of decades forced by meteorological data. The conditions are then transformed to the site in question using a local detailed model. The parameters of interest are then extracted at the relevant locations and used for statistical analysis.

Morphodynamic analysis. Use models for waves, hydrodynamics, sediment transport and maybe also morphology to analyse the optimal configuration of a new beach to be built for coastal protection and/or recreational use. The models can be used to determine the consequences of different orientations of the beach, division of the beach into sections, the choice of possible structures to support the beach and the expected maintenance. Such analyses will require simulations covering a period of one or more years and typically also extreme storm conditions.

Dike and dune height. Analysis of a future dike or artificial dune field: How high is the run-up on a given dike or dune? What is the overtopping maximum and mean rate over a storm period? What are the consequences of a dike breaching for hinterland flooding? What is the effect of climate change 1) in itself and 2) on all of the above questions? How can we best mitigate against unwanted consequences?

Impact assessments. Assessment of the impact of a major coastal project, such as a port or a coastal protection scheme. The question to be addressed could be: How much sedimentation is to be expected in the in the access channel and in the entrance area and? What is the impact on the adjacent shorelines in terms of upstream sand accumulation and leeside erosion? Should leeside erosion to be mitigated and should upstream accumulation be bypassed artificially? Can the layout of the port be optimised to reduce sedimentation and leeside erosion and to optimise natural bypass?

21.2.1.2 The accuracy

When planning a model study it is important to be aware of the accuracy that can be expected for the results. Hydrodynamic models for waves and currents will often give reasonable results based on boundary conditions from tidal data, hindcast wave data and meteorological data and hydrodynamic models can be calibrated to a high accuracy with recordings of waves, water levels and currents. In contrast sediment transport simulations can be very uncertain. A sediment transport model may give only the direction of the transport and an expected order of magnitude if not calibrated properly. It is therefore very important to plan how sediment transport modelling can give meaningful answers to the important questions to be addressed. Often calibration data can be difficult to obtain. Progress is being made in the development of field instruments, but direct measurements of the transport rate are difficult and still considered unreliable, and the most relevant data would be for severe wave conditions where direct measurements are often impossible. Bed sediment should always be collected in considerable numbers and analysed for grain size distribution to provide the minimum basis for the study. Otherwise all relevant information should be collected and used to calibrate the model or to compare with the simulation results.

The information could be:

- Historical shoreline evolution from old maps and charts, aerial photos and satellite images, especially shoreline evolution adjacent to coastal structures is useful
- Maintenance dredging records from access channels and port entrances

When the available data have been collated it should be analysed how the model can contribute to the project: Can it be expected to give reliable rates of sediment transport and expected sedimentation and erosion rates? Is it relevant to make a sensitivity analysis? Can it be expected to give rather reliable information on the expected morphological evolution even if the absolute transport rates and therefore the times scale are uncertain? Can the error be cancelled – at least partially – by making comparisons between simulations of the past and present conditions or making inter-comparison of different schemes considered?

21.2.1.3 Application of models in projects

In a given project, a model should be used as a mean to support the project. Therefore it is important to find out how the model should be implemented in the project to give the most value. An overall guideline of such a process is given below:

21.2.1.4 Defining a model project, general considerations

When defining and working with a project there are a number of interrelated “cross-cutting” considerations to be made. One can use the questions below as a guide for getting an overview of the project and the modelling:

Problem:

- What is the problem?
- What are the main important processes involved?
- Can we represent these processes with a model?

Model:

- What engineering models are available?
- What computational resources are available?
- What is the pre- and post-processing time?
- What modelling skills does the modeller have?
- What data are available to drive the model?

Accuracy:

- What accuracy/quality is needed?
- What accuracy/quality can be obtained?

Concerns:

- Who has the problem?
- What is the interest of the client?
- Who are the interest groups? Company (ports, industry, dredging companies etc.) - Society (authorities, administrators, laws, politicians, public utility, infrastructure authorities etc.) - Individuals (house owners, citizens etc.)?
- What are the interest groups attitude towards using models in the project
- Are there any conflicts of interest between parties?

Project:

- What is the time limit of the project?
- What is the project budget for modelling?
- Does this fit with the time and man hour budget?

Outside the box:

- Are there other demands?

In compressed form:

How can we illustrate important processes and quantify (model) the relevant processes with the wanted accuracy within the budget and time limit of the project (including other potential concerns, demands and limits)?

21.2.1.5 Screening the project

The initial part of a project phase is where the problem dimension is analysed, before considering application of any models. Here we need:

- Data: What data are available and what data are not?
- Think before modelling and make simple calculations and estimates before starting advanced modelling
- Guidelines and engineering experience
- The first parts of the present Shoreline Guidelines can be very helpful in this process.
- The following considerations shall be done in the initial phase of a project:
- Spend a little time studying the given problem from a more overall viewpoint by doing some general estimates of the order of magnitudes involved in the specific project
- What physical processes are expected to govern the problem
- Propose preliminary layout optimisation before initiation of the model line

This can most easily be done by an experienced engineer using experience from similar projects and making general considerations about the nature of the problem at hand.

21.2.2 The user's background and training

Model users are as different as all humans are. Therefore the user adds – to some degree - a subjective factor to the model result which is based on the persons experience and training. In order to minimise the subjective factor, the user could try to be aware of his/her own role and try to be aware of the fact that the model results are affected by the choices he or she makes.

The modeller should have a sufficient scientific background together with knowledge on how to choose and apply a model in a given context in order to use the model in an optimal way. It is the user that translates the reality of the problem into a virtual, i.e. modelled, way of looking at the problem.

Scientific background

- Physical processes (theoretical understanding and physical/engineering intuition)
- Mathematical description of processes
- Numerical treatment
- Computational processing

Application skills

- Conceptual description of the problem, including all relevant areas
- Limitations of the above mentioned compared to reality
- Assessment of the necessary approximations – wanted and not wanted
- Calibration and validation – how to, when, what?
- Model critique: Gain from the model what can be gained, judging bias and errors

Notice that to some degree the education from a technical university will help an engineer to train the scientific part of this total skills needed, but as a large part of the total set of skills is actually in the cross-field between application and scientific understanding some sort of training and experience is needed in that specific context.

21.3 Coastal processes – modelling a complex environment

The processes to be quantified by the model are the ones described in the first part of the present guideline. Hence, we return to the coastal zone definition:

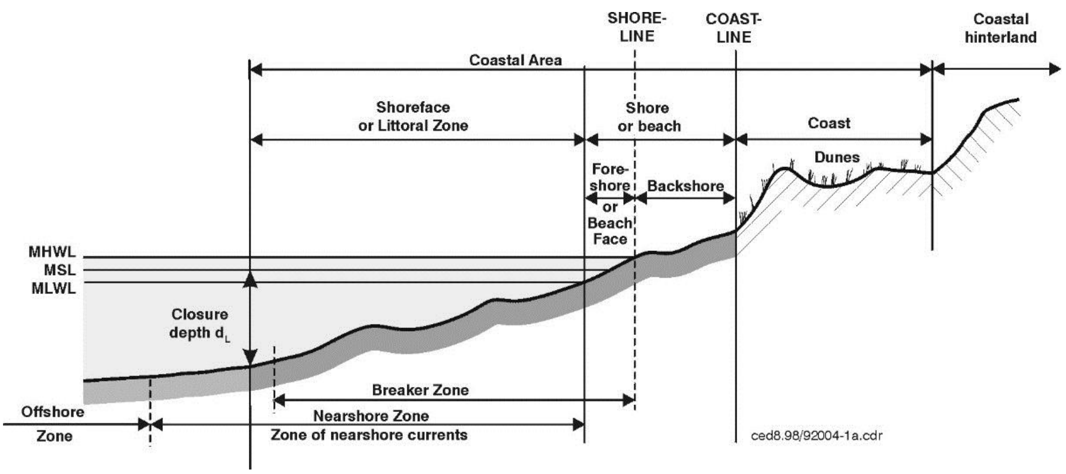


Figure 21.8 The coastal area and morphological zones.

In Figure 21.9, a stormy situation is captured for a coastal area illustrating the wave action over the shore and the shoreface.

Figure 21.9 Waves approach the coast and break on the bars inducing longshore and cross-shore currents. Swash bores reach the open soft sandy cliffs and causes erosion.

The satellite photo in Figure 21.10 also give a good impression of the many different marine forces and processes involved in the hydrodynamics and sediment transport active over the coastal area during a storm.

Figure 21.10 Waves approach the coast at an angle showing depth refraction and wave breaking on two bars.

Longshore currents and littoral transport – as well as undertow and cross-shore transport - are expected to be generated. The system is in general quit regular with ordered features combined with fluctuations deviating from the ideal case.

In order to translate the real physical world to a model world, a number of considerations about the hydrodynamic processes and their impact on mobilisation and resettling of sedimentary material on the coast are needed. An overview of different important processes to consider is given In Table 21.1. The table shows what processes are active in different regions of the profile, and how they are interlinked. This can be used to set up a model that includes the most important or significant processes, and neglect processes that can be considered less important.

Table 21.1 Feed forward and backward for processes and zones including interventions for different morphological zones defined in Figure 21.8.

	Feed Backward	Feed backward				
	Feed Forward	Feed forward				
Feed forward Feed backward	Process Zone	Waves	Currents	Sediment Transport	Morphology	Intervention
	Offshore	Generation Interaction Grouping White capping ...	Tidal currents Wind generated currents ...	Combined wave-current boundary layer	Tidal ridges Sand waves ...	Wind mill farm Breakwater Dredging Mining
Feed backward Feed forward	Shoreface	Shoaling Refraction Groups Breaking Surf Beat Wave-wave ... Storm surges Seasons ...	Longshore Cross-shore 3D circulation Tidal current ...	Bead load Suspended load Longshore Undertow Wave asymmetry Wave groups Grain sorting ...	Mean profile Erosion profile Summer profile Bars/troughs Rip channels Crescentic bars ...	Breakwater Groyne Nourishment Headland ...
	Beach	Swash Run-up Run-down Storm surge ...	...	Cross-shore zig-zag motion Wind ...	Shoreline Undulations Beach profile Berm ...	Breakwater Revetment Headland ...
	Coast	Run-up Overtopping Storm surge ...	Overflow	Dune erosion Vegetation Wind	Cliffs Dunes Erosion 3D breaches Dune build up ...	Dike Revetment Dune foot protection ...
	Hinterland	Overtopping Storm surge ...	Flooding	Flushes	Sediment tongues	

The table shows how the coastal area can be seen in two perspectives, namely

- Process elements
- Spatial distribution of zones

One can use these to get an overview of how one process is affecting another and how one part of the profile is affecting other parts.

We have distinguished between

- Feed forward
- Feed backward
- Morphological changes

Feed forward. In terms of process, one process affects other processes in an explicit way. *In terms of space*, feed forward means how events taking place in the outer parts affects flow, sediment transport and/or morphology in the inner parts, e.g.

Feed backward. In terms of process, feed backward is when a process affects a process that affects back on the first process, i.e. implicit effects. *In terms of space*, we may check if there could be a case where inner parts implicitly affect outer parts, for example in the case of rip current taking sediment from the inner part to the outer, or undertow taking sediment out in the profile.

Morphology is an example of a process that in principle gives rise to a combined feed forward and feed backward process - and always will be an implicit process. For example one may talk of as morphological “self organisation” – when different kinds of bed forms, e.g. rip channels or barred profiles, emerges.

21.3.1.1 Human intervention in processes

In the case of human intervention, the processes can in principle interfere at any level of the system. Similar to the to the process table, Table 21.2 is showing different kinds of interference for different kinds of interventions.

Table 21.2 Human intervention and process classes.

	Feed Backward	← Feed backward			
	Feed Forward	Feed forward →			
Feed forward Feed backward	Process Zone	Waves	Currents	Sediment Transport	Morphology
↑ Feed backward / ↓ Feed forward	Offshore	Wind mill farm Breakwater Dredging Mining	...	Dredging Mining	Dredging Mining
	Shoreface	Breakwater	Groyne	Nourishment Dredging Mining	Nourishment Dredging Mining
	Beach	Breakwater Revetment	...	Nourishment Mining	Revetment
	Coast	Seawall Dike	Seawall	Nourishment Dune foot protection	Dike Revetment
	Hinterland	Dike	Dike	...	...

21.3.1.2 Long term and short term - cross-shore and longshore

Long term processes change the beach's condition over long time, forming the overall condition of the morphology. This overall morphology is modified by variations in the driving forces on a smaller time scale, i.e. "normal" average condition, more or less regularly reoccurring variations (characteristics observed over hours, weeks, months and seasons) and more extreme and/or unusual short term events (unusual or even "unlikely" events). For the coastal area the question of sand availability and grain size distribution are important examples of factors changing over long time, factors that are reflected in the morphology of the local region: E.g. steep profiles in the case of coarse material, or rip current under certain conditions on a beach with plenty of sand, etc. The appearance of the beach and the shape and dynamics of the profile under different weather conditions are hence connected to these factors.

In the context of modelling, the two scales are often separated. As the cross-shore migration of bars and erosion of upper parts of the profile typically are due to short or medium term events and shoreline evolution are due to processes working over longer time, the separation in short and long term is typically reflected in the separation in cross-shore and longshore processes. Hence long term models would typically be dominated by the longshore processes (longshore transport) and short term models often do not model directly the overall sand budget along the shore:

- Long term shoreline models often assume a long term equilibrium profile to be representative for the profile during the shoreline's yearly and decadal evolution. This relates to chronic erosion

- Short term events may take sediment from the inner part of the profile to the outer parts mostly due to the presence of undertow currents around the breaking point (storm/winter profiles), and over longer or medium term periods sediment are in many cases transported onshore due to the net effect from wave orbital motion (summer profile). Model evaluation of short term profile changes are often focused on the erosional period, so-called acute erosion, but could in principle cover situations where both on- and offshore transport dominates.

21.3.1.3 Simplification - Complexity reduction

Models are approximations of reality, and coastal zone models in particular. This is because the coastal zone processes consists of a wide range of scales and the boundary conditions in most cases are approximations to the real situation.

Hydrodynamics space and time scales

- Molecular fluctuations (Brownian motion)
- Near bed turbulence fluctuations
- Wave boundary layer
- Large scale eddies
- Wave breaking flow (plunging, spilling)
- Wave height
- Water depth
- Wave length
- Long bound waves, surf beat
- Surf zone width, longshore current
- Tidal waves
- Seiching and Oceanographic flows

For some processes - like sediment transport - a number of benefits can be obtained by modelling the flow on a rather detailed level, e.g. resolving the distribution of turbulent kinetic energy over the vertical and obtaining bed shear stresses from wave boundary layer models, while other processes like the overall depth averaged flow patterns can be modelled sufficiently accurately without such detailed information.

21.3.1.4 Simplifications and dedicated models

Coastal flow, sediment transport and morphology models are dedicated models meaning that they focus on a given environment and combine the knowledge about the forces and nature of the system with the demand for numerical modelling. Therefore, a number of simplifications are often seen. One example is the approximation of alongshore uniformity, as illustrated in Figure 21.11.

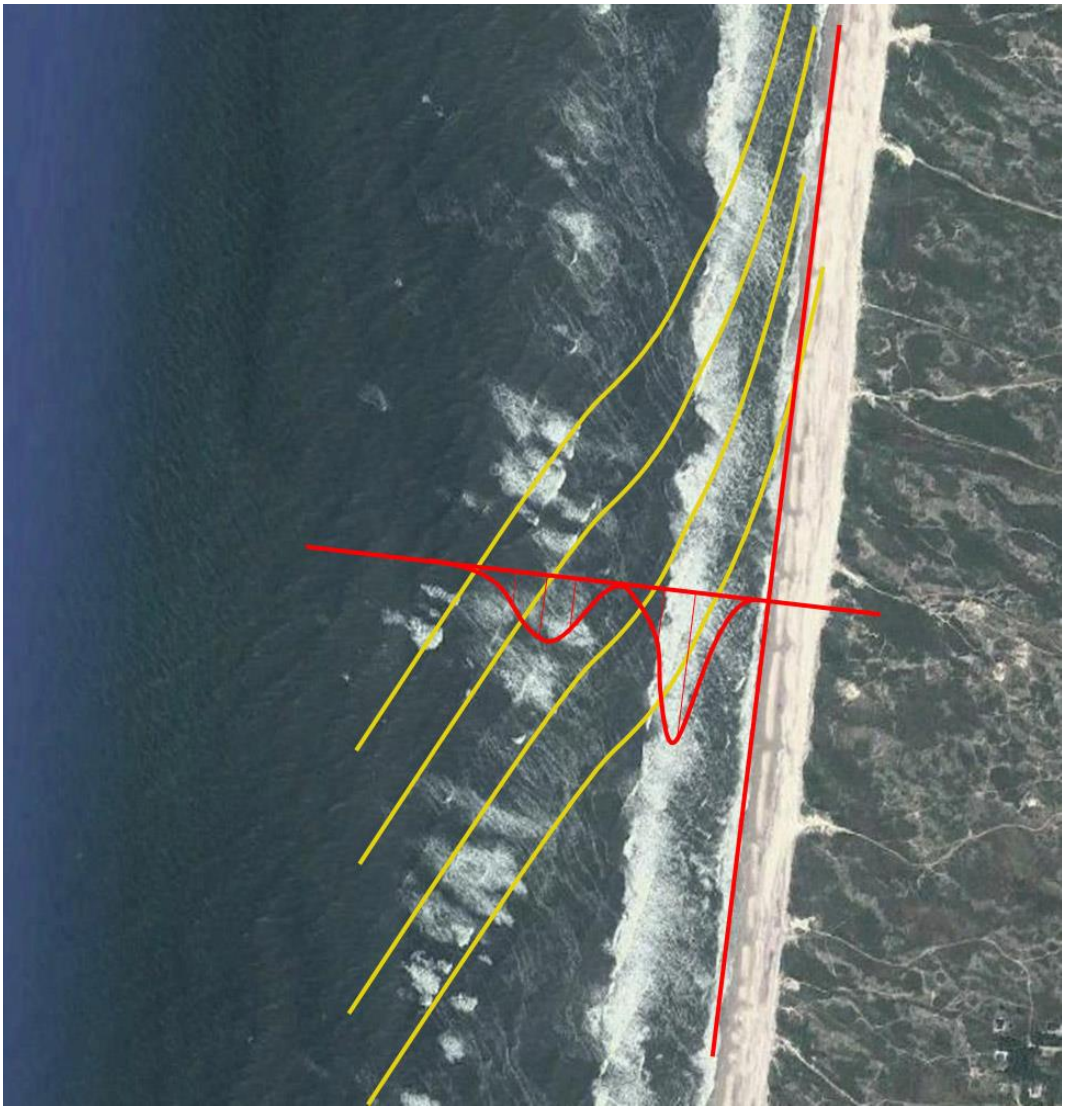


Figure 21.11 Example of simplification of a coastal system into its main physical processes. Stationary situation, wave refraction and wave breaking (yellow). Longshore current and sediment transport (red). Locally alongshore uniform.

21.3.1.5 Models for coastal processes and coastal applications

One may distinguish between the models as being models for coastal processes without having determined the actual problem and models that are dedicated to specific types of problems or phenomena:

Models for coastal processes

- Phase averaged 1D models (alongshore uniformity, resolving the profile)
- Phase averaged 2D area models (includes alongshore non-uniformity)
- Phase averaged 3D models (includes resolving the vertical)
- Phase resolving 1D models (alongshore uniformity, resolving the profile)

- Phase resolving 2D area models (includes alongshore non-uniformity)
- Phase resolving 3D models (includes resolution over the vertical)

Specific "domain applications"

- Shoreline models
- Profile models
- Coastal Flooding modelling
- Climate Change modelling

21.4 Models for coastal processes

21.4.1 Hydrodynamic models

To understand how sediment is mobilised, distributed and redistributed along the coast, a model for the flow in and outside the surf zone is needed. Here a number of choices are available.

In the space domain there are 3 types:

- One-dimensional models (vertical profiles or along a shoreline/channel)
- Two-dimensional models (covering a horizontal area)
- Three-dimensional models

In the time domain two types appear:

- Phase resolving (describing the time variation during a wave period)
- Phase averaged (describing quantities averaged over a wave period and wave parameters such as wave height and - period)

Furthermore, the importance of vertical acceleration in the wave motion shall be considered, i.e. simplification of the complete flow equations to cover the most important flow characteristics only (cf. the concept of engineering models) in this specific region, the coastal area:

- Shallow water assumption (hydrostatic pressure)
- Models including additional or excess pressure "due to" vertical acceleration

The above "categories" can be combined in different ways, to obtain different types of models (resolving different aspects of the flow), for example:

- 2D area (or "2DH") phase averaged wave and current models
- Phase resolving non-hydrostatic wave models (e.g. Boussinesq models)
- Littoral transport model for the sand transport along a shoreline
- Fully 3D phase resolving model (Computational Fluid Dynamics (CFD) models

21.4.2 Phase averaged 2D area models

21.4.2.1 Model concept

Phase averaged 2D area models are based on a decomposition of the temporal variation into a time varying (with periods corresponding to the periods of wind waves) part and a slowly varying (mean current) part. Furthermore the decomposed flow is treated by depth integrating and phase averaging the two parts. This leads to a model with two separate (but interacting) models:

- Wave model describing quantities like wave energy, -height, -period and -direction
- Current (or slowly varying surge waves) model

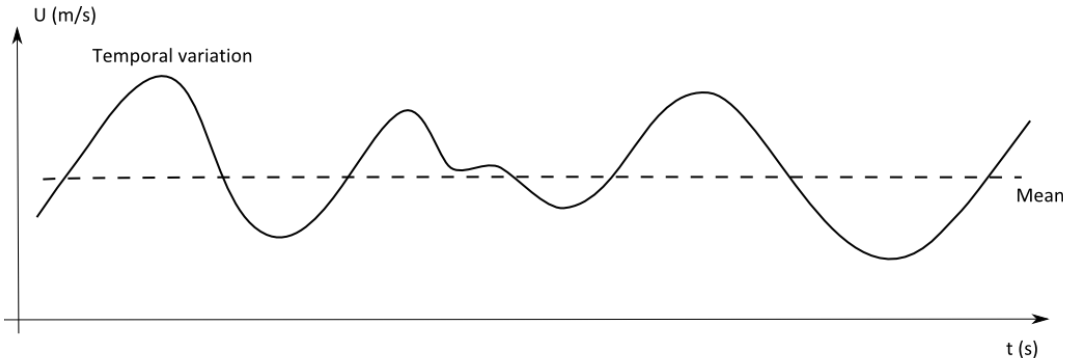


Figure 21.12 The signal is divided into a variation with wind waves periods and a slow or stationary variation (mean).

Using a mathematical expression for this, the total flow $\boldsymbol{U}$ is a sum of a wave component $\widetilde{\boldsymbol{U}}$ and a mean current component $\overline{\boldsymbol{U}}$

$$\boldsymbol{U} = \widetilde{\boldsymbol{U}} + \overline{\boldsymbol{U}}$$

and similar for e.g. the water surface $\eta(x, y, t)$.

21.4.3 Waves

In phase averaged 2D area models, the waves are described as random and irregular by the energy spectrum, which is the distribution of the wave energy as a function of the frequency and wave direction. This means that the irregular waves at a given location are composed by a number of components with different frequency, ω, and direction, θ. The direction of propagation is described by introducing the wave number, k, as a vector: $\overline{\boldsymbol{k}} = (k\sin\theta\,, k\cos\theta) = \left(k_x, k_y\right)$.

This corresponds to a Fourier decomposition of the wavy part of the flow signal, with a number of individual migrating wave components, the surface elevation can thus be expressed as:

$$\tilde{\eta} = \sum \frac{H_i}{2} \sin(k_{xi}x + k_{yi}y - \omega_i t + \phi_i)$$

Index i represent the i'th component of the wave train.

H is the wave height
k_x is the wave number in the x-direction
k_y is the wave number in the y-direction
ω is the angular frequency
ϕ is the phase

The energy of the i'th component can be expressed as $E_i = a_i^2/2 = H_i^2/8$, and the total wave energy at a given location is:

$$E = \sum E_i = \sum H_i^2/8 = H_s^2/16$$

where H_s is the significant wave height.

21.4.3.1 Model equations

The wave field is then described by the equation expressing the budget for the wave energy: the wave energy travels with the group velocity, it is deflected by depth refraction and due to interaction the energy may be transferred from one frequency to another. Actually, when the wave field is also affected by the current (current refraction) the budget is expressed for the quantity called wave action, which is the wave energy divided by the frequency: A = E/ω.

The waves can gain and loose energy in the model domain. The energy source is the action of the wind on the waves and the sink is due to energy dissipation in the wave boundary layer at the bed and dissipation due to wave breaking as white caps or depth induced breaking in the surf zone.

The equation for conservation of wave action:

$$\frac{\partial A}{\partial t} + \frac{\partial c_{gx} A}{\partial x} + \frac{\partial c_{gy} A}{\partial y} + c_\theta \frac{\partial A}{\partial \theta} + c_\omega \frac{\partial A}{\partial \omega} = PROD_A - DISS_A$$

Left hand side

- Term 1 is the temporal change in wave action over time
- Term 2 and 3 is the net flux of wave action into a unit water column
- Term 4 is the transfer of wave action from one direction to another
- Term 5 is the transfer of wave action from one frequency to another

Right hand side

- Term 1 is the production of wave action typically due to wind
- Term 2 is the dissipation of wave action due to wave boundary layer and wave breaking

The spectral formulation of the wave field where the water surface elevation is found by summation of all the components implies linearity and each wave component is propagating as a Stokes first order wave, which is used for the dispersion relation between the wave frequency and the wave number.

Simplified versions of the model are often applied. Current refraction may be neglected. The wave field may be treated as stationary if the domain it not too large and the conditions are determined by the waves coming in at the boundaries from offshore. The frequency spectrum can be represented by a standard spectrum, so that only integrated quantities such as the wave height and the mean frequency are used to characterise the distribution of the energy on the frequencies while the distribution on directions are still resolved in the model.

21.4.3.2 Discretisation and inputs

The wave action is now divided (resolved) into a number of frequencies and directions.

Change in wave action is due to the total effect of

- Energy transfer between frequencies
- Refraction and shoaling
- Dissipation of energy
- Production of energy
- Diffraction

Frequency resolution

The frequency domain can be either resolved or integrated using a parameterisation of the frequency space, i.e. two modes are possible:

- Frequency resolving
- Frequency parameterised

Frequency resolution is needed if we want to model the transfer of energy between frequencies. This could e.g. be due to triad interaction in the shallow area, or because the boundary conditions contain information on wind waves (sea) as well as swell, which have different mean periods and may come from different directions.

Refraction and shoaling

Refraction is modelled as a transfer of energy from one direction to another. The directional space should hence be resolved properly, meaning around 5-10 degrees intervals depending in the application and set-up

Shoaling is inherent in the model.

Dissipation terms

There are two main mechanisms for dissipating wave energy

- Wave breaking
- Wave boundary layer

Wave breaking. When waves reach shallow water they will eventually break and the energy of the wave is dissipated. Wave breaking is one of the key elements in much coastal engineering. It is important to know a little about the wave breaking dissipation models. One of the most used models is probably the Battjes and Jansen model, where three parameters should be given: a coefficient α (about 1), a breaking parameter γ_2 related to depth dependent breaking (about 0.8) and a parameter for breaking due to white capping γ_1 (about 1).

Wave boundary layer. Dissipation in the wave boundary layer is depending on the roughness of the bed, which is the only input parameter needed.

Energy input

Waves are generated by wind, which means that energy (or wave action) is added to the system when wind is present. Different semi-empirical models for wave generation due to wind are typically used here.

For local models with small domains the conditions are controlled by the offshore boundary conditions and wind generation can therefore be neglected.

Diffraction

Approximate methods exist in some models of the present type for describing the effect of diffraction, e.g. around breakwaters.

21.4.3.3 Boundary conditions

In terms of mathematical conditions for the model equations there are three types of boundaries:

- Absorbing boundaries, where all energy of a wave reaching the boundary is taken out
- Reflecting or partially reflecting boundaries, which returns all or a prescribed fraction of the wave energy reaching the boundary. The reflected wave direction is mirrored of the incoming
- Boundaries with prescribed wave parameters, where the properties of waves coming into the model domain are given on the basis of another regional model or measurements

In physical terms the boundaries are divided into closed and open boundaries:

Closed boundaries

Closed boundaries could be Land or Infrastructure:

Land boundaries could be sand beaches, where the bed slope is so gentle that all energy is taken out of the waves due to wave breaking. The beach can be included in the model bathymetry or, if the conditions at the beach is unimportant for the areas of interest it can be represented as an absorbing boundary. Steep rocky shorelines can be represented as reflecting or partially reflecting boundaries.

Infrastructure like rubble mound or vertical breakwaters, groynes, seawalls or embankments are modelled either as fully absorbing boundaries or as reflecting/partially reflecting boundaries.

Open boundaries

Open boundaries can be Offshore, Lateral or On-shore:

At the *off-shore boundary*, the wave conditions are prescribed by the user in time and space along the boundary.

A *lateral boundary* is a special case of the offshore boundary. It is normally used to connect an offshore boundary to the shoreline and will be approximately normal to the shoreline. It is treated as a local alongshore uniform coast such that a 1D wave transformation is used to define wave conditions along the boundary. In this way the boundary does noes not disturb the wave field but correspond to the assumption of an alongshore uniform coastline.

The *on-shore boundary,* which is not land, could be at the lagoon side of an inlet, where the waves are of no interest for the project. It will then be an absorbing boundary.

21.4.3.4 Example: Wave field in an estuary

An example of running a phase averaged wave model for the case of an estuary is shown in Figure 21.13, The Bristol Channel. Wave conditions have been given at the western boundary and the waves have been transformed from the deeper and wider areas into the more and more narrow parts of the system.

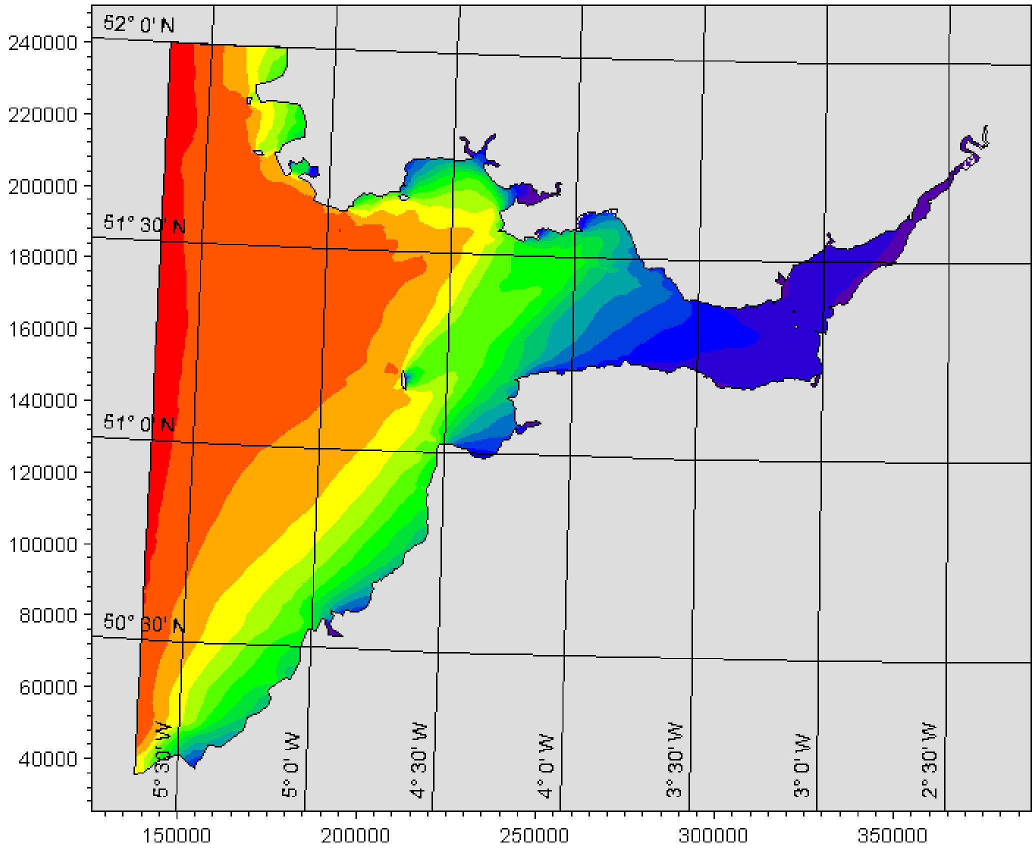


Figure 21.13 Example of waves reaching a coastal area and penetrating an estuary.

21.4.4 Currents and long waves

- The parameters describing the current field in a 2D area model are:
- Depth averaged current in two dimensions: U and V
- Surface elevation: η

The current model is solving Newton's 2nd law for the conservation of the wave averaged, depth integrated momentum, i.e. *acceleration times mass equals the sum of forces*, combined with an equation for *mass conservation*.

The forces are

- Pressure forces
- Bed shear stress
- Wind shear stresses
- Lateral shear stresses
- Wave forces due to wave energy dissipation – e.g. inside the surf zone

The effect of wave forces will be treated later.

Furthermore, for a fluid flow the acceleration has two contributions. The water column can accelerate temporally and spatially. The temporal acceleration can be measured at a fixed point as changes of velocity of the water inside a given control volume with time. The spatial acceleration is acceleration due to contraction of streamlines which - due to conservation of mass - for a fluid element traveling from one location to another increases (or decreases) its velocity. In a fixed frame of reference this gives the terms for:

- Temporal acceleration (at a given point in space)
- Spatial or convective acceleration (at a given point in time)

Model equations

Conservation of momentum in the x- and the y direction:

$$D\frac{\partial U}{\partial t} + DU\frac{\partial U}{\partial x} + DV\frac{\partial U}{\partial y} + gD\frac{\partial \eta}{\partial x} + \frac{\tau_{b,x}}{\rho} - \frac{\tau_{s,x}}{\rho} + F_x = 0$$

$$D\frac{\partial V}{\partial t} + DU\frac{\partial V}{\partial x} + DV\frac{\partial V}{\partial y} + gD\frac{\partial \eta}{\partial y} + \frac{\tau_{b,y}}{\rho} - \frac{\tau_{s,y}}{\rho} + F_y = 0$$

- Term 1 is temporal acceleration (for a given location in space)
- Terms 2 and 3 are convective or spatial acceleration (for a given point in time)
- Term 4 is the pressure force due to the surface slope
- Term 5 is the bed friction force
- Term 6 is the surface shear force
- Term 7 represents other forces (not in focus here)

Conservation of mass (or volume):

$$\frac{\partial \eta}{\partial t} + \frac{\partial DU}{\partial x} + \frac{\partial DV}{\partial y} = 0$$

- Term 1 is the accumulation term (surface elevation change per time)
- Terms 2 and 3 are gradients of fluxes (flux in minus flux out)

21.4.4.1 Discretisation

Different types of numerical strategies can be found in different models available on the market (commercial and free codes). Some models use rectangular or semi-orthogonal meshes and use semi-implicit solvers. Other models use finite volume methods on arbitrary shaped cells for flexible meshing. The user should be familiar at least with the basic principles behind the model applied as this will help to understand how to work with and interpret the model results.

The description of the numerical aspects in the introductory sections also holds for the present model type.

21.4.4.2 Boundary conditions

As already discussed the quality of the boundary conditions are of utmost importance for the quality of the modelled current fields.

Types

A number of different types of boundary condition can be imposed on the model

- Water level
- Mass Inflow
- Mass Outflow
- Closed – zero cross-velocity
- Zero velocity

Closed boundaries

The closed boundaries are:

- Bathymetry
- Structures or (rocky) coasts

Open boundaries

The open boundaries are

- Off-shore
- Lateral
- On-shore (flood and dry at land)

At the *offshore boundary* the water should be able to pass in and out of domain. If not the global mass conservation may be forced in an unrealistic way by the conditions at the lateral boundaries. If one chose to close the off-shore boundary, a test should be performed to justify that the lateral boundaries can compensate for – or ”absorb” - this approximation without disturbing the flow in the domain.

As *lateral boundary* conditions one may use flux or surface elevation conditions. In special cases with great symmetry, one may consider to use periodic conditions if the problem is suited for this special condition.

At the *on-shore boundary* the transition from wet cells to dry cells – which in the general case will be changing over time - are often taken care of by special models such as flood and dry- models or slot technique models where the flow is confined to very narrow channels when the water surface is lower than the bed.

Dynamic boundary conditions

There are a number of boundary conditions that are not kinematic but dynamic, e.g. the surface boundary conditions applied for wind stress.

21.4.4.3 Sub grid models

A number of possible optional sub grid models may be applied in some model complexes

- Source and sinks introducing mass and momentum in a grid point
- Drag losses (due to structures)
- Line structures (lines representing culverts, breakwaters, …)

21.4.4.4 EXAMPLE: Current through The Sound

A 2D HD model was set up for The Sound, the waters between Denmark and Sweden, and thoroughly calibrated against measurements. In the figures below a comparison between modelled and measured current speeds, directions and surface elevations are seen. The flow in this region is known to be quit complex and stratified, still the 2D model is seen to capture the flow features very well.

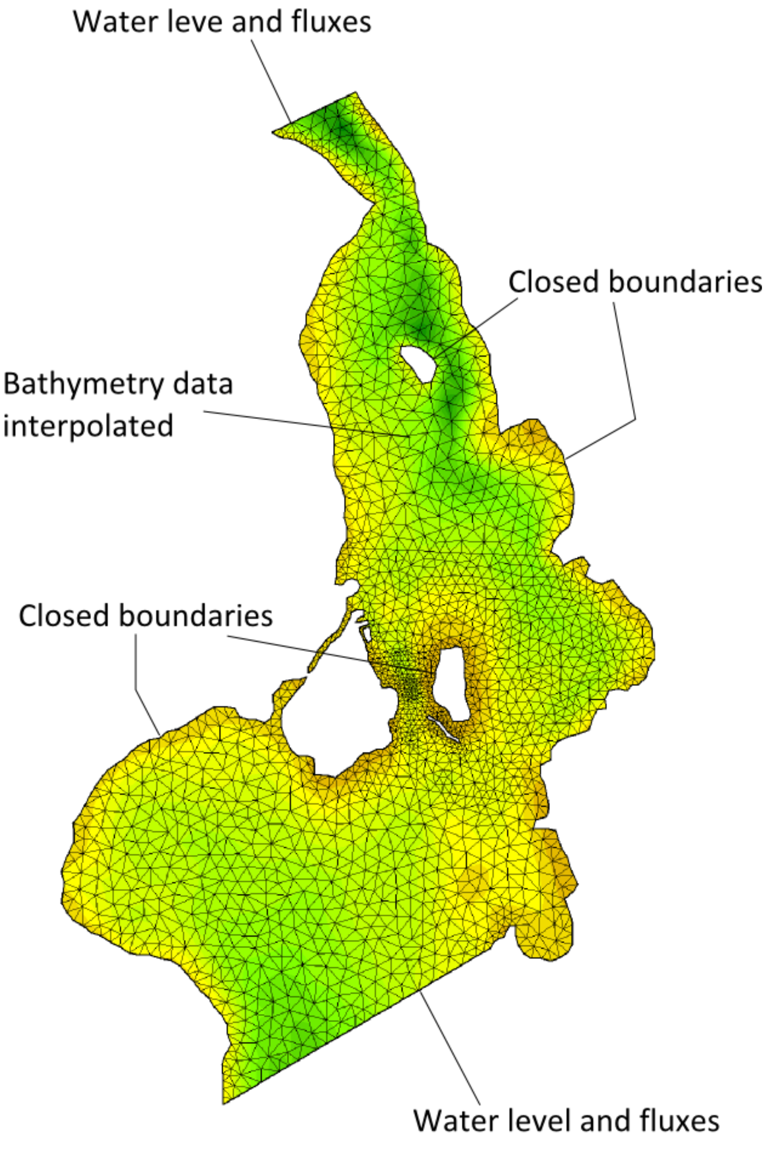


Figure 21.14 Boundary conditions for flow model.

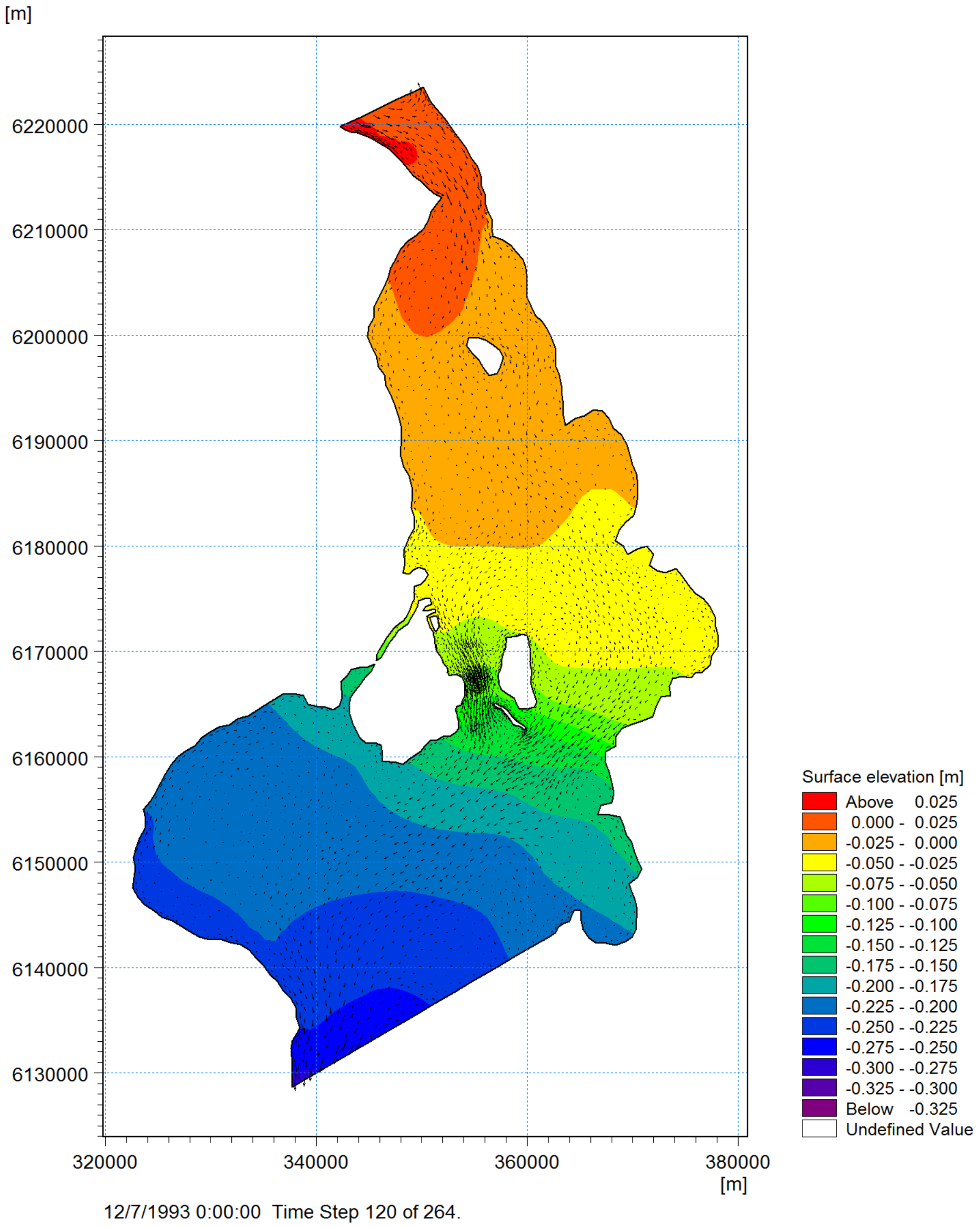


Figure 21.15 Example of surface elevations and depth averaged flow field during the simulation.

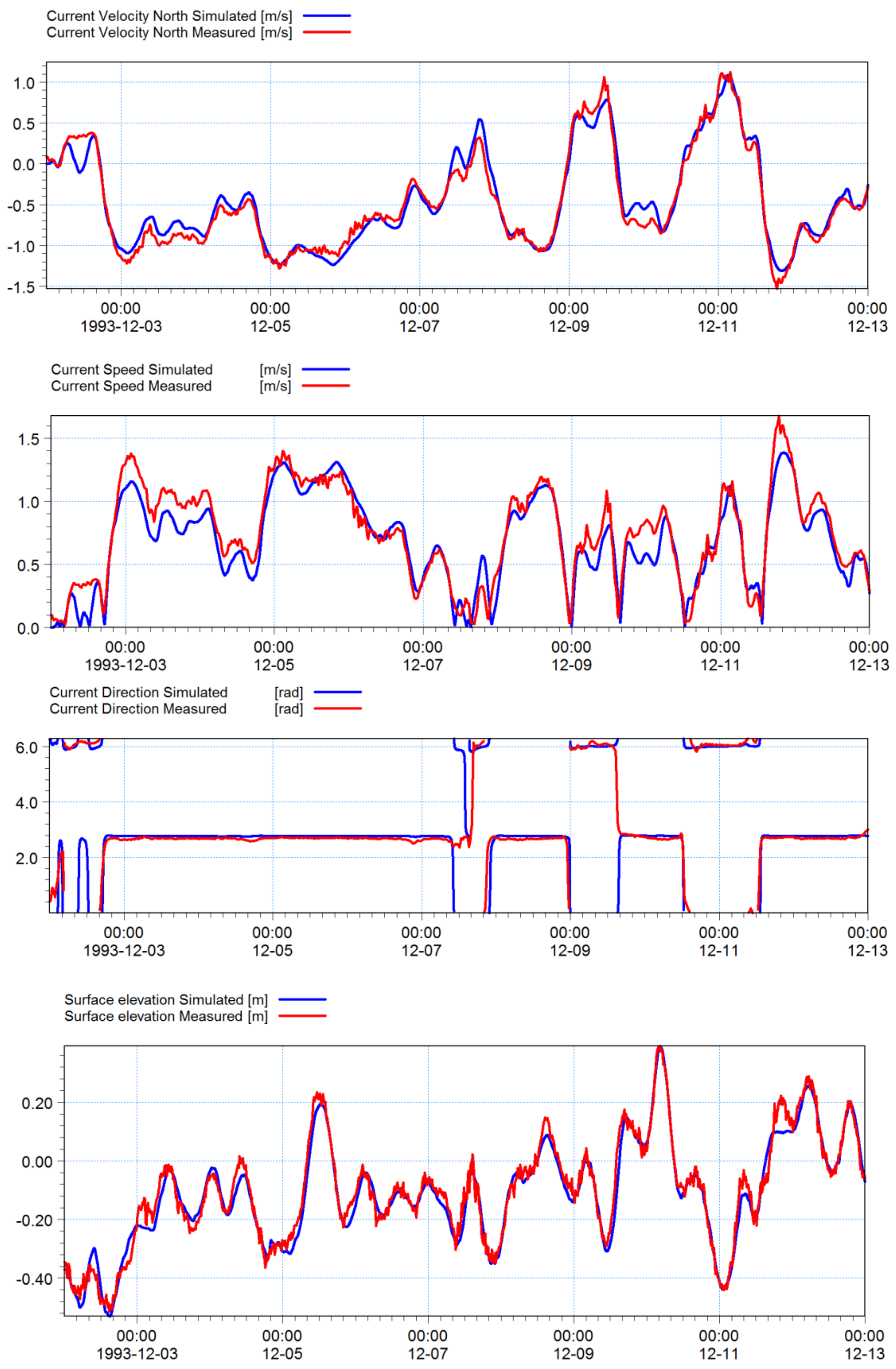


Figure 21.16 Calibration of model for flow through the area with most flow contraction.

21.4.4.5 Example: Current around the Port of Hanstholm

An example of 2D area hydrodynamics around the breakwaters of the Port of Hanstholm is given below, where a calculation has been carried out for the current that passes the port breakwaters. The current is driven by tides, wind and waves in the area. The calculation is compared to measured currents. The model is seen to reproduce all the right features found in the measurement, i.e. streamline contraction and recirculation current in the diverging part of the flow behind the port.

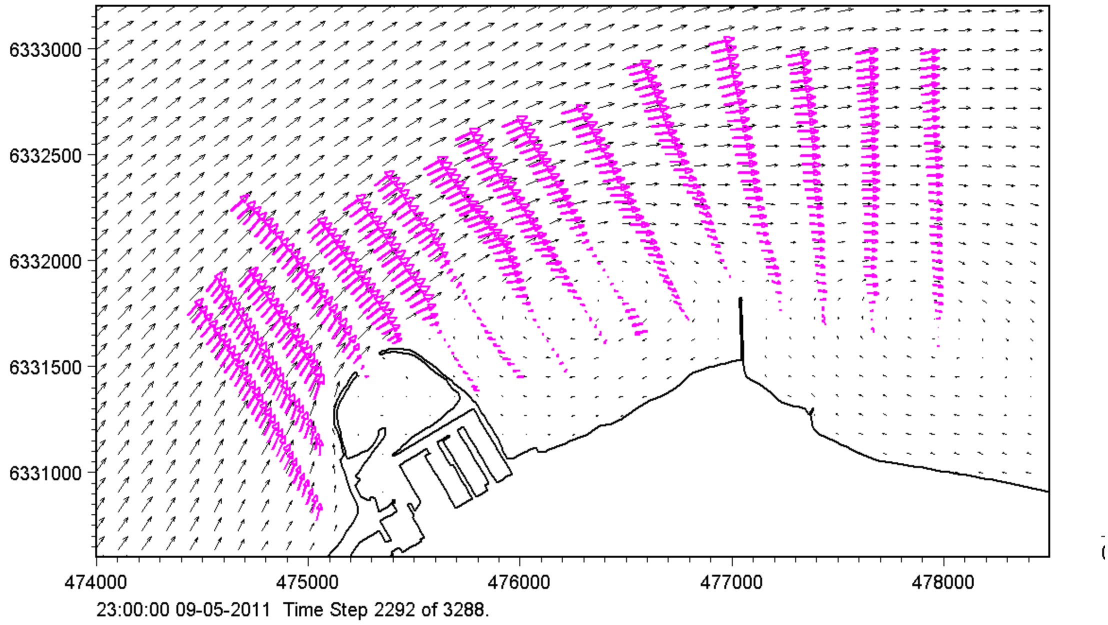


Figure 21.17 Validation of MIKE 21 FM HD model in the case of a northward current along the coast passing a harbour. The magenta arrows are ADCP measurements of the depth averaged current and the dark arrows are the modelled current.

21.4.5 Coupling between waves and currents

The surface waves give rise to an additional phase averaged horizontal momentum flux, both in the direction of propagation and normal to it, known as the radiation stress tensor. Gradients in the radiation stresses arise in the case of wave dissipation due to wave breaking. Because gradients in radiation stresses act as driving forces on the water column a flow can be generated. This is the main mechanism behind most of the currents seen in the surf zone:

- Longshore currents
- Cross-shore undertow currents (2DV circulation currents directed offshore near the bed)
- Circulation currents over non-uniform bathymetries (2DH)

To model these phenomena a coupling between the wave model and the current model is needed.

The main coupling is from the wave to the current model through the radiation stresses (gradients).

Furthermore, there is a coupling from wave to current namely:

- An increased bed friction due to the turbulent interaction between the current and the wave boundary layer

In many cases a plausible modelling approach will be omitting the bed friction coupling but compensating for this by adjusting the bed roughness to a value in the right order of magnitude.

Process couplings from the current model to the wave model do also exist:

- Surface elevation
- Wave-current refraction

The effect of surface elevation is important in the case of tide and storm surge. The additional effect of wave set-up (and set-down) may in some cases be omitted, depending on the application.

Omitting the effect of wave-current refraction will in most cases be acceptable, except for example for a tidal inlet.

If these approximations are not plausible in the given application one of course needs to include the full set of couplings, but it is in practice a rare situation. It can be done, but the couplings make the modelling more computational demanding, more difficult to operate and less robust (possibility for instabilities).

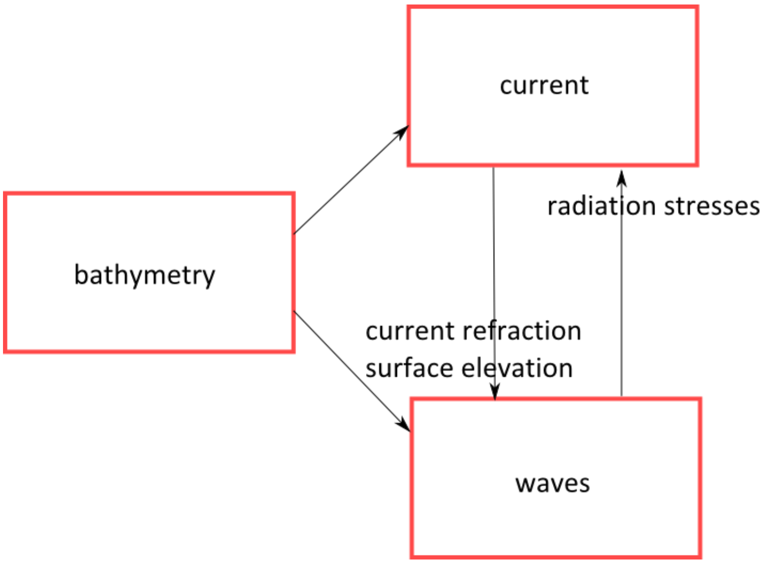


Figure 21.18 Coupling between current and wave models.

Another example of where the wave-current model coupling is important is in cases where one wants to simulate bound long waves due to travelling wave groups. Approximate methods may be applied, explicitly attempting to take into account the variations in the short wave field at the boundary. The state of the art of such approximate wave group simulation is however a little questionable. In most practical cases these effects are omitted.

21.4.5.1 Example: Wave driven longshore current

One of the most generic examples in coastal zone hydrodynamics is the case of a uniform wave field propagating from deep waters towards the coastline over an alongshore uniform bathymetry with a linear profile. The waves approach the coast at an angle and in the surf zone the alongshore radiation stress gradient $(\partial S_{xy}/\partial x)$ drives a longshore current as seen in Figure 21.19. The modelled wave field is shown in the top panel, where the change in direction due to depth refraction and the decrease in wave height in the surf zone are seen. Below the flow field and mean surface elevation is shown. It is seen how the breaking waves pile up the water near the shoreline, the so-called wave set-up, which is caused by the cross-shore radiation stress gradient $(\partial S_{xx}/\partial x)$.

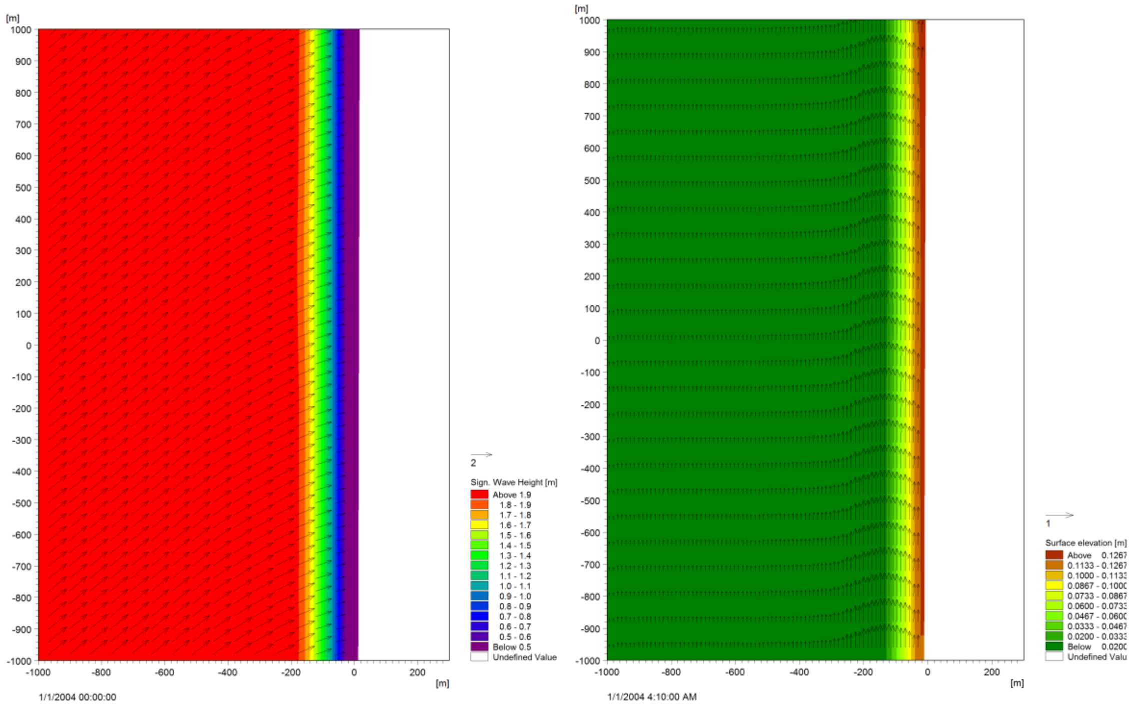


Figure 21.19 Waves and longshore currents on a linear coastal profile. Upper: Wave directions and heights. Lower: Longshore current and wave set-up generated by wave shoaling, refracting and breaking.

21.4.5.2 Example: Wave driven circulation current on barred beach for perpendicular wave approach

Normal wave incidence (perpendicular wave approach) on a barred beach in presented in Figure 21.20. There is a gap, a so-called rip channel, in the bar. It is seen how the wave breaking causes a strong gradient in the wave height over the bar, while the wave height varies more gradually in the gap. This causes a strong on-shore directed force $(\partial S_{xx}/\partial x)$ over the bar, which drives a flow over the bar and into the trough resulting in a strong offshore directed flow out through the rip channel. At the shoreline the flow pattern is reversed, the higher waves passing through the rip channel causes a higher wave set-up than the smaller waves behind the bar and the gradient in the water level along the shoreline due to the wave setup drives a flow away from the stretch inshore of the rip channel.

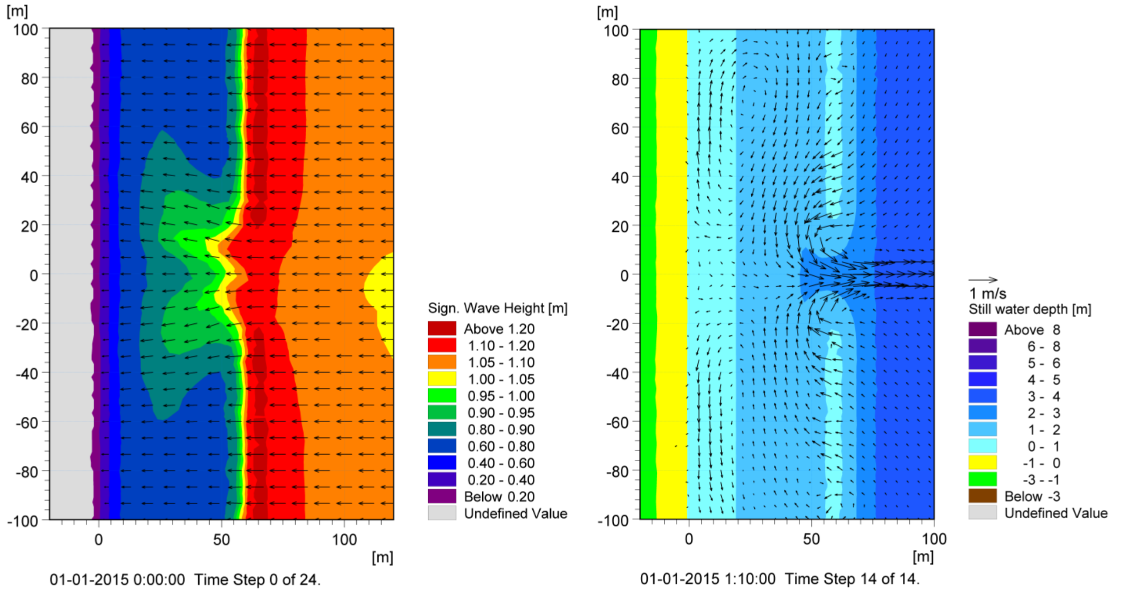


Figure 21.20 Rip current on barred beach for normal wave incidence: Current superimposed on bathymetry (right) and wave pattern (left) over bar with rip channel.

21.4.5.3 Example: Wave driven circulation current behind breakwater

The example shown in Figure 21.21 is in several ways similar to the previous. Here the breakwater creates a lee zone. The wave set-up at each side of the breakwater forces the water to flow in behind it creating two circulation cells.

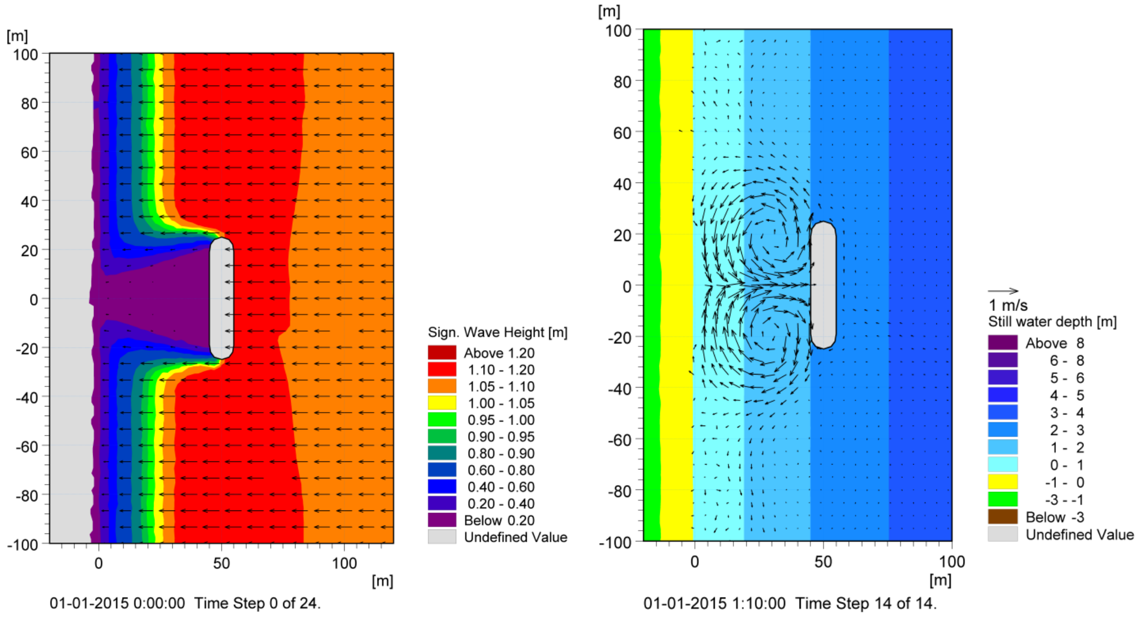


Figure 21.21 Wave generated circulation behind breakwater for normal wave approach: Current (right) and wave (left) patterns around breakwater.

21.4.5.4 Example: Wave driven flow passing harbour mouth

This example is a real case with a harbour on an open coast. The oblique waves drive a longshore current. It is seen in the lower panel of Figure 21.22 that there is a longshore current along the shoreline and along a longshore bar, the latter being strongest.

The harbour blocks the nearshore flow and forces the two longshore components to merge. The combined flow and the flow contraction in front of the harbour mouth gives and increased flow velocity in front of the entrance.

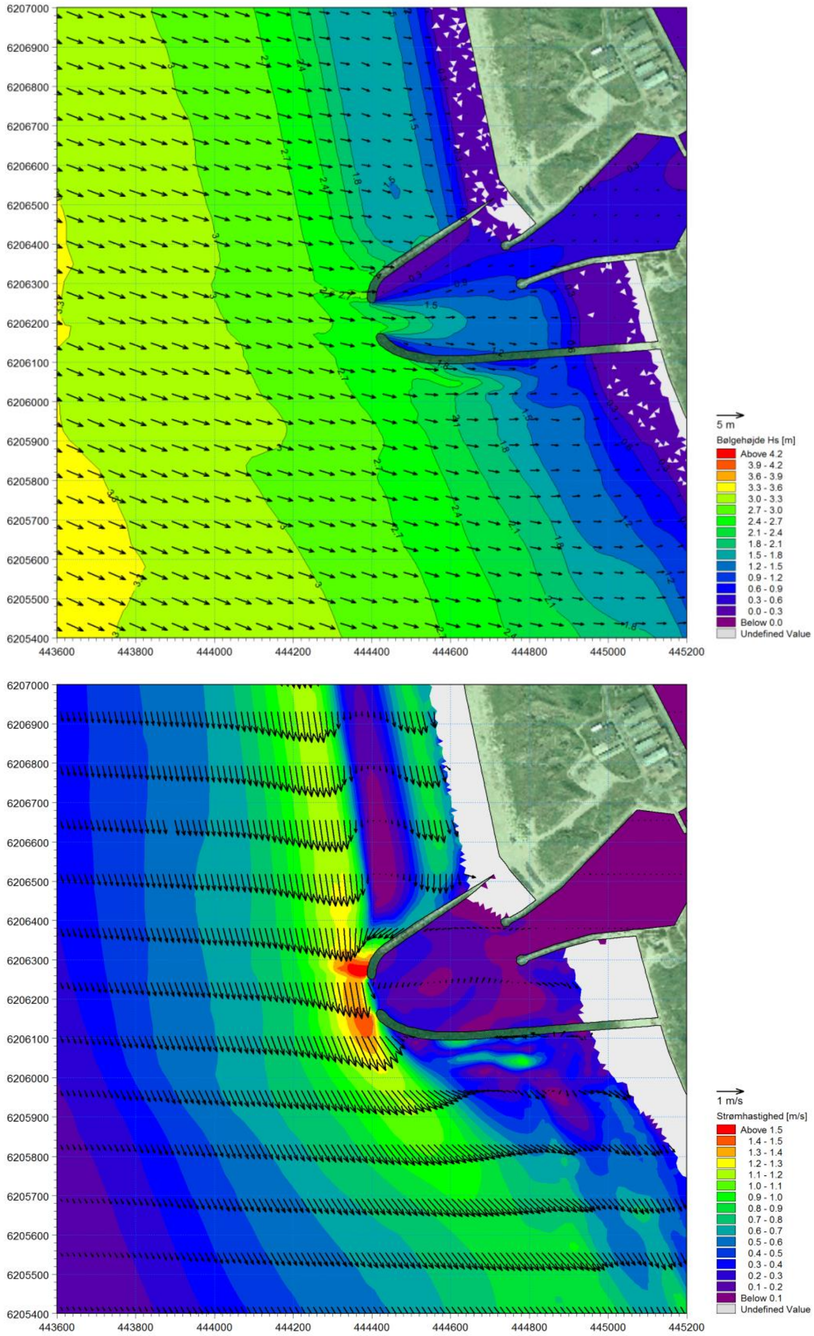


Figure 21.22 Waves and wave generated currents at harbour. Top figure: Wave pattern around the harbour. Bottom figure: Longshore currents passing the harbour.

21.4.6 Sediment transport models

For sandy coasts it is of obviously important to have a reliable model for how much sediment is mobilised due to the action of waves and currents on the sea bed. There are, however, a number of different approaches to sediment transport modelling, and one of the main tasks for the coastal engineer is to distinguish between the different types and their characteristics.

- Purely empirical models
- Energetics based models
- Deterministic models

In space and time there are two principal types to consider:

- Point models: Local sediment transport at a given point
- Area models: Advection and dispersion of suspended sediment over the area

The vertical distribution of sediment transport for sand grains (and grains with a larger diameter than sand) is normally concentrated very close to the seabed. Therefore only a smaller fraction of the total transport may be suspended high enough in the water column to give significant advection and dispersion effects. Usually the length scale for such advection effects for sand transport is much smaller than the grid sizes usually used in the surf zone. Only in the case of very strong gradients - navigation channels for example - such effects become important.

In the following we will give a description of the deterministic approach, which is based on a description of the basic processes for sediment mobilisation and transport. The following gives a brief description of how fundamental processes are modelled “inside” such a model type in order to obtain the sediment transport rates.

21.4.7 Sediment transport processes modelling

Sediment is moved by the near bed flow. The near bed flow may be understood as a mean flow combined with energetic turbulent eddies. Turbulence is generated in the water column by internal friction due to the shear of the flow, and in particular near the bed where the velocity gradient and the shear stress are largest and the sediment grains acts as roughness elements on the flow.

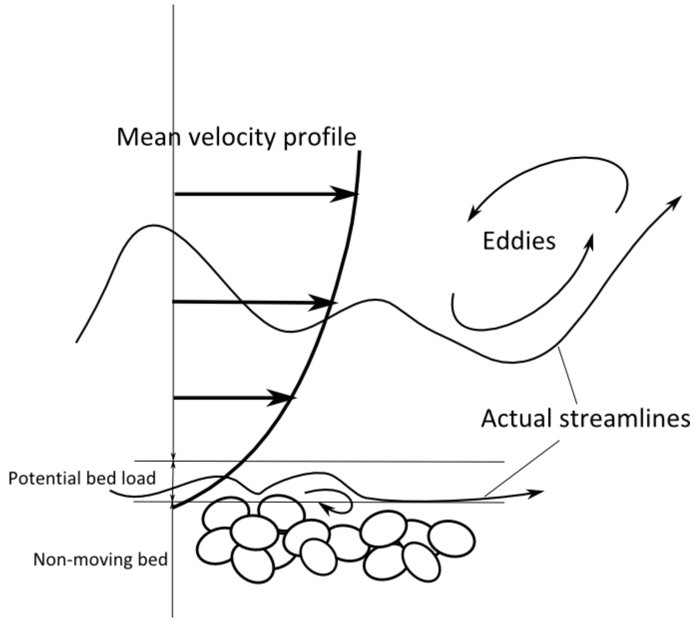


Figure 21.23 Flow near bed. Mean velocity profile and details in near bed streamline curvature and eddies.

In this chapter we will give a sketch of the processes governing sediment transport dynamics in the coastal area.

21.4.7.1 Transport Modes

First of all there are three basic transport modes as described in the following.

Bed load

The bed load consists of particles, which move in almost continuous contact with the bed sliding and rolling over the particles lying in the bed.

Sheet flow

Sheet flow is often considered as a form of bed load. It occurs at high transport rates and consists of particle moving close to the bed but in a layer, which is thicker than one grain diameter. It is characteristic for sheet flow as well as for bed load that the weight of the particles in transport is transferred to the grains in the bed through collisions and is carried as part of the effective stress in the grain skeleton in the bed.

Suspended load

Particles in the suspended load move away from the bed kept in suspension by the vertical turbulent fluctuations of the flow. The weight of the sediment in suspension is thus carried by the fluid and can be felt as part of the pressure in the pore water in the bed.

It should be noted that the different transport modes are interchangeable in the sense that a particle change from one mode of transport to another or the particle is deposited in the bed or eroded from it. As an example a particle lying in the bed can be entrained in the bed load or even the suspended load and a suspended particle can be deposited in the bed or settle and continue as a bed load particle

Transport of non-cohesive sediments (sand)

We will here only consider transport of non-cohesive sediments such as coarse silt, sand and coarse sand. This is a reasonable assumption for an open coast subject to wave exposure, as fine sediments cannot settle in the littoral zone. Consequently, fine sediments are normally not of significance in the nearshore morphology. However, it is important to notice that there may be a high transport of suspended fine sediments along an exposed sandy coast but whereas the fine sediments are not important for the nearshore morphology the presence of fine suspended sediments may cause siltation in e.g. a navigation channel or in a harbour basin, even at a coast characterised by at sandy beach.

The transport loads in association with transport of non-cohesive sediments will in most cases be a combination of bed load and suspended load, cf. Figure 21.24.

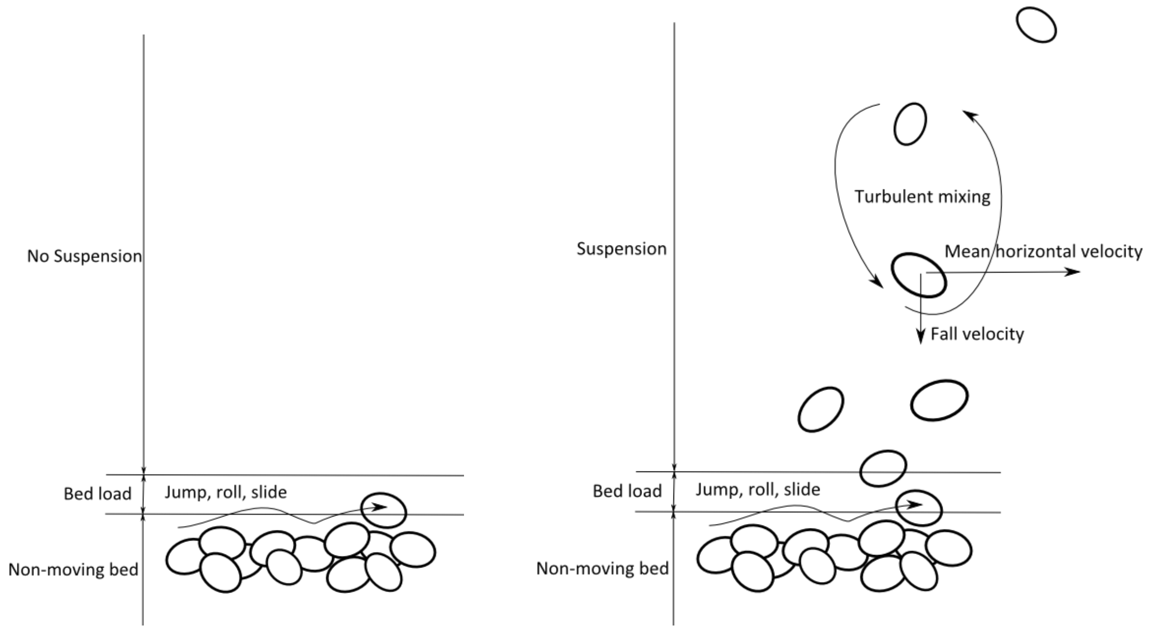


Figure 21.24 Transport modes for non-cohesive sediments. Left: Bed load in layer close to the bed. Right: Bed load and suspended load.

Two non-dimensional parameters govern the transition between a) non-moving bed, b) bed load and c) suspended load.

The Shields parameter:

$$\theta = \frac{\tau_b}{(s-1)\rho g d} = \frac{U_f^2}{(s-1)gd}$$

Where τb is the bed shear stress, U_f is the shear velocity ($U_f = \sqrt{\tau_{b/\rho}}$), ρ is the density of the water, s is the relative sediment density (typically $s = 2.65$) and d is the grain size. The Shields parameter is a measure of the relative strength of the agitating forces of a grain in the bed (the bed shear stress) and the stabilising force (the submerged weight). The sediment transport is initiated when θ exceeds a critical value, typically $\theta_c = 0.05$.

The Rouse parameter:

$$B = \frac{w_s}{0.4U_f}$$

Where w_s is the settling velocity of the sediment grain. The Rouse parameter is a measure of the relative strength of the vertical turbulent velocity fluctuations which are active in suspending a sediment particle, characterised by U_f, and the settling, which counteracts the suspension. The parameter B is important for describing the concentration profile of the suspended sediment. The smaller the value of B the more evenly the suspended sediment is distributed over the wave column. The criterion $w_s < U_f$ $(or\ B < 2.5)$ is often used to determine whether suspended transport can occur.

21.4.7.2 Grain size distribution

The sediments in the bed consist of a variety of different grain types and sizes. Sieve analysis of the sedimentary material will reveal the distribution of the different grain sizes. The distribution can in many cases be approximated by a log-normal distribution. This means that two measures are often enough to describe the sediment – a median diameter and a measure of the variance.

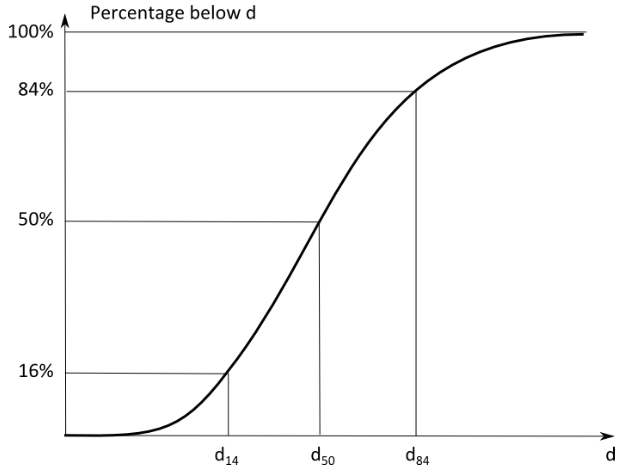
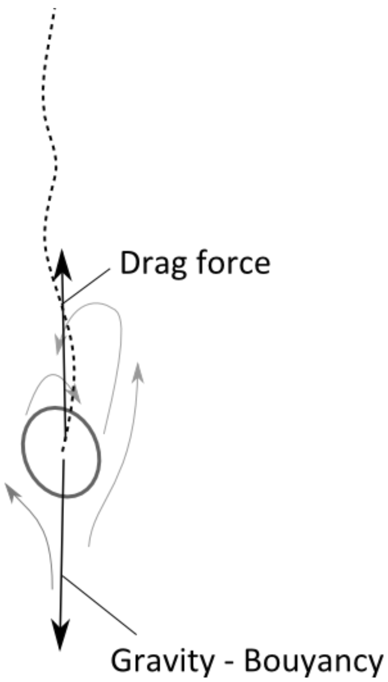


Figure 21.25 Log-normal distribution of sediment sizes.

- Median diameter d_{50}
- Grading coefficient or geometric standard deviation: $\sqrt{d_{84}/\, d_{16}}$

21.4.7.3 Fall velocity

When a sediment particle is suspended in water and is subject to gravity, a balance between gravitational forces minus the buoyancy force on the particle, and the drag force - arising because the particle is moving in water - will almost instantaneously arise. This also means that a given grain with a given diameter and a given relative density will have a given fall velocity. In the table in a number of different values of the fall velocity are given for a number of different grain diameters. Notice also how the temperature influences the fall velocity due to its relation to the water viscosity. The table describes the properties of typical natural sand grains. Different measures of the grain size are given. The quantity d_s is the grain size found in a sieve analysis, d_v is the diameter of a sphere with the same volume as the particle and d_f is the diameter of a sphere with the same settling velocity.



d_s mm	d_v mm	d_f mm	w_s(10°C) m/s	w_s(20°C) m/s
0.089	0.10	0.10	0.005	0.008
0.126	0.14	0.14	0.010	0.013
0.147	0.17	0.16	0.013	0.016
0.208	0.22	0.22	0.023	0.028
0.25	0.25	0.25	0.028	0.033
0.29	0.30	0.29	0.033	0.039
0.42	0.46	0.40	0.050	0.058
0.59	0.64	0.55	0.077	0.084
0.76	0.80	0.70	0.10	0.11
1.25	1.4	1.0	0.15	0.16
1.8	1.9	1.2	0.17	0.17

Figure 21.26 Sediment grain fall velocity w_s in water as function of sediment sieve grain size d_s for temperatures 10˚ and 20˚C, respectively.

21.4.7.4 Suspended sediment

The grains at the surface of a sediment bed is put into suspension through the action of bed shear stresses (and small scale turbulence) loosening the grains at the bed, and turbulence dispersing the loosened material up in the water column. At the same time the suspended material will fall through the water while being mixed.

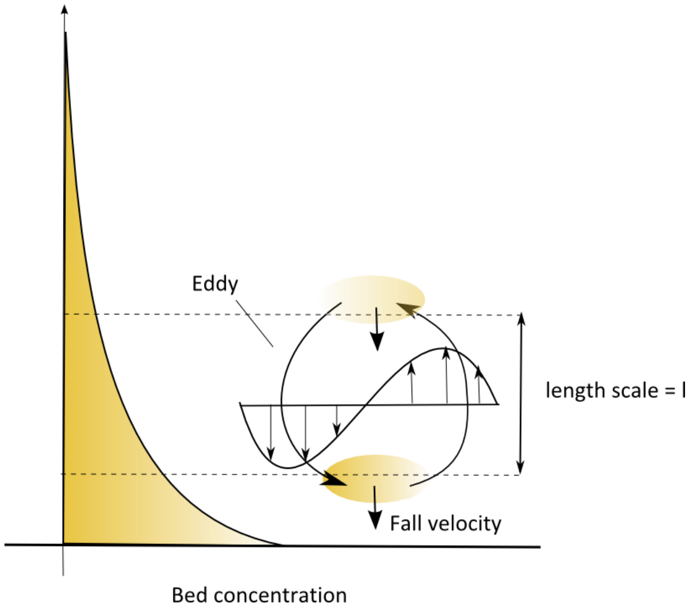


Figure 21.27 Suspended material profile – turbulent dispersion and fall velocity of grains.

Hence there are three physical effects that a process based model for this phenomenon should include

- Shear stress and how the material is made available for the suspension process
- Turbulence to mix the material
- Sediment fall velocities

In the case of empirical or semi-empirical models these processes should still be represented - more or less indirectly.

21.4.7.5 Near bed concentration

The near bed concentration is the concentration of bed material that is available for the suspension process, and is a function of the shields parameter.

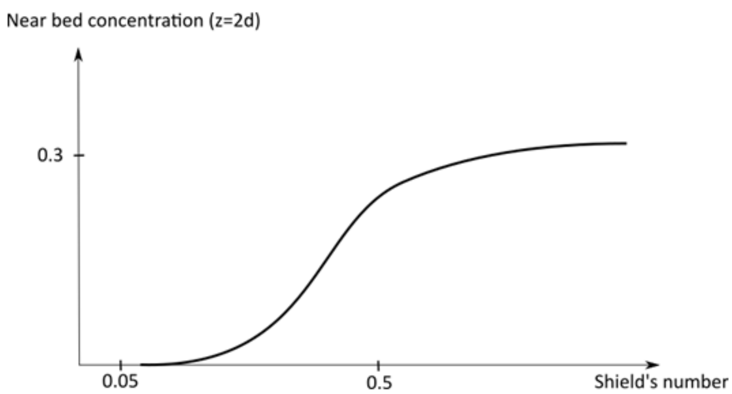


Figure 21.28 Concentration of sediment near bed available for suspension.

A number of models exist for the near bed concentration:

- Einstein
- Fredsøe-Engelund
- Zyserman-Fredsøe

They all have the same approximate shape, and have only some "minor" quantitative differences. It is important to notice that suspended sediment moves practically all the way down to the bed and that the bed boundary condition should be prescribed at a distance of a few grain diameters from the bed.

21.4.7.6 Bed shear stress and turbulence

We may think of a number of cases where flow phenomena are generating turbulence and bed shear stresses for supporting sediment suspension.

- Pure current
- Pure wave
- Pure wave with breaking
- Wave and current (with and without wave breaking)

In the case of pure current, turbulence is generated by shear in the flow and shear stresses. This may suspend and mix the available sediments (if the current is strong enough). Calculating/modelling suspension in the pure current case is relatively straightforward and will in the case of total equilibrium end up with the so-called Vanoni concentration profile for the suspended sediment.

In the case of waves, turbulence is generated near the bed in the thin wave boundary layer, where the sediment suspension thus happens. To obtain values for the time varying turbulence and bed shear stress under a wave (to estimate the sediment suspension), models for the wave boundary layer are needed. Such models can be either very simple models based on empirical relationships or more advance models that resolve the flow under the wave in time and space.

In the case of breaking waves, turbulence generated in the surface roller should be included to obtain the effect of turbulence dispersing down the water column to the near bed flow and enhancing the sediment suspension here.

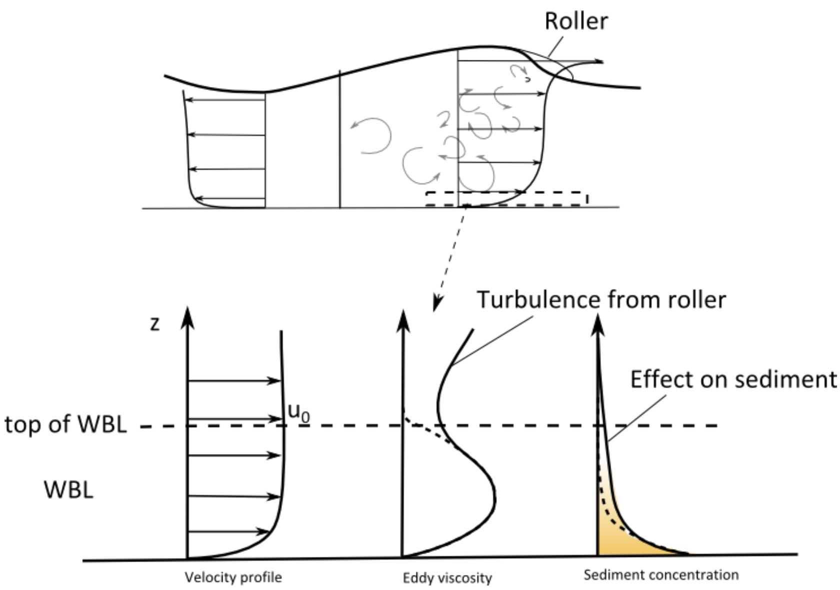


Figure 21.29 Suspension of sediments in the surf zone. Wave boundary layer and wave breaking.

In the case of coexistence of waves and a mean current, a contribution to the turbulence from the current will enhance the suspension compared to the pure wave case (and vice versa). The interaction of the turbulence generated in the wave boundary layer and the turbulence generated by the current will increase the flow resistance for the current and in turn increase the turbulence and the sediment concentrations.

21.4.7.7 Example – a deterministic model for suspended sediment

Following the principles of boundary layer modelling, one can formulate a 1D vertical model for suspended material that take into account the effects just described. Mean concentration results from such a model type is presented in Figure 21.30, where the effects of adding different turbulence sources to the water column has been tested.

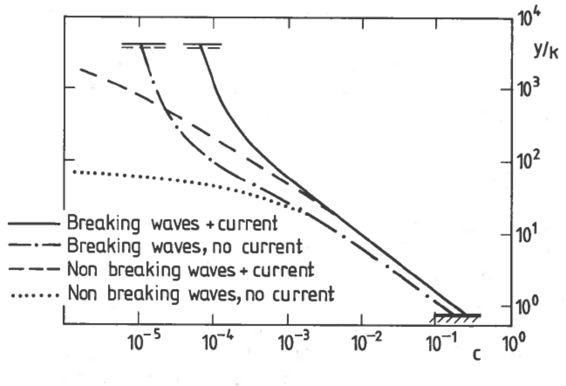


Figure 21.30 Mean sediment concentration over depth calculated versus measured concentration. Effect of breaking waves is calculated by a deterministic approach.

21.4.7.8 Suspended sediment transport

To obtain the total transport due to advection of the suspended sediment the model needs the following parameters:

- Suspended sediment concentration
- Flow field

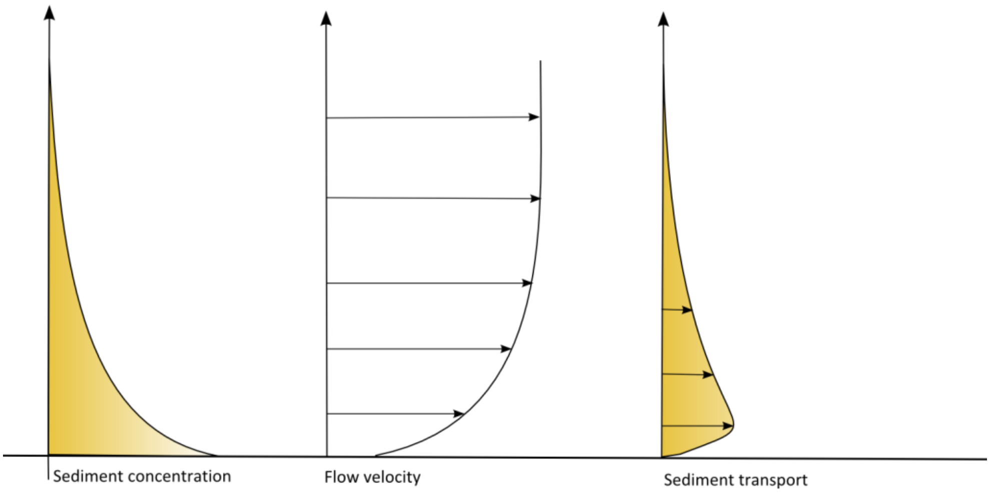


Figure 21.31 Suspended sediment transport.

Both are available following the deterministic approach described in the previous chapters, and obtaining the resulting suspended sediment transport is straightforward.

Only currents

In the case of having only a current the sediment transport is found by integrating the product of the velocity and the concentration over the vertical:

$$q = \int_b^D cu\,dz$$

Where the lower limit, b, is the level where the bed sediment concentration is determined.

Waves

When waves are (also) present, the sediment concentration and the velocity will vary over the wave period, hence the wave averaged sediment transport is found from

$$q = \frac{1}{T}\int_t^{t+T}\left(\int_b^D cu\,dz\right) dt$$

21.4.7.9 Sediment transport in the surf zone

The transport mechanism of currents in the surf zone is related to the combined effect of two contributions:

- Longshore currents
- Cross-shore currents

21.4.7.10 Net wave effects

A number of wave effects are present both inside and outside the surf zone.

- Streaming in the wave boundary layer
- Waves with skewness
- Irregular wave train

These effects are typically small compared to the current contributions inside the surf zone, but are essential for understanding and modelling the transport outside the surf zone.

21.4.7.11 Longshore current and breaking waves

The canonical example in coastal sediment transport is the case of a longshore current generated by breaking waves approaching the surf zone with an angle to the shore normal. In this case, sediment experiences a combination of breaking waves, and a longshore current almost perpendicular to the wave orthogonal – as sketched in the figure below. This situation can be modelled by a process based sediment transport model as outlined above.

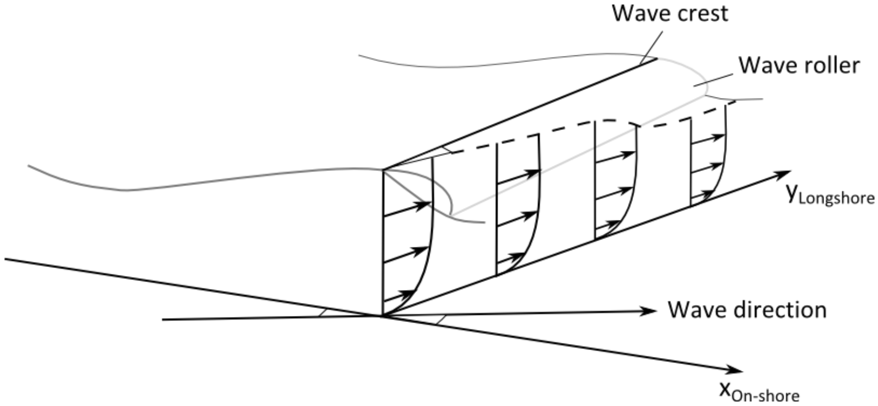


Figure 21.32 Longshore current under a breaking wave approaching the coast at an angle.

21.4.7.12 Cross-shore currents and wave breaking: Undertow

In the cross-shore direction, the effect of non-zero shear forces over the vertical will induce a cross-shore current. In order to calculate this flow for modelling the cross-shore sediment transport one may again use the principles for sediment transport discussed in the above chapters. As the eddy viscosity of the combined, wave boundary layer, wave breaking and current has been established together with the vertical distribution of shear stress (which is a subject that needs more explanation than we will go into here), the velocity profile can be calculated for a given cross-shore flux of water.

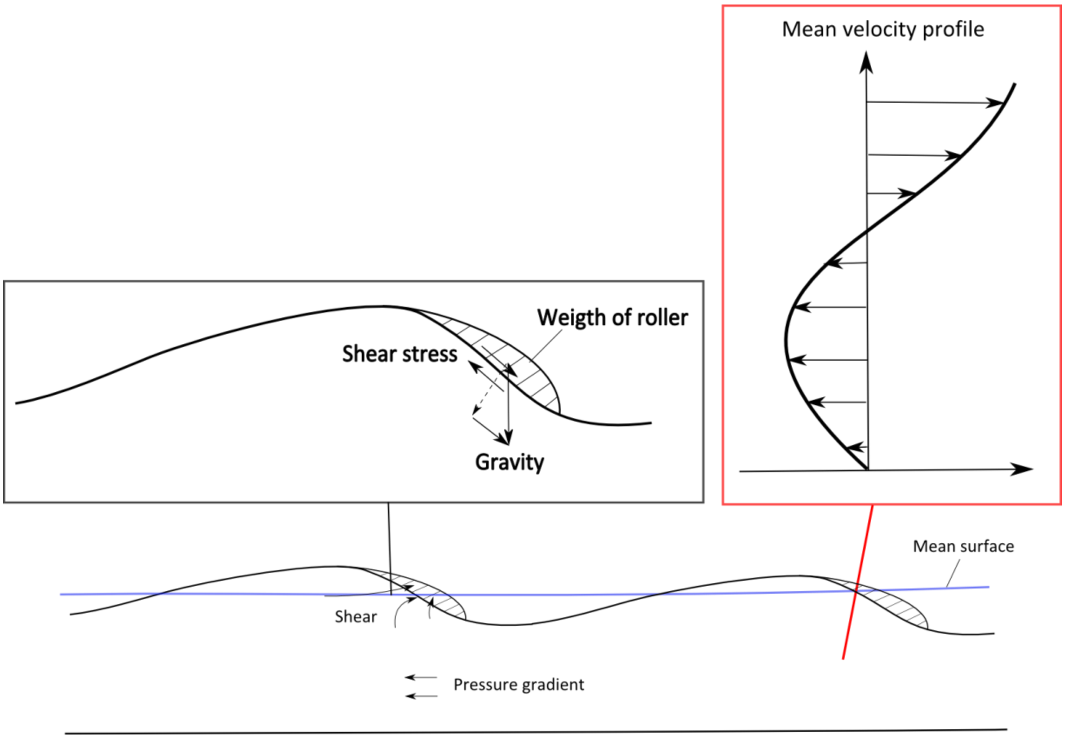


Figure 21.33 Elements in undertow flow: Wave roller at surface and mean pressure gradients.

21.4.7.13 Sediment transport model input

Because the sediment transport is a non-linear phenomenon and the combination of sediment types and flow conditions vary a lot, it seems to be difficult to obtain a general algebraic expression for the sediment transport's dependency on the governing parameters

- Wave field parameter H_{rms}, T_p
- Depth integrated current
- Angle between current and wave
- Sediment characteristics

Instead one can pre-calculate the sediment transport rates and save them in tables that can be interpolated later.

21.4.7.14 Example: Validation of sediment transport in waves and currents

A number validation tests between a sediment transport model for waves and currents - based on the process based method described above and – measurements, are presented in the below figure. It should be noted that even for this fine example of agreement between measurements and model results there are data points with a deviation of about a factor two. This illustrates the inherent uncertainty in sediment transport modelling.

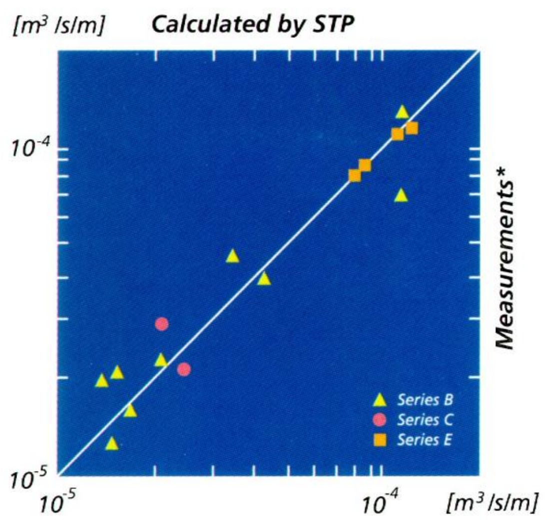


Figure 21.34 Example of validation of deterministic Q3D wave and current driven sediment transport model.

21.4.7.15 Wave, current and sediment transport model coupling

When having established a 2DH wave-current model, the calculated wave- and current field can be used as input to a sediment transport model. The sediment transport model can be based on deterministic principles like the model described in previous chapters or it can be algebraic formulations either based on empirical relations or energetics principles.

In either case, the sediment transport can be found in each cell as a function of the wave and current field quantities. This can be used to study local or regional sediment pathways and sediment budgets.

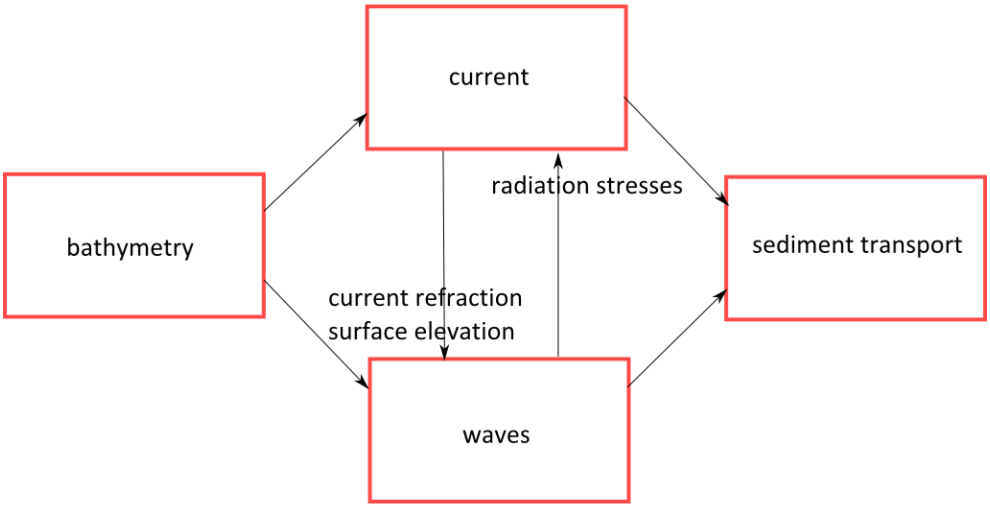


Figure 21.35 The combined wave and current motion induces sediment transport.

21.4.7.16 Example: Sediment bypass harbour

In Figure 21.36 the example with the harbour in Figure 21.22 is continued. The wave field and the current field presented in the previous example have been used as input to a sediment transport model (a model that follows the process oriented principles shown in previous chapters). The result is a sediment transport field showing how the sediment is mobilised, suspended and transported by the waves and currents from one side of the harbour, passing the harbour mouth and reducing in strength on the other side. This model can hence be used to analyse how sediment is bypassing this specific harbour under different wave conditions. The sediment transport capacity right in front of the harbour is reduced because the water depth is increased in the navigation channel, which is maintained by dredging. The figure thus illustrates how sand is transported towards the navigation channel where it is partly deposited due to the reduced transport capacity and partly bypassed as there is still a considerable transport capacity left due to the streamlined shape of the protective breakwaters.

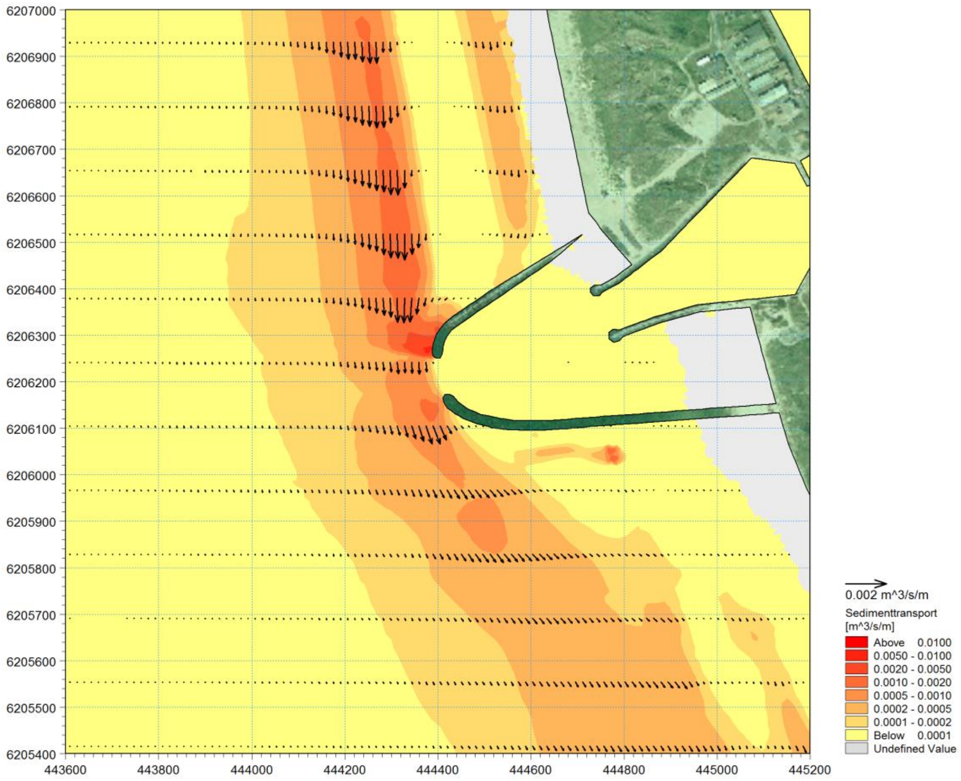


Figure 21.36 Sediment transport modelled using input from waves and current results from previous example.

21.4.7.17 Bed level change and morphological change

The bed evolution can be calculated from a sediment transport model. This can be done at two levels of sophistication: without and with feedback:

- Sediment balance in each cell, which determines the rate of bed level change
- Morphological modelling: Update bed level in each cell at each morphological time step

The first is a simple bookkeeping where the accumulation or loss of sediment is found in each cell over a period, which can be transformed to bed level change.

It should be noted that this will often produce a very noisy result with large variations and even change of sign between neighbouring cells. It is therefore often advisable to integrate the result over larger well-defined units to prepare a sediment budget describing the interaction between different morphological units. The reason behind the noisy results is that there inevitably will be inaccuracies in the bathymetry and that there will be small local inconsistencies in the combined system of hydrodynamic- and sediment transport models and the bathymetry. The noise would be smoothed out if the bathymetry had been formed exactly by the processes described in the models, as is the case with a fully morphological model described next.

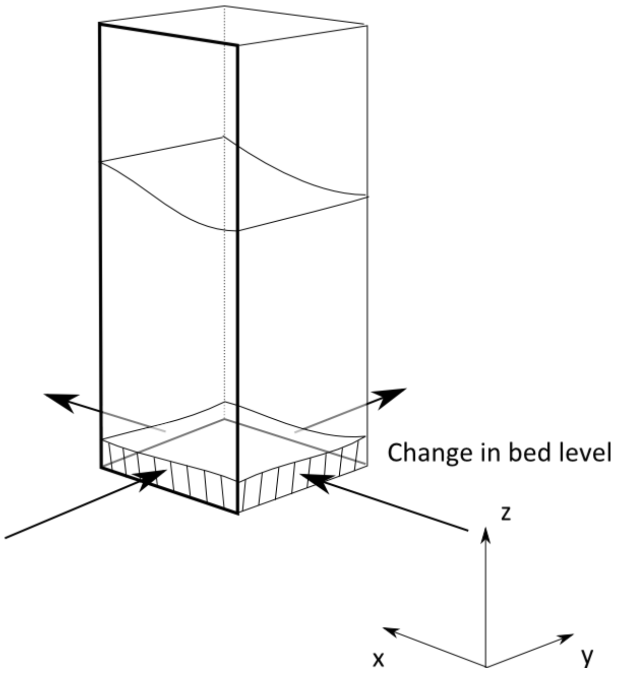


Figure 21.37 Sediment transport balance for each computational element yields change in bed level for each time step.

21.4.7.18 Morphological feedback loop

The coupled wave-current-sediment transport model can be used to update the bed level in each cell at a given time step, and the change in bed levels now feeds back into the wave and current models. This means that a morphological feedback loop is created. Such a model can be used to investigate details of the morphological evolution of the bed, e.g. around coastal structures.

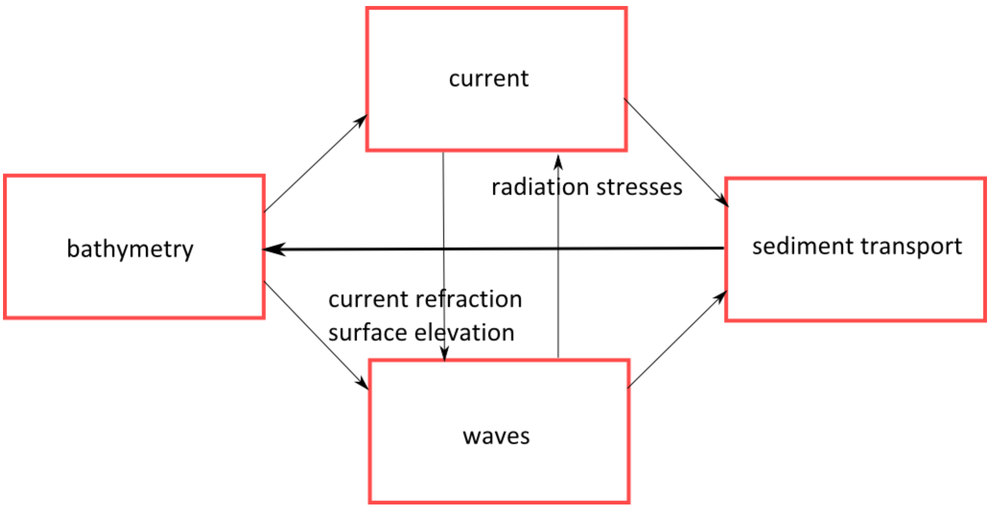


Figure 21.38 The morphological loop.

21.4.7.19 Example: Morphological modelling of bypass bar

When introducing the possibility of dynamic feed-back on the bed levels from the sediment balance for each cell, one obtain a models that can evaluate more realistic the bypass of sediment of the harbour already used as example. As shown in Figure 21.39, this model type is capable of reproducing the growth (or rather: migration) of a bypass bar from a given up-drift start location and past the harbour mouth during a typical storm. The end result then yields an estimate of the resulting bypass depth in front of the harbour mouth for the given typical storm situations analysed, and hence gives an indication of the typical navigation depth available after a storm and if it required to perform maintenance dredging to maintain the prescribed navigation depth.

Warning: It should be noted that even though this modelling approach seem very attractive, it is not a straightforward exercise to do such a calculation. In fact it demands very skilled modellers with a deep insight into the nature of sediment transport and coastal flows, and knowledge of the pitfalls when trying to model morphology.

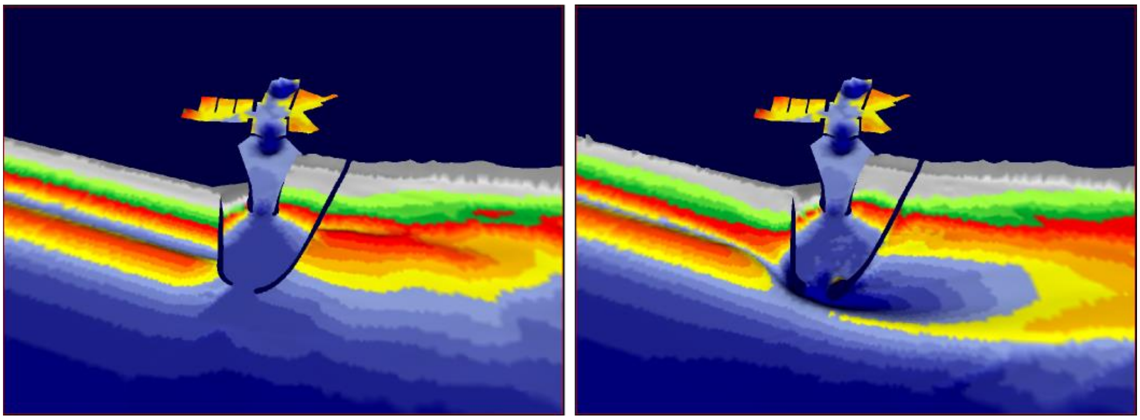


Figure 21.39 Morphological simulation of the development in the navigation depth for a so-called bypass harbour layout during a storm.

21.4.7.20 Example: Morphological instabilities

A very interesting aspect of the 2D area morphological models is that rip channels and other alongshore non-uniform features may emerge in the solution spontaneously because of a morphological instability mechanism in the feed-forward and feed-backward between morphology and flow (waves and currents). In the figure below, two examples are given in the case of what in the beginning of the simulation is a long and uniform coast with no disturbances. The figure to the left (A.) shows how alongshore bed waves after a while have grown along the bar crest as a result of the morphology instability mechanism (the case is for oblique wave incidence). The result is from a model that combines the 2D area model with a bar generation mechanism in the form of undertow. The figures to the right (B.) show how rip channels have emerged after some time (starting from a long and uniform coastline) in the case of normal wave incidence. The middle figure to the right show the wave breaking dissipation rate resembling - more or less accurately - the wave foam that one would observe. The right figure shows the rip currents out through the channels that have been eroded in the bar.

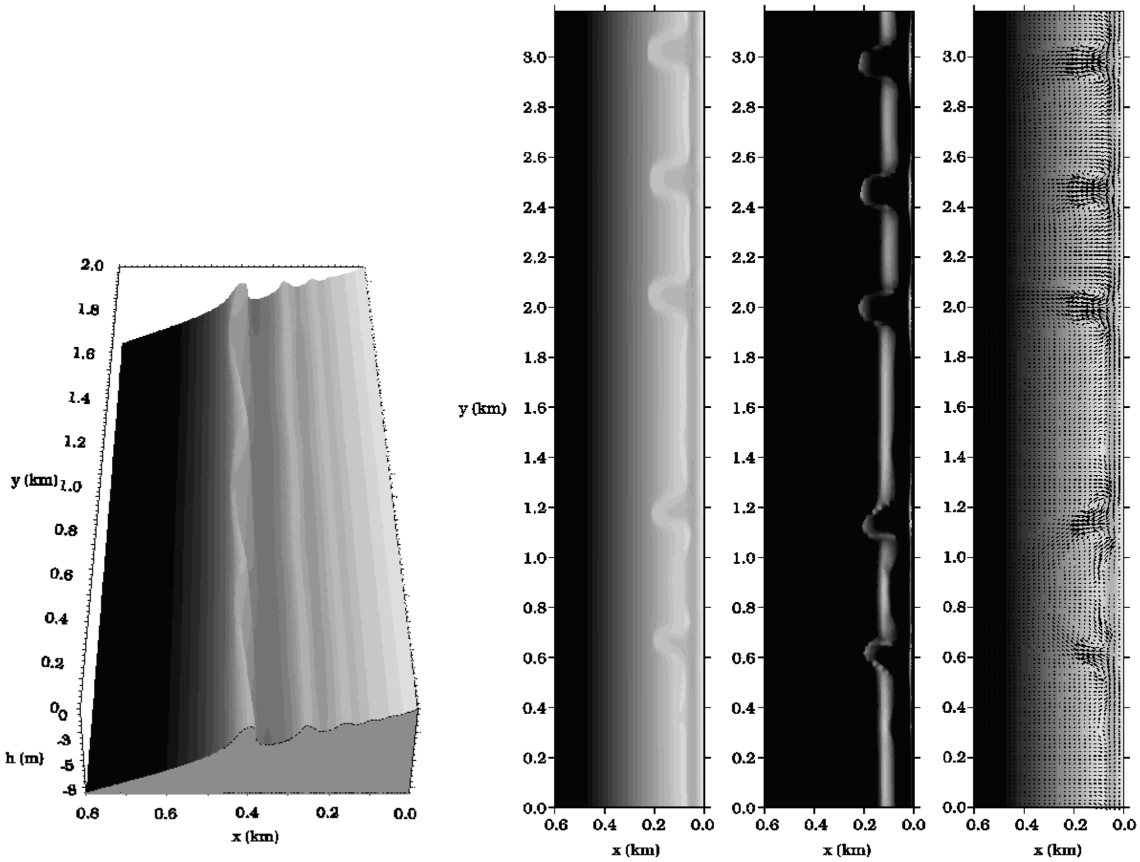


Figure 21.40 Morphological instabilities emerging in a 2D area model. Left: Oblique wave incidence and bar migration. Right: Normal wave incidence for a stationary bar (Left: Bathymetry. Mid: Wave dissipation rate. Right: Current field).

21.4.7.21 Phase resolving 2D area models

Phase resolving models are models that resolve the waves in time and space as they migrate and transform over the bed. In principle one could model the waves in time and space in a spatial three dimensional way, but in order to save important computational time, a class of models have been developed that instead operate with depth integrated (instantaneous) horizontal velocities. To properly resolve the waves and model their shape and propagation characteristics, special techniques are needed in the case of depth integrated models. This is because the effects of non-hydrostatic pressures are important for reproducing the right shapes and properties of the coastal waves. Also methods for taking out energy from the waves in the surf zone are needed. The most common model type seen in this context is the Boussinesq wave model type combined with a model for energy dissipation e.g. by introducing an effect of a moving roller in the momentum equations. The Boussinesq model solves the same equations as the 2D phase averaged flow model with some extra terms in the momentum equations. These extra terms are introduced to take into account the vertical acceleration in the wave motion, which gives a pressure distribution different from the purely hydrostatic assumed in the flow model. The Boussinesq models rely on the principle of transforming the vertical non-hydrostatic pressure to different gradients, curvatures and third order derivatives of the governing variables. These terms can be derived to a given order, and the order will reflect the accuracy of the result. It is furthermore known that higher order Boussinesq models become more difficult to implement, and possibly also more unstable. For engineering practice in the surf zone Boussinesq model of the order 2-3 are believed to be sufficient for most applications.

The Boussinesq model type can be used to study details in the flow around structures, run-up and overtopping. When wave breaking is included in the model, surf zone current will also be induced in the model.

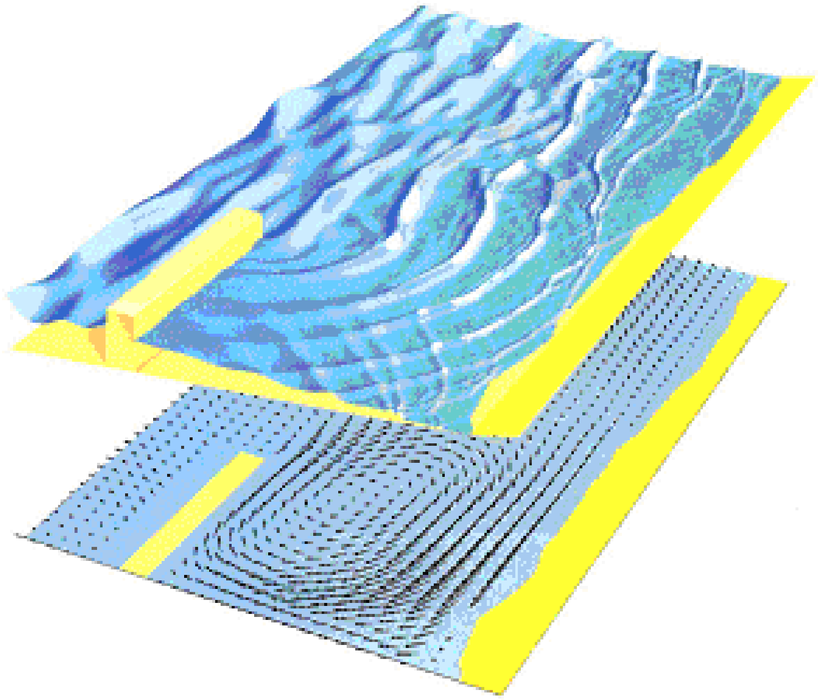


Figure 21.41 Example of results from a Boussinesq wave model. On top is a snap shot of the wavy surface and in the bottom picture the mean flow circulation patterns behind the breakwater can be seen. The wave breaking is simulated by surface rollers, which can be seen as white fronts on the breaking waves.

There are alternative ways of formulating a model that has the effect of non-hydrostatic pressure, especially the multilayer models, where the number of layers over the vertical can be compared to the order of the Boussinesq terms.

21.4.8 Shoreline models

Figure 21.42 A complex shoreline situation around a stabilised tidal inlet with updrift shoreline accretion and a large number coastal breakwaters to stabilise the downdrift coast.

Shoreline models combining littoral drift models with shoreline evolution techniques are the working horses of the coastal engineer, because the longshore transport is such a dominant process along any sand laden coast. Shoreline models can give extremely valuable information about the conditions of the given coastline, the problems and the possible remedies.

21.4.8.1 The Shoreline management project

A Shoreline management project should always start by analysing the sediment transport along the coastline. Three phases are considered:

1. Data set – statistics, historical analysis
2. Littoral drift models
3. Shoreline evolution. – two cases:
    a. Alongshore quasi-uniform
    b. Alongshore non-uniformity, structures and complex geometries

21.4.8.2 Data set and statistics

Data of the coastal sediment characteristics, bathymetry and wave climate should be collected and analysed before starting a shoreline modelling study. A suggested list of analyses to perform is given here:

- Sediment characteristics and spatial distribution
- Bathymetry
- Waves, tides and storm surges, and correlations
- Historical shoreline analysis, chronic and acute erosion trends
- Seasonal variation
- Random fluctuations

Samples of sediment type and grain size distribution are needed to set up the sediment transport model.

Shoreline position along a base line axis is found from satellite images and local measurement of profiles.

Nearshore bathymetry and beach topography are needed to establish the model for wave transformation, current generation and sediment transport distribution over the profile.

Data of waves – wave height, wave direction and wave period - are needed at the offshore limit of the profiles. This often means that a 2D area model for wave transformation is run first for the wave data at hand. Typically wave data over several years (depending on the purpose of the study) are needed to establish statistically reliable estimates. Sometimes wave measurements do not have directional information. In that case one may try to construct the directions from wind data.

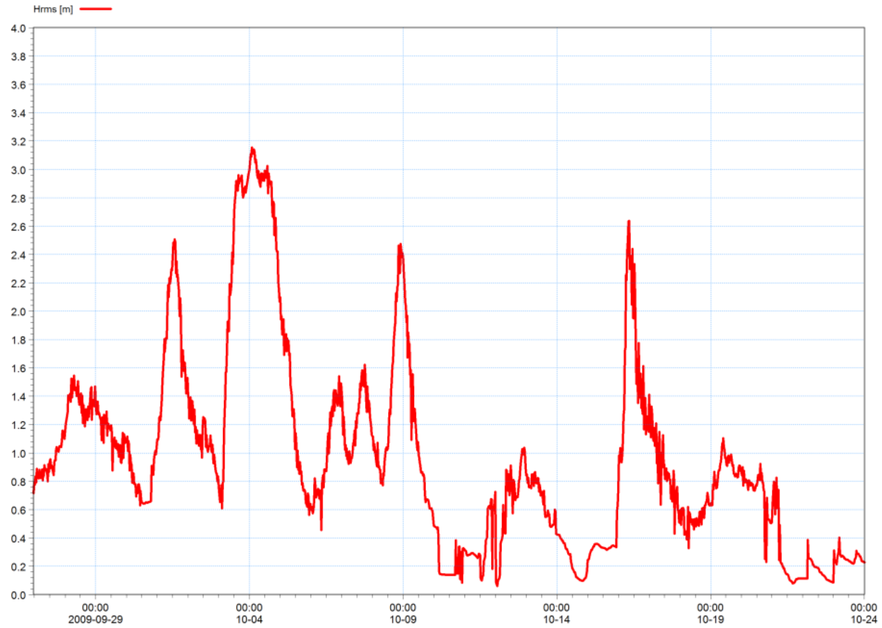


Figure 21.43 Example of time series of root mean square wave heights over a month.

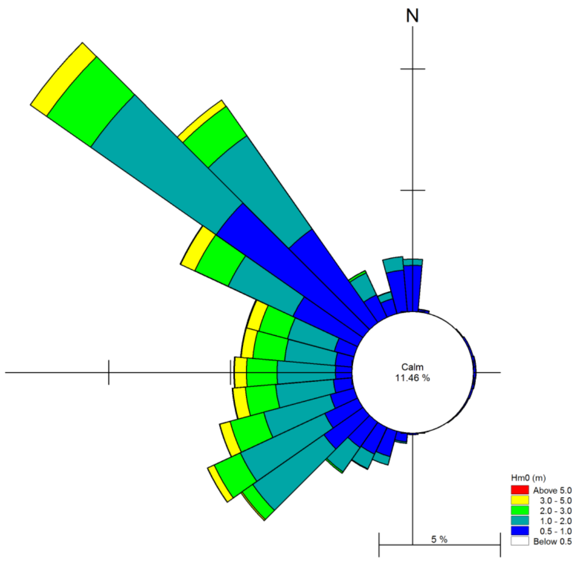


Figure 21.44 Wave rose illustrating the directionality of the wave height statistics.

Data of water levels (tides and storm surges) are also needed to establish the water depth over the near shore profile. Ideally simultaneous time series of wave parameters and water levels can be analyses for correlation.

Long term shoreline evolution may be extracted from satellite photos and historical records. This is vital information for interpreting the coastline dynamics in a long term perspective and may be used for calibration.

Information on the seasonal variation may be found in the profile data sets, which are also important for relating the longshore and cross-shore transport mechanisms to the observed variation.

The degree of fluctuations that are of a more random character, e.g. certain special storm surge events associated with acute erosion etc. should also be identified.

21.4.8.3 Littoral drift models

When modelling the littoral drift along a given shore, two main calculation levels should be worked with

- Littoral transport characteristics
- Q-alpha curve, i.e. the correlation between net littoral drift and shoreline orientation

21.4.8.4 Littoral transport

The following pre-processing and modelling levels are needed

- Coastal profile
- 1D wave and flow equations
- Sediment transport model (as described)
- Total longshore transport, i.e. littoral drift

The coastal profile

The data set should be converted into a data format used by the model.

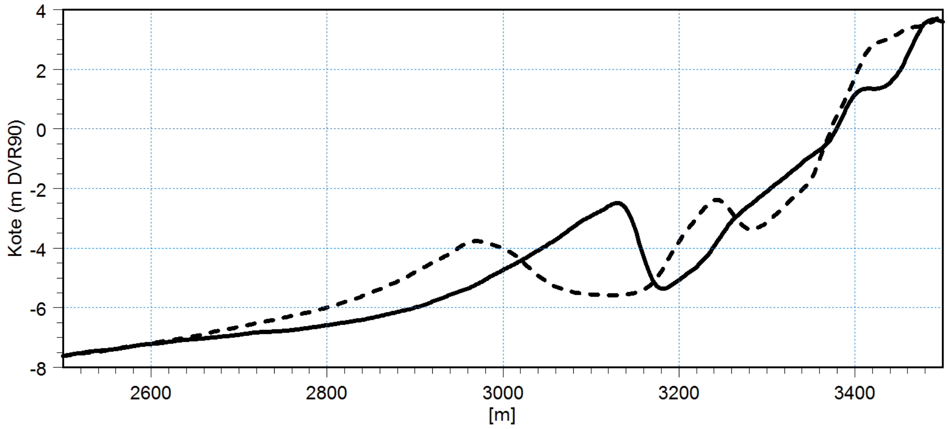


Figure 21.45 Examples of profiles at the same location measured an interval of years. The profile evolves because the bar system gradually migrates offshore.

1D wave transformation

The model calculates the wave transformation over the profile from a boundary condition at the outermost point of the profile and on-shore. Effects of water level, wave directional spreading, wave boundary layer and wave breaking should be considered.

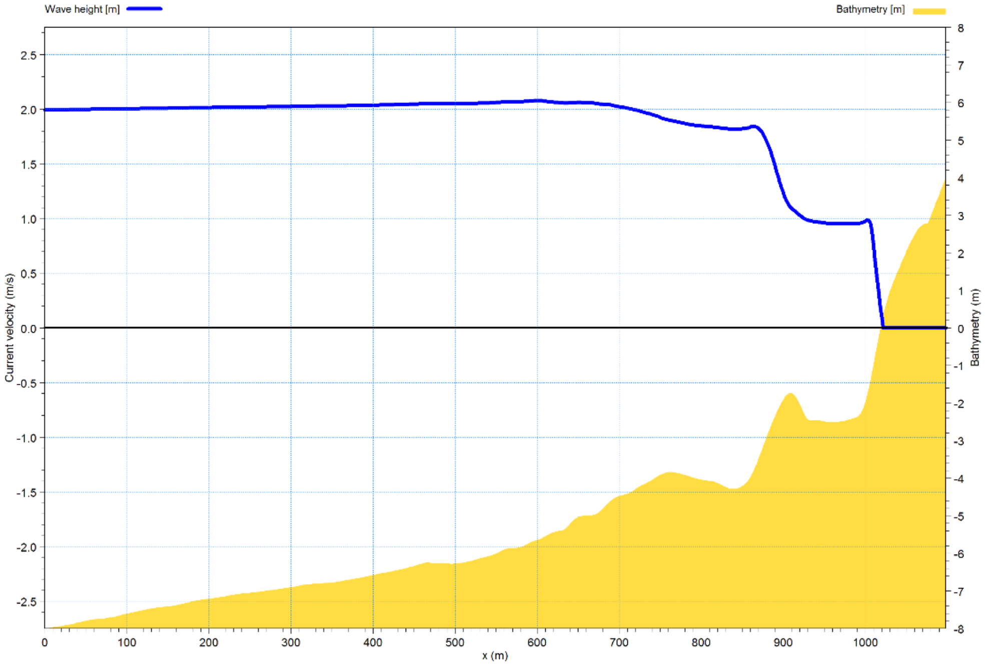


Figure 21.46 Calculated variation over the coastal profile of a Rayleigh distributed wave train with a significant wave height of 2 m at 8 m depth.

1D current calculation

The wave transformation gives rise to gradients in radiation stresses that generates the longshore current and the wave set-up.

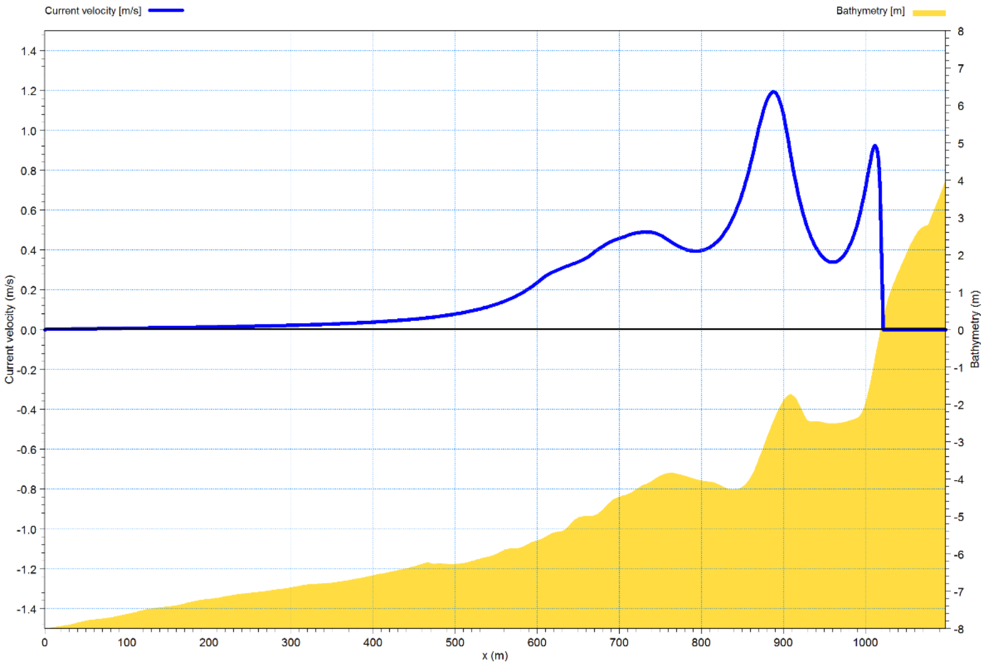


Figure 21.47 Resulting longshore current generated by waves from previous example.

1D sediment transport

When the transformation of wave characteristics and the distribution of the alongshore current have been calculated, a sediment transport model can be applied in each point over the profile to calculate the longshore sediment transport distributed over the shoreface profile. The sediment transport model could be based on the concepts explained in a previous chapter.

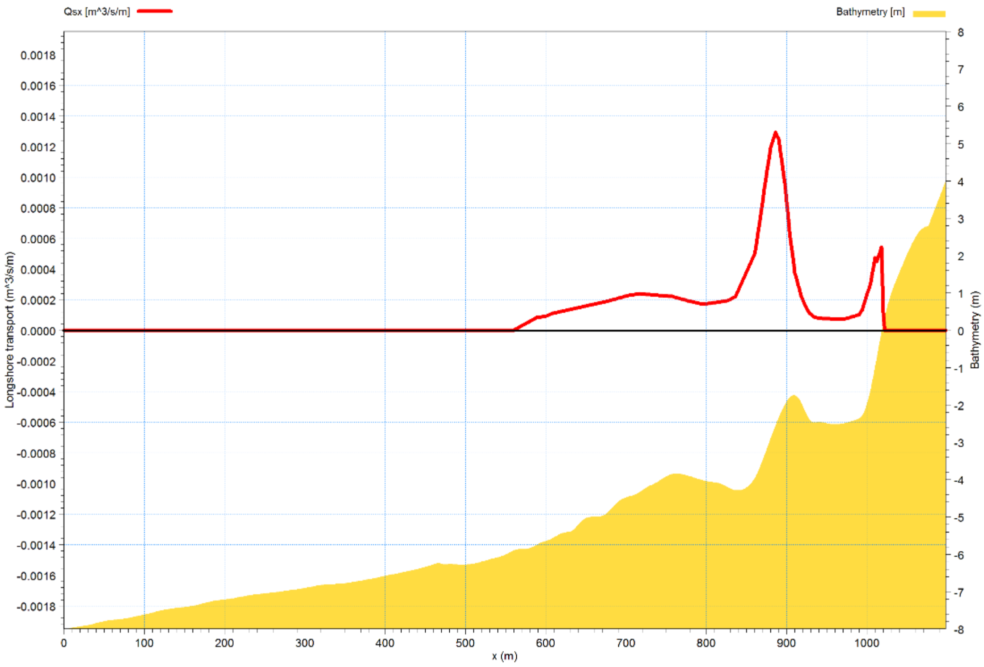


Figure 21.48 Distribution of longshore transport over the profile.

1D yearly sediment transport statistics

When calculating the sediment transport rates over a longer period (say several years) a number of mean sediment transport components are convenient measures of the long term statistics:

- Net transport
- Right/left transport
- Gross transport

Right/left transports corresponding to yearly mean transport rates in one or the other direction - right or left - as one would see it standing on the beach heading seawards.

Net transport rate is the mean transport rate based on a data set spanning several years, i.e. a mean yearly net transport calculated as the difference between right and left mean yearly transports. A net transport rate is associated with a direction, such as northward net transport rate

Gross-shore transport is the total amount of sediment transport left and right, i.e. the sum of the amount per year in both directions. Gross transport has no direction.

If the calculation is based on the assumption that the total profile is covered by sand, the total transport should be termed the sediment transport capacity. By this term we indicate that some part of the profile may not be sand covered and the transport calculated therefore represent an upper limit for the sediment possible carried alongshore by the transport processes.

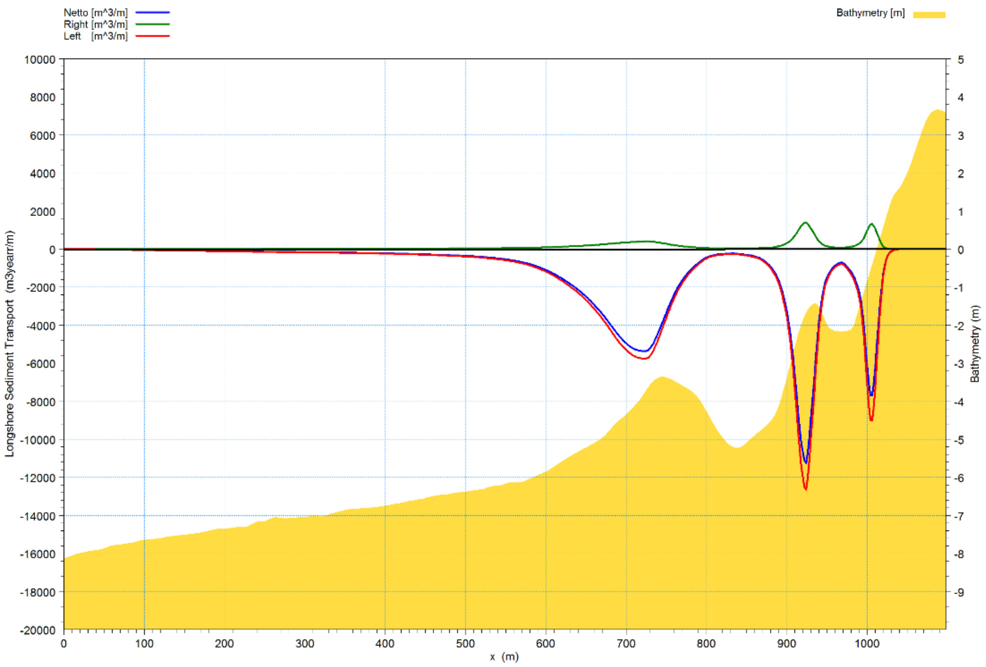


Figure 21.49 Distribution of the yearly mean longshore sediment transport rates, towards right and left, and the net, respectively.

The littoral drift

The total longshore transport (also known as the littoral drift) is the longshore transport integrated over the profile.

$$Q_{littoral}(y) = \int_S^{D.C.} q_{s,y}(x,y)dx$$

D.C. is the location of the Depth of Closure and S is the location of the shoreline.

Three transport rate components are (again) considered

- Right/left transport
- Net transport
- Gross transport

Net transport is the total net transport typically per year found from the statistics associated with a direction.

Right/left transport is the sum of all transport events to the right/left when standing on the beach and looking towards sea.

The gross transport is the sum of the magnitudes of the right transport and left transport rates, i.e. the total amount of sediments moved forth and back along the coast.

21.4.8.5 Q-alpha curves

A very strong tool for getting valuable information about the stability and morphological characteristics of a given shoreline is the Q-alpha curve. The magnitude of the net littoral drift depends on the angle at which the waves reach the shoreline. For a given constant wave field (direction) the transport therefore depends on the orientation of the shoreline as depicted in Figure 21.50.

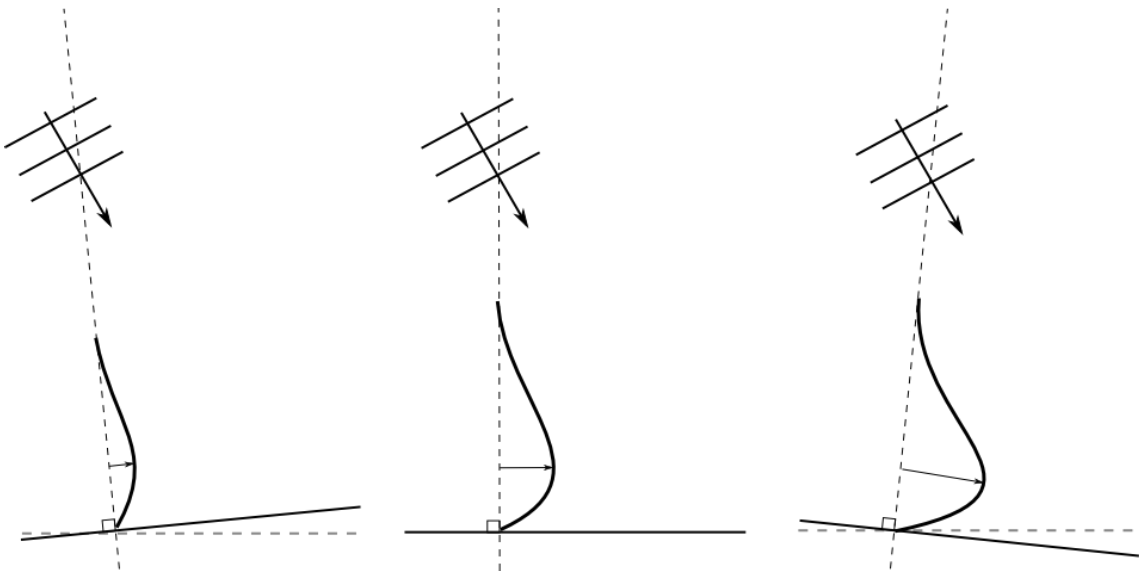


Figure 21.50 Illustration of the relation between coastline orientation and sediment transport (for a given wave climate).

By repeating a given sediment transport calculation for different shoreline orientations (same wave climate), one obtain a curve for the relation between net littoral drift (and the right and left and gross transports as well) and shoreline orientation. For a simple wave climate with a well-defined direction one obtain curves as shown in Figure 21.51.

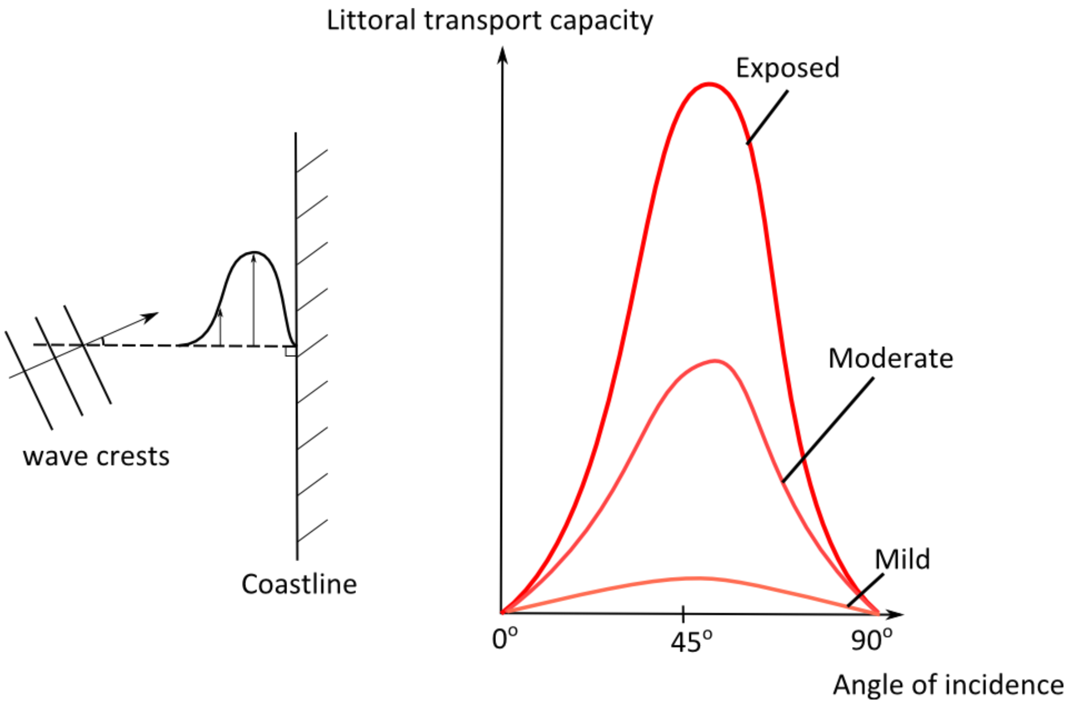


Figure 21.51 Relation between littoral transport and angle of incidence for different wave climates: Q – alpha curves.

For a complex wave climate with different wind and wave systems reaching the shore over the year(s), one may obtain both right and left transport rates that are not zero. In the figure below an example of such a case is given.

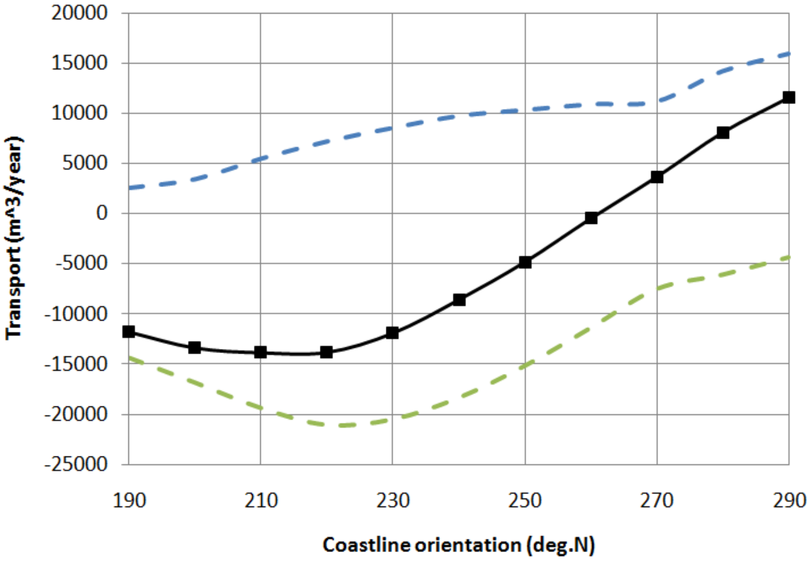


Figure 21.52 Q-alpha curves for right, left and net transport as function of orientation of coastline. Black curve is net longshore transport. Blue curve is transport to the right (positive). Green curve is transport to the left (negative).

Here the concept of equilibrium shoreline orientation is useful. The equilibrium shoreline orientation is the orientation of the shoreline which results in zero transport and where the shoreline is consequently in total equilibrium with no net movement of sediment along the shore. In the figure above this orientation corresponds to around 260 degrees. This can be the case for a pocket beach with no import of sediment, or it can be observed as the local updrift orientation close to a coastal structure blocking the longshore transport 100%, as depicted in the top part of Figure 21.53. In the case of sediment bypassing the blocking structure, the local orientation will be a little different corresponding to the bypass rate that can (approximately) be found from the Q-alpha curve.

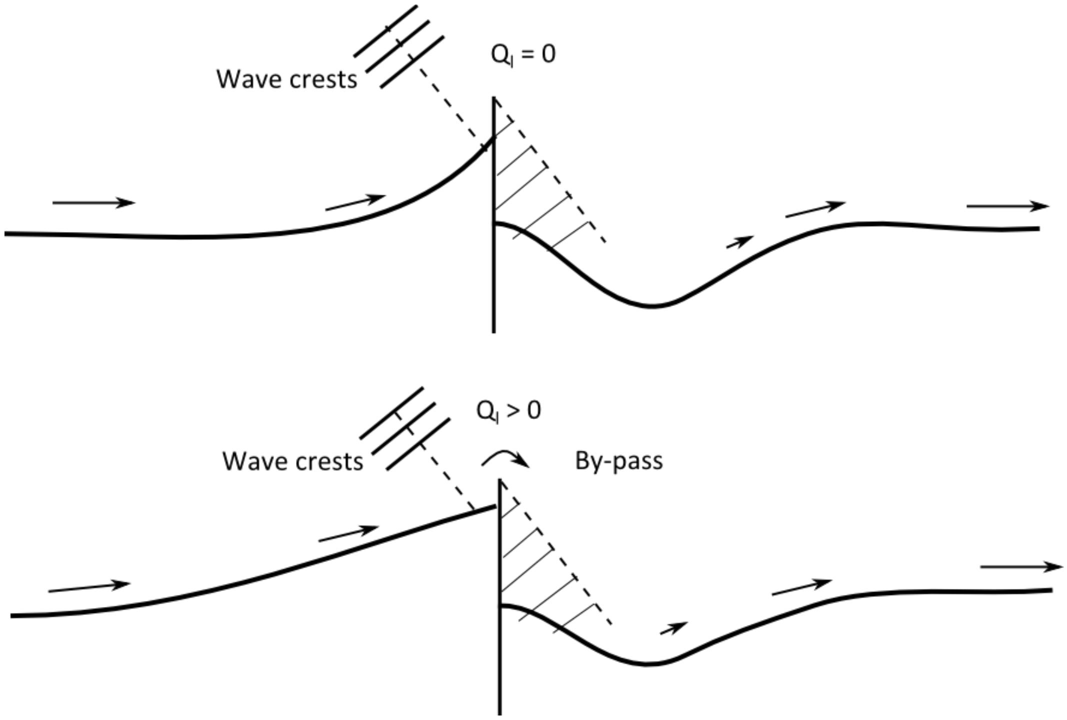


Figure 21.53 Top: Zero littoral transport close to a coastal structure. Bottom: A certain amount of sediment bypasses the coastal structure.

In the same way as one can visualise the directional distribution of wave heights by a wave rose, one can also introduce the same concept for sediment transport, i.e. a sediment transport rose or directional transport scatter diagram, to illustrate the different wave direction-height combinations contribution to the gross sediment transport. This is typically used for selection of the wave height-direction combinations, which are responsible for the highest transport contributions. These combinations are typically applied in subsequent 2D transport simulations, whereby the total 2D transport regime can be established by summarising the transport contributions according to their respective frequency of occurrence.

21.4.8.6 Shoreline evolution modelling

Using the littoral drift model at different sections along the coast a number of values for the littoral drift is found. If the wave climate and the bed contour are not perfectly uniform all along the coast, there will differences in the transport capacity calculated at the different locations, as illustrated in Figure 21.54.

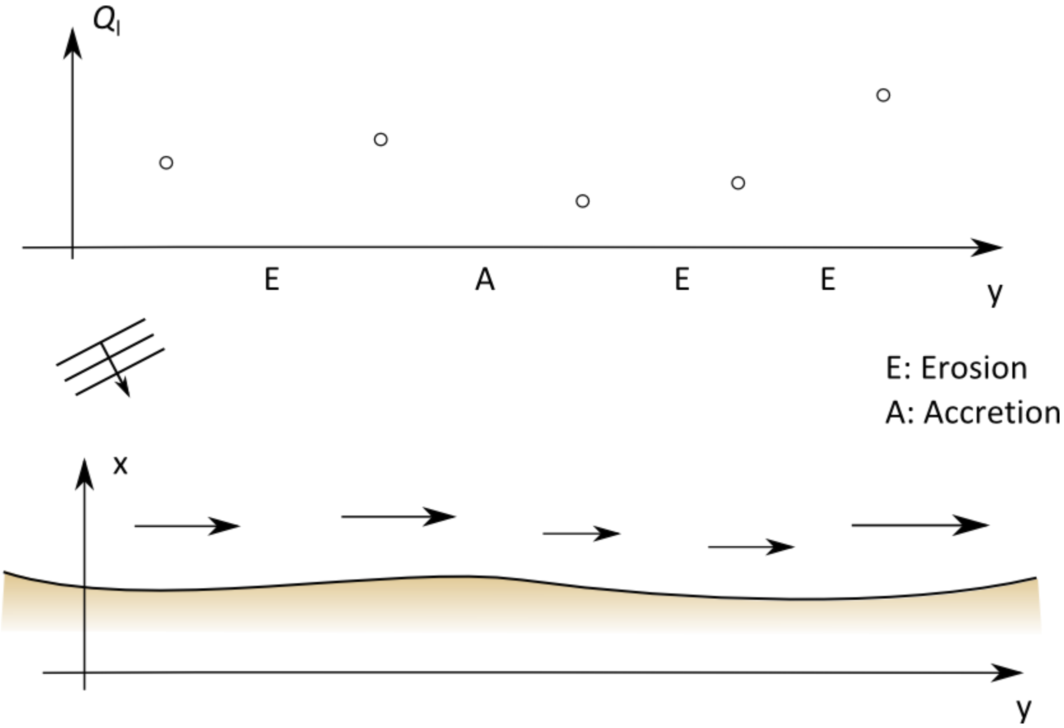


Figure 21.54 Variation of littoral drift along the coast gives insight into erosion and accretion tendencies.

This means, due to continuity that accumulation and erosion between the calculation locations can be recognised:

$$Sand\ bed\ Accumulation\ =\ -\frac{\Delta Q_{littoral}}{\Delta y}$$

(erosion is “negative accumulation”)

21.4.8.7 Morphological updating

Three main assumptions often used in the 1-line model concept are:

Assumption 1: The morphologically active part of the profile ranges from the shoreline to the Depth of Closure

Assumption 2: The morphological active part of the profile is constant in shape

Assumption 3: The local longshore transport can be calculated by the littoral drift model, which assumes the conditions similar to a long straight uniform coastline

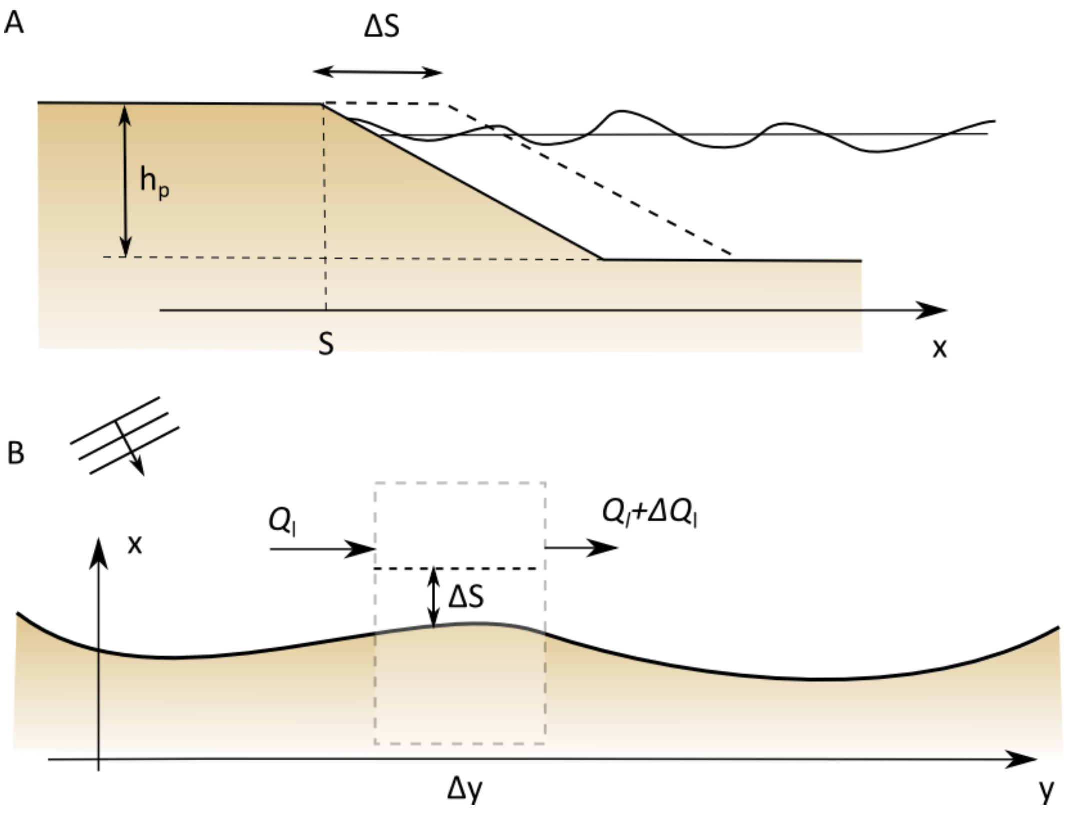


Figure 21.55 Shoreline evolution model. Translation of profile as function of the gradient in the longshore transport

Assumption 1 may be considered to be a quite valid approximation

Assumption 2 is plausible if an equilibrium exists between on- and off-shore sediment transport over a longer period, and if the deviation from the equilibrium profile at a given time does not affect the longshore transport significantly.

Assumption 3 requires gradual variations and a small curvature of the shoreline.

Different kinds of profiles can be used over the year (cf. summer and winter profiles) and/or along the coast. This may be relevant if data show that this is in fact the case.

21.4.8.8 Example: Study of re-designing coastal protection

An example of running the one-line shoreline evolution model for different cases of re-designing a series of coastal protection hard structures is shown in Figure 21.56.

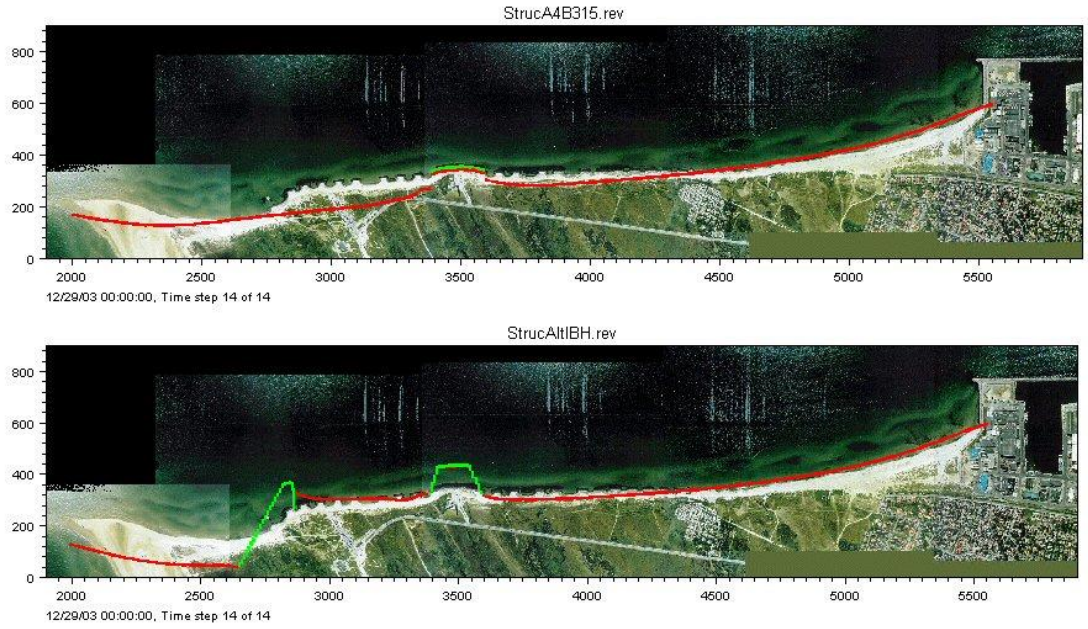


Figure 21.56 Simulated shoreline evolution over 14 years after a) removing old structures expect one revetment and b) installing new large structures (green).

21.4.8.9 Limitations

A number of limitations are inherent in the 1-line model concept

- User defined profile
- Curving shoreline
- Circulation currents
- Streamline contraction
- Wave shadow behind a large structure
- High angle of incidence

The model user needs to specify the profile used in the model. On one hand this may seem to be a limitation, but it also means that the user is controlling the model which for an experiences user will result in more reliable results compared to a model with a free profile development. This is because long term modelling including free profile development tends to produce a degeneration of the profile into unrealistic shapes.

When the shoreline is not uniform different circulation current and/or streamline contraction phenomena may be important for the flow and sediment transport.

When bypassing a headland or a coastal structure, the flow contracts upstream and diverges downstream. The assumption of local uniformity means that these effects are not taken into account in a 1-line model.

Furthermore, the effect of waves being blocked by constructions like shore parallel breakwaters may not be easily represented in a 1 line model.

In the case of high angles of wave incidence the 1-line model turns out to be incorrect and starts producing unrealistic instabilities. Eventually the model becomes completely unstable and breaks down. This behaviour occurs because non-uniformity effects on the coast are not represented in the model as illustrated in Figure 21.57.

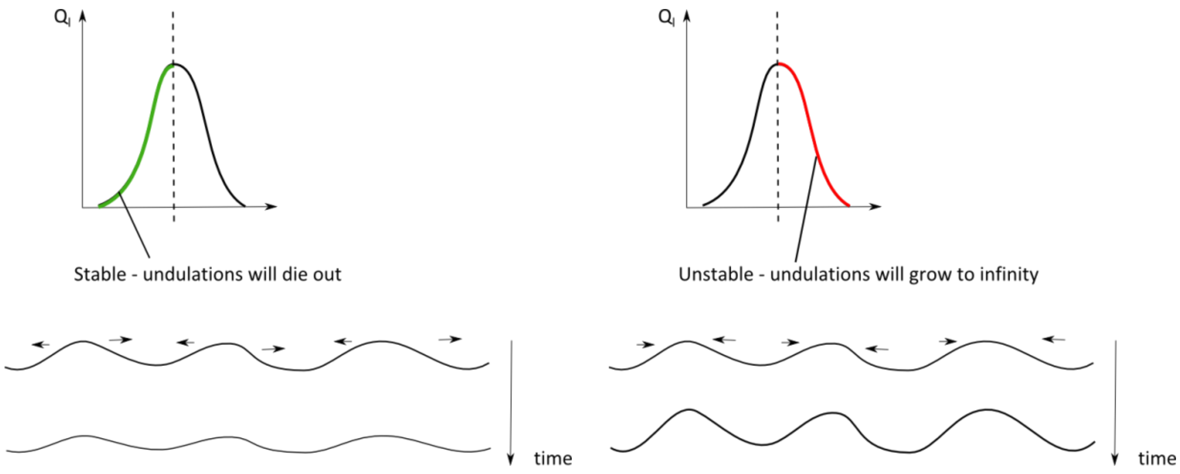


Figure 21.57 Evolution of an undulation for shores with different shoreline orientations under the assumptions used in a 1 Line model. Below 45 degree, i.e. right behaviour (left). Above 45 degrees, undulation will grow to infinity, i.e. unrealistic behaviour (right).

21.4.8.10 Shoreline hybrid model

In order to overcome a number of the major limitations of the one-line models described in the previous chapter, a hybrid model may be formulated, where the 2D area model is used to calculated the sediment transport but the morphology is still updated according to the one-line concept.

This is illustrated in the figure below, where a control volume of a section of the coast has been introduced and based on the longshore gradient of the integrated sediment transport, The profile is translated in the cross-shore direction in the next time step (erosion or accretion).

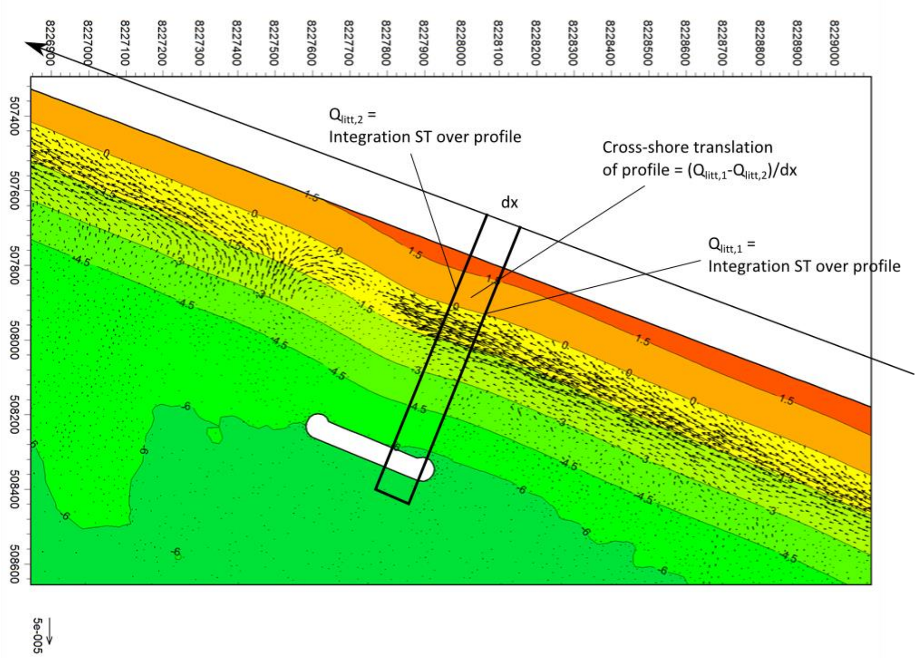


Figure 21.58 Shoreline hybrid model. Translation of sediment transport field from 2D area model for sediment transport to one-line concept.

21.4.8.11 Example: Shoreline change behind breakwater

In the present example the response to a detached breakwater is modelled using the hybrid concept. The model was setup in a larger area out to a depth of 20m, where the boundary condition corresponds to measurement taken at that depth. The model was run with waves, currents and sediment transport and with daily shoreline updating as described above for a period of four years, where a bathymetric survey has been performed. The comparison between modelled and measured morphology is seen in Figure 21.59. Compared to traditional 1-line models, this model reproduces the right amount of sediment trapped behind the breakwater without the modeller having to adjust/calibrate the model. This fact is believed to be due to the fact that the model correctly represents the most important physical processes (2D area model and process based sediment transport description).

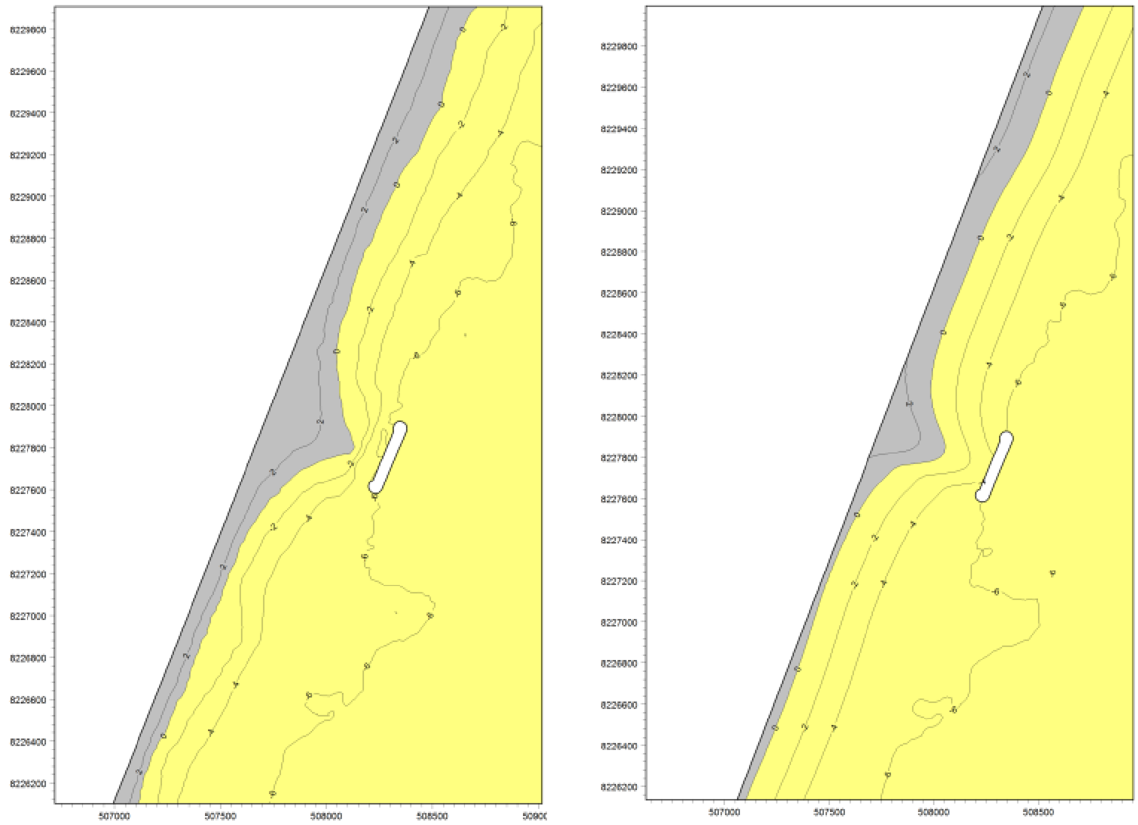


Figure 21.59 Comparison between measured bathymetry response for a breakwater (left) and the simulated bathymetry using the shoreline hybrid model (right).

21.4.8.12 Example: Ship wreck

A spectacular example of sand accumulation behind a structure sheltering for the waves is a case where a ship has grounded on a shoreface. The shipwreck was not removed and affected the coast over several years, resulting in accumulation to happen behind the wreck. The hybrid shoreline model approach was used to model the growth of the salient behind the ship, and in Figure 21.60, the model result is seen compared to a satellite image of the situation and time corresponding to the simulation.

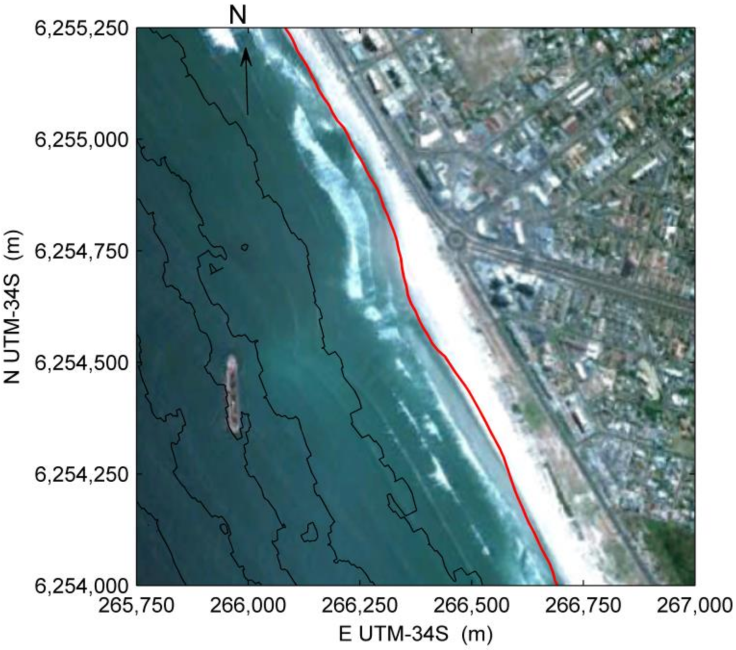


Figure 21.60 Comparison between recorded shoreline salient caused by a ship wreck (satellite image) and the simulated shoreline using the shoreline hybrid model (red line).

21.4.8.13 Example: Sand engine

The hybrid concept model has its strength in being able to model situations where the traditional 1-line model concept fails. One example is the case where wave approach the shoreline at a very oblique angle. This is the case for the so-called mega nourishment named the sand engine (or the sand motor), which is a large experimental project being carried out in the Netherlands, cf. Figure 21.61. See also Subchapter 17.6.2.3. The aim of the project is to see how a very large beach nourishment behaves and to see if the placement of such an enormous amount of sand in fact can be a more economic and maybe even a better ecological solution for sand nourishments for mitigating shoreline erosion. In this case, the hybrid shoreline model concept was applied to test the model's capabilities for large wave angles. In Figure 21.62 the model results from the first number of years of development are shown. When comparing to observations from the real nourishment, the model is seen to capture a number of features right and also to have the right order of magnitude with respect to the temporal and spatial evolution.

Figure 21.61 The sand engine 2011.

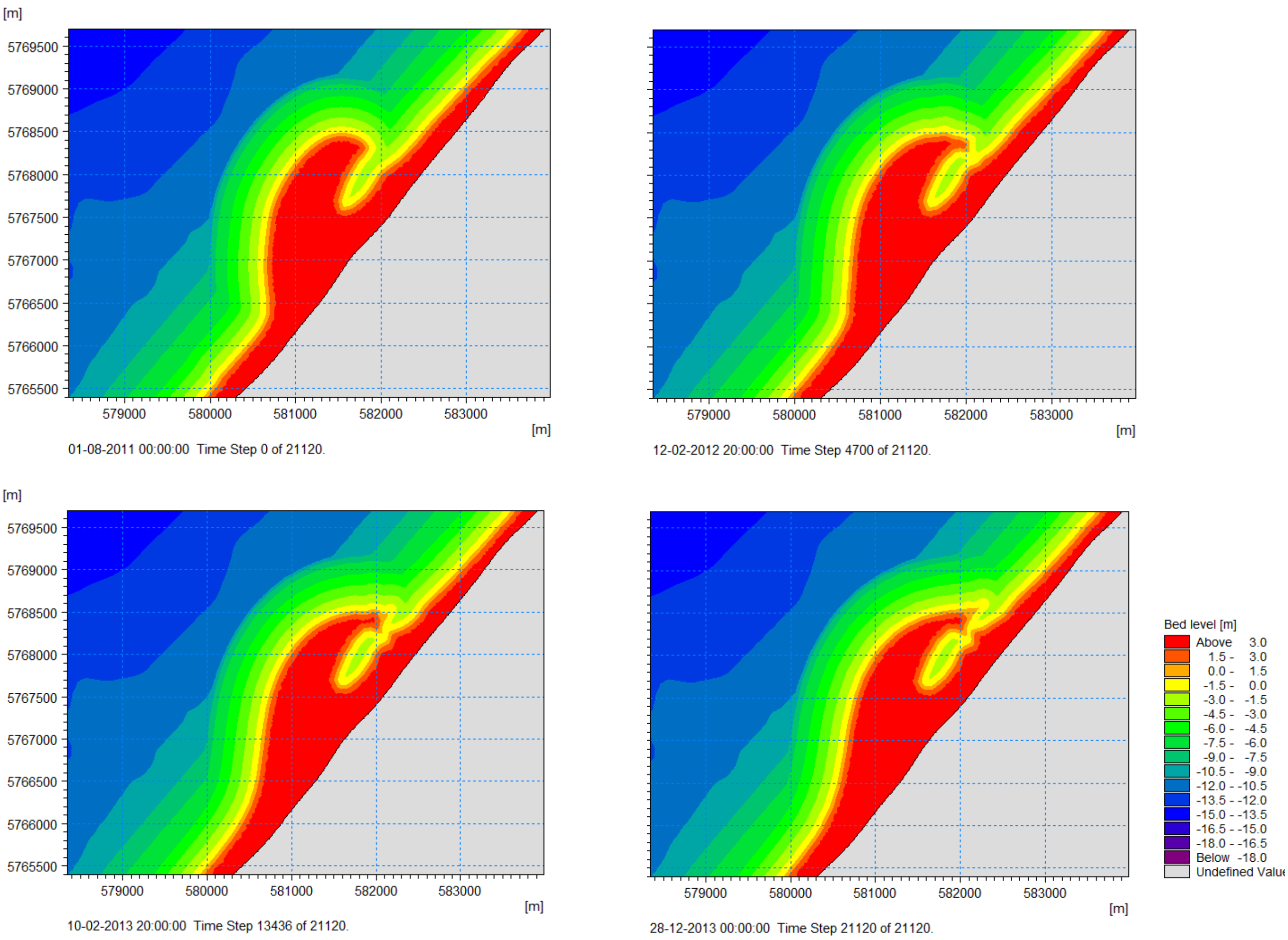


Figure 21.62 Modelled development of the mega nourishment from beginning to after three years, see also Figure 17.51.

21.4.9 Profile models

21.4.9.1 Short term models

There are a number of levels of model approaches to consider

- Profile response model
- Cross-shore sediment transport
- Phase resolving modelling

21.4.9.2 Profile response model

A very simple and robust model for dynamic response to changes in water level and forcing is a profile response model where it is assumed that an equilibrium profile can be defined for a given case, combined with time scale parameter for profile adjustment. The long term equilibrium profile and a time scale for the adaptation are required inputs for this model. Assuming a constant profile the model reduces to a shoreline recession model:

$$\frac{dS}{dt} = \frac{1}{T_s}(S - S_{eq})$$

S_{eq} would be the recession e.g. as calculated by assuming the Bruun rule (explained elsewhere in the guideline).

This model does not say much about how fast the adaptation will occur, but forces – on the other hand - the user to think about the aspect in order to choose a plausible input.

21.4.9.3 Phase averaged profile models

Historically, the first attempts to model in more detail the coastal profile – its shape and evolution in time and space - in a process oriented framework relied on phase averaged methods. A number of main principle physical elements can be represented in such a model, i.e. cross-shore transportt mechanisms such as undertow, streaming in wave boundary layer, non-linear wave motion etc. Furthermore, the order of magnitude of sediment transport rates calculated by these models is actually often seen to be right. Therefore it may come as a surprise that these models have only been partially successful in modelling the profile evolution. They are - when calibrated sufficiently - relatively successful with regard to erosional events, where the calculated generation and off-shore migration of bars can be calculated for the short duration of a storm. The models tend however not to be robust over a long time period, deforming the profile in different ways, leaving the resulting shape to be more and more unrealistic with time. The modelling of on-shore movement also needs a thorough separate calibration, but the uncertainty with regard to which process actually being dominating for on-shore transport is considerable. For this reason cross-shore profile model can only be used when “forced” to resemble already existing data through aggressive “calibration” or tuning of the model, but they tend not to be able to produce much new information, and over long term simulations even drift towards unrealistic profile shapes.

The generation of bars seems to be coupled with phase shifts between the bathymetry and the forcing (and hence sediment transport). Such phase shifts are really not modelled in phase averaged models, and different ways exists to include the phase shifts through empirical models has been attempted. This may be one of the reasons why a free phase averaged model has not yet been shown to be the best way to model profile evolution.

21.4.9.4 Example: Bar generation

This simple test case show how a phase averaged model produce a number of bars due to wave breaking and off-shore directed sediment transport generated by undertow.

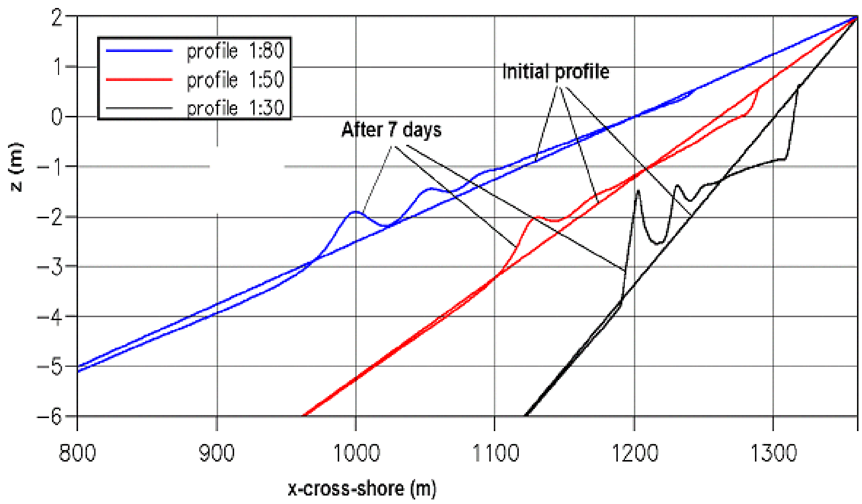


Figure 21.63 Simulation of profile evolution over 7 days for three different bed slopes ($H_{rms} = 1\ m$, $T_p = 6\ s$, normal wave incidence).

21.4.9.5 Phase resolving profile models

Recent model efforts suggest that three-dimensional phase resolving models are better at describing the profile dynamics (both erosion and accretion sequences). Such models are of course more computationally demanding than the phase averaged models. Models that can be used for commercial work of profile evolution have therefore not yet emerged, but are expected to come because the computational power is much larger now compared to when the first profile models started to come forward.

It has over the last number of years been shown that depth integrated, phase resolving models can be used to study dune erosion and wave overtopping.

21.4.9.6 Example: Dune erosion

A Boussinesq wave model has been used to calculate the erosion of a dune front by introducing simple formulations of sediment transport and a simple dune front notching and failure model. An example of the result of such a model is shown in Figure 21.64.

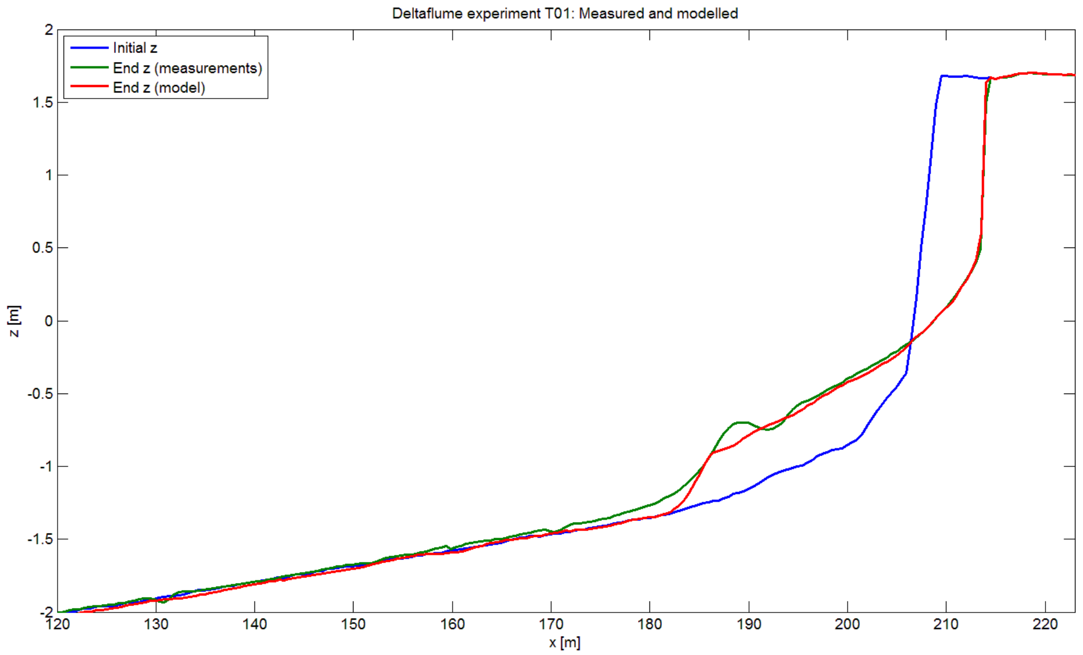


Figure 21.64 Profile evolution as calculated by a Boussinesq model combined with a dune erosion and a sediment transport model. Comparison between model and large scale laboratory experiment, see van Gent (2008).

21.4.10 Modelling coastal flooding

Coastal flooding will in many cases be an interdisciplinary field - at least in the case where the interaction between the sea water and rain run-off and impacts on and effects from urban area and rivers are important feature in the problem.

The coastal zone constitutes the boundary that separates sea from land. The sea side can either be the open sea, a lagoon system (with protecting barrier islands) or a Fjord. The land side can be a rural or an urban area, or a combination of both. In many regions around the world the coast is a dynamic area where sediment is eroded and deposited in different patterns depending on the local sediment and wave/current conditions. In such morphological active areas, climate change will directly - both for chronic and acute erosion - have an impact on the coastal morphology, and therefore impact the vulnerability/resilience for erosion and flooding during extreme storm surge events.

In other regions the morphology is less dynamic and it is more the direct changes in water level and hydrodynamic forcing that causes extra or unexpected pressure on the coastal boundary during an extreme event.

Numerical models can be strong tools for estimating the consequences of forces from the sea on the coastal boundary and the consequences of this for the landside – i.e. erosion and flooding. Models for waves and currents, erosion and overwash and a methodology for transforming these into predictions of breaches and hinterland flooding are hence relevant.

The forcings to be considered are:

- Tide
- Storm surge (local and regional wind set-up, atmospheric pressure drop)
- Waves

Three types of modelling perspectives are relevant for coastal flooding

- Hindcast driven model
- Forecasting
- Future projection

Hindcast driven models can be used to validate the model response to certain historical events that caused coastal flooding. When validated, the hindcast model can be used to test a number of what-if scenarios where different strategies for preventing damages seen in the historical data can be tested (flood defences, etc.). In other words, the hindcast model can be used as a design tool for prevention of reoccurrence of damaging events and to determine the events to be designed for.

Forecasting models are obvious of significant importance for local communities when preparing either mobile flood prevention for a storm and/or preparing for rescue actions.

Future projection models are informative when trying to cope with climate change and sea level rise. Future projection models could be used to test the response of a given area to different extreme event scenarios.

21.4.11 Modelling the sea-land boundary

The coast constitutes the boundary between sea and land, and processes going on in this region affect the coast's capacity for resisting the forces of sea water under extreme conditions (waves, storm surge, tsunamis).

21.4.11.1 Run-up and overtopping

Two options may be considered when trying to estimate the level of maximum run up and possible overtopping of coastal barriers such as dune or dikes

- Empirical relations
- Numerical modelling

Empirical relations between wave height, wave period, beach and barrier slope – and the run-up level or overtopping volumes exists. We will not go into details about this but refer to the larger amount of work on statistical parameterisation of existing data for the phenomena to be found in the literature and in the form of publicly available guidelines.

Numerical modelling is a method that is expected to become more used in the future, but at present the models need more validation to become fully accepted as practical tools.

21.4.11.2 Barrier breaching

A barrier such as a dune or a dike can be breached due to the effect of waves acting on the barrier with forces that exceeds the barriers strength. Two types of breach mechanisms – or failure modes - may be of importance

- Shear stress failures
- Geotechnical failures

In the case of dunes - and dikes constructed from soil, e.g. sand cores with a clay layer - the shear stress failure mode is a relevant mode to analyse. In order to analyse this failure mode, a model for the shear forces acting on the barrier is needed. This may be in the form of a numerical model for wave impact and overtopping. Such models are currently being developed, and the models have shown that they are in principle capable of reproducing the right behaviour of barrier breaching. However as erosional shear strength data for dune and dike breaching (under controlled circumstances) are still scarce, and as questions about how to obtain strength parameter for real dikes still remain, it has so far not been possible to validate these models sufficiently.

The knowledge and the model capacity to analyse the geotechnical failure mode is in its infancy. A number of unknowns are to be identified and the big question of how to obtain estimates for strength parameters for a real barrier has not been answered yet.

21.4.12 Intrusion of sea water into the coastal hinterland

If the barrier has been breached - or the sea water has reached a level in areas where no natural or man-made barriers are present - sea water will intrude into areas that are normally not in direct connection with the sea water of the water body off the barrier. In order to estimate the water levels in the flooded lagoon and land areas in such situations two methods can be considered:

- Static modelling
- Dynamic model - Numerical modelling of storm events taking the development of the flooding into consideration

By static modelling one means that the water level of the adjacent sea area is transferred directly onto the lagoon and land areas, i.e. giving a result that all land that is in contact with the sea and has a ground level below the sea water level, will instantaneously have water up to the level of the sea water level. This approach is a conservative method that neither takes into account the time it takes for the sea water to enter the land areas nor the duration of the storm surge event.

To take these conditions into account a dynamic model is needed, where the actual flow from sea to lagoon/land is modelled (in general numerically) to resolve the flow in time and space. It is noted that such a dynamic model would also constitute a method to overflow areas where the dynamic effect is of less importance, i.e. an on-land “extrapolation” method, so to speak.

21.4.12.1 Example: Storm event in a fjord system

During an unusual passage of a low pressure system a storm passed a fjord system resulting in extreme storm surge levels due to local wind setup and high surge levels occurring at the entrance of the fjord. The fjord is usually a sheltered area and flooding has not to a large degree been taken to be a large problem in these areas. Therefore many low lying areas had at that time not a suitable flooding defence system ready and a number of houses were flooded causing damages to a large number of private properties. A 2D area model was set up to study the event in hindcast mode. The mesh used in the example is presented in Figure 21.65.

Notice the use of combining rectangular and triangular meshes, i.e. a utilisation of a flexible mesh strategy for modelling the complex geometry of the system.

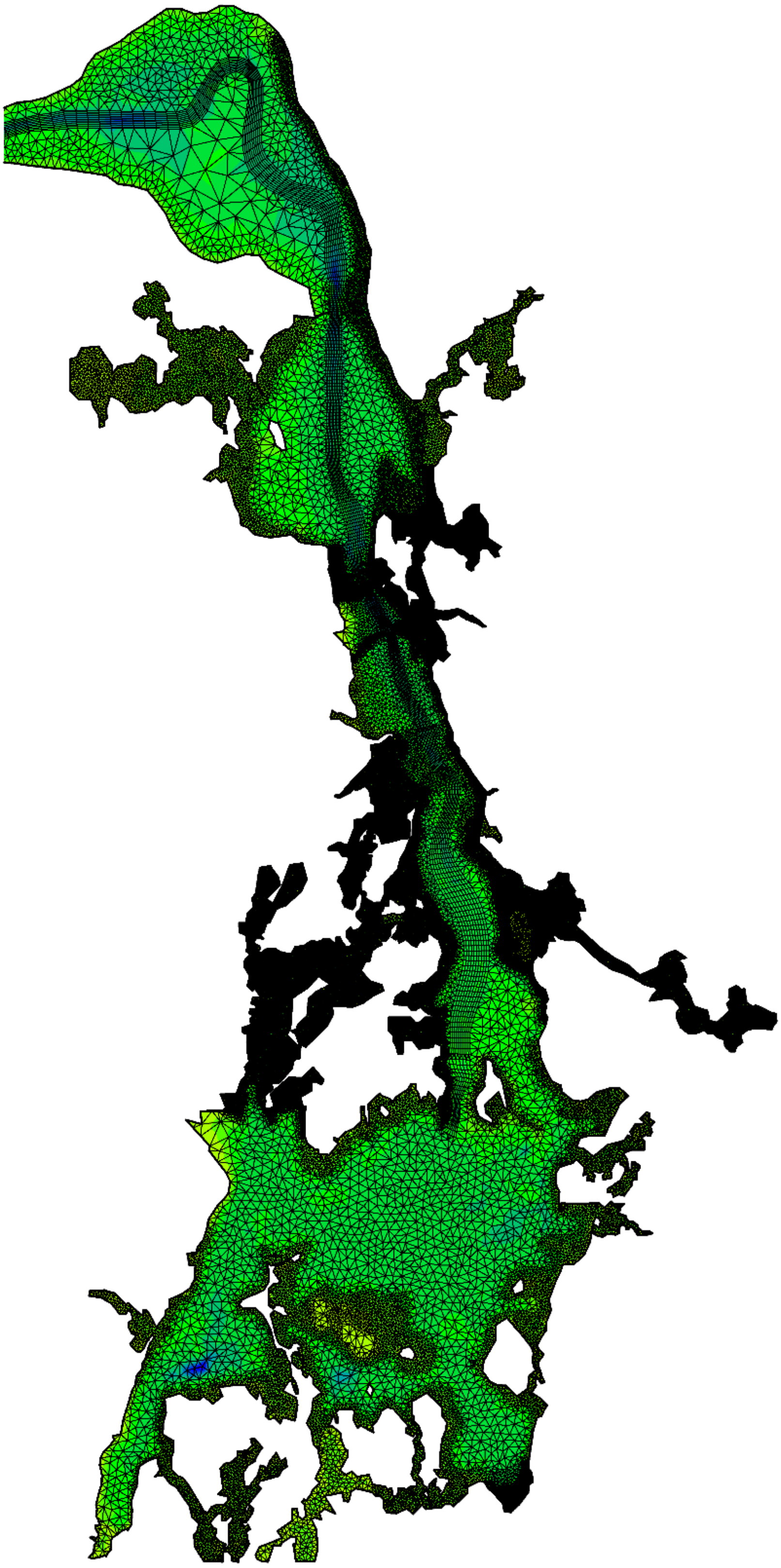


Figure 21.65 Flexible mesh technique is well suited for complex estuarine or fjord systems.

In Figure 21.66 the water level close to the entrance at the northwest end of the fjord is depicted. It is noted that water level above 1.6 m at the entrance to the fjord lasted about 16 hours due to an unusual long duration of the northwesterly storm. A water level of 1.6 m corresponds to a 100 years recurrence period at the entrance to the fjord and the extreme water level of 1.76 m corresponds to a recurrence period of 500 years.

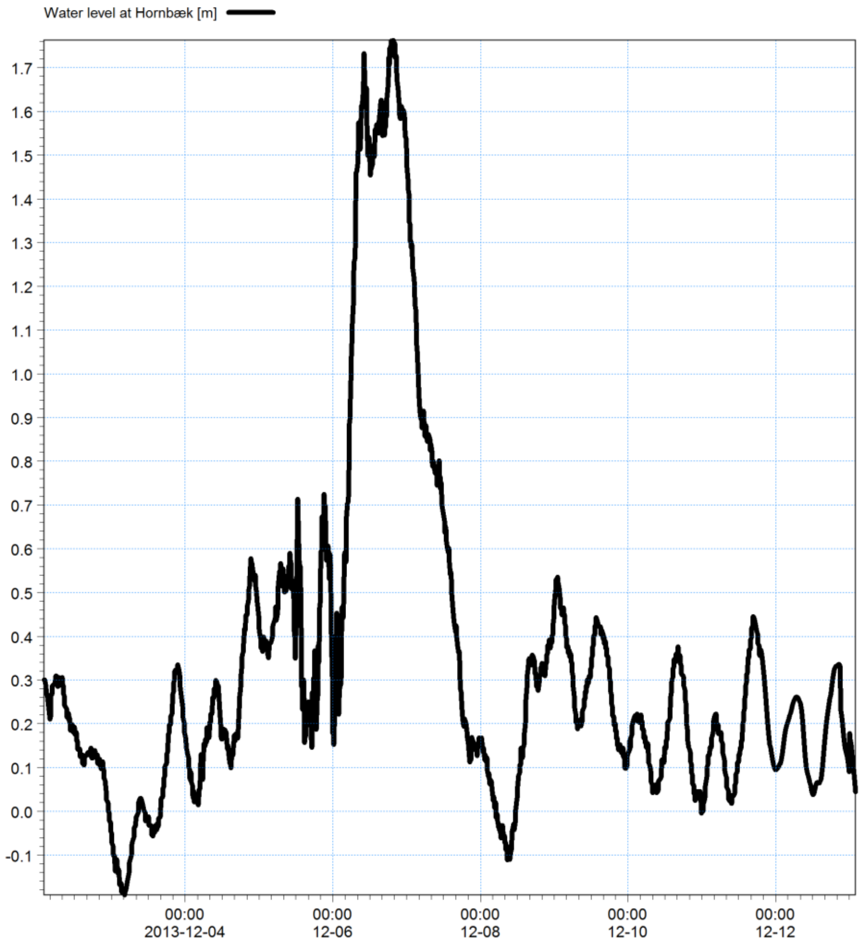


Figure 21.66 Northern water level boundary conditions during extreme storm.

In Figure 21.67 the result in the form of water levels in the model over the entire area is shown for a time step where the maximum water levels in the inner parts of the fjord were observed. The figure reveals an increase in water level from north to south around the peak of the event. It is noted that the maximum water levels increase towards south into the fjord, this is due to the long duration of the storm combined with the local wind setup along the fjord.

In Figure 21.68, an example of an area where flooding was reported is shown. The red dots represent houses that reported damages to their insurance company.

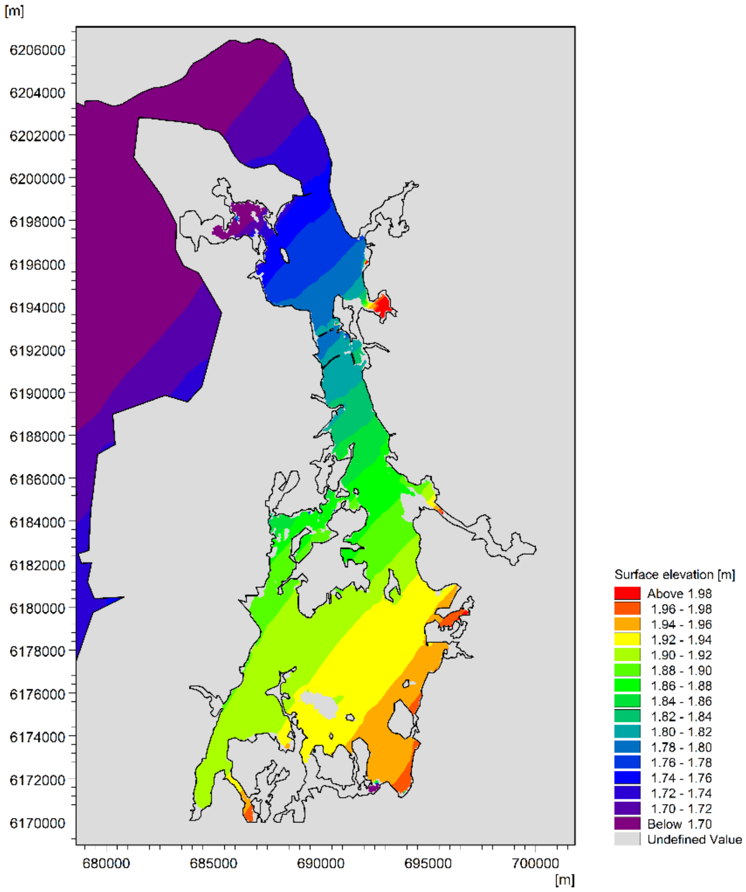


Figure 21.67 Surface elevation around the peak of the storm.

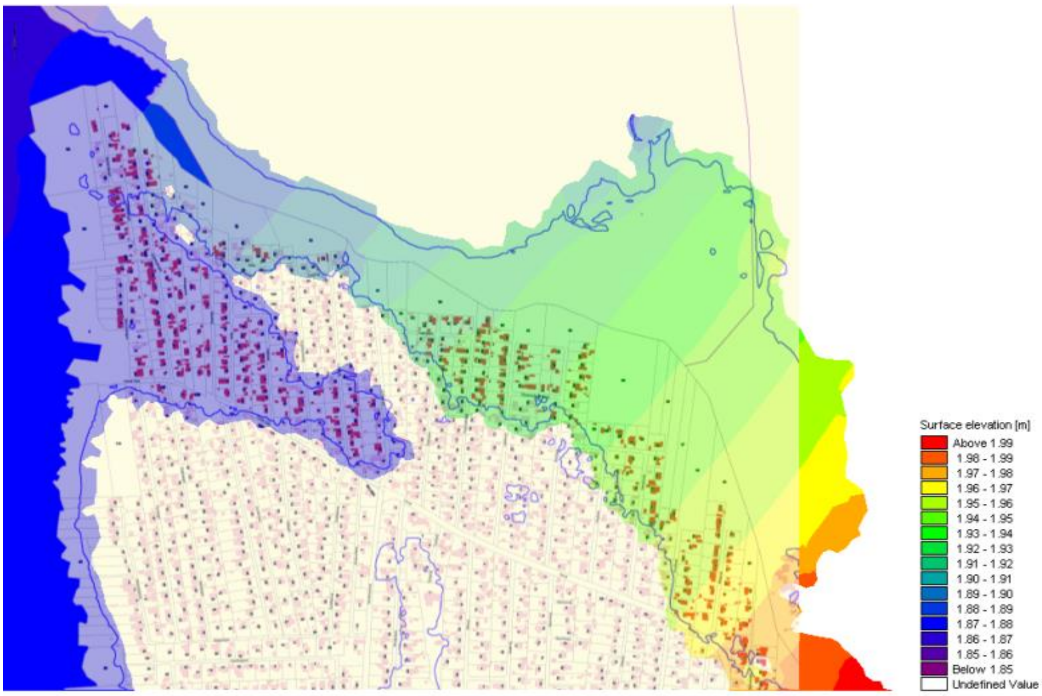


Figure 21.68 Observed flooding of houses (dark red dots) with modelled maximum flood levels as overlay.

21.4.12.2 Example: Analysis of dike breaching for a climate projection

In the case of breaching of dunes or dikes, one needs to include a way of modelling the breaching process of the barrier as basis for simulating the sea water intrusion. One way to do this is to actually model the detailed geometry of the dike and then let part of the bathymetry become lower/wider in the area where the breach is anticipated to happen. This demands a very fine mesh around the breach, which will slow down the overall computation significantly.

Another approach is to include a so-called line-structure that runs through the landscape where the dike is. The height and width and other hydraulic information about the dike are then associated to the line. Furthermore, information about when, where and how the breach will occur is incorporated. The line will then be “seen” in the model as an obstruction between to cells, i.e. an obstruction at the cell face between two adjacent cells. With such an approach, the dike and the dike breach does not need to modelled with very fine cells, but are instead “collapsed” into a line, and the computational speed will not suffer from refined meshing around the breaching dike, see Figure 21.69 and Figure 21.70.

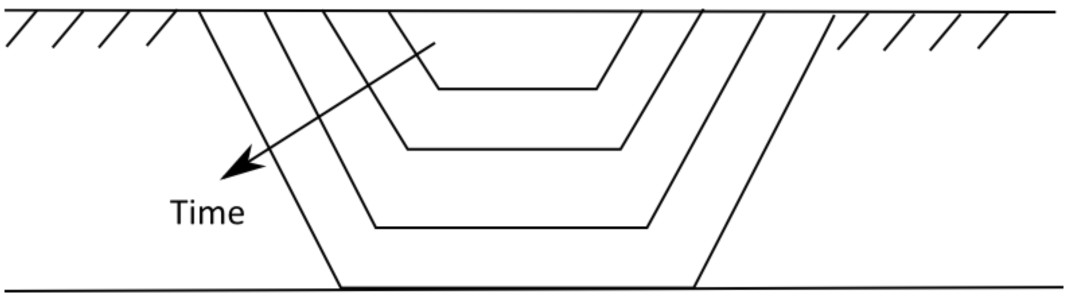


Figure 21.69 Prescribed temporal opening of dike and dune barrier.

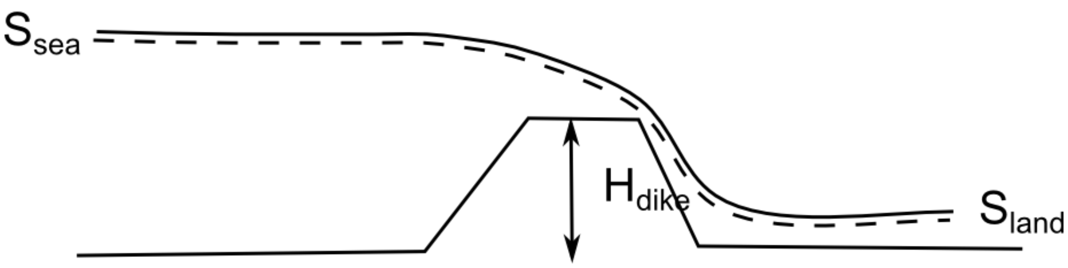


Figure 21.70 Dike overflow represented by a flow resistance for quasi stationary overflows.

The result of a coastal flooding model exercise with a prescribed dike breach is shown in Figure 21.71. The case shows a future projection of higher storm surge levels combined with a dike breach at a section of the dike line that was anticipated to be most vulnerable. The figure show how a flooding wave is created in the hinterland behind the breach, but also that the temporal extend of the storm and size of the breach opening have put a limit to how far the water can penetrate and to the level of local flooding.

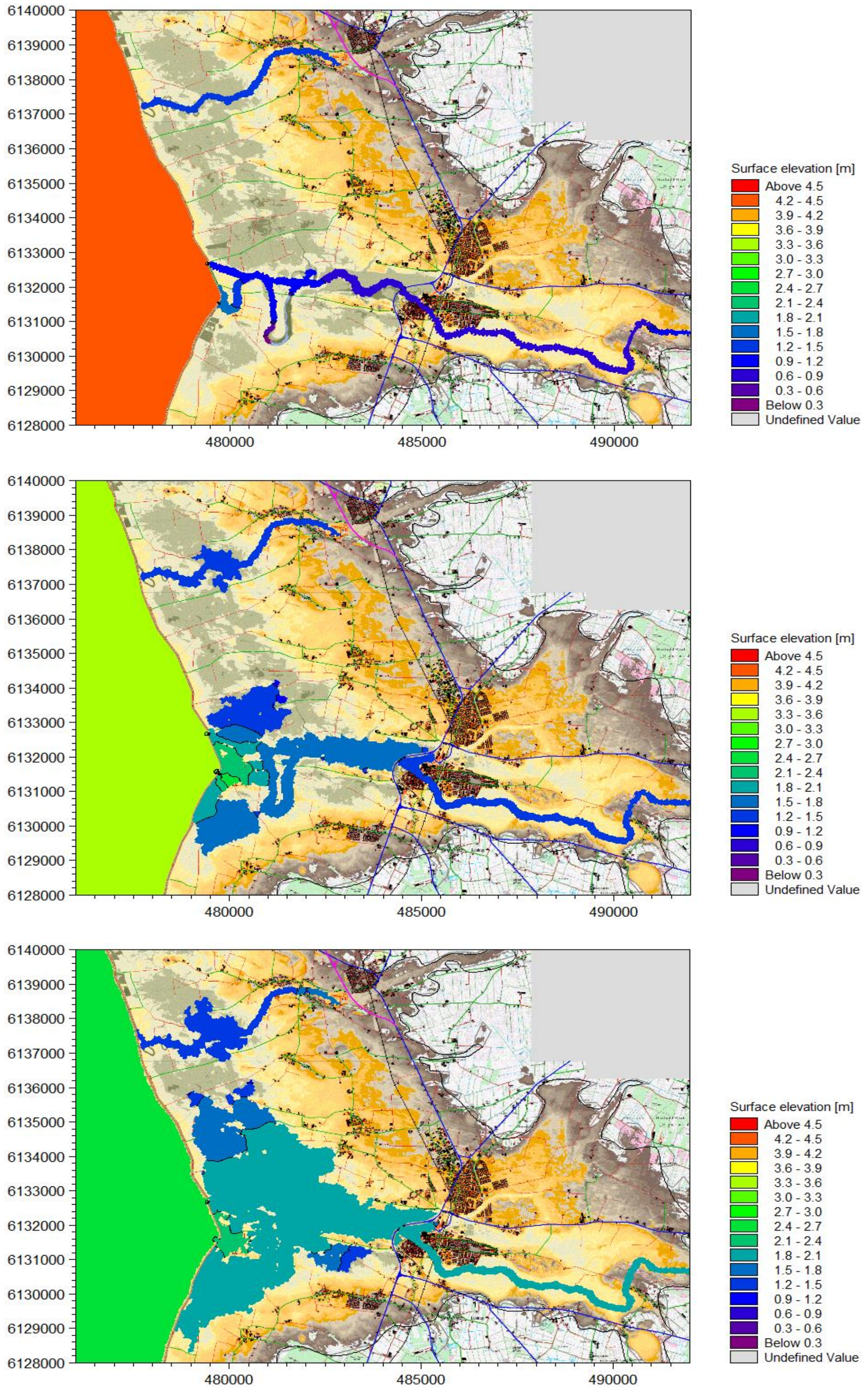


Figure 21.71 The evolution of the flooding intrusion for a 1000 year storm surge event in the case of a dike breach. Top: Breach at maximum sea water level. Middle: 12 hours later. Bottom: 18 hours later.

21.4.13 Modelling climate change impact on coasts

The impact of climate change on the coastal area is per definition an area where numerical modelling gives a significant contribution to the understanding of both the impact of nature on society and anthropogenic effects on nature. A number of inherent problems have to be taken into account though.

Future projections of the global changes in the main climate parameters such as wind and temperature can per definition only be based on the latest data and the latest development within the field of climatology and meteorology (scientific knowledge and model capabilities), hence limitations in the predictability of climate change are inherent. The scientific knowledge and the computational capabilities within long term predictive meteorology are still under development, and predictions and methods for downscaling global predictions to regional and local conditions are uncertain. These capabilities are however expected to be improved in the coming future but in which direction the results will point cannot be foreseen. This means that the future climate data available for computing climate change within the coastal zone are uncertain and that the predictions may undergo changes in many ways during the coming years and decades. There are however a number of hypotheses that are expected to hold in the overall picture, see also Chapter 6:

- Water levels will rise globally
- More intense storms will happen
- Changes in wind and wave direction will be a reality

And also

- Predictions are not accurate
- Statistics for future events and design data including climate change cannot be constructed from historical data without expecting some bias from future changes

This is because climate change is a change in the statistical properties of the different meteorological phenomena.

Therefore the coastal engineer cannot expect to be able to deliver exact predictions of the storms to come and the exact consequences of such changes.

There are at least two options

- To use the best future projection data available now
- To investigate the general vulnerability to different potential changes to the system

So one option is to calculate the coastal response of climate change based on the best available data set. In some cases this means to make different projections and down-scalings based on different meteorological models and make statistics on the ensemble.

21.4.13.1 Coastal responses

As it has already been discussed the coast is subject to two timescales in the context of erosion, hence there are two scales where the climate change will have its impact:

- Long term effects, chronic erosion (vulnerability)
- Changes in acute erosion patterns

21.4.13.2 Vulnerability – long term evolution

An important exercise is in this light to make estimates of the vulnerability of a given coast to climate changes. This can be done by investigating the potential rate of change if a given parameter changes. For example:

How much will the coastal system change for:

- Change in the wave height under storms by +-10%
- Changes in peak wave height of e.g. ± 1m
- Changes in reoccurrence of an extreme event (return period).
- Changes in water level by 0.5, 0.7, 1m (or what prediction for SLR is reasonable for the given region).
- Changes in the directionality of waves by ± 5 deg, ±10 deg

By doing such exercises, the coastal response to different types of changes can be mapped, and a lot more information will be available for managers to look for potential threats, and to update their management plans according to the continuous inflow of new data about the future climate (globally or at a given location). Some coasts may turn out to be resilient to the expected changes and others may be vulnerable, hence giving the managers the possibility to focus their effort on such coasts.

21.4.13.3 Short term extreme events

A very important aspect of climate change is the extreme events – not only events that are likely to occur from a statistical point of view but also events that are qualitatively different from events seen in the statistics. In fact two examples of such analyses were given in the coastal flooding examples. In the general case the models described in the guideline open up to a broad spectrum of possibilities to investigate almost any possible situation that may be of interest for the coastal communities.

22 Physical Modelling

Physical scale models can be relevant for some aspects of a Shoreline management project. Due to the steady increase in the applicability and reduction of costs of numerical modelling the use of physical modelling has decreased and it is now mainly used in connection with very large projects and for specific purposes.

It should be noted that only model tests at a reduced scale, which are used in connection with an engineering project, is considered here. Physical experiments investigating physical processes and natural phenomena will continue to be a very active and important field of research, which are carried out in the research facilities available in many countries.

Physical modelling is a vast field in itself, and only the very basic and general background information is outline in the following, instead reference is made to: Frostick et al. (2011) and Hughes (1993).

When making a hydraulic scale model with the same fluid in model and prototype a model law must be applied and only a single force can be reproduced fully correct in the tests. Of possible forces: viscosity, gravity, surface tension etc., gravity is the most important for free surface flow and the model is to be designed and interpreted by use of Froude's model law. In a model at a reduced scale this means that viscous forces and surface tension will be relatively stronger in the model than in the prototype, which puts a limit to how much the model can be scaled down, and in reality physical models can only cover areas up to a size of the order a few kilometres in the field.

The scale effects become even more important when considering movable bed tests. Gravity is the stabilising force when mobilising sand or gravel and Froude's model law is therefore still relevant. However, when scaling sand particles down by, say, a factor 35 the model sediment would become fine silt. This means that cohesive forces would become important and also that the settling velocity, which depends on viscosity, would be scaled incorrectly. A direct scaling of the sediment would therefore lead to behaviour completely different from the prototype. Instead movable bed tests are carried out with fine sand, while ensuring that the scale and the conditions are such that there is active sediment transport in the model as well as there is in the prototype. Scale models with movable bed can therefore not reproduce more subtle details and can for example not be used to analyse coastal morphology in any detail. They are well suited for describing conditions with a 'strong signal' such as local scour and erosion around structures and for large scale experiments on profile evolution carried out in very large wave flumes.

The main areas where physical modelling can be suitable in connection with a Shoreline management project are:

Fixed bed models

- Stability and overtopping of structures
- Wave disturbance in marinas planned as part of the project
- Wave conditions and wave driven currents in very complicated environments

Movable bed models

- Local scour and erosion around structures
- Investigations of small beach compartments and conditions around structures for relatively coarse bed material

The present Shoreline Management Guidelines mainly address the meteormarine factors, the associated coastal processes and coastal morphology, coastal erosion and flooding, planning concepts and the need, functionality and impacts of coastal protection and sea defence systems, all with emphasis on planning, functionality and layout rather than on construction details. These items are what come under the umbrella of Shoreline management. None of the main applications areas for physical models are core areas for Shoreline management. Consequently, physical modelling will not be further described in the present context.

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In addition to the above references, experience gained from numerous DHI coastal and shoreline management studies has also been utilised. No specific references have been given to all these studies, as the reports are not available to the public.

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SHORELINE MANAGEMENT GUIDELINES

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