Coastal Engineering Volume I

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<thead>
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<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_c$</td>
<td>Coriolis acceleration</td>
</tr>
<tr>
<td>$A_{\text{min}}$</td>
<td>minimum equilibrium cross section area of the entrance in m$^2$</td>
</tr>
<tr>
<td>$c$</td>
<td>wave propagation speed [m/s]</td>
</tr>
<tr>
<td>$c_g$</td>
<td>group speed</td>
</tr>
<tr>
<td>$c_0$</td>
<td>wave speed in deep water</td>
</tr>
<tr>
<td>$c(z,t)$</td>
<td>sediment concentration as a function of time and place</td>
</tr>
<tr>
<td>$C$</td>
<td>Chézy friction factor</td>
</tr>
<tr>
<td>$d$</td>
<td>water depth [m]</td>
</tr>
<tr>
<td>$e$</td>
<td>water vapour pressure (mb)</td>
</tr>
<tr>
<td>$e_w$</td>
<td>saturation vapour pressure (mb)</td>
</tr>
<tr>
<td>$E$</td>
<td>Wave energy per unit of water surface area</td>
</tr>
<tr>
<td>$E_j$</td>
<td>chance that $H_d$ is exceeded at least once in a single storm period</td>
</tr>
<tr>
<td>$g$</td>
<td>gravity acceleration [m/s$^2$]</td>
</tr>
<tr>
<td>$h$</td>
<td>water depth</td>
</tr>
<tr>
<td>$h(t)$</td>
<td>measured tidal curve</td>
</tr>
<tr>
<td>$h_{av}$</td>
<td>average depth</td>
</tr>
<tr>
<td>$h_0$</td>
<td>mean level</td>
</tr>
<tr>
<td>$h_i$</td>
<td>component number $i$ (diurnal, semi-diurnal, higher harmonical components)</td>
</tr>
<tr>
<td>$H$</td>
<td>wave height [m]</td>
</tr>
<tr>
<td>$H_0$</td>
<td>wave height in deep water, before shoaling</td>
</tr>
<tr>
<td>$H_i$</td>
<td>wave height at location 1, after shoaling</td>
</tr>
<tr>
<td>$H_{1ms}$</td>
<td>root mean square = 0.7 $H_{1sig}$</td>
</tr>
<tr>
<td>$H_{av}$</td>
<td>average wave height = 0.62 $H_{1sig}$</td>
</tr>
<tr>
<td>$H_{1sig}$</td>
<td>significant wave height</td>
</tr>
<tr>
<td>$i$</td>
<td>wave configuration number (harmony number)</td>
</tr>
<tr>
<td>$k$</td>
<td>wave number [m$^{-1}$] = $2\pi/L$</td>
</tr>
<tr>
<td>$L$</td>
<td>wave length [m]</td>
</tr>
<tr>
<td>$L_b$</td>
<td>length of the basin [m]</td>
</tr>
<tr>
<td>$L_w$</td>
<td>length of wedge [m]</td>
</tr>
<tr>
<td>$L_d$</td>
<td>wave length in deep water</td>
</tr>
<tr>
<td>$M_l$</td>
<td>number of possible storms in the structure's lifetime</td>
</tr>
<tr>
<td>$n$</td>
<td>ratio of group speed to phase velocity (phase velocity of individual wave)</td>
</tr>
<tr>
<td>$n$</td>
<td>normal to the current</td>
</tr>
<tr>
<td>$P$</td>
<td>tidal prism volume in m$^3$ (storage volume between low tide and high tide levels)</td>
</tr>
<tr>
<td>$p$</td>
<td>water pressure</td>
</tr>
<tr>
<td>$p'$</td>
<td>atmospheric pressure = 1.0133 * 10$^5$ Pa.</td>
</tr>
<tr>
<td>$P(H_d)$</td>
<td>chance that a $H_d$ is exceeded</td>
</tr>
<tr>
<td>$Q_w$</td>
<td>inflow in the wedge</td>
</tr>
<tr>
<td>$Q_f$</td>
<td>fresh water river flow</td>
</tr>
<tr>
<td>$Q_l$</td>
<td>net outflow through the cross section</td>
</tr>
<tr>
<td>$S$</td>
<td>salinity [in %o]</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>$S_1, S_2$</td>
<td>respective salinities</td>
</tr>
<tr>
<td>$t$</td>
<td>time [s]</td>
</tr>
<tr>
<td>$T$</td>
<td>wave period [s]</td>
</tr>
<tr>
<td>$T'$</td>
<td>tide period</td>
</tr>
<tr>
<td>$T_i$</td>
<td>period of wave configuration number $i$</td>
</tr>
<tr>
<td>$T_{av}$</td>
<td>average period</td>
</tr>
<tr>
<td>$T_s$</td>
<td>absolute temperature of the sun surface, which can be considered to be 6000K</td>
</tr>
<tr>
<td>$U$</td>
<td>relative humidity (%)</td>
</tr>
<tr>
<td>$V$</td>
<td>current velocity</td>
</tr>
<tr>
<td>$V_D$</td>
<td>velocity in the dry bed curve</td>
</tr>
<tr>
<td>$V_{eq}$</td>
<td>maximum velocity where equilibrium is present</td>
</tr>
<tr>
<td>$V_r$</td>
<td>velocity in the river upstream from the wedge</td>
</tr>
<tr>
<td>$V_1$</td>
<td>velocity in the fresh water above the wedge</td>
</tr>
<tr>
<td>$V_2$</td>
<td>velocity in the salt wedge</td>
</tr>
<tr>
<td>$V_{\text{max}}$</td>
<td>maximum flood current</td>
</tr>
<tr>
<td>$x$</td>
<td>distance in propagation direction [m]</td>
</tr>
<tr>
<td>$\alpha_i$</td>
<td>phase</td>
</tr>
<tr>
<td>$\eta$</td>
<td>instantaneous vertical displacement of the surface [m]</td>
</tr>
<tr>
<td>$\phi$</td>
<td>latitude</td>
</tr>
<tr>
<td>$\phi_0$</td>
<td>angle of incident waves with depth contours in deep water</td>
</tr>
<tr>
<td>$\phi_{br}$</td>
<td>angle of incident waves at the outer edge of the breaker zone</td>
</tr>
<tr>
<td>$\rho$</td>
<td>mass density of water</td>
</tr>
<tr>
<td>$\rho_D$</td>
<td>mass density of denser layer</td>
</tr>
<tr>
<td>$\delta$</td>
<td>relative density $= (\rho_D - \rho)/\rho_D$</td>
</tr>
<tr>
<td>$\theta_1, \theta_2$</td>
<td>respective layer thicknesses</td>
</tr>
<tr>
<td>$\theta$</td>
<td>friction factor</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>constant of Stefan-Bolzmann $= 5.67 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$</td>
</tr>
<tr>
<td>$\sigma_H$</td>
<td>standard deviation of wave height $= 0.25$ Hsig</td>
</tr>
<tr>
<td>$\sigma_i$</td>
<td>the density values under atmospheric pressure minus 1000</td>
</tr>
<tr>
<td>$\tau_i$</td>
<td>friction stress along the interface</td>
</tr>
<tr>
<td>$\omega$</td>
<td>phase velocity [s$^{-1}$] $= 2\pi/T$</td>
</tr>
<tr>
<td>$\omega_e$</td>
<td>angular velocity of the earth $= 72.9 \times 10^{-6}$ rad/s (based on sidereal day)</td>
</tr>
<tr>
<td>$\omega_i$</td>
<td>angular velocity of tidal component number $i$</td>
</tr>
</tbody>
</table>
Preface

The goal of this book is to draw a profile of the world behind the coastal engineer's work. For a good understanding of this world, many other disciplines are needed. For example historical, geological, physical and economical information and activities are integrated into the terrain of the coastal engineer. Other disciplines, like biology and sociology, yield extremely important information for the coastal engineer, but as they are not integrated yet into the engineering approach, they are not worked out in this introduction. Apart from that, a good approach cannot be made without a personal sense of "what is going on". No book can give a complete picture of the coastal engineering practice, so in addition to studying this book, it is necessary to be curious and have a look at the coast. Not only in summer, but also during stormy weather; to sniff the spray and feel the sand blown by the wind.
1 Introduction

1.1 The coast

If you would ask a Dutch Coastal Engineer to define "the coast", what would he or she say? And what would a Chinese colleague answer, if you asked her or him the same? If these two Coastal Engineers would have read this book properly, they would answer to you: "Why do you need the definition?". Because, to put it simply: the definition of the coast and the coastal zone is not absolute. The area involved depends on the physics of the case. Besides, in different countries, different definitions can be common. For example: are river mouths included? The culture and nature in which the coast is situated characterize it. Therefore, in every specific case, one must determine what definition of the coastal zone is best. In the Netherlands, the coastal zone is often defined as the area where tide is present. However, another definition is equally possible; for instance the dune area.

In general, a coastal zone has a number of (often conflicting) functions. Among those functions are very important ones: housing, production of food and water, transport, nature, recreation (social well-being). In the Dutch case, main function of the dune coast is the defence of the hinterland against inundation. Next to that, the recreational beach is an example of one far-developed function of the coast. Other functions could suffer from that. (Scheveningen at the Dutch North Sea beach on a sunny day can be very crowded. In Dutch it is said "people are like herrings in a little barrel".)

Let's take a closer look at this coastal zone in general. The coastal zone system can be defined in different ways. Next to that, the elements and processes inside the system must be defined. In case of the coastal zone, the system elements can be grouped into two subsystems: the natural and the artificial subsystem. The last one consists of infrastructure and socio-economic user functions. The natural subsystem is everything else. It is not hard to imagine that the two subsystems have strong interactive links.

Another thing which is not difficult to think of is the necessity of conscious coastal zone management. It is predicted (World Coast Conference '93 [1994]) that more than half of the human world population will soon be living in the coastal zone (coastal zone in a rather broad sense in this case). Most of the largest metropolitan areas are located along the coast: Tokyo, Jakarta, Shanghai, Hong Kong, Bangkok, Calcutta, Bombay, New York, Buenos Aires, Los Angeles. A lack of balance in the natural and cultural processes in the coastal zone can lead to great poverty, pollution, social problems and structural deficiencies. In short: the world's future depends largely on the future of the coastal zones.
1.2 Coastal engineering

Coastal engineering is the general term for all engineering activities related to the coast. Typical engineering activities are: system, process and problem analysis; management of information and measurement programs; system schematization and modelling; planning, design and construction of artificial structures; preservation of the natural system. If we translate the main elements of this general definition into coastal engineering terms, we get: coastal system, coastal processes, coastal problems, coastal zone management. Two mentioned key words are very important: coastal system and coastal zone (management). How can they be defined?

The coastal system consists of natural and cultural elements (dunes, beach, river mouth, bird population, coastal zone authority). In order to determine which engineering activities might serve a given situation, the coastal system must be studied in all relevant aspects. Coastal processes can also be divided into natural (for example, sediment transport) and cultural processes (for example, economic growth of the coastal zone). For coastal engineers, the study of the natural processes is a focal point. The study of cultural processes tends to be part of the subject coastal zone management.

As was said before, the coastal zone borders cannot be defined clearly. Where the sea starts, the coast does not stop. But where does it stop? At the edge of the continental shelf perhaps? Or at the edge of one's technical skills? The landside border is even more difficult to determine. A river can influence a coast via the sediment it carries; it can be a sediment source. Any change in the river regime may thus have serious consequences for the coast. Thus the whole, or at least part of the flow area of the river may need to be considered as an element of the coastal zone.

Engineering activities are an ever increasing influence on the coast; the coastal zone management and engineering fields have definitely not finished developing. The contrary holds true; the working terrain is still growing as the size, the intensity, and the importance of the coastal zones are growing.

Back to the engineering key words. The most of them (problem, information, measurement, model, artificial structures) need a larger context. The context is in the rest of this book, and of course: in working practice.
1.3 Structure of these lecture notes

In these lecture notes, a selection of subjects is made, in order to inform the reader about the basics of coastal engineering. This means: many things cannot be taken into account, because the practice of coastal engineers is too diverse to put all important topics into one book. This syllabus does describe the main processes which take place around the coast. Literature, out of which much information has been put into this book, is listed and recommended warmly.

First of all, in Chapter 2, the coast as a physical system is given a brief description. As an important basis, plate tectonics theory is described. This is the terrain of the geology. Next to that, smaller-scaled processes which form the coast are treated. Climatology, oceanography and morphology are the names under which these processes can be defined. Together they form a complex system of natural processes which give shape to the coast.

The third chapter gives a view on coastal formations. Different parts of the world are visited to give more detailed information about the dynamics of different coastal types.

Chapter 4 deals with the cultural aspects of the coastal system, as far as they are relevant for the engineering practice. This relevance exists especially for social and economic aspects. To man, the coast has always been very attractive. Socio-economic activities have always been intense in the coastal zone, and they are still growing. Therefore, global socio-economic problems, like poverty, are intense in the coastal zone, too. The answer to them is commonly thought to be (Integrated) Coastal Zone Management. An introduction to this form of management is given.

What about the Netherlands? The country has had a long history of engineering works related to the coast. A review of its main facts is given in Chapter 5. The coastal history of the Netherlands does not start, like history in school, with Karel the Great or the Fifth, but with a time, long long ago, some 18,000 years before present. Then, the sea level started rising and brought the coastline nearer to what is now the Dutch coast. The story went on and now there are the Delta project and many other visible and less visible aspects of coastal engineering practice.

Where fresh and saline water meet, density problems can be expected. Another aspect of the coastal zone is its vulnerability to pollution. Chapter 6 is dedicated to both types of problems.

Chapter 7 of this introduction into coastal engineering goes into some practical details of the subject. Several problems are treated which could be expected to be found in the everyday practice of the coastal engineer. Design skills form a major part of this practice. Attention is given to some (coastal) design basics.
The natural subsystem

2.1 Introduction

2.1.1 Dynamics of a coast

How is a coast (being) formed? Any single coast is the result of processes at three time scales: the slow geological processes of mountain formation and erosion that require millions of years; the gradual sea level changes requiring thousands of years; and superimposed over these the day-to-day and year-to-year combination of long-term and short-term action of the wind, waves, currents, and tides. And on a very recent scale, there is the influence of mankind. Originally, people were causing no more than scratches on the world map. With modern construction equipment, human influence on the coastal forms is even visible from space.

Coast formation is driven by three major energy sources: solar energy, gravitation and earth rotation energy, and geothermal energy. The sea level interacts with the other system parameters geology and climate. Geology and climate influence the coast in their own way, both from the
seaside and from the landside of the coast (Figure 2.1). In order to take a closer look at these influences, this chapter deals with the following specialities: geology (science of the earth), oceanography (science of the ocean) and tide (influences of other celestial bodies), climatology (science of the atmosphere) and morphology (science of the processes that shape the coast).

2.1.2 Genesis of the universe, earth, ocean, and atmosphere

Geologists believe that the ocean covered the face of the earth for about 200 million years between 3.9 and 4.1 billion years ago, and according to theories, life originated in geothermal springs deep in the ocean. The ocean contains 1,360,000,000 km$^3$ of liquid water and covers more than 70% of the earth's surface. This vast blue ocean is unique in our solar system. Water does exist on other planets, but it is either locked in ice or suspended as vapor in thick, hot atmospheres, prevented from condensing and falling to the surface below. Why is the earth unique in this respect?

For a possible answer, before diving into geological times, ocean depths and games of the elements, let's take a look at still more fundamental theory: the origin of the universe, earth, ocean, and atmosphere (Ingmanson and Wallace [1985]). When did the universe originate? Scientists think that the universe came into existence between 10 and 20 billion years ago (NB one billion $= 10^9$!). This estimation is changing and has been made via three approaches. These approaches are:

1. nuclear chronology (based on rates of formation and relative amounts of the elements uranium, thorium, osmium, plutonium, and rhenium);
2. studies of the age of the oldest stars;
3. measurements of the rate at which the universe has expanded.

According to the model most widely accepted by astronomers, the universe originated in a great explosion, the so-called big bang. This model is consistent with observations first made in 1929 that distant galaxies are receding from the earth at velocities proportional to their distance from earth. In 1948 George Gamow predicted that astronomers would one day detect background microwave radiation left over from the big bang. In 1965, Penzias and Wilson proved Gamow right when they detected that radiation, and subsequent measurements provided further confirmation. Other theoretical models have been proposed to explain the origin of the universe, but these have proved deficient when tested against observations and physical measurements. In Table 2.1, the chronology is shown.

Although we shall never know all the details of how the sun formed, many astronomers accept the gravitational collapse theory (Figure 2.2). According to this theory all stars, including the sun, are formed in much the same way, and planets sometimes emerge as a natural by-product of their formation.

Interstellar space contains vast amounts of gas, of which 99% consists of hydrogen and helium.
atoms. These gases frequently accumulate into more or less coherent clouds, or nebulae (Latin for clouds or mist). One such nebula is believed to have collapsed in response to gravity to form our solar system. Its initial mass was probably slightly greater than the present mass of our sun (approximately $2 \times 10^{30}$ kg).

Table 2.1  
Chronological history of the origin of the universe, earth, and life  
(Ingmanson and Wallace [1985])

<table>
<thead>
<tr>
<th>Event:</th>
<th>Time before present:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big Bang</td>
<td>20 billion years</td>
</tr>
<tr>
<td>Particle creation</td>
<td>20 billion years</td>
</tr>
<tr>
<td>Universe becomes matter dominated</td>
<td>20 billion years</td>
</tr>
<tr>
<td>Universe becomes transparent</td>
<td>19.7 billion years</td>
</tr>
<tr>
<td>Galaxy formation begins</td>
<td>18-19 billion years</td>
</tr>
<tr>
<td>Galaxy clustering begins</td>
<td>17 billion years</td>
</tr>
<tr>
<td>Our proto-galaxy collapses</td>
<td>16 billion years</td>
</tr>
<tr>
<td>First stars form</td>
<td>15.9 billion years</td>
</tr>
<tr>
<td>Our parent interstellar cloud forms</td>
<td>4.8 billion years</td>
</tr>
<tr>
<td>Proto-solar nebula collapses</td>
<td>4.7 billion years</td>
</tr>
<tr>
<td>Planets form; rock solidifies</td>
<td>4.6 billion years</td>
</tr>
<tr>
<td>Intense cratering of planets</td>
<td>4.3 billion years</td>
</tr>
<tr>
<td>Oldest terrestrial rocks form</td>
<td>3.9 billion years</td>
</tr>
<tr>
<td>Microscopic life forms</td>
<td>3 billion years</td>
</tr>
<tr>
<td>Oxygen-rich atmosphere develops</td>
<td>2 billion years</td>
</tr>
<tr>
<td>Macroscopic life forms appear</td>
<td>1 billion years</td>
</tr>
<tr>
<td>Earliest fossils recorded</td>
<td>600 million years</td>
</tr>
<tr>
<td>Early land plants appear</td>
<td>450 million years</td>
</tr>
<tr>
<td>Fish appear</td>
<td>400 million years</td>
</tr>
<tr>
<td>Ferns appear</td>
<td>300 million years</td>
</tr>
<tr>
<td>Conifers appear</td>
<td>250 million years</td>
</tr>
<tr>
<td>Reptiles appear</td>
<td>200 million years</td>
</tr>
<tr>
<td>Dinosaurs appear; continental drift occurs</td>
<td>150 million years</td>
</tr>
<tr>
<td>First mammals appear</td>
<td>50 million years</td>
</tr>
<tr>
<td>Homo sapiens appears</td>
<td>2 million years</td>
</tr>
</tbody>
</table>

As the nebula contracted, its rate of rotation increased and the nebula began to flatten as a result. It continued to contract until most of the matter had coalesced into a central mass, which ultimately became the sun. A small portion of the nebula survived as a flat disc spinning around the central mass, and it was from the matter contained in that disc that the planets eventually formed.

As the proto-sun (proto- from the Greek for "first, foremost, earliest form of") continued to contract, its internal temperature rose from tens of thousands to several million degrees Kelvin. The immense internal pressure that developed due to particle collisions eventually halted further gravitational contraction, and the sun stabilized. Nuclear fusion, which occurs at such extreme temperatures, released sufficient energy to maintain the temperature and pressure at constant levels, thus stabilizing the sun at essentially the same size as it is now. This whole process of
formation, from nebula to stable star, probably required several tens of millions of years and
curred some 4.6 billion years ago.

While the proto-sun was undergoing the final stages of contraction, the flat disc of gas, solids,
and liquids spinning around it, was forming into planets. The planets are believed to have grown
through a steady process of accretion in which dust particles, molecules, and atoms at first joined
together to form larger bodies, which in turn coalesced into larger and larger bodies. In time,
through collision and gravitational attraction, these bodies developed into what we call planets.
Reasons to regard this scenario as plausible are many. The orbits of the planets lie in roughly the
same plane (except Uranus, Figure 2.3), and they revolve around the sun in the same direction
and in virtually circular orbits (except Pluto). It seems likely that these highly regular orbital
characteristics were established during the collapse of the nebu, before the planets formed.

The third planet out from the evolving sun was the earth. As it grew in mass, its temperature
increased as a result of the energy released by impacts with meteors and the decay of radioactive
elements within the planet. Although its temperature never rose to the level needed to initiate
uclear reactions, it did rise high enough to melt the interior. When this happened heavier
elements, such as iron and nickel, were differentiated from lighter elements, such as carbon, and
light minerals, such as quartz. The heavier elements formed the earth's core, and the lighter
materials formed the mantle and crust.
The lightest gases, hydrogen and helium, were too light to be held by the earth's gravitational field. In fact, in these very early stages of the earth's history, the gravitational field was probably not strong enough to hold any gases at all. Since the heavier, chemically inert gases (neon, argon, and xenon) are less abundant on the earth than on other planets, scientists infer that the earth lost its early atmosphere to space.

Where did the water now contained in the earth's oceans and atmosphere come from? The answer lies in the assumption that volcanoes were abundant early in the earth's history and that impacts by meteors caused gases to escape from the earth's surface. Volcanic gases consist mainly of...
water vapor, nitrogen gas, and carbon dioxide. If the surface temperature of the early earth was about the same as it is now, the water vapor would have condensed to liquid water and the nitrogen gas and carbon dioxide would have formed the atmosphere.

Would the condensation of the water vapor into liquid water have been sufficient to form the oceans? At the present rate of volcanism, the earth would have to be three times as old as we believe it to be (4.5 billion years) for condensation to have produced the oceans as they exist today. The rate of volcanism may have been considerably greater in the past than it is today, in which case condensation of the water vapor produced by volcanoes might have been sufficient to create the present-day oceans.

Water vapor may also have been released when the impact of meteors raised the surface temperature of the early earth high enough to melt the outer layers. If the composition of those layers was similar to that of meteorites, which contain about 0.5% water, melting would have released large amounts of water vapor. As time passed, the frequency of impacts would have declined, since the meteors near the earth would have collided with it early in its history. The earth would have subsequently cooled, and the water vapor would have condensed, contributing to the formation of the ocean. Volcanic activity has probably continued to increase the volume of water in the ocean.
2.1.3 Sea level change

Since it was formed, the ocean has never been constant or static. The process of "new water formation" by volcanic activity, as was referred to in the previous paragraph, produced very small water level changes. But there have been, and are other processes, which affect the global sea level much stronger. The most important of these definitely is temperature change. If the global temperature rises, it leads to expansion of the total water mass, and to melting of ice caps. This has happened often during the earth's history, and it is still happening.

Sea level changes can affect the coastal zone very strongly. Sea level rise is relative; it can be caused by absolute sea level rise or by absolute descent of the continent. As the shoreline moves, it either exposes or inundates coastal areas and, in doing so, causes the character of the coast to change. Additionally, the position of the shoreline influences coastal processes that shape the coastal environments.

Sea level changes are considered to be caused by the following processes (Davis [1994]):

1. tectonic activity;
2. climatic fluctuations;
3. regional subsidence due to compaction and fluid withdrawal;
4. subsidence and rebound of the lithosphere;
5. changes in the volume of the world ocean;
6. advance and retreat of ice sheets;
7. continental rebound;
8. holocene rise in sea level;
9. human-induced climate change.

In order to explain these processes, the geological, climatological, oceanographical and morphological background of them must be described first. These descriptions follow in the next paragraphs.

Sea level rise is a danger to the people in many countries. As coastal defence is an expensive business, poor countries are the most vulnerable to this danger.
2.2 Geology

2.2.1 Geologic time and definitions

Figure 2.4 Geologic time scale (Spectrum Atlas [1973])
Geologists do not go back to the big bang in their descriptions. They have their own way of subdividing the past time into eras, periods, and epochs. Figure 2.4 shows how. Chronological ages are based on radiometric dating methods.

Radiometric dating is a relatively new technique of determining the absolute age of units. Before the mid-20th century, the only available technique was fossil time scaling. This technique only gave information about the relative age of rock bodies, compared to each other. For example, the boundary between the Mesozoic ("interval of middle life") and the Cenozoic ("interval of modern life") eras is marked by the disappearance of hundreds of species, including the dinosaurs, and the appearance or sudden proliferation of many new species (Stanley [1986]). The Cenozoic is subdivided into the Tertiary and the Quaternary. The Quaternary consists of the Pleistocene and the Holocene.

The epochs of most concern to coastal engineers and geologists are the Pleistocene and Recent or Holocene, extending back a total of 1.8 million years before present. During the Pleistocene, pronounced climatic fluctuations happened. Continental glaciers periodically covered vast areas of the continents in what is called the modern Ice Age. Many, today still recognizable, geomorphic features were shaped or deposited at that time. The Holocene Transgression started around 15 to 18 thousand years ago with the beginning of global sea level rise. In the same time, the global climate was warming. Many morphological features associated with the coastal environment are Holocene in age, but the preexisting geology is often visible, as well.

2.2.2 Plate tectonics: the changing map of the earth

The theory of plate tectonics has a complicated history that reaches back to the global maps created after the great ocean voyages of the 16th and 17th centuries. As the maps became more accurate, the landmasses took on the appearance of pieces of a giant puzzle. Sir Francis Bacon is credited as the first to note this resemblance; in 1620 he wrote that the coastlines of South America and Africa would fit together perfectly if the ocean were not between them.

In 1912 Alfred Lothar Wegener presented a comprehensive scheme to explain the distribution of the continental landmasses. He believed that the continents had slowly drifted apart from a primordial super-continent, which he called Pangaea (Greek for "all earth"). He envisioned a single world ocean, Panthalassa ("all ocean"), with a shallow sea, Tethys (from Greek mythology, the mother of all oceans), located between Laurasia and Gondwanaland, the northern and southern portions of the super-continent (Figure 2.5). Using accepted geologic and paleontologic data, Wegener provided good supporting evidence for the continuity of geologic features across the now widely separated continents. Three years later, Wegener produced his major work, "Die Entstehung der Kontinente und Ozeane", in which he presented an enormous amount of evidence in support of his theory.
Figure 2.5  Continental landmasses during the early Triassic Period (Davis [1994])

Figure 2.6  Continental drift (Wegener [1924])
The continental landmasses that formed Pangaea gradually drifted from their original positions. In Figure 2.6 this process is illustrated. They reached intermediate locations 135 million years ago, between the Jurassic and Cretaceous Periods. After almost 200 million years, the continents reached their present positions.

Plate tectonic theory states that the continents, being part of the lithosphere, the Earth's uppermost layer containing the crust, drift on the semi-molten underlying material we call the asthenosphere, or the upper mantle. By the 1960's, scientists had concluded that the lithosphere is divided into 12 large, tightly fitting plates and several small ones. Six of the large plates bear the continents; the other six are oceanic. And, as Wegener asserted, all of the plates are in motion (Figure 2.7).

![Figure 2.7 Movements of the crust plates (Spectrum Atlas [1973])](image)

Correlated to the process of plate drift, at certain places, the semi-molten asthenosphere material can be driven to the earth surface. This happens in the so-called oceanic ridges. Following from that, new earth crust is being formed (Figure 2.8). This process is called divergence. The crust around a trench is older at a greater distance from the trench. Therefore, to geologists, the characteristics of the sea bottom can reveal information about earth history.

At other places, the contrary from divergence happens: convergence. In the so-called oceanic trenches, one plate dives under the other. The earth crust is returning to the asthenosphere there and partly melting again. This process of convergence is often accompanied by seismic and volcanic activity.
Since Wegener published his theory, many years of debate and research have passed. Only during the last three decades, proof for the tectonic movement of plates has been found. This proof has been yielded mainly by the so-called Ocean Drilling Program (ODP). It consists of basic research into the history of the ocean basins and the nature of the crust beneath the ocean floor. Many countries take part in this project, and it is still continued today. Special drilling equipment is used, in order to take samples of the ocean floor in great depths (up to 9 kilometers below the water surface). Hundreds of drillings have been made.

In the Ocean Drilling Program, the top layers of bottom sediment are examined with respect to their origin. In this way, plate velocities can be estimated. Secondly, fossils found in those layers can tell their story of temperature change. What makes ocean bottom so interesting, among others, is their ability to show a continuous earth history by means of a relatively thin bottom layer. Usually, continental crust consists of huge quantities of sediment, which are precipitated during relatively short periods.

The rates of plate movement appear to vary from about 1 cm a year at the Mid-Atlantic ridge to 10 cm a year at the East Pacific rise in the southeastern Pacific. The majority of the rates is
calculated from the positions of marine sediments and magnetic minerals of known ages. Other rates are determined by direct observation from satellite data. The interiors of the plates are relatively stable.

2.2.3 Tectonic classification of coasts

Coasts are created under the influence of plate tectonics. If a coast is situated close to a plate boundary, it develops differently from a coast that is not. Inman and Nordstrom (1971) made a classification of coasts, which divides all the continental coasts into three major types: those associated with the leading edge of a crustal plate (leading edge or collision coasts), those associated with the trailing edge of a plate (trailing edge coasts), and those bordering a sea enclosed between the landmass and a volcanic island arc at the plate boundary (marginal sea coasts). Island coasts are not considered in this classification.

The formation of the first two types, the leading-edge and the trailing edge coast, is drawn in Figure 2.9.

**Figure 2.9** Formation of leading and trailing edge coasts (from Inman and Nordstrom, [1971])

*Leading edge coasts* develop along the border of a landmass where the oceanic edge of one plate converges with the continental edge of another. They are distinguished by rugged, cliffed shorelines. The convergence between the two plates may produce subduction zones as the denser oceanic plate descends beneath the continental edge of the other plate. The tremendous friction created by the converging plate edges causes the lighter continental crust to fold and buckle, creating the mountain ranges often set near leading edge coasts. An example is the coast near Antofagasta, Chile, shown in Figure 2.10.

In addition, rising magma may create volcanic ranges such as the Andes of South America.
Because the angle of subduction is less steep under continental crust than under oceanic crust, the volcanic range may be some distance from the trench. Thus, the Cascades lie inland from the Coast Range.

The steep mountain slopes of leading edge coasts have rapidly flowing streams and small rivers that quickly erode their beds. Because the watershed is at a high elevation near the coast, the rivers are short, steep, and straight. They transport large quantities of sediments directly to the coastal areas, giving no opportunity for sediments to become entrapped in a meander, on a natural levee, or on a flood plain. The rivers deposit their sediment loads into coastal bays or directly onto open beaches.

Even though mountain streams deposit large amounts of sediment on the coast, they do not produce deltas (Davis [1994]). In fact, none of the world's 25 largest deltas occurs on leading edge coasts, because this tectonic setting does not have a shallow, nearshore area on which the sediment can accumulate, and because waves are usually large along leading edge coasts. If sediment eventually does accumulate, it is soon dispersed by the large waves coming from the deep ocean.

Trailing edge coasts develop in association with a part of the continental lithosphere that is not at the leading edge of a plate (Figure 2.7) and that typically has been tectonically stable for at least tens of millions of years. Inman and Nordstrom have categorized trailing edge coasts on the basis of their plate tectonic settings as Neo-trailing edge coasts, Afro-trailing edge coasts, and Amero-trailing edge coasts. The three subtypes refer to the erosion process after the breaking up of a landmass. The initial settings are coasts with high relief, small rivers, and little deposition - like
leading edge coasts. As the separated landmasses drift apart after their breakup, there is plenty of time for the coastal areas to erode (the drift velocity is 1 to 2 cm per year). Their cliffs become low plains where sediment can be deposited, eventually to form deltas, barrier islands, and other sedimentary features.

A Neo-trailing edge coast occurs as plates diverge from an active spreading center. If the newly produced crust forms a coast, it represents the first stage of coastal development. It is only a few million years old. Coasts like this existed just after the proto-Atlantic developed, as the continents split up during the Triassic period, 190 million years ago. The coarse gravel beach along a high-relief coast on the Sea of Cortez, Mexico, provides an example of a Neo-trailing edge coast. Its photograph is shown in Figure 2.11.

An Afro-trailing edge coast forms on a continent that has coasts of only the trailing edge variety.
Such a continent occupies a position in the middle of a crustal plate that has little tectonic activity along its margins, and has been relatively stable for many millions of years. Afro-trailing edge coasts have developed pronounced continental shelves and plains, but these features lack the extent of more mature coasts, and sedimentary features such as large deltas are rare. The African continent has been relatively stable for a long time, so no extensive, high mountain ranges are present. The modest to large river systems drain areas of only modest relief, so sediment gets a lot of time to be deposited before arriving in the river mouth. The setting of the Namibian desert, where huge dunes meet the Atlantic Ocean, viewed in Figure 2.12, provides a good example of an Afro-trailing edge coast.

Amero-trailing coasts, geologically the most mature coastal areas, are represented by the east coasts of North and South America. Both are tectonically stable portions of the continents, well away from the plate boundary, and have been located so for at least several tens of millions of years. The combination of long-term tectonic stability, a temperate climate, and the development of a broad coastal plain has provided huge quantities of sediment to trailing edge coasts since the continents separated. During this time numerous large, meandering river systems have developed. For more than 150 million years, these rivers have been carrying sediment across a gentle incline. As they have deposited sediment at or near their mouths, they have created broad, low-relief coastal plains on the landward side and, on the seaward side,

Figure 2.13 Coast near the mouth of the Amazon River in Brazil (Davis [1994])

gently sloping continental shelves. Wave action along Amero-trailing coasts is limited, because
the water of the gently sloping inner continental shelf is shallow. Large mid-ocean waves lose energy as they progress across the shelf, and consequently do not inhibit deposition of sediment along the coast. An example is the extensive mangrove stands and tidal flats which cover the low relief Amero-trailing edge coast near the mouth of the Amazon River in Brazil, in Figure 2.13.

**Marginal sea coasts** are near to the plate boundary where a collision is occurring, but are kept apart from its influence. In these places, a moderate-sized marginal sea separates a passive and tectonically stable continental margin from the volcanic island the plate edge at a subduction zone. Although fairly close to the convergence zone, the marginal sea coast is far enough away to be unaffected by convergence tectonics - it behaves like a trailing edge coast. Well-developed rivers carry large quantities of sediment to the coast, where a broad and gently sloping continental shelf provides an ideal resting place for large quantities of land-derived sediment.

The restricted size of the marginal sea limits the size of waves that develop. In addition, the gentle slope and shallow waters of the continental shelves in these areas attenuate wave energy. Hence, the combination of relatively low-energy coastal conditions and sizable sediment loads allows the formation of large deltas and other coastal sedimentary deposits such as tidal flats, marshes, beaches and dunes. The great rivers of southeastern Asia and the Gulf region of the US, both areas of mild climate and abundant rainfall, have deposited their sediment loads on marginal sea coasts to create some of the largest deltas of the world.
2.3 Climatology

2.3.1 Introduction

You need not to be a mountain climber to know the effect of the landscape on the weather. The presence of mountains, oceans, and other natural features of course influence the climate of the area. (You'd better plan your holidays on the sunny side of the mountains.) This effect is two-sided; natural features would not be what they are, if they would have been subjected to another climate. In other words: the climate and the morphological system of a region are closely related to each other.

The climate is important for coastal engineering, as it determines the way in which the naturally available water behaves. This influences the movement of sediments, which has a major influence on the use of the Coastal Zone and on the design of coastal structures.

2.3.2 Meteorological system

The climate is the total of all the effects caused by the weather. As it can rain or shine, weather effects are variable. Therefore, weather effects are quantified by so-called meteorological variables, which are:

1. Temperature;
2. Atmospheric pressure;
3. Atmospheric humidity;
4. Air density;
5. Vertical air velocity;
6. Winds.

The motor of all meteorological processes is the transformation of energy coming from the sun. The atmosphere and the earth surface receive the sun energy by radiation and lose it in the same way. The energy transformation processes (conversions) in between give value to the meteorological variables. If the different conversions are listed, an energy balance of the atmosphere can be constructed. This balance shows the different components of the energy cycle, which is governed by the following meteorological equations:

1. The gas law;
2. The first law of thermodynamics (heat equation);
3. The equation of contiuity (mass conservation);
4. The moisture equation (conservation of moisture);
5. The vertical equation of motion (Newton's second law);
6. The horizontal equation of motion (idem).

Given the six variables and the six equations, it is possible, in principle, to solve meteorological
problems by integrating the equations from a given state forward. In this integration, proper boundary conditions must be applied at the bottom and top. Finally, when the domain of interest does not extend around the globe, lateral boundary conditions have to be prescribed as well.

2.3.3 From meteorology to climatology

In order to quantify a climate, averaging the weather effects over 30 years is usual. Apart from the average values of the meteorological variables, other values are needed in order to characterize a climate properly, especially for engineering purposes. For example monthly minima, maxima, and threshold values for a given lifetime are necessary statistical information.

Primary sources for climatological data are the monthly tables in the archives of meteorological services. Others are bulletins and year books for meteorology. Climate atlases and (global) climate maps are also available.

Going from meteorology to climatology, we see the time scale growing (via statistics). A somewhat comparable step can be taken with respect to the spatial dimensions. It is also possible to make generalizations in the case of many spatial processes. Many of those are described in literature. In this section, only few processes are shortly described (Harvey [1976]):

1. The hydrological cycle and cloud formations;
2. Solar radiation and temperature distributions;
3. Pressure gradients and winds;
2.3.4 The hydrological cycle

The cyclic stages and processes of water are drawn in Figure 2.14.

The process whereby water is transferred from ocean and land surfaces into the atmosphere is known as evaporation. When it occurs from plant surfaces it is called transpiration, and when it occurs directly from an ice surface to the vapour state it is known as sublimation. The water vapour which is thus added to the gases in the atmosphere increases the pressure within the atmosphere. The part of the total pressure that is attributable to the water vapour is referred to as the vapour pressure $e$. An alternative way of specifying the amount of water vapour present in the air is by using the humidity mixing ratio, which is the ratio of the mass of water vapour to the mass of dry air.

The opposite process to evaporation is condensation. When the processes of evaporation and condensation balance one another, an equilibrium is reached; the air is said to be saturated with water vapour. The pressure at which this is the case is called saturation vapour pressure $e_w$. This saturation vapour pressure is very temperature-dependent, increasing more and more rapidly as temperature increases. Therefore, while cooling an amount of partly saturated air, the dew point is reached, that is the temperature at which the air is fully saturated (at constant pressure). When there is no surface of any kind for water to condense on, air can become supersaturated and still retain its water vapour.
A measure for the amount of water vapour in the air is the relative humidity (U).

where:

\[
U = \frac{e}{e_w} \times 100\% 
\]

The relative humidity is increased not only by an increase in the water vapour content, but also by a decrease in temperature (if the water vapour remains constant). (And so, the diurnal variation in relative humidity often mirrors the diurnal variation in air temperature).

Although no surfaces seem to be available in a free cloudless atmosphere, there are many impurities such as salt particles from the evaporation of sea spray, dust from deserts and volcanic eruptions and smoke from fires on which condensation can take place. These are known as condensation nuclei. On most types of nuclei, condensation already takes place below a relative humidity of 100%.

The saturation of air leading to condensation usually results from the air being cooled. This cooling happens, for instance, when air rises. There is another important process leading to condensation, which is illustrated by Figure 2.15.

Figure 2.15 Saturation vapour pressure as a function of temperature (Harvey [1976])
Consider the samples of air represented by points D and E. Neither is saturated with water vapour, but if they are thoroughly mixed together in equal quantities the resultant mixture will be represented by point F - which is saturated. Hence it is seen that mixing of two different types of air can lead to saturation and condensation.

Back to cooling of the air by air ascent. There are three principal causes of air rising in the atmosphere:

1. When air which is moving horizontally encounters a hill or mountain barrier, it must pass over or around it;
2. Horizontal convergence of air, which can lead to uplift of the warmest (lightest) air (frontal uplift);
3. Convection by warming of the air near the ground (making it less dense).

2.3.5 Solar radiation and temperature distributions

The sun emits electro-magnetic radiation, which is a source of thermal energy for the earth. The total amount of radiation per unit surface area (E) coming from the sun is given by Stefan's Law:

\[ E = \sigma T_s^4 \]  

(2.2)

where:
\( \sigma \) = constant of Stefan-Bolzmann = \( 5.67 \times 10^{-8} \) W m\(^{-2}\) K\(^{-4}\)
\( T_s \) = absolute temperature of the sun surface, which can be considered to be 6000K.

Using Equation 2.2, the amount of radiation per unit surface area is \( 3.402 \times 10^{2} \) W/m\(^2\). This sun radiation is divided over different wave lengths (Figure 2.16).

![Figure 2.16 Distribution of radiation intensity with wave length for a black body, surface temperature 6000 K, representing the sun (Harvey [1976])](image)
As the radiation passes through the atmosphere, however, it is subject to absorption, scattering, and reflection by clouds (Figure 2.17). The proportion which the cloud reflects is called its albedo.

![Reduction of solar radiation intensity as it is transmitted through the atmosphere (Harvey [1976])](image)

The radiation which reaches the earth surface may be absorbed there, be transmitted downwards if it encounters a material which is transparent to it, or be reflected. The albedo of the surface depends on its substance and texture, the angle of incidence of the radiation, and the wavelength of the radiation. The absorption of radiation leads to heating. The heat may be transmitted downwards by conduction or, in the case of fluids, by convection.

If the earth would continue to absorb solar radiation without any loss of heat, its temperature would rise indefinitely. This does not happen, because the earth, in her turn also, emits electromagnetic radiation into space. Taking mean annual values, and ignoring any change in the earth's mean annual temperature from one year to the next, a balance must exist between incoming solar radiation and outgoing terrestrial radiation.

The earth emits mainly visible and infrared radiation (wave lengths > 4 µm). The gases in the atmosphere which absorb this long wave terrestrial radiation are water vapour, carbon dioxide and ozone. They emit long wave radiation in all directions, this is called secondary reflection. They therefore act as a layer of insulation around the earth analogous to the glass of a greenhouse, and their effect on earth temperatures has been called the greenhouse effect.

The earth follows an elliptical path around the sun, its mean distance away being about 150 million km, but this varies at the present time by about 5 million km in the course of a year. Therefore, the amount of radiation received in a day depends upon the length of time the area is exposed to the sun's rays, the angle between the sun's rays and the earth's surface, and the distance
of the earth from the sun. These factors vary with latitude and season.

If annual mean values of the incoming and outgoing radiation at any location on the earth are determined, an imbalance will almost certainly be found. This is because there are processes other than radiation which lead to the transfer of heat, particularly in the atmosphere and ocean.

In high latitudes, a net loss of heat by radiation is found. In low latitudes, there is a net gain. Horizontal transfer (advection) of heat is necessary to compensate for that (Figure 2.18). The change-over from a surplus to a deficit in the net annual radiation balance occurs at about $37^\circ$ latitude N and S. The winds and ocean currents are responsible for this advection. These heat transport processes themselves also depend on the uneven distribution of heat over the earth's surface for the energy which maintains them.

![Figure 2.18: Long-term mean values of incoming, short wave radiation and long wave, outgoing radiation for the earth atmosphere system, averaged over zones of latitude (Harvey [1976])](image)

In short: the days and nights, and the seasons, result in variations in temperature. An ocean responds differently to these variations than a continent. In water, the solar radiation penetrates further than in land; water has a greater heat capacity than land; water has a big storage possibility for heat by the process of mixing and evaporation. These differences between water and land cause differences in the air temperature distribution over the earth surface (Figure 2.19).
The distribution of air temperature over the earth's surface depends on four major factors:

1. Latitude;
2. Altitude;
3. Nature of the surface, in particular the distribution of land and sea;

Figure 2.19  Air temperatures reduced to sea level in January and July, after Barry and Chorley (1971)
2.3.6 Atmospheric circulation and wind

If the earth did not rotate, and if its surface albedo were entirely uniform, transparency to solar radiation, heat capacity and thermal conductivity, then we might expect a simple convection cell circulation to exist within the troposphere in each hemisphere (Figure 2.20). Each cell would have a horizontal dimension of the order of $10^4$ km compared with a vertical dimension of only some 10 km. Due to interference between the upper poleward flow and the lower equatorward flow, perhaps the convection cell would break up into a number of smaller cells (Figure 2.21).

Figure 2.20 Convection cell circulation on a non-rotating uniform earth

Figure 2.21 Simple Three-Cell Convection
Without earth rotation, a symmetrical global atmospheric circulation pattern could be expected. However, this symmetry is disturbed by rotation of the earth. The so-called Coriolis effect, which is the result from the earth rotation, works in different directions in each hemisphere. Therefore, the global atmospheric circulation system is asymmetrical (Figure 2.22). It consists of three major cells on each hemisphere. The lowest latitude cells are called Hadley Cells. This series of zonal pressure belts and wind systems is kept going by this so-called A-engine (a combination of solar radiation and earth rotation).

When the non-uniformity of the earth's surface is introduced, the situation becomes considerably more complex, and the influence of the continents can be found. The influence of the ocean/continent contrasts is called the B-engine. The seasons can generate thermal effects; for example, pressure systems can be stable during the summer and alternate into another relatively stable configuration during the winter. Seasonally reversing winds correlated with this seasonal change are called monsoons.

The last major influence on the climate is the topography of a certain area. Mountains affect the pressure distribution in their own way. Local phenomena like land or sea breezes together form the C-engine. The most terrifying phenomenon coming from this is the hurricane, which develops above the ocean. It follows a path which is partly predictable, and is stopped only after crossing into a continent.

Wind conditions can be described statistically. The wind climate consists of both velocity data
and direction data. Velocities can be expressed as a certain number on the scale of Beaufort (Table 2.2). The Beaufort wind scale originates from the time that the British Navy mainly existed of sailing ships. In that time, the captain's conflict on a war ship was the following: how to set sail enough for the battle, and how to prevent the ship from being ruined by the wind?
Table 2.2  Beaufort wind scale

<table>
<thead>
<tr>
<th>Beaufort nr.</th>
<th>Character</th>
<th>Wind speed (m/s)</th>
<th>State of sea surface</th>
<th>wave height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>calm</td>
<td>0.0 - 0.2</td>
<td>like mirror</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>light air</td>
<td>0.3 - 1.5</td>
<td>ripples</td>
<td>0.1 - 0.2</td>
</tr>
<tr>
<td>2</td>
<td>light breeze</td>
<td>1.6 - 3.3</td>
<td>small wavelets;</td>
<td>0.3 - 0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>glassy crests</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>gentle breeze</td>
<td>3.4 - 5.4</td>
<td>large wavelets;</td>
<td>0.6 - 1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>crests begin to</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>break</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>moderate breeze</td>
<td>5.5 - 7.9</td>
<td>small waves;</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>white horses</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>fresh breeze</td>
<td>8.0 - 10.7</td>
<td>moderate waves;</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>chance of spray</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>strong breeze</td>
<td>10.8 - 13.8</td>
<td>large waves;</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>white foam crests</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>moderate gale</td>
<td>13.9 - 17.1</td>
<td>sea heaps up;</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>spindrift</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>fresh gale</td>
<td>17.2 - 20.7</td>
<td>moderately high</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>waves; edges of</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>crest break into</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>spindrift; foam is</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>blown in streaks</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>strong gale</td>
<td>20.8 - 24.4</td>
<td>high waves; dense</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>streaks of foam;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>sea begins to roll;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>spray may affect</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>visibility</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>whole gale</td>
<td>24.5 - 28.4</td>
<td>very high waves;</td>
<td>12.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>heavy rolling sea;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>visibility reduced</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>storm</td>
<td>28.5 - 32.7</td>
<td>exceptionally high</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>waves; small and</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>medium sized ships</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>might be lost</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>to view</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>hurricane</td>
<td>&gt;32.7</td>
<td>air filled with</td>
<td>&gt;15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>foam; visibility</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>greatly reduced</td>
<td></td>
</tr>
</tbody>
</table>
2.4 Oceanography

2.4.1 Introduction

Oceanography has been put into practice since 1725, when Count Marsigli wrote one of the first books on the subject. Maury, a United States Naval Officer, wrote the first "modern" oceanography book in 1855. Many of his observations - compiled from ship logs - are excellent; all are interestingly explained, even though he had no knowledge of geophysics.

The first systematic, specific study of the oceans was carried out by the H.M.S. Challenger. This ship sailed from Portsmouth, England on the 21st of December 1872, and in 3 1/2 years sailed more than 100,000 km. Its measurements resulted into a 50 volume report. This was also the first report to subdivide oceanography into its four modern major fields: biological, chemical, geological and physical oceanography. In this paragraph, a little bit of physical oceanography is described. However, one must realize that biological, chemical, and geological processes have a major influence on, and are influenced deeply by coastal engineering measures in the marine environment.

The mean depth of the oceans is about 3.8 km (the North Sea is 94 m deep on average). The shallowest part of the ocean is called the continental shelf. This makes 7.6 % of the total ocean area (Figure 2.23A and B). This part has depths up to 100, 200 meters. The oceans are further subdivided into a series of interconnected basins in which most of the interesting physical oceanographic activity takes place. These basins are 3 to 5 km deep with occasional deeper or shallower sections. Most of the interesting processes in the oceans take place in the upper 1 to 2 km. Deeper than this, the oceans are of rather uniform salinity (3.5‰) and temperature (3° - 4°C). Currents in the deep zone are very weak - often assumed to be zero. In Subparagraph 2.4.2 and 2.4.3, processes in the upper zone are described.

![Figure 2.23 A Continental shelf](image1)

![Figure 2.23 B Continental shelf](image2)

The three primary forces that produce surface waves are wind (wind waves), earthquakes
(tsunamis), and gravitational attractions within the sun, moon and earth system (tides). Tides are described in subparagraph 2.4.4. Seiches are the subject of Subparagraph 2.4.5. In Subparagraph 2.4.6, a short description is given of short wave theory. Statistics of wind waves is given in 2.4.7. Storm surges are the subject of Subparagraph 2.4.8. And the last Subparagraph, number 2.4.9 is explaining what tsunamis are.

If one wants to know more details about the subjects treated in this paragraph, please dive into the specific lecture notes (CTwa3310, OT3620, CTwa4320, CTwa5316, CTwa5317) for a fresh-up.

2.4.2 Variable density

The density of sea water is a function of three variables: salinity, temperature and pressure. The pressure influence on the density can be neglected unless the depth is more than ±500 m. In contrast to pure water, sea water will continuously increase in density as it cools until it reaches its freezing temperature.

Most sea water has a salinity varying between 34 and 36%. However, some smaller isolated seas can show significant variations: The Baltic Sea, for example, sometimes has a salinity as low as 7%. The Red Sea, on the other hand, has as much as 41% salinity.

Over the water depth, salinity and temperature are not constant. With increasing depth, both salinity and temperature decrease (usually). Evaporation is responsible for the higher salinity of the surface layer. A higher salinity means a higher density, whereas a higher temperature causes a lower density. Still, the temperature differences are sufficient to maintain a density profile which increases with depth.

There are several methods to measure water salinity:

1. titration;
2. determination of $\rho$;
3. measurement of electric conductivity.

Since the density of salt water usually is a bit more than 1000 kg/m³, oceanographers often subtract 1000 from the density values and denote the value by $\sigma$. If this is done for conditions under atmospheric pressure, then a subscript $t$ is usually added:

$$\sigma_t = \rho - 1000$$  \hspace{1cm} (2.3)

Values of $\sigma_t$ as a function of salinity and temperature are computed using

$$p' = 1.0133 \times 10^5 \text{ Pa}.$$  

Since the equations and tables are a bit cumbersome in use, WL/Delft Hydraulics uses a simpler relationship:

$$\sigma_t = 0.75S$$  \hspace{1cm} (2.4)

where:
This relationship neglects influences of temperature and pressure and is therefore more limited in use. In practice it is sufficient for situations in which density differences result exclusively from salinity differences.

Density variations can be used in ingenious ways. Imagine, we take a long (1km) pipe and put it vertically down from the ocean surface. Next, we attach a pump and slowly draw up the deep water. We do this slowly so that the rising water can be warmed by the surrounding ocean. After deep water reaches the surface we remove the pump and find that the water continues to flow. Why? It is not perpetual motion; the process stops as soon as the upper 1 km layer of the ocean has become mixed. The cause for the motion is the difference in specific mass between colder and warmer water.

![Diagram of OTEC system](image)

**Figure 2.24** The system of OTEC (Delta Marine Consultants)

This form of energy conversion has been the subject of many research projects. Under the name OTEC (Ocean Thermal Energy Conversion), nowadays a part of DOWA (Deep Ocean Water Applications), many countries tried to develop power plants based on this principle (Figure 2.24). The interest for this sustainable energy source grew especially in times of increasing oil price. On Hawaii, such a plant has been realised.

Nowadays, the hunt for more sustainable energy has not ended. As the heating capacity of the sun is a multiple of the possible OTEC plant production, OTEC is a promising energy production method. People tend to think of plants which make direct use of temperature differences, instead of converting it into for example electricity. Especially tropical areas are suitable for ocean energy systems.
Until now, density differences in the vertical profile have been described. Horizontal density variations can occur, too. For example: in a tidal river mouth, salt water enters the estuary during rising tide (unless there is more than enough fresh water flow in the river to completely fill the entire tidal prism; few rivers have sufficient flow over the entire year to prevent from the intrusion of salt water). According to this, salinity at some point in a river can be expected to vary according to the tide. Often, a density gradient causes a density current. This depends on the stability of the actual configuration, and will be discussed in Chapter 6.

2.4.3 Geostrophic currents

The ocean is not a static thing. (If it were, then "bottle mail" would never work out, right!) In the North Atlantic for example, the following current pattern is present: the North Equatorial Current flows westward from the Cape Verde Islands to the Caribbean Sea (Figure 2.25). A portion enters this sea and a portion turns northwest east of the Caribbean Islands (Antilles Current) and joins the Florida Current. Water flows out of the Caribbean between Florida and Cuba in the Florida Current. The Florida Current (often called the Gulf Stream) continues north along North America to about 45° N latitude where it turns eastward and spreads out forming the North Atlantic Current. A branch of this turns south, along Portugal to form the Canary Current and close the circuit. Similar current patterns can be found in the South Atlantic and the other oceans. These major east-west currents correspond in latitude to the prevailing winds. The north-south currents guarantee continuity and conservation of mass.

The major driving force for these so-called geostrophic ocean currents is the prevailing wind at different latitudes on earth. The maximum velocities occur in the upper layer (the upper 2 km) and are small (< 1 m/s). Although the total body of moving water is enormous, friction is relatively unimportant. On the other hand, the Coriolis effect is important.

The Coriolis effect can be understood considering a fixed grid, which is bound to the
turning earth. A perfectly straight moving mass (in this grid) must change its direction in order to follow the earth surface. This means that the eastwardly directed velocity component of the mass must change when it moves to the north or to the south. If it doesn't, it gets a deviation from a straight path following the earth bound grid. This deviation is expressed in the form of a Coriolis acceleration. It depends on the latitude and the velocity of the mass. (Figure 2.26)

An ocean current is in fact a big moving water mass, which has to follow the earth surface. Therefore, it experiences a Coriolis acceleration. In the case of an ocean current, this acceleration can be expressed in the form of a force working on the total moving water mass. This so-called Coriolis force is balanced by a pressure gradient, generated by a surface slope.

The formula for Coriolis acceleration is:

$$a_c = 2 \omega_v V \sin \phi$$  \hspace{1cm} (2.5)

where:

- \(a_c\) = Coriolis acceleration
- \(\omega_v\) = angular velocity of the earth = \(72.9 \times 10^{-6}\) rad/s (based on sidereal day)
- \(V\) = current velocity
- \(\phi\) = latitude

The acceleration acts towards the right facing in the flow direction in the Northern hemisphere, and opposite in the Southern hemisphere. In the case of a balanced situation (a steady current), the equilibrium is expressed by the equation:

$$\frac{1}{\rho} \frac{\partial p}{\partial n} = 2 \omega_v V \sin \phi$$  \hspace{1cm} (2.7)

where:

- \(\rho\) = water density
- \(p\) = water pressure
When computing the sea level difference across the Straits of Florida, the result is 0.52 m (elevation difference). The Florida Current is located at a latitude of 26° N; the current velocity is about 1.0 m/s; the width of the Straits of Florida is about 80 km.

\[
\frac{1}{\rho} \frac{\partial p}{\partial n} = 2 \times 0.729 \times 10^{-4} \times \sin 26^\circ \times 1.0 = 6.4 \times 10^{-5} \frac{m}{s^2}
\]

(2.7)

The elevation difference over 80 km is computed as follows:

\[
\Delta z = \frac{6.4 \times 10^{-5}}{9.81} \times 80 \times 10^3 = 5.2 \times 10^{-1} m
\]

(2.8)

The observed value is 0.45 m. (The same sort of computation could be made for the Westerscheldt!)

2.4.4 The tide

The earth and the moon together form a system, that is ruled by gravitation force, which is known since Newton (Figure 2.27). They turn around a collective axis, which is the gravitation centre, \( Z \), of the system. This gravitation centre is situated inside the earth. The translation around \( Z \) sends every point on the earth surface in an orbit around its own centre, with the same radius, \( d_1 \). Following from that, centrifugal force on a (water) particle has the same value in every point on earth. It is directed opposite to the acceleration that gravitation force alone would cause, that is, outwardly, parallel to the earth-moon connection line. Gravitation force itself is directed to the centre of the moon. Resulting from that, all points on the earth surface experience a different tide-generating force by the moon.

![Diagram](image)

Figure 2.27 Rotating Earth-Moon system (van Urk and de Ronde [1980])
If the earth would be covered by water completely, its equilibrium configuration would be an ellipsoid (Figure 2.28). As the earth turns around her own axis, an observer can see two high and two low waters passing every day. In the meantime, the moon has changed position (1/29th of the total orbit around the earth); the water ellipsoid has turned, too. Therefore, the period of the lunar tide is 12 hours and 25 minutes. The earth’s axis (from North to South Pole) is not perpendicular to the earth-moon connection line (Figure 2.29). The angle between the equator plane and the earth-moon line is called declination, $\delta$. Following from that, the two high and low waters on a day are not equal. At some latitudes, this daily inequality becomes so big, that there is only one high and one low water.

Like the moon, the sun causes a water ellipsoid, too. The contributions of sun and moon to the tides have names: $M_2$ and $S_2$. The sun has a mass that is 27 million times that of the moon, but it is nearly 150 million km away; the moon is only about 400,000 km away. The gravitational attraction between the sun and the earth is just about half of that between the moon and the earth. When sun, earth and moon are in one line (full and new moon), the solar and lunar tides reinforce each other. The tide gets a bigger amplitude and is called spring tide. When the solar and lunar tide are 90° out of phase, their effects cancel each other (first and last quarter). This situation is called neap tide (Figure 2.30).
So far, the earth was thought to be covered with water only. In reality, continents disturb the development of the equilibrium tide. In the Southern Hemisphere, the original ellipsoid can develop; there the tidal wave travels around the earth, southerly from Africa, South America and Australia. From there, the tidal wave propagates to the North. This propagation takes time; therefore, a certain astronomical tide takes place some days after the correlated phase of the moon (2 days in the Netherlands).

The tidal wave is a long wave (L>d). Its average height is less than 0.5 meter. Geometry and bathymetry of the continents distort it on its way. The water motion can be expressed by the long wave equation in two dimensions. If friction can be neglected, the wave propagation speed is:

\[ c = \sqrt{gd} \]  

(2.9)

where:

- \( c \) = wave propagation speed [m/s]
- \( g \) = gravitation acceleration [m/s²]
- \( d \) = water depth [m]
Every place along the coast has its own specific tidal curve. At some locations, the difference between high and low water is up to 12 m. The variation of the water level is called vertical tide. The currents resulting from it are called horizontal tide. Coriolis and reflection effects make the tidal pattern on a sea very complex. At some locations, the amplitude of the vertical tide can become zero. This is called an amphidromic point (Figure 2.31).

Some rivers located at the landward end of an estuary experience another extreme tide-dependent condition - a tidal bore, an abrupt and migrating rise in the water level at the beginning of the flood tide (Figure 2.32). This "wall of water" is a response to the quick reversal from an ebbing tidal condition to a flooding one. Bores are uncommon, forming only in special circumstances that depend on tidal conditions and the morphology of the estuary. The bore in the Truro River of the Bay of Fundy is typically only about half a metre high. In the Bay of St. Malo on the northern coast of France, a bay with the world's second largest tidal range, the bore rarely exceeds a meter in height. Large tidal bores occur in the Pororoca River, a branch of the Amazon, and in the Chien-tang estuary in China. The bore reaches 5 m in the Pororoca and nearly that height in the Chien-tang.
Apart from meteorological effects, the tide can be predicted. The method used for tide prediction is called harmonical analysis. The water level at a certain location as a function of time is expressed by the following formula:

\[ h(t) = h_0 + \sum_{i=1}^{N} h_i \cos(\omega_i t - \alpha_i) \]  

(2.10)

where:
- \( h(t) \) = measured tidal curve
- \( h_0 \) = mean level
- \( H_i \) = component number i (diurnal, semi-diurnal, higher harmonical components)
- \( \omega_i \) = angle velocity
- \( \alpha_i \) = phase

Figure 2.32  Tidal bore on the Petitcodiac River, New Brunswick (Stowe [1987])
### Table 2.3 The main constituents of the tide at several places in the Netherlands

<table>
<thead>
<tr>
<th>Component</th>
<th>Angle velocity</th>
<th>Amplitude and phase angle</th>
<th>Bath</th>
<th>Terneuzen</th>
<th>Vlissingen</th>
<th>Roomp-Heemskerk</th>
<th>Rotterdam</th>
<th>H. van Holland</th>
<th>EuroPodium</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>NLK</td>
<td>SA</td>
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<td></td>
<td></td>
<td></td>
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<td>0.041</td>
<td>A0</td>
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<td></td>
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<td></td>
<td>8</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
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<td></td>
<td>5</td>
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<td>6</td>
<td>g°</td>
<td>5</td>
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<td></td>
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</tr>
<tr>
<td>MNS,</td>
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<td>H.cm</td>
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<td>6</td>
<td>g°</td>
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<td>6</td>
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<td>μ,</td>
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<td>g°</td>
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<td>6</td>
<td>g°</td>
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<td>g°</td>
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<td>g°</td>
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<tr>
<td>M,</td>
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<td>g°</td>
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<tr>
<td>λ,</td>
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<td>6</td>
<td>g°</td>
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<td></td>
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<tr>
<td>2MN,</td>
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<td>g°</td>
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<tr>
<td>S,</td>
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<td>2MK,</td>
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<td>g°</td>
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<td>6</td>
<td>g°</td>
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<td></td>
</tr>
<tr>
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<td>6</td>
<td>g°</td>
<td>276</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MN,</td>
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<td>H.cm</td>
<td></td>
<td>6</td>
<td>g°</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In Table 2.3, the main harmonical components are given, used for prediction of the tide at several places in the Netherlands. Nota bene: A₀ gives the difference between NAP and MSL. Close to the coast this difference can be negotiated; however, if one looks at a river farther upstream, the river gradient influences it. A₀ changes a little bit during the year.
Predicting tides for a specific location along the coast cannot be done without the use of tide measurements. These measurements used to come from tide gauges. The first reliable tidal gauge was invented in 1882 by Sir William Thomson, Lord Kelvin, a Scottish physicist. A version of it is still the standard type. It consists of a float inside an open pipe attached to a pier. The top of the pipe extends from near the floor of the harbour to above high tide. The base of the pipe is above the bottom; only the slow rise and fall of the tide invades the pipe. A pen records its movement on a graph-paper cylinder that is driven at a constant speed. Now most stations have more modern electronic recorders that automatically transmit digital information to a computer.

Every year, hydrographic Departments around the world prepare a new tide table for each of their major ports and harbors and for numerous other locations. The reference level used is LLWS, which is defined as the minimum water depth at a certain location. This habit reduces navigation mistakes which would lead to running aground. It is inherited from the intensive Dutch shipping culture. Note that this reference level is not a horizontal plane! Many countries use another reference plane, often the average sea level MSL (NAP in The Netherlands). This is reestablished for each location every few decades. MSL is not horizontal either; it varies from place to place. See also Paragraph 7.6 in this respect.

It is possible that a civil engineer needs tidal data for a location, where no one has predicted the tide. Then, this engineer can make a reasonable prediction based on an experiment during 28 days, making observations every hour. One must realize that a tidal curve is strictly bound to a certain location. Along coasts, even if they are from the same estuary, big differences can occur.

### 2.4.5 Seiches

Between long periodic waves, like the tide, and short waves, like wind waves, a category of waves exists with periods from 10 to 10000 s. They are called seiches. Seiches are standing waves in a closed body of water (Figure 2.33) or in a semi-closed body of water (Figure 2.30), for example a harbour. Driving forces can be: pressure variations, discharge variations, tidal influences and swell. Seiches can cause havoc at a harbour by setting up reversing currents at the entrance or by rocking ships free from their moorings. They can also abruptly surge onto piers and beaches and sweep people away. The Great Lakes of North America and some of the large lakes in Switzerland are especially susceptible to seiches, because they are enclosed basins with large fetches and strong winds.

![Standing wave in a closed body of water](image)

Figure 2.33  Standing wave in a closed body of water
In simple cases the wave length is twice or four times the basin lengths, but other possibilities exist:

\[ T_i = \frac{4 L_b}{i \sqrt{gh}} \]  

(2.11)

where:
- \( T_i \) = period of wave configuration number \( i \)
- \( L_b \) = length of the basin
- \( i \) = wave configuration number (harmony number)

Usually, the vertical amplitude of a seiche, even at an antinode, is small. However, especially at a node, the horizontal displacement of the water can be significant. This can cause mooring difficulties for ships. Another related influence on large ships is the effect of the water surface slope.

As seiches are a resonance phenomenon, it is obvious that the basin size is an important factor in it. Therefore, measures against seiche generation usually consist of size restrictions on (harbor) basins, and on the use of irregularly shaped basins. As the damping usually is very small, this is very important.

2.4.6 Short waves

Short wave theory can be found in lecture notes CTwa4320, and also in many textbooks on the subject. Here, for completeness, a brief summary is given. This is done in the following small sections:

- sinusoidal wave form
- propagation velocity
- refraction
- wave energy and group speed
- shoaling
- wave breaking
- reflection
- diffraction
Generally speaking, the behaviour of short waves is described starting in deep water, and going closer to the shore later on in this subparagraph.

**Sinusoidal wave form**

When the sea surface is subjected to wind, short waves ($L < 25 d$) are generated. In order to describe the motion of the water, a single wave is reduced to a sinusoidal form (Figure 2.35). It propagates along the $x$-axis. This sinusoidal form is the basis of linear short wave theory, which can be used to describe many characteristics of the moving sea water, for example the motion of the sea surface:

$$\eta = \frac{H}{2} \cos(kx - \omega t)$$  \hspace{1cm} (2.12)

where:

- $\eta$ = instantaneous vertical displacement of the surface [m]
- $H$ = wave height [m]
- $x$ = distance in propagation direction [m]
- $k$ = wave number ($k = 2\pi/L$) [m$^{-1}$]
- $t$ = time [s]
- $\omega$ = phase velocity ($\omega = 2\pi/T$) [s$^{-1}$]
- $L$ = wave length [m]
- $T$ = wave period [s]

**Propagation velocity**

The expression for propagation velocity is:

$$c = \frac{L}{T} = \frac{\omega}{k} = \sqrt{\frac{g}{k} \tanh kh}$$ \hspace{1cm} (2.13)

where:

- $c$ = propagation velocity [m/s]
For the derivation, which is not given here, of Equation 2.16, the assumption has been made, that pressure is zero at the surface (dispersion relation for free waves). Linear short wave theory also describes the orbital movement below the surface (Figure 2.36). The water particles move along elliptical paths; the size of these ellipses is greatest at the water surface and decreases with distance below the surface. In deep water, the elliptical orbital paths become circles.

![Orbital movement in short waves (linear theory)](image)

The expression for propagation velocity and the expressions for other short wave characteristics contain hyperbolic functions of the term \( kh \). These can be simplified in the case of deep water and in the case of shallow water (Table 2.4). Note that in shallow water, propagation velocity depends on the water depth only.

<table>
<thead>
<tr>
<th>Table 2.4 Approximations of propagation velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{d}{L} )</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>deep water</td>
</tr>
<tr>
<td>transitional area</td>
</tr>
<tr>
<td>shallow water</td>
</tr>
</tbody>
</table>

Wave energy and group speed

Wave energy per unit of water surface area \( E \) is:

\[
E = \frac{1}{8} \rho h H^2
\]

(2.14)

Wave energy is also propagated by means of waves. This energy propagation has its own
speed, called group speed. A wave train, consisting of a restricted number of waves approaches shore with group speed, but the individual waves move faster and die out in the front of the wave train. Group speed can be computed with:

\[ c_g = \frac{c}{2} \left(1 + \frac{2}{\sinh 2kh}\right) = nc \]  

where:
- \( c_g \) = group speed
- \( n \) = ratio of group speed to phase velocity (phase velocity of individual wave)

**Refraction**

A consequence of the depth-dependence of wave propagation speed in transitional and shallow water is the phenomenon of refraction. If waves approach the coast under an angle, they will turn towards the coast (Figure 2.37).

![Wave refraction diagram](image)

**Figure 2.37  Wave refraction**

This effect can be compared to light being broken by a prism. The wave crests tend to get the same shape as the embankment (Figure 2.38).
Shoaling
If waves approach the shore perpendicularly, their height changes. This effect is called shoaling. It is related to the energy propagation process. If the wave crests are parallel to the depth contours, and wave breaking does not take place, the assumption of a constant wave energy propagation process yields:

$$E_2 n_2 c_2 = E_1 n_1 c_1$$

(2.16)

The subscripts depend on the location.

Starting in deep water, this equation leads to:

$$\frac{H_1}{H_0} = K_{sh} = \sqrt{\frac{c_0}{c_1}} \frac{1}{n_1}$$

(2.17)

where:

$H_0$ = wave height in deep water, before shoaling
$H_1$ = wave height at location 1, after shoaling
$K_{sh}$ = shoaling factor

As

$$n = \frac{1}{2} \left( 1 + \frac{2kh}{\sinh 2kh} \right)$$

(2.18)
the expression becomes:

\[
K_{sh} = \sqrt{\frac{1}{\tanh kh(1 + \frac{2kh}{\sinh kh})}}
\]

(2.19)

In case of shallow water the approximation can be made:

\[
\frac{H_1}{H_0} = K_{sh} = \sqrt{\frac{d}{8\pi h}} \frac{\lambda_0}{h}
\]

(2.20)

Table 2.5 Wave variations in shoaling water

<table>
<thead>
<tr>
<th>Water depth ( h )</th>
<th>( h_0 )</th>
<th>Wave length ( \lambda )</th>
<th>( c/\sqrt{g} )</th>
<th>Wave steepness ( N )</th>
<th>Surface velocity ( V_s )</th>
<th>Water depth ( h )</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.307</td>
<td>deep 1.232</td>
<td>76.92</td>
<td>0.500</td>
<td>1</td>
<td>1</td>
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<tr>
<td>100</td>
<td>1.307</td>
<td>deep 1.232</td>
<td>76.92</td>
<td>0.500</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>0.276</td>
<td>deep 0.272</td>
<td>76.31</td>
<td>0.500</td>
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<td>1</td>
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<td>0.500</td>
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<td>1</td>
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<tr>
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<td>deep 0.256</td>
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<tr>
<td>0.075</td>
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<td>76.31</td>
<td>0.500</td>
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<td>1</td>
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<tr>
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<td>0.055</td>
<td>deep 0.106</td>
<td>76.31</td>
<td>0.500</td>
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<td>deep 0.106</td>
<td>76.31</td>
<td>0.500</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

The \( K_{sh} \) for deep, intermediate and shallow water waves can be compared for various values of \( h/\lambda_0 \) (Table 2.5; a more extended table can be found in the Shore Protection Manual; with a pocket calculator one could determine the values easily, too). This might be helpful for reviewing the criteria for determining which, if any, approximation to use. Shoaling is a reversible process, because it is based on conservation of energy.

Wave breaking

Wave breaking is not a reversible process. It is a dissipation process; the height of a breaking wave diminishes and some of its energy is transformed into turbulence, bottom friction, reflected waves, sound, other waves, heat and currents. Especially current generation is an important phenomenon in coastal engineering.
In theory, a wave breaks if the steepness limit of $H/L = 1/7$ is reached. There is also a theoretical water depth limit of $H/d = 0.78$. Often especially this limit causes a wave to break in shallow water. $H/d$ is called the breaker index, $\gamma$. In practice, a wave breaks when $0.6 < \gamma < 0.8$.

Difference is made between spilling, plunging and surging breakers (Figure 2.39). The parameter which guides the breaker type is (Battjes [1974]):

$$\xi = \frac{\tan \alpha}{\sqrt{H/L_0}}$$

(2.21)

where:

- $\alpha$ = steepness of the beach
- $L_0$ = wave length in deep water

**Figure 2.39** Various types of breakers may develop in the surf zone, each caused by a different combination of wave type and nearshore slope

Spilling breakers are usually found along flat beaches. Waves begin breaking at a relatively great distance from shore and break gradually as they approach still shallower water. During breaking, a foam line develops at the crest and leaves a thin layer of foam over a considerable distance. There is very little reflection of wave energy back towards the sea.

A plunging breaker is a type of breaker often found on the travel posters for the Pacific Islands with a beautiful windsurf professional below it; it is spectacular. The curling top is characteristic of such a wave. When it breaks, a lot of energy is dissipated into turbulence; little is reflected back to the sea, and a little is transmitted towards the coast, while forming a "new" wave.

Surging breakers occur along rather steep shores such as might be encountered along rock coasts. The breaker zone is very narrow, and more than half of the energy is reflected back
into deeper water. The breakers form up like plunging breakers, but the toe of each wave surges upon the beach before the crest can curl over and fall.

**Reflection**

In the case of a structure like a breakwater, the process of shoaling and breaking is disturbed. When meeting an obstacle, a part of the wave energy is reflected. When a wave approaches a cliff or wall at an angle, the angle of reflection will be equal to the angle of incidence. The amount of wave energy reflection is proportional to the steepness of the obstruction that the wave encounters (Figure 2.40). For a vertical wall, the reflection coefficient $K_r = 1.0$. For a slope, $K_r < 1$. In order to describe the phenomenon of reflection, take an endless long obstacle. Part of the wave energy will go over or through the obstacle (in case of a semi-permeable construction), and part of the energy will be reflected back into the basin.

![Standing wave and reflection](image)

**Diffraction**

Usually, wave reflecting structures are not endless. Behind them, diffraction takes place. This three-dimensional effect arises as a result of a shadow formed by an obstacle (Figure 2.41). The problem can be tackled using source theory or the Cornu spiral graphical method. For this method, see the lecture notes on fluid mechanics (CTwa4320).
Source theory is based on the fact, that a potential flow configuration can be replaced by a set of sources being put on its boundaries. A source is a point in which discharge is being generated. Every source has its own strength. If it has a value below zero, it is called a sink. As a wave passes the end of the obstacle shown in Figure 2.41, the end of the breakwater may be considered as a source. It generates arc shaped waves in the shadow zone behind the breakwater. The wave height decreases as we proceed along a wave crest arc in this shadow zone. Diffraction computations can be based on this principle; however, they must also include reflection effects to yield useful results.

![Figure 2.41 Wave diffraction](image)

**Swell**
When waves move beyond the influence of the winds within a local storm or when the wind stops, the persisting waves are called swell. The long swell waves have a low trough and a little height, and they lack steepness. Their propagation is due to gravity.

### 2.4.7 Wind wave statistics

Up till now, we have been working with sinusoidal waves. In reality however, wind waves are irregular. When different wave patterns caused by varying wind strength and direction come together, they form a complicated sea surface (Figure 2.42). A photograph of such a sea state is shown below the diagram. The actual set of waves is called a wave field. Such a field can be characterized by the set of different wave components that are causing it, called wave spectrum. This is the distribution of wave energy with frequency. Often, the wave field is characterized by two parameters, the significant wave height $H_{\text{sig}}$ and the peak wave period. The $H_{\text{sig}}$ is defined as the average of the highest third of all waves.
Observation of the surface elevation during a certain wave field yields a graph like Figure 2.43. A wave is defined here as the water movement between two adjacent downward intersections of the mean water level. So every wave has a different height and period. The average period can be determined as the observation period divided by the number of observed waves. How can such an irregular wave field be analyzed? When using the significant wave height $H_{\text{sig}}$, the wave field is characterized by this parameter together with the average period $T_{av}$. The parameter $H_{\text{sig}}$ "draws" the actual wave height out of a Rayleigh distribution (Figure 2.44). The chance, that the actual wave height exceeds a certain value, can be expressed by the Rayleigh distribution:

$$P(H>H) = e^{-\frac{H}{H_{\text{sig}}}}$$

(2.22)

- $H$: wave height
- $H_{\text{sig}}$: significant wave height
- $T$: time
- MWL: mean water level
- $T_m$: interval between maxima
- $T_z$: interval between up-going zero crossings

Figure 2.42 Different wave patterns forming a complicated sea surface (Davis [1994])

Figure 2.43 Irregular surface elevation resulting from waves
The same wave field can also be characterized in the form of an energy spectrum as a function of wave frequency. For the same wave field, the $H_{\text{sig}}$ and the wave energy spectrum are correlated (Figure 2.45). The $H_{\text{sig}}$ is the wave height that has an exceedance frequency of 13.5%.

The use of $H_{\text{rms}}$ (root mean square), $H_{\text{av}}$ (average), and $\sigma_{H}$ (standard deviation) instead of
the $H_{\text{sig}}$ is also possible. Definition of $H_{\text{rms}}$:

$$H_{\text{rms}} = \sqrt[2]{\frac{N}{\sum_{i=1}^{N} H_i^2}}$$ (2.23)

The other parameters are related to it in the following ways:

$$H_{\text{rms}} = 0.7 H_{\text{sig}}$$
$$H_{\text{av}} = 0.62 H_{\text{sig}}$$
$$\sigma_H = 0.25 H_{\text{sig}}$$

What is the chance that a certain wave field occurs? This is the domain of wave climatology, which is an application of long-term statistics. The actual wind field "draws" a realization (in the form of a certain wind field) out of a Weibull distribution (Figure 2.46). Out of this distribution, one can read the chance that a certain significant wave height will be exceeded (i.e. that the correlated wind field will occur).

![Figure 2.46 Weibull distribution for the $H_{\text{sig}}$ at a specific North Sea site](image)

2.4.8 Storm surges

Storms and near-storm conditions increase the water level, raising the high tide level beyond the level predicted on tide tables - sometimes dangerously so. Coastal warnings are issued on the basis of the predicted level and the weather reports. The rise in water level often begins with a local atmospheric low pressure system that lifts the sea surface. The high winds that rush into the low pressure area add to the rise. The meteorological energy generates storm surges, or, as they are sometimes called, wind tides or storm tides.

Depending on wind direction and coastal configuration, the surge may move towards the shore as a positive storm surge or away from the shore as a negative storm surge. Positive
surges commonly cause flooding; negative expose areas usually underwater, and many marine organisms perish.

How devastating a storm surge works out depends on its development. First, the depression must be traveling slowly, because rapid systems do not give the surge enough time to develop to full height. Next to that, the strong winds must be moving toward the shore (onshore winds). A third factor is the configuration of the adjacent continental shelf over which the storm winds travel. A broad and gently sloping shelf facilitates a high storm surge by allowing the wind to push large amounts of water shoreward across the relatively shallow offshore waters. For this reason, the storm surges on narrow, steep coasts are not as large as those on trailing edge coasts or broad gulfs.

Depending on the region, different names are given to a storm causing a storm surge. In America, it is called a hurricane or tropical storm. In Asia, man speaks of a typhoon. In the Netherlands, storm winds from the North-West are feared the most, called a North-Western storm. The hats people used to wear during such weather are called "South-Westerns".

2.4.9 Tsunamis

A tsunami, also called seismic wave, originates when a forceful earthquake or landslide suddenly shifts or displaces a large amount of seawater and sets a train of waves in motion on the sea surface. It moves at great speed, depending on the depth \( c = \sqrt{gh} \) which, for example in 4000 m of water amounts to 200 m/s (700 km/hr). Its length depends on the period \( L = cT \). If \( T = 10 \) sec, \( L = 2 \) km. In deep water a tsunami often passes unnoticed because it is not so high in deep water. As it approaches the continental coast, it begins to slow and steepen already in relatively deep water (at depths of hundreds of meters) because of its enormous wavelength. This steepening can begin as far out as 50 km offshore, and the wave that finally hits the coast is huge and energetic, as high as 25 m - a prescription for disaster.

The most life-destroying tsunami on record appears to have hit Awa, Japan, in 1703. It killed more than 100,000 people. Among the uncounted victims of the Lisbon earthquake of 1755 were those drowned by tsunami waves in Lisbon and in nearby coastal villages of Portugal and Spain. The trough of the tsunami arrived first, drawing water out of the bay and exposing the sea floor. (Recall that water in a wave moves backward in the trough). Among the drowned were those who came to see the strange sight of the receding waters and were swept away when the crest arrived. Unfortunately, the same situation has recurred numerous times in association with this phenomenon.
In Figure 2.47, the situation after the 1983 tsunami in Minehaha is shown. The tsunami lifted large fishing boats about 6 to 8 m above sea level. After the 1946 tsunami, seismologists began work on a seismic sea-wave warning system. By the early 1960s, a network of seismic monitoring stations covered the entire Pacific Ocean, the only basin where strong earthquakes are common. Knowing the location of the earthquake, seismologists can now predict the path and rate of tsunami movement and provide warnings for most areas, thereby allowing at least a few hours of preparation time before the waves hit a given coast. Generally this is enough time to evacuate people. Although coasts near the origin of the earthquake may receive as little as 10 to 15 minutes advance notice, loss of life has been greatly reduced since the system went into effect.
In the coastal zone, oceanography, geology, ecology and morphology are strongly interweaved. There are three types of processes that influence the configuration of the coast: physical, chemical, and biological processes. Foremost are the physical processes: tides, waves and currents, and their resultant sediment transport. These processes wear down the coast in some places and build it up in others. Transport of sand and shell plays an important role in this. Barriers, spits, the shape of a coastal bay, and the course of a river, are all features regulated by sediment transport. Transgression and progradation of coasts result from sediment transport, too.

Morphology expresses itself in a sediment balance for a given situation. In such a balance, all processes with sediment-transporting capacities must be counted. In this Paragraph, physical processes underlying morphological change are presented. Many of them take place in the surf zone; therefore the surf zone is described in Subparagraph 2.5.2. The sediment transporting mechanisms are treated in Subparagraph 2.5.3. The last subparagraph is focussed on coastline changes in general. The resulting coastal formations and their development are so important that Chapter 3 is specifically dedicated to them.
Morphological processes are correlated. Sand transport is caused by waves, currents and wind; wind also causes currents, and waves, which drive currents; the tide causes currents, too. The resultant geometry of the coast influences sediment transport again. In Figure 2.48, a scheme of this coherence in the morphological subsystem is shown. It is a complex system. The elements (input variables) are:

1. Coastal formation;
2. Water level;
3. Wind/wave power;
4. Tidal power.

2.5.2 Surf zone processes

In the surf zone, wave energy is dissipated by breaking. If the waves approach the shoreline with crests parallel to the beach, the effect of the breaking is set-up and of course, depending on the wave height, mixing of sand and water in a water column (stirred sediments). However, if the waves approach the shore under an angle, or if wave conditions change along the shoreline, they may cause a current parallel to the coast. Called the longshore current, this current acts like a shallow river channel, mainly confined to the surf zone (Figure 2.49). The process of momentum transport, which is the driving force behind it, is called radiation stress. More detailed information can be found in the lecture notes on the subject CTwa5309.

![Figure 2.49 Longshore current velocity profile](image)

Next to longshore currents, other currents are produced by incident waves: undertow and rip currents. Wave set-up is related to this last type. Typically, a low area of the sea floor or a break in a sand bar allows the water to move seaward. The rapid flow of this narrow stream of water is called a rip current. Low spots in the approaching breakers in the surf zone and clouds of suspended sediment moving seaward are the best clues to their presence. A rip current forms one side of a cell-like system of circulating water within the breaker zone. In Figures 2.50 and 2.51, these different types of currents are shown.
In short, the surf zone can be characterized as a place where currents and waves together give shape to their own morphological boundaries.

2.5.3 Sediment transport

Sediment transport plays an important role in nearly every coastal engineering problem. Frequently a shortage of material occurs at some location (undesired erosion); at other places an overabundance of material can be just as troublesome (siltation of a navigation channel, for example). An important goal of coastal engineering is to predict the sediment transport rates along a coast. Every sediment transport process has its own time scale. Waves for example can have periods of a few seconds and up, and a structural erosion component can be related to a morphological process lasting tens of years.

Compared to similar predictions for river sediment transport, calculations in coastal engineering tend to be more difficult; oscillating water movements under waves and the multitude of current-causing forces increase the number of involved variables considerably. At the other hand: along coasts, the sediment size is often rather uniform (well-sorted),
while in rivers often a wide range of particle sizes occur (well-graded). In coastal engineering transport calculation, the particle size aspect is more simple than in river engineering.

Cross-shore transport and longshore transport (Figure 2.52) are determined by morphological and hydraulic variations in the cross-shore and the longshore direction. Gradients in the transport lead to erosion or siltation. Cross-shore transport takes place on different time- and space scales. Dune erosion is a relatively fast cross-shore transport process. It happens during severe wave attack during high water levels.

![Figure 2.52 Longshore and cross-shore transport](image)

The general shape of a coast profile is the result of a dynamic equilibrium. Such an equilibrium profile can be characterized by a certain steepness. This steepness depends on the wave height and the grain size. As wave heights change during the season, the resulting profiles are called summer and winter profiles. During a short time, a change of the profile can appear in the form of erosion. This is not the same as permanent, structural erosion(!), which is often due to a longshore transport gradient. Nota bene: The difference between structural and temporary erosion cannot be seen above the water surface. For more details about coast profiles and erosion see Subparagraph 7.4.

Gradients in the (longshore) transport can result from incident waves under a different angle, wave height differences along the coast, bottom material changes and wind- and wave driven currents (Figure 2.53).
Figure 2.53  Causes of a positive longshore-transport gradient

Sediment transport can be described quite generally as the product of velocity V and the amount of sediment in a water column. If the sediment concentration c is constant over depth, it can be multiplied by the depth in order to get the amount of sediment in the column. If it is not constant over depth; both V and c as functions of the depth must be known. Then, they must be integrated over depth after multiplying them. However, not every situation is suitable to release those functions to us. In Figure 2.54, the result of tests are given: many different records of c(t) are shown, all measured at a constant elevation and under identical, regular wave conditions.
transport by currents

In rivers, $V$ and $c$ vary slowly as functions of time $t$ or horizontal position $x$. Sediment transport rate becomes:

$$S(t) = \int_{-h}^{0} c(z,t) \cdot V(z,t) \, dz$$

(2.27)

In case of a relatively constant current velocity and a stable sediment concentration, this equation can be simplified into:

$$\overline{S(t)} = \overline{S} = \int_{-h}^{0} \overline{c(z)} \cdot \overline{V(z)} \, dz$$

(2.28)

transport by waves

If waves play an important role in the water motion, the water velocity and the sediment concentration vary strongly with time. In this case, the simplification of the transport Formula 2.28 cannot be used; especially if the time average of $V$ is close to zero. In the case of irregular breaking waves, hardly anything is known about the behaviour of $c(z,t)$. Onshore-offshore sediment transport is difficult to handle using this formula, since refraction makes the angle of wave incidence small along a shore.
transport by wind
This process exists especially at sandy beaches and dune coasts. The process of dispersive movement by wind is dependent on geometry and vegetation (Figure 2.55 and Table 2.6).

![Figure 2.55](image)

Figure 2.55  Wind blowing over a little vegetated dune

### Table 2.6  Correlation between wind force, wind velocity and blown sand transport

<table>
<thead>
<tr>
<th>Wind force (Beaufort)</th>
<th>Wind speed (m/s) (approx.)</th>
<th>Sediment transport ($10^6 \text{m}^3/\text{s/m}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>4.5</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>7.0</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>10.0</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>12.5</td>
<td>14</td>
</tr>
<tr>
<td>7</td>
<td>15.5</td>
<td>31</td>
</tr>
<tr>
<td>8</td>
<td>19.5</td>
<td>86</td>
</tr>
<tr>
<td>9</td>
<td>22.5</td>
<td>165</td>
</tr>
<tr>
<td>10</td>
<td>26.5</td>
<td>310</td>
</tr>
<tr>
<td>11</td>
<td>31.0</td>
<td>408</td>
</tr>
</tbody>
</table>

2.5.4  Coastline changes

It is dangerous to look at a coastal form as a slide instead of a movie. The four input variables of the morphologic subsystem are dynamic. (These input variables are: coastal formation, water level, wind/wave power and tidal power.) Therefore, the output variables are changing all the time, too. The output variables are: sediment transport and coastal form.
Morphological processes still are a subject of intensive research. Many structural erosion problems are caused by a change in the longshore transport. Therefore, being able to quantify the longshore transport is of extreme importance. Many empirical or semi-empirical formulas have been developed in order to estimate the longshore transport rate. One of them is the so-called CERC-formula. It is treated in Chapter 7.
3 Coastal formations

3.1 Introduction

Today, as a central concept behind all attempts to model coastal changes, the idea has been formulated of two major steering processes: progradation and transgression. These processes shape a coast according to the sediment supply in relation to the relative sea-level rise.

Figure 3.1 Coastal forms for prograding and transgressive coasts (from Boyd et al [1992])
rise. If the sea-level rise is high, and the sediment supply relatively low, then marine transgression of a coast is taking place. If the sea-level rise is low, next to a high sediment supply, then coastal progradation is happening. In Figure 3.1, this concept of prograding and transgressive coasts is shown. In all cases, there is a net supply of sediment to the coast (net erosion is not considered here but can of course occur, e.g. when a river is dammed off and river sediment supply comes to a halt, while there is no source of marine sediment supply). The left of Figure 3.1 represents prograding situations. Then the landside is on the winning hand, either because of a falling sea level relative to the land, or because of an excessive sediment supply. The right represents the transgressive case, which is synonymous for a relative sea-level rise, exceeding the effect of sediment deposition. Note Bene: the change in sea level is relative, meaning that subsidence of the land with a constant sea level has the same effect.

In the prograding case, deposition of river sediment leads to delta formation. When wave power and tidal power are low, the sediment of the river will build a long narrow ("elagante" or "birdfoot") delta. Strong waves with longshore currents tend to stretch the delta coast parallel to the general orientation of the shoreline, while strong tidal action usually creates patterns perpendicular to the shoreline. Outside the influence of the river, a strand plain develops when wave action is dominant, and tidal flats when tidal action is the strongest.

In the transgressive case, an estuary is the equivalent of a delta in the prograding case, but now, the sediment supply is not enough to keep pace with the relative sea level rise. Now, the sediment is no longer merely fluvial, but has also a marine source, since the flood tide or waves bring in sediment from the sea. A lagoon even has only a marine sediment source,
as no river is flowing into it.

Based on morphological processes, Figure 3.2 gives a classification for prograding and transgressive coasts. The ternary diagram presents the fluvial power on the vertical axis, and the coastal powers on the horizontal axis, wave power to the left and tidal power to the right. The top of the triangle represents deltas; the bottom strand plains and tidal flats; estuaries are situated in between. Lagoons form, in this diagram, the end member of the estuary spectrum. The "depth" in the figure gives a possible idea about the evolution in time, relative to the change in sea level and sediment supply. With a rising sea level, all deltas change into estuaries and vice versa. Strand plains and tidal flats vanish and become shelf when the sea level rises.

In the following paragraphs, different types of shoreline are discussed. Transgressive types of coast are treated in Paragraph 3.2. The prograding types in 3.3. Ecology-dominated coastal features are presented in 3.4. Paragraph 3.5 is giving a view on (the relatively inert) rocky coasts.
3.2 Transgressive coasts

3.2.1 Definition

Transgressive coasts are coasts, where a relative sea level rise exceeds the effect of sediment deposition. The general form of a transgressive coast is the estuary (Subparagraph 3.2.2). It forms at the mouth of a river; it is the place where fresh and salt water meet. When wave power is relatively strong, the estuary is called wave-dominated. Tide-dominated estuaries consist of more marine sediment than wave-dominated estuaries. Tidal flats occur where the marine sediment supply is large enough to form them (Subparagraph 3.2.3).

A special type of estuary is the lagoon (Subparagraph 3.2.4). It has no (fresh) river discharge. When the sediment supply is big enough for keeping it, a beach occurs (Subparagraph 3.2.5). Correlated with lagoons and beaches are barriers (Subparagraph 3.2.6) and dunes (3.2.7). In this paragraph, special attention is also paid to tidal inlets (3.2.8), as they are important in many engineering problems.

3.2.2 Estuaries

Estuaries are turbulent bays, receiving fresh water from rivers, and salt water from the sea. As seen from the sea side, an estuary is an arm of the ocean that is thrust into the mouth and lower course of a river as far as the tide will take it. Every estuary has three main sections. The inland end, where the river enters, is called the head. The middle part is the fully estuarine area, where fresh water and salt water occur simultaneously. The seaward end is called the mouth.

Estuaries with wide mouths and narrow heads have a large tidal range. A tidal wave carries a given amount of water into an increasingly narrower part of the estuary. This geometry produces an increase in the high tide level. The ebbing of the same amount of water results in a similar relative decrease in the low tide level. An example of this effect can be seen in Canada's funnel-shaped St. Lawrence River. There, the tide increases in range from 0.2 m at the mouth of the river up to 5 m at Quebec City, a relatively isolated part of the estuary located at the landward end. These are the largest tidal ranges in the world.

Sea water has a salinity - the content of total dissolved solids - of about 35 parts per thousand, or 3.5 percent; fresh water has essentially zero salinity. This difference in salinities leads to different densities for the two water types: 1000 kg/m³ for fresh water and 1.026 kg/m³ for seawater. More details about the salinity-density relationship are found in Subparagraph 2.4.2. How does the estuary water behave under influence of this density difference?

Stratification of the two types of estuary water is the simplest circulation pattern. The alternatives are: partially mixed and fully mixed. In a stratified estuary, the fresh water and sea water masses are almost completely separate; no significant amount of mixing occurs. The upper, freshwater mass flows as a distinct layer from the head to the mouth of the
The subsurface saltwater mass flows along the floor of the estuary underneath the freshwater layer, with incursions and excursions as the tides flood and ebb, respectively.

The incoming saltwater mass takes the form of a wedge as it proceeds up the slope of the river bed. If no strong mixing processes exist, estuaries dominated by large rivers have a stratified circulation pattern. In a partially mixed estuary, tidal currents are the dominant factors in circulation. Although freshwater discharge from rivers is rapid, tidal currents are relatively strong and turbulent in comparison with those in stratified estuaries. As a result, mixing takes place at the interface between the upper freshwater layer and the lower saltwater layer. In Figure 3.3, stratification in an estuary is schematized.

This mixing produces brackish water, that is, water with salinities that are typically 15 to 20 parts per thousand. Therefore, the salinities in a partially mixed estuary form a gradient that ranges from 0 for pure fresh water to 35 parts per thousand for undiluted seawater.

Figure 3.3   Stratification in an estuary: density variations and velocity profiles
Because of the partial mixing, this type of estuary contains fresh water, salt water and water with intermediate salinities. The positions of different water types vary from estuary to estuary. They also depend on the time and specific conditions in any given estuary. The best way to show these positions is by plotting isohalines, or lines of equal salinity.

In a partially mixed estuary, salinities in a vertical water column are typically highest near the bottom, and lowest at the surface. An isohaline in the vertical plane slopes down from the seaward side of the estuary to the river mouth, because on the surface (the horizontal plane), salinities become higher and higher in the seaward direction, until the salinity of undiluted seawater is reached. At some position in the mouth of the river, we find the zero isohaline - or fresh water. Remember that this three-dimensional distribution of salinities is very dynamic. It can vary in as short a time period as a single tidal cycle. It also varies with the seasons, and in relation to events like a storm and subsequent flood.

The fully mixed estuary produces a homogeneous profile of water salinities. At any given place within the estuary, the salinity is the same from the surface to the bottom of the water column. Consequently, isohalines in the vertical plane have no slope. In the horizontal plane, there is pure fresh water at the river mouth and fully saline seawater where the estuary opens into the ocean, with brackish water in the middle.

Several conditions can produce a fully mixed estuary. Large waves entering a shallow bay have motion extending to the bottom. Therefore, they completely mix the bay waters from top to bottom. In other situations very strong tidal currents can produce this fully mixed condition. All these situations produce extreme turbulence within the estuary.

Many estuaries experience seasonal shifts in circulation patterns. A shallow estuary in which mixing depends on wave action will revert to the stratified pattern in the summertime (when waves subside). A large river that produces a partially mixed estuary during the spring snow melt, when its currents are strongest and most turbulent, will change into a stratified pattern in midsummer (when its current subsides). In winter, when an estuary's surface waters are touched by storm winds and become more dense as they cool, the upper and lower layers will mix temporarily. Other estuaries have the same circulation pattern throughout the year.

The geologic lifetime of an estuary is short because of sediment deposition. Some estuaries fill so rapidly that they have a short life even in historical time. When in the late thirteenth century Marco Polo visited the port of Hanghou (he called it Kinsai) on the Chien-tang estuary in northeastern China, it was a great commercial city with over a million inhabitants. Less than 200 years later, the bay had filled with sediment and trade had moved elsewhere.

River-deposited sediment tends to be a mixture of sand and mud, whereas sediments brought in from the sea generally consist of sand mixed with marine shell gravel. Within the estuary, mud is typically transported as suspended load and sand is carried as bed load, rolling and bouncing along the floor of the estuary. In low-energy estuaries with sluggish currents, fine-grained sediment accumulates on the bottom, although some of it is carried
out of the estuary with the ebb tides.

Estuaries can be divided into three regions on the basis of the most energetic factor influencing sediment distribution and deposition. We can, therefore, speak of river-dominated, tide-dominated, and wave-dominated estuaries. The different processes in the estuaries are located differently, as can be seen in Figure 3.4. Figure 3.5 shows how the dominating processes characterize the estuary. In Figure 3.6, sediment transport processes averaged over time are situated in the estuary profile.

As sand is a non-cohesive material, it is typically transported as bed load. Mud-sized particles are not, especially clay-sized ones [<4 micrometers]. They are transported as suspended load. In the zone where fresh and salt water mix, these very small clay particles combine to form various larger particles: floccules, inorganic particles bound by electrochemical forces; aggregates, inorganic particles strongly bound by intermolecular or cohesive anatomic forces; and agglomerates, inorganic particles bound together by organic matter or surface tension. Floccules are especially important in estuaries, particularly in the middle zone of partially mixed estuaries, where suspended clay particles first encounter the saline conditions that foster clumping.

Flocculation generally takes place in water with salinities above 3 parts per thousand. The clay particles have highly negative surface charges that are balanced by the strong positive charges on the ions in seawater: calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^+). The neutralized clay particles attract one another electrochemically (van der Waals force), and flocculation takes place. Composed of individual particles of less than 4 micrometer in diameter, floccules attain diameters up to 30 micrometer and create a characteristic region of muddy water called the zone of turbidity maximum.

The middle portion of the estuary where flocculation occurs has the most sluggish currents, because it is remote both from the river mouth and from the strong tidal currents at the estuary mouth. Consequently, large quantities of mud are deposited in the middle portion of most low-energy estuaries. The problem often exists that this mud is polluted. The little clay particles tend to capture polluting material. If the mud is taken out by dredging, it should be tackled very carefully.

Estuaries have another form of sediment in addition to that which is contributed by the rivers and the sea, namely: the biogenic material produced in the estuary itself, by its own population of plants and animals. Numerous organisms that find seawater inhospitable thrive in the brackish parts of the middle portion of the estuary where salinities range from 0.50 up to 17 parts per thousand. Ostracods (tiny shrimplike crustaceans in a bivalve shell), foraminifera, marine worms, and various snails, crustaceans, and bivalves are common estuarine animals. Shells and hard body parts from these organisms make an important contribution to the sediment of the estuary.
Figure 3.4 Plan view of distribution of energy and physical processes in estuaries

Figure 3.5 Schematic definition of estuary according to Dalrymple, Zaitlin and Boyd (1992)

Figure 3.6 Time-averaged sediment transport paths
3.2.3 Tidal flats

More than half of the margins of most estuaries are rimmed by tidal bays. These are areas that are exposed at low tide and flooded at high tide. Their extent is determined by the shape of the estuary and by the tidal range. Obviously, a large tidal range will provide a broader intertidal environment under any given set of circumstances. Not so obvious is the influence of the gradient of the estuary margins. Some are very gradual and therefore provide wide intertidal flats. Others, however, are steep; for example, the sides of fjords or tectonically formed estuaries. These estuaries have narrow intertidal flats, even in a setting with a large tidal range. Nevertheless, much of the area of many estuaries is made up of tidal flats intersected by tidal channels. Notable in this regard are the Westerscheldt tidal estuary on the North Sea coast of northern Europe and the Bay of St-Malo, on the Normandy coast of France.

The same currents that distribute sediments throughout the estuary and along the shoreline also deposit them onto the tidal flats. Local waves and longshore currents play a part, but most tidal flat systems are dominated by tidal currents. Tidal flat sediment is composed of mud and fine-grained sand and the shells of the small animals that have lived there; coarser grains settle out in the tidal channels. When exposed at low tide, the tidal flats have the appearance and texture of sandy mud or muddy sand.

As the tide floods and ebbs, the grains sort themselves according to size. The sediment on the tidal flat is deposited in thin, regular layers called tidal bedding. Each individual bed or stratum in this sequence can be from a few millimeters up to more than a centimeter thick. The tidal cycle leaves its own imprint on this bedding, producing alternating layers of sand and mud. Two sand layers represent the flood and the ebb portions of the cycle when currents are flowing rapidly. Thinner mud layers are deposited between the sand layers at, or near, slack high and slack low tide, when fine sediment settles out of suspension. With the spring tides, neap tides, and storm tides also leaving their own specific record of sediment accumulation, it is sometimes possible to recognize hundreds of layers and reconstruct a coastal calendar of events. Geologists studying ancient stratigraphic records can recognize ancient tidal flats and tidal channels from their bedding characteristics and can even reconstruct the behavior of tides.

3.2.4 Lagoons

Figure 3.7 Section through a barrier closing a lagoon (Bird [1984])
Lagoons (Figure 3.7) are bays which are closed off from the sea. They can be seen as a specific type of estuaries. Generally, they are protected from the open ocean by a barrier island, a reef, or an obstruction that prevents wave attack and inhibits tidal circulation.

Stages in the evolution of a barrier to enclose a lagoon are shown in Figure 3.7. The prolongation of the spit, as is shown in the upper part of the figure, is caused by the longshore transport. Shoreward migration of a barrier that originated offshore is caused by the cross-shore transport. It is shown in the lower part.

![Figure 3.8 Stages in the evolution of a barrier to enclose a lagoon (Bird, 1984)](image)

Usually, there is no large freshwater influx in a lagoon. Sometimes, a river does discharge into a lagoon, causing the water to become brackish or fresh. This cannot be a large discharge however, otherwise the connection between the lagoon and the sea would change into a tidal inlet including all correlated dynamic processes. The typical lagoon configuration would vanish.

In a lagoon, specific morphological processes are at work. They are mentioned in Figure 3.9.

![Figure 3.9 Processes which control evolutionary processes in a lagoon](image)
3.2.5 Beaches

Nearly anything that can be transported by waves can form a beach. A beach extends from the low tide line landward across the un-vegetated sediment to the beginning of permanent vegetation, or to the next geo-morphic feature in the landward direction - a naturally occurring dune, a rocky cliff, or a constructed seashore. The overall profile of a beach and the adjacent near-shore depends on sediment supply, wave climate, overall slope of the inner continental shelf, tidal range, and a variety of local conditions. Sandy beaches include a foreshore and a back-shore (Figure 3.10). In many places, a pair of persistent sand bars, over which waves break during storms, parallels the beach.

The back-shore, or back-beach, extends from the berm at the landward end of the foreshore across the remainder of the beach. Gravel beaches of shell and rock fragments commonly include a storm ridge that is just landward of the foreshore. Sometimes this storm ridge may grow until it rises several meters above high tide and entirely replaces the back-beach. Its composition depends on the nature of the gravel material in the immediate area; its size is proportional to the rigor of the storms that produce it.

Figure 3.10  Sandy beach profile nomenclature (distorted scales)

In Paragraph 2.5, morphological processes causing beach change were mentioned. Many of them are cyclic processes. Their scale of time and space can differ very much from one process to the other. Cycles can be long- or short-term. For example, the season causes beach variation. Depending on the climate, on one hand there are the fair-weather, low-energy, accretional beaches and on the other hand foul-weather, high-energy, erosive beaches. The correlated beach profiles are called summer and winter profiles.
3.2.6 Dunes

In developing dunes, the prevailing winds or diurnal sea breezes provide the transport mechanism. Vegetation is one of the best and most widespread facilitators of dune development. Different dune types are shown in Figure 3.11. Dunes can be two- or three-dimensional (Figure 3.12).

![Diagram of dune types]

Figure 3.11 Variety of dune types (adapted from Carter, 1988, Reading, 1986, and Flint, 1971)

A dune ridge - a linear arrangement of dunes, one dune wide - is the typical configuration of dunes just landward of the beach. It is called the foredune ridge because of its location...
Figure 3.12 Two-dimensional and three-dimensional dunes (adapted from Reineck and Singh)

seaward or in front of the barrier or mainland. The presence of several dune ridges marks a portion of the coast as one with a history of growth or progradation towards the sea. This is an optimal condition for any coast because it indicates an overall lack of erosion. On the contrary, some of the dunes migrate inland. A huge sediment supply or an absence of stabilizing vegetation can be causes for that.

Dunes often have the function of sand reservoir. Although dunes are beyond the regular influence of waves, they are vulnerable to even modest storm surges. The other major factor is the wind, which can cause migration of part of, or all of the dune! Blowover is the most common wind-driven process responsible for dune migration.

3.2.7 Barriers

A barrier can be defined as an elongate, shore-parallel sand body which may consist of a number of sandy units including beach, dunes, tidal deltas, wash-overs, and spits. Barriers separate lagoon and estuary embayments from the marine environment and are best classified as components of estuary and lagoon systems. General barrier types are given in Figure 3.13. Barriers rise above sea level, naturally protecting the landward part of the coast against wave attack.

Barrier islands develop in any geologic and tectonic setting that has a plentiful supply of sediment, agents to transport it, and a site where it can accumulate. Therefore, barrier islands and other barriers are often found along trailing edge margins, as well as on
scattered parts of leading edge margins. They form as sand accumulates through the combined action of waves and wave-generated long-shore currents.

Figure 3.13 General barrier types: bay, spit, island

Barrier islands can range from a few hundred meters to more than 100 km in length. They can be defined as wave-dominated and mixed-energy deposition systems. They are found worldwide, from Alaska to Australia; they constitute approximately 12 to 15 percent of the earth’s outer coastline. Some are barely above high tide; others have dunes that rise 30 m above the sea.

Whether a barrier island develops at all depends on the predominance of wave over tides. Regardless of its specific origin, waves and wave-generated currents must be present to produce the linear accumulation of sediments. When tides become dominant over waves, the barrier island gives way to a tidal flat and marsh.

Barrier islands generally assume one of two forms. One is long and narrow and derives its shape from distinctly wave-dominated conditions. They are likely to be transgressive in nature. However, when abundant sediment is available, multiple parallel dune ridges develop as they prograde. The other form of barrier islands is relatively short, with one end much wider than the other. Barrier islands of this type are built up and maintained by a combination of wave- and tide-generated processes. Such mixed-energy barrier islands have been named drumstick barriers (Figure 3.14).
Barrier islands tend to "walk". If deposition of storm-transported sediment continues over an extended period of time at the back of a barrier island, a landward displacement of the barrier occurs. As the barrier transgresses, it loses some of the sand-sized sediment. Unless more sand becomes available, largely through longshore transport, the barrier is destroyed before it reaches the mainland. Sea-level rise makes barriers more vulnerable to this type of movement.

Addition of sediment can also cause barrier islands to prograde, that is, to grow in a seaward direction. This condition is different from transgression in that the barrier island as a whole does not move. Instead, the addition of sediment causes the development of multiple beach-dune systems, and the openwater shoreline actually moves seaward, while the landward backbarrier shoreline remains in place. An individual barrier island can experience transgression and progradation at the same time.

A special feature along the barrier coast is a washover fan. This is a fan-shaped accumulation of sand and shell, that is deposited in a thin layer during intense storm conditions, when part or all of the beach-dune system is overtopped or breached by incoming waves and storm surges.
3.2.8 Tidal inlets

Barriers generally are breached at various points by tidal inlets (Figure 3.15), which link the open marine environment and the coastal environments landward of the barrier islands. Like beaches, tidal inlets are dynamic parts of the barrier system and range widely in size, stability, and water flux. They owe their origin to a variety of circumstances, although storms and human activities are the most important factors. Flood tidal deltas and ebb tidal deltas both can be tide-dominated or wave-dominated. Another important factor is the bathymetry of the back-barrier bay. Along many barrier coasts, for example the Dutch Wadden Coast, the longshore transport causes a structural asymmetry in the ebb-tidal deltas.
3.3 Prograding coasts

3.3.1 Introduction

In Paragraph 3.2, tidal flats and strand plains (beaches) have been discussed in the context of a transgressive coast. In the case of a prograding coast, these two features can be present, too. However, estuaries are not found in the transgressive situation. The prograding variant of the estuary is the delta. In this Paragraph, more information is given about this fascinating coastal form.

3.3.2 Classification of deltas

Deltas are transitional coastal environments that are neither fully terrestrial nor fully marine. They have no easily recognizable landward or seaward boundaries, but change by imperceptible stages from open sea to solid ground. A delta begins at the point where a large, sediment-laden river leaves its upland drainage basin and flows onto a region adjacent to the ocean. Built primarily from river-borne sediment, deltas form when the amount of sediment delivered at the mouth of a river exceeds the amount removed by waves and tidal currents.

Figure 3.16 William Galloway's triangular delta classification diagram
Like estuaries, although being their "morphological opposites", deltas are strongly influenced by rivers, waves, and tides. William Galloway's triangular diagram classifies river deltas according to the relative influence of these three major factors affecting their development. It is given in Figure 3.16. Placed somewhere toward the middle of Galloway's schematic triangle are deltas, shaped by rivers, waves, and tides in various combinations.

Deltas occur on every continent and in a wide range of climatic settings, but the geologic settings are generally similar. A tectonically stable trailing edge coast provides the right conditions for delta formation. It has low- to moderate-relief terrains, such as coastal plains or geologically old mountain areas. Rivers bring an abundant sediment supply across wide, gently sloping land, where the river channels meander back and forth on their way to the coast. On the seaward side of this tectonic setting, the broad continental shelf provides a platform suitable for sediment accumulation; it also reduces the size and energy of the incoming waves.

The Sao Francisco Delta in South America and the Senegal Delta in Africa have developed on trailing edge coasts. Marginal seas with trailing-edge characteristics provide shelter from large waves and tides, and very large deltas have developed in tectonic settings of this type. Excellent examples are: Mississippi River Delta in the Gulf of Mexico; the Rhone, Nile, Po, and Ebro Deltas in the Mediterranean Sea; and the huge deltas of China that empty into the South China Sea.

3.3.3 Young or old?

Most of the present active deltas are geologically very young features; some are only a few hundred years old. Because a delta develops at the coast, its existence is, in part, controlled by the sea level. It therefore is, and was, vulnerable to (global, eustatic) sea-level rise, too. During the periods of extensive glaciation, sea levels were much lower and rivers traversed the present continental shelves, dumping their sediment loads at or near the outer shelf edges. This suspended sediment cascaded down the continental slopes in turbulent, high density flows called turbidity currents. New deltas did not form during this period, and deltas that had previously existed near the positions of present-day coasts were abandoned and entrenched by rivers as they flowed across the continental shelves.

Melting glaciers brought a rapid rise of sea level, and river mouths retreated so rapidly that deltas could not develop. Finally, about 7000 years ago, the Holocene sea level rise slowed, and in some parts of the world it stabilized at approximately its present position. Where conditions were appropriate, deltas began to develop as large quantities of river sediment accumulated.
Not all present-day deltas are only up to a few thousand years old. Many of them have formed on ancestral deltas built up during previous interglacial periods. A few, such as the Mississippi (Figure 3.17) and Niger (Figure 3.18) Deltas, are underlain by ancestral deltas that formed tens of millions of years ago. The upper regions of these mature deltas are also ancient, but their active delta lobes are only between 3000 and 6000 years old. The lower Mississippi Delta includes 16 detectable lobes. A new lobe forms, whenever the location of the river mouth changes. The channels of abandoned lobes fill up with sediment, contributed both by the river, by the waves and by the tides of the coast. The present delta lobe of the Mississippi dates back only 600 years; its most active portion has developed since New Orleans was founded in 1717.

Figure 3.17  Mississippi Delta

---

Channel deposits
Sand ridge
Swamp
Marsh
Terrace (Pleistocene)
3.3.4 Delta shape

The formation of a delta depends on the interaction between the flow and distribution of the river sediment, the waves and tidal currents. As the water flows from the river mouth, its velocity decreases and it loses its capacity to carry sediment. Consequently, sediments accumulate in the river mouth area. At the seaward edge of the delta front, the suspended sediment in the river water finally settles out into the deeper coastal water, as the velocity of the outflowing river water decreases. This mud accumulation is generally very thick and extends across part of the continental shelf.

The amount and configuration of sand accumulations in the delta front (Figure 3.19) depend on the relative roles of the interacting river, wave, and tidal currents. A common type of sand accumulation is the distributary mouth bar, a sand bar that accumulates just seawardly of the channel mouth and typically causes the channel to bifurcate. Waves that approach the delta at an oblique angle create currents that carry this sand from the mouth of the channel and distribute it along the outer delta plain, thereby forming a nearly continuous system of sand bars.
The relative influences of the river and the marine processes determine the fate of the sediment. Many factors are important, among which are the climate, topography, sediment availability in the drainage basin, and the river gradient. However, the most important are rainfall and soil type. Human activity also has a tremendous influence on delta conditions.

As the river deposits sand in the mouth, the situation can be reached where its water level gradient is affected by the sand deposits. Then, it could rise over its banks and the river divides into distributary channels. Each distributary channel then continues to transfer massive amounts of fine-grained sediment to the coastal area. When this new-born delta is situated in a low-wave climate, it can grow out into a birdfoot type of delta. This process is illustrated in Figure 3.20.

A so-called river-dominated delta has a well-developed delta plain with several distributaries projecting seaward in a digitate, bird-foot configuration. The river-dominated Balize lobe of the Plaquemines-Modern complex of the Mississippi delta, as can be seen in Figure 3.19, shows the elongate "bird-foot" morphology.
Tide-dominated deltas develop where a large range between the high and low tides leads to strong tidal currents that flow essentially parallel to the coast. On these deltas, the wave height is moderate to low, and longshore currents are weak. They deltas resemble estuaries because of their embayed setting of salt marshes, swamps, and tidal flats.

If the wave climate is more severe, the bars at the river mouth are influenced by the waves. This situation is drawn in Figure 3.21. This effect can be quantified using the CERC-formula, as will be explained in Chapter 7.

Wave-dominated deltas typically have a rather smooth shoreline with well-developed beaches and dunes. The delta plain tends to have few distributaries; some deltas of this type have only a single channel. A wave-dominated delta is generally smaller than other types, because the distributing power of the waves striking the delta front is stronger than the carrying power of the river. Were the wave processes to become strong enough to carry all the river sediment away, the delta would shrink and eventually disappear. Two different shapes characterize these deltas. The general shape is symmetrically cuspate. The other shape is characterized by a strong longshore current. A sand spit develops and protects the extensive wetlands that cover the delta plain. An example of this is the Senegal River Delta, as can be seen in Figure 3.22.
The landward and very flat part of a delta is the delta plain (Figure 3.23). The upper delta plain is merely an extension of the upland meandering river system, except that the river here consists of one or more distributary channels. Each time a distributary channel overflows its banks, the coarser sandy sediment particles are dumped first, producing a low ridge of accumulated sediment along the bank margin. This ridge is the natural levee. It may build up to an elevation of a meter or two above the surrounding delta plain. During subsequent flooding, the natural levee may be breached either through a naturally low section or through cuts made for human passage. When the sediment-laden floodwaters pass through the breach, generally called a crevasse, there is an immediate reduction in carrying capacity as their velocity decreases abruptly. A thin, fan-shaped sediment accumulation forms beyond the breach. This formation, called a crevasse splay, can extend several kilometers across the upper delta plain.

The major landforms of the delta plain - natural levee, crevasse splay, interdistributary bay and marsh - are distinguished from one another on the basis of elevation, sediment character, and vegetation. As time passes, continued flooding and sediment unloading enlarge the delta and bring more and more of its features above water level. Much of the mature delta plain between the distributary channels eventually turns into fertile farmland, interspersed with small lakes and fresh water marshes and swamps. All these are periodically replenished by flood waters. The inside edges of the bends in the distributary channels on a delta plain fill with thick accumulations of sand and gravel. These deposits are called point bars. As the channels migrate across the delta plain, they leave subtle but recognizable scars marking their former locations.
Figure 3.22 Senegal River Delta

Figure 3.23 Basic environments of a delta (from Wright, 1985)
3.3.5 Human interest

Early civilizations developed on deltas to take advantage of both the fertile soil and the nearby fisheries. Access to the sea also provided military advantages as well as avenues for trading. As delta regions became more populated, upland forest clearing and cultivation usually advanced delta growth by intensifying soil erosion. The more common effect is to shrink the size of a delta by diminishing the velocity of its river and depriving it of sediment. Diverting of water, navigational locks, and hydro-electric dams and reservoirs are due to this. Once a river and its delta have been tamed by giant engineering projects, it seems almost impossible to return them to a more natural state. All attempts to control deltas have weakened them.

Figure 3.24 Sketch map showing the location of the Aswan High Dam, the flooded area, and Khasm el-Girba (H.M. Fahim, 1972b)

An example of this can be found in the Nile Delta; the Aswan Dam. In Figure 3.24, the location of it is shown. In 1980, Fahim discussed the performance of the Aswan Dam in its major aspects. In Table 3.7, his conclusions are given.

Coast line recession on the Nile Delta has been extensive as a sequence to barrage and dam construction on the River Nile during the past century, and especially since the completion of the Aswan High Dam in 1964. Discharge of water and sediment to the sea from the two main distributaries has declined, and this diminished sediment yield has been followed by coastal erosion, especially near the mouths of these distributaries. (E.C. Bird, 1985)
Table 3.1  The Aswan High Dam debated: a summary sheet (H.M. Fahim [1980])

<table>
<thead>
<tr>
<th>Logistics</th>
<th>Benefits to Date (1980)</th>
<th>Major Side Effects</th>
<th>General Assessment and Prospects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land development was a necessity to cope with the incredible imbalance between the country's population growth and agricultural production. Agriculture is basic to the Egyptian economy.</td>
<td>Controlled high floods and supplemented low ones; saved Egypt from the monetary cost to cover the damage from both high and low floods. Allowed for increase in cultivated land area through reclamation, and increased the crop production of the existing land through conversion from basin to perennial irrigation. Improved Nile navigation and changed it from seasonal to year-round. Electric power generated by the dam supplies 90 percent of Egypt's current consumption, although the dam was built primarily not for power generation but for water conservation. The new lake resources are potentially economic, including land cultivation and settlement, fishing, and tourist industries.</td>
<td>Water loss, through seepage and evaporation, is likely to affect the water supply needed for development plans; studies show that the water loss is within the predicted volume. Loss of the Nile silt would require costly use of fertilizers; it has also caused riverbed degradation and coastal erosion of the northern delta. Soil salinity is increasing and land in most areas is becoming waterlogged, due to delays in implementing drainage schemes. Increased contact with water through irrigation extension schemes is expected to affect schistosomiasis rates adversely; evidence exists rates have not increased due to use of protected water supplies. The Nile water quality has been deteriorating; studies indicate the occurrence of change in the water quality parameters, they do not constitute a health hazard at the present time.</td>
<td>The Aswan High Dam is solid engineering work; more importantly it is fulfilling a vital need for 40 million people. All dams have problems; some are recognized while others are unforeseen at the time of planning. The lesson learned from the Aswan project, however, is that dams may be built with missionary zeal but little careful planning and monitoring of side effects. As a result of both (1) the new semicapitalist policies and (2) the technical and monetary aid Egypt has lately been receiving from several Western countries, it is expected that several of the dam's problems will be efficiently controlled and monitored. Dam-related studies have given recognition to present problems and have provided possible solutions. The dam would meet its expectations on several aspects providing that research findings are utilized. The development potential and economic returns of this water project are expected to be very rewarding in the long run, if the project's developments are systematically studied and monitored.</td>
</tr>
</tbody>
</table>
3.4 Ecology-dominated coastal features

3.4.1 Salt marshes

On the fringes of estuaries, lagoons, and other bays, in places where sediment deposits are sheltered from wave action and are above the level of neap high tide, vegetation eventually takes hold and forms a salt marsh. An extensive marsh is a sign of a natural estuary that has largely filled with sediment. Many marshes mark the locations of old estuaries that have filled with sediment to the requisite elevation for plant germination.

In the upper intertidal region between the level of the neap high tide and that of the spring high tide - generally a short vertical distance of 20 to 50 cm - the velocity of the tide waters drops drastically and fine sediment settles without being disturbed by energetic waves. Opportunistic, salt-tolerant grasses, or in low latitudes, mangroves, are the first to take hold in this environment. The grass blades further slow tidal currents and trap more of the fine sediment carried in suspension. Once a stand of marsh grass is established, it becomes denser, thriving on its ability to tame the tides and accumulate sediment.

Their facility for trapping sediment, either by physically capturing it from passing currents or by slowing currents and permitting the sediment to settle into the plant community, makes these plants very important contributors to coastal sediment accumulation. In addition to their positive role in catching sediment to the substrate, marsh grasses are very important sediment stabilizers. They prevent or inhibit currents and waves from removing sediment from the vegetated substrate.

Figure 3.25 A cross-section of a salt marsh

The upper limits of the salt marsh coincide with the landward or upper limit of the spring high tide, the highest level of regular inundation and sediment supply. A salt marsh may be a few meters wide or it may occupy the entire estuary except for the tidal channels. In Figure 3.25, a cross-section of a salt marsh is drawn, together with the subenvironments and distribution of marsh grass. From the edge of the tidal creek to the high marsh is cordgrass (Spartina, Figure 3.26); the high marsh is needle rush.
The development of an entire marsh can be characterized by the relative abundance of two common species of vegetation: cord grass and needle rush. Young marshes are dominated by cord grass, with only a fringe of needle rush around the upper margin. Tidal channels are abundant and provide good avenues for tidal flux and sediment delivery. As a marsh matures, sufficient sediment collects in the upper intertidal zone to support more and more needle rush. In time, a marsh enters an intermediate stage of development in which the grasses and rushes are about equally distributed and tidal channels are fewer. In a mature marsh, sediment has become plentiful in the outer zones and only a few large tidal creeks interrupt a continuous stand of rushes. Eventually, land plants encroach on the outer edges of the rush stands.

Individual marsh flats can develop into extremely valuable nature terrains. Apart from many specific vegetation species, animals use the place for breeding, feeding and moving from one place to the other. A beautiful Dutch example of such a marsh is the East part of Schiermonnikoog.

The marsh environment is quite similar to that of river and delta floodplain. Channels, bordered by natural levees and crevasse splays, cut through the marshy plain. Some channels meander and produce cutoffs and oxbow lakes. This system delivers sediment to the marsh in two ways: regular but slow flooding of the marsh by turbid water carried by sluggish currents that permit settling; and storm tides that push large amounts of sediment-laden water onto the marsh and deposit considerable sediment in a short time. Although a paradigm for marsh development has been given here, the present global situation is one of eroding marshes due to sea level rise.

For hundreds of years, the Dutch, Germans, and Danes have been converting marshes to farmland by draining them through a system of dams, dikes, and canals. Then the sediment compacted and dried, and their reclaimed land sank - so higher dikes were needed for protection. This process has now been stopped, and the Netherlands is trying to prevent further subsidence by flooding selected areas of farmland, and returning them to marsh or open water for recreational boating.
3.4.2 Mangrove swamps

In tropical and subtropical climates, extensive stands of mangroves - woody trees of various taxonomic groups - invade the intertidal zones of estuaries and other bays. Thick tangles of shrub and tree roots, commonly called swamps but properly known as mangals, form an almost impenetrable wall at about water level. Most trees grow from 2 to about 8 m high, some much higher, depending on the species and the environmental conditions - rare stands may be twice that high.

The root systems of mangroves (Figure 3.27) are not only dense, but also diverse in appearance and function. The most spectacular root display is put on by the red mangrove (Rhizophora mangle), which has large, reddish prop roots that support the tree. It also has vertical drop roots, which are long vertical appendages that sprout from low-lying branches and eventually reach the ground and give support. Pneumatophores, another common type of roots, occur in another common species, the black mangrove, Avicennia germinans. The pneumatophore is a short root growing upward from lateral runners extending from the central trunk. Although there is considerable argument about their function, it is believed that they are respiratory organs for exchange of oxygen. The third species of mangrove in Florida and the Caribbean Islands is the white Laguncularia racemosa. In places like tropical Australia or India, there are more than 20 species of mangroves.

![Mangrove roots and typical cross-section of mangal](image)

The thickets of mangrove roots at the water line provide a sheltered habitat for a special community of organisms, that are adapted to an environment intermediate between land and water. Barnacles and oysters encrust the roots and branches, looking almost like fruit. Fish, snails, and snakes all find protection, nesting sites, and food among the roots. Besides, they make a practically indestructible coastal defense against storms and hurricanes (Figure 3.28). On the
other hand, if once they are removed, usually immediate and very rapid erosion takes place.

Figure 3.28  The massive root systems of mangroves create dense sediment stabilizing mazes

3.4.3 Coral reefs

Reefs built by coral and associated organisms occur extensively in tropical waters. Stoddard (1969) has identified four major forms of large-scale coral reef types (Figure 3.29):

1 Fringing reefs
2 Barrier reefs
3 Platform reefs
4 Atolls.

Where reefs border the coast they are termed fringing reefs; where they lie offshore, enclosing a lagoon, they are known as barrier reefs; and where they encircle a lagoon, they are called atolls. Platform or table reefs form from shallow banks on the seafloor, that have been capped with reef-forming organisms. They cover extensive areas of the seafloor and are not associated with the formation of barriers and lagoons.
Atolls are ring-shaped reefs that grow around the edges of extinct volcanic islands, enclosing lagoons from open water. The shallow lagoons may contain patch reefs. Atolls are primarily found in isolated groups in the western Pacific Ocean. Small low islands composed of coral sand may form on these reefs. These islands are quite vulnerable to inundation, and to tropical storms. The first theory concerning the development of atolls, the subsidence theory proposed by Charles Darwin in 1842, has been shown to be basically correct (Strahler 1971). The evolution of a coral island exists in different stadia, as drawn in Figure 3.30:

a  Active volcano rising from the seafloor;
b  Extinct volcanic island with fringing reef;
c  Subsiding island; reef builds upward and seaward, forming barrier reef;
d  Continued subsidence causing remnant volcanic island to be completely submerged.

Growth continues upward and seaward until remnant volcano is covered. It is important to stress that reef islands are naturally dynamic. Sediment production occurs around reef islands, and erosion, deposition and cementation can occur concurrently on atolls today (Wiens, 1962). Some islands may be in a stable equilibrium with neither addition nor loss of sediment. However, on most islands, sediment is added and lost over time, and there is more likely to be a dynamic equilibrium between inputs and outputs. Islands adjust over a range of timescales.

The term coral reef refers to rigid, sublittoral, benthic structures composed of calcium carbonate. The calcium carbonate is excreted by organisms. One of the dominant types of organisms are the corals, Cnidaria; another is Lithothamnion, a coral-like red algae. Many other organisms contribute calcium carbonate to the reef, and their shells and debris are encrusted by Lithothamnion into a well-cemented structure. Some of the most common of those organisms are Halimeda, a green algae, foraminifera, many bivalves, and many
gastropods.

Figure 3.30  Evolution of a coral island (adapted from Press and Siever, 1986)
Warm water and light penetration are essential to the development of coral reefs. Light is important, because Lithothamnion and Halimeda are both photosynthetic plants. Also, since corals are benthic animals that rely on currents to provide oxygen, the seawater must be well circulated, and rich in calcium and carbonate ions. Because the warm waters of the tropics are generally deficient in carbonate, the upwelling of relatively carbonate-rich water from depths of 100 to 300 m is necessary for coral reefs to develop. This means, that coral reefs are most likely to form near steep island or continental slopes on the western boundaries of the oceans. The easterly equatorial currents are deflected upward when they meet the slopes, producing an upwelling of nutrient-rich water.

The reef-building corals (Figure 3.31) themselves depend on light penetration. This is because the corals are inhabited by symbiotic, photosynthetic dinoflagellates, called zooxanthellae, which provide oxygen for the corals and remove wastes. The corals in turn provide carbon dioxide, nutrients, and protection for the zooxanthellae, such as radiolaria, sponges, sea anemones, bivalves, and echinoderms. The giant clam, Tridacna gigas, is able to digest zooxanthellae, enabling it to reach a much larger size than it could achieve by feeding on the plankton brought by currents.

The coral reef ecosystem is based on a closed energy cycle. The amount of plankton living at the front of the reef is approximately the same as the amount living at the back. The apparent primary producer of organic nutrients from inorganic nutrients in the system is filamentous green algae, which thrive on the nutrients and carbon dioxide provided by the corals and other animals.

Figure 3.31  Cross-sectional model of an individual coral
Lithothamnion forms an algal rim within the surf zone, and corals and Halimeda inhabit the reef front and reef flat where wave action is less severe. Typhoons and predators such as the crown-of-thorns starfish (Acanthaster) can decimate corals. When this occurs, Lithothamnion or other encrusting algae form on the coral skeletons.
Coral reefs are, like tropical rain forests, among the most complex communities on earth, and rock-producing reef communities are among the most ancient life forms found in the fossil record. Because of their complexity, the dynamics of coral reefs are not yet well understood. Coral reefs are being adversely affected by man during the last centuries. Some of the most wide-spread impacts are water pollution from various human activities, deforestation (erosion leading to increased cloudiness), dredge and fill operations, over-harvesting of fish and shellfish, and the harvesting of some corals for souvenirs. All forms of stress on the coral slow its growth. Any destruction cannot be replaced; natural recovery would take thousands of years. Implantation experiments have been carried out, but they failed.
3.5 Rocky coasts

3.5.1 Origin of rocky coasts

75 percent of the world's continental and island margins consist of rock. Rocky coasts appear where the wave climate is always energetic. Rocky coasts are commonly tectonically-active convergent coasts, that produce a high-relief border. Because they are formed on continental plate margins, under which an oceanic plate is descending, virtually no continental shelf is present. The western edges of North and South America are excellent examples of this type of coast. On other, tectonically unrelated, cliffed coasts, various sedimentary strata are horizontal or dip at low angles. The adjacent continental shelf is wide, with a gentle slope. But here, also, the waves are large because of a great fetch.

Figure 3.32 Fjord at Kenai Fjords National Park, Alaska

Pleistocene glaciers have also had a hand in producing cliffed coasts. The moving ice masses gouged out steep valleys, which were subsequently drowned as the sea level rose. Although their profiles are similar, some are rocky and others are not. In Figure 3.32, the rocky coast along a fjord at Kenai Fjords National Park, Alaska, is shown. It was carved by a glacier.

Still other cliffed coasts are formed of glacial drift - sediment deposited by glaciers beneath
and at the margins of the ice. The drift is over 100 m thick in some places and includes nearly any type of material from stiff clays to sand and gravel. Some of it is well layered and some is massive, with essentially no internal organization. The accumulations known as end moraines tend to be linear and thick. When these end moraines meet the sea, the waves sculpt steep bluffs. Irregular bluffs of glacial drift show erosion on the coast at Gay Head, Martha's Vineyard, Massachusetts, Figure 3.33.

Another variety of rocky and commonly cliffed coast is associated with areas where the continental shelf and adjacent coast are dominated by skeletal shell debris. A similar type of rocky coast has been constructed from the abundant carbonate sediment in these contrasting areas. In the Pleistocene, onshore winds blew carbonate sediment landward, where it accumulated in wide beaches and dunes. In a process called lithification, the calcium carbonate grains are welded together by a cement created as ocean spray or percolating ground water reacts with the calcium carbonate. The evaporation of the regularly wetted surfaces in arid climates enhances the lithification of the sediments. The rapid cementation converts the dunes to a rock called eolianite.

3.5.2 Rock erosion

Along rocky coasts, wave energy is high; the size of the waves is related to the nearshore bathymetry and refraction patterns. The wave energy is focused on the headlands and dispersed in the bays, so the headlands erode as the intervening bays fill up. Wave erosion of an indented coast line produces a straightened, cliff-bound coast, as shown in Figure 3.34. Wave-cut platforms and isolated stacks and arches may be left offshore.
Along rocky coasts, the reflection rate can be high. This causes reinforcement of the next wave; a standing wave is born. When there is no dissipation in the form of breaking, the waves become more powerful. When a wave hits the steep rock surface, pressurized air is trapped beneath it, and provides a cushion for the water hammer that the wave represents (Figure 3.35). But the pressure itself works on the rock, too. It is greatest near still water level. Rapid transport of large gravel particles across the rock surface produces considerable impact and abrasion. Sand can also be an abrasive agent.

Tidal range varies greatly. Steep or vertical cliffs tend to have wave energy focused in a narrow intertidal area, whereas a gently sloping rocky coast spreads the wave energy over a relatively wide zone. Macrotidal coasts are coasts on which wave energy is distributed over a relatively wide zone; on microtidal coasts the contrary happens. The erosional notches in cliffs are testimony to this relationship (they are more common along microtidal coasts).

Storms do not appear to have important effects on rocky coasts. Other, subtler physical processes contribute to change along rocky coasts. Evaporation and temperature change can
cause mineral grains and rock fragments to expand and contract slightly. When water freezes under confinement, it can break rocks. Porous and permeable rocks are particularly vulnerable to frost damage.

Various parts of a particular rock differ in their ability to resist erosion. A structural weakness caused by fracturing can be present. The coast can consist of layers of various rock types. Different levels of cementation are possible. The one feature that all stacks and arches share is some type of vertical character. Some examples follow here.

Steep cliffs of unconsolidated sediments constitute much of the shoreline along Drake's Bay in Pt. Teyes National Seashore, California, see Figure 3.36.
Figure 3.37 is an example of wave erosion: waves have eroded the softer layers of these sandstone cliffs.

![Figure 3.37 Tasmanian coast of Australia](image)

Rempton Cliffs in Yorkshire, England (Figure 3.38) are a good example of vertical cliffs.

![Figure 3.38 Rempton Cliffs in Yorkshire, England](image)

Note the people atop the cliffs for an indication of scale.

The shore platform at Schooner Gulch, Mendicino State Park, California, was cut by waves across dipping sedimentary strata (Figure 3.39).
The London Bridge arch along the Great Ocean Road in southwestern Victoria, Australia,
as it appeared in July 1986, is shown in Figure 3.40.

Figure 3.41 shows the London Bridge arch after it collapsed, stranding two tourists in
February 1989. The remains of the arch can be seen in the surf.
Figure 3.41  The London Bridge Arch in Februari 1989
4 Coast and culture

4.1 Introduction

All through recorded history, and probably long before, the ocean has been a recurrent theme in religious accounts, folklore, and scientific investigations. Archeologists confirm that human societies have long had close ties to the ocean and its shores—ties that persist to this very day. Of the world's twenty largest cities, eighteen have direct access to the ocean. We swim in the ocean, fish in it, sail on it, dump waste into it, and probe it to discover its origins and the processes that govern its surface waters and its depths.

An engineer working in the coastal area needs to be acquainted with all the processes which are outlined in the previous chapters. Apart from those, this poor engineer must also be familiar with the people who surround him during his work, and with the people who would surround him in case his work turns out wrong. In other words: engineering practice is strongly related to social environment, politics and economy. These aspects together form the socio-economic subsystem. This subsystem is discussed in Paragraph 4.2.

The coastal zone can be seen as the background for many social and economic developments and conflicts. Therefore, a special form of management is finding its way, which is called Coastal Zone Management (CZM). A general introduction to Coastal Zone Management is given in Paragraph 4.3.

Strongly related to CZM is its "big brother": ICZM, Integrated Coastal Zone Management. It is a specialism concerned with global problems like poverty, environmental problems and global (eustatic) sea level rise. In Paragraph 4.4, particular attention is paid to global changes, problems and possible solutions out of the field of ICZM.
4.2 Description of the socio-economic subsystem

4.2.1 Boundaries of the socio-economic subsystem

In general, the boundaries of the socio-economic subsystem do not coincide with those of the natural subsystem. Many activities in an area, wider than the coastal zone alone, may be affected by changes in this zone. No general guidelines are available to define its boundaries. In case of one specific coastal zone, the boundaries should be based upon an analysis of the present and future social and economic activities there and in its hinterland. They can be found in national and regional development plans.

4.2.2 Structure of social and economic life

Social and economic activities are to be found everywhere in the coastal zone. The coastal zone can be described in socio-economic terms. In this subparagraph, the most important socio-economic terms are explained. The central issue here is the interest in quality of life. Human well-being depends directly or indirectly on the availability of environmental goods and services provided by marine and coastal systems.

One coastal zone usually has many different functions, which are all relevant for human well-being. Which functions are most significant depends on the ecological characteristics, the socio-economic circumstances and the management objectives of the area in question.

What has a coastal zone to offer to the production process? Many natural resources are related to the coastal zone. Biotic resources (like fish) and abiotic resources are the bases of different industries. Transport to and from a harbor makes use of space as a resource. In order to "cause" production (the so-called aim of the system), natural resources are used in combination with labour and capital. Renewable and non-renewable resources are being used. N.B. Capital exists in different forms; one form of it is infrastructure (both physical and institutional infrastructure).

It must be clear that the term "institutional infrastructure" refers to organizations, networks, codes and cultivation of human relations. So if an engineering company is going to build a breakwater for a government, and the bank director asks a lawyer advice for the credit which can be given to this government, then a real institutional crossroad is in active use.

What is the result of all the economic activities in the coastal zone? Distinction is made between four categories of use:

1 Basic use: food, water, energy;
2 Social use: housing, recreation;
3 Economic use: transport, mining, industrial development;
Examples of economic activities are fishery, shipping, recreation, defense, waste disposal, sand and gravel mining, laying of pipes and cables, land reclamation, harbor development, oil and gas exploration and nature conservation. Each of these activities requires certain (environmental, infrastructural) conditions. For example, fishery requires a well-developed ecosystem for breeding fish populations. Such requirements can be conflicting to conditions, required for other activities. For example, nature conservation requires diversity of population and is not served by disturbance of the area. Therefore, good planning and management of the activities are very important!

4.2.3 The necessity of management

Historically, the major functions of the coast were defense against inundation and military defense. If there was anything to manage, this management was a pure engineering task (construction and maintenance of the defense structures). Recently, other priorities have developed. Nature values, water quality and recreation are examples of this change.

Most coastal areas around the world are under extreme pressure. Causes for this are given in Table 4.1.

<table>
<thead>
<tr>
<th>Table 4.1</th>
<th>Pressures on the coast (Kamphuis, 1997)</th>
</tr>
</thead>
</table>
| Population Density | Historically, population densities were high along the coasts  
50% of the population of the United States lives near the coast  
80% of the population of Australia lives near the coast  
> 80% of the population of Canada lives near its oceans or the Great Lakes  
Most of the world's major cities are near the coast |
| Recent Migration | Younger, more affluent people value the life style projected by coastal areas  
Redevelopment of coastal areas and high real estate values result in high-density development of living space  
Many people can now afford to live near the coast in spite of high real estate values |
| Tourism | People can afford to go on vacations to far away places and often choose a coastal area  
There has been a tremendous increase in air traffic, particularly of package vacations at destination resorts |
| Linear | The coast is a always narrow, linear strip of land which receives visitors from cities, states, etc. whose population density is measured as a function of area  
If a new "coastal area" is developed, the focus is still always on the coastal strip |
| Erosion | Most of the world's coasts are eroding |
Initially, people who lived near the coast were integrated into the coastal fabric. They were fishers, sailors, dockhands, trades people or workers in the factories that existed along the coast. They also lived in a tenuous balance with the coastal resources. The recent large migration to the coast has resulted in stress and overloaded conditions. Many coastal zones have become economically dependent on tourism and recreation, and where the knowledge-intensive, technological industry has been developed, this also induces migration: from the technological workers to the places where the standards of living are highest (along the coast).

An important constraint on the coastal zone is that it is essentially linear; it is a narrow strip of land (few kilometers) along the coast. This puts high pressure on land prices and recreational facilities. The coastal zone is essentially a very scarce commodity. Finally, the coastal zone is very fragile, and there is a world-wide tendency for coastal formations to erode. This puts high priority on protecting and maintaining what is there, particularly because real estate values along the coast are so high.

In order to demonstrate the importance of Coastal Zone Management another time, a short description is made of the situation around one of the major resources: fresh water. This is a very precious resource in a maritime coastal region. It has two sources: the fresh water in rivers and lakes, and precipitation. Both of these sources feed fresh water into the ground water reservoir. The sea feeds salt water into the reservoir. Since the flow rates of the ground are very small, there is little mixing of the salt and fresh ground water and the lighter fresh water overlies the heavier salt water as shown in Figure 4.1.

![Fresh water coastal aquifer](Kamphuis, 1997)

The ground water level is higher than the surrounding sea level and the density difference in level between the ground water table and the sea. Clearly, any lowering of the ground water table has a disastrous multiplier effect (40 times) on the volume of fresh water present in the lens and hence the fresh water aquifer needs very careful management. The fresh water reservoirs of small island communities are very susceptible to damage. Some of
the commonly occurring disturbances, partly as a result of phenomenal increases in coastal populations are given in Table 4.2.

Table 4.2 Common disturbances of the fresh water aquifer (Kamphuis, 1997)

<table>
<thead>
<tr>
<th>Disturbance</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumping the aquifer for fresh water supply</td>
<td>Lowers the water table</td>
</tr>
<tr>
<td>Lowering of the land mass by cutting away the dunes</td>
<td>Lowers the water table</td>
</tr>
<tr>
<td>Construction of buildings, roads and parking lots</td>
<td>Prevents the recharge of the fresh water aquifer by infiltration;</td>
</tr>
<tr>
<td>Dredging the rivers and creeks for navigational improvements</td>
<td>Result in salt water intrusion (the salt water comes further up the river and hence further into the coastal fresh water aquifer).</td>
</tr>
</tbody>
</table>

One serious consequence of pumping a coastal fresh water aquifer for water supply is that the depletion of the aquifer causes subsidence of the land mass, which in turn, results in increased flooding. Similar subsidence is caused by extraction of oil and natural gas from the area. An example of such subsidence is the (now) regular flooding of Venice by the Aqua Alta.
4.3 Coastal Zone Management

4.3.1 Introduction

As coastal zones represent the narrow transitional zone between the world’s continents and oceans, characterized by highly diverse ecosystems such as coral reefs, mangroves, beaches, dunes and wetlands, a great number of functions are performed over a relatively small area. This concentration of functions, together with their spatial location, makes coastal zones and small islands highly attractive areas for people to live and work in. It is predicted that 50-70% of the human population will soon be living in the coastal zone. The rate of socio-economic development in coastal zones is unprecedented and the same holds true for population growth. For demographic trends, see Table 4.3.

Table 4.3 Demographic trends (WCC’93, 1994)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mexico City</td>
<td>Mexico</td>
<td>9.12</td>
<td>17.30</td>
<td>25.82</td>
<td>16.70</td>
</tr>
<tr>
<td>2</td>
<td>Sao Paolo</td>
<td>Brazil</td>
<td>8.22</td>
<td>15.88</td>
<td>23.97</td>
<td>15.75</td>
</tr>
<tr>
<td>3</td>
<td>Tokyo/</td>
<td>Japan</td>
<td>14.91</td>
<td>18.82</td>
<td>20.22</td>
<td>5.31</td>
</tr>
<tr>
<td>4</td>
<td>Calcutta</td>
<td>India</td>
<td>7.12</td>
<td>10.95</td>
<td>15.53</td>
<td>9.41</td>
</tr>
<tr>
<td>5</td>
<td>Greater</td>
<td>India</td>
<td>5.98</td>
<td>10.07</td>
<td>15.00</td>
<td>10.02</td>
</tr>
<tr>
<td>6</td>
<td>New York</td>
<td>USA</td>
<td>16.29</td>
<td>15.54</td>
<td>15.78</td>
<td>-0.51</td>
</tr>
<tr>
<td>7</td>
<td>Shanghai</td>
<td>China</td>
<td>11.41</td>
<td>11.96</td>
<td>14.30</td>
<td>2.89</td>
</tr>
<tr>
<td>8</td>
<td>Seoul</td>
<td>South-Korea</td>
<td>5.42</td>
<td>10.28</td>
<td>13.77</td>
<td>8.35</td>
</tr>
<tr>
<td>9</td>
<td>Tehran</td>
<td>Iran</td>
<td>3.29</td>
<td>7.52</td>
<td>13.58</td>
<td>10.29</td>
</tr>
<tr>
<td>10</td>
<td>Rio de Janeiro</td>
<td>Brazil</td>
<td>7.17</td>
<td>10.37</td>
<td>13.25</td>
<td>6.09</td>
</tr>
<tr>
<td>11</td>
<td>Jakarta</td>
<td>Indonesia</td>
<td>4.48</td>
<td>7.94</td>
<td>13.25</td>
<td>8.77</td>
</tr>
<tr>
<td>12</td>
<td>New Delhi</td>
<td>India</td>
<td>3.64</td>
<td>7.40</td>
<td>13.24</td>
<td>9.60</td>
</tr>
<tr>
<td>13</td>
<td>Buenos Aires</td>
<td>Argentina</td>
<td>8.55</td>
<td>10.88</td>
<td>13.18</td>
<td>4.53</td>
</tr>
<tr>
<td>14</td>
<td>Karachi</td>
<td>Pakistan</td>
<td>3.14</td>
<td>5.70</td>
<td>12.00</td>
<td>8.85</td>
</tr>
<tr>
<td>15</td>
<td>Beijing</td>
<td>China</td>
<td>8.29</td>
<td>9.25</td>
<td>11.17</td>
<td>2.88</td>
</tr>
<tr>
<td>16</td>
<td>Dhaka</td>
<td>Bangladesh</td>
<td>1.54</td>
<td>4.89</td>
<td>11.16</td>
<td>9.62</td>
</tr>
<tr>
<td>17</td>
<td>Cairo/Giza</td>
<td>Egypt</td>
<td>5.59</td>
<td>7.59</td>
<td>11.13</td>
<td>5.44</td>
</tr>
<tr>
<td>18</td>
<td>Manila/Ouezon</td>
<td>Philippines</td>
<td>3.60</td>
<td>7.03</td>
<td>11.07</td>
<td>7.47</td>
</tr>
<tr>
<td>19</td>
<td>Los Angeles</td>
<td>USA</td>
<td>8.43</td>
<td>10.05</td>
<td>10.99</td>
<td>2.55</td>
</tr>
<tr>
<td>20</td>
<td>Bangkok</td>
<td>Thailand</td>
<td>3.27</td>
<td>5.07</td>
<td>10.71</td>
<td>7.44</td>
</tr>
<tr>
<td>21</td>
<td>London</td>
<td>UK</td>
<td>10.59</td>
<td>10.35</td>
<td>10.51</td>
<td>-0.08</td>
</tr>
<tr>
<td>22</td>
<td>Osaka/Kobe</td>
<td>Japan</td>
<td>7.61</td>
<td>9.45</td>
<td>10.49</td>
<td>2.88</td>
</tr>
<tr>
<td>23</td>
<td>Moscow</td>
<td>Russia</td>
<td>7.07</td>
<td>8.97</td>
<td>10.40</td>
<td>3.33</td>
</tr>
</tbody>
</table>
Over time, coastal zones have increasingly been subjected to unsustainable use. Unrestricted development of land and resources is happening in order to maximize the financial gain provided by the natural systems. This has led to an increasingly large area of cultivated and managed ecosystems, where the performance of one particular function is overexploited. Over-exploitation results not only in the depletion of the resource stock or flow that is provided by this particular function, but also in the inability of other functions to perform to their full potential.

The performance of functions in any natural coastal system can be valued differently by different members of the coastal community. Resources are appraised from a range of viewpoints. When one or more of the desired functions cannot perform to its full capacity, conflicts may arise. This can be due to internal or external stresses on the coastal system. For example, when mangroves are polluted beyond their filtering capacity or logged and cleared in an unsustainable way, this will be at the expense of functions that enable fish to breed and be caught in the same area, and hence of those who depend on fisheries. Therefore, maintenance of all functions at a sustainable level would provide higher economic returns over a longer period of time.

How to define sustainable development then? One can state that sustainable development in coastal zones and small islands is only realized when it enables the coastal system to self-organize, i.e., to perform all its potential functions, without adversely affecting other natural or human systems. Over-exploitation of resources, pollution, urbanization etc. may inhibit or destroy the working of essential functions. Provision of resources that are valued less financially may suffer from it, or the resilience of the coastal system to external stresses may decline. The impacts of unsustainable development may then ultimately result in the degradation of natural systems that provide protection against the sea, habitat for many species and food for many people, and may pose significant risks to public health. Degradation problems already exist in many places. Therefore an important question in that case is: how to stimulate recovery?

Coastal Zone Management has the objective of optimizing the utilization of coastal resources for the benefits of regional economic development. It should be based on understanding of the complexity of the coastal systems and of the interaction between the coastal system and adjacent urban systems, river basins and seas/oceans. Not only the coastal area which is subject to analysis must be taken into account; a coastal system never exists alone.

Types of projects where coastal zone management is of importance are mentioned below. Here they are:

1. Shore protection;
2. Water quality management;
Environmental assessment and planning;
Tourism and economic development;
Integrated coastal planning and management.

Each type is characterized by a specific level of integration between natural system, functions and infrastructure. An important aspect of this integration is the so-called conforming use. If an activity can be classified as a conforming use, depends on the question: does it have to be situated along the coast out of necessity? Examples are swimming beaches, fishing ports and marinas. If a project does not need to be specifically along the coast, such as for casinos, theaters and car parks, it is not a conforming use. This is not simple; for instance, a harbor is required to supply sufficient infrastructure to support its operation. Therefore a car park may become a conforming use, because it is needed to support a conforming use.

The interests for many ways of use change with time. In Table 4.4, recent changes are shown. For example the qualification of many a railroad as conforming use has turned into non-conforming use during the last century. The reason for that is the change of the economy as a whole during that time. Another reason for changing accents is the change of the use itself. For example tourism. Recently a development has started, which gives tourists a more positive image towards nature. "Eco-tourists" prefer nature and physical activities such as hiking, bicycling, birding, boating and fishing. In a way tourism is becoming a more conforming use of the coastal nature.

Table 4.4 Changes in priorities as conforming use (Kamphuis, 1997)

<table>
<thead>
<tr>
<th>Higher Priority</th>
<th>Lower Priority</th>
<th>Changed Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>Industrial and Commercial</td>
<td>Fishing</td>
</tr>
<tr>
<td>Recreational</td>
<td>Agriculture</td>
<td>Waste Disposal</td>
</tr>
<tr>
<td>Nature Reserves</td>
<td>Transportation</td>
<td></td>
</tr>
<tr>
<td>Aquaculture</td>
<td>Military and Strategic</td>
<td></td>
</tr>
</tbody>
</table>

In this context, Kamphuis remarks: "Nevertheless, tourism development is clearly driven by economics. Income is considered first and environment second. (...) It should be clear that ideals such as enhanced environment, ecosystem planning, etc. are laudable, but that, if these are presented as an alternative to crass money matters, the economic considerations will eventually gain the upper hand. Fortunately, it is possible to find sufficient room within the economic framework of at least the developed countries to enhance the environment and that is the only way any environmental consideration will reach the agenda of governments."

Key concepts of economy are: scarce resources, human wants, problems of choice. Main types of resources are: natural, labor, capital. The key principle of the market mechanism
is: the price. It forms the feedback mechanism between resource owners, producers and consumers. Therefore, a certain, actual economic situation, characterized by a specific allocation of different resources, is induced by the actual price. Economic management can influence this situation. Optimal allocation of resources can be its goal.

4.3.2 History of Coastal Zone Management

The coastal zone is focal point in many national economies. It is a multi-resource system, and it is a multi-user system. It is used for subsistence, economic activities and recreation. Industrialization, commercial development and steadily growing population pressure in many places have resulted in an increase of erosion and flooding, loss of wetlands, pollution and over-exploitation of land and water resources in the coastal zone.

Growing awareness about the finiteness of resources, about environmental degradation and consequent problems to mankind, has triggered numerous studies to provide a long term solution of the resources problem. Such studies are based on the concept of carrying capacity in terms of guidelines for socio-economic activities to achieve long-term conservation of vital elements and areas of the environmental system. The concept of sustainable development has been introduced. Two famous studies are: "The limits to growth" from the Club of Rome, and: "Our common future", also called the Brundtland report.

The Brundtland report formulated the following objectives for a world conservation strategy:

1. Maintenance of essential ecological processes and life support systems;
2. Preservation of genetic bio-diversity;

In 1992, a special conference was held in Rio de Janeiro: the United Nations Conference on Environment and Development (UNCED). An integrated approach was underlined by an updated version of Meadows' book: "Beyond the limits". It is now widely accepted that development of the coastal zone should be based upon a proper understanding of the processes in the coastal zone, supported by a sound engineering technology and socio-economic skills to obtain an acceptable balance between short-term benefits and long-term assets.

4.3.3 Policy analysis and its function

CZM is a continuous process of decision-making. The problem formulation, the formulation of management objectives and the design of appropriate policies should follow a systematic procedure of generating, analyzing and evaluating alternative strategies. This
procedure can be made easier by the use of policy analysis.

Policy analysis is centered around the comparison between the future and the desired situation, as it can be influenced by different policies. Many aspects of the future and desired situation must be taken into account, especially the different interests of all present parties. Advantages of a policy analysis are evident in the following situations:

1. When social issues are involved;
2. When there are many contradictory interests;
3. When non-comparable values are to be judged;
4. When there are many values to be compared.

In other words: in case of a complex selection problem. Figure 4.2 shows a scheme of the divergence of different problem approaches. This is a typical situation where policy analysis is needed.

![Figure 4.2 Divergent problem approaches](image)

The use of policy analysis becomes more complicated in the phase of execution. In many cases, iteration loops have to be made. Goals and standards must be written down in an early stage. There are two kinds of questions to be answered using policy analysis:

1. Is it necessary to carry out a project?
2. Which alternative is the best one?

Policy analysis is an inquiry whose purpose is to assist decision makers in choosing a preferred course of action. This choice is made out of a number of complex alternatives, under uncertain conditions. The framework of the decision making process, which is a cyclic process, consists of three phases:

1. Problem identification and analysis
Development of optional solutions

Evaluation and selection of the best solution

There are simulation models available to strengthen a policy analysis. For example: economic models, resource models, emission and deposition models. To avoid unnecessary sophistication (easily causing confusion), tools should be as simple as possible.

4.3.4 Management tools and strategies

One basic management tool is the compatibility matrix. Examples may be found in Carter (1988). The compatibility matrix for the conforming-use categories in Table 4.2 is given in Table 4.5. Compatibility is measured there on a scale of -2 (bad) to +2 (good). Each of these has within it, its own set of conflicts.

Table 4.5 Compatibility matrix (Kamphuis, 1997)

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
<th>h</th>
<th>i</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Residential</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>Recreational</td>
<td>-1</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>Nature Reserves</td>
<td>-1</td>
<td>2</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>Aquaculture</td>
<td>-1</td>
<td>-2</td>
<td>-1</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>Fishing</td>
<td>1</td>
<td>1</td>
<td>-2</td>
<td>0</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>f</td>
<td>Waste Disposal</td>
<td>-2</td>
<td>-2</td>
<td>-2</td>
<td>-2</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>Industrial and Commercial</td>
<td>-2</td>
<td>-2</td>
<td>-2</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>h</td>
<td>Agriculture</td>
<td>-2</td>
<td>-2</td>
<td>-2</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>x</td>
</tr>
<tr>
<td>i</td>
<td>Transportation</td>
<td>-1</td>
<td>-1</td>
<td>-2</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>x</td>
</tr>
<tr>
<td>j</td>
<td>Military and Strategic</td>
<td>-2</td>
<td>-2</td>
<td>-2</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>1</td>
<td>-1</td>
</tr>
</tbody>
</table>

Next to tools like the compatibility matrix, we have management principles, shown in Table 4.6 and the management issues shown in Table 4.7.

Table 4.6 Management principles (Townend, 1994)

- The coast is dynamic and policies must reflect this
- Management boundaries should reflect natural processes
- Conflict cannot always be resolved, requiring planning and legislation
- Conflicts change with time, requiring a flexible management framework
Table 4.7 Management issues (Townend, 1994)

<table>
<thead>
<tr>
<th>Frameworks (Conceptual and Computational)</th>
<th>Geographic Information System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tools</td>
<td>Zoning, Regulations and Enforcement, Public Awareness and Consultation</td>
</tr>
<tr>
<td>Responsiveness</td>
<td>Legal Considerations, Economics Considerations, Social Considerations, Other Scientific and Technical Disciplines, Many Jurisdictions involved</td>
</tr>
</tbody>
</table>

Geographic Information Systems (GIS) are recommended as conceptual/computational framework. On the geographic base are stored all pertinent data such as locations of buildings and infrastructure, coastal protection structures, sewerage outfalls, property ownerships, legal jurisdictions and physical conditions such as flood and erosion hazards, sediment sources and sinks, etc. The tools by which management is effected are: Zoning, Regulation Enforcement, Public Awareness and Consultation. These tools should be carefully selected and sharpened, showing sensitivity to the projects and the physical environments involved. They need to be incorporated into an appropriate decision making process and a responsive management framework. Legal, economic and social considerations and the involvement of many disciplines require a responsiveness to and cooperation with others who may not think the way we do.

4.3.5 Description of management practice

Every participant in matters of coastal zone management has his own reason for being so. And his own particular field of interest. Government agencies may be involved in the planning process for several reasons:

1. Many of the resources are public goods; this can lead to exhaustion of them;
2. Most uses of the resources will have adverse effects on other uses;
3. Merit wants must get a price via politics, like clean environment and basic human needs;
4. Equity in the allocation of scarce goods and services must be safeguarded.

In the decision making process, the following parties may be involved:

1. Government agencies;
2. Ministries;
3. Provinces;
4. Regional water boards;
The existence of a legal and institutional framework is necessary, through which the allocation of tasks and responsibilities is made. Possible elements are: international councils, agreements, the transfer of all responsibilities to a single existing or newly created agency, or one of the agencies concerned is given a leading role. Institutional changes are generally slow and are not a suitable way to improve coastal zone management. Most essential is the political desire to improve the management of the system.

Social aspects of management are two-sided. Firstly, there are the so-called human factors. These are the social factors that influence the efficiency of the utilization of resources. Secondly, there are the so-called social impacts. They are the social effects of the conducted management, due to implementation of a coastal zone resources development strategy. Multi-objective planning will result in a certain distribution of benefits and costs over groups in society. Implementation is an important phase in the planning. This phase consists of financing, and cleaning the road from legal and technical obstacles.

Economic aspects of management can be divided into three types:

1. Micro-economic (analysis of the behavior of a user);
2. Cost-benefit: financial analysis to evaluate economic feasibility, and financial viability of development strategies;

An important step in economic analysis is the expression of environmental impacts in monetary terms. For example: what is the cost of erosion due to upland farming, water logging and salinization due to irrigation or the destruction of mangrove forests for aquaculture development? Use of market or surrogate prices is made to provide better estimates of environmental impacts and a more balanced appraisal of projects. Some authors argue that parameters like the GNP have to be corrected for the decrease of natural resources, in order to give a more balanced and sustainable development of the natural resources.

A basic relationship between development and economic growth has been widely recognized, which leads to the use of economic indicators such as the Gross National Product (per capita) as an indicator. This type of parameter has several weaknesses, such as the lack of information about the types of goods and services produced, and about negative impacts, such as environmental degradation and on the distribution of income. Nowadays, the attention is going further, to factors such as the degree to which the basic needs of the population are satisfied and to selective growth, with increasing emphasis on "the quality of life".
4.3.6 Where is the coastal engineer?

Coastal management is primarily the management of conflicts. This means bringing about legislation and enforcing the proper use of the coast, all the time keeping in mind the economic considerations, which realistically will over-ride altruistic ideals. Coastal management pre-supposes technical skills to be able to make informed decisions. These skills must be based on geological, biological, legal, engineering and other training. They also involve political savvy and skills in communicating with everyone from government officials to children (or adults) building sand castles. Although coastal management is interdisciplinary, it is often the engineers who are asked to make the crucial technical decisions. For this, we need to be properly informed and we need to establish necessary and appropriate networks with the other disciplines.

For politicians, public opinion is important. Different phases in the political process are difficult to recognize. They are: recognition of a problem, policy design, choosing a solution, management. Long-term activities are usually not suitable for influencing public opinion. ("I won't get re-elected by painting the bridge"). In politics, a balance is found between short and long-term solutions, between different interests. This balance often consists of a series of compromises. The engineer's approach however is directed towards one optimal solution to a given problem. The typical action of decisionmaking in a difficult situation requires more than convergent reasoning alone. Therefore, the engineer involved in political decisionmaking situations must realize the difference in culture between engineers and other people.

Now back to the engineer, the main character of this subparagraph. Results of a personality test among would-be engineers showed that they were:

1. Good at and interested in mathematics and natural science;
2. Poor on verbal fluency, uninterested in history and literature;
3. Narrowly interested in mathematics, science and technology, but more generally informed than their interests would point at;
4. Introverted, uninterested in social welfare questions. Average on dominance and achievement drives.

In ways of thinking: from convergent and divergent thinking, engineers seem to choose convergent thinking. Therefore, they can have some restraint when it comes to confrontation between society and operation. Reduction of a complex problem is the engineer's profession, but social aspects are easily denied.

Kamphuis (1997): "Coastal management is at the same time very simple and very complex. It is based on simple, common-sense principles, such as "live and let live". The complexity comes because such principles need to be carried out in a complex, high pressure environment.
environment that has many competing uses and which is governed by over-arching economic considerations. As we have seen, priorities are changing. It is very important that these changes are supervised well and that things are done right. This is both a daunting task as well as a unique opportunity.

(\ldots) It involves concerted effort from the whole community (business, politicians, land owners and the public - both young and old). It involves education, particularly of the young people and in the schools. It concerns various disciplines (such as geology, biology, engineering), it requires a communal willingness to overcome a total legislational - jurisdictional jungle and finally it needs to take place within a political, social and especially economic framework that was not developed to provide for good coastal management. The engineer is at the centre of this task, partly because coastal management has developed from coastal engineering historically, but more so because we have the appropriated background to synthesize many diverse ideas into coherent working systems.

Make no mistake, we have lost the confidence of the general public and people would like to do without us, because we have messed up big time in the past (and still in the present). (\ldots) We must also learn to explain our knowledge clearly to land owners and elementary school children alike. Final we must learn from our mistakes and educate ourselves and those fellow engineers who only want to think about sheet pile and rock."
4.4 Global changes

4.4.1 The world doesn't stay still

Long-term global developments like demographic trends, economic developments, and human interference with global environmental systems, such as the climate, are perhaps the most challenging issues since ever. The most pronounced examples are: accumulation of contaminants in coastal areas, erosion, rapidly increasing decline of habitats and natural resources. They are a threat of sustainability of coastal areas. One impact of human-induced change of the climate is for example sea level rise.

Climate change is likely to aggravate the impacts of unsustainable development of coastal areas and resources, leading to greater vulnerability. Following a United Nations medium projection, in the year 2025, a number of 8.5 billion people will be living in urban settings and coastal zones. To get up to this number, 95% of the growth has taken place in developing countries. Increasing demands for food require increasing productivity in fisheries and agriculture, crossed by urban expansion and reduction of fish habitats and pollution.

Global vulnerability assessments suggest that presently some 200 million people live below the once-per-1000-years storm-surge level. 46 million experience flooding every year (on average). These numbers will increase with sea level rise. Tourism and recreation represent growing and important activities. 5% of GNP’s of all nations comes out of them. Tourism is jeopardized by other profitable activities. It also gives rise to conflicts, for example: pollution, environmental degradation, destruction, killing the goose with the golden eggs.

An example of the goose-killing can be found in the branch of fisheries: in the world, 200 million people depend on fisheries. Many nations depend on it as a food source. Due to industrialization, declination in number of persons employed takes place. Over-exploitation is actually happening, degradation of coastal habitats also; the total world commercial marine catch is declining. This unfavorable development is partly explained by pollution.

In general, nature conservation is important. Biospheric functions that are responsible for environmental goods and services, are essential for human social and economic well-being. The natural coastal system’s dynamic behavior allows, within certain limits, the exploitation of resources. However, radical changes to the natural system may adversely affect the availability, or regeneration of these resources.

The importance to conserve natural coastal systems is increasingly acknowledged. This is done especially in the light of anticipated global changes. In case of a balanced, full potential performance of all relevant functions (for example: protection against erosion and waste assimilation), the coastal zone is more robust and resilient to sea-level rise and
pollution. The total economic value of a coastal system usually far exceeds the short-term returns from non-sustainable use of a given area.

4.4.2 Human-induced climate change

Climate change can be caused by many things. Examples are: vulcanic explosions, variations in energy exchange between ocean and atmosphere, solar radiation and changes in the composition of the atmosphere. All these factors affect the radiation balance of the earth surface and the atmosphere.

The climate system naturally knows a strong greenhouse effect. In other words: the emission of energy by the earth surface into space is hindered very much. Without the greenhouse effect, the temperature at the earth surface would be thirty degrees lower. The most important greenhouse gas is water vapour. Next to that, carbon dioxide and methane are important. Their concentration in the atmosphere varies with the climate. During the Holocene, the carbon dioxide concentration has been relatively constant.

It is undoubted that the composition of the atmosphere changes substantially under human influence. Greenhouse gases are produced. Since the end of the nineteenth century, their concentrations are rising. During the last decades they rise very rapidly. Next to that, other effects of human activity can be seen, which affect the energy balance of the atmosphere.

One very important element in the climate system is the ocean and the ocean current system. This system is correlated to the global atmospheric pressure division. The global pattern of ocean currents is also very sensitive to changes in the fresh/saline water balance. The effects of a possible collapse of the the global ocean current system cannot be predicted (yet) as they are so large, unprecedented and complex phenomena.

Apart from an eventual ocean current system collapse, people are trying to predict climate change and its effects. Using climate models, predictions are made for temperature change. The effects of a temperature rise on the water cycle are studied. Sea level rise is one, important, aspect of this.

4.4.3 Global sea-level rise

Changes in global sea level are based on four factors:

1. Thermal expansion of ocean water;
2. Changes in masses of land ice in Greenland;
3. Changes in masses of land ice in Antarctica;
4. Changes in smaller ice caps and glaciers.
Different models give different results; uncertainties are large. A large part of real measured values are inexplicable. During the last century, the measured relative sea level has risen over 18 cm. Only 8 cm are computed to be caused by thermal expansion and changes of land ice. In order to predict future levels, the unexplained part is simply extrapolated into the future.

Next to historical extrapolation, several scenarios are studied. In Figure 4.3, the basis for this approach is schematized. For each factor or relationship, high and low assumptions were developed using the published literature.

Figure 4.3  Basis for scenarios regarding global sea level rise (Hoffman, 1983)

Table 4.8  Estimated sea level rise 2000-2100, by Scenario (in cm) (Hoffman, 1983)

<table>
<thead>
<tr>
<th>Year</th>
<th>Conservative</th>
<th>Moderate</th>
<th>High</th>
<th>High Scenario</th>
<th>Historical</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>4.8</td>
<td>8.8</td>
<td>13.2</td>
<td>17.1</td>
<td>2-3</td>
</tr>
<tr>
<td>2025</td>
<td>13.0</td>
<td>26.2</td>
<td>39.3</td>
<td>54.9</td>
<td>4.5-8.25</td>
</tr>
<tr>
<td>2050</td>
<td>23.8</td>
<td>52.3</td>
<td>78.6</td>
<td>116.7</td>
<td>7-12</td>
</tr>
<tr>
<td>2075</td>
<td>38.0</td>
<td>91.2</td>
<td>136.8</td>
<td>212.7</td>
<td>9.5-15.5</td>
</tr>
<tr>
<td>2100</td>
<td>56.2</td>
<td>144.4</td>
<td>216.6</td>
<td>345.0</td>
<td>12-7.1</td>
</tr>
</tbody>
</table>
Considering only changes in greenhouse gases (not the special case scenarios that deal with other causes), sea level could rise as much as 345 cm and as little as 56.2 cm (Hoffman et al., 1983) by 2100. Neither of these extreme estimates is likely, however, since the probability of all the conservative or all the high assumptions turning out to be true is very small. The moderate thermal expansion scenario, because it assumes either the middle ground for all assumptions or the assumption that appeared most realistic, constitutes a much more likely trend for this component of sea level rise. Two scenarios were produced for snow and ice contribution. For the moderate scenario, the low snow and ice ratio was assumed. For the mid-range-high scenario, the high snow and ice ratio was used. The moderate scenario produces a rise of 144.4 cm by 2100, while the mid-range-high scenario produces a rise of 216 cm by 2100.

Table 4.8 summarizes the changes by quarter century, for the conservative, moderate, mid-range-high and high scenarios. Extrapolations of the historical rate of rise are included for comparison. In all foreseeable circumstances, sea level is likely to rise by amounts considerably greater than this past century’s rise. The most conservative assumptions used in this analysis lead to an accelerating sea level rise and a total rise that is 400 percent greater than that of the last 100 years. Nevertheless, many uncertainties exist about the rate of rise. The very high scenario has over seven times the sea level rise of the conservative scenario.

In order to improve substantially the estimates of future sea level rise and to narrow the range of scenarios, more time and more scientific research will be needed. To maximize the value of future observations, the theoretical base and models used to interpret the relevant data must be improved. Rapid progress can be made by accelerating the research aimed at improving our basic understanding of the processes that underlie climatic change and sea level rise.

The physical consequences of sea level rise can be broadly classified into three categories: shoreline retreat, temporary flooding, and salt intrusion. Shoreline retreat can have different causes: inundation (of low-lying areas) or erosion (change of equilibrium profile, overwash and landward migration, increased storm damage). Salt intrusion happens via aquifers, rivers and estuaries. If the sea level rises, the boundaries between salt and fresh water rise and move landward. A decrease in fresh water runoff can also be caused by the sea-level rise, which allows salt wedges to move even further upstream.

The costs associated with the physical effects of sea level rise could be very high. Although the worst effects would not begin to be felt until 2025, low-lying areas and beach resorts could be seriously affected before then. Furthermore, a wide variety of decisions made in the next decade will significantly influence the extent of the damages from sea level rise in the next century. People, buildings, infrastructure, drainage systems and water intake points are all vulnerable to water and salt damage. The same is true for nature: vegetation
and animals could be destroyed by higher water levels and by salt.

### 4.4.4 Integrated Coastal Zone Management

Coastal resources are being degraded and lost in many parts of the world. Expensive sanitation, restoration and protection measures are necessary to prevent further reduction of the viability of local communities, and to prevent further increase in the vulnerability to longer-term climate change and sea-level rise. Thus, some policy making process is needed that can address the resource use conflicts as well as find the balance between short-term economic and longer-term environmental interests. In other words, a management process is needed that serves the needs of society now and in the future best.

(Integrated) Coastal Zone Management has been recognized as the most appropriate process to deal with these current and long-term coastal challenges. For coastal societies, it can provide for an opportunity to move towards sustainable development. Taking into account rates of climate change, and other expected developments, Integrated Coastal Zone Management can provide a framework, within which flexible responses to deal with these developments can be developed. In short, it can create a process to enhance economic development and improve the quality of life.

At the World Coast Conference, Integrated Coastal Zone Management was defined as follows: "It involves the comprehensive assessment, setting of objectives, planning and management of coastal systems and resources, taking into account traditional, cultural and historical perspectives and conflicting interests and uses; it is a continuous and evolutionary process for achieving sustainable development."

Planning and management decisions aiming at the sustainable use of natural resources can be accomplished through carefully harmonizing the different sectoral development options and needs. This process has by definition an extended time horizon; long-term thinking is a key component, and it is also economically feasible.

Important international initiatives for understanding of sustainable development of coastal zones and resources, and promoting integrated coastal zone management to both scientists and policy makers, are described below. For more, see Table 4.9.
Table 4.9  Overview of activities of international organisations in the field of ICZM
(WCC'93,94)

<table>
<thead>
<tr>
<th>Organisation</th>
<th>Information</th>
<th>Education and training</th>
<th>Concepts and tools</th>
<th>Research, monitoring and evaluation</th>
<th>Funding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asian Development Bank</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Alliance of Small Island States</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comm. on Sustainable Development</td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>European Union</td>
<td>*</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Food and Agricultural Organisation</td>
<td>*</td>
<td>+</td>
<td>+</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Global Environmental Facility</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Int. Geosphere-Biosphere Programme</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Intergov. Oceanographic Committee</td>
<td>*</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intergov. Panel on Climatic Change</td>
<td>*</td>
<td></td>
<td></td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>The World Conservation Union</td>
<td>*</td>
<td>+</td>
<td>+</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Organisation for African Unity</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Organ. for Economic Cooperation and Development</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>UN Div. of Ocean Affairs and the Law of the Sea</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>UN Development Programme</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>UNEP Ocean and Coastal Areas Programme</td>
<td>*</td>
<td></td>
<td>+</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>UNESCO</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>UN University</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>World Bank</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>World Meteorological Organisation</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>World Wide Fund for Nature</td>
<td>*</td>
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<td>*</td>
</tr>
</tbody>
</table>
In June 1992 the UNCED was held in Rio de Janeiro. It was the first time in history that such a major conference explicitly linked the issues of environment and development. It was organised in response of the worldwide growing recognition that environment and development should not be considered as separate policy areas, but that sustainable development involves their integration. Subject areas have been:

1. Protection of the atmosphere by combating climate changes, depletion of the ozone layer and transboundary air pollution;
2. Protection and management of land resources by combating deforestation, desertification and drought;
3. Conservation of biological diversity;
4. Environmentally sound management of biotechnology;
5. Protection of the oceans and all kinds of seas, incl. enclosed and semi-enclosed seas, and of coastal areas and the protection, rational use and development of their living resources;
6. Protection of the quality and supply of fresh water resources;
7. Environmentally sound management of wastes, particularly hazardous wastes and toxic chemicals, as well as prevention of illegal international traffic in toxic and dangerous products and wastes.

This list shows important topics when dealing with ICZM as an answer to global change.
The Netherlands, one specific coastal zone

5.1 Introduction

"The Netherlands" means: low lands. Large parts of The Netherlands are situated close to, or below sea level. They incorporate an interesting coastal area. Its specific geological history is reviewed in Paragraph 5.2. Paragraph 5.3 gives insight in the coastal engineering history of the Netherlands, which is an important element of its foreign reputation. The nature of the Dutch coast as it is now is described in Paragraph 5.4. In Paragraph 5.5, the socio-economical aspects of the Dutch coastal zone are characterized. Future developments like the impact of global sea level rise for the Netherlands are mentioned, too.

5.2 Genesis of the Dutch coast

5.2.1 Geological time schedule

In general, geological data are expressed in a number of C14 years and not in sun years. C14 is a carbon isotope which originates from nitrogen-14. The process of decay is caused by radioactive decay. The production of carbon-14 has not been constant over time; therefore C14 years are not the same as sun years. The difference has been rectified by means of counting and dating annual circles of recent and fossil trees. In Figure 5.1, the geological time schedule is shown in C14 years and calendar years.
Figure 5.1 Geological time schedule, in C14 years and in sun years.

The geological division of the Holocene has been based mainly on the development of vegetation in North West Europe after the melting of ice roofs. The different geological periods can be found in the soil structure. The Holocene sediment covers an area as shown
The Pleistocene sediment can be found at the surface in the inner part of the land. Towards the sea, the top of this sediment is situated lower in the bottom profile. The seaward movement of the coast during the Middle Holocene has resulted in the characteristic bottom profile, as is shown in Figure 5.3.
5.2.2 Geological overview

As a result of melting ice sheets, the sea level rose since ± 18,000 years BP with an amount of 120 meters. At 9000 years BP, the coastline was situated north of the Doggersbank, but 1000 years after that, a connection had been formed to the Canal. At that time, the Dutch coast could be defined, although it was found far seawardly compared to today.

The sea intruded via the depressions, river plains and brook valleys which characterized the landscape formed during the Late Glacial Period (about 15,000 years BP). Due to the relatively small relief, extensive tidal basins developed. The watersheds between the valleys formed the land-abutments, and coastal drift-formed bars were the first coastal forms. In Table 5.1, the average sea level rise velocities during the last millennia are given.

Table 5.1 sea level rise velocities during the last millennia

<table>
<thead>
<tr>
<th>Time</th>
<th>Sea Level Rise</th>
</tr>
</thead>
<tbody>
<tr>
<td>18,000</td>
<td>9,000 BP</td>
</tr>
<tr>
<td>9,000</td>
<td>7,000 BP</td>
</tr>
<tr>
<td>7,000</td>
<td>6,000 BP</td>
</tr>
<tr>
<td>6,000</td>
<td>5,000 BP</td>
</tr>
<tr>
<td>5,000</td>
<td>3,000 BP</td>
</tr>
<tr>
<td>after</td>
<td>3,000 BP</td>
</tr>
</tbody>
</table>

The river plain of the rivers Rhine, Meuse and Scheldt went westward at the height of the
present-day plain of the Meuse. In spite of the sea-level rise, the river mouth area did not change into a tidal basin. The big rivers were able to transport enough sediment into the area, in order to cope with the sea-level rise. The form and orientation of the oldest beach bars close to Rijswijk show that this river plain just formed a land abutment at the coast before 3500 BP. In this manner a coastal plain developed from roughly 8000 BP, consisting of three tidal basins, separated by land abutments. These three basins are:

1. The tidal area of Zealand between a land abutment at the height of Zeeuws Vlaanderen, and the Rhine/Muse plain;
2. The Dutch tidal area at the confluence between the Overijsselse Vecht, Eem and other rivers. The Dutch tidal area is limited by the Rhine/Muse plain in the south, and a watershed in the north, the land abutment "Texel Hoog". When the sea level was lower, this last area extended from the Hondsbossche Zeewering until Vlieland. It
contented the whole western Waddengebied;

3 The third tidal area was the eastern Waddengebied, originated from the valley plains of the Boorne and the Hunze.

In Figure 5.4, a reconstruction of the Dutch coastal plain is shown from around 7000 years BP. The position of the coastline is hypothetic.

On a coastal plane where are extensive tidal basins, a small sea-level rise can easily create a large storage for sediment. Before 6000 BP, this process took such a big speed that the

Figure 5.5 Qualitative view of the sand transport along the Dutch coast in the Atlanticum and early Subboreal (Beets, v.d.Spek et al, [1994])

sediment import was insufficient to compensate the sea-level rise. Nevertheless, the sediment import was at its height at that time. Caused by the fast sea-level rise, the tidal basins moved landward, forcing the coast to move the same way as a consequence of a demand of sediment. Especially on the north-south oriented part of the coast, optimal conditions for sediment transport were created (Figure 5.5).
Apart from sand and silt import by the tide, wave driven long-shore and cross-shore transport were stimulated. The increase of long-shore transport was due to the non-equality of motion between the coasts of the tidal basins and of the land-abutments (the coasts of the tidal basins went faster). The increase of cross transport was caused by the movement of the coast. The North Sea was shallow, and a large amount of sand coming from outer deltas and older positions of the coast was left behind in it. Despite the relatively large import of sand and silt in this period, the sediment import was insufficient to maintain intertidal plains over the whole tidal basin. At the landside of the inner deltas lagoon conditions were dominant. (Those deltas had developed behind the inlets.) At the back of the tidal basins, these lagoons transformed into a fresh tidal area. Extensive reed lands were there; marsh was practically not formed.

After 6000 BP, when the sea-level-rise velocity decreased, the sediment import started being able to cope with the sea-level rise. The consequence of this was that the Dutch and Zeeuwse tidal areas became filled totally during the time between 5500 and 3500 BP. Therefore, the inlets accreted and the coast stabilized. The Dutch coast grew over a distance of ± 10 km. As the sea level continued growing, although this happened more slowly, the ground-water level in the formal tidal basins rose, too. These tidal basins
changed into marshes with peat accumulation (Figure 5.6).

Around 3000 BP, the marine influence on the coastal plain was smallest. Except a few inlets in the Eastern Wadden area and the mouths of the Rhine, Meuse and Scheldt, the coast was closed and defended an extensive peat area. However, the extra sand sources which had made the growth of the Dutch coast possible, were exhausted at this time. As the sea level continued rising, a new demand for sand rose for compensation. The amount of imported sand became insufficient; therefore coastal inundations took place on a big scale during the Middle Ages (Figures 5.7 - 5.11).
Figure 5.7  Inundations of 1404, November 19

Figure 5.8  Inundations of 1409
Figure 5.9  Inundations of 1421, November. Rivers: December

Figure 5.10  Inundations of 1424, November 18
Zealand and the Western Wadden area changed into tidal areas, the Eastern Wadden Sea grew and in Holland, inundations took place out of the upper part of North-Holland and the Zuiderzee, too. During the same period, the Young Dunes were formed. This meant erosion of the subsurface shore. At the same moment, the organisation of the Dutch society became developed far enough to undertake collective, directed actions in order to maintain the coastline in its old position. The whole process can be seen in cross-profile stages in Figure 5.12.

5.2.3 Sediment balance

The Dutch coast is a sediment importing system. During the Holocene 200 up to 250 billion m$^3$ of sediment, existing of sand (70%), silt (25%) and peat (5%), has been settled. The biggest part of the sand was eroded from the Pleistocene soil of the present North Sea; about 10% was transported by the Holocene Rhine.

The sediment import during the Holocene decreased smoothly from an average of ± 42 million m$^3$ per year between 8000 and 5000 BP, via ± 27 million m$^3$ per year between 5000 and 3000 BP to an average of ± 7 million m$^3$ per year after 3000 BP and seems to be linked (partly) to the velocity of sea level rise. This mechanism is thought to have worked by the
creation of big sand wells during fast sea level rise, coupled with the declining coast line. At smaller speed of sea level rise the coast could more or less stabilize; remainders of the wells were spent. After that, new sediment could be drawn by new declination of the coast.

From the geological analysis the conclusion can be drawn, that since several millennia the import of sand from outside the coast system probably is too small in order to stabilize the coast. Today the expectation can neither be kept that this import will increase. Recently, the decision is made to maintain the coast line on her present position. This decision implies the necessity to find (artificial) ways of sand import.

Figure 5.12  Reconstruction of coastal development in cross profile (van Straaten, 1965)
5.3 Dutch coastal engineering history

5.3.1 Old times

Figure 5.13 The Netherlands in the Carolingian time, i.e. ca 800 (G.P. van de Ven, Leefbaar Laagland, 1993)
During the ninth century (Figure 5.13), man starts cultivating the peat lands, which had been formed under the conditions shaped by a cool and damp climate. The cultivation of the land was done because of the population pressure. Big parts of the land consisted of peat masses, situated some (1-3) meters above sea level, not vulnerable to storm flooding. In the

Figure 5.14 The Netherlands around the year 1000 (GIRUG)
North and the South, marine sediment fields were found, inundated only during high floods. Peat and marine sediment fields were a buffer against the sea. At that time, the coast was closed, apart from a few river mounds and sea arms. There were sandy dune rows, parallel to the coast (Old Dunes).

In the eleventh century (Figure 5.14), population growth was big. Peat quarries and salt mining weakened the water weir function of the peat and dune lands. Cultivation of the land was also done in order to provide for food. In the case of peat lands, artificial drainage led to land surface decline; this has lead to more vulnerability to the sea.

Between the twelfth and the fourteenth century, the big peat area between the Old Dunes and the Utrechtse Heuvelrug was cultivated (Grote Ontginning = Big Cultivation). In the thirteenth and fourteenth century, the land declined so much (sometimes even 4 to 5 meters), that it came to lie at sea level. Drainage was a problem; therefore agriculture yielded to cattle breeding. In the fourteenth century, the Utrechtse Laagvlakte became green, and has remained so until today.

The real fight against the sea started. The sea took a lot of cultivated land in the South West (In Figures 5.07 - 5.11, the results of the first storm floods have been shown). Man won a lot of land between the dikes (Figures 5.15, 16, 17).

The loss of cultivated land was the result of human activity. A series of inundations, those of 1163/64, 1170, 1173, 1196, 1214, 1219, 1220, 1221, 1246 and 1248, increased the
amount of water in the center of Holland: the Southern Sea (fresh until the 16th century).

Figure 5.16  Low river land and Alblasserwaard, end 13th century (P.A.Henderikx)

Figure 5.17  Diking history of the Middle Sea (Beets, v.d.Spek et al [1994])
Figure 5.18  The Netherlands around the year 1300 (GIRUG)
During the thirteenth century (Figure 5.18), drainage became more and more problematic. The sea level increased, the land is declined, lakes were formed from peat mining. Rivers caused inundations, as the upper parts of their areas were also affected negatively by cultivation (loss of woodland). In order to meet all these problems, organization of the water management had to improve, and so it did. During the first half of the thirteenth century, many local dike projects were closed to one another. The first real polders were created. The organization of the increasingly complex water defense structures developed into water boards (this means a form of hierarchy and cooperation). Water boards got their own political power, based on the land they "owned".

About the Wadden Islands, some remarks can be made. Some of them are very old. Texel existed already in the 8th century, as a part of the continental area, but in the Eastern of Texel, real islands existed. When the time passed, the islands we know today moved eastwardly (several kilometers). A number of islands has disappeared since the Middle Ages. During storm floods, many devastations must have taken place, but not many details are known nowadays.

During the second half of the fourteenth century, people got to know the phenomenon "dike failure due to flow slides" more and more often. During a flow slide, the dike suddenly gives way during low tide. Sometimes inundation is the consequence. People used to respond by building another, second dike behind the first. The first and second dike got a name: waking and sleeping dike. A flow slide is often caused at places in the dike where the sand is coarser (effect: piping). Human, negative influences on dike stability can have been: peat or salt mining close to the root of the dike. Dike repair after local failure could only take place, if a good organized society was behind it. In cases of war or other chaotic situations, dikes were sometimes left un repaired. Then the loss of land became bigger during every flood.

In such a way the Southern Sea was formed. (The age of the Southern Sea can be estimated using salt profiles of the bottom of the present IJsselmeer.) After the fourteenth century however, every dike collapse was repaired. This happened often in the form of a new dike around the place of inundation, resulting in a lake in the form of a circle (a "wheel"). In this way the growth of the Southern Sea was stopped.

During the centuries that followed, the technical developments enabled people to influence the landscape of the country more and more directly. The result of those developments can be seen in the Dutch landscape; no tree is existent in an uncontrolled place in this country, let alone a whole dune or an island. The tradition of fighting against the sea in order to gain dry land is kept until today, when plans are made about expansion of the Rotterdam harbor complex by means of an artificial Meuse plain. However, nature does her work, too, so man cannot develop the idea of being the only generator of initiatives along the coast.
Even stronger: man slowly starts recognizing the wisdom of non-fighting nature, but cooperating with nature. This way of thinking gains ground among coastal zone managers: the sea should be respected, not blocked. Respect for the natural processes is needed in the first place, and serving one's own missions in the second.

5.3.2 Modern times

Water mills are known since the early Middle Ages. Wind mills, however, are built only since the 13th century. The first wind mill in Holland used for fixing the ground water level (i.e. development of a modern polder) was found in Alkmaar in the year 1408. Together with polder mills, the system consisting of polder and bosom was developing. [Polder system: the water from the polder is pumped into the bosom, usually a broader (ring) channel. From there it is drained off onto open water or the sea.] It may be clear that this fundamental technical innovation changed the position of people concerning the (coastal) landscape.

In 1667 already, Hendric Stevin suggested that a closure of the Southern Sea could diminish the inundation danger in big parts of the Netherlands. At his time, this plan was regarded infeasible. In 1825, new proposals were made (not by the same man). When the dikes broke

Figure 5.19 Southern Sea closure plans
again in 1916, the final decision was made to carry out this ambitious plan. In Figure 5.19, the different designs are shown. At the time that the Afsluitdijk was finally planned, knowledge about hydraulic and morphological effects of closure was small. Man could not determine the influence of the dam on the storm water levels. The commission Lorentz developed a method for calculation of those levels. Afterwards they turned out to be right. Still, this uncertainty during the design and construction stage has been a complication during the whole work. The work was delayed by economic crises, the Second World War, and by the storm disaster of 1953 (repair works).

Another problem was the need of integral planning concerning landscape architecture, economy, agriculture and fishery. Together with the closure of the Sea, new polders were created such as the Flevopolder.

During the Second World War, part of the South-West of Holland had become inundated. At the end of it (in 1945), the broken dikes had to be closed again. This provided for a large amount of experience, new technical skills and methods how to do so.

In 1953, the most recent large-scale inundation sea water took place in the Netherlands. In the night of February the first, spring tide coincided with Northwestern storm. The water level along the Dutch coast had risen too far for the dikes. In very many places they broke, leading to great losses. 1835 people died. Cattle and goods were lost. The shock following this disaster lead to a great public interest for the plan called the Delta Plan. This plan consisted of the closure of all sea arms in Zeeland (South-West of Holland). A new law was made: the Delta law, which said that the total inundation risk should be diminished to a socially accepted level. Therefore, the dikes had to be heightened and several dams must be built. After many years of work, the Delta Works have been finished recently by the construction of the New Waterweg Weir (Maeslant Kering).

In Figure 5.20, an overview is given of all elements of the Delta Plan, as it has finally been carried out. Many concepts have passed the design tables of many engineers during its preparation age". The time between preparation of the first steps of sea arm closure and the last steps of the whole Delta plan was so long, that the social and political climate had changed considerably when the finish came in sight. During the whole period, the important closure of the Eastern Scheldt had become a controversial point of public debate. Nature defenders created a strict viewpoint on the manner in which this closure should happen (and in which manner this shouldn’t). The final Eastern Scheldt Storm Surge Barrier can be called a result of coastal zone management dealing with ecological interests.
In the same time, the Delta project is a start of a new period of coastal zone management. Morphological processes caused by the Delta works have begun to develop. Ecological processes are much more a focal point of public and managers than before. In fact, the direction of management is rather two-sided; instead of defense of the people against natural phenomena, the starting point is also: defense of nature against people.

In the meantime, the consciousness began to grow, that the eustatic sea level might be
rising. Predictions are made about this process. In case of a rising sea level, the Delta Law tells us, that water defense structures must rise, too. An important step in this political process has been the acceptance of a fixed position of the coast line by the government (1990). Such a coast-line position must be maintained dynamically by artificial means. You see that the sea level and the required number of coastal engineers on the labour market may be positively correlated.

5.3.3 Human influence on morphology

Morphological changes caused by human actions are sometimes part of the design, but often they are unwanted consequences of the project. The oldest example of the second type is the historical "Great Cultivation period" in the Netherlands, which finally led to the devastation of the original, flexible Dutch peat landscape. The following inundations (and the Delta Works) surely were not planned by the poor people of that time!

After finishing the Afsluitdijk, the whole Wadden Sea started to change, which it is still doing. The tidal prism became smaller than before. That made the flow in the gullies between the islands slower. The gullies accreted and so did the Wadden Sea. The Delta works caused a new foreshore delta to develop. This might result in one of the most promising regions with respect to the nature function combined with the water weir function and recreation. Figure 5.21 shows a place in Zeeland. In front of the Zeeuwse Kust, a new delta is developing; breeding place for fish, birds and seals, and at the same time breakwater.

Figure 5.21 New developing nature (Meegroeien met de zee, WNF, Helmer et al.)
Last but not least: the global sea level rise is a huge morphological change correlated with the greenhouse effect. Overproduction of CO$_2$ is said to be one of the main causes of this (overproduction in terms of what the natural dynamic equilibrium can cope with). There are also people who think this is not true. Regarding the large uncertainties about the expected sea-level rise, the Rijkswaterstaat maintains 60 cm as the expected relative sea-level rise during the coming century.
5.4  Nature of the Dutch coast nowadays

5.4.1  Types of coast

The flexible character of a dune is typically expressed in the process of deformation and dune erosion during a storm flood. In order to meet the declination of the dune front, a certain dune volume is needed to protect the land against inundation. The amount of dune erosion can be computed using different computation models.

Structural erosion is something different than "storm erosion". Structural erosion affects the available dune volume, as dune erosion during a severe storm surge only changes the configuration of the available material. The effects of structural erosion on the safety can be estimated quite well. Another problem rises when measures have, out of the nature of the matter, contradictory consequences like in the case of anti-erosion measures.

Nowadays, the sediment balance of the Dutch coast as a whole is close to stable. For the total country, the erosion and accretion keep up with each other. However, locally, the differences are big. Naturally, the position of the coastline fluctuates largely over many years. This is abandoned by measures following the Governmental Decision of 1990 to maintain the coastline on the same position.

The following types of coasts are present: dune coast, sea dikes (for sea defence), and beach plains (which need a special weir construction). Morphologically different regions are: the Delta coast, the Dutch coast, and the Wadden coast (Figure 5.22).
The Wadden Sea and the Western Scheldt (the biggest Delta estuary) are taking sediment from the neighbouring parts of the coast, which causes retreat of them.
5.4.2 Wadden coast

The Wadden coast is a unique, valuable and beautiful nature area in the North West of The Netherlands and Germany. It has a specific, tidal character. A row of barrier islands, an ebb and a flood delta dominate the area.

In the past, the Wadden Sea and the IJsselmeer were in open connection (called the Southern Sea). The construction of the Afsluitdijk (finished 1932) has led to changes. For example: the bottom profile and locations of the gullies has changed. This is related to a decrease of the tidal prism. Nowadays a new equilibrium has been established (Figure 5.23).

Figure 5.23 New equilibrium after closure of the Southern Sea (RWS 1990)

Nationally and internationally, the Wadden Sea has a big nature value as a breeding place for migratory birds. Fish, seals and many other species find their home here. Therefore, many people are worried about the future of this region. Aggressive types of recreation like speedboating and hunting, as well as military exercises have a strongly negative impact. Therefore, a national policy was developed that would protect the Wadden Sea from adverse consequences of our human society. Wadden management is concentrated on a zoning system.

5.4.3 Delta coast

Along the Delta coast, the tide is dominant. Estuaries and peninsulas form the area. A complex of grown-together outer deltas is the foreshore delta. This specific form has always been subject of worries, as it is a vulnerable situation with respect to inundation. The idea to shorten the actual defending coastline is very old. It has found its performance in the Deltawerken, which have been completed by finishing the Maeslant Kering Nieuwe Waterweg (in 1996).

The Deltawerken cause morphological changes. An example is a walking sand bar directed
towards the land, caused by erosion of the seaside of the foreshore delta. The gullies that
date from before the closure of estuaries are changing in position and depth. In fact they still
are too big. Peninsula heads are attacked by waves and tide. Phase shifts between estuaries
can cause shortcut gullies along the peninsula heads. Wave induced sand transport causes
growth at the east side of the shelf. Island heads loose their stability partly.

Nature in the Delta area has undergone enormous changes since the Deltawerken were
started and estuaries were cut off from the sea. The new situation has not developed
completely yet. The sharp contrast from saline to fresh water offers a specific environment
for a variety of organisms. Estuaries like the Veersche Gat (Figure 5.24), which are fully
closed off from the sea, nowadays lack tidal movement of the water. The Eastern Scheldt

![Veerse Dam. Formation of plain after the closure of the Veersche Gat (RWS 1990)](image)

has kept an open connection to the sea and has experienced a more gradual response to its
"closure".

5.4.4 Dutch coast

Along the Dutch coast, the sediment transport is more even, but still there are gradients. A
wave induced surf current causes accretion in the middle part and erosion of the outer ends.
Movement of surf bars happens and is also influenced by human interferences like
Europoort and the jetties of IJmuiden (Figure 5.25).
In order to protect the land behind this long dune coast, beach nourishments are necessary. This is a flexible type of coast protection. The amount of sand put to the coast is determined in order to guarantee the so-called Delta-safety. For part of the North Sea sea defences, this inundation frequency limit has a value of 1/10,000 per year. This is a relatively low inundation chance, which is chosen because of the high population density and economical value of the land behind these dunes.

The dune coast has a big nature value, too. Certain areas are closed for the public in order to keep them quiet so that animals can stay undisturbed. The area is also used for water winning purposes, as dune sand has great water storage and cleaning capacity.
5.5 Social and economic environment of the coast in the Netherlands

5.5.1 Functions

The dune coast functions as sea defence. It consists of foreshore, beach, sea bar and inner dunes. The total makes a flexible weir. Other functions are: recreation, nature defense, water winning, and building. Therefore, integral water management is necessary. Maintenance cannot be forgotten. During coastal management processes, enough attention must be paid especially to environmental and natural values.

"The governmental mills turn slowly" is a saying in Holland. Nevertheless, they produce all kinds of plans which are important for coastal engineers. Here, in Figure 5.26, an example is given of one such a planning product. In the figure, the South West of Holland is shown, where coasts are subject of functional planning. Different functions are thought to be conflicting and the stresses that might follow are localized here.

Figure 5.26  Potential stress areas in Zeeland (Integraal Beleidsplan Voordelta, "Vorm in verandering", [1993])
Good marriages between different functions are also found, example in figure 5.27.

Figure 5.27  Sport fishing along the Brouwersdam, part of the Delta Works (Integraal Beleidsplan Voordelta, "Vorm in verandering", [1993])

In the 1970s, a number of serious threats to nature in the area were recognized. Water pollution as a consequence of an ever growing industry and more intensive agriculture, large-scale harbour projects, land reclamation, and oil and gas extraction with irreversible ecological consequences for the coast. At the end of the 1980s, especially as a consequence of national and international environmental disasters, the necessary realisation grew that national protection is only partly effective. "International thinking" about nature conservation and environmental protection has been started. The awareness that man is part of a worldwide ecosystem is essential in this respect.

5.5.2 Politics, interest groups

After the inundation of 1953, the "Delta Works" are made to meet the safety rules coming from the "Delta Law" (Deltawet). In the Deltawet, the Dutch government has fixed a certain inundation risk limits, which are based on a view of economic and social acceptability of inundation. These limits are expressed in the form of a chance, that a certain water level is exceeded.

Big safety interests of the people and industry make good sea defence important. Water boards are responsible for that. They manage the coast by law; this is a form of
decentralized management. This leads to divergence in defence strategies. The "Law on the Weirs" gives rules concerning the safety limitation and judgement. However, detailed insight in the real chance of inundation of a dike circle area is not available yet. The safety of a dune coast is judged from separate cross profiles. Technical guidelines (TAW richtlijnen) have been edited.

Apart from the weir function and the natural value of the coast, the other functions put their requirements on the landscape, too. Exceptional situations like function conflicts are not put into law. Instead, the dynamics between different participating groups determine how the functions are combined together. Participants in the management of coast and water are closely linked to its functions. They are: water boards, provinces, Rijkswaterstaat, industry, townships, education, nature defense, and nature management organizations. Detailed information can be found in: Basisrapport Zandige Kust, TAW, 1995.

The water winning function of the dunes is based on the possibilities of infiltration and storage underground of significant amounts of water. Dune ground is clean and untouched. Water winning needs buildings, roads, channels, ponds and winning installations. Relatively small towns, industry, harbors, marine entrances, landing of transport lines for oil and gas from the Continental Shelf, telecom cables, waste water lines and military exercise ground, all claim the dune terrain in their own way. The recreation function is treated as follows: recreating people are divided into those who are present for one day, or those who stay longer in the area. Respectively, semi-permanent building on the beach, or permanent building (and more services behind the dunes) have to be available; infrastructure and beach entrances must be there.

Good coastal zone management does keep attention to all these. The maintenance obligation is linked to management. Therefore, the borders of any management area must be chosen carefully.

5.5.3 Economy

In history, harbors and trade have always had an extreme influence on the Dutch economy. In the Netherlands, many people live on a small area. Next to that, the economical value of the land is enormous. Therefore, a good functioning defense against the intruding sea is based on huge safety and material interests. At present, these interests are given a place in the design procedure of water defense structures. This happens via risk analysis.

A coastal zone like (part of) the Netherlands, is often the place where conflicts arise between different functions (for example recreation and fishery), between external and internal factors (for example global pollution and local nature), between people and nature (for example sea level rise and cultivated land interests), and between people themselves.
(about access to resources or privileges). A specific coastal zone has its own lay-out and configuration with respect to these potential conflicts. In one way or another, a specific allocation of resources is made, let alone if it is happening by a functioning market or not. Efficient use of coastal resources might be reached by using applied economics, concerned with all participants of the coastal zone. For all actual conflicts, an integral compromise should be found, without forgetting the non-market character of certain resources. These compromises could be found using the help of economic science.

In order to make proper use of the economic insights in the matter of coastal zone engineering, a viewpoint should be chosen which is suited for a broader objective than individual micro-economical money-making. As the coastal zone is important for the whole society, which it is part of, all economical aspects should be seen from a social point of view. The question becomes: What does society as a whole lose when labour, capital, land, and the natural environment are used to produce one thing rather than another - condominiums replacing marinas, golf courses replacing wetlands, private homes replacing public beaches?

Nature values are difficult to express in terms of money. Nowadays, resource and environmental economics try to facilitate economic valuations of natural resources where markets do not exist. These valuations are based on the (principle of) antropomorphous character of economic science. Thus, if potable groundwater, access to beaches, opportunities to go fishing, uncrowded streets, and other unpriced resources and opportunities are valued by coastal residents, there is now an opportunity to represent these interests on equal footing with traditional economic growth.

This general concept about coastal zone economy definitely can find its application in the Dutch coastal zone management practice. One example of such an application is to aim for economical and ecological flexibility of the Dutch coastal zone.

5.5.4 Infrastructure

Without the harbor complex of Rotterdam, lots of infrastructure would be different (or non-existent). Recently, the conflicts about the train link with Germany through the Betuwe showed that transport facilities from and to the Rotterdam Harbor keep the political and economical brains busy.

Infrastructure opens up a system; a city, the landscape, society, or: an ecosystem. Infrastructure therefore cannot be treated as one isolated subject. It should be main topic of an integral management plan. Mobility, which is strongly linked with and determined by the infrastructure, represents value for the members of the system. This statement holds true if we are talking about an eco-system, where the members are 4-, 6-, or non-footers, and a
different way of life than people. Many ecosystems profit from good links between different regions where the nature function is well-developed. Therefore, such links must be part of the planning process. Different configurations of function-groups must be studied in order to arrange optimal infrastructure.

A Dutch example from historically developed infrastructure is the sea dike net. Figure 5.28 shows the net of sea dikes which is found in the Netherlands. The net of smaller dikes is much finer. Dikes usually carry roads, too. They have a big influence on the planning.
process, as they give shape to the water household of the land.

5.5.5 Flexibility

In order to cope with the sea level rise and ecological demands, a call for flexibility of the coastal zone is heard. This flexibility could be created in the Netherlands as follows (WNF report "Growing together with the sea"):

1. Combining the functions nature and water winning in one area (water storage);
2. Linking housing projects financially to nature development;
3. Making nature areas more accessible for public;
4. Creating more big nature areas as buffer zones between extreme water levels;
5. Purification of surface water, in order to reach a more flexible ecosystem (stimulating its selfpurificating power);
6. Letting peat areas grow again and letting marshes exist (by rising the ground water level); this type of soil has carbon binding capacity;

In Figures 5.31 - 5.34, the natural side of these proposals are illustrated (Wereld Natuur Fonds, "Meegroeien met de zee, naar een veerkrachtige kustzone", Helmer et al.)
Figure 5.29  Terschelling (Wereld Natuur Fonds, "Meegroeien met de zee, naar een veerkrachtige kustzone", Helmer et al.)
Figure 5.30  Schoorl-Bergen
Figure 5.31  Bergen-Egmond
Figure 5.32 Bloemendaal-Kennemerduinen
6 Pollution and density problems

6.1 Introduction

In the coastal zone, many engineering problems are related to the difference between saline and fresh water. Another common feature is pollution. This chapter deals with both.

6.2 Pollution

6.2.1 Types of pollution

Pollution can consist of:

1. Human wastes;
2. Oil;
3. Halogenated hydrocarbons;
4. Other organic materials;
5. Heavy metals;
6. Heat;
7. Radioactive materials;

Human faecal waste is often first considered, since it raises such a great aesthetic problem. On the other hand, it is certainly a natural product and faecal wastes are also produced in great quantity by marine life (six million tons of anchovies off the California coast produce as much faecal material as 90 million people, according to Bascom (1974-1). Two aspects of the disposal of faecal wastes remain important, however: oxygen consumption from the water, and bacteria. The oxygen demand can lower the dissolved oxygen level below the level that is needed by marine life. While most bacteria are killed soon by contact with sea water (within hours), it is not sure that this is true for all types, thus epidemiological problems can be conceived.

Oil and petroleum products are perhaps the most controversial pollutants. The public reaction to oil spills by ships is usually emotional and vehement. Shipping is not the only source of marine oil pollution, however. Unknown quantities of it naturally seep into the oceans. A report compiled for the Connecticut State Legislature concludes that more than two thirds of the oil discharged by man into the seas comes from automobile engines and oil sumps of other machines. This oil causes no great problems, since its rate of input is low enough and it is sufficiently dispersed to be broken down by natural processes, something which is not the case if an oil tanker is broken. Oil pollution from major spills often is a temporary problem. The short term biological influences can be severe, but the pre-existing...
natural situation most of the times restores itself within a few years. This is not true for the next category of pollutants.

Halogenated carbons include the most common organic pesticides. While a few of these chemicals, such as TEPP lose their lethal properties rather quickly, others such as DDT seem to be virtually indestructible in nature. The process of concentration of pesticides in certain types of marine life is rather well known.

Discharge of nutrients into bodies of water can have stimulating effects on the marine life. Done in an uncontrolled manner, this soon becomes a way of overstimulating, which can be disastrous for the ecological equilibrium. Oxygen is consumed in the biodegradation of the nutrient materials. Not necessary to say, that the last word about this item has not been spoken yet.

Because of the electrostatic properties of clay, fine sediments may bind heavy metals that are present in the water column due to natural causes or human activity. Therefore, the concentration of heavy metals (and other organic components) in fine sediments are relatively high. As long as the pollutants are bound to the sediment, they cause relatively little harm. The binding force may be lost, however, due to strong mechanic action (turbulence) and changes in the chemical and physical conditions (acidity, salinity, presence of oxygen, temperature). In such case the pollutants become available in high concentrations, and they can easily be introduced into the biological cycle. Uncontrolled discharge of heavy metals has led to serious environmental disasters, among others in Japan, where Itai-Itai and Minimata disease have affected the human population.

It is extremely difficult to separate the heavy metals from the (large quantities of) silt in the estuaries. Therefore, emphasis is laid on reduction of the emissions on one hand, and controlled storage of polluted sediments on the other hand. Examples: Slufter basin in the part of Rotterdam, Ketelmeer. Heavy metals also enter the sea from the atmosphere. Forest fires, for example, add metallic oxides to the atmosphere which deposits them over the whole world. Just as with discharges of many pesticides, the influence of heavy metal discharges is cumulative. An example of the cumulative action as influenced by man is shown in Figure 6.1, which shows the lead concentration in layers of sediment in the ocean near Long Beach, California. The sharp rise in concentration in recent years is attributed to airborne lead from automotive emissions.
Thermal emissions may be either warmer (power station cooling water) or cooler (liquified natural gas conversion) than the surrounding water. Most marine life can adapt to the modified thermal climate near such a heat source or sink, but are often killed either mechanically or as a result from abrupt temperature and pressure changes as they are drawn through the plant. Heat discharged into the oceans is only of local biological significance.

Radioactive wastes form the seventh category of pollutants. Marine life can tolerate a larger radiation dose (before it becomes fatal) than man. Man can conceivably ingest a fatal dose of radio poisons from seemingly healthy fish. Therefore, radioactive wastes should not be put into the environment of fish (the sea). Disposition of wastes into subduction sinks is not a logical solution, because the natural recycling processes in the deep water are very slow.

Fine sediment itself, as residu from dredging, can be a danger for marine life on certain locations. High concentrations of suspended clay particles can inhibit sunlight to penetrate into the water. Disaster for certain species may follow. In other places it might not be a problem. So sediment has two ways of being a threat to the environment: by reducing light penetration and by carrying other pollutants such as heavy metals.

### 6.2.2 Control measures

Control measures are legal sanctions, which are attainable and consistent. Environmental assessment of plans can be a control instrument. Common problems during environmental assessment are:

1. Effects on man, flora, and fauna often are indirectly related to direct consequences of an activity;
2. Direct consequences of an activity often are not easy to quantify;
3. Direct consequences are given in different units;
4 Direct consequences are not easy to express in money;
5 Alternatives are evaluated on final effects, and passing stage effects are forgotten.

These problems could be met by creating a social basis of the evaluations. Effects should be quantified and expressed on the same basis and in the same units. Passing stage effects should not be forgotten! In a project, specific attention must be given to the responsibility issue. Companies who produce pollutants, often do not register waste disposal properly. Many times this is contracted out to a cleaning company. This can create legally unclear situations.

Many pollution problems cross the borders of a country. In the case of river pollution, polluting companies which are situated upstream cause problems for downstream river sections. Then, coastal zone management practice should include the upper part of the river. The problem in the case of air pollution is even more complicated. A lot of environmental measures must be tackled internationally. Especially different standards in neighbouring countries generate unclear situations and (political) dissatisfaction.

During the last forty years, international reglementation has been developed with respect to the marine environment. This started with the Treaty for the Continental Plane (1958), which determines the rights of coastal countries, and also obliges them to take protection measures for marine life. The London (Dumping) Convention (1975) consists of an updated black list (chemicals which may not be dumped or burnt on sea) and a grey list (dumping/burning only with an allowance). In order to prevent ships from polluting activities, the MARPOL-agreement (1982) has been accepted. The Convention of the United Nations on the Right of the Sea (1982) includes the juridical framework for worldwide use of seas and oceans. Rules concerning conservation and management of sea life, and protection and conservation of the marine environment are part of it.

6.2.3 Density currents in harbors

The tide causes ebb and flood currents in a harbor. Inertia terms are less important here. This means, that the current in the harbor mouth will be slack just at the time of high and low water, if no density effects are involved. However, the tide also causes density currents. If such effects are involved, the density stratification at the mouth of a harbor basin just after the river salinity has changed can be outlined by a vertical interface. This configuration may be called vertical stratification of the salinity profile.
This situation is very much the same as that of a lock, where one side meets fresh, and the other side meets salt water. Hydrostatic pressures differ on both sides, and the result is shown in Figure 6.2. One will discover that the lock is opened when water levels are unequal on both sides. The head over the lock can be computed as follows. The horizontal force on the door must be zero. Then:

$$\frac{1}{2} \rho_1 gh_1^2 = \frac{1}{2} \rho_2 gh_2^2$$

(6.1)

where:
- $g$ = gravity acceleration
- $h$ = depth
- $\rho$ = mass density of water

When $\rho_2 > \rho_1$, then Equation 6.2 yields:

$$\frac{h_1}{h_2} = \sqrt{\frac{\rho_2}{\rho_1}}$$

(6.2)

While the resultant force on the door is zero, the resultant moment on the door is not zero! After opening the lock, this condition is unstable. It therefore leads to a current pattern; the flow of the more dense layer can be compared to the flow of water down a river valley just
after a dam has burst. This is called a dry bed curve (Figure 6.3).

The velocity of the dense layer is:

\[ V_D = 0.45 \sqrt{\delta gh} \]  

(6.3)

where:
\( \delta = \) relative density \( = (\rho_D - \rho)/\rho_D \)
\( h = \) water depth
\( V_D = \) velocity in the dry bed curve

In Equation 6.3, \( V_D \) is proportional to \( \sqrt{\delta} \). The factor 0.45 is due to friction. In a real harbor on a tidal river, the flow in the harbor is the superposition of the filling flow and that
Figure 6.4  Idealized current profiles and their superposition for various times

caused by the density current (Figure 6.4). Therefore, velocity distributions can be
superimposed while the sediment transports cannot be simply added, except when the
sediment concentration is constant over the entire depth (which usually is not the case).

The average salinity increase and the density current depend on the configuration. How does
one examine the progress of a density tongue in a harbor then? The continuity of the
progression of the density tongue is a calculation item. There are two conditions:

1  The salt must have somewhere to go;
2  There must be a driving force (i.e. the density difference).

The first condition is dependent only upon the harbor geometry while the second criterium
depends on the water alone.
Example. In order to separate these conditions for discussion, let us first assume that initially all of the water in a harbor basin and the adjacent river has a density of 1005 kg/m³. At some instant, the density of the water in the river increases to 1015 kg/m³, and maintain that value indefinitely; thus, the driving force is maintained. There is no tide. The harbor has a rectangular form and has a depth $h = 7$ m ad length $L = 2500$ m, Figure 6.5a.

![Diagram of harbor and river](image)

Using Equation 6.3, we find the density current speed of 1042 m/h. With this speed, the tongue progresses without hinderance over the length of the basin - 2500 m - arriving at the inner end in 2.24 hours. The wave then reflects from the inner end of the harbor, just as does any other long wave, and propagates back towards the entrance at the same speed arriving there 4.48 hours after the cycle started. The progress of the tongue after each half hour interval is shown by the dashed lines in Figure 6.5b. After the tongue has returned to the harbor entrance, the process stops, since there is no longer a density difference across the harbor entrance.

What has happened to the less dense water that was originally in the harbor? That water has spread over a large area of the river in a thin layer, where wave action enhances its mixing with deeper water. The time required for the density current to enter a harbor and exchange
the contents explains the phase lag between peak salinities in a river and in an adjacent harbor. Does a complete water exchange take place? It does, except when the driving force (density difference at the entrance of the harbor) is removed in the meantime.

The second type of problem, in which there is insufficient time for a complete exchange, is somewhat more complex. This is illustrated via the following example. It is exactly the same as the previous one in that the harbor initially contains water having \( \rho = 1005 \text{ kg/m}^3 \) and the river abruptly changes density from 1005 to 1015 \( \text{kg/m}^3 \). This time, however, this higher density will be maintained in the river for only 1.12 hr, after which the river density will again become 1005 \( \text{kg/m}^3 \). Indeed, the problem is exactly like the previous example in all respects for the first 1.12 hr.

After 1.12 hr the situation will be as shown in Figure 6.6. The driving force is no longer present. Momentum will keep the slug of salt water moving for a time, by other influences become important since the trailing end of the slug of dense water is unstable. A dry bed curve will develop at this end of the 3.5 m thick lower layer causing the slug of water to spread out in a thinner layer along the harbor bottom. Ultimately, of course, this thin layer could retreat entirely to the deeper river. Quantitative evaluations of all these processes are beyond the scope of this course and are not necessary for our main purpose: the determination of the quantity of silt which enters the harbor along with the more dense water. An impression of the form of the interface between the two water masses at some
later time is shown in the figure.

In practice, physical model studies and semi-empirical equations are used. Maintenance dredging costs are predicted. As more than 80% of the harbor siltation is caused by density currents, the water exchange is an important factor. The water exchange depends on the form of the entrance. Other determining factors for the current pattern are eddies and river currents.

Combatting density currents happens via:

1. Narrowing the entrance; as the volume of water exchanged is thought to be proportional to the entrance area. Thus, reducing the entrance width should reduce the volume of exchanged water. In practice, such a narrowing will not be quite that effective. The intruding density current stream will spread in both horizontal directions in the wider harbor basin; this tends to increase the effective driving force by increasing the slope of the interface between the water masses. This effect is difficult to quantify, however.
2. Installing a single set of doors at the entrance to the harbor. The harbor level is then
maintained at a constant level - even the filling current is eliminated. The water level in the harbor remains constant; this is handy for the cargo handling operations. Does a density current cause a water exchange? It does not have to. If the doors are opened only once during the tide cycle and at the same time in the cycle when the water levels are equal, then the harbor water will eventually have the same density as the river water and no dredging problems will be experienced. On the other hand this means that the doors are opened only once every tide period and it may be unacceptable to force the shipping to wait so long to pass through the entrance. What would happen if the doors were opened twice per tide cycle while the water levels were the same - once on a rising tide and once on a falling tide? There will still be no filling current, but there is no guarantee that the density in the river will be the same at both times. In general it will not be, and a density current and water exchange will take place during the time that the doors are open. Indeed, such a solution is of little value except when very great tide level variations might make cargo handling inefficient in an open basin.

3 Putting in a lock: the ships could enter and leave the harbor at any time irrespective of the water levels. Each locking operation can be accompanied by a water exchange within the lock, however. Since the lock is relatively small, this exchange progresses rather rapidly - 27 minutes for the large lock at IJmuiden, for example. Special facilities have been built at IJmuiden to trap this intruding salt water and retain it for later disposal. These special facilities consist of a deep pit just landward of the lock connected via an equally deep channel to a sluice.

4 Constructing a deep pit connected to a sluice: salt water coming in through the inner door opening of the lock falls into the pit. Later during low tide at sea this salt water can be discharged through the sluice.

5 Using an air bubble curtain: this is a stream of rising air bubbles released from a perforated submerged pipeline at the end of the lock near the door. The rising bubbles increase the turbulence and hence the mixing; this reduces the driving force of the density tongue and reduces the intrusion.

A combination of measures can be taken. Other more exotic devices have been proposed from time to time to combat density current intrusions into harbors. For example, a device looking like a giant brush with vertical bristles bend in order to allow a ship to pass. Many other similar devices can be conceived using a bit of ingenuity.

The assumption that the river density changes abruptly, such as presented in the example, does not hold true in nature. Next to that, not so many harbors are rectangular in form. A dependable theoretical computation of the water exchange in a harbor of arbitrary shape on a given river is extremely time consuming at best. For this reason, physical model studies are often used; part of WL Delft Hydraulics is devoted to the modeling of saline density currents. A second approach of the problem is the development of a semi-empirical equation for the water exchange and to determine its coefficients based upon experience with existing
harbors. Such an equation can then be used to predict the exchange taking place in a similar harbor under the same conditions.

The density current can be of major importance for harbor siltation resulting in maintenance dredging costs. An estimate of the density current, therefore, can be of vital importance for feasibility studies. Even a crude computation can be helpful in such cases. The current pattern in a harbor mouth can be complicated. The complication can exist in the form of an eddy rotating about a vertical axis in the harbor entrance. Water exchange between the harbor and eddy on one side and between river ad eddy on the other can increase the transport of salt and suspended sediment into the harbor. When a harbor is small, the density current can usually carry out a complete water exchange rather quickly, but then stops transporting silt laden water into the harbor. The eddy, on the other hand, continues functioning exchanging sediment laden river water for clearer harbor water. This cause can be the most important of all three causes for the transport of sediment into a small harbor.

Eddies form at the entrance to larger harbor basins as well. However, these tend to be excited by the other current components in the harbor entrance rather than the river current. As such, they contribute little to the supply of sediment to the harbor. It takes little imagination to realize that near the mouth of a harbor, where eddies, density currents, river currents and harbor filling currents are all competing with one another, the current pattern can be rather confused. Small, shallow draft ships will only be concerned with the surface currents. Larger, deeper ships which penetrate the interface between layers are subjected to dead water phenomenon and we should realize easily the respect with which harbor pilots are usually treated.

"Dead water" is a phenomenon which is related to horizontal stratification; the situation in which a generally stable salt layer is lying under a fresh layer. Internal waves (Figure 6.7) can be caused by a disturbance such as a ship, earthquake or underwater landslide. They can also result from shear forces along an interface between two layers in relative motion.

![Figure 6.7 Internal wave](image)
The celerity of a wave on an interface is given by:

\[ c = \sqrt{\frac{(\rho_2 - \rho_1)g \theta_1 \theta_2}{\rho_2 \theta_1 + \rho_1 \theta_2}} \]  

(6.4)

where:

- \( c \) = wave speed
- \( \theta \) = layer thickness

As \( \rho_2 \) is nearly equal to \( \rho_1 \) in Equation 6.4, it can be approximated by:

\[ c = \sqrt{\frac{(\rho_2 - \rho_1)g \theta_1 \theta_2}{\rho_1 h}} = \sqrt{\frac{\delta g \theta_1 \theta_2}{h}} \]  

(6.5)

where:

- \( \delta \) = relative density \( = \frac{\rho_2 - \rho_1}{\rho_1} \)
- \( h \) = total depth \( = \theta_1 + \theta_2 \)

These waves can be very high, since the gravitational influence on them is small. They are accompanied by much smaller negative waves on the water surface. Indeed, as a first approximation, the ratio of surface wave height to internal wave height is equal to \( \delta \). These internal waves can absorb a considerable energy from a ship causing the so-called "dead water".

This is explained via an example. A ship of 4 m draft sails into a stratified harbor having a surface layer 3 m thick of relatively fresh water (salinity \( S = 5\% \) and temperature \( T = 2^\circ C \)) above a deeper layer of 7 m thick with \( S = 36\% \) and \( T = 4^\circ C \). What is the maximum speed that this ship can attain?

\[ \sigma_{\theta_1} = 4.00; \quad \rho_1 = 1004.00 \text{ kg/m}^3; \]
\[ \sigma_{\theta_2} = 28.70; \quad \rho_2 = 1028.70 \text{ kg/m}^3 \]
\[ \theta_1 = 3 \text{ m}, \quad \theta_2 = 7 \text{ m}; \]
\[ c = \sqrt{\frac{(1028.7-1004)(9.81)(3)(7)}{(1004)(7)+(1028.7)(3)}} = 0.709 \text{ m/s} = 1.38 \text{ kt} \]

The only way the ship can move faster than this wave is to cut through it or climb over it; neither is very likely! This dead water phenomenon also played a role in a naval battle some centuries ago. In this area the rather fresh Baltic Sea water flows over more dense water from the Skagerak.
Variations in salinity cause flocculation and rapid settlement of fine material. This settlement of material proceeds even faster in harbors because of the relative tranquility of the water there. Obviously, all of the phenomena which cause water exchange between harbor and river also increase the supply of sediment to the harbor. For dredging, it is important to know the harbor siltation quantitatively. This is computed by multiplying the volume of water exchanged in one tide cycle in the basin by the difference in sediment concentration between in-flowing and out-flowing water. This is a rough estimation which has practical value.
6.3 Tidal inlets and estuaries

6.3.1 Introduction

The importance of rivers for nature and people can hardly be overestimated. Biological activity is concentrated along and in them. Although rivers only bear a small part of the total amount of fresh water on earth, they allow 50% of all species to "make a living". People use rivers intensively. Their use is always growing, think of irrigation and water energy.

The lowest part of rivers is often influenced by the tide (in case they find their end directly or indirectly in the ocean). Deltas are one form in which the transition of fresh to salt water can take shape (although rivers flow so rapidly that the whole delta and surrounding area in the ocean stays fresh).

In this paragraph, special attention is paid to tidal rivers, which are rivers influenced by the tide. The tide may be perceptible over a large part of the river up into the continent. The tidal part of a river is in fact (partly) ruled by sea levels. It is important to notice, that coastal zone management measures concerning anything in the tidal river mouth area have impact on the whole tidal river. Therefore, the tidal part of a river must be included in the coastal zone.

6.3.2 Tidal inlets

A tidal inlet is not fixed but dynamic. Important factors for the inlet dynamics are: tidal currents, storms, tidal prism, littoral sediment transport. Escoffier made a model for this. Runoff plus tidal flow create a situation in the river mouth, of which the stability depends on different parameters. Maximum entrance velocity as a function of hydraulic radius, cross sectional area and tidal range gives insight in the stability behaviour of the inlet by a curve ABCD (Figure 6.8). D is the stable situation. Maximum velocity where equilibrium is present is $V_{eq}$, below which no erosion happens. The equilibrium cross section area of the entrance has got a minimum value $A_{min}$.
Figure 6.8  Maximum entrance velocity as a function of hydraulic radius, cross sectional area and tidal range

The tidal prism is defined as the product of the tidal range and the area of backbarrier bays. $A_{\text{min}}$ is linearly related to the volume of the tidal prism:

$$A_{\text{min}} = 6.56 \times 10^{-5} \, P$$  \hspace{1cm} (6.6)

where:

$A_{\text{min}}$ = minimum equilibrium cross section area of the entrance in m$^2$

$P$ = tidal prism volume in m$^3$ (storage volume between low tide and high tide levels)

With this insight, it is possible to evaluate the influence of changes in an estuary mouth.

Since point D represents a naturally stable situation, most natural estuaries will tend to be in that region. A severe storm can largely fill the entrance, moving it suddenly to branch A-B of the curve. In such a situation immediate dredging is called for to prevent from complete closure. One need not to restore the original situation, however; once the entrance geometry is placed on branch B-C-D of the curve, nature will do the rest of the work after enough time.

Shipping interests can make it desirable to enlarge a given estuary entrance to accommodate larger ships. If such an expansion scheme places the channel on branch D-E of the curve, then the dredging industry will remain profitable for the foreseeable future. It may be possible to prevent from that by changing the channel alignment and artificially constructing its width - techniques often used in rivers - so that the larger channel cross-section remains stable. A new curve $V_m(x)$ has been generated which yields a higher value $V_m$ for a given $x$ value; the equilibrium D has been moved to the right.
6.3.3 Tidal curves in a river

The tide travels along the river as a long wave. Convection, inertia and friction each play their part in the game. In general, distortion of the horizontal and the vertical tide curves takes place as the tidal wave moves up a river. For example, if friction is relatively important (shallow river, bottom slope negligible), there is a phase shift between the two tidal curves. As the tidal prism becomes smaller when going upstream, the horizontal tide amplitude usually gets smaller, too.

6.3.4 Density problems

Let us take a look at the salinity profiles as they are found in rivers. Salinity profiles can be drawn using haloclines, lines of equal salinity. If the haloclines are vertical, man speaks of vertical stratification. Horizontal haloclines and stratification can show a stable situation; vertical can not. In Figure 6.9, longitudinal sections of an estuary show different salinity distributions (%).

The basic flow pattern in an estuary is a surface flow of less dense freshwater toward the ocean, and an opposite flow in the subsurface of salty seawater into the estuary. The dimensions of each flow, and the degree of mixing between the two, depend on specific conditions in each estuary. Note that surface freshwater flow toward the mouth of the estuary extends seaward much farther along the right-hand shore as one faces seaward. This is due to the Coriolis effect. The opposite side of the estuary experiences a greater marine influence. In most estuaries, the marine water inflow occurs in the subsurface.
In a fresh water river, discharging into a saline sea, a salt wedge occurs (Figure 6.10). The sea water intrudes along the river bottom under the fresh discharge water. The length of the intruding wedge is determined by an equilibrium between the friction, $\tau_1$, along the interface and the horizontal pressure gradient resulting from inclination of the interface. When this equilibrium is strictly satisfied, the salt wedge will be in a stable position with the fresh water flowing seaward on the surface and spreading out in a thin surface layer at sea. Schijf and Schönfeld (1953) derived an expression for the length of such a wedge in a prismatic, horizontal, rectangular channel discharging into an infinite, non-tidal sea.

\[
L_w = \frac{h}{f_I} \left[ \frac{1}{5F^2} - 2 + 3F^3 - \frac{6}{5}F^4 \right]
\]

where:

\[
f_I = \frac{8\tau_1}{\rho(V_1 - V_2)V_1 - V_2}
\]

\[
F = \frac{V_r}{\sqrt{gh}}
\]

where:

$L_w$ = length of wedge
$V_r$ = velocity in the river upstream from the wedge
$V_1$ = velocity in the fresh water above the wedge
$V_2$ = velocity in the salt wedge
$\tau_1$ = friction stress along the interface
In a real situation there is a state of dynamic equilibrium. Mixing will take place along the interface between the water masses. Salt and sea water will be transported along with the river water back to the sea. Since the total net flow out of the river must be equal to the fresh water runoff:

\[ Q_1 = Q_r + Q_w \]  

(6.8)

where:
\( Q_w \) = inflow in the wedge
\( Q_r \) = fresh water river flow
\( Q_1 \) = net outflow through the cross section

Continuity of salt must also be maintained. This implies that:

\[ Q_1 S_1 = Q_w S_2 \]  

(6.9)

where \( S_1 \) and \( S_2 \) are the respective salinities.

Generally, the tidal influence is most important - it leads to an oscillatory motion of the entire two-layer system over an uneven bottom. This motion, of course, increases mixing across the interface. Indeed, in estuaries with strong tidal influence and little fresh water flow, stratification can essentially be destroyed, leading to a well-mixed estuary. At a given time and place there is little vertical salinity gradient. In such an estuary, the average seaward transport of salt by the river flow forms an equilibrium with the transport of salt into the estuary by diffusion. The effect of this diffusion (which is always present to some extent) combined with the momentum of a possible inward flowing salt tongue can delay the time of maximum average salinity at a point on a tidal river until a bit later than the H.W. slack.

As has already been indicated, tide cycles cause the salt tongue or the haloclines to move back and forth in the river as a function of the tide. The most direct consequence of a salt tongue in a river is its effect on the siltation pattern of the estuary. The current along the estuary bottom is drastically changed by the presence of the salt tongue. Upstream from the tip of the tongue, the velocity along the bottom is directed towards the sea, while within the wedge there is often a small velocity into the estuary. Since the bottom velocity at the tip of the tongue must be zero, it can be expected that material will be deposited there. In estuaries where there is little tidal influence and the position of the salt wedge remains relatively stable, this local sedimentation can form a pronounced shoal in the river. Besides, this phenomenon can also be found in an estuary having a density difference caused by other factors such as thermal gradients.
When the suspended sediment in a river consists of clay and the density tongue is caused by salinity differences, then physical chemical processes can also strongly influence the siltation pattern in the estuary. Suspended clay in fresh water consists of flat or needle-shaped particles having a maximum dimension less than a few micrometers. Because of their form, large surface area and the crystal structure of the clay minerals, these particles are negatively charged on the surface. Since the particles are so small, the electrostatic forces rather than the gravity forces control the behavior of the clay particles, and work to keep the particles separated and in suspension.

As the salinity of the water increases, the positive ions (Na\(^+\), Mg\(^{2+}\), Ca\(^{2+}\) etc.) present tend to neutralize the electrostatic forces, thus allowing the clay particles to flocculate, and settle. A salinity of about 3\(\%\) is critical in this process. The physical chemical influences are only important for salinity variations below this value. The flocculation caused by an increase in water salinity is at least partially reversible. When, later in the tide cycle, the salinity decreases, the flocks of clay particles exposed to the fresh water can explode, dispersing the individual particles once again in suspension. This process can provide disturbing influences on suspended sediment measurements in areas where low, variable salt concentrations can be found. An impression of the magnitude of this influence on siltation can be gained by comparing the fall velocity of clay particles in fresh water to the fall velocity of flocks of particles in salt water (S > 5\(\%\)). Allersma, Hoekstra and Bijker (1967) report that the apparent ratio between these fall velocities was more than 1 : 50.

The quality of the material forming the river bed in such an area is not the same as the usual form of compact clay. Indeed, the sediment which forms as a result of flocculation contains a large quantity of water. The volume of the sediment (solid particles plus water) can be 5 to 10 times the volume of the particles. (In soil mechanics terminology, the void ratio can be as high as 90\%). Obviously, such a high volume of water will keep the mud density low—usually between 1100 and 1250 kg/m\(^3\). The material behaves as a viscous fluid with a viscosity of in the order of 100 to 5000 times that of water; this is comparable to yoghurt (except for colour). This material called sling mud is difficult to detect when making soundings. It appears as a faint reflection on an echogram. The sediment is so soft that ships can often sail through it. The consolidation process for such a soft silt is very slow. Layers up to 2.5 m thick remain fluid for several weeks— even in a laboratory settling tube. This sling mud can be brought into suspension again when the current velocity above it reaches a critical value ranging between 0.2 and 1.0 m/s.

The upper portions of the mud layer behave as a viscous fluid and while it is easy to pump with a dredge, its extremely low density results in poor dredge productivity measured in terms of quantity of solids moved per hour. One means of improving this situation is to dredge a deep pit so that the silt layers can move to that pit and consolidate slowly there. Mud of higher density can then be withdrawn from the deepest part of the pit using a
dredge. Now, one has only a problem of getting the mud layer to move to the pit. There are two possibilities:

1 If sufficient surface slope is available, gravity forces will cause the sling mud to flow towards and into the pit;
2 The second approach relies on the shear stress exerted by water flowing above the bed, (the tide, for example) to provide a driving force for the mud movement. A danger is that if the surface shear stress becomes too high, the boundary between mud and water becomes turbulent stirring the mud into suspension. Mud in suspension will, of course, simply pass over the nicely prepared pit.

Density currents can cause environmental pollution problems. The most obvious source of environmental pollution is the infiltration of salt water into the surrounding ground water along a river. The deleterious effects of water salinity on the growth patterns of plants have been well documented by agricultural specialists. The prediction of the severity of saline pollution for a given location is a topic of study for specialists in ground water hydrology. Another, often less obvious, pollution problem can be caused by the presence of thermal density currents. Marine life such as shellfish often is unable to adapt to rapidly varying water temperatures experienced when the edge of a thermal plume drifts over it at some time in a tide cycle. Several large and elaborate model studies have been conducted in various laboratories, both in the United States and the Netherlands to determine the extent and severity of thermal flumes from power stations to be located along estuaries. Demonstration that the plume of discharged cooling water will not harm the surrounding marine life is often required before a construction permit will be granted.

There are relatively few techniques which are economical for combatting the intrusion of a salt tongue in a river. Many more techniques are available for more restricted areas such as harbor basins and channels. It has been indicated that the length of the salt wedge can be reduced by decreasing the water depth and by increasing the fresh water flow. In the Netherlands, the discharge of fresh water through the New Waterway has been increased as a result from the completion of the Northern part of the Delta Project (Volkerak dam and locks, Haringvliet sluice). In addition, the development of the Europoort harbor area has eliminated the necessity for bringing large, deep ships into the New Waterway past the Europoort entrance. In recent times, therefore, parts of the New Waterway in Rotterdam have been partially filled in order to decrease their depth and drive the salt water tongue back towards the sea to a greater extent.

Thermal density currents can be combatted by either enhancing the mixing of the two water layers or stimulating the heat transfer process between layers or to the atmosphere. Although not too common in use, mixing can be enhanced, for example, by increasing the turbulence in the thermal discharge or artificially generating an unstable stratification.
Increasing discharge velocity and construction of a pile supported jetty in front of the discharge flume of a power station have been suggested as means to increase mixing by increasing turbulence. Naturally unstable stratifications are often artificially generated when warm, low salinity sewage is discharged near the bottom of the sea. As the lighter sewage rises through the sea water, the resulting turbulence helps to disperse it. Obviously, another solution to thermal pollution problems is to re-cool the discharge water before it is released. This may be accomplished by retention in shallow pools or by circulation through a cooling tower. Sometimes, simply a long wide discharge channel can serve the purpose. The objective in all of these solutions is to transfer the heat to the atmosphere.

### 6.3.5 Tidal river morphology

In natural channels, the deepest channel sections develop along the outside of the river bends with the channel shifted somewhat downstream from the shoreline bend. By the presence of tidal action, this is modified. In a narrow channel, the influence from the tide on the river bathymetry is to make the location of the deeper channel in the river bend correspond more closely to that of the shoreline bend. The position represents a compromise between the development to be expected with only an ebb current and that expected with
In areas where the river width is not restricted, an entirely different pattern can develop. These tidal river reaches often have two rather independent channel systems: the ebb current concentrates in one set of channels while the flood current is often strongest in another set of channels. Flood channels are shallower than ebb channels; they tend to die out. Ebb discharge is bigger than flood discharge; ebb channels are deeper and more continuous. Long wave equations must be used to describe the time-dependent variation in water level. Maximum ebb discharge happens during lower tide levels. When the tide travels along the river, distortion of vertical tide curves causes greater maxima of the flood currents.

As we have seen, the tide strongly influences the morphology of a low river. Among the main problems are the density current influences. Methods to combat these are:
Decreasing the water depth and increasing the fresh water flow against salt intrusion;
Mixing of the two water layers or stimulating the heat transfer between layers, or
between water and atmosphere, against thermal density currents.

Density currents induce sedimentation problems. An important process is: optimization of
the dredging strategy. This is related to the shipping practice; after all, it is not always
economical to dredge away shoals along a river to sufficient depth so that all ships can
navigate at all tide stages. It may be possible to allow larger, deeper ships to wait at the
entrance for high tide and then to "ride" the tidal wave up the river. Unfortunately, the
ships of concern here are not able to attain a speed as high as that of the tidal wave. Thus,
interruption of their travel may be necessary. In order to determine the best strategy for a
pilot on a ship, it is necessary to predict the water depth at each shallow channel reach at the
time or arrival of the ship. To accomplish this the propagation velocity of the tidal wave
must be determined. Since friction tends to slow the tidal wave, Equation 6.10 includes a
friction factor.

\[ c = \sqrt{gh} \left( 1 - \tan^2 \theta \right) \]  \hspace{1cm} (6.10)

where:
\( h_{av} \) = average depth
\( \theta \) = friction factor computed from
\[ \theta = \frac{1}{2} \arctan \left( \frac{T^2 g V_{max}}{8 \pi^2 C^2 \hat{h}} \right) \]  \hspace{1cm} (6.11)

where:
\( C \) = Chézy friction factor
\( T' \) = tide period
\( V_{max} \) = maximum flood current

**Example**

A pilot needs to bring a ship needing a minimum channel depth of 11.5 meters up a 250 km
channel to a harbor. Three shoals are located along this channel as shown in Figure 6.12.
The depth over each of these shoals is only 11.0 m relative to the mean water level. The rest of the river is 13.0 m deep. The Chézy friction factor for this river is 60 m\(^{1/2}\)/s. The tide is semi-diurnal (period = 12.25 h) and is assumed to be sinusoidal. The tide range is 3 meters and the maximum current is 1.2 m/s. It is assumed that this tidal form is valid for the entire river reach. The tidal information is also shown in Figure 6.12. As an additional limitation, the ship must maintain a minimum speed of 5 ks (9.26 km/h) relative to the water. Her maximum speed is 8 ks (14.82 km/h).

First, determination of the speed of the flood tide wave through the channel is required. Using Equation 6.13:

\[
\theta = \frac{1}{2} \arctan \left[ \frac{12.42 + 3600}{6\pi^2} \times \frac{8 + 9.81}{60^2} \times \frac{1.20}{13} \right] = 28.33^\circ \tag{6.12}
\]

Thus, from equation 6.14:

\[
c = \sqrt{9.81 \times 13 \times (1 - \tan^2 28.33^\circ)} = 9.52 m/s = 34.2 km/h \tag{6.13}
\]

The position of the ship at any time can be accomplished by integration of its velocity with
maximum speed through the water. Their velocities with respect to the ground is integrated with time steps of one hour. To determine these, the tidal current at the ship's location at the end of each hour must be known. Since the horizontal and vertical tides are known only at the entrance, the assumption is made that the tide wave propagates along the channel at speed $c$ and is unchanged in amplitude and form. The depth and current at the ship can be obtained from the tidal curves by converting the distance between the ship and the crest of the tidal wave into an equivalent time. Thus, the time listed in the left hand column of the Table 6.1. is an absolute time, while the tide time listed in the first column for each ship is determined by this distance between ship and tide wave crest. Since all times are related to a single high water crest, the times can have values greater than one tide period. Obviously, adding or subtracting a multiple of the tide period to these times would not affect the result of the computation.

The first line of Table 6.1 is computed as follows: the start time is arbitrarily chosen as zero. Since the water depth over the first shoal must be 11.5 m, the corresponding tide level

### Table 6.1 Numerical integration in tabular form

In this table, two identical ships are considered, one moving at a minimum and one at maximum speed through the water. Their velocities with respect to the ground is integrated with time steps of one hour. To determine these, the tidal current at the ship's location at the end of each hour must be known. Since the horizontal and vertical tides are known only at the entrance, the assumption is made that the tide wave propagates along the channel at speed $c$ and is unchanged in amplitude and form. The depth and current at the ship can be obtained from the tidal curves by converting the distance between the ship and the crest of the tidal wave into an equivalent time. Thus, the time listed in the left hand column of the Table 6.1. is an absolute time, while the tide time listed in the first column for each ship is determined by this distance between ship and tide wave crest. Since all times are related to a single high water crest, the times can have values greater than one tide period. Obviously, adding or subtracting a multiple of the tide period to these times would not affect the result of the computation.

The first line of Table 6.1 is computed as follows: the start time is arbitrarily chosen as zero. Since the water depth over the first shoal must be 11.5 m, the corresponding tide level
must be +0.5 m. From Figure 6.12, this tide corresponds to a tide time of 3.8 hours. At this time, the current is +1.2 m/s, from the same figure. The time interval between the tide time and High Water is 6.21 - 3.8 = 2.41 h. With a tide wave speed of 34.2 km/h, the tide wave crest is located at -82.4 km at the time the ship crosses the first shoal. In each succeeding hour, the tide wave progresses 34.2 km. A typical line, for the time interval 16-17 hours goes as follows. At t = 16 h, the ship is at 151.0 km and the tide crest is at 464.8 km from the mouth. The tide phase in Figure 6.31 is then: (464.8 - 151.0)/34.2 + 6.21 = 15.4 hours. Entering Figure 6.31 with a time of 15.4 hours yields a tide level of -0.1 m and a current of +1.0 m/s. The tide level gives a depth of 12.9 m. The incremental distance for the ship in one hour is 1.0 m/s * 3.6 + 9.3 = 12.9 km, resulting in a distance after 17 hours of 163.9 km. The results of Table 6.1 can be visualized in a graph of position versus time. In Figure 6.13, the positions of ships and tide crest are shown, along with the positions of the three shoals. The time intervals during which the shoals can be crossed are also shown. Several interesting conclusions can be drawn from Figure 6.13:

1. Both ships must wait for the second tide to cross the third shoal. The extra speed of the fast ship makes no difference to the time needed to navigate the first 170 km of the estuary.
2. The slow ship could avoid stopping at all by delaying her departure a short time. This would (approximately) move the curve for this ship a bit to the right in Figure 6.13. The second shoal should still be cleared on the first tide and the ship would arrive late enough at the third shoal to navigate it easily as well.
3. Dredging away the third shoal would be nearly as effective as dredging out both the first

Figure 6.13  Distance-time curves for tide and ships
and the second shoals for improving the navigation.

4 Dredging only the outer bar would allow the fast ship to cross both the second and third shoals on the first tide.

5 Dredging of the second bar would not change the pilot strategy for either ship.

The choice, which shoals and bars to dredge and how deep to make the channel through them is a problem lending itself well to economic optimization techniques.
7 Practical problems and common methods how to solve them

7.1 Introduction

When dealing with coastal engineering problems, first of all, the boundaries of the considered system must be defined. As coastal systems in general are huge, this is an important step, which requires a lot of courage. Often, this choice of boundaries already defines the problem. However, engineers need a lot more courage and skill than that which is required for defining their problem.

A good coastal engineer knows where to get the right information. Sometimes it is available in the required form: in data bases; other times it is not. Then one must know how to measure and how to model. The next step in the process from problem to solution (or from nothing to something) is design and optimization. In order to simplify these steps, special techniques must be present in the engineer’s mind. After the design step, when action is required, a well-developed set of tools may be helpful. In many cases, as for example in the case of the Delta Works, we are talking about a whole fleet of special machines. The same tools may be needed during maintenance.

This chapter is dedicated to practical problems out of every sub-specialism in the coastal engineering field. Attention is paid to all aspects of the engineer’s work; methods, equipment, and numerical example problems & common solutions are described. Last, but not least!
7.2 Design under wave load conditions

7.2.1 Introduction

In offshore engineering, many disciplines are involved. Civil, mining, mechanical, electrical, naval and oceanographic engineers, all these have a place in offshore practice. The following types of constructions are discerned:

1. Fixed (gravity structures, jackets and jack-ups);
2. Anchored (ships, semi-submersibles, articulated platforms and buoys);
3. Free floating (dynamic positioning).

Offshore constructions are used for navigational aids, moorings, oil exploration, production and storage, pipelines, and construction equipment. Civil engineering aspects are: environmental loads, structural design, foundations, corrosion and fouling, pollution control, and construction. Specific offshore problems are the isolation of personnel, legal questions, and strategic defense questions. In this paragraph, attention is paid to the acquisition of wave data, and to wave load and optimum design techniques, which are needed in offshore practice.

7.2.2 Wave data

Wave data are obtained by hydrographic information centers. Government agencies accumulate data on waves and currents in areas under their jurisdiction. Weather services and hydrographic offices manage information on national scale. Local agencies (such as departments of public works) control measurements specially for a given project. Most of the information is published or available upon request; occasionally, some is secret. Major hydrographic offices manage wind, wave and current data from the whole world. The British Admiralty and the United States Naval Hydrographic Office have impressive collections.

If wave data are not directly available, in some cases a new measurement program can be started. However, the length of time which can be used is seldom sufficient. Simultaneous measurements as a part of a longer record, at a nearby location, can shorten the required measurement period. Different wave height meters are available. Some measure water-surface elevation directly with reference to a fixed staff, while others ride the waves and record the vertical water-surface acceleration. A third type measures pressure differences at some point in the water.

Wave predictions out of wind data are also useful. There is a semi-empirical wave forecasting method using three dimensionless equations, valid for deep water: the SMB
prediction method (detailed information in the CTwa5316 lecture notes). As wind blows across the sea, wave size increases with increased wind speed, fetch, and duration. As waves advance beyond the sea, they continue to advance across the ocean surface as swell, free waves that are not driven by the wind but sustained by the energy they obtained in the sea.

Wind itself can often be predicted from pressure gradients. Equilibrium between a pressure gradient, Coriolis and centripetal force yields a wind velocity. The computation is similar to that used for ocean currents.

7.2.3 Wave load and optimum design techniques

Wave load is correlated with water level. In order to determine the instantaneous water level, the average sea level is taken as a reference. Superposition of tide cycle, shower-oscillations, shower gusts, wind and wave raising yields the actual water level (without the effect of waves). Wave load is a statistical parameter. The strength or stability of a structure may be evaluated in the form of two types of problems.

In case of the first type of problem, one characterizes the waves by one parameter, such as the significant wave height $H_{sig}$. The construction is subjected, either in a physical or mathematical model, to the entire Rayleigh distribution (determined by the chosen parameter value). If the structure is tested in a physical model, the entire Rayleigh distribution of wave heights should be reproduced. If, on the other hand, a mathematical model is used, then the fact that our characteristic wave represents an entire population of waves is taken into account in the formula preparation. The probability of occurrence of the design parameter is produced directly by the long term wave height distribution.

In the second type of problem, the structure is designed using just a single wave, called design wave. The probability of exceedance of a given design wave height must be determined. Unfortunately, any certain wave height, no matter how high, has a certain, finite chance to be exceeded; some risk must be accepted. In many problems, it is sufficient to choose the height of one such design wave; the realization of the design wave would mean direct failure of the construction. For other problems, the number of extreme waves passing is important. An example is the determination of a channel depth as a function of the vertical ship motions. (This is a statistical optimization problem.)

The precise problem statement in the second problem type is: "What is the chance that a chosen design wave height, $H_d$, is exceeded one or more times during the life of a structure?". This chance is equal to the sum of the chances that $H_d$ is exceeded n times with n>1. This sum can be extremely difficult to evaluate. Possibilities have, per definition, the property that:
the chance something happens + the chance something doesn’t happen = 1

In other words: the chance that something does happen can be determined by evaluation of the chance that it does not happen.

Each occurring storm can be characterized by a given value of the significant wave height $H_{\text{sig}}$. This wave height characterizes a set of $N$ waves to which the structure is exposed during the storm. These $N$ waves are distributed according to a Rayleigh distribution.

![Rayleigh Distribution](image)

Figure 7.1 Rayleigh distribution

(Figure 7.1). It is assumed that significant wave heights obey a long-term frequency distribution such as shown in Figure 7.2.

The chance that a chosen design wave height $H_d$ is exceeded one or more times during the lifetime of a structure is:

$$p(H_d) = 1 - (1 - E_3)^M_l$$  \hspace{1cm} (7.1)

where:

$P(H_d)$ = chance that a $H_d$ is exceeded

$E_3$ = chance that $H_d$ is exceeded at least once in a single storm period

$M_l$ = number of possible storms in the structure's lifetime
In order to calculate this chance, one needs a computer. In order to see the derivation of this formula, one needs the lecture notes of the subject CTwa5310. The inverse problem is: what wave height $H_d$ occurs with a given chance of being exceeded during the given life time of the structure? This problem can only be solved by trial and error (iterations).

Another important question is: What is the chance of exceedance of the maximum wave height occurring in a certain storm? Two approaches are possible: determining $H_d$ in a particular storm (having a given chance of exceedance) and: determining the most probable maximum wave height in the chosen design storm.

In general, a project risk analysis must be made. Elements of the project are:

1 Alternative solutions;
2 Construction costs;
3 Chance of damage or failure;
4 Losses resulting from damage or failure.

Figure 7.2 Long-term frequency distribution (Weibull distribution)

The optimum is:

\[
\text{lowest total cost} = \text{sum of construction} + \text{capitalized damage}
\]

In this sum, both direct and indirect costs must be counted. Boundary conditions could be
The prime question is: "What is the most responsible risk to assume?" The project suitable for optimum design technique must satisfy certain criteria:

1. There must be alternative solutions available. For example: similar structures which vary in some detail such as size or strength;
2. Assessment of construction costs of each project alternative;
3. The chance of damage or failure of each alternative must be known;
4. The economic loss resulting from damage or failure of the construction must be determinable.

In terms of decision making, item 4 is the most difficult, generally speaking. The technical consequences of failure are reasonably easy to evaluate, but the social, environmental and aesthetic consequences usually are much more difficult to express in amounts of money. The technique to do so is developing. However, assuming that the necessary costs can be expressed in economic units, the optimization procedure is described below.

Design optimization proceeds from four steps.

1. A design from the available alternatives is chosen;
2. For this design, the total capital investment involved in construction is determined in convenient unit such as current money value;
3. By multiplying the chances of damage or failure by the economic consequences of such damage, the current capitalized monetary value of total damage to be expected during life time of the project can be obtained;
4. For every alternative such a computation must be made. The optimum design is the design with the lowest sum of construction plus capitalized damage costs.

Damage costs include direct and indirect costs: reparation, replacement, interruption of production or loss of human lives are involved. If the amount of capital is limited, the optimum design might not be feasible. Decision making gets more difficult then. Also capitalization is a long story, using the principle of cash flow and so on. Design codes might lead to so-called over-design of structures.
7.3 Breakwaters

Protection by breakwaters can be provided to make dredging operations more efficient or to reduce the amount of dredging necessary. Next to that, breakwaters can have other functions such as providing quay facilities for ships. However, the main functions are those which make breakwaters cost-effective. For management, the optimum depth of the approach channel is an important parameter. Another is the form of the harbor by building the breakwaters. If the harbor form is changed, its dynamic water behavior changes; the natural resonant period of standing waves could be modified by building breakwaters. If the new resonant period should happen to correspond with that of a tidal component, (a multiple of) a persistent ocean swell or a gust oscillation, then some significant problems can be expected in the harbor (seiches).

Reduction of wave action could make it possible to use more efficient equipment for the dredging operation. Blocking the longshore transport of sand is done by extending breakwaters through the breaker zone. The effect of that can be reduction of the amount of necessary maintenance dredging. However, man must be careful to interrupt the longshore transport; material which once simply passed along the coast will now pile up against the breakwater; erosion can be expected on the opposite side of the approach channel.

When there is a large sediment supply from a natural river flowing through the harbor, then a shoal can often be expected slightly offshore from the river mouth. Such a shoal can also be formed after the accretion has reached the end of the breakwater and material passes around the end. This shoal can form a major obstacle for shipping, especially during a severe storm when waves can be breaking on this shoal. Many ships have been wrecked attempting to cross such a bar under these circumstances. Breakwaters built out in such a way that the entrance is kept narrow until deeper water is reached increase the entrance current velocities; the resulting increased sediment transport capacity tends to keep the entrance open. A new equilibrium between sediment transport rate and bottom position is reached in both river (upstream) and offshore (downstream). The slope must therefore slightly decrease, since the river has in effect been made longer by building the breakwaters. Inland from the entrance, a siltation problem can appear. At least, this material can be dredged out under excellent circumstances—no wave action and often less shipping traffic.

A special type of breakwater is a jetty. A jetty (Figure 7.3) should extend at least through the breaker zone, even after storms and accretion has taken place. Material transported along the coast will accumulate against the jetty on the up-drift side, opposite the channel (Figure 7.4). A jetty has a local function, usually the defense of a harbor entrance against accretion.
Figure 7.3  Jetties in IJmuiden (Kustlijnkaart 56, situation 1996, RIKZ)

Figure 7.4  Accretion next to jetties in IJmuiden (RWS 1990)
7.4 Shore protection

7.4.1 Introduction

Natural processes like erosion or accretion sometimes do not agree with the wishes of man. A brief summary of shore protection methods is given here; detailed information on functional and structural design of a protection method can be found in the Shore Protection Manual/Technical Guide. In Figure 7.5, an overview is given of the different levels where coastal erosion works. Measures against erosion of the shore can be designed on the same different levels. They differ in construction scale and in scale of effect.

Often, erosion or accretion problems are localized along one coast section. Eroding shores tend to be relatively steep for the material from which they are composed. The opposite is true for shores where accretion is the dominant process. If the longshore transport is the cause for structural erosion or accretion, this transport should be influenced by the applicable measures (for example groynes). Measures based on changing the cross transport (for example) differ in their effect from measures based on longshore transport change. Special types of measures are beach nourishment (negative dredging) and artificial bypassing of sand.

In Figure 7.6, an upper view is given of an eroding coast section. In this case, it is thought
to be caused by a long-shore sediment transport gradient. The transport is getting bigger when going downstream (to the right). Therefore, the shore is eroding. The right coastal defense measure would be the one which restores the long-shore transport distribution to line number (3). The other lines represent non-stable situations; (2) means only partial reduction of erosion, where (4) gives accretion of the shore.

Figure 7.6   Eroding coast section

Note well: all solutions influencing the long-shore transport do only work out positively for the coastal section itself. In fact the erosion problem is displaced downstream. The next section suffers in any case from growing gradients which mean growing erosion. The stronger the measure, the bigger the problem for the neighbour section.
Unlike jetties, a set of groynes tends to stabilize the entire coastal section. They are a series of smaller jetties spaced at relatively short intervals along a coast. A spacing equal to a few times the length of the groynes is common (like in The Hague, Figure 7.7). The purpose of groynes is to reduce the longshore sediment transport so that the desired situation is caused. Proper design implies that the correct choices for groyne length, spacing, height and possibly even permeability to sand have been made. The physics of a groyne system is not completely understood, making the successful design of a groyne system more an art than a science. Still, groyne systems often prove to be very effective for influencing longshore sediment transport.

Long groynes extending through the breaker zone tend to block the sand transport, which causes erosion on one side and accretion on the other side of the groyne coast. If for such a solution only a small portion of the sand transport has to be stopped, the groynes should be short - shorter than the width of the breaker zone. A special groyne type is a row of piles purposely spaced so as to make a porous barrier thus reducing but not totally blocking the longshore sand transport (Figure 7.8).
The consequence of a set of groynes is a coast line in the form of saw teeth, see Figure 7.9. The angle which the shoreline develops depends on the angle(s) in which the waves are approaching the shore. This correlation is illustrated in Figure 7.10.
7.4.3 Dune protection

Neither a jetty nor a set of groynes does anything to prevent material transport perpendicular to the coast. This was dramatically demonstrated late in 1973 when several severe northwest storms caused a significant coastal erosion near Scheveningen. This was an example of offshore transport. It can result in too severe a (temporary) beach erosion.

![Diagram](image)

Figure 7.11 Storm dune-erosion

(Figure 7.11), so that beach or dunes must be reinforced (Figure 7.12).
Dunes can be protected by making the beach profile more like the equilibrium storm profile. The easiest way to accomplish beach reinforcement is to increase the sand volume in the higher portions of the shore. Making a row of dunes wider rather than higher requires less sand to provide a given degree of protection. Even simply moving sand from the foreshore to the higher part of the beach can be effective. The offshore erosion will take place more slowly then.
Detached breakwaters (Figure 7.13) do not block the longshore transport, but they suffer from foundation problems, like seawalls (Figure 7.14). Detached breakwaters can stimulate tombolo development (Figure 7.15). However, the reduction of the cross transport works in both directions; therefore their effect could make the situation worse than it was without measures.
Before a seawall, the increased turbulence due to reflection of waves stimulates the erosion of a deep trench (Figure 7.16). Its stability must be guaranteed by maintaining enough sand at the seaside; therefore the measure sometimes is contra-productive.

7.4.5 Artificial by-passing and beach nourishment

If the distance between the accretion and erosion area is not too big, artificial by-passing operations may be economical. A dredge or a pipeline on a suction dredge may be used.
Occasionally, it can be built on a fixed platform in the accretion area.

Another form of flexible measures against erosion is beach nourishment. Sand is put into the beach profile. As cross transport gives a helping hand, the sand can be put into the cross profile in more than one place (Figure 7.17).

![Nourishment](image)

Figure 7.17 Different types of beach nourishment depending on the position in the cross profile (RWS, Beach Nourishment Manual 1988)

### 7.4.6 Coast-line dynamics

Determination of a coast line must be done by measurements of the coast line positions in different rays. The coast exists in a horizontal plane only. As a measurement level for the composition of coast position points, either the dune-toe line, or the average low water level or the average high water level is used.

Short-term fluctuations and long-term developments must be discriminated (Figure 7.18). Long-term means: centuries; middle-long-term means: 10-100 years; short-term: up till 10 years. Natural processes can have a long-term character. Generally speaking, human interference effects have their own time scale: the period in which they are caused. The bigger the time-scale, the bigger the space scale. A special type of periodical changes are sand waves.
In order to discriminate between different process periods, different techniques of analysis are used. For example: filtering (short-term fluctuations are taken out). Linear regression analysis is useful for linear coast developments. A long measurement series is needed, and the possibility of discontinuities must be taken into consideration. Verification must be done using meteorological data. Analysis of whole coast sections might give the best results, unless the behavior is too complex.

Prediction of the coast line position is based on extrapolation of the regression line. Effects of periodical developments are studied; also sand wave effects are part of a prediction.
When taking a measure against beach erosion, it is important to make a good estimation of the beach response. The quantitative aspect is the most difficult. If the longshore transport is the cause for an erosion trend, it is possible to use the CERC formula (derived by the Coastal Engineering Research Center). This formula is based on the assumption, that the longshore current and transport are driven exclusively by the incident waves. The CERC formula expresses the longshore transport in the surf zone as a function of the wave height, wave speed, and the angle of incidence of the waves. If the depth contours in the area are parallel, then the CERC formula is:

\[ S = 0.020(H_{\text{sig}})^2 c_o \sin \phi_{br} \cos \phi_o \]  

(7.2)

where:
- \( c_o \) = wave speed in deep water
- \( \phi_o \) = angle of incident waves with depth contours in deep water
- \( \phi_{br} \) = angle of incident waves at the outer edge of the breaker zone
- \( H_{\text{sig}} \) = significant wave height

The CERC formula is a rough estimation. It ignores many parameters, which could be important, like:
1 Other driving forces for the longshore transport;
2 Sand properties like grain size and density;
3 Sand transport distribution over the breaker zone (the CERC formula gives the total transport only).

A very important question is: When is the sand transport zero? Two possible answers:

1 The angle of wave incidence on deep water = 90° (perpendicular approach);
2 The groynes totally block the breaker zone transport. In this case, in the stable situation: angle of accretion next to the groyne = angle of wave incidence. The CERC formula shows the saw teeth pattern in the case of a groyne-defended coast as is shown in Figure 7.9.
7.5 Harbors and dredging

7.5.1 History

Provision of safe harbors for ships has got a long history. The type of disturbing influences changed as well as the size of ships. Inventions like the ship camel and dredging generated new possibilities for harbor design. Migration of the harbor activities towards the shoreline is still taking place. Offshore locations become more and more important.

Originally, harbors were built at locations where both good hinterland connections and protection from the evils of the sea were naturally available. These evils of the sea include both natural (waves and currents) and human enemies (pirates). Since settlements developed around the harbors, sites were usually inland, at least far enough to assure dry land. Harbors sometimes developed well along rivers or estuaries. New Orleans, for example, is more than 100 km up the Mississippi River from its mouth.

Since ships were small some hundreds of years ago, their shallow draft allowed them to navigate easily over and around the numerous shoals found in these natural water courses. This meant, even so, that local knowledge of the waterway was needed. Was this a disadvantage or an advantage for shipping? The use of pilots did hinder commerce somewhat, but it hindered pirates even more!

As time passed, and ships became larger and deeper, the difficulties with shoals increased. The use of pilots became more common; they knew the deepest channels. Inventive people even developed strange-seeming devices to reduce the draft of ships. One of the successful

Figure 7.20 Ship camel
devices, a ship camel, was designed and used to help ships cross the bar near the island of Pampus as they approached the port of Amsterdam. In Figure 7.20, such a camel is shown schematically. This was really the predecessor of the floating dry-dock.

More than 100 years ago people started deepening shallow areas artificially by means of underwater excavation (dredging). Sometimes even whole new channels were excavated, as has been done in Amsterdam (North Sea Canal) and Rotterdam (Rotterdam Waterway). As ships became even larger, the required dredging to open and maintain such channels over a long distance has become a formidable economic burden. Next to that, the long sailing distance through such channels by the modern very large oil tankers presents a hazard to navigation and to people living close to it. Moreover, as ships carry higher value cargo such as containers, the time lost in navigating along a channel has an increasing economic impact (in general, goods move faster over land than over water). These factors, along with the decreasing pirates threat have led to expansion of the harbors nearer to the shoreline (Maasvlakte). Often, artificially filled land is used.

7.5.2 Soil type

Dredging companies have to earn their own work, before they can start. For example, if a new harbor is being built, for which a lot of dredging is required, the dredging job is put out to tender. An interested dredging company has to make a good estimate of the whole dredging process, before it can accept the work. This estimating is a difficult thing to do. After a few soil samples, one must decide what the quality of the whole product is going to be. In an early stage of the communication between dredging company and principals, the question must be asked: "What is the soil type?"
As one can imagine, the soil type can make a tremendous difference in the working speed and the costs of the dredging process. Possible soil types are: rock, sand, clay, silt. Apart from that, working conditions can influence this choice. Dredging equipment should be chosen according to the situation. Main engineering projects, where dredging is inevitable,

Figure 7.21  Sand supply for road construction

are:

1  Harbor construction and maintenance;
2  Putting a pipeline into a trench;
3  Artificial land winning;
4  Polluted soil dredging and storage.

Every type of project needs its own specific treatment. In this paragraph, some of the terminology and production processes in the dredging world are described. This is done using these four common types of projects 1-4. So if one gets close to dredging work in later life, one has an idea what happens on the other end of the soil pipe which sometimes can be seen coming onshore (Figure 7.21).

7.5.3 Harbor dredging

Distinction is made between dredging for maintenance and for new work. In general, harbor maintenance dredging is a returning business. The soil often consists of silt or sand. The lack of cohesion often is a characteristic. Under normal conditions, a plain suction dredger (Figure 7.22) can be used. However, sometimes a special combination of fine sand and silt
is more difficult to cut. Then, a cutter suction (Figure 7.23) or a bucket dredger (Figure 7.24) is needed. Under more severe wave conditions, a seagoing type must be used. Often a hopper dredger (Figure 7.25) can do the job.

A relatively new type of dredger is the water injection dredger (Figure 7.26). It makes use of the difference in density between a mixture of soil and water and water. It injects a jet of water into the soil over a large width, which changes into a density current. This density current moves into deeper places, for example out of the harbor.
Figure 7.23  Cutter suction dredger

Figure 7.24  Bucket dredger
Dredging a gully or the harbor itself is called capital dredging. The soil often is consolidated. Sometimes it is rock. A cutter dredger is often seen. Explosives can be used in combination with a hopper dredger, too.
7.5.4 Pipeline into trench

A pipeline going into a trench requires a combination of activities, often far offshore. If the soil consists of sand, the flow-dredging method (Figure 7.27) can be used. Trailing suction hopper dredgers or water injection dredgers can be used in such a way, that the seabed material is eroded from the work surface in a controlled manner by a large volume of water flow. This water flow is generated several metres above the seabed, which enables accurate and safe excavation near pipelines or structures.
A handy help can be a so-called trencher. Such a thing is shown in Figure 7.28. In Figure 7.29, the special equipment of a trencher is clarified.
7.5.5 Artificial land winning

Artificial land winning can be huge-sized. Examples are: Maasvlakte in the Netherlands, airport Hongkong, Singapore harbor. For such large projects, a fast, not to precise way of dredging is required. A hopper dredger is often used.

7.5.6 Polluted soil dredging

Polluted soil dredging and storage puts strict requirements to the accuracy of the dredging process. It should happen without any spills, the water should not get muddy, and there should not be put too much water into the pumped mixture of polluted soil and water. Suitable techniques can be: the use of wormwielzuiger (Figure 7.30) or bodemschijfcutter (Figure 7.31).

Special attention must be paid to the transport of polluted soil. The hydraulic method, using pipeline and pump, can be used only when the mixture of soil and water contains enough water. Usually this is not the case when the soil is polluted. The alternative is the use of barges or hopper dredgers.

In Figure 7.32, chemical processes during sediment discharge (possibly affecting the environment) are shown.
Figure 7.30  Wormwielzuiger

Figure 7.31  Bodemschijfcutter
Figure 7.32  Chemical processes during sediment discharge
7.6 Map reading

Did you ever lose your way? If you did, did you ask for it to someone else? Some people have enormous stamina against asking their way to someone. It is commonly thought that especially men rather walk around the earth before asking where they are. Women are generally supposed to be more flexible in that matter!

In this paragraph, some example situations are given where orientation on a map plays an important role. In Figure 7.33, part of a map shows of a coast section near Plymouth, England. The coast formation called "A" in the figure, can that be spit, and why? Such a map is an inexhaustible source of examination questions. In Figure 7.34, another part of it is shown. Take two different locations in river "B", one up- and one downstream. What would be the main difference between the two?

Here follow answers to the questions. Map 7.33 shows no spit. In case of spit, the longshore transport causing the coastal formation must be driven by waves incident under an angle. In this case, and angle is not there. This can be derived from the depth lines close to High Pine Ledge. They would follow the same angle as the incident waves.

The main difference between two river locations is found in their tidal curves. The farther upstream, the smaller the tidal prism, and therefore the horizontal tide will be smaller, too.

In Figure 7.35, a Dutch map is shown which is used for shipping purposes. What do the numbers mean exactly? Which depths are meant, and what is the reference level? Note that the reference level is not the least of a horizontal plane!
Figure 7.33  Coast section near Plymouth (1)
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