Chapter 1

Introduction

1.1. What is this Book About?

Why are coasts the way they are?

Why are coasts the way they are: Multiform, infinitely complex, quasi-fractal, always changing and unpredictable in many aspects. But also: Why have coasts so many features in common? Any answer to these questions should be based on the universal nature of fundamental physical laws. This approach is known as ‘coastal morphodynamics’.

This book is about the physical processes that shape sedimentary coastal landscapes. It introduces the reader to the physical-mathematical concepts developed during the past decades to explain the underlying basic principles. Most of the coastal landscape is under water, so landscape is a confusing word; we will use the term morphology instead.

Coastal morphology is shaped essentially by the action of waves and currents, with often an important role of the tide. This looks as an obvious statement, but it raises a puzzling question. Coastal morphology exhibits in general a great richness of structures at many scales, from very small to very large. This strongly contrasts with the comparatively poor spatial variability of waves, tides and wind-driven currents. One of the central themes of this book is to provide clues for explaining this apparent contradiction.

Sediment in motion

Coastal zones are among the most dynamic and energetic environments on earth, as stated in many articles or textbooks on coastal processes. Waves, currents and tides are the very visible expression of this dynamic nature. Acting on the shore and the seabed, the motion of the sea causes erosion and transport

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of seabed material. In the coastal zone, large quantities of sedimentary particles are perpetually in motion. In the Dutch coastal waters, for instance, the average quantity of sediment in motion at any moment is comparable to the net annual volume of coastal erosion (a few million cubic metres). The magnitude and direction of this sediment transport depend on waves, currents and tides, which are driven by external forces such as incoming waves, incoming tides and wind.

The coastal zone is characterised by the interdependence of water motion and seabed morphology

A crucial notion is that waves, currents, tides and sediment transport do not depend only on external forces, but also on the local topography and composition of the seabed. Hence, the magnitude and direction of sediment transport is not the same at different places in the coastal zone. At some places there will be erosion and at other places there will be deposition of sediment. As a result, seabed and shoreline are continuously changing: Changing position, changing form and changing composition. This change, in turn, affects waves, currents and tides. In other words: Coastal morphology and water motion evolve in an interdependent way. Sedimentary coastal environments are characterised by the continuous mutual adaptation of coastal morphology and water motion. Coastal systems in this book are defined by:

- water motion is substantially influenced by oceanic conditions;
- water motion and seabed topography are interdependent.

Typical coastal systems corresponding to this definition are sketched in Figs. 1.1 and 1.3.

Analogy with traffic

The interaction between water motion and seabed topography bears some analogy with the mutual dependency of car speed and car density on a highway. Variations in the traffic density along a highway are caused by speed differences; the traffic density increases where fast cars catch up slower cars. But there is also an inverse relationship because the traffic density influences how fast you drive your car. Variations in traffic density along the highway cause variations

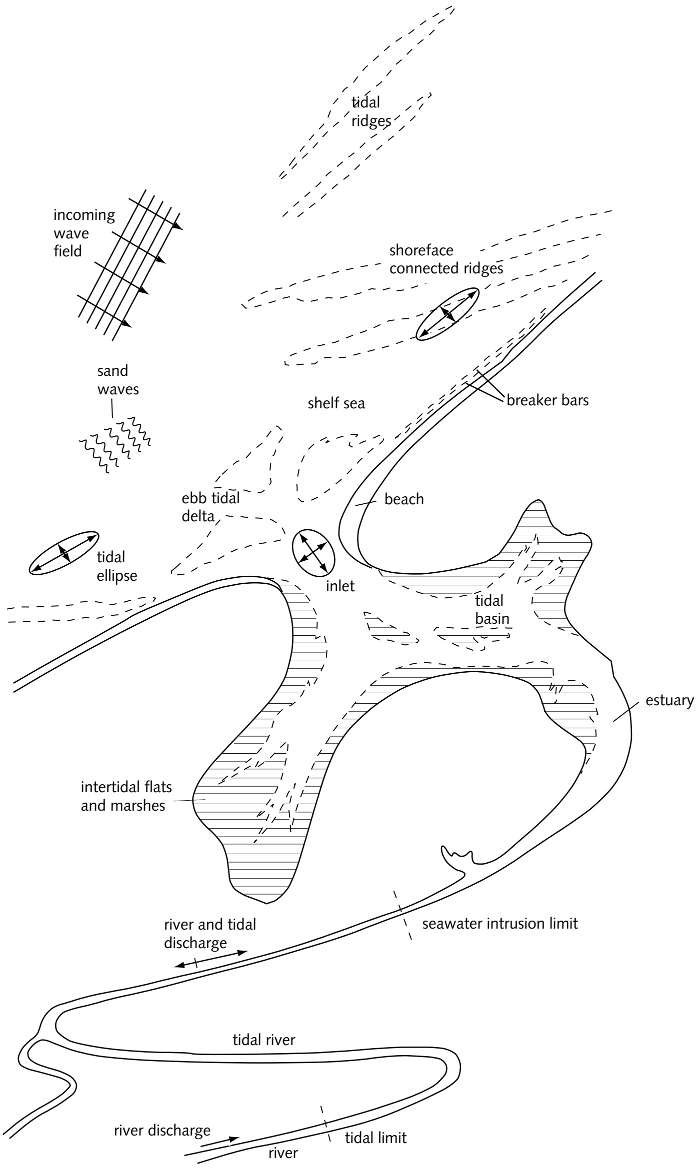

Fig. 1.1. The coastline may ingress far inland. The systems sketched in the figure are characteristic for low-lying coastal plains. The morphology of these coastal systems and the offshore seabed morphology mainly result from nonlinear interaction with water motion. The figure presents several features of the coastal environment and the corresponding terms used in this book.

in car speed and variations in car speed along the highway cause variations in traffic density. Hence, both evolve continuously in a mutually dependent way. If traffic density and speed differences are high, this mutual dependency leads to traffic jams caused by 'spontaneous' amplification of density peaks.

Scale dependency of erosion and sedimentation

At small spatial scales seabed morphology and water motion adapt to each other in a short delay, but at large spatial scales the adaptation period can be very long. If erosion and sedimentation are in balance averaged over large temporal and spatial scales it may happen that there is an imbalance at smaller scales or vice versa. In fact, the phenomena erosion, sedimentation and sediment transport always have to be defined with respect to particular spatial and temporal scales. In general we will choose these scales larger than the scales of turbulent motion and smaller than the time scale of sea-level rise. This last time scale is in the order of thousand years; during the past thousand years the sea level has risen about one metre. If necessary, a more precise definition of the spatial and temporal scales is given in the text.

Stability of a morphologic equilibrium

Suppose a situation where erosion and sedimentation are in balance; such a situation is known as a morphologic equilibrium. What happens if this morphologic equilibrium is disturbed, for instance, by an additional sedimentary deposit? There are several possibilities. The sediment may be dispersed and the deposit may disappear after some time; in that case the equilibrium is stable. The additional sedimentary deposit may also remain unaffected; in that case the equilibrium is called marginally stable. The third possibility is that the deposit starts to grow. In this last case the equilibrium is unstable.

Formation of morphologic features

The last possibility seems counter-intuitive if we agree that the added sediment does not possess any special attractive force. What makes the deposit grow? There is no unique answer to this question; it will be shown later that different processes may play a role. All these processes have in common that the flow perturbation produced by the sedimentary deposit affects the existing sediment motion in such a way that sediment converges at the deposit. This phenomenon is contained mathematically in the nonlinearity of the equations describing water motion and sediment transport. However, the underlying principles are more general and also play a role in other systems with nonlinear feedback processes, such as the earlier mentioned occurrence of traffic jams on a highway. In Chapter 2 it will be shown that these basic principles can be captured in the concept of symmetry breaking, which is inherent to the nonlinear nature of the interaction between seabed morphology and water motion [325]. The concept of symmetry breaking applies to the emergence and evolution of most morphologic structures in sedimentary coastal environments, from ripples to sandbanks, from creeks to tidal inlets.

Time scale of coastal morphodynamics

We have mentioned above that the physics of sedimentary coastal environments is related to temporal and spatial scales. The physical processes that determine coastal morphology span a range of temporal scales covering more than ten

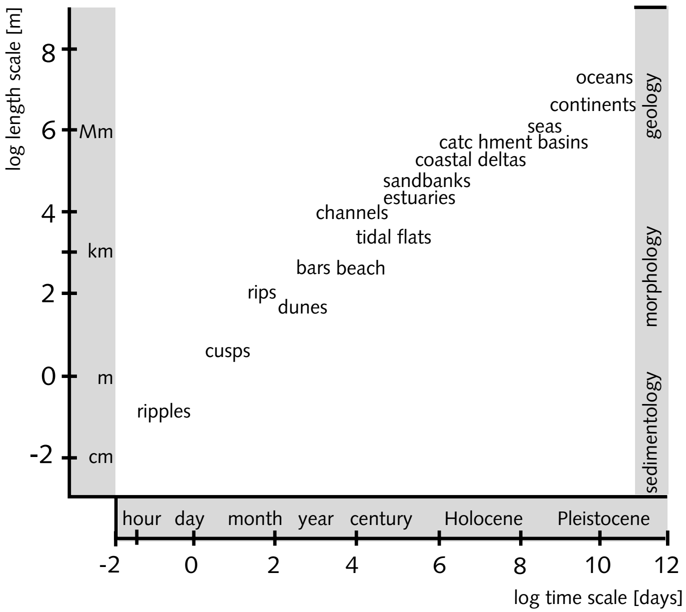

Fig. 1.2. Geomorphologic patterns in coastal systems span a very large range of space and time scales. Space and time scales are closely related. Adapted from [208].

orders of magnitude, see Fig. 1.2. At the lower end of this range we will not discuss processes at time scales smaller than the time scale of turbulence; this time scale is typically between one second and a few hours, depending on the type of flow. For these processes we will adopt empirical parametric descriptions. At the upper end we will limit the discussion to the time scale of substantial sea level change, which is in the order of ten thousand years. This excludes long-term geological processes, such as plate tectonics and glacial cycles, which are responsible for the global distribution of coastal environments. We will not try to answer the question why certain types of coastal systems are where they are; we accept inherited large-scale characteristics, such as the width of the continental shelf, the seabed composition and the external hydrodynamic forcing by waves, wind and tides.

Spatial scales of coastal morphodynamics

The restriction on the range of time scales is equivalent to a restriction on the range of morphologic scales. The temporal scale T_m and the spatial scales L_m (length), Z_m (depth) are related by

$$q_m = Z_m L_m / T_m, \tag{1.1}$$

where q_m is a measure of the magnitude of residual sediment fluxes (expressed as a volume per unit width and unit time). From the examples discussed later we will see that typical values are in the order of

$$q_m \approx 10^{-6} - 10^{-5} \quad \mathrm{m}^2/\mathrm{s}, \tag{1.2}$$

in the case of sufficient sediment supply and sufficient current strength. This estimate holds for coastal systems with a bed of mobile sediment and with near-bottom flow that substantially exceeds the threshold for incipient sediment motion. Taking $T_m \leq 10^4$ years and $Z_m \approx 10\,\mathrm{m}$ as a typical estimate for the vertical scale, we find $L_m \leq 100\,\mathrm{km}$. According to (1.1), this is also an estimate of the largest spatial scale at which coastal morphology can adapt to sea-level rise ($Z_m \approx 1\,\mathrm{m}$ during the past $T_m = 1000$ years). Therefore we may expect that, under conditions where (1.2) holds, the large-scale morphology of natural coastal systems at spatial scales in the order of tens of kilometres will not be far from equilibrium. Examples of such coastal systems are sketched in the Figs. 1.1 and 1.3.

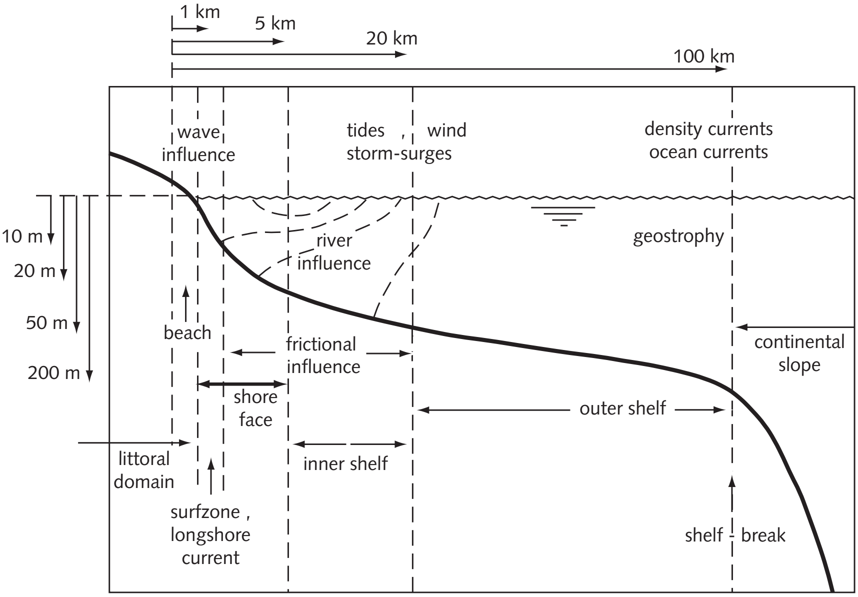

Fig. 1.3. The coastal zone is a continuum from beach to shelf break. Different zones can be distinguished related to prevailing hydrodynamic processes and external forces; these zones correspond to characteristic depth ranges, but the transitions are gradual. The intensity of bed-flow interaction increases from the outer shelf to the beach. At the time scale of sea-level rise the concept of morphodynamic equilibrium only applies to the beach-shoreface zone.

1.2. Why this Book?

Breakthrough in understanding

Our understanding of coastal morphology has made spectacular progress during the past decades. The productivity of coastal research has benefited from technical innovation: Refined observation techniques and increased computing power. But a major key to this progress is conceptual innovation: Relating coastal morphology to symmetry-breaking properties of the nonlinear feedback with water motion. Time-symmetric sinusoidal forcing of the water motion yields a morphology-dependent time-asymmetric response; a uniform equilibrium morphology may under certain conditions become unstable and evolve spontaneously into a spatially modulated morphology. This approach allows a unifying description of land-sea interaction and therefore runs as a leading thread through this book.

A laboratory of stereotypical idealised coastal settings

The basic mechanisms of symmetry breaking can best be illustrated for stereotypical idealised settings in which particular processes are singled out and most of real-life complexity is ignored. This artificial reduction of complexity makes the physics easier to understand; it cannot claim, however, to provide accurate predictions in real-life situations and entails the risk that the true complexity of the coastal environment is underexposed.

Stereotypical idealised settings that will be discussed include steady unbounded flow over a flat seabed, steady unbounded flow over a sloping seabed, unbounded oscillating flow over a flat seabed, tidal flow in a basin with uniform geometry, and tidal flow in a basin with exponentially converging geometry. Qualitative descriptions of the symmetry-breaking feedback mechanism are presented, followed by a mathematical description. This last part can be skipped by the less mathematically inclined readers, although some features only appear through the mathematics. The mathematical analysis of spatial symmetry breaking is based on linear stability analysis. This imposes a major restriction: Only the initial emergence of morphologic patterns can be described in this way and not the evolution towards fully developed patterns.

Important contributions to the discipline

The great progress in physical coastal science of the past fifty years is related to the economic expansion after WWII, which led to major investments in coastal and harbour development. It was soon recognised that the coastal zone is a dynamic environment which may respond to interventions in an unexpected way. In many countries research laboratories have been established or expanded in order to develop better knowledge of coastal behaviour. This book highlights essential discoveries made by these research groups and puts them within a coherent framework. It does not attempt, however, to review all scientific developments; more complete reviews can be found in other recent textbooks [259, 496, 102, 304]. The approach of this book is closer to the symposium volume 'River, Coastal and Estuarine Morphodynamics' [399], edited by Seminara and Blondeaux (2001), with many excellent review articles. The editors rightly mention R. A. Bagnold [19] and F. Engelund [138] as the leading pioneers of sediment transport mechanics. Their work has led to important breakthroughs in understanding sedimentary processes in both the fluvial and the coastal environment. Due to the many similarities between the two fields, river research has strongly stimulated progress in coastal morphodynamics. Important generic insight has been gained from research on the formation of ripples, dunes, bars and meanders in rivers, with leading contributors such as L. B. Leopold [274], J. F. Kennedy [252], M. S. Yalin [501], W. H. Graf [177], G. Parker [343] and S. Ikeda [228].

Sediment transport mechanics

The Danish school of river and coastal morphodynamics founded by F. Engelund, with leading scientists as J. Fredsøe and R. Deigaard [157], has greatly contributed to the development of a theoretical framework for sediment transport mechanics and bed-flow interaction. Important insight in coastal zone wave dynamics and its influence on sediment transport is due to M. S. Longuet-Higgins (1953) [287] and later works of J. Battjes [24] on wave-breaking processes. Major contributions to the practical description of sediment transport in the coastal zone were made by E. Bijker (1967) [35], L. van Rijn [472], D. Huntley [224], R. Soulsby [418], P. Nielsen [326] and others. Our knowledge of the behaviour of cohesive sediments was greatly advanced by the pioneering experimental work of R. B. Krone [262] and A. J. Mehta [312].

Beach processes

The introduction of the equilibrium profile concept (Fig. 1.3) was a crucial step in coastal morphodynamics. It was first proposed a century ago [85, 86, 243], but in 1954 P. Bruun highlighted the implications of this concept for predicting long-term coastal evolution [56]; the theoretical foundation of this concept was advanced further by R. G. Dean (1973) [98] and A. J. Bowen (1980) [49]. The first comprehensive description of beach processes was made by L. D. Wright and A. D. Short (1984) [499], members of a very productive Australian coastal science community including other leading scientists such as R. W. G. Carter [67] and C. D. Woodroffe [495]. After first exploratory work by M. Hino in 1974 [201], the Catalan research group of A. Falqués and coworkers managed to unravel the basic mechanisms responsible for longshore surf zone instability [143]. The observational basis of this work was laid by R. Holman [208], who developed the ARGUS-camera technique and initiated the establishment of a worldwide network of observation sites.

Seabed structures

The coastal environment is characterised by a broad spectrum of seabed structures; sand ripples are at the small-scale end of this spectrum and tidal sandbanks at the large-scale end. The mechanics of ripple formation has long been one of the most challenging coastal phenomena: the basic mechanisms were first described in detail by J. R. L. Allen [2] and J. F. A. Sleath [410] and later simulated with process-based analytical models developed by the Genua morphodynamics school of P. Blondeaux and coworkers [44]. Important field investigations of tidal and nontidal sandbanks have been conducted by the research groups of T. Off [336], J. J. H. C. Houbolt [212], J. H. J. Terwindt [438], I. N. McCave [306], D. J. P. Swift [433], B. A. O'Connor [331] and others. The mechanics of tidal sandbanks were first described by J. D. Smith [414], J. T. F. Zimmerman [510] and J. M. Huthnance [226, 227].

Tidal morphodynamics

The first morphodynamic description of tidal basins was presented by J. van Veen (1950) [476]. This description was corroborated and extended with observational evidence on depositional processes in the estuarine environment by the research groups of G. P. Allen [5], R. W. Dalrymple [91], J. S. Pethick [348], C. L. Amos [8] and others. The essential role of tidal asymmetry and its morphological consequences was first recognised in 1954 by H. Postma [354]. Generation mechanisms of tidal asymmetry were first studied by P. H. LeBlond [271], D. Prandle [358] and D. G. Aubrey [16]; the relationship with estuarine morphology was further explored by C. T. Friedrichs [161], D. A. Jay [238], G. Seminara [401], S. Lanzoni [269] and others. Important steps towards process-based models of the full coastal system, including tidal basins and the adjacent shoreline, were realised within the Netherlands Centre for Coastal Research, with major contributions by H. De Vriend, M. J. F. Stive and D. J. A. Roelvink [424].

A complementary approach

This short overview of important contributions to our present understanding of sea-land interaction is far from complete. No existing textbook covers the entire field. The classical textbook on coastal sedimentary processes is K. Dyer's 'Coastal and Estuarine Sediment Dynamics' (1986) [123]. Recent important textbooks are ‘Beach Processes and Sedimentation’ by P. D. Komar (1998) [259], ‘Coasts’ by C. D. Woodroffe (2002) [496], ‘Coastal Processes’ by R. G. Dean and A. Dalrymple [102] and ‘Introduction to Coastal Processes and Geomorphology’ by G. Masselink and M. Hughes (2002) [304]. The present book complements these recent overviews by its focus on the basic physical principles underlying sea-land interaction.

1.3. Who is this Book Intended for?

Sustainable coastal management

Coastal zones directly support a growing part of the world population [412]. Highest densities of urbanisation are found in sedimentary coastal plains, which have been shaped by land-sea interaction. This interaction has not ceased, and coastal morphology continues to evolve. Coastal evolution can be frozen, locally and temporarily, by engineering interventions. But the large-scale evolution can hardly be stopped. Artificial constraints may even speed up coastal evolution instead of slowing it down; this will occur if the coastal system is brought further away from equilibrium. Sustainable coastal planning aims to avoid conflicts with natural coastal evolution; therefore it has to rely on a solid understanding of the mechanisms of land-sea interaction.

Continuing efforts to maintain the coastline

The ancient village of Egmond along the Dutch North Sea coast disappeared into the sea in the past centuries (Fig. 1.4). It could have been protected against the natural retreat of the coastline by the construction of sea walls, but for how long? At present, the coast around Egmond is nourished with sand taken from far offshore, in order to bring the coast locally closer to a morphologic equilibrium; it is expected that sand nourishment will have to continue for centuries before a situation close to equilibrium is reached. In the meantime the Dutch coast will continue to adapt to sea-level rise and to sand loss to the dunes. Hence, coastline maintenance can only be sustained by using the North Sea bottom as a permanent sand source for coastal nourishment [261].

Cost-effectiveness of coastal policies

The example of Egmond illustrates the dilemmas related to coastal development. It implies striking a balance between benefits and costs; this balance is

Fig. 1.4. The church of Egmond was swallowed by the sea in the 18th century. The picture was drawn shortly before.

more easily evaluated for the short term than for the long term, but the latter is often more significant. Several policies for responding to coastline retreat are possible, ranging from hard protection structures to abandonment of settlements, from supratidal beach nourishment to subtidal shoreface nourishment. The effectiveness of different policies depends to a large degree on the long-term response of the coastal system to the intervention. A coast eroded by tidal currents may require other measures than a wave-dominated coast. Estimating the cost-effectiveness of measures is possible only if the natural dynamics of the coastline is well understood.

Coastal observation is essential

Any attempt to understand the coast should start with observing the coast. This is a major investment, because the time scale of coastal evolution is long and trends are masked by short-term fluctuations. In The Netherlands a coastal monitoring programme started since the 1960s. Each year, the shoreface-profile is measured over a cross-shore distance of 800 m along the entire coastline, with a longshore spacing of 200 m. The coastal data set already covers almost 40 years; this information guides the annual coastal nourishment planning. Interpreting this data set is essential to the planning efforts. Each year large fluctuations occur in the coastline position, but many of these fluctuations do not correspond to long-term trends. Effective coastline management requires a thorough interpretation of observed coastline behaviour.

Management of river mouths, tidal basins and coastal wetlands

Sustainable management of river mouths, estuaries, tidal basins and coastal wetlands poses dilemmas similar to those in shoreline development and maintenance. Such dilemmas arise from the wish to protect existing features or from new claims on the coastal environment, which are mutually conflicting or conflicting with natural coastal evolution. Decision-makers need to know whether an intervention may conflict with natural coastal evolution and at which scale, in space and time. How can such conflicts be avoided or mitigated? At which costs? Does the intervention influence coastal evolution? Will this affect existing uses and opportunities? How can competing claims and interests be reconciled? Credible policy choices should make the best possible use of the progress achieved during the past decades in understanding coastline dynamics; this understanding has increased substantially the capability to produce more reliable predictions of the natural evolution of the coastal environment and its response to intervention.

Models, rules and analogies

Present knowledge is not yet sufficiently advanced, however, for delivering reliable standard tools for predicting large-scale and long-term coastal evolution. Certain (semi-)empirical relationships are often successful, for instance, the ‘Bruun rule’ for coastal retreat (Sec. 5.5.2), the ‘Dean rule’ for the shoreface slope (Sec. 5.2.1), the ‘O’Brien rule’ for the cross-sectional area of tidal inlets (Sec. 4.2.6) and the ‘Walton rule’ for the ebb-delta volume (Sec. 4.2.2). In this book some additional relationships are derived from simple models, which help predict coastal evolution and the coastal response to intervention. It must be emphasised that these relationships have a restricted validity; they are applicable only under certain conditions. Understanding these conditions is more important than knowing the relationship. This requires for each case knowledge of the specific field situation, which can only be obtained through observation programmes. The most important benefit of the morphologic relationships is the help they offer for interpreting the observations and for drawing the right conclusions. Models and rules can easily be misused. The emphasis in this book is therefore primarily on the processes governing land-sea interaction, rather than on practical field cases that may give rise to misleading analogies.

Coastal diversity

The land-sea interaction mechanisms discussed in this book are often illustrated with field evidence from the coastal zone of the Netherlands. This is a deliberate choice; many of these data were collected for special coastal management purposes by the Dutch Ministry of Public Works and Water Management and are not available in the open scientific literature. It must be realised that these data are not necessarily representative of other coastal environments; the main characteristics of the Dutch coast are the relative minor influence of ocean swell, the modest fluvial sediment supply and the geological setting of a steadily subsiding basin. The basic land-sea interaction mechanisms are the same in most sedimentary coastal environments; however, the relative importance of these processes may differ greatly from one coastal zone to another, even over short distances.

Students and coastal professionals

This book is written primarily for learning purposes; it is based on a lecture course on coastal morphodynamics given at the Universities of Utrecht and Delft in The Netherlands for graduate students who are familiar with the basic concepts of coastal hydrodynamics. The material has been extended to provide an overview of the main physical principles of land-sea interaction. It enables coastal engineers to complete their background knowledge and to facilitate access to cutting-edge scientific literature on specific topics. The book may also serve to familiarise professionals in other coastal disciplines with modern concepts of land-sea interaction. The mathematical subsections, often presented at the end of a section under the heading ‘A simple model’, can often be skipped without affecting the understanding of the essential concepts.

1.4. How is this Book Organised?

Principles of symmetry breaking

Chapter 2 introduces the concepts of spatial and temporal symmetry breaking; these concepts provide a unifying framework for the multiple morphodynamic feedback processes discussed in the following chapters. The tidal bore in the Qiantang estuary (China) is discussed as an illustration of time symmetry breaking; spatial symmetry breaking is illustrated by the instability of a system of parallel channels. The history of the Rhine delta (at a timescale of centuries) and the history of the Ameland reef (at a timescale of years) are discussed as examples.

Current-topography interaction

Chapter 3 starts with a brief overview of some general properties of water flow and sediment transport over a rough, mobile seabed. The main body of the chapter is devoted to seabed instability inherent to the interaction of currents with topography, resulting in spatial symmetry breaking and the generation of rhythmic seabed structures. Spatial symmetry breaking is associated with both steady currents and oscillating currents; the basic principle is the same in both cases. Different symmetry-breaking processes are discussed, which produce seabed structures at very different scales, from ripples (wavelength of tens of centimetres) to tidal sandbanks (wavelength of kilometres). Symmetry breaking in flow bounded by channel banks leads to channel meandering and building of tidal flats. Understanding these processes is a great help in interpreting observations of seabed and basin topography and in extracting information on morphologic processes and coastal evolution.

Tide-topography interaction

Chapter 4 deals with the morphodynamic feedback responsible for the topography of tidal basins. Tide-topography interaction affects the time symmetry of the tidal wave, producing differences in the strength of flood and ebb currents and in the duration of high-water slack tide and low-water slack tide. This asymmetry changes the topography of tidal basins due to net erosion or sedimentation, and results in feedback to tidal-wave asymmetry. We distinguish two types of tidal inlets: River tidal inlets and barrier tidal inlets. The stability criteria of both types of inlets are discussed with reference to a large number of tidal basins which are documented in the literature. The results are relevant for answering questions like: 'How do tidal basins respond to human interventions (dredging, sand mining, tidal flat reclamation) and to sea-level rise?'

The chapter ends with a discussion of fine-sediment dynamics in tidal basins. The fine-sediment fraction responds to tidal asymmetry in a different way than the coarse fraction and it is also more sensitive to other transport and sedimentation processes, including biotic activity. No in-depth treatment of eco-morphologic processes is presented, in spite of their potential importance for long-term morphologic evolution of tidal basins.

Wave-topography interaction

Chapter 5 deals with the nearshore zone where sediment transport is primarily influenced by wave activity. Waves interact with coastal topography in several different ways, involving both time-symmetry and space-symmetry breaking. The increasing wave asymmetry in shallow water, finally leading to wave breaking and to the production of radiation stresses, is at the root of net sediment fluxes and topographic adjustment, which result in feedback to wave asymmetry, wave breaking and radiation stresses. In this way a broad spectrum of seabed structures is generated, for instance, longshore bars, transverse bars, rip cells and beach cusps. The shape of the coastal profile itself is also the result of wave-topography interaction. Understanding these processes is essential for answering questions like: 'How can the sea help us maintain the coastline?'

Basic mechanisms

Throughout this book much emphasis is placed on explaining the mechanisms responsible for the generation of coastal morphology. A rough indication of the morphologic spatial and temporal scales can already be derived from these qualitative descriptions. These descriptions also provide an understanding of the conditions under which different topographies develop. For each interaction mechanism, a qualitative discussion is followed by an analytical model which is solved for a particular idealised stereotypical situation. The solution repeats the qualitative discussion, but sharpens the underlying assumptions. The predictive value of these models for real-life situations is very limited; they should be considered primarily as tools for analysis and understanding. The appendix provides an introduction to the basic equations and a mathematical derivation of certain results for which only a qualitative justification is given in the main text.