Eco-morphodynamic processes in the Rhine-Meuse-Scheldt delta and the Dutch Wadden Sea

J. de Brouwer	NIOO-CEMO
A. Crosato	WL | Delft Hydraulics
N. Dankers	Alterra
W. van Duin	Alterra
P.M.J. Herman	NIOO-CEMO
W. van Raaphorst	NIOZ
M.J.F. Stive	WL | Delft Hydraulics
A.M. Talmon	WL | Delft Hydraulics
H. Verbeek	RWS/RIKZ
M.B. de Vries	WL | Delft Hydraulics
M. van der Wegen	IHE
J.C. Winterwerp	WL | Delft Hydraulics

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Samenvatting

Dit rapport betreft eco-morfologische processen in de Waddenzee en de Holland/Zeeland delta. Het is het resultaat van de eerste fase van het onderzoek dat wordt uitgevoerd door de onderzoeksgroep ‘eco-morfologie van estuaria en kusten’ in het kader van Delft Cluster. In dit inventariserend rapport worden behandeld: beheervraagstukken gerelateerd aan eco-morfologie, ecologische en morfologische processen relevant voor de ecomorfologie en hun onderlinge interacties. Verschillende bedrijven, instanties en instituten hebben hun specialistische kennis ingebracht: ALTERRA, IHE, NIOO-CEMO, NIOZ, NatuurMonumenten, RIKZ, RIZA, TNO-NITG, TNO-MEP, TUD, VBKO, WL | Delft Hydraulics.

In dit rapport worden eco-morfologische interacties veelal op kwalitatieve wijze besproken. In sommige gevallen waarin reeds een meer kwanitatieve beschrijving beschikbaar is wordt deze behandeld. Voorbeelden hiervan zijn: de relaties tussen diatomee dichtheid en het slikgehalte van slikken en schorren, en de sedimenthuishouding van mossel- en kokkelbanken.

Het is niet mogelijk om alle in dit rapport aangeduide interacties in de volgende fase van het onderzoek te behandelen. De deelnemers stellen voor om de ontwikkeling, de degeneratie en het gedrag van slikken en schorren te onderzoeken. Dit op basis van prioriteiten van beheervragen voor de verschillende Nederlandse systemen en de wetenschappelijke relevantie. Daarbij dient het onderzoek binnen de looptijd van het project te leiden tot een significante vooruitgang , over het begrip van de processen en de op te stellen beschrijvingen.

Abstract

This report concerns the eco-morphologic processes in the Wadden Sea and the Holland/Zeeland delta. It is an inventory report on the managerial questions related to eco-morphology, on the ecological and morphological processes relevant for eco-morphology and on the ecological-morphological interactions. The inventory is based on existing experience within the eco-morphological team: many of its members have been involved in previous projects with an eco-morphological component. The eco-morphological team consists of personnel from: ALTERRA, IHE, NIOO-CEMO, NIOZ, NatuurMonumenten, RIKZ, RIZA, TNO-NITG, TNO-MEP, TUD, VBKO, WL | Delft Hydraulics.

Within the report many of the eco-morphological interactions have been identified qualitatively. In some cases more quantitative descriptions have been developed, such as the influence of diatom density on the mud content of intertidal mud flats, and the sediment budget above beds of filter feeders.

It is not possible to study all interactions identified in the next phase of the research programme. As a conclusion the eco-morphological team proposes to study the generation, degeneration and behaviour of salt marshes. This is concluded on the basis of priorities in the management of the various Dutch systems and with respect to the scientific relevance, and a pragmatic argument, that is that the study should result in significant progress within the study period in our description and understanding of subject.

1 Introduction

1.1 Aim of the project

The sustainability, resilience and carrying capacity of coastal systems is determined to a large extent by ecological and morphological processes. Usually, these processes have been treated separately. It has been recognised however, that there is a strong mutual interaction. A classical example is the dispute, ongoing since the early 1950s (sic), whether bottom fauna facilitates deposition of particles on intertidal areas, thus affecting the morphology, or if morphological processes create the conditions suitable for bottom-fauna development. Reconsideration of this dispute and related debates strongly implies that the ecology and morphology of coastal areas form an eco-morphological continuum, and that ecological and morphological processes should be studied in coherence, with emphasis on their interactions. The aim of the project is therefore:

> *to identify, describe and analyse, in a multi-disciplinary fashion, the direct, and possibly indirect, interactions between ecological and morphological processes, which ultimately determine the eco-morphological developments of estuaries and coasts*.

This state-of the-art report addresses the Rhine-Meuse-Scheldt Delta region, consisting of the Western Scheldt, the Eastern Scheldt and Haringvliet, as well as the Dutch Wadden Sea. It is part of a first inventory phase dedicated to a description of the present eco-morphological state, summarising existing knowledge and establishing the needs of end-users. A synthesis of the gathered knowledge on ecomorphodynamic interactions in estuaries and coastal lagoons will be presented in a second report.

The end-objective of the study is the definition of measurable, quantifiable parameters (indicators such as bio-mass, mud content, etc.), necessary to characterize the eco-morphological structures of coastal areas and their responses to internal and external forcing. These parameters should be useful also to monitor and predict the eco-morphological development of coastal areas as a result of natural dynamics and human interferences.

1.2 Present status

Within The Netherlands, extensive studies have been performed and large data sets exist on many water systems, including the Delta area, the Wadden Sea and the coastal North Sea. However, most of that work was mono-disciplinary and only few multi-disciplinary eco-morphological studies have been carried out, so far. Multi-disciplinary studies and interpretations will be in increasing demand, as the questions and problems from society become more and more complex. Typical examples are the development of the Western Scheldt as a valuable eco-system in relation to further deepening and sand mining, the effects of gas exploration on the eco-system of the Wadden Sea. The ongoing debates on these and other subjects, partly in the national press, indicate the need for in-depth scientific studies.

Furthermore, as the large-scale infra-structural works that are scheduled in the Netherlands have a scale beyond any experience, thorough knowledge of the relevant processes is a must for a successful completion of these works.
A third national interest is the availability of eco-morphological know-how to the Dutch hydraulic engineering community to increase their competitive edge abroad, as the environmental impact becomes an ever more decisive factor in the feasibility of many projects throughout the world.

It is nowadays fairly common to study the morphological development of dynamic systems at various temporal and spatial scales. For instance, for estuaries, lagoons, etc., which are characterised by large intertidal areas, the following four scales have been recognised:

- *mega-scale*, which is the scale of the entire estuary or lagoon with typical time-scales on the order of centuries;
- macro-scale, which is the scale of the main ebb and flood channels, meanders, etc., with typical spatial scales on the order of the tidal excursion and with typical time scales on the order of decades; note that the habitat distribution for species is on the mega- and macro-scale;
- meso-scale, which is the scale of small channels, tidal flat-channel exchange processes, salt marshes, etc., with typical spatial scales on the order of a few 100 m's to a few km's and with typical time scales on the order of months to years;
- *micro-scale*, which is the scale of bedforms, etc., with typical spatial scales on the order of a few m's to a few 10 m's and with time scales on the order of days to weeks; species distributions of micro-phytobenthos and zoo-benthos are of the micro-scale.

For the ecological processes, a similar distinction can be made. On the mega- and macro-scales, entire ecosystems may vary under the influence of climate variability, morphological developments, or other changes. Meso-scale variability is dominated by the annual cycles of light and temperature, and micro-scale variability by daily (light, temperature) and tidal cycles (currents, exposure, etc.). For interactive processes to be effective they should act on similar temporal and spatial scales. For morphological and ecological processes, this condition appears to be met particularly on the meso- and micro-scales.
Intertidal areas, for example, are ecologically valuable if they are highly productive, which requires low-dynamic conditions. However, it is believed that they should possess a certain regenerative capacity. Nevertheless, fairly stable conditions should exist for a few years at least to allow an eco-system to develop properly. This can be translated into morphodynamic behaviour in the sense that these requirements imply small net sediment transports, hence dynamics, on the meso-scale, and moderate gross sediment transports on the meso- and micro-scale.
A strong hierarchy exists within the cascade of scales. Processes at small scales react fairly instantaneous on changes on a larger scale, whereas a large-scale response of the system to changes on a smaller scale is slow. Additionally, small-scale processes show so-called free behaviour, whereas larger-scale processes have stochastic driving forces. As a result, the predictability of the exact development of morphological systems is limited. However, the long-term behaviour of such systems may possibly be described in terms of a morphodynamic climate in which for instance the number of channels and the surface of intertidal area can be established, but not the exact locations of channels, intertidal areas, etc.

It is believed that the response of a system to variations in forcing or other (human) interference becomes manifest first at the scale of those forces, and that at larger scales their effects become manifest only through the scale cascade. This concept provides a starting point for studying the interaction between ecology and morphology, and implies that the ecological processes also have to be described at various spatial and temporal scales.
An important parameter in ecological habitat evaluation is the sediment composition at the sediment-water interface. For instance, the mud content of intertidal areas is a primary factor governing the kind of eco-system that may develop c.q. flourish in such areas. However, at present, no robust and validated tools are available to predict the sediment composition in tidal systems.
With respect to eco-morphodynamic interaction, sediment fluxes (water-bed exchange processes) are an important issue. For instance, in the Western Scheldt estuary and in the Wadden Sea relationships between morphology and the distribution of benthos species have been studied. These relationships suggest a positive correlation between occurrence of benthic algae and sediment stability. Also in the Wadden Sea, a relationship between the occurrence of filter feeding bivalves and sediment composition was identified. Interactions between benthic algae, grazing of zoobenthos, as well as foraging of birds and fish possibly affect, on a micro- and meso-scale, the stability and composition of the sediment. In addition, anthropogenic impacts on the densities or distribution of species may further affect sediment stability. It is the aim of this report to describe such potentially important eco-morphological interactions in more detail.

2 Managerial questions and strategies

2.1 Strategy plans

2.1.1 Delta area

The most important strategy plan in the Netherlands is the fourth national water policy plan, in which two fundamental tasks are expressed:

- to have and to keep a safe-guarded land
- to support healthy and resilient water systems with a sustainable use

Part of this policy plan regulates the policy plans around the Delta area. There are three topics of main concern:

- the development of the long-term vision on the Scheldt Estuary in co-operation with the Belgium authorities
- the exploration of the conservation and restoration of the estuarine character of the Eastern Scheldt
- the aim for a natural transition between salt and fresh water by partly opening of the Haringvliet sluices.

2.1.2 Wadden Sea

The international Wadden Sea falls under the jurisdiction of Denmark, Germany and the Netherlands. Co-operative protection was formally started with the 'Joint Declaration on the Protection of the Wadden Sea' in Copenhagen in 1982. Since 1997, arrangements are embedded in the Trilateral Wadden Sea Plan, which entails policies, measures, projects and actions, which have been agreed upon by the three countries.

Guiding principle for the trilateral Wadden Sea policy is 'to achieve, as far as possible, a natural and sustainable ecosystem in which natural processes proceed in an undisturbed way' (Esbjerg Declaration, 1991). The principle is directed towards the protection of the tidal area, salt marshes, beaches and dunes (Leeuwarden Declaration, 1994).
In addition seven Management Principles have been adopted, which are fundamental to decisions concerning the protection and management within the Wadden Sea area (Esbjerg Declaration, 1991). These are the principles of Careful Decision Making, Avoidance, Precaution, Trans-location, Compensation, Restoration, and Best Available Techniques (BAT) as well as Best Environmental Practise (BEP).

The Dutch Wadden Sea Conservation Area is the area subject to the Wadden Sea Memorandum (PKB, Planologische Kernbeslissing Waddenzee). The Memorandum is a national physical planning document, which is the basis for all further planning, conservation and management for the area of all state, regional and local authorities.

The first National Wadden Sea Memorandum was issued in 1980 and amended in 1993. A new Memorandum is currently being elaborated. In the new Memorandum the area covered will probably be extended to the north, to coincide with the trilateral co-operation area and the area designated by the Bird Directive. Furthermore, a major part of the Wadden Sea area was designated as nature reserve (partly Staatsnatuurmonument, partly Beschermd natuurgebied). In 1993, the total area covered by the Nature Conservation Act (Natuurbeschermingswet) was extended to 95% of the total area.

Recently a number of policy documents are produced, dealing with the water management of the Netherlands. The most pronounced is the advice of the commission on the Water Management in the 21st century (WB21). In the most recent documents, the Fifth Policy Document on Environmental Planning, water is used as a structuring element.

2.1.3 Other policy documents

The role of water must be more pronounced in the planning. Under the slogan "Room for Water" three stages will be used to ensure the safety against flooding:

- 1: TO KEEP: contain excess water upstream in subsurface and surface watersystems
- 2: TO HOLD: temporarily water containment in allocated retention basins
- 3: LET GO: if 1 and 2 are not sufficient: discharge of water or controlled retention in dedicated areas.

2.2 Questions per water system:

2.2.1 Western Scheldt

On the basis of extensive research Vroon *et al* (1997) report on observed changes in tides and geomorphology. There is an increased high water rise in combination with diminished storage within the estuary. The estuary is getting deeper due to the dredging activities, which results in a morphological "stillness", particularly on the macro- and meso-scale. The micro-scale dynamics, however, seem to have increased, especially in the lower intertidal areas. The dredging also decreases the area of shallow-water and intertidal flats, as well as of salt marshes. By this area decrease the nature function of the estuary is under threat.

The ongoing hydrodynamic and morphological changes affect major estuarine characteristics, expressed in the terms like

- natural dynamics
- self regulation and sustainability
- completeness and biodiversity

Despite the evidenced changes in de physical structure of the system, any (negative) responsive development in the ecology at the level of higher organisms has not been proven yet. The link between morphology and ecology was not made satisfactorily.

At the moment, the Dutch and Belgium authorities are preparing a long-term vision. This vision will take into account the whole Scheldt estuary addressing developments in the next 30 years. The leading policy for this water system is expressed in the themes: *safety, navigation and resilience*:

- the need for control of safety standards against flooding;
- the possibilities for strong economic development;
- the possibility for more and larger ships to reach the Scheldt-harbours of Antwerp, Vlissingen, Terneuzen and Gent. This implies the need for extension and deepening of thalways as well as for larger harbour facilities;
- the opportunities for commercial sand mining;
- the possibilities of ecological restoration and development alongside the estuary:
  - where Saeftinge is assigned as a RAMSAR-area
  - the protection of existing salt marshes needs human interference (e.g. Zuidgors)
  - the control of breeding sites should be effectuated (e.g. Hoge Plaaten);
  - the protection and restoration of morphodynamic systems should be taken into account during dredging and dumping activities.

In reaction to the temporary plans a reaction from the Dutch parliament is that nature compensation within the system must be part of the Long-term Vision on the Schelde estuary. Since there is little room for possibilities of natural development the creation of nature compensation is advised strongly.

2.2.2 Eastern Scheldt

The Eastern Scheldt will be assigned National Park in the near future and, therefore, nature conservation has high priority. Nevertheless, recreation and some fishery should be accommodated also. Upon to the building of the storm surge barrier in 1987, some problems remained unsolved:

- the continuous loss of intertidal flats (the so-called sand hunger);
- the limited resources for both shell fishery and birds

On the one hand, problems occur due to the reduction of the tides by the storm surge barrier. There is no sediment import, possibly due to the constant change of the Voordelta and the trapping of sediment around the storm surge barrier. The existing tidal flats are slowly eroding to balance the oversized cross-sections of the channels. But not only the tidal flats are eroding, the few salt marshes are eroding also. Moreover, the salt marshes are presently positioned at a high altitude due to the diminished tidal range.

On the other hand the fresh water outflow from the rivers is diverted from the Eastern Scheldt to keep out pollution as much as possible. At the moment, water quality has improved such that possibilities for re-establishing fresh water outflow are being investigated. This will return the Eastern Scheldt from a tidal basin into the original estuarine function. The advice of the Commission Watermanagement 21st century is important here, because hydraulic control problems arise during high river discharges. Besides this issue of water control, the Fourth National Water Policy Plan (1999) aims at restoration of fresh-salt gradients, which are (almost) absent in the Delta waters nowadays.

2.2.3 Haringvliet

At the northern boundary of the Delta area the rivers Rhine and Meuse flow into the North Sea. The Haringvliet sluices were constructed and became operational in 1970 to regulate the water flow in the Rotterdam Harbour and the Nieuwe Waterweg. The water body functions as a fresh water resource for drinking water supply and agricultural use. The sluices are only opened at large river discharges during the ebb phase of the external tide. The steep salinity gradient near the sluices during large river discharge may deteriorate local habitats like musselbeds. The passage of migrating fish was cut off due to the sluice construction.

After an extensive Environmental Impact Study (1998) it has been decided to partly re-open the Haringvliet sluices, in the near future. Although the use of the fresh water resource is of vital importance to the surrounding agricultural land the western part will become a brackish transition zone.

A first step is decided to take place in 2005. Than the “Kier” (=small opening) will be operational, leading to a passage for migrating fish.

It is expected that it will take at least 10 years to go towards this so-called “reduced tide” scenario. The environmentally most optimal scenario in which the sluices are closed only during severe storm surges (the “storm surge barrier” scenario) will not come into reach within the coming 25 years, due to the expensive compensation measures needed.

2.2.4 Dutch Wadden Sea

The Wadden Sea was much larger in previous centuries when there was a gradual transition from intertidal area to salt marshes and finally freshwater marshes. Due to large scale embankments, the creation of the Afsluitdijk and the creation of large dikes due to the Delta Plan, large dikes now border the Wadden Sea. As a consequence, the borderline between land and sea is fixed and natural gradients from land to sea are scarce.

In the eastern part of the Dutch Wadden Sea, large salt marsh areas are present at the eastern/southern side of the isles and along the mainland coast of Friesland and Groningen. Most of the mainland exists due to active maintenance only. In the western part, only small fragments of salt marshes are present, which are used by wading birds as refuge during high tide. It is uncertain whether the salt marshes in the western Dutch Wadden Sea are sufficiently large to function as a refuge for all the birds that visit the area, and if not so, if it is possible, and desirable, to enlarge the salt marsh area in this region.

In the past, large sublittoral and eulittoral areas were covered with eelgrass. Since 1932 a sharp decline in eelgrass vegetation has occurred, almost towards extinction. Nowadays only small patches of eelgrass are found near the island of Terschelling and in the Dollard estuary. Eelgrass meadows have an important role as spawning and hiding place for fish and other animals and may function as food source for grazing birds as Brent Goose. Eelgrass meadows affect water currents and may stabilise the sediments. Successful recovery of eelgrass may be induced by protection of remaining eelgrass stands and by measurements taken e.g. to reduce intertidal fisheries to improve light conditions.

Due to the (near) absence of natural transitions from freshwater to salt water, the migration of katadromous and anadromous fish species is severely restrained. The main migration is now through the drainage sluices of the Afsluitdijk, although recently the installation of additional *fish passages* should facilitate some migration to freshwater canals in the hinterland.

Further questions are related to the robustness of the Wadden Sea area with regard to human activities, such as shrimp fisheries, shell fisheries (cockles and mussels), extraction of sand and shells, recreation and exploration of gas and oil. Extraction of sand is already constricted to maintenance activities of channels and harbours. The exploitation of shells, however, is of growing concern to management and policy makers.

The exploration of oil and gas results in subsidence of the bottom. It is not clear yet if the Wadden Sea will be able to keep pace with both sea level rise (natural and antropogenically induced) and subsidence. If not, tidal flats area may decrease.

3 Morphodynamic developments

3.1 Historical overview

3.1.1 The Delta Region

The Rhine-Meuse-Scheldt delta is the area between and including the Nieuwe Waterweg connecting Rotterdam to the North Sea, in the North, and the Western Scheldt connecting Antwerp to the North Sea, in the South. The region is depicted in Figures 3.1 and 3.3.

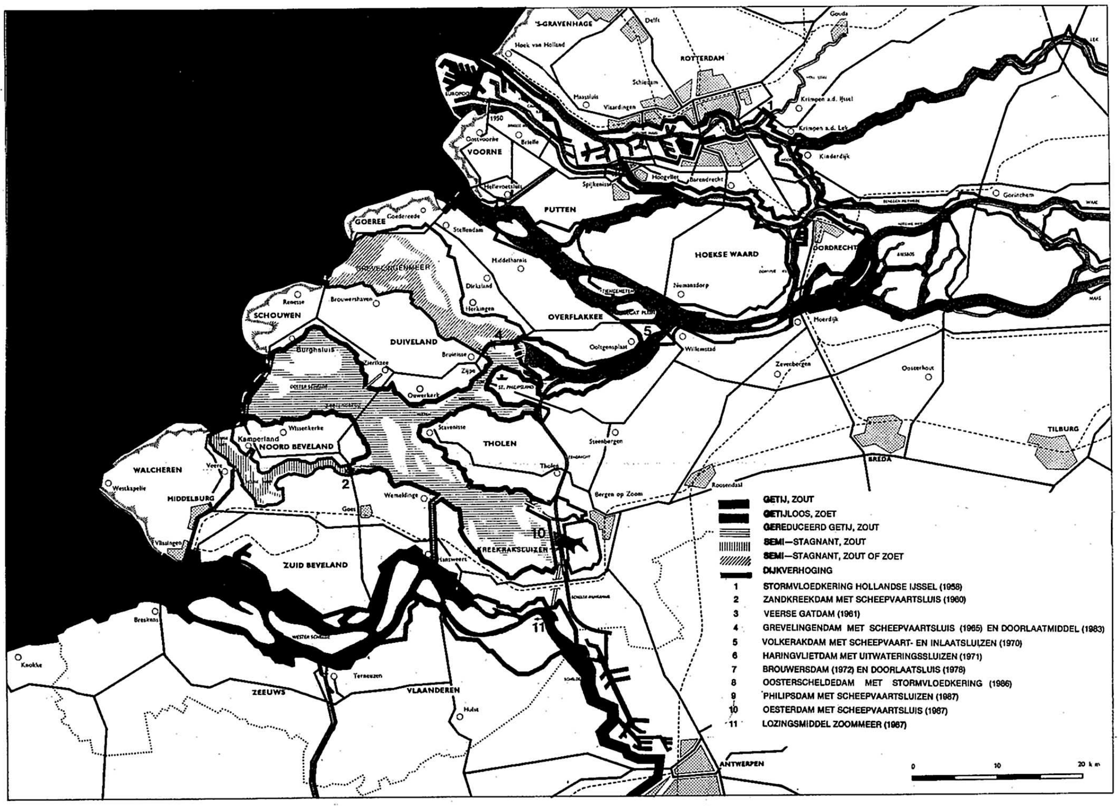

Figure 3.1 The Delta Region according to the original Delta Plan, which included the upgrading of the dykes in the Rotterdam Region (Rijkswaterstaat, 1988).

The region had a very different configuration in the past. The rivers Scheldt and Meuse formed a common delta with a mosaic of islands, intertidal areas and channels. A combined map of South Holland and Zeeland in the Middle Ages (Verburg, 1955) can be seen in Figure 3.2. At those times the Eastern Scheldt formed the main mouth of the river Scheldt. The Meuse discharged at the present location of the Nieuwe Waterweg near Hoek van Holland and the mouth of the Rhine lay near the present village of Katwijk, close to the city of Leiden.

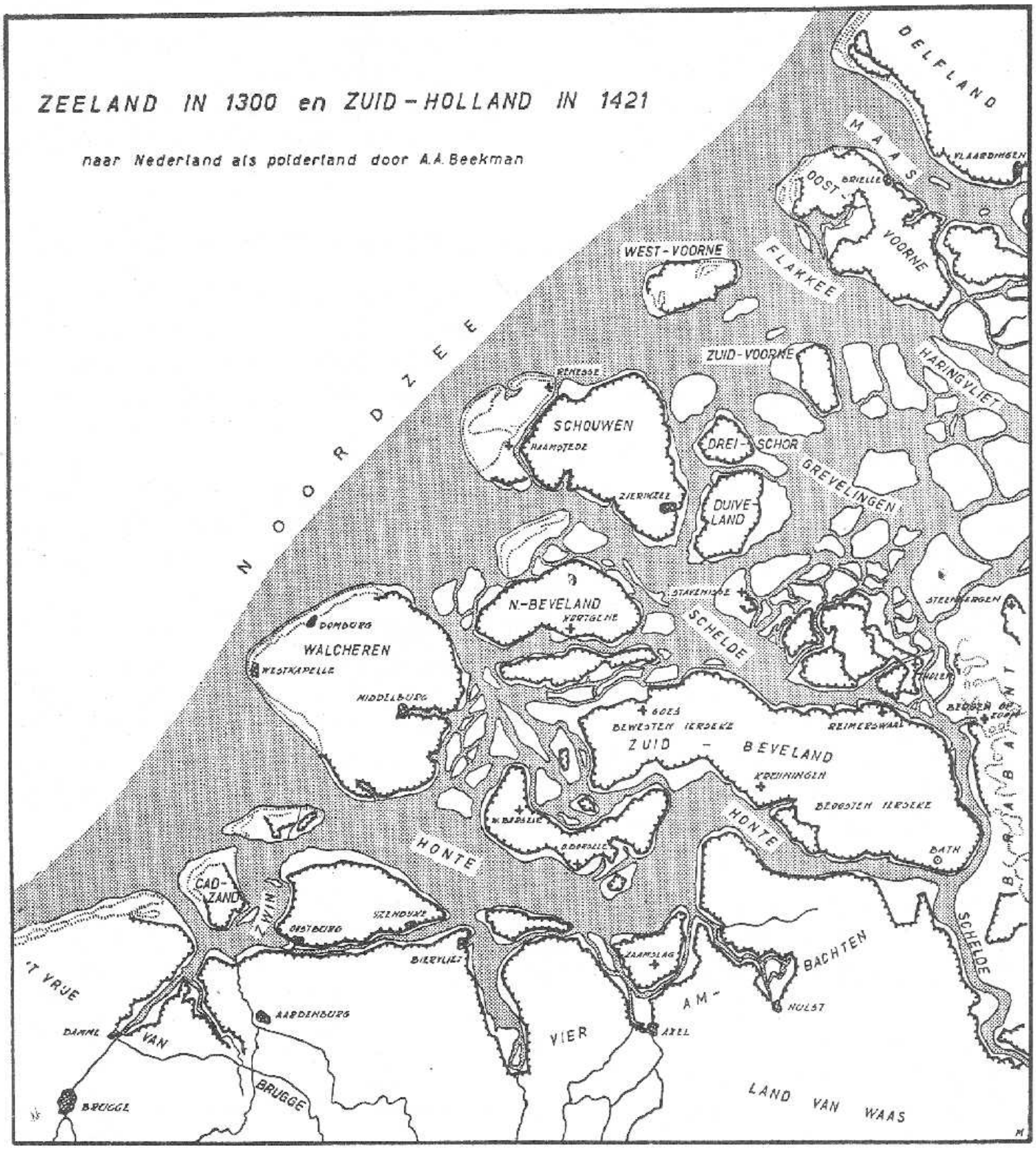

Figure 3.2. Composition map showing Zeeland in 1300 and Zuid-Holland in 1421 (Verburg, 1955).

Already in the Middle Ages the local people had begun to embank the sandy shoals and the muddy intertidal areas, transforming them into new land. The islands of Voorne, Putten and Hoekse Waard were created in this way between 1200 and 1600 (Verburg, 1955). The island of Goeree-Overflakkee originates from the unification of the early-embanked islands of Schouwen, Duiveland and Drieschor. The peninsula of St. Philipsland was embanked in the 17th century and connected to the mainland in 1908. The peninsula of Tholen was build up from a number of small islands and intertidal areas, which were joined together in the 15th and 16th centuries. The island of Noord Beveland was embanked in the early 14th century already, but was destroyed by several flood events in the 16th century. After a long process of reconstruction and embanking, Noord Beveland reached its present shape in the beginning of the 19th century.
The island of Zuid Beveland was present in the 14th century already. It got its present shape in 1808. Walcheren originates from seven small islands, already joined together in 1300. Severe

floods damaged the western part of Zeeuws Vlaanderen several times and for this reason its shape has changed in the course of the centuries. In contrast, the eastern part of Zeeuws Vlaanderen has remained unchanged since about 1300. At that time it included also the later drowned Land van Saeftinghe (now: ‘Verdronken Land van Saeftinghe’). In 1300 the Zwin estuary was connected to the Honte, which later became the Western Scheldt estuary.

Until 1950 the Delta Region was sparsely populated. Urbanization and industry took place only in its northern and southern parts, around the harbors of Rotterdam and Antwerp. The islands were used mainly for agriculture (Nienhuis & Smaal, 1994). Nowadays, recreation and tourism have become important local activities on the islands.
In 1953 a violent storm breached the dykes at many places and caused a disastrous flooding, which killed 1835 persons. Subsequently, with the aim of protecting the region for future flooding, the Government decided to carry out major interventions in the area, the so-called Delta Plan (See Figure 3.1). Following the Delta Plan, the construction of several embankments (Grevelingendam in 1964, Volkerakdam in 1969, Haringvlietdam in 1970, Brouwersdam in 1971) transformed the Haringvliet and the Grevelingen tidal basins into fresh water lakes. Two secondary dams were built to disconnect Lake Veere from the Eastern Scheldt. After long debates concerning the safeguarding of the ecological values of the Eastern Scheldt, the Government decided to construct a storm-surge barrier, isolating the Eastern Scheldt from the sea only at dangerous storm conditions, instead of a permanent-closing dam. The construction of the storm-surge barrier was completed 1986. Ten years later another storm-surge barrier was built across the Niewe Waterweg. This was considered the best alternative for the rise and improvement of the 700 km of longitudinal dykes, as was planned in the original Delta Plan (see Figure 3.1). Completion of the Delta Plan has drastically transformed the Delta Region during the last four decades. Figure 3.3 gives an overview of the waterbodies as they are now.

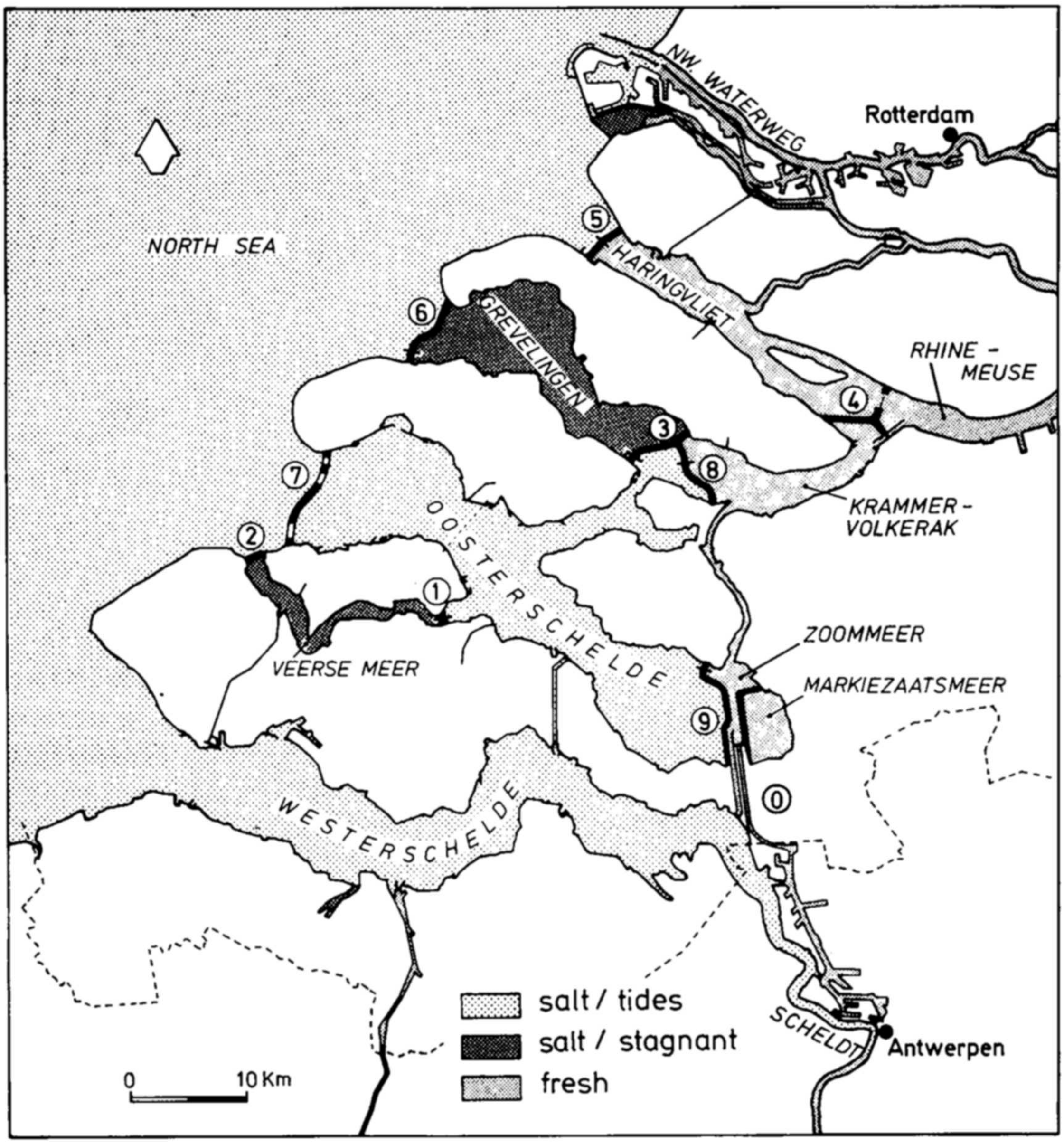

Figure 3.3. Overview of the present-day Delta Region, i.e. after completion of the Delta Plan (Nienhuis & Smaal, 1997). 0 = Kreekrakdam (1867), 1 = Zandkreekdam (1960), 2 = Veersegatdam (1961), 3 = Grevelingendam (1964), 4 = Volkerakdam (1969), 5 = Haringvlietdam (1970), 6 = Brouwersdam (1971), 7 = Storm-surge barrier (1986), 8 = Philipsdam (1987), 9 = Oesterdam (1986). Markiezaatsmeer has been disconnected from Zoommeer in 1983.

3.1.2 The Western Scheldt

The Western Scheldt estuary lies in the southern part of the Delta Region. It is the actual mouth of the river Scheldt and the main shipping route towards the harbour of Antwerp. This estuary evolved from the Honte, a tidal channel which formed a vast marsh area since the early Middle Ages. The Honte became connected to the Scheldt river north of Antwerp and evolved into the new river mouth. As a consequence the Eastern Scheldt gradually lost its function as river mouth. In the 14th century the Western Scheldt had already become the new shipping route to the harbour of Antwerp (van der Spek, 1994).

In the 17th century the Western Scheldt was a highly branched estuary with extensive intertidal flat and marsh areas having large storage capacity. Since then the system gradually developed into the funnel-shaped estuary of the present days. Both morphology and tidal characteristics have changed with time. Coen (1988) reconstructed the tidal ranges and the propagation of high water along the estuary from nautical almanacs. He discovered that the tidal range increased considerably: from the about 3.2 meters of 1650 A.D. near Antwerp, to the 5.2 meters of the present days. The celerity of the tidal wave also increased: in 1650 A.D., the distance Vlissingen-Antwerp was covered by the wave crest in about 4.5 hours, at present it is covered in about 2 hours. The extensive storage areas present in the 17th century delayed the tidal wave. Another factor which has influenced the changing of the estuary characteristics is the rise of the sea level, which since 1650 has become half a meter to one meter higher.

In the 17th century the Western Scheldt was connected to the Eastern Scheldt by the channels Sloe and Kreekrak. At that time, the channels Braakman and Hellegat were connected to each other and formed an island (with the city of Axel at its southern shore), large salt marshes and tidal flats lied along their banks. The Kreekrak was basically a very extensive intertidal area on the other side of the Western Scheldt with respect to the Verdronken Land of Saeftinghe. The latter is the only vast salt marsh area which has remained at the present times. Between 1650 and 1800 A.D. many branches silted up, some intertidal areas accreted to supratidal levels and were embanked. In 1800 A.D. the Hellegat and Braakman channels were not in contact anymore.

The Braakman has been totally reclaimed, at present a harbour and a little lake, the Braakmanmeer, still remind us of its ancient origin; the Hellegat channel has been closed and only a drainage channel remains. The whole area between the two channels has been embanked. The Kreekrak intertidal area, near Bath, which in 1800 A.D. was still connecting the Western Scheldt with the Eastern Scheldt, and the Sloe, the second connection with the Eastern Scheldt, have been both reclaimed. The actual harbour of Vlissingen Oost (Sloehaven) lies on the ancient location of the Western Scheldt end of the Sloe.

3.1.3 The Eastern Scheldt

The history of the Eastern Scheldt is characterized by an increasing isolation from riverine influence: in the course of time the Eastern Scheldt changed from an estuary into a tidal bay. The present morphology of the Eastern Scheldt is the result of both natural evolution and human interventions, such as embanking and dredging. After the most recent human interventions its tidal volume has decreased significantly.

The Eastern Scheldt was the main mouth of the river Scheldt until the Middle Ages, in the 14th century it had already lost this function to the Honte (later Western Scheldt estuary). In 1867 the closing of the Kreekrak definitely separated the Easter Scheldt from the river Scheldt. In 1969 the Volkerakdam deprived the estuary also of the fresh water from the Rhine. At present the input of fresh water is negligible (25 m^3/s, Nienhuis & Smaal, 1997).

The Eastern Scheldt has been an eroding basin for centuries. Due to extreme floods, in the 15^{th} and 16^{th} centuries the estuary increased its tidal volume by at least 50%. A further increase of the tidal volume, this time due to human interventions, occurred in the second half of the 19^{th} and in the 20^{th} century, when the contour lines of the Eastern Scheldt were fixed by rigid sea walls and dykes. Also the construction of the Grevelingendam (1965) and of the Volkerakdam (1969) which closed off the Eastern Scheldt from adjacent basins, resulted in an increase of the tidal volume at the inlet of about 6% (Rijkswaterstaat, 1988). After the construction of the dams the fresh water inputs, which were low already, became insignificant.

The construction of the storm-surge barrier took place between 1980 and 1986. At the same time also two compartmentalisation dams were built in the eastern part of the basin. The storm-surge barrier decreased the effective cross-sectional area at the mouth from 80000 to 17900 m^2. The compartmentalisation dams reduced the surface of the basin from 452 to 351 km^2. The storm-surge barrier creates a discontinuity between the water levels outside and those inside the basin, because of its resistance to the tidal flow. The major consequences are the reduction of the tidal volumes, of the current velocities and of the tidal range. Maximum depth-averaged velocities in the channels decreased from 1.2 to 0.8 m/s. The tidal range reduced from 3.7 m to 3.25 m at Yerseke. This had important consequences for the salt marshes: from the original 17 km^2, 11 km^2 of salt marshes are not subject to the tidal influence anymore.

Due to the presence of the storm-surge barrier the traditional morphological evolution trends have reversed, the Eastern Scheldt has become a sedimentation basin. All sediment inputs come from the coastal zone. The construction of the storm-surge barrier has strongly reduced the sand input from the sea so that at present nearly only fine sediment enters the Easter Scheldt, this fine sediment tends to settle in the tidal channels.

In the Eastern Scheldt we observe a general decreasing of depth gradients. The channels are silting up, but at the same time the sandy shoals and the mudflats are eroding. Data indicate an average lowering of their surface levels between 0.1 and 0.2 m (Nienhuis & Smaal, 1997) after the construction of the storm-surge barrier.

3.1.4 Haringvliet

The Haringvliet Estuary, an intertidal basin in the northern part of the Rhine-Meuse Delta, developed between 1200 and 1600 due to the flooding of low polder areas during several storm surges. The storm surge of February 1, 1953 urged the development of flood-protection works in the delta (see 3.1.1). The Delta Plan included a closure dam (the Haringvliet dam) and discharge sluices in the Haringvliet. These works were completed on November 2, 1970. Earlier, in the eastern part of the estuary, the Grevelingen dam (1964) and the Volkerrak dam (1969) were constructed, disconnecting the Haringvliet from Lake Grevelingen, the Volkerrak and the Eastern Scheldt (Figure 3.4).

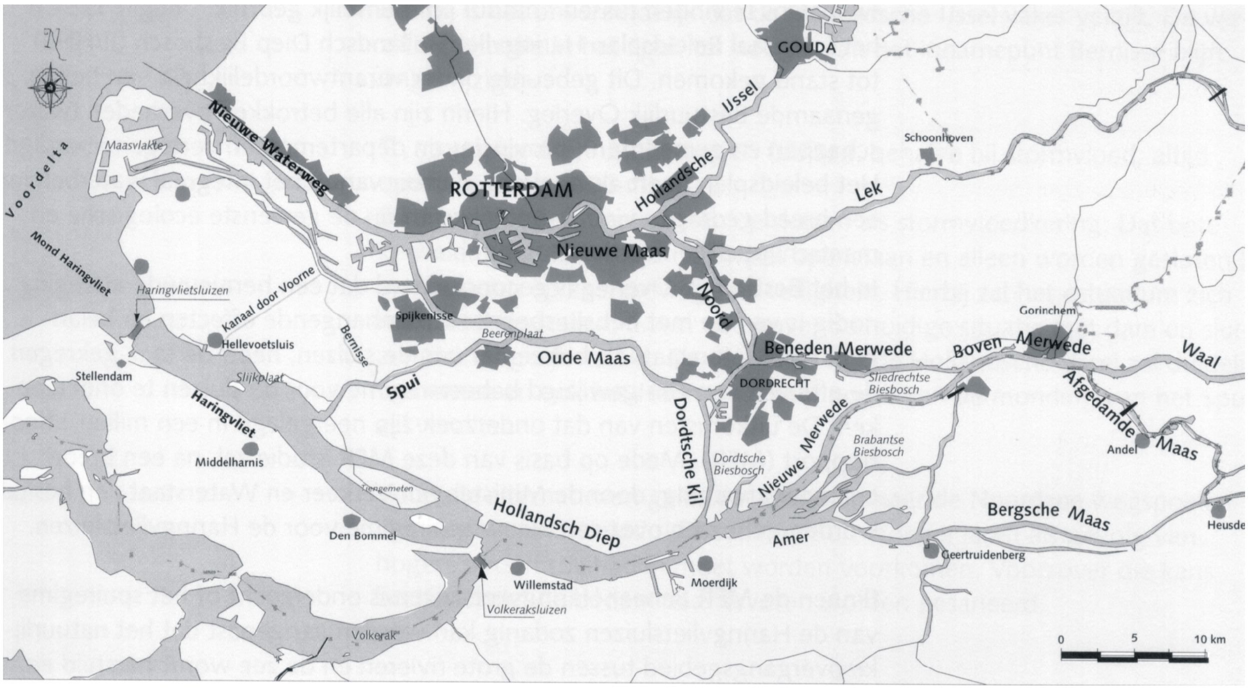

Figure 3.4 The Haringvliet and surrounding area.

Before closure, the tidal difference was 1.80 m with flow velocities ranging from 1.60 to 1.20 m s^{-1} at Hellevoetsluis, and 2.25 m with 0.80- 0.85 m s^{-1} at Moerdijk. After closure, the tidal difference decreased to 0.3 m in the inner basin, being influenced only by the tide entering from the Nieuwe Waterweg. As a result, the Haringvliet has developed into a fresh water basin without salt water entering from the sea.

The discharge management of the Haringvliet sluices aims at controlling the salt intrusion into the Nieuwe Waterweg. During high discharges of the Rhine and Meuse, the sluices are opened whereas they are closed during low river discharges. In the latter case, the river water is forced to flow through the Nieuwe Waterweg, thus counteracting salt intrusion from the sea. Generally, the sluices are opened during ebb tide only. Characteristic discharges are listed in Table 3.1. The water level in the Haringvliet is kept constant as much as possible at 0.50 m +NAP.

	Maximum	Average	Minimum
Rhine	12000	2200	800
Meuse	2000	320	-
Sluice	9000	877	0

Table 3.1. Discharges ($m^3 s^{-1}$) of the rivers Rhine and Meuse as well as from the Haringvliet sluices since 1972

Currently, the sluice discharge management programme is under discussion. Main objective of the new regime will be:

> "To manage the Haringvliet sluices in such a way that it offers good conditions for characteristic estuarine habitats and for sustainable use of the water on both sides of the sluices"

This objective implies the restoration of tidal difference and natural salt gradients to promote characteristic ecological values, however without endangering safety against flooding. Out of different alternatives, the government has chosen for a situation in which the doors are kept open slightly, except in case of storm surges. This allows salt water to enter the Haringvliet during flood tide and fresh water to discharge in the sea during the ebb. The policy after 2005 has not been decided yet. Possibly, this will be the damped tide alternative that involves (partial) opening of the Haringvliet sluices for 95 % of the time.

Description of morphology

The Haringvliet dam blocks any bed-load transport due to the sill in the discharge sluices (~ 8 m above the bed). Exchange of sediment is possible only by suspensive transport during fresh water discharges towards the sea. Maximum transports occur during high river floods. During average and low discharges sediment transport through the sluices is negligible.

Mouth

The present Haringvliet can be divided into its mouth, seaward from the closure dam, and its inner area. The mouth comprises the area between the -12 m NAP boundary west off the Haringvliet and the dam itself. The northern boundary is west of the Maasvlakte and in the south the coast of Goeree and a line parallel to the tidal movements bound it (see Figure 3.4). The mouth consists of three major intertidal areas (Hinderplaat and Garnalenplaat-Noord and -South) surrounded by five major gullies (Hindergat, Bokkegat, Middengeul, Rak van Scheelhoek and Slijkgat). In total, the area covers ~110 km^2 with a coastline of approximately 26 km length.

After closure of the Haringvliet, the damming of the Brielse Gat as well as the construction of the Maasvlakte and Slufter determined the morphological developments to a high degree. Although the tidal difference at the mouth of the Haringvliet increased from 1.8 m to 2.3 m, the tidal flow velocities decreased and wave influences became relatively more important.

Sedimentation processes in general

Different sediment transport processes are involved in the morphology in the mouth, of which tidal sediment transport probably dominates. The tide of the North Sea transports sediment from south to north along the Belgian-Dutch coast. At the mouth of the Haringvliet tidal current interferes with the currents associated with the, tidally induced, filling and emptying of the mouth. The closure of the Haringvliet decreased the strength of these currents and thereby decreased the sediment transports as well. At the same time, waves became relatively more important for the local sediment dynamics. Waves bring sediment particles into suspension and, in cross-shore direction, transport sediments landward. Before closure, in the period from 1956 to 1969, $6x10^6$ m^3 of sediment settled yearly in the mouth of the Haringvliet. After closure net accumulation decreased to about $3.1x10^6$ m^3 per year (Figure 3.5). The tidal volume passing the mouth has decreased with 68% upon closure, which disturbed the then existing equilibrium between cross-sectional area of the mouth and the tidal volume. As a result, $2.1x10^6$ m^3 sediment now is eroding yearly from the foreshore towards the mouth. Most sedimentation occurs above 4 m ¯NAP. Long-shore transport along the coast of Goeree provides ~$0.9x10^6$ m^3 y^{-1} and the Haringvliet provides ~$0.1x10^6$ m^3 y^{-1}. In addition to the sand, ~$0.5x10^6$ m^3 of finer particles (silts and clays) enters the mouth via the Haringvliet every year. Most of these slowly settling particles are flushed out of the mouth towards the North Sea.

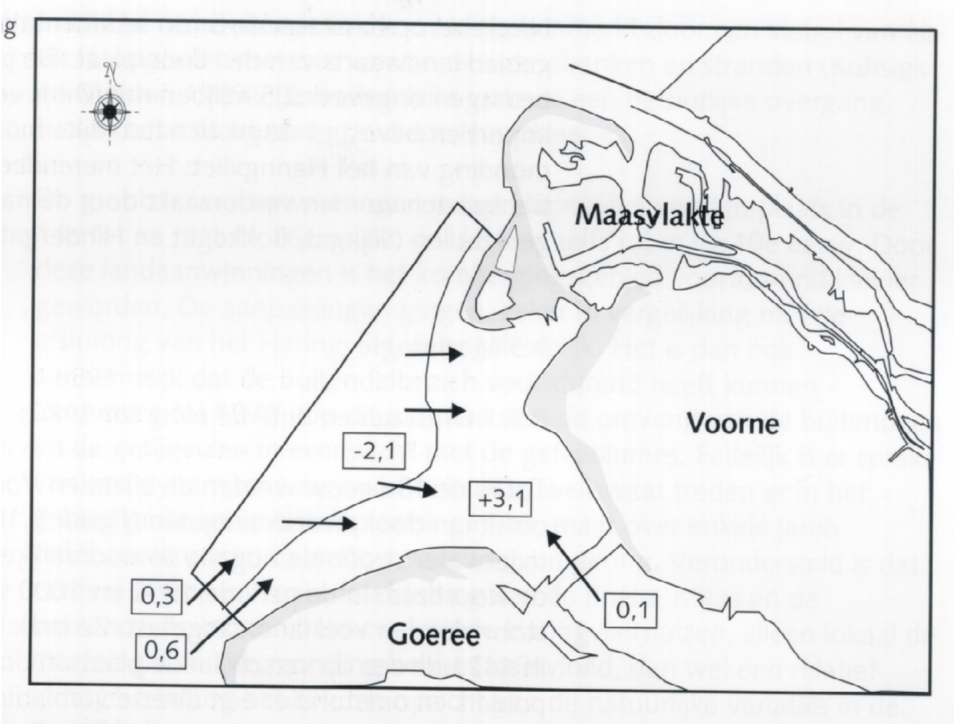

Figure 3.5 Mean sediment transport fluxes (10^6 m^3 y^{-1}) in the mouth of the Haringvliet

The closure of the Haringvliet also caused that the gullies silted up with sands and mud, because they became too deep in relation to the reduced tidal volume. Thus, the intertidal flats have doubled their surface to 11 km^2 during the past 25 years and the area covered by sandbanks increased also (Fig. 3.6). Since a few years, the Rak van Scheelhoek and the Slikken van Voorne are not silting anymore, suggesting that a new equilibrium has been reached.

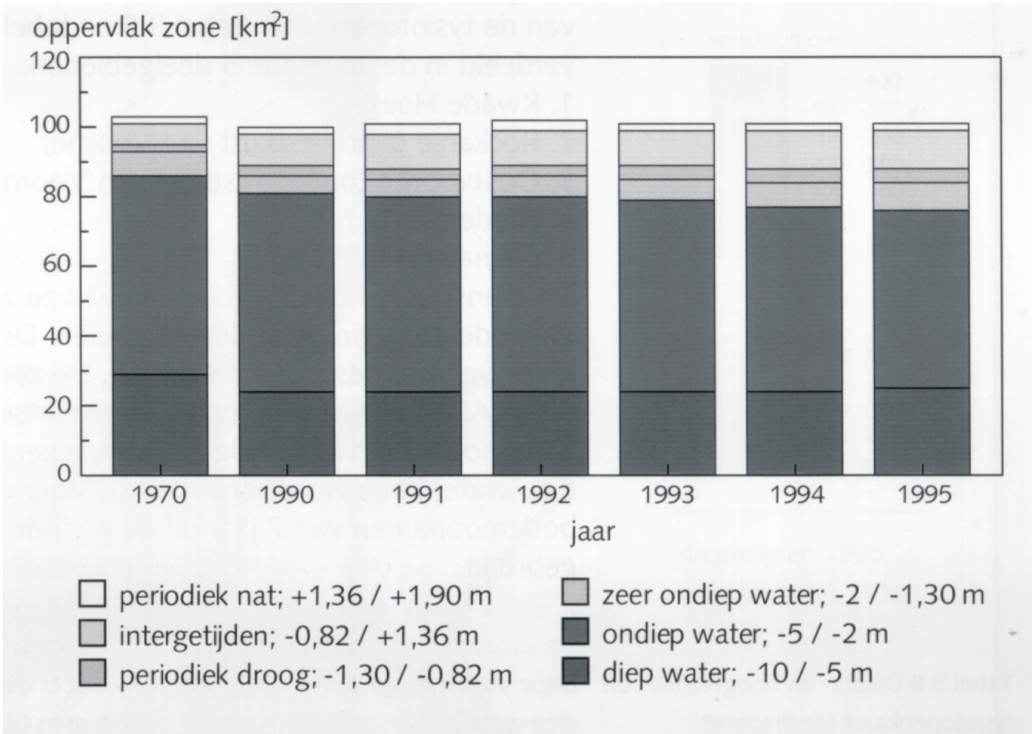

Figure 3.6 Development of the surface areas of different compartments in the mouth of the Haringvliet

Sediment processes in detail

In the following paragraphs the most important gullies or sandbanks are discussed in detail. References are made to Figure 3.7.

Hinderplaat

The Hinderplaat is exposed to direct wave attack and this causes a slow landward movement (110 m per year) together with an increase of its top (up to 1.4 $^{+}$NAP). The Hinderplaat shelters the shallower banks in front of the Slufter and the coast of Goerree from waves.

Hindergat

Upon construction of the Slufter, the Hindergat was dredged to replace the former gully in the Gat van Hawk. The dimensions have not changed much in time. On both the western and eastern sides of the Hindergat underwater delta's have developed, which indicates large sediment transports each tidal cycle. The beach hook south west of the Slufter has developed due to longshore sediment transport by waves and tidal currents.

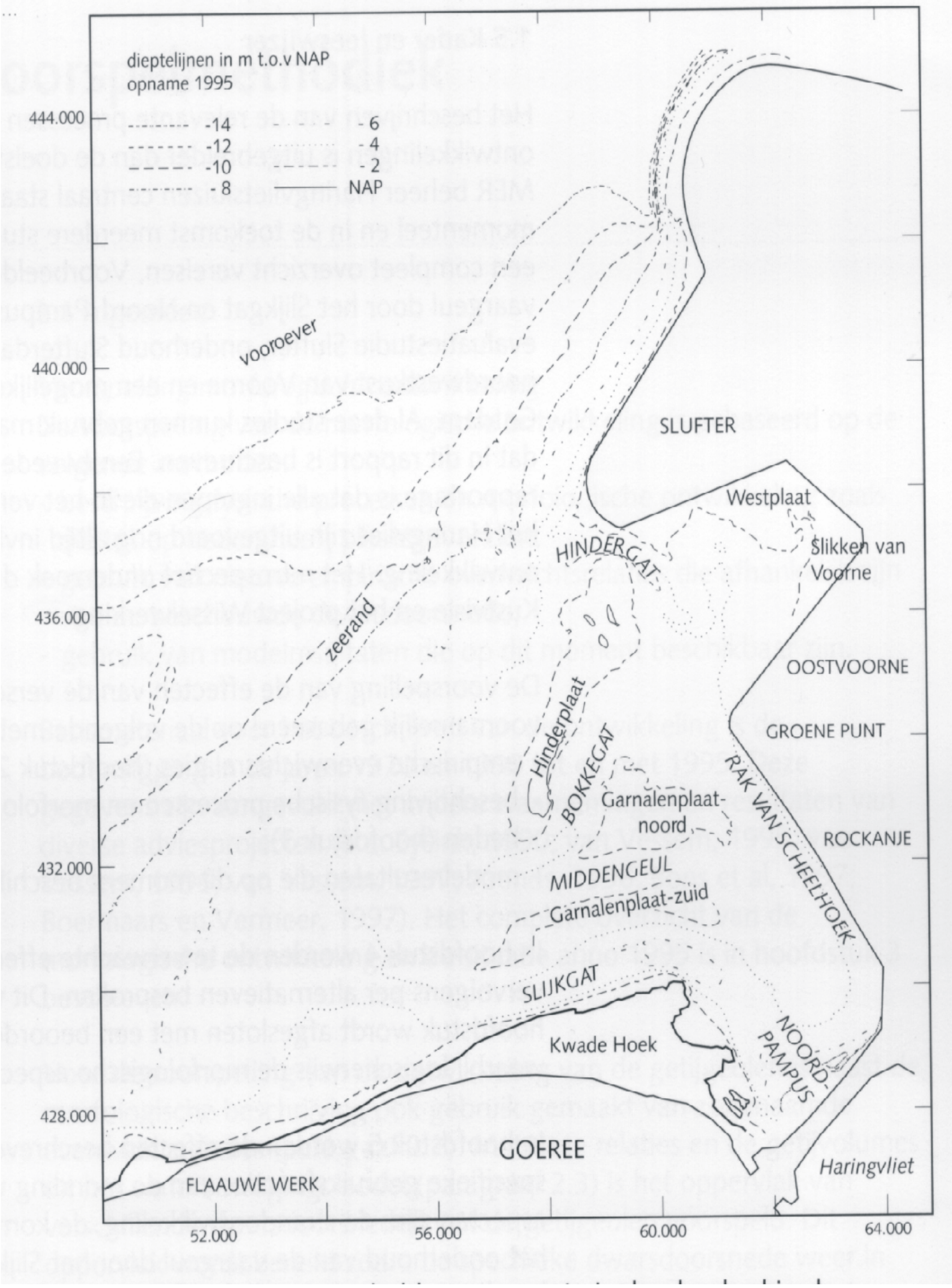

Figure 3.7 Gullies and sandbanks in the mouth of the Haringvliet

Slijkgat

The Slijkgat is the major gully in the mouth of the Haringvliet discharging 61% of the total tidal volume during normal sluice dicharges. Also, it provides the access channel along the coast of Goerree following towards the locks south of the Haringvlietdam and, to maintain this function, needs regular dredging. This points at active sedimentation in the Kwade Hoek area, which increases with 9 ha per year, probably because it is sheltered by the coast of Goeree from waves attacking from the south-west. The average longshore sediment transport is eastward. The sill in the western part of the Slijkgat is due to the ebb-dominated currents in the Slijkgat.

North-eastern part

Sedimentation occurs in the Slikken-van-Voorne, the Westplaat and along the beaches of Oostvoorne. Conditions suitable for sedimentation are shelter from wave attack and low tidal flow velocities. The scour hole directly in the Rak-van-Scheelhoek and Noord Pampus west of the Haringvliet dam, which developed, in 1970 during the full and continuos opening of the sluices, is filled in with mud.

Extreme sluice discharges

During normal sluice discharges the fresh water is mainly discharged via the Slijkgat. However, the distinct body of fresh water that is formed during sluice discharges larger than 4000 m^3/s, occurring 2% of the total time, is flushed mainly via the Rak-van-Scheelhoek and Hinderplaat. Under these extreme conditions the fresh water carries substantial amounts of suspended sediment. The high sluice discharges maintain the Noord Pampus gully next to the Haringvliet dam at depth. Also, they may be responsible for the limited height of the Garnalenplaat and for the shoaling of the sill west of the Slijkgat.

3.1.5 Wadden Sea

Present situation, geomorphological description

Along the entire Wadden Sea coast stretching from the Netherlands via Germany to Denmark three categories of tidal basins can be distinguished (De Jong, 1999):

1. Tidal lagoons. These are basins protected by barrier islands and have a narrow inlet, occurring in the western and northern regions of the Wadden Sea.
2. Estuaries. These are the tidal basins with a significant fresh water inflow, such as the Ems-Dollard, the Elbe, the Weser, the Eider and the Varde Å.
3. Tidal bays. These are wide-open tidal basins and occur only in the central region of the Wadden Sea, not in the Dutch part.

The Dutch Wadden Sea can be subdivided into ten tidal basins, which are all tidal lagoons, except the Ems-Dollard Bay, which is an estuary. From West to East the basins are:

Tidal Basin	**Barrier island shores of the inlet**
Marsdiep Channel (tidal lagoon)	Coast of North-Holland and Texel
Eijerlandsche Gat (tidal lagoon)	Texel and Vlieland
Vlie Gat (tidal lagoon)	Vlieland and Terschelling
Borndiep Channel (tidal lagoon)	Terschelling and Ameland
Pinke Gat (tidal lagoon)	Ameland and Engelsman Plaat
Frisian Gat (tidal lagoon)	Engelsman Plaat and Schiermonnikoog
Eijerlanderbalg Creek (tidal lagoon)	Schiermonnikoog and Simons Zand
Lauwers Gat (tidal lagoon)	Simons Zand and Rottumerplaat
Schild (tidal lagoon)	Rottumerplaat and Rottumeroog
Eems-Dollard Bay (estuary)	Rottumeroog and Borkum

The Ems-Dollard estuary, like many estuaries, is characterised by deep channels and relatively small intertidal areas. The lagoons are characterised by extensive tidal flats of mud and sand, drained and flooded through branching channels. The channels are relatively shallow and the intertidal areas are relatively large. The tidal wave in the estuary propagates as a progressive, damped wave. Since the tidal lagoons are relatively short, the tidal wave in the lagoons is reflected and has a nearly pure standing character. As a result there exists a phase difference between high water and low water level and ebb- and flood-slack moments in the estuary, while the phase difference is zero in the lagoons. This also is the case in the inlet throats. The tidal motion in the North Sea propagates anti-clockwise from South/West to North/East and has a standing character along the Wadden coast. For this reason the moments in which maximum ebb- and flood current occur in the inlet throats and for the alongshore tide are in phase for the lagoons and out-of-phase for the estuary. This promotes the Northwest orientation of the flood- and ebb-channels in the inlets of the lagoons, and the more arbitrary orientation of these for the estuary (Sha and van de Berg, 1993).

The different tidal basins can be distinguished as morphodynamic independent entities. These entities comprehend their adjacent barrier islands, which separate the tidal basin from the open sea, the outer or ebb-tidal delta, the inlet throat, the inner or flood-tidal delta and the tidal watersheds. In contrast to the tidal lagoons along the Eastern USA coast, the inner flood-deltas of the Dutch Wadden Sea are fully developed towards the basin boundaries, their typical characteristic being the branching nature of the channels, incising the intertidal flats. Data analysis of Cleveringa & Oost (1999) reveals that the channels are four times branching networks, with fractal length properties. The branching does not continue under the one kilometre scale. The size of the channels is directly related to the size of the tidal prism and the drainage surface. This implies that the currents produced by the tide are strongest in the tidal inlets and lowest on the intertidal areas near the watersheds.

Geological and historical evolution

The geographic area now known as the Wadden Sea started its development in the recent Holocene period (approximately 8,000 calendar years B.P.) and for this reason it can be considered a geologically young formation. The Holocene period follows the last ice age and is – as all interglacial periods – characterised by a gradual warming up of the earth, which causes melting of the ice-caps and ocean thermal expansion, both contributing to eustatic sea level rise. In those regions with large glacial ice masses, such as the north-east region of the North Sea, a glacio-isostatic rebound, that is regional landmass uplift due to the melting of glaciers, competes with the eustatic sea-level rise. In adjacent regions such as the Wadden. Sea, however, the glacio-isostatic rebound of the fenno-scandinavian region is accompanied by land subsidence. In addition hydro-isostatic loading of the North Sea basin contributes to a differential land subsidence. For the Wadden Sea region this has resulted in deceleration of relative (i.e. the sum of eustatic and regional effects) sea level rise rates, from more than 80 cm per century stabilising to in between 10 cm and 20 cm per century over the last 2000 years. The present contribution of the land subsidence is of the order of 4-8 cm/century (Louters &Gerritsen, 1994). Today a new acceleration of eustatic sea level rise seems to be attributable to human activities, but the issue is still controversial.

Both relative sea-level change and sediment losses and gains determine the morphological evolution of coastal areas on a geological time-scale. Sediment losses and gains can be due to internal and external sources and sinks, such as river input, marine input, longshore redistribution, dune formation, backbarrier accommodation space. A semi-quantitative diagram based on these two variables can express the four basic modes of large-scale coastal evolution (see Figure 3.8). These modes occupy different segments of the diagram and consist of transgression, regression, retrogradation and progradation (and combinations thereof).

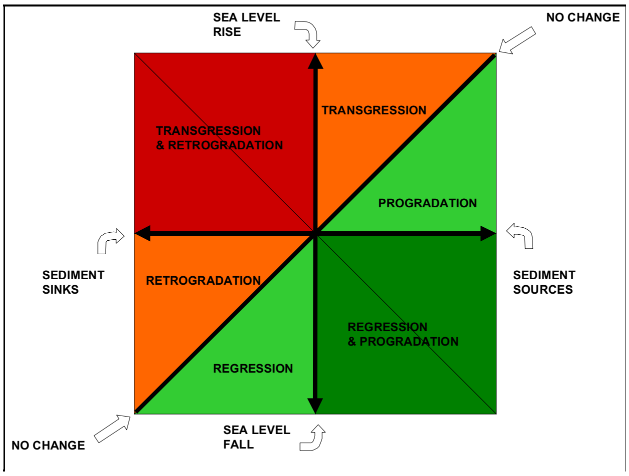

Figure 3.8

Diagram (interpreted after Curray, 1964) presenting the four basic modes of coastal evolution as a function of sea-level change and sediment sources and sinks (reds are retreat, greens are advance; see text for further explanation).

Sea-level rise and fall respectively lead to *virtual loss or gain* of sediment for the coastal system, as a result of which the coast retreats or advances. Quantitatively this is broadly described by a Bruun-type of rule (Bruun, 1988) applied to the shoreface body (Cowell and Thom, 1994). Since the retreat coincides with sea-level rise, the phenomenon, from a marine perspective, is called *transgression* and vice versa the advance, coinciding with sea-level fall, is called *regression*. When these phenomena are combined with a sediment source or sink, the result depends on the relative importance of these with the virtual loss or gain due to sea-level change. A transgressive situation may thus change into progradation (coastal advance) if the sediment sources quantitatively exceed the virtual loss due to sea-level rise. Vice versa, a regressive situation may change into retrogradation (coastal retreat) if the sediment sinks exceed the virtual source due to sea-level fall.

The Pleistocene topography of the western and northern Dutch coast (Fig. 3.9) and the strong relative sea-level rise during the first half of the Holocene (80 cm per century and more) has led to a transgressive and retrograding coastal system, in which the river valleys acted as backbarrier sinks. As the sea level-rise rates dropped below 80 cm per century a diversion in coastal evolution started to occur between the western and the northern part of the Dutch coast: the western part became a prograding coast and the northern part remained transgressive. The following description is based on geological reconstruction studies of amongst others Beets et al. (1992), Van der Spek (1994) and Beets & Van der Spek (2000).

At the end of the fast Holocene transgression about 5,800 B.P., the sea had invaded the Pleistocene river-valleys in the western and northern parts of the Netherlands. In the western part this had resulted in a lagoon-type coast, while the eastern part of the Dutch Wadden Sea area was developing into an estuarine coast. The Pleistocene Texel High region, due to its relative high elevation, most probably remained a closed barrier type coast (see Figures 3.9 and 3.10).

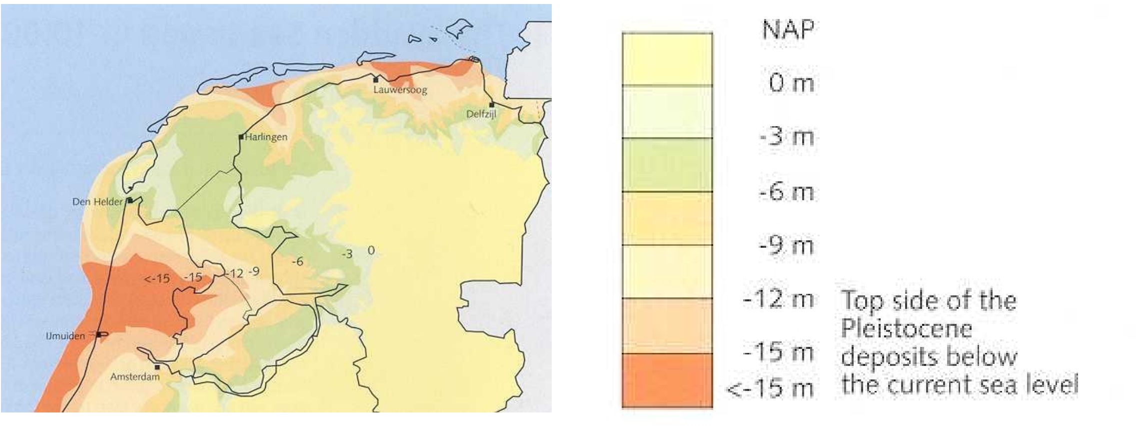

Figure 3.9 Irregular Pleistocene landscape with deep depressions (Figure from Louters & Gerritsen, 1994, after Zagwijn, 1986).

In the period between 7000 and 5000 years ago the rate of sea-level rise had decreased to a value between 80 and 40 cm/century. The rate continued to decline and reached the value of 20-40 cm/century after another 2000 years (Jelgersma, 1979, van de Plassche, 1982, Roep & Beets, 1988). During those four thousand years the lagoons in the western part of the Dutch coast, thanks to the availability of large amounts of sediment, choked their entrance channels and evolved into a prograding closed barrier coast. The northern barrier/lagoon, the paleo Wadden Sea, instead, even though it decreased in surface, did not close and remained into a transgressive coastal evolution mode. The reason lies in the smaller availability of sediments (probably due to the absence of large-river mouths) and the accommodation space of the Wadden backbarrier, acting as a sedimentary sink.

Figure 3.10a Approximately 7000 (C14) years ago, that is 5800 B.C.

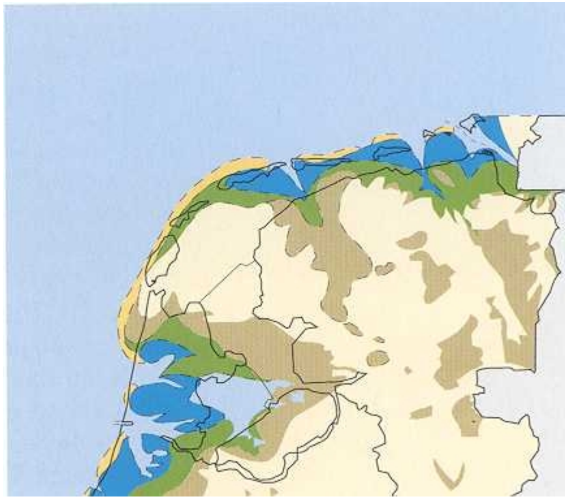

Figure 3.10b Approximately 5300 (C14) years ago, that is 4000 B.C.

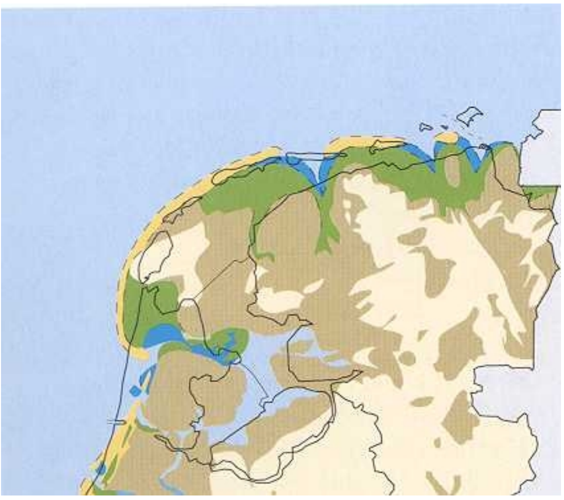

Figure 3.10c Approximately 3700 (C14) years ago, that is 2100 B.C.

Figure 3.10d Approximately 500-700 A.D.

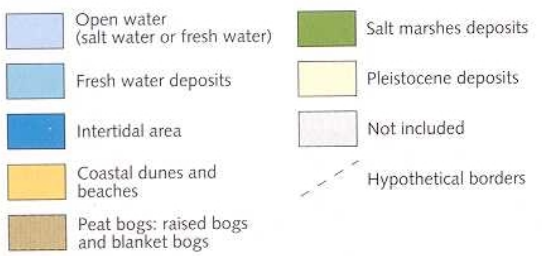

Figure 3.10
Development of the Wadden Sea on geological time scale (figures from Louters & Gerritsen, 1994, after Zagwijn 1986)

Sedimentary successions (van der Spek, 1994) confirm that 6000 years ago the environment of the northern basin, the paleo Wadden Sea, was characterised by channels bounded by tidal flats which landwards became clay-rich and further landwards transformed into fresh-water marshes.

Salt marshes occurred since 4000 years ago and became widespread 3000 years ago. Most of the sediment filling in the paleo Wadden Sea originated from the erosion of the open sea coast of the barrier islands, by overwash and by the erosion of the inlets so that the islands slowly, but constantly moved landwards (the transgressive barrier roll-over model of Van Straaten, 1961). Study of remainders of ancient outer deltas and channels has revealed that 5000-6000 years ago the position of the sea coasts of the islands of Ameland and Schiermonnikoog were, respectively, 11 and 14 km farther north (Louters & Gerritsen, 1994). About 4000 years ago the precursor of the Zuider Sea had appeared in the form of a fresh water inland lake into which the rivers from the south flowed. About 2000 years ago (41-54 A.D.) the Roman Pomponius Mela in his "De Situ Orbis, Part III" wrote about this lake, calling it "Flevo lake" (Sebus, 1923).

Internal erosion between 800 and 1000 A.D. (1000-1200 years ago) enlarged the northern tidal basin again. This new erosive state is most probably a combination of continuing slow sea level rise and local peat extraction and other human interventions, such as the digging of ditches and channels to drain the marshes, which exposed the area to flooding. The sea, most probably in storm surge conditions in which the water level surpassed the altitude of the Texel High, swept away the easily eroding peat strata, which were mainly present in the western region of the Dutch Wadden Sea. This caused a great enlargement of the basin to the West and inland, at a certain stage giving access to the Flevo Lake and thus creating the Zuider Sea. After this erosive period, during which a large accommodation volume available for sedimentation was created, the basin gradually silted up again, to the point that a few centuries later parts of it could be reclaimed. This is thought to have aggravated the transgressive open barrier character of the Wadden islands and adjacent North Holland coast. The evolution of the Dutch coast during the Holocene is schematised in Figure 3.10.

Since the early Middle Ages human activities gradually intensified and increasingly shaped the Wadden Sea basin. With the construction of dikes, at first mainly for flood protection, later also with the purpose of land reclamation, the local inhabitants progressively reduced the Wadden Sea extension. In response to this the tidal prisms reduced, causing the inlets and the channels to become shallower and the ebb-tidal deltas to decrease in volume. Whether or not this has led to an increase of sediment demand to the coasts of North-Holland and of the Wadden islands is an unresolved issue.

However, it is clear that significant changes must have occurred because of the relatively large longshore sediment transports in eastern direction along the Wadden island coasts. The ebb-tidal deltas, although rather stable in a global sense according to the Bruun-Gerritsen ratio between tidal prism and longshore transport capacity, must have experienced decadal scale fluctuations because of the channel migrations and bar-type bypassing mechanisms. These phenomena are caused by the nature of the sediment bypassing processes and result in important changes at the island heads of a strongly fluctuating nature.

In addition, major human interventions took place in the 20th century, among which the most significant are the closure of the Zuider Sea, with the construction of the Afsluitdijk (1932), and of the Lauwers Sea (1969).

The Afsluitdijk had been planned in such a way that its impact on velocity fields and tidal oscillations would be as slight as possible, but inevitably, by strongly reducing the size of the tidal basin, its construction had relevant consequences, such as:

- the increase of the tidal range in landward direction (local increases between 10 and 80 cm);
- the increase of the current velocities (estimates indicate: 26% increase at Den Helder, 10% increase at Eijerlandse Gat, 19% increase at Vliestroom);
- the change of propagation direction of the tidal wave;
- the rise of storm surge heights;
- the change of salinity gradients;
- short-term and long-term morphological changes.

The western tidal basins are the most affected by the closure of the Zuider Sea, especially the Marsdiep Channel basin, where it initiated a clear sedimentation trend, especially in the channels which used to feed and drain the Zuider Sea. From regular depth soundings, which took place in the last decades, it is observed that the major part of the coarser (sandy) sediments originates from the ebb-tidal delta. Measurements indicate that morphological changes caused by the damming of the Zuider Sea were very clearly occurring until quite recently. The same measurements over the last decade are less clear about this.

The closure of the Lauwers Sea had the main effect of further reducing the size of the tidal basin, which resulted in a shallowing of the channels. Since in this case also the tidal prism reduced significantly, the excess sediment in the ebb-tidal delta, the Zoutkamperlaag, is expected to be larger than the sediment demand of the inner flood-tidal delta.

It is uncertain to what extent the effects of the closures of the Zuider Sea and the Lauwers Sea are still occurring and whether this influences the erosion or accretion of the Wadden islands. However, two aspects are clear. First, the increase of sediment accommodation space due to sea level rise causes a net import of sediments to the cost of the barrier island coasts. Second, due to a decrease of tidal prisms and due to wave-induced longshore bypassing processes around the tidal inlets apparently migrations of the inlet throats towards the East seemed to occur. Presently, the intensity of these migrations has decreased. In some cases where human intervention is moderate to absent a movement of islands towards the east is still observed, as for the island of Rottumeroog.

3.2 Future evolution

3.2.1 Expected climatic change

The west-European climate is slowly changing. Information on climate change and its effects for the Dutch coastal areas can be found at *www.waddenzee.nl/dutch/frames.htm* and *www.vu.nl/ivm/publications/online_publications.htm.* The following long-term changes can be expected:

- Increased sea level rise up to 40 or even 105 cm per century. Measurements have shown a sea level rise of ~30 cm over the past 150 years;
- Increase in the rivers peak discharges;
- Increase of the tidal range in the Western Scheldt estuary (higher flow velocities) related to the rise of the sea level and to the long-term consequences of human interventions, such as dredging (D. Roelvink, personal communication);

- Increase of number and intensity of rain showers;
- Increase of number and intensity of storms (wind speed and wave height);
- Increase of temperatures;
- Drier summer seasons.

3.2.2 The Western Scheldt

The Western Scheldt is characterised by a more or less sinusoidal plan form with a *multiple channel system* and a series of intertidal areas in between the channels and along their banks. These channels can be further divided into ebb and flood tidal channels: the ebb tidal channel is more or less the main, continuous (sinusoidal) channel through the system, whereas the flood tidal channel is often straight and ends into a sill. The intertidal areas are typical macro- and meso-scale morphological formations and may be more or less dynamic in the sense that they may migrate and regenerate. They are of particular importance with respect to the ecological functioning of the Western Scheldt, as they form important habitats. These intertidal areas have a variation in bed composition, their mud content is higher in the eastern part of the estuary.

The present multiple channel system was formed many centuries ago when the channels still fed large tidal basins, like the Braakman, the Sloe and the Kreekrak. As a result of natural developments (land formation) and human interference (reclamation), large areas of these tidal basins have disappeared, and many channels have lost their original function. The present form of the Western Scheldt estuary is therefore the result of a combination of natural and anthropogenic processes. At present the interventions on the system have the same order of magnitude as the natural sediment transport and for this reason human interventions have a major effect on the morphodynamic system. Dredging activities in the estuary maintain or increase the channel depth for navigation. Higher water depths may raise flow velocity and then favour the erosion of the edges of the intertidal areas. Dumping of dredged material keeps the dredged sediment within the system and can contribute to the formation or growth of neighbouring intertidal flats, as it happens for instance, to the Valkenisse tidal flat.

In general human interventions in the Western Scheldt result in the attempt of “freezing” the system at the present state. “System freezing” means the reduction of the amplitude of the fluctuations superimposed on the present estuarine configuration, which is taken as the basic configuration of the dynamic equilibrium. While “freezing” the system at the present configuration, human interventions can have the consequence of altering the secular-term trend. This alteration is difficult to perceive, since the secular-term variations are very small and cannot be easily detected on the temporal scale of decades, which is the time-scale covered by regular monitoring. We need therefore a long period of time to be able to detect the long-term trend.

The Western Scheldt estuary is entirely constricted by dikes. For rivers, where the channel, due to its natural migration, reaches the dike, the cross-section becomes deeper (this typically occurs at the outer side of a bend). When a river channel migrates, its cross-section tends to remain relatively large. In this case the discharge is distributed through a relatively large width and, even though the channel is deeper at the eroding side, the large width limits the velocity at the eroding side. When the channel is not free to migrate anymore, an extra scour is formed near the dike and there the velocity increases. The channel conveys more and more water in its deeper part, while the shallower part and the secondary channels convey less water and tend to silt up (Friedkin 1945, Nanson & Hickin 1983, Mosselman ea. 2000, Germanoski & Schumm 1993). The deep channel can only be kept in equilibrium by means of heavy interventions to stabilise the dike and possibly also its bottom. This process could possibly play a role also in the morphodynamics of the Western Scheldt, where it might lead to a local gradual transformation of the multiple channel system into a single channel system. Extra-interventions, such as dredging of the secondary channels and dumping into the main channel, could be necessary to maintain the multiple channel system, as it is now the Western Scheldt, caused by the fact that the estuary is constricted between dikes.

In general, estuaries can be considered to be in a transient phase and three *trends*, operating at different time-scales, can be distinguished:

1. Silting up, this is due to net landward sediment transport. Due to sedimentation, the estuary gradually reduces in size.
2. Eroding, this results from net seaward sediment transport and might include large-scale sediment extraction. Due to erosive processes, the estuary becomes wider and deeper.
3. Dynamic equilibrium: this is characterised by a basic estuarine configuration which is maintained over a time horizon of several decades, on which shorter-term fluctuations leading to smaller-scale morphological changes may be superimposed (change of function of a tidal channel, migration of intertidal flats). It is believed that the Western Scheldt is in such a dynamic equilibrium at present, possibly also as a result of human interference. As part of this equilibrium it has been hypothesised by Winterwerp et al. (2000) that the present multiple channel system is self-preserving.

We cannot expect that an equilibrium configuration is maintained over the temporal scale of several centuries: in a morphodynamic system a long-term trend is always present. Instead, when considering a shorter temporal scale (tens of years, up to a hundred years) we can also find a situation of dynamic equilibrium, for which the secular-scale trend, which is always present, is small with respect to the fluctuations and can be neglected when the considered time-scale is sufficiently short.

The fate of the Western Scheldt is a question of sediment budgets, concerning all sediment fractions: sand and fines (silt and clay). These are the inputs and outputs of sediment (see Figure3.11), they depend on: the river Scheldt solid discharges, the transport from and to the sea (tide and sediment availability from the coast), the human activities, such as sand extraction, dredging and dumping and the effects of biology.

From the last report on the sand balance, published by Rijkswaterstaat, Direction Zeeland, in the period 1955-1999 the total import of sand from the sea was equal to 63 Mm^3, the total amount of extracted sand 92 Mm^3, the amount of dredged material 335 Mm^3 and that of material dumped within the Western Scheldt 315 Mm^3 (not all dredged material is dumped within the system). The input of (fine) sediment from the river has not been quantified.

The numbers prove that human interference is large and it is expected that it will not change in the near future. However a new future trend may be that the managing authorities will interfere more actively to preserve habitats and nature resorts or even start actually constructing natural resources.

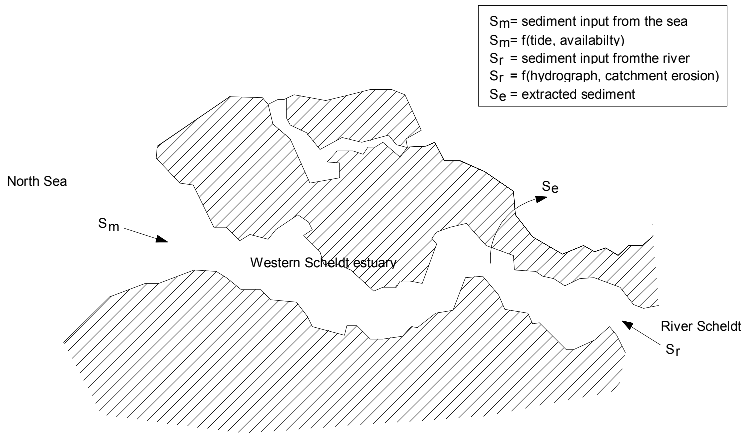

Figure 3.11 Sediment budget Western Scheldt.

The ebb tidal delta at the mouth of the estuary plays an important role in the exchange of sediment between the North Sea and the Western Scheldt. The interaction between ebb tidal delta and Western Scheldt will affect the morphological developments of the estuary to a large extend at the mega-scale. At present the ebb tidal delta is probably below its equilibrium level.

For the study of the long-term evolution of the estuary we have to consider also the expected climate changes. In the far future (50 years or more) we can expect to have appreciably higher water levels, due to sea-level rise (expected future rate 50 cm/century, present rate 10-20 cm/century), a larger tidal range and, most probably, also higher wind waves. The deepening or shallowing of the estuary depends on sediment inputs and outputs and on the accommodation space to be filled in. Accommodation space is the new volume occupied by water which should be filled in by the sediment to maintain the same cross-sectional area. The volume to be filled in during a given time interval is a function of the speed of sea level rise and of the extension of the estuary. The system remains in equilibrium when the cross-sectional area remains constant. For a rectangular cross-section, this happens when the rise of water level equals the rise of the bottom level due to sedimentation. In any case we can expect that beyond a critical speed of sea level rise the system will drown (Van der Spek, 1994).

The surface area of the intertidal areas depends on their elevation and on the tidal range: the larger the tidal range, the larger the extension of those areas which become alternatingly dry and submerged by water. In the Western Scheldt the tidal range near Antwerpen has increased by three meters since 1650 A.D. (see Section 3.1.2), but, in spite of this increase, due to embanking and land reclamation, the intertidal surface area decreased from 350 km^2 to 90 km^2, which caused the doubling of the tidal-wave celerity (van der Spek, 1994). Due to the combination of increased tidal range and decreased estuarine surface, the flood volume has decreased only slightly (13 %) in the same period.

Because of a more simultaneous flooding of the intertidal areas, due to the higher celerity of the tidal wave, the flood has reduced and the ebb velocity increased, so that since 1650 A.D. the tide has become more symmetric (has become less flood dominated). In the current situation the tide is still flood dominated near the inlet, at Vlissingen, with the consequence that the tide-induced residual sediment transport is still positive landward, but the amount of sediment transported into the estuary has decreased considerably since 1650 A.D (van der Spek, 1994). Actually, in the last decade the net marine sediment import results changed into a natural export, for a total loss of 6 Mm^3 of sand, as reported in the sand balance report 1955-1999 carried out by Rijkswaterstaat, Direction Zeeland. However since 1998 there is sand import again. It is not clear whether this is a short-term fluctuation or the starting of a new trend. Both phenomena could be induced by human interference.

An important consequence of confining the estuary between dikes is the decreasing of the amount of free space for the development of salt marshes. Salt marshes can be regarded as the biological component which most strongly affects the long-term morphological changes of an estuarine system. Macrophytes make the substrate more resistant to erosion and favour sediment deposition. The effects of zoo-benthos are generally milder and species-dependent. Benthic species can influence the bottom characteristics by either making the bed sediment more resistant to erosion or by favouring the conditions for erosion. In the first case we speak of *biogenic stabilisation*, in the latter of *bioturbation* (Paterson, 1997). Microphytobenthos secrete extracellular polysaccharides (EPS), which increase the cohesion of sediment, favours the deposition of fine particles and protects the soil against erosion (Van de Koppel, in press). Both zoobenthos and microphytobenthos are strongly seasonal, for example the effects of diatoms are restricted to the summer months. On the long-term, if the morphological changes are dominated by the hydrodynamic conditions of the cold season, the effects of zoobenthos and microphytobenthos on bed level changes and on soil properties can merely be seen as “noise” (seasonal fluctuations). Since the plants characterising the salt marshes are also present and active in the colder seasons (less active than in the summer), their effects on the morphological changes can be assumed greater than those of zoobenthos and microphytobenthos. In this case we can speak of a “dynamic interaction between salt marshes and those physical factors responsible for the morphological changes”.

The presence of salt marshes along the channel sides, by working against erosion and favoring local sedimentation, hinders the movement of the channel towards the dike. Therefore the role of salt marshes in opposing channel shift should be studied in view of future climatological changes and, when possible, quantified. Their efficiency in preventing soil erosion should be quantified as a function of their relative extension, their succession stage, the inundation time etc.

Confining the estuary between dikes means also that, for the Western Scheldt, sea level rise, when not counterbalanced by sedimentation, could eventually only result in cross-section deepening, since cross-section widening is limited by the dikes. Cross-section widening could help in forming large areas of salt marshes along the banks, which would favour riparian sedimentation. In the Wadden Sea the salt marshes, or “kwelders”, rise 30 to 80 cm per century, due to sediment supply and deposition (see internet site: *www.waddenzee.nl*).

No cross-section widening but only deepening could mean that the salt marshes might not be able to develop because of steepening of the banks of the estuary and could not prevent the drowning of the system by sediment trapping.

Besides sea level rise, the expected future climatic conditions also include higher peak river discharges, higher wind waves and a larger tidal range. An increased tidal range also means larger current speeds. In this context we can reasonably expect that the salt marshes will also have to withstand a higher erosive power, especially if they are located along steep channel banks.

Predictions of the system fate on the secular scale are complicated by a number of phenomena which are difficult to predict. What is difficult to predict, for instance, are the possible future changes of the tidal-wave asymmetry which can be induced by the characteristics of the intertidal areas and salt marshes in the future (extension of storage areas) with consequences on the sediment inputs from the sea. Changes in the tidal-wave asymmetry due to the increased celerity of the tidal wave have already occurred in the past (van der Spek, 1994). Moreover, with respect to cohesive sediment, at present the riverine sediment input in the Western Scheldt is much smaller that the marine input, but in the future the riverine input can become relatively more important with respect to the total budget of fine sediment (possibility of having higher peak river discharges and negative sediment balances in the future).

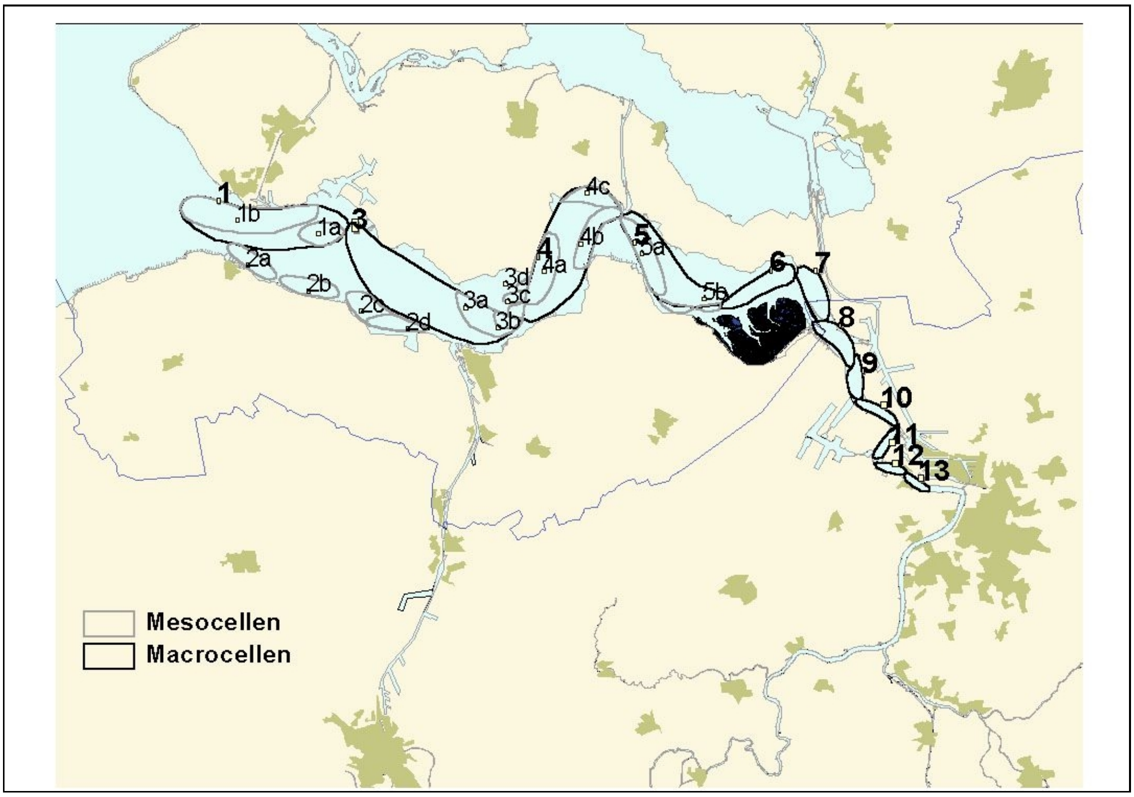

Figure. 3.12 Morfological schematisation of the Scheldt estuarium in morfometrical units.

Winterwerp et al. (2000) provide a good historical analysis and considerations about the future based on computations of sediment budgets for various scenarios. The Western Scheldt can be schematised as a chain of morphological cells; each cell containing a flood and ebb tidal channel and an intertidal area in between (see Figure 3.12).
From morphological analyses of this cell system they concluded that this system is not largely affected when channels are deepened (dredging activities), although the area of intertidal flats will decrease and their slopes will steepen. The system may become unstable if the cross sections of channels are decreased, for instance as a result of dumping activities. In that case, the multiple channel system may degenerate into a one-channel system. Such a one-channel system contains far less degrees of freedom and its resilience against external forcing decreases as well.

3.2.3 The Eastern Scheldt

At present, depth gradients are decreasing in the Eastern Scheldt. Channels are silting up with fine-grained sediments and sandy shoals and mudflats are eroding. This process had been predicted as a consequence of the construction of the storm-surge barrier (Rijkswaterstaat, 1988) and will most probably continue for the next 30 years or more. The loss of intertidal areas has been estimated to amount to about 1500 hectares, which is 10-15 % of the present total area (Nienhuis & Smaal, 1997). Loss of intertidal areas will favour erosion of the edges of the tidal basin, which are more exposed to wind and waves. This will lead to further reduction of the salt marshes. Sea level rise will enforce the loss of intertidal areas. Similar to the Western Scheldt, the Eastern Scheldt is constrained by dykes. Therefore, sea level rise will mainly result in cross-section deepening and drowning of intertidal flats drowning.

In general, on the secular temporal-scale, the Eastern Scheldt is expected to decline in its morphological variety and dynamics and become a more uniform intertidal basin.

3.2.4 Haringvliet

Partly opening of the dam (“Sluis op een kier”) will not significantly change the morphology of the Haringvliet mouth. Sedimentation will continue and the intertidal area will increase with time. The damped-tide alternative will increase tidal velocities and thereby sediment transports. Especially, the gullies in the southern part of the mouth will be eroded more strongly.

Inner area

Since the closure of the Haringvliet, almost no tidal currents are present any more in the inner area. The fresh water basin that has developed is slowly silting up, slightly more in the eastern than in the western parts (approx. 10 mm/year). Especially in the parts that are shallower than 6 m $^{+}$NAP, silt is mixed with sand under influence of wave action, resulting in a sand-silt top layer of the bed.

Sedimentation front

Directly after closure of the Haringvliet, sedimentation took place in the Nieuwe Merwede and the eastern part of the Hollands Diep (6-8 m silt layers). These areas are now in equilibrium, having both bed-load and suspended transport. The sedimentation front is slowly moving westward, currently silting up the gullies in the western part of the Hollands Diep (1-2 m silt layers have been reported for the deepest gullies). Only on the very long term (>> 100 years), it is expected that the western parts of the Haringvliet will be in equilibrium as well.

Shores

The shores in the Haringvliet are subject to direct wave attack. Because no tidal differences in water level occur since the closure, the shores are being eroded at one water level. In the 1980s, foreshore protection works have been carried out.

Dordtse Kil and Spui

The Dordtse Kil and Spui were relatively unimportant flows before closure, but after 1970 their tidal velocities increased considerably filling the Haringvliet and other connected waters. The material eroded has partly been moved to the Haringvliet and partly to the Hollands Diep. Both branches are in equilibrium now.

3.3 Dutch Wadden Sea

3.3.1 Morphodynamics

The morphologically most dynamic area of the tidal basin system includes inlet throat and outer or ebb-tidal delta. Figure 3.13 gives a schematised representation of this system, in which the generally preferred north-west orientation of the tidal channels is accounted for. The overall stability of this system is assumed to be dependent on a balance between tidal prism, representing the tidal energy, and net longshore sediment transport due to the wave conditions. The Dutch Wadden Sea inlets seem to obey this stability criterion. This does not mean that within the system there is no temporal variability. The continuous feeding of the system through bar- and tidal bypassing gives rise to cyclic behaviours of channels and marginal shoals.

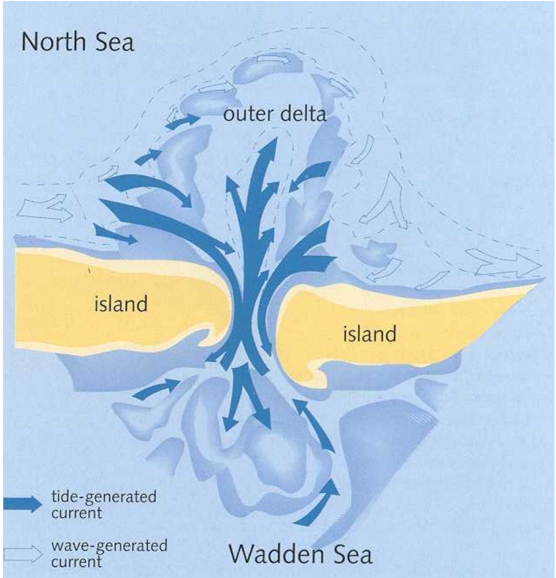

Figure 3.13

Schematisation of the interaction between the open sea and a typical Dutch Wadden Sea lagoon (Louters and Gerritsen, 1994).

The very existence of the tidal basins over appreciable time-spans indicates that they can display a large rate of stability. This stability demands that channel widths, channel depths, intertidal area extent and depths are dynamically inter-related. In this case the internal dynamics can restore the morphological stability of the basins when for instance the channel depths are disturbed. Data-analysis indicates that the ratio between average channel depths and intertidal areas is such that ebb- and flood-related sediment transports are approximately in balance.

On the longer time-scale (say decades to centuries) the combination of sea-level rise and decrease of basin area due to riparian sedimentation, although small in magnitude on a year scale, results in the creation of accommodation space for sedimentation. Consequently the Wadden Sea basins act as sedimentary sinks.
Of the sediment that settles within the Wadden Sea, some 70-80% consists of sand and the rest is silt and clay. Sand is found near the inlets, in the channels and on the intertidal areas near the inlets. The granulometry diminishes landward.

When we extend the tidal basin systems, by including their adjacent barrier islands, the Wadden Sea system can be considered to have an almost closed sand economy. Almost no sand is exchanged with the open North Sea. Most of sand that settles inside the tidal basins comes from the inlets, the outer delta and the open sea coast of the barrier islands, a – not well-quantified – contribution is also given by the coast of North –Holland, see Figure 3.14. This movement of sand from the outer border of the tidal basin to inside the basin causes the islands to move landward. It can be reasonably assumed that fixing the position of the islands by preventing the erosion of their open-sea coast could cause a deficiency of sand within the Wadden Sea.

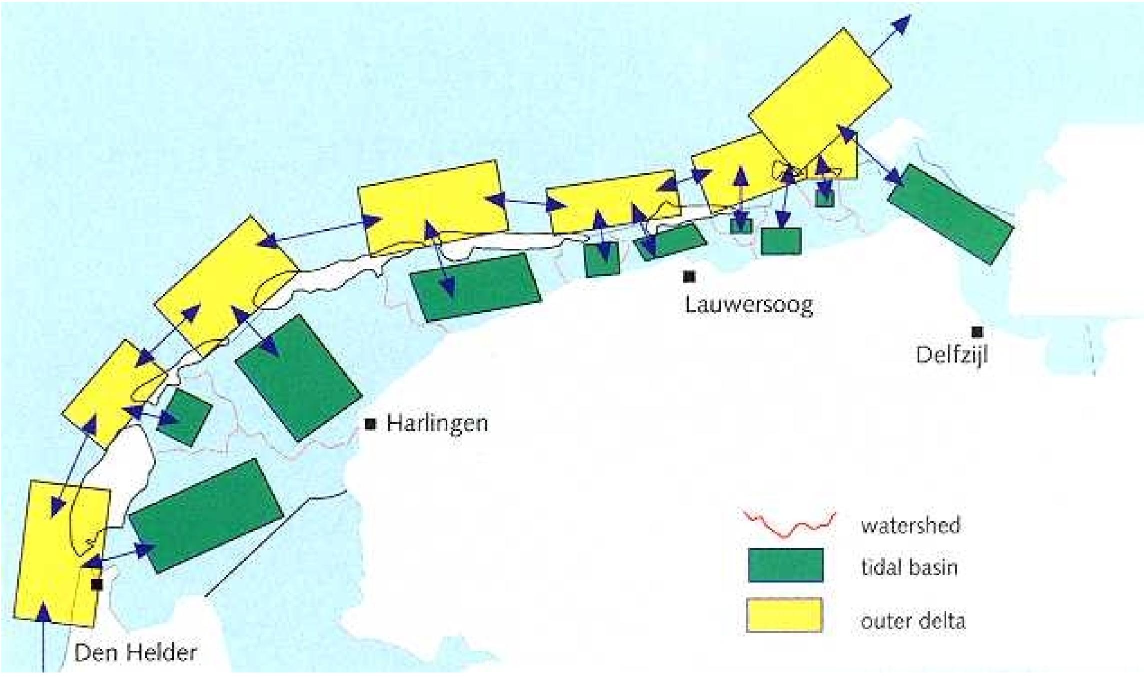

Figure 3.14 Sand sharing system. The sediment budgets are all interlinked (Figure from Louters & Gerritsen, 1994, modified after Stive and Eysink, 1990)

The largest part of the fine sediment is found on the mudflats, which cover about 25% of the area, or is trapped in the marshes and in the land reclamation areas, where deposition is made possible by lack of both strong currents and waves. It is not clear if at present the intertidal flats are being eroded or not (their total surface seems stable). The system seems in a dynamic equilibrium, even though the reclamation areas recently show diminished sedimentation rates.

The fine sediment that enters the Wadden Sea comes from the North Sea, but originates mainly from rivers, mud banks and shorelines in the Southern Bight (Postma, 1981). Apart from the large and rather stable mud field in the North Sea, located at the north and north-east of the Wadden Sea (at water depths larger than 30 m), deposits of fine sediments are present in the shallow water along the Dutch coast and between shoals in the Southern Bight. These deposits seem rather ephemeral and are probably the major sources of fine sediment for the western part of the Wadden Sea. This sediment enters the Wadden Sea through the inlets. Sediment grain size diminishes landward. More to the east large amounts of fine sediment are brought in by the rivers Ems, Weser, Elbe and Warde (Postma, 1981).

3.3.2 Present human interventions

- **Coastal protection works**. Dikes protect the entire Dutch mainland Wadden Sea coast and the reclaimed areas along parts of the barrier islands. The salt marshes along the mainland coast are protected against erosion by brushwood groins perpendicular to the coastline. The North Sea coast of the Wadden islands is generally subject to erosion, although some stretches with natural accretion are present on a few islands to the east. Dunes protect the largest part of the open seacoast and only on Texel and Vlieland some hard breakwaters are present. Embankments and fixed coastal constructions have seriously reduced the volume of the tidal basins and the ability of the system to compensate for sea level rise and bottom subsidence. The actual policy against beach erosion is that of applying sand nourishment. In 1993 the first (pilot) large-scale sub-shore sand nourishment was carried out off Terschelling. This method seems very promising (de Jong et al. 1999) even if the sand is taken from the intertidal areas in the Wadden Sea basin.

- **Fishing (cockles, mussels, shrimps)**. Since 1950 mussel farming has been extensively developed in the Dutch and German parts of the Wadden Sea. In the past mussel fishery was mainly carried out on natural areas, mainly on intertidal banks. Now fishing on natural banks is small when compared to the quantities fished on culture lots. Today one fourth of the area is closed to cockle and mussel fishery and the quantities allowed are regulated on the demands of food stocks for birds. Also sea grass fields, which since the construction of the Afsluitdijk have become very scarce, are protected against fishing. The loss of biogenic structures, such as sea grass fields and mussel beds, can possibly reduce the ability of capturing sediment in relation to the sea level rise phenomenon. Most shrimp fishery is carried out north of the Wadden islands, where it is allowed during the winter also. Most of the vessels there are used for both shrimp and flatfish fishery. The number of fishing vessels has not increased in the last decade, but their mechanisation has increased the intensity of the fishery (de Jong et al. 1999).
- **Harbours and shipping (dredging)**. Dredging within the Wadden Sea is only carried out to maintain the shipping routes. In the last decades the number of ships passing through the Wadden Sea has decreased, but the average size of ships has increased. In Germany the recent increase of ship volume has led to the decision to deepen the Elbe and Weser estuaries (de Jong et al. 1999).
- **Dumping of dredged material.** Material dumped into the Wadden Sea mainly consists of the material dredged to maintain the shipping routes. The amount of dumped material in the Dutch Wadden Sea varies between 2.3 and 5.9 million tons per year. The dredged material from Delfzijl (Eems-Dollard) is all being dumped within the estuary.
- **Extraction of sand and shells.** The yearly amounts of sand extraction have reduced to less than one million of cubic meters recently, while the average amount of shell extraction is 85,000 m^3. These activities lead to local bottom subsidence and therefore contribute to aggravate the process of relative sea level rise (even though only locally) and the connected risks for the Wadden Sea basin.
- **Hunting.** In the past hunting of seals and water birds was part of the traditional life of the inhabitants of the Wadden islands. Nowadays hunting has become a recreational activity and takes place mainly on the salt marshes behind the dikes and on the dunes, but only on private properties. Hunting is allowed only for a number of water birds species and is restricted to certain periods.
- **Recreation.** The principal activities are recreational boating, wading (tidal flat walking) and land-based tourism. The number of recreational boats crossing the Wadden Sea can be derived from the number of sluice passages. This has increased from about 70,000 in 1982 to almost 98,000 in 1996, in the same period the peak season extended by some weeks. A number of regulations on speed, protected areas and periods limit the impact of recreational boating. The number of people participating in organised wading increased from about 14,000 in 1978 to 40,000 in 1989 (there has been no significant increase since then). Annually 130,000-180,000 persons carry out ship-based tidal flat walking. Land-based tourism counts 12 million overnight stays in 1993 in the Netherlands (data from de Jong et al. 1999). Regulations restrict all activities in the Conservation Area (see Figure 6).
- **Military activities.** The use of the Wadden Sea for military exercises has started after the Second World War and has been reducing in the last years.

- **Gas extraction.** There are two gas exploitation zones within the Dutch Wadden Sea, the Zuidwal (western part) area and the North Frisland area (three locations around the island of Ameland). The gas is transported to the treatment stations at Harlingen and at the coast of Groningen via pipelines. The extraction of gas in the northern part of the Netherlands has caused (and will cause) considerable subsidence of the bottom (see Subsection 3.2.3). This phenomenon is due to the diminished underground pressure and consequent soil compaction. Expectations for the next 50 years are a maximum subsidence of 20-30 cm.

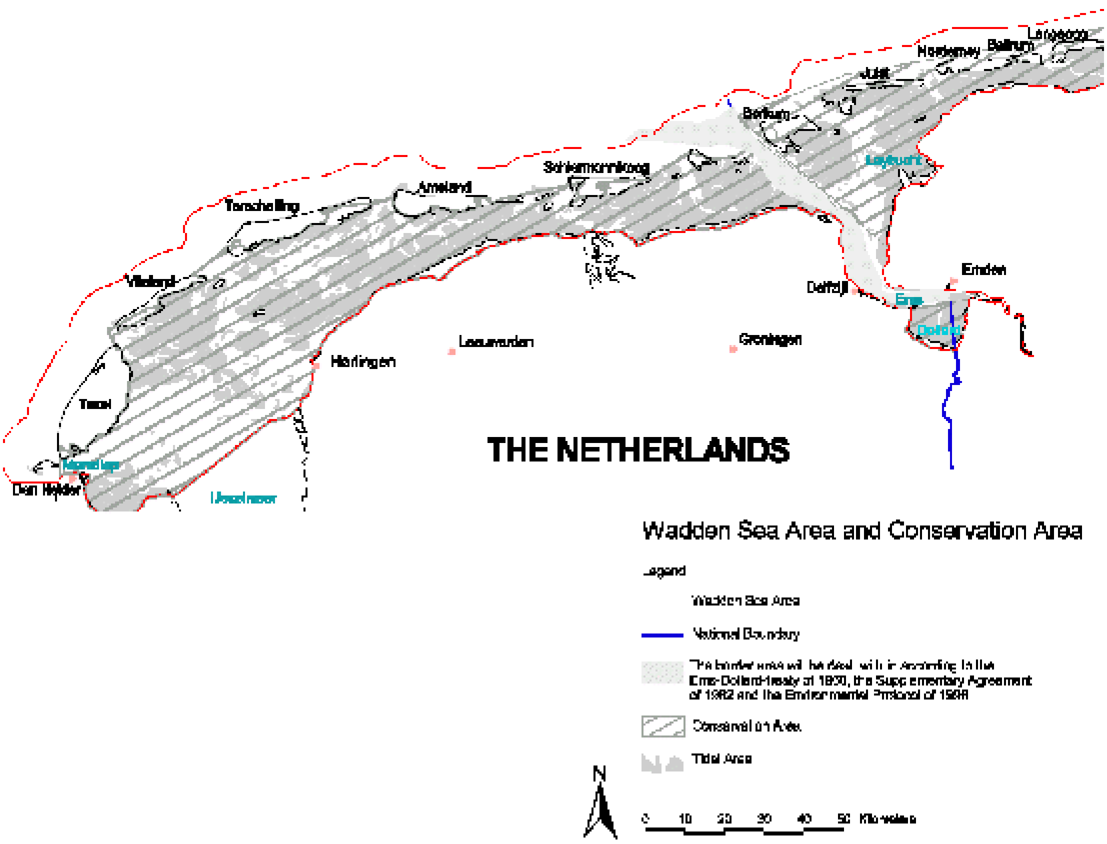

Figure 3.15 Conservation Areas in the Dutch Wadden Sea (RIKZ, CWSS, 1998)

3.3.3 Future scenarios

Measurements of mean sea level along the open Dutch coast from the past 150 years indicate a sea level rise of somewhere in between 10 and 20 cm/century. At present along the northern Dutch coast, due to glacio- and hydro-isostasy, the sea bed is subsiding at a rate of 4 to 8 cm per century and will most probably continue with the same rate also during the next century (Louters & Gerritsen, 1994). Also the present human activities, such as gas extraction, and to a lesser extent sand and shell extraction, contribute to the lowering of the sea-bed, even though locally. The largest gas field (Slochteren) is expected to produce a maximum subsidence of 20-30 cm in the next 40 years. The average expected subsidence due to gas extraction is different for the different basins: for the Borndiep Channel it is 3 cm, for the Pinke Gat 15 cm, for the Frisian Gat 5 cm and for the Lauwers Gat 6 cm.

There appears to exist a reasonably general scientific consensus that the Wadden Sea tidal lagoons are able to maintain their morphological stability relative to mean sea-level given the current rate of relative sea-level rise. A necessary condition for this is thought to be that there exists sufficient sediment availability, which seems to be the case based on long-term bathymetric surveying. It must be stressed though that this has not been proven unambiguously.

Warrick and Oerlemans (1990) for the next century expect an *additional* eustatic sea-level rise between 0.31 and 1.1 m, with a best estimate of 0.66 m, if the rates of greenhouse gases production remain constant. An additional 0.66 m to the present sea-level rise, would bring the Wadden Sea back to the sea-level rise conditions of about 7000 years BP. There are different opinions on the implications of this.

Louters & Gerritsen (1994), amongst others based on the ISOS*2 reports (Eysink and Biegel, 1991, 1992, 1993), do not anticipate major changes in the Wadden Sea tidal basin one-century from now, even in case of accelerated sea-level rise, unless also the storm climate changes. In the latter case additional erosion due to wave action can be expected along the edge of the salt marshes which, since in that case the development of their pioneer zone will be restrained, will most probably disappear. They also conclude that the present rate of sea-level rise will cause steepening and retrogradation of the barrier-islands coastline by one meter per year, while an increased sea-level rise of 85 cm/century would cause an additional retrogradation of 2-3 m per year.

In contrast, Van der Spek (1994) through geological analogy suggests the possibility that the subtidal area will expand at the expense of the former flats and the salt marshes will disappear. However, a number of conditions are different. The tidal basin of 7000 years BP and the present Wadden Sea differ for instance in tidal regime, basin shape and nature of sea-level changes (accelerating versus decelerating sea-level rise). Through human fixation of the barrier islands and of the basin boundaries the system has no possibility of shifting landward anymore. In order to maintain its configuration it needs to build up with sea level rise, which requires more sediment input than in the past. This issue must therefore be considered unresolved.

4 Ecological developments

4.1 The Western Scheldt

In the last century the Western Scheldt estuary has become deeper and narrower. The storage areas have been reduced in the period 1930-1960 and the channels have become deeper and larger (Vroon et al., 1997). The large-scale dynamics, that is main and secondary channel migration, have decreased due to the fixing of the estuary contours. Comparison of the bathymetries in 1800 and 1990 shows that deepened main channels lie for a longer reach against the dykes now. In the eastern part of the Western Scheldt the channels are kept in place by dredging/dumping operations. Meso-scale dynamics, such as migration and formation of short-cut channels, have decreased also due to the positioning of the main channels against the dykes. As a consequence of their increased depth (scour) the main channels convey more and more discharge, while the secondary channels cutting the intertidal areas convey less and less water, loose dynamics and tend to silt up.

In the Western Scheldt the following ecoseries (here, ecoseries are defined as ecologically relevant units having the spatial scale of a whole intertidal flat, that is of hundreds of meters) can be distinguished: channels, shallow waters, mudflats, sandy shoals, salt marshes and hard substrates associated with bank protection. Mudflats and sandy shoals can be subdivided further in ecotopes on the basis of mud content, dynamics and bottom level (Huijs, 1995). Ecotopes are homogeneous units having spatial scale of tens of meters. The following table summarises the changes of surface area of the different ecoseries between 1960 and 1990.

	Year	Total	channels	shallow waters	sandy shoals	mudflats	Salt marshes
Marine area	1960	17 210	10 340	2 080	2 800	1 400	580
	1990	16 130	10 740	1 660	2 700	890	160
Transitional area	1960	5 610	3 010	1 000	990	560	50
	1990	5 590	3 140	630	1 280	540	20
Brackish area (NL)	1960	10 060	2 810	1 370	690	2 300	2 890
	1990	9 210	3 090	880	960	1 912	2 360

Table 4.1. Surface area of ecoseries in ha in 1960 and 1990.

During last decades, the most important change in the area of ecoseries in the Western Scheldt estuary was the disappearance of “young” and erosion of “mature” salt marshes (“schorren”). This process has been slowed down because the stronger *Spartina*, of English origins, has replaced the weaker local species. In the eastern part of the estuary the intertidal mudflats have reduced also. Low-dynamic mudflats are potentially the richest ecotopes with respect to benthic fauna and consequently the most important foraging areas for birds and fish. The reduction of intertidal mudflats is, therefore, an ecologically relevant problem.

When compared to the Eastern Scheldt and the Wadden Sea, The Western Scheldt is relatively poor in macrofauna. (Table 4.2). The brackish intertidal areas of the Western Scheldt are rich in aviofauna. Buise & Tombeur (1988) give a good description of the situation in the Verdronken Land Van Saeftinghe. This area is mainly characterized by the presence of ducks and stilt species. Swimming and diving fish-eating birds have never been numerous in the Western Scheldt estuary. Ducks feed mainly on seeds of water plants, but also on small animals such asoligochaetes (small worms) by slurping the silty bottom surface. The stilt species live on zoobenthos, especially worms, such as oligochaetes and *Nereis*, snails, such as *Hydrobia*, and Crustacea, such as *Corophium*.

1994	Crustacea (g/m^2)	Mollusca (g/m^2)	Vermes (g/m^2)
Western Scheldt sea-side	0.43	7.27	3.01
Eastern Scheldt sea-side	0.18	15.18	4.87
Western Scheldt inland	0.08	3.11	0.62
Eastern Scheldt inland	1.40	40.66	5.79

Table 4.2. Biomass in the Western and Eastern Scheldt measured in 1994. (Ministerie van Verkeer en Waterstaat, 1996).

4.2 The Eastern Scheldt

Before the construction of the Volkerakdam in 1969, the rivers Rhine and Meuse were connected with the Eastern Scheldt basin. At that time about 10% of the river waters discharged through the Eastern Scheldt. River discharge determined the salinity gradients and fluctuations. At present the river discharge in the Eastern Scheldt is regulated by the sluices of the Volkerakdam and is kept minimal. Some additional fresh water enters the Eastern Scheldt from the Oesterdam in its southern branch. Freshwater inputs are lowest in winter and highest in summer (Haas, 1998). At present there are discussions about a future regulation of the river water inputs which, allowing higher fresh water discharges, could partly restore the estuarine character of the Eastern Scheldt. The construction of the Storm-surge barrier has reduced tidal range, tidal volumes and current velocities. Furthermore, the sand input from the sea has almost diminished only fine sediment now enters the Eastern Scheldt basin. This fine sediment settles in the tidal channels, which are silting up. However, due to lack of sand input to compensate the erosion rates, the sandy shoals and the mudflats are eroding at the same time.

With the present regulation of the fresh water inputs the Eastern Scheldt has become a system poor in nutrients and with high salinity. However, turbidity has decreased also. The improved light climate compensated for the lower availability of nutrients, so that net productivity in the Eastern Scheldt, against all expectations, has not decreased. The important interventions of the last decades have had great consequences for the biology of the Eastern Scheldt basin. The decrease of the tidal range strongly affected the salt marshes: from the original 17 km^2, 11 km^2 of salt marshes are not subject to the tidal influence anymore. After the construction of the Storm-surge barrier the surface of the Eastern Scheldt basin covered by sea grass has drastically decreased from the 1100 ha in 1984 to the 67 ha in 1997. This strong reduction seems to be caused by the increased water salinity. Common sea grasses in the Netherlands require salinity levels equivalent to 10-16 g Cl/l. Therefore, an increase of fresh water input might improve the situation. Sea grass fields are ecologically important, since they form special biotopes. They provide food and shelter to several benthic species and they play an important role as spawning and nursery area for fish. Birds take advantage of the abundance of food they provide, comprising both zoobenthos and the sea grass itself. In the Eastern Scheldt there are two species of sea grass: *Zostera noltii* and *Zostera marina*. Both species live in the middle and high parts of the intertidal areas, dependent on the transparency of the water, and may potentially colonise lower parts now the transparency has improved. Several algae species (*Enteromorpha spec., Ulva spec., Fucus spec.,* and *Gracilaria verrucosa*) grow on the intertidal flats. Because of the reduction of currents and waves since the construction of the Storm-surge barrier the algae seem to have found an optimal habitat in the Eastern Scheldt. Since 1985, their biomass has increased appreciably, to the point that it can suffocate zoobenthos and sea grass locally.

Studies carried out by NIOO-CEMO and RIKZ (Haas, 1998) on 54 zoobenthic species show that 11 species have disappeared since the compartmentalisation of the Eastern Scheldt basin. An increase of fresh water input could lead to the return of four of these species, but at the same time it could also deteriorate the habitat of the Japanese oyster (*Crassotrea gigas*). For the cockle, *Cerastoderma edule*, the effects of increased fresh water input is unclear, mainly because competition with the brackish-water species *Cerastoderma glaucum* could lead to a decrease of its population density. The Eastern Scheldt is an important area for shellfish culture (mussels, oysters) and fishery (cockles). It is therefore important to maintain the water salinity within the tolerances of these commercial species (Haas, 1998).

The fish population in the eastern Scheldt has a high diversity, especially when compared to the neighbouring Western Scheldt and outer delta. The most common fish species are either marine juveniles such as *Pleuronectes platessa*, *Limanda limanda*, *Solea solea*, *Clupea harengus Trisopterus luscus*, *Merlangius merlangus*, or estuarine resident species such as *Myoxocephalus scorpius*, *Zoarces viviparus*, or diadromous species, such as *Anguilla anguilla.* The major effects of the Delta works on the fish population has been the disappearance of those fish species that ascend rivers to spawn, such as the salmon (*Salmo salar*) and the sea trout (*Salmo trutta*). This is mainly due to the physical hindrance to their free migration, caused by the presence of the dams and the sluices, but also by the poor quality of the spawning areas upstream. With the creation of an estuarine gradient (increase of fresh water inputs) the typical marine fish species will most probably disappear from those zones of the Eastern Scheldt that will become brackish. However, it will promote the occurrence of typical brackish species. It is expected that increased freshwater inputs will improve the total species diversity.

Similar to the Western Scheldt, birds foraging in the Eastern Scheldt are mainly ducks and stilts. Lowering of the intertidal flats as a consequence of the construction of the Storm-surge barrier may reduce the extension of the foraging areas of the stilts. This adds to strong reduction of sea grass fields.

4.3 The Haringvliet

The sluices in the Haringvlietdam became operational in November 1970. Since then, the Haringvliet has become a freshwater body (van Wijngaarden & Ludikhuize, 1998). Before closure the tidal range in the Haringvliet estuary was relatively low in comparison to the neighbouring tidal basins (~ 1.8 m). At the inner side of the Haringvlietdam stagnant freshwater channels accumulate polluted sediment, while, due to both the higher mean water-level (increased by 0.4 m) and the vanishing of the tide, the mudflats are almost all submerged now. The absence of emerging flats accrues the stirring of the waves against the shores and for this reason the marshes have soon been eroded and the banks have required protection works. At the outer side the closure induced an increase of the tidal range from 1.8 to 2.26 m and, mainly due to disappearance of currents entering and leaving the Haringvliet basin, a radical modification of the water motion. These changes have caused the accretion of shoals and the formation of new salt marshes, beaches and dunes at the shore of Goeree. The former channels have silted up and have become shallow water areas. In general, the area has increased importance as nursery area for fish and has a higher macrobenthic biomass. The irregular flushing with fresh water causes sudden relatively large salinity fluctuations, with negative consequences for local species diversity. The formation of new shoals, beaches and dunes has brought characteristic pioneering flora and fauna.

The switch from a salty-brackish-fresh intertidal system into an almost stagnant fresh-water system inside the Haringvliet meant the development of a completely new ecosystem. Fresh water habitats have quickly developed at the expense of marine and brackish fish species. The Haringvlietdam prohibits free migration of fish between the open sea and the freshwater basin. The former intertidal areas are now almost all submerged and form important foraging areas for herbivorous birds, such as ducks, geese and swans.

4.4 Long term development of mussel beds in the Wadden Sea.

In this section a summary will be given of the available information on long term developments (in both time and space) of organisms and communities which are considered to have an important influencing on sedimentation and erosion in the Wadden Sea. A distinction is made between biomass and biogenic structures. When organisms have a direct influence on sediment properties or suspended matter concentrations, biomass is an important parameter. In many cases, however, the structure build by a community is more relevant. For example reefs (coral, polycheate worms, oyster), mussel beds, eelgrass and kelp beds strongly influence wave action.

Following the argument in Herlyn & Millat (2000), a mussel bed is defined as structure *“consisting of a spatially well defined, irregular collection of more or less protruding smaller beds, which may be called patches, separated by open spaces”.* When describing a bed they measure its spatial extent as well as the percentage covered by these patches. For different sections of the Wadden Sea, maps showing the locality and size of mussel beds are available since the 1950’s or earlier. They are based on surveys by foot, or roughly mapped from a boat.

Only one integral study of the occurrence of mussel beds has been carried out so far. Dijkema et al (1989) mapped all mussel beds on the basis of aerial photography conducted in 1968 (western part) and 1976 (eastern part). The final map was produced after ground truthing in 1978, so only beds that were been present in 1968/76 and 1978 were included. The Dijkema map showed 4120 ha of mature beds in the Dutch part of the Wadden Sea. Comparison with other (general) inventories, and navigation maps along tidal walkways indicate that the map of Dijkema is representative for the period 1970-1988 (see also Dankers & Koelemaij 1989). Fisheries had a large impact in the 80s, and almost all beds disappeared when fisheries continued in a period with no or limited spatfall. Reasonable spatfall occurred in 1994, but the young and unstable beds disappeared because of a storm in the spring of 1995 and two subsequent severe winters. Less than 200 ha were covered with mussel beds in the Dutch Wadden Sea in the spring of 1999. Two of these beds were old (> 10 years), one was of 1992 and the rest originated from the 1994 and 1996 spatfalls. These spatfalls occurred mainly on, or close to, locations where beds had been present previously. Fisheries have not influenced the structure of the present beds. In 1999 a reasonable spatfall occurred again, mainly on cockle beds, resulting in at least 470 ha of seedbeds. Some of the beds were wiped out by storms in the winter of 1999-2000. These and similar observations in the German and Danish Wadden Sea show that mussel beds can survive for long periods. When they disappear, their remnants often provide suitable substrate for new settlement.

In the course of the 1980s strong declines of the mussel population were recorded from different parts of the Wadden Sea. The phenomenon gave rise to several large-scale surveys and other scientific activities trying to elucidate the reasons of this sudden and extraordinary stock reduction. The decrease involved reductions in both the area covered by beds and biomass per unit area. Several investigations showed that mussel beds in the Wadden Sea were distributed in a more or less constant pattern during several decades, albeit that the number of beds varied (Dankers & Koelemaij 1989, Obert & Michaelis 1991, Nehls & Thiel 1993). Biomass can vary greatly between years, and within years. When good spatfall occurs, biomass may show a 10-100 times increase in autumn. Often, the new beds will disappear again in the following winter. Reviews of biomass estimates were reported by Dankers et al (1998) for the the Netherlands, Herlyn & Millat (1997), Herlyn & Michaelis (1996) Michaelis et al (1995) and Zens et al (1997) for Niedersachsen, Ruth (1994) for Schleswig-Holstein and Kristensen (in MS) for Denmark.
In all areas biomass on beds of more than two years old has decreased over the last decades.
A initial indication is given in Table 4.3, in which only beds of more than two years old were taken into account. The data have to be treated with caution, as the individual investigations were not completey comparable.

	Area (ha) before 1980	1987	1997	Biomass (tons) 1980s	1990s
Netherlands	4120	650	< 200	100,000	< 10,000
Niedersachsen	5000	2700	170		1000
Shleswig-Holstein		1000-1500	615		
Denmark				23,500	43,500

Table 4.3. Development of mussel beds (in ha) and biomass of mussels (in tons) in the Wadden Sea.

5 Scale issues in biogeomorphology

5.1 Spatial and temporal scales

Scale issues are important for both geomorphology (de Vriend, 1991, 1998, Stive & de Vriend, 1995) and biology (Schneider, 1994, and Haury et al., 1997). Blöschl & Sivapalan (1995) give a good review of scale issues in hydrological modelling which may be generalised, although not in all aspects, for both geomorphology and biology.

Each component of a research cycle has its own temporal and spatial scales. Here, we distinguish the scales of processes, observations, modelling and policies.

Process scale
The process scale is the scale of the natural processes. Some processes exhibit one or more preferential scales, in the sense that certain length- or time-scales are more likely to occur than others. The preferred scales are also called the natural scales. For coastal inlets and tidal basins we find the following coupling between morphological processes and scales:

- micro-scale: evolution of bottom ripple and dune structures due to flow and waves;
- meso-scale: evolution of channels and shoals, ebb and flow chutes, channel-flat exchange;
- macro-scale: evolution of ebb-tidal delta, channel branching, channel meandering;
- mega-scale (this is the scale of the whole system): morphologic interaction between coastal inlet, tidal basin and adjacent coast.

Observation scale
The observation scale has two aspects: the spatial/temporal extent of data sets (coverage) and the spacing between samples (resolution) or the volume/time of a sample.

Process versus observation scale
Ideally processes should be observed at the scale they occur, but this is not always feasible. Processes acting at larger scales than the observational coverage appear as trends in the data, whereas processes at smaller scales than the observational resolution appear as noise. Day et al. (2000) illustrate the typical problems which can occur in the latter case: a misleading in the interpretation of causes and effects, in their case the causes of loss of wetland in the Mississippi Delta.

Modelling scale
The modelling scale is partly related to the processes and partly to the aimed applications of the models. Models depend on the observations, for both process description and calibration, but often the modelling scale is either much smaller or much larger than the observational scale. In those cases a *scaling operation* is needed, where “to scale” means “to zoom” or to “reduce/increase” in size. Thus *upscaling* means transferring information from a smaller to a larger scale (it is also referred as *aggregation*), while *downscaling* means the opposite, that is transferring information from a larger to a smaller scale. De Vriend (1991, 1998) deals with the scaling procedures related to the modelling of large-scale (long-term) morphological evolutions.

Policy scale
The policy scale is the spatial and temporal scale used by the authorities responsible for the management of the system and is often different from the process, observation and even modelling scales. In order to be able to give an answer to the many questions posed by the decision makers, often upscaling and downscaling procedures are needed, that is transferring information from processes/observation/modelling scales to the policy scale. Bierkens et al. (2000) treat the problems related to such upscaling and downscaling operations and provide a good overview of this type of procedures.

Biogeomorphology is a relatively young (sub)discipline, in which the biological and the hydromorphological aspects of a system are treated as fully coupled. Biogeomorphological studies are therefore typically multidisciplinary and complicated by the (often non-clear) inter-relations between the features of the two parent-disciplines, i.e. biology and hydromorphology. Important inter-relations also involve the temporal and spatial scales typical for the biological and hydromorphological components of the system. In recent years the importance of scale has been increasingly recognised (Legendre et al. 1997, Schneider, 1994) as an essential aspect of understanding the biological and abiotic processes that influence the bio-geo-morphology of, for instance, an estuarine system. Legendre et al. (1997) state: "Scale is one of the critical factors in ecology because our perception of most ecological variables and processes depends upon the scale at which variables are measured. A conclusion obtained at one scale may not be valid at another scale without sufficient knowledge of scaling effects; this is a source of misinterpretation for many ecological problems". The scale issue is therefore a rather new and important subject and deserves much attention for the progress of biogeomorphological studies.

Populations of benthic species can have specific spatial distribution patterns. This can be uniform, that is the individuals are evenly spread, well defined (bumps, troughs or waves), or patchy with aggregations randomly disseminated. The spatial distribution of a population can have a typical dimensional-scale also. Specific patterns can be recognised, for instance, at the large-scale (hundreds of meters), at the meso-scale (tens of meters) or even at the small-scale (meters). Furthermore for every species distinct distribution patterns and scales can be expected for the different life stages. Considering that many biological processes (spawning, life-stages, growth, and death) show seasonal variability, it can be expected that the spatial distributions of benthic populations reflect typical temporal scales also.

Scale factors play an important role in the study of benthic populations and therefore should be carefully analysed. To detect the influence of the abiotic factors on benthic populations one should identify all those parameters having effects at the proper spatial and temporal scales. For example the phenomena operating at the micro-scale (one meter or less), such as the small-size vortexes downstream of a ripple crest, cannot have important effects on those benthic populations which are uniformly spread over hundreds of meters. Instead it can be relevant to describe the micro-habitat of distinct species which are mostly found to live in the troughs between ripple ridges.

5.2 Scale concepts in biology and morphology

Theoretical concepts and techniques for the treatment of spatial and temporal scales are handled in both morphology and biology, but not always in the same way. Differences are found in the way of defining spatial scales as well as in the relation between spatial and temporal scales.

Definition of spatial scales
In hydro-morphology it is often customary to define scales relatively to the dimensions of the water body, but in doing this there is no general accord. This is done especially for river systems, where, for example, the meso-scale is the scale of the water depth, the macro-scale is that of the river width. For mega- and micro-scale there is no standard definition, even though mega-scale is often referred as the distance over which the drop of water level equals the water depth. In biology, scales are often defined in an absolute way and expressed in quantities, such as meters or hectares, as for instance “the surface occupied by salt marshes”. Klijn (1994, 1997) uses a hierarchical approach to define ecosystems in relation to their typical spatial-scale (i.e. ecoregions, ecodistricts and ecoseries), this approach can be used for ecological land classification.

Relation between spatial and temporal scales
For hydro-morphological processes, time- and space-scales are strongly linked. Phenomena and processes with small time-scales also have small space-scales, and phenomena with large time-scales also have large space-scales (de Vriend, 1991, 1998, and Blöschl & Sivapalan, 1995), see Figure 5.1

In geomorphology the linkage between spatial and temporal scale is formed by the sediment transport. For the development or migration of a small bedform only a small amount of sediment needs to be transported, which can occur relatively fast. The development or migration of a large bedform requires transport of a large amount of sediment and hence a much longer time. The fact that a single process (sediment transport) is the decisive factor for the speed of processes on all scales makes that the relation between time scales and space scales can be plotted nicely along a line in a graph, see Figure 5.2. This is much less so in biology, where more than one process plays a role in the dynamics of a biological population (e.g. growth, colonization, mortality and migration) and thus leads to larger complexity.

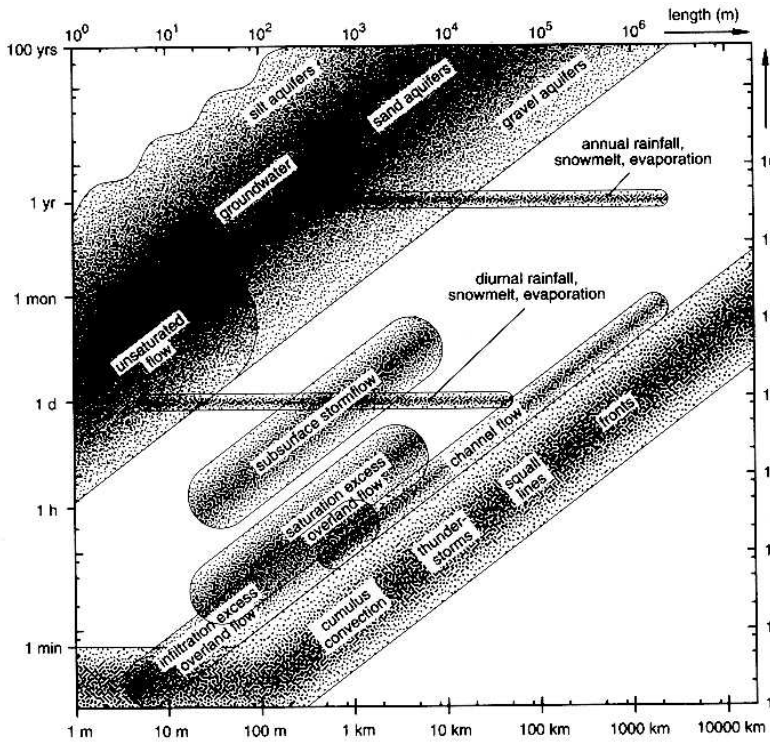

Figure 5.1.

Hydrological processes at ranges of characteristic space/time scales after Blöschl & Sivapalan (1995).

Scale interactions

Different processes may interact dynamically when they operate on more or less the same spatial and temporal scales. Processes on a very small scale appear as noise in the interactions with processes on larger scales, but they can produce residual effects on larger scales. Their effect can be accounted for by proper averaging procedures (upscaling), as for example for turbulence. Processes on a much larger scale can be treated as slowly varying or constant features, which define scenarios for field parameters and extrinsic conditions when studying their effect on processes on smaller scales (downscaling). For example when considering sea level rise due to climate change, the sea level can be assumed constant when studying the morphological developments within a decade. For hydromorphological modelling the combinations of processes operating at different scales have been treated by de Vriend (1991). They are referred to as techniques for 'scale interactions'. However, it not clear yet if these techniques can be extended to biological processes as well.

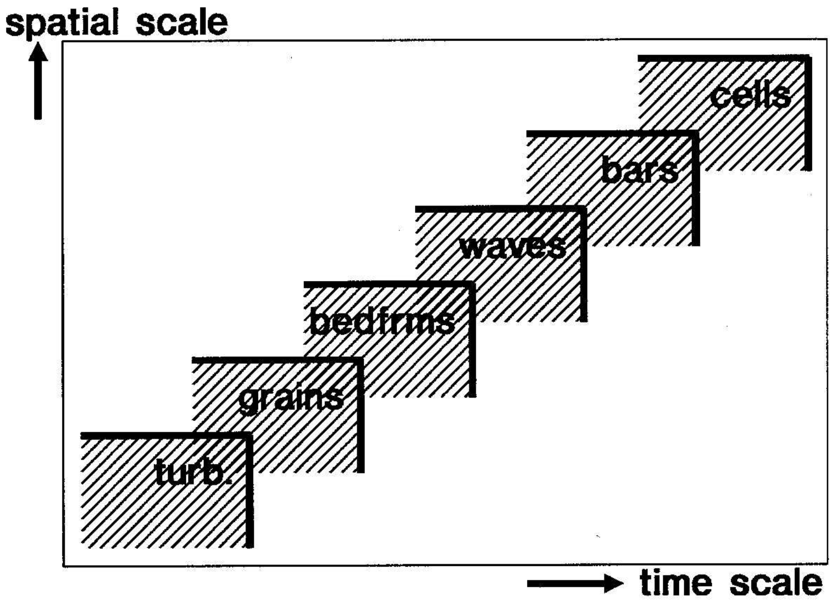

Figure 5.2. Morphological scale cascade, after de Vriend (1998).

6 Eco-morphological interactions

6.1 Introduction

Although it has always been apparent that organisms may modify their physical surroundings, only recently it was recognised in the ecological literature that these changes constitute an important mechanism of interaction between populations. The phenomenon is described and systematically studied under the name of 'ecosystem engineering' (Jones et al., 1994; Lawton & Jones, 1995; Jones et al., 1997). 'Ecosystem engineers' are defined as follows (Jones et al., 1997): *"Physical ecosystem engineers are organisms that directly or indirectly control the availability of resources to other organisms by causing physical state changes in biotic or abiotic materials. Physical ecosystem engineering by organisms is the physical modification, maintenance, or creation of habitats. The ecological effects of engineering on other species occur because the physical state changes directly or indirectly control resources used by these other species"*. A distinction is made between *direct* engineering, via the creation of habitat and control over the supply of abiotic resources, and *indirect* engineering, by modulation of abiotic forces that, in turn, affect resource use by other organisms. Another classification distinguishes *autogenic* engineering where the engineer is part of the altered physical state (e.g. a tree providing habitat) and *allogenic* engineering where the new physical state is caused by the engineer but the engineer is not itself part of the new physical state. An essential feature of physical ecosystem engineering is that the ecological interactions are non-trophic. Trophic resources may be affected, but only indirectly through physical changes in the environment. The importance of physical ecosystem engineering for the dynamics of ecosystems is not fully explored in the ecological literature. Jones et al. (1997) argue that the effect on biodiversity at the local scale is unpredictable, but that at landscape and global scale the diversity of habitat types increases as a result of ecosystem engineering, with most probably a global increase of biodiversity as a net result. However, these authors stress that more detailed analysis of the effects on biodiversity is needed.

Gurney & Lawton (1996) have investigated the stability properties at the population and community level of a system where ecosystem engineers modify their habitat, depending on each other (to a variable degree called co-operativeness) to achieve the habitat modification. The modified habitat degrades to a state where it is no longer favourable to the engineers, after which it returns to the virgin state and may be engineered again. Stable conditions for the engineering populations are achieved when the degree of co-operation between the ecosystem engineers is low and the rate of recovery of habitat from the degraded to the virgin state is very variable. Unstable limit cycles tend to occur where the engineers are highly co-operative or where the recovery time for degraded habitat is almost fixed (and consequently any onsetting oscillation is not damped by a variable rate of recovery but rather propagated at the landscape level).

A high degree of co-operation between ecosystem engineers represents a strong positive feedback in the system. If an engineering individual can only modify the habitat (and thereby increase its chances for survival and reproduction) in the presence of other engineers, population development will be rapid once a population has established itself, but chances of population growth will be small when the population is sparse. Similar results can be expected when recruitment of juveniles into the population depends on the presence and engineering activities of adults. Wilson & Nisbet (1997) show that this may easily lead to patchiness or sharp boundaries in the spatial distribution of a species, even when environmental gradients are weak and continuous. Bertness & Leonard (1997) argue that positive interactions are important to set upper limits to the intertidal distribution of marsh plant species. They adopt the general model (after Bertness & Callaway, 1994), where positive interactions are expected to be important either under harsh physical conditions, or under high competition or predation. Positive interactions between primary producers and environmental conditions have been identified for a wide variety of systems (Wilson & Agnew, 1992). Mathematical studies have shown that they induce the existence of alternative stable states (Walker et al., 1981; van de Koppel, 1997). Van de Koppel et al. (in press) analysed the existence of alternative stable states for a diatom-silt system. They showed that multiple stable states will occur provided a limited set of qualitative conditions are fulfilled. Basically, the growth of diatoms should be promoted by the presence of silt in the sediment, and the erosion of silt should be decreased when diatoms are present. Under these conditions and under moderate shear stress, the system will evolve either to a high diatom - high silt situation, or to a low diatom - low silt situation. At either high or low shear stress, only one of these situations can be stable.

Even though studies of the dynamics of engineered habitats have not fully explored the range of possibilities yet, some consistent patterns emerge. On a small scale, the presence of co-operative ecosystem engineers, and therefore of positive feedback mechanisms, may lead to strongly non-linear relations between abiotic forcing and the presence-absence of particular habitat types or communities. This may be in the form of sharp habitat boundaries in environments forced by gradually changing conditions. It may even be in the form of randomly determined patches of one or the other of a set of stable states under a uniform abiotic forcing. In general, co-operative ecosystem engineering will lead to a decrease in the predictability of species-environment relations and, especially when the engineered habitat is subject to degradation, it will easily lead to unstable and constantly changing patterns of occurrence of the ecosystem engineer and its associated species. At the large (landscape to global) scale, ecosystem engineering may lead to an increase of the diversity of habitat and community type, and therefore lead to a higher biodiversity than would be possible without.

From the point of view of ecomorphological, the link between the small scales at which the ecological interactions operate and the larger scale of the system or of considerable parts of it (e.g. one ebb-flood channel system in an estuary) is of particular importance. An important question to be raised is if the physical modifications of the habitat by the organisms have net carry-over effects from the small to the large scale. Is local fixation or mobilisation of mud by organisms sufficiently large to modify the mud balance of the estuary ? Are similar effects to be expected for the sand balance? At what scale should one take into account the effects of organisms on the processed determining long-term morphological developments in the estuary? Are organism-effects 'hidden' in empirical relations used to describe and predict morphological evolution?

In this chapter we will explore these questions by focusing on a number of cases of ecosystem engineering. From the description of the processes we will derive hypotheses on scale interactions and formulate research questions.

6.2 Diatoms and sediment stabilisation

It is well established that microphytobenthos can stabilise surface sediments of intertidal mudflats, thereby modifying sediment transport processes in these areas. Benthic epipelic diatoms are the most important group of primary producers in intertidal mudflats (Admiraal 1984, Smith and Underwood 1998). Diatoms form biofilms that serve to produce their own microenvironment protecting them from the rapidly changing conditions in intertidal mudflats (Decho 1994). The presence of diatom biofilms increases the stability of the sediment surface (Kornman and de Deckere 1998, Paterson 1989) and can have a profound effect on the morphodynamics of mudflats (Dyer 1998, de Brouwer et al. 2000).

Benthic diatoms stabilise the surface layer of the sediment by means of the excretion of extracellular polymeric substances (EPS) that mainly consist of carbohydrates (Hoagland et al. 1993). Microbial extracellular polysaccharides are anionic and the negative functional groups (uronic acids, sulfated sugars) are believed to play an important role in cross-linking of sugars and binding of sediment particles to form a biofilm (Decho, 1994). Using LTSEM, it has been shown that the matrix of diatom biofilms consists of a diffuse medium of polysaccharide strands coating sediment particles, filling interstitial voids and forming aggregates incorporating diatoms and particles (Paterson & Black 1999). In this way, the geometry of the sediment surface is modified, thereby changing its stability and rheology (Ruddy et al. 1998a). Benthic diatoms can produce up to 40% of the carbon fixed as extracellular carbohydrates (Goto et al. 1999, Middelburg et al. 2000). The production of EPS is coupled to photosynthesis (Staats et al, 2000a, de Winder et al 1999), although small amounts of EPS can also be produced during diatom movement (Smith & Underwood, 1998, 2000). Culture experiments (Staats et al, 2000b) and model calculations (Ruddy et al. 1998b) suggest that EPS is produced under conditions of nutrient limitation. Therefore, production of EPS, and thus biogenic stabilisation at intertidal mudflats, may be influenced by both light regime (for example emersion time) and growth stage of the diatom population (see also Yallop et al, 2000).

The interactions between factors that determine sediment stability are complex and comprise both physical and biological components (see Black et al, 1998) In cohesive sediments, benthic diatoms are believed to play an important role in stabilising the sediment. For example, Amos et al (1998) observed that variations in carbohydrate contents had an impact on sediment stability up to 4 orders of magnitude greater than equivalent variations in bulk density. Also, Yallop et al. (2000) came with a relationship that related sediment stability to a combination of biological and physical variables (carbohydrates, chlorophyll *a* and water content). On the other hand, Amos et al. (1998) showed in the same study that at other stations in the same mudflat variations could be explained in terms of consolidation and desiccation only. Houwing (1999) studied temporal and spatial variations in erodability of intertidal sediments. He also concluded that biology was of minor importance for the erodability of sediments. This indicates that the potential of biogenic stabilisation may be high, but that it can vary to a large extent on both temporal and spatial scales.

A vast amount of literature exists that investigates temporal and/or spatial dynamics in benthic biomass, extracellular carbohydrates, sediment stability or a combination of these. The minimal scale of measurement investigated bed forms (cm-m range) over an emersion period (Blanchard et al. 2000, Taylor & Paterson, 1998). The maximum scale typically measured a mudflat (m-km range) at weekly to monthly time intervals. (de Brouwer et al 2000, Kornman & de Deckere, 1998, Underwood & Paterson, 1993). In general, sediment stability is high in the presence of diatom biofilms (i.e. high chlorophyll *a* and carbohydrates). However, once highly stable sediments erode the erosion rate and the sediment mass eroded is often higher compared to sediments without an obvious biofilm (Widdows et al. 2000, Lucas et al. 2000). The stabilising effect of EPS is not only a result of increased cohesion between particles but it also reduces the bottom roughness of the sediment bed, reducing the surface shear for a given flow (Paterson & Black, 1999). It has been suggested that irregularities at the sediment surface act as initiators for erosion, because of turbulence generated at these spots (de Deckere et al. in prep.). Therefore, the macrofauna may have a double effect on removal of diatom biofilms. They graze on diatoms but they also induce turbulence in the boundary layer by bioturbation and tube formation, thereby altering the critical bed shear stress. This may lead to an effective removal of complete biofilm structures (i.e. sloughing).
Although it is well established that micro-phytobenthos (and biology in general) influences sediment stability, very little is known about the significance of these processes in the morphological development of intertidal areas. In situ treatments of diatom inhabited sediments with biocides showed a rapid erosion of the sediment (de Boer 1981, Underwood and Paterson 1993). A finer sediment fraction was quickly winnowed and the sediment bed formed ripples that are characteristic for non cohesive sediments (Daborn et al, 1993). This suggests that diatoms are able to capture fine-grained sediment as was observed by de Brouwer et al. (2000). Frostick and McCave (1979) calculated that up to 10^5 tonnes of sediment was accreted on the banks of the Deben estuary (Suffolk, Great Britain) in summer. It was suggested that this material be transported within the estuary from the channels to the mudflats, involving micro-phytobenthos to trap and bind the material. The magnitude of sediment transport to or from a mudflat, is determined by tidal currents (Postma, 1961; Bell et al., 1997) and wind generated waves (Postma, 1957; de Jonge and van Beusekom, 1995; Bell et al., 1997). At mudflats, wind generated waves are believed to be important for resuspension of sediments (De Jonge & van Beusekom 1995). Christie and Dyer (1999) showed that offshore transport is correlated with the wave activity while onshore transport is determined predominantly by the maximum current speed. Erosion of several cm's of sediment occurred during storms but this material was replenished in a few days under calm conditions. In this study the effect of micro-phytobenthos was not investigated. However, after disturbance diatoms also recolonise the sediment over a period of a few days (Daborn et al. 1993) and therefore they could potentially play a role in the recovery from erosion events. In addition, de Brouwer et al (2000) observed that diatom biofilms were efficient in stabilising the sediment surface under wind conditions that caused erosion when diatom biofilms were absent, stressing the potential role of biofilms in large-scale sediment transport processes.

The literature that exists on the role of micro-phytobenthos in ecomorphological dynamics mainly focuses on identifying the mechanisms of sediment stabilisation and the factors that are important in this process. In order to identify the significance of biogenic stabilisation in the morphology of coastal areas it is necessary to quantify the influence of biology in parameters useful for morphologists (e.g. sediment flux). For example, Herman et al. (in prep) show that the increase in particulate suspended matter in the water column during the winter may be in the same range as the amount of sediment that is deposited in the summer (and eroded in the autumn). This suggests that sources and sinks for this material stay largely within the estuary as was also found by Frostick & McCave (1979). In addition, relatively little is known about the mechanisms of stabilisation. Thus far, the binding of sediment particles by EPS to form a stable surface layer has been considered as the key process in sediment stabilisation. However, recently it has been shown that other mechanisms can be important also. This includes the reduction of the bottom roughness of the bed (de Deckere et al. in prep., Paterson & Black 1999) and the importance of the dynamic viscosity and rheology of the sediment water interface (Ruddy et al. 1998a).

Biology is likely to have a different impact depending on the temporal and spatial scales that are investigated. Most of the research has been done on micro- or meso-scales, while morphological dynamics are typically studied at larger scales. Modelling approaches including biogenic processes in sediment dynamics can be particularly useful when investigating the importance of biology in morphodynamics. Ruddy et al. (1998b) and Willows et al. (1998) were able to demonstrate the importance of biology over short time scales using these kind of bio-sedimentary models.

In a more principal analysis, van de Koppel et al. (in press) show that multiple stable states of the diatom/silt complex will occur if the necessary positive interactions are present. In particular, it is required that silt erosion decreases with diatom biomass, and that net diatom growth increases with silt content. Multiple stable states are expected to occur at intermediate bottom shear stress values, and are characterised as either low diatom / low silt or high diatom / high silt conditions. These authors provide field evidence from the Molenplaat that the dynamics might occur at physically realistic ranges of bottom shear stress. Whereas the first of their assumptions is corroborated by many studies in the literature, the second (diatom net growth rate increases with increasing silt content) is based on relatively limited laboratory experiments. A recent field study by Middelburg et al. (2000), also on the Molenplaat, shows that rates of primary production at a sandy and at a silty site are very similar, despite an order of magnitude higher diatom biomass at the silty site. Consequently the biomass turnover time at the sandy site is much shorter. The difference between the primary production rate as measured by Middelburg et al. (2000) and the net growth rate as modelled by van de Koppel et al. (in press) is in the biological loss processes. There is strong evidence that the grazing on micro-phytobenthos by protozoan, meiofaunal and macrofaunal assemblages is much more intense at the sandy site (Hamels et al., 1998) than at the silty site. The dynamics of this interaction between diatoms and grazers need more study. Moreover, as is also assumed by van de Koppel et al. (in press), specific growth rate of diatoms may be inversely related to diatom biomass. However, it would require a detailed biogeochemical model of diatom growth to investigate the relative importance of nutrients, inorganic carbon availability and biomass limitation to corroborate this assumption. Such a model, which should also take into account pH variations, is a very complex task that has at present not been accomplished at a sufficient level.

6.2.1 Scales and questions for research.

Process scales at the micro scale (1mm-1m).
Detailed models for growth and growth limitation of micro-phytobenthos are still lacking, but are needed for predicting EPS production and biomass development. Process models for sediment binding and consequences for erodability are unavailable, yet. No clear insight exists in the loss processes of micro-phytobenthos: what determines their biomass (grazing, erosion, migration?). What is the balance between growth and loss processes?.

Scale of sediment patches as influenced by presence/absence of biofilms (1-100m).
How predictable are the patterns observed? Is there sufficient evidence for the existence of multiple stable states?

Scale of sediment storage and remobilisation (~10 km).
Is silt storage as a consequence of sediment stabilisation really important for the seasonal cycle of SPM in an estuary? How does the silt stored/remobilised interfere with morphodynamics?

6.3 Bioturbation

'Bioturbation' is the general term for the movement of sediment particles by the activity of benthic animals. Deposit-feeding benthos uses tentacles, appendages and mouth parts to consume and rework various components of the sediment, often at remarkably rapid rates (Thayer, 1983). In addition, many species irrigate their dwellings by beating appendages, by peristaltic movements or by oscillating like pistons in their tubes. These activities have dramatic effects on many important properties of the sediment, including biogeochemistry, microbial activity, benthic community ecology and contaminant transport (reviewed by Berner, 1980, Aller, 1982, Olsen et al., 1982, Lopez et al., 1989, Boudreau 1997). Particle reworking rates of many species have been directly observed in the laboratory (reviewed by Cammen, 1980; Thayer, 1983). These studies have identified a number of different particle transport mechanisms. Particles may be collected at the surface or at (variable) depth, and deposited either at depth or on the surface. The diverse combinations of origin and deposition of particles has lead to classifications in different types of bioturbators (Wheatcroft et al., 1994). In the field, bioturbation is usually quantified using profiles of tracers, e.g. radionuclides such as ^{234}Th, ^{210}Pb, ^{7}Be (Aller & Cochran 1976; Nozaki et al., 1977), chlorophyll-a (Sun et al., 1991), artificial particles such as glass beads etc. (e.g. Wheatcroft 1991, 1992), or isotopically labelled algae (Levin et al., 1997; Middelburg et al., 2000). When using tracer profiles, particle mixing is quantified by fitting modelled profiles with observations by tuning the mixing parameter(s). Classically, bioturbation is modelled as a diffusion-analogue (Goldberg & Koide, 1962; Boudreau, 1997). However, more complex models are needed often since the profiles do not correspond to what is expected as a result of diffusive mixing only. Mechanistic models for this process, called non-local exchange models, have been developed by several authors, most notably in the seminal papers of Boudreau 1986a,b and Boudreau & Imboden 1987). Soetaert et al. (1996) have developed a method to derive the most parsimonious non-local exchange model from observed tracer profiles.

Animals typically are selective in the type of particles they take up and displace. As a consequence, estimates of bioturbation rates depend on the tracer used. Estimated rates tend to be higher when the tracer is shorter-lived, probably because fresh particles are taken up preferentially and moved faster than ‘old’ particles which have smaller nutritional value (Smith et al., 1992) Selectivity has been described also with respect to particle size. This may have consequences for the sediment composition (see below).

Although bioturbation is a fairly common phenomenon, large and important bioturbating organisms are not ubiquitous. They are typically confined to the 'mature' or 'undisturbed' community type, *sensu* Pearson & Rosenberg (1978). As enhanced carbon loading or even enhanced loading with inert fine particles stresses benthic communities, large and deep-burrowing animals tend to disappear from the community. They are replaced by small surface-dwelling benthic species, typically polychaetes. This community response is a paradox, since it could be expected that enhanced carbon deposition would improve the food availability for the benthic species. Dauwe et al. (1998) and Herman et al. (1999) have discussed the problem from different points of view. Dauwe et al. (1998) used an analytical diagenetic model composed of a bioturbated top layer and a non-bioturbated layer, forced by a constant flux of organic carbon and a constant sediment accretion rate.

With this model they calculated the mineralisation rate (expressed as a fraction of the arriving flux) at the bottom depth of the bioturbated layer as a function of bioturbation rate and of quality (first-order degradation rate) of the organic flux. The model shows that, although bioturbation always increases, the fraction of the organic flux mineralised at depth in the sediment responds in a non-linear way. For very refractory organic matter, the change in mineralisation rate at depth is negligible. Very labile organic matter is always degraded before it can be mixed deep in the sediment, except if bioturbation rates would exceed any realistic range. Only at intermediate quality will bioturbation activity be able to bring down an appreciable fraction of the incoming flux. Herman et al. (1999) show that at least one extra factor should be considered to explain an actual reduction of biomass of deep bioturbators with increasing organic flux into the sediment. They show with a simple diagenetic model that bioturbation always leads to more reducing conditions in the sediment. This can be partly counteracted by ventilation of the sediment by animal activity. However, since some organic matter is lost to the non-bioturbated layer and since this amount increases with increasing bioturbation, there is a limit to the efficiency with which ventilation can prevent the sediment from becoming strongly reducing. Based on these results, they predict that (i) clogging of the sediment by deposition of fine material should have similar detrimental effect on the bioturbators as increased organic loading. (ii) The transition between communities dominated by bioturbators to communities dominated by surface deposit feeders should be sharp, since ventilation of the sediment would decrease with disappearance of the bioturbators, leading to even more adverse conditions in the sediment. (iii) Large bioturbating animals should create a niche for a suite of associated species as a consequence of their activity leading to enhanced availability of both food and oxygen at depth in the sediment. These qualitative predictions are in line with observations on the effects of a broad class of organic waste and/or fine sediment dumpings on benthic communities (Valente et al., 1992). Associations between large bioturbating animals and meiofaunal and macrofaunal assemblages are well known, e.g. Reise (div publ.) for *Arenicola marina*. The reverse process, species being expelled as a consequence of bioturbating activity, has been extremely well documented for *Arenicola marina* and *Corophium* species by Flach (div. publ.).

The activities of bioturbators and their consequences listed here typify bioturbators as ecosystem engineers. Their dynamics are characterised by a high degree of mutual dependence, co-operation and positive interactions. Due to the non-linear interaction between bioturbation rate and the fraction of incoming organic flux mixed deeply into the sediment, individual bioturbators dependon the presence of other bioturbators in order to provide sufficient food at the depth where they are feeding. Similarly, sufficient ventilation activity is required to prevent the sediment from becoming anoxic and can most probably only be achieved if a sufficient population density of bioturbators is established, particularly in non-permeable silty sediments. Therefore the conditions for complicated dynamics (e.g. the occurrence of multiple stable states, establishment of patchy distributions in a gradually varying environment) seem to be fulfilled for these species. Field evidence for exclusion of other species by *Arenicola marina* and therefore the establishment of patches dominated by this species and its associated assemblage (Flach, Flach et al.) also points in this direction. There is need for both theoretical (modelling) and field validation studies to explore the dynamics of bioturbators as key species in sediment communities.

The relevance of these processes and interactions for ecomorphological research depends on the degree to which bioturbating species modify the sediment and the sedimentation/erosion processes. Such modification may be the result of different processes:

Selective uptake and handling of particles by deposit feeders may give rise to graded beds, where the grain size composition of the bed varies with depth as a consequence of bioturbation. Van Straaten (1952) has first described the phenomenon for *Arenicola marina* beds, where a layer of shell fragments and other coarse particles may develop underneath the bioturbated layer. It has been extensively studied in beds of this and other species (e.g. Cadée, 1976, 1979). Whether the animals actively or passively select finer particles is unclear, but the composition of the material ingested by deposit feeders tends to be more dominated by finer particles than the surrounding sediment. A consequence of this is that faeces of deposit feeders usually are richer in organic material than the sediment they are feeding on (organic matter content is a direct function of the surface of the sediment grains, and a large fraction of it is unattainable for digestive enzymes) (Hylleberg, 1975). ‘Conveyor-belt' deposit feeders, which feed at depth and deposit their faeces at the sediment surface, bring finer particles to the surface, where they may be prone to erosion.

Physical disturbance of the bed surface is a direct consequence of burrowing or movement of benthic animals through the sediment. The destabilisation of the bed surface as a consequence of animal movement has been reported in a number of cases. Often, especially for surface deposit feeders, it is difficult to distinguish the effects of movement from the effects due to grazing on the micro-phytobenthos. Direct disturbance must be involved to explain the destabilisation of the bed caused by suspension feeders, e.g. the cockle *Cerastoderma edule* (Willows et al, 1998).

Grazing on microphytobenthos reduces the stabilising effects of the latter. Grazing and/or direct physical disturbance has been invoked as the mechanism by which surface deposit feeders may destabilise the sediment bed. Willows et al. (1998) describe and model the effect of *Macoma balthica* on sediment stability. They show that the destabilising effect of the species is pronounced but very specific. The clams do not change the critical erosion threshold, but significantly increase the amount of sediment resuspended once the threshold has been passed.

Gerdol & Hughes (1994) and Grant & Daborn (1994) describe the destabilising effect of grazing by *Corophium volutator* on microbenthic algae. Note, however, that depending on circumstances this species may also increase sediment stability (see below).

Direct resuspension is part of the animals' activities. Burrow excavation, particle processing for feeding and other activities bring particles into suspension, and this may enhance (particle-selective) resuspension (Rhoads, 1974). De Deckere et al. (2000) has described the process in detail for Corophium volutator.

Changing sediment microtopography by constructing mounds and burrows may create points where current impact is more important and erosion can start (Eckman et al., 1981).
Mucus excretion and burrow construction may stabilise the sediment because particles are glued together into consolidated structures. Where burrows protrude above the sediment they may protect the underlying sediment from erosion by creating skimming flow (e.g. Meadows & Reid, 1966; Widdows et al., 2000). This, however, depends on burrow height, density and diameter.

Changing sediment porosity by the creation of voids in the sediment (feeding voids, burrows) or by the compaction of sediment as a consequence of burrowing (e.g. Meadows & Tait, 1989; Jones & Jago, 1993, Limia & Raffaelli, 1997) may change the erodibility of the bed.

Because of the diversity of processes involved, it is impossible to predict their net outcome on sediment stability for a particular macrobenthic community. The difficulties of measuring sediment erodibility (Paterson & Black, 1999) have prevented the build-up of a large database from which statistical correlations could be deduced. There is a need for dedicated field studies at spatial scales which are relevant to estuarine geomorphology. Sediment stability characteristics should be statistically related to macrobenthic community composition, and a hierarchy of relevant processes should be established.

6.3.1 Scales and questions for research

Process scale: 1-10 cm. Most important question is how the different possible actions of macrofauna scale to one another, how forcing may determine which of the possible effects dominates. Process modelling of bioturbation effects on sediment composition is largely lacking also, as most modelling has concentrated on profiles of organic matter and/or of tracers.

Patch scale: 100 m-1km. How important are biotic interactions for establishing exclusive patches dominated by one or a few key species? Can the *Arenicola - Corophium* type of mutual exclusion be extrapolated to other assemblages? How important is this for the relation between physical forcing and community composition, and its non-linearity? Is there influence of estuarine-scale processes, such as the availability of food, silt and SPM, on the local dynamics of bioturbating species and therefore on the forcing-community relation?

6.4 Biodepositors / Reef-builders

Biodeposition is the direct filtering and deposition onto the sediment surface of suspended sediment and organic matter. It is mediated through (permanent or facultative) suspension feeders. Important suspension-feeding species in Dutch estuaries are the cockle *Cerastoderma edule*, the mussel *Mytilus edulis*, the Japanese oyster *Crassostrea gigas*, and the clam *Mya arenaria*. Important species that can switch between surface deposit feeding and suspension feeding are *Macoma balthica* and *Scrobicularia plana*, but other species may feed also as suspension feeders to a certain extent.

Gross rates of biodeposition can be very high. Suspension feeding bivalves typically have clearance rates in the order of several liters per hour for a 1 g AFDW animal (Heip et al., 1995). As these animals often occur at high local biomasses (Herman et al., 1999), biodeposition can easily be in the order of 0.1-1 kg per m^2 per day in the suspension feeder beds. Due to selective feeding, most of this material will be fine-grained and organic-rich particles, which tend to be pelletized by the animals. From the point of view of silt accumulation and morphological evolution of the bed, the fate of biodeposited sediment is very important. Species (e.g. mussels, oysters) that build banks or reefs, i.e. structures protruding from the sediment and protecting the sediment surface from direct impact by currents, may create favourable conditions for accumulation of the biodeposited material in the bed and consequently for a steady accumulation of material. Buried species that may also be bioturbators, e.g. the cockle, deposit their filtered material on top of the bed where it may be swept away easily. Biodeposition by this species can be demonstrated experimentally (e.g. Widdows et al., 2000, Herman et al., 2000) but it is uncertain to what degree it actually contributes to long-term changes in the bed structure or composition.

The presence of banks or reefs has a number of important consequences for the ecosystem. The longevity of these structures exceeds that of the individual animals and can be several decades. They consist of a mixture of sediment, dead shells and live animals, and are physically robust. Consequently, the evolution of these structures is at similar time scale as morphological changes, and extreme events may be of high importance for their long-term evolution. The longevity of mussel banks and oyster reefs is based on differential recruitment success within and without the reef structures. Whereas recruitment of these species is widely spread, the recruits depend for their survival on the availability of a robust substrate, which in the absence of hard substrates is provided by the banks and reefs. This mechanism is a form of co-operation in the sense of ecosystem engineering theory. It can be a source of instability in the system: if recruitment depends on the existence of old structures, and the latter are subject to physical destruction during extreme storms, it may take a long time to recover from major storm events. A field example of this is the evolution of wild mussel banks in the Wadden Sea after the storms of the early nineties (which may have been worsened by fishery activities on remaining mussel banks).

The places where mussel banks and oyster reefs can develop have to fulfil a number of conditions. Water currents must be sufficient to advect food at a rate high enough to prevent local seston depletion (see Wildish & Kristmanson, 1997; Herman et al., 1999 for a thorough discussion of the process) but should not exceed a level where erosion could wipe the bank away. Water depth should be sufficient to provide immersion times that are non-limiting and sufficient amounts of food. However, water depth should not be too large since this would reduce the specific productivity of the phytoplankton which is grazed throughout the water column while it only grows in the euphotic zone. See Lucas et al. (1999a,b) for a thorough discussion on this subject, also in relation to SPM content and water transparency. The site must be protected from wave impact during severe storms and the basic substrate on which the bank develops should be sufficiently firm. These conditions are both straightforward and well described and discussed in the literature, which should allow predictive modelling of where banks can be expected to develop. It would be most interesting to use such models to predict deterioration of the habitat as a consequence of the (vertical) growth of the bank or reef. At some point, the reef structure might become more vulnerable or less advantageous with respect to feeding currents. Such deterioration might determine a natural lifecycle of the structure. Based on theoretical considerations, one could expect that such dynamics would destabilise the system, or induce long-term cycles that could affect the whole estuarine system.

Effects of suspension feeder banks on the ecosystem could be expected at a number of levels. Benthic suspension feeders may dominate the dynamics of shallow estuarine ecosystems (Herman et al., 1999 and references therein). In recent experiments it was shown that mussel beds substantially change the vertical water velocity profiles (van Duren et al, 1999, in prep.). The presence of the mussels increases the bottom roughness substantially and under certain conditions leads to the formation of an internal boundary layer comparable to what is observed over pebble beds in rivers. Activity of the animals, in particular the ejection of exhalant water jets from the siphons, is a factor that further increases bottom roughness considerably. Reynolds stress, expressing the transport of momentum towards the bed, is higher above active than above inactive beds. Lamy et al. (1999, in prep.) and Herman & Lamy (1999, in prep.) have incorporated these local effects in a large-scale coupled hydrodynamic-ecological model. Simulations showed that local changes in bottom roughness, parameterised on the basis of flume experiments, are large enough to change horizontal current patterns in an estuary by 5-15 %. Also filtration and (partial) biodeposition of faeces and pseudofaeces change the silt dynamics in the estuary on the bed.

6.4.1 Scales and questions for research

The scale of the process of reef-building is 100m - 1 km. The associated time scale is years to decades. The scale of the effect is 1km - 10 km. Ecological effects on phytoplankton and nutrients is at a scale of 10 km. Effect on silt dynamics is probably at a similar scale.

Interesting research questions may concern the interaction of filtration and reef building with silt dynamics in the estuary and the Influence of large-scale, long-term morphological changes on the development (and gradual change in position) of mussel banks and oyster reefs. Which are the differences in dynamics of mussels and oysters? For these research questions both historical research (partly done in the Wadden Sea - to be done for recent years in the Oosterschelde), field research, laboratory flume experiments and modelling are needed. The recent development of oyster reefs in the Oosterschelde seems to be an excellent topic for this research.

6.5 Vegetation on salt marshes

Vegetation and sediment accretion rate of salt marshes are determined by (a) the availability of sediment, (b) the input of organic matter, (c) the inundation frequency, (d) small-scale morphology of the salt marsh, and (e) soil maturing and compaction during growth of the marsh. Strong self-regulating mechanisms are active at intermediate and high levels of well-established marshes. Hence there is a tendency to follow sea-level rise if sufficient sediment is available (rising sea level = increase in flooding frequency = increase in sedimentation). Also, strong positive feedbacks occur at low-level (pioneering) vegetation: once vegetation is established sedimentation increases, which results in better possibilities for plant survival.

Salt marshes generally develop when intertidal flats have risen to such a level that it provides the possibility for growth of pioneer vegetation. In the Wadden Sea the most common pioneer is Salicornia sp. As soon as this vegetation develops it strongly influences sedimentation and erosion processes. Flood and ebb tides run around the individual plants or clumps of vegetation. Close to the plant the sediment becomes drier and consolidates. The moist parts remain more prone to erosion and intricate drainage patterns develop and may develop further into creek systems. As soon as creeks have developed, water content of the elevated area decreases and soil aeration increases, thus making possible next succession stages in vegetation development. Often, however, succession haltered when development of the next stage is not quick enough, and storms destroy the drainage structure. Although the balance between sedimentation and sea-level rise is clearly the key to coastal marsh survival, the mechanisms controlling sedimentation in marsh environments concern relationships between period of emersion, sediment deposition and vegetative growth (Nyman *et al*., 1993). Despite the dominance of some hydrological mediated depositional events, marsh vertical accretion is the sum of both mineral and organic contributions. Organic matter may be introduced to the marsh surface by hydrological mediated processes e.g., the transport of detritus during high tide. However, *in situ* below-ground production may contribute importantly also.

Seasonal or short-term variations in sediment supply or local hydrodynamic conditions can result in changing patterns of sediment deposition. During (winter) storms, large sediment transports can occur, which cause accretion at one place and erosion at another. For sites in France and the Netherlands it was shown that winter storms usually cause high accretion in the *Puccinellia* zone and/or on creek levees and erosion in the pioneer zone. (See also Stumpf, 1983 and Ehlers *et al*., 1994). Apparent erosion in summer is mainly caused by compaction of the sediment due evaporation. This phenomenon happens especially on the less flooded salt marsh areas with short (or removed) vegetation. During wet summers this soil shrinkage usually is less pronounced (Erchinger, 1995). The sand/silt ratio influences the compaction and recuperation (swelling) of the sediment and therefore is an important parameter to measure in future experiments.

Recently, measurements have been performedt at sites with different physical characteristics (tidal range, wave action) in France and the Netherlands. The sites included natural salt marshes (Ferme Foucault, Bay de Mont Saint Michel, Waarde, and Neerlands Reid), man-made marshes (Negenboerenpolder), and inundated marshes that had been empoldered previously (Peazemerlannen). Although at most sites there was a trend for higher sedimentation rates at lower marsh levels (influence of the number of floodings), sedimentation rates varied considerably between marshes of similar elevation.
Sediment supply to creeks and subsequently through the creek system to the marsh possibly controls differences in sedimentation rate in those cases (Stoddart et al., 1989). This was observed in the Peazemerlannen as well as in the Waarde salt marsh. Creeks represent the main sediment source for much of the marsh surface. The velocity pulses in the creek system in response to spring tides not only transport considerable volumes of water and sediment onto the marsh, but may also mobilise sediments from within the creek which has accumulated under low velocity conditions during (neap) tides. Thus, fine-grained sediments were collected in the

basins of Ferme Foucault in winter, and in spring when they were filled to a maximum the sediment was spread over the marsh during spring tides and favourable (=north western) winds. There were large differences in measured accretion rates at the sites studied, and sometimes even on for station when different measuring techniques were applied. Nevertheless, most observations indicate that the annual accretion of the marshes is higher than the present sea-level rise of ~1.7 mm/y.

The correlation between the rate of accretion and the species composition of the vegetation is not clear always. Sometimes, the rate of accretion vegetation seems better correlated to the height or stiffness of the vegetation. The plants must be sufficiently high to substantially reduce wave energy and water velocity, and to allow the sediment particles to settle (Moeller *et al*., 1997). At the same time, the plants must be sufficiently stiff to keep them standing upright. Otherwise if the vegetation is relatively tall, even relatively slow water flows may flatten the vegetation and thus restrict its ability to trap sediment. Moreover, if the plants are lying on the bed surface, sediment is partly deposited on the plants and is washed away easily during subsequent high tides. Thus, relatively short vegetation usually is more effective in trapping sediment. A species that performs quite well is *Puccinellia maritima* (Wohlenberg, 1933; Jakobsen 1954). Once the sediment has reached the close maze of *Puccinellia* leaves and roots it becomes well fixed (Grumblatt, 1987). Besides effectively trapping sediment, a good root system enlarges the strength of the sediment bed, which reduces its erodibility (Van Eerdt, 1985). A high stocking rate (>1.5 animals/ha) causes a decrease of the *Puccinellia maritima* vegetation due to feeding and trampling (Bakker, 1985). As a result heavy grazing may have a negative effect on the rate of sedimentation (Andresen *et al*., 1990). Extensive grazing, however, has a positive effect on the species diversity and the development of the roots (Erchinger, 1995).

Transient sedimentation can be very high in the pioneer zone. Once vegetation is established the sediment trapping ability is increased relative to the bare tidal flat. Due to the vegetation, water velocity near the bed decreases, thereby reducing the energy available to move sediment through fluid shear stress (Pethick *et al*., 1990). Nevertheless, in the pioneer zone deposited sediment is still very easily washed away. Although the annual *Salicornia* may create suitable circumstances for sediment to settle by reducing wave energy, it provides an ineffective long-term sediment trap (Wiehe, 1935). Moreover, the woody part often remains in winter as a bare bush at the place of growth during the previous summer. The rotating movement of these remains caused by water currents stirs up the sediment deposited earlier. Nevertheless, *Salicornia* can fulfil a role in the spreading and seaward expanding of *Puccinellia*. This important species for silting up is spread mainly by vegetative parts torn off from the parent plant. Part of these tillers get caught behind living or dead *Salicornia* plants and can establish themselves especially on the higher parts of the pioneer zone (Kamps, 1962). In secondary pioneer zones and on creek levees the expansion of *Puccinellia* could proceed in a similar way. The presence of *Salicornia* can, therefore, be very important for the expansion of salt marshes.
When the rate of sea-level rise may increases to possibly 5 mm/year, as has been predicted in response to climate change, problems may arise in many salt marsh systems due to cliff formation at the transition of the pioneer zone to the lower marsh. A second point of concern is that summerpolders may not be capable of keeping pace with sea-level rise, because of the low number of floodings and sediment import. As a consequence, the difference between the soil level of summerpolders and the level of the salt marsh in front of it will increase over the years. Since the last few years, the restoration of summerpolders is considered an acceptable option to

increase or maintain the present salt marsh area. To be succesful, summerpolders suitable for restoration should be turned into salt marshes as soon as possible.

On Neerlands Reid, a sheltered marsh where cliff erosion is prevented by a revetment, the number of floodings determines the accretion rate. In the (secondary) pioneer zone the mean annual sedimentation is ca. 11 mm, in the low/middle marsh 6.5-7 mm and on the high marsh only 0.5 mm. Most years there was a clear seasonal pattern: shrinkage of the soil by drought in summer and high sedimentation in winter. In winters with strong easterly winds (like in 1995/1996) the flooding frequency is low in the Wadden Sea salt marshes, which is reflected in low sedimentation rates (Figure 6.1).

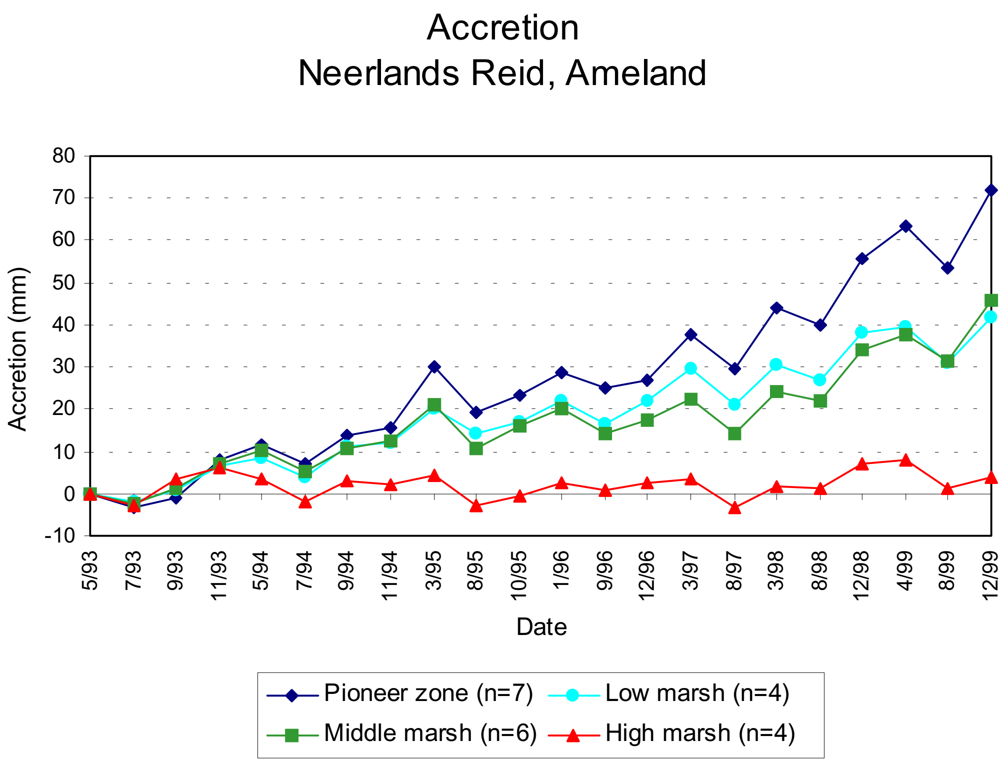

Figure 6.1. Cumulative accretion measured with a sedimentation-erosion bar in four vegetation types on the Neerlands Reid salt marsh (Ameland, Friesland, The Netherlands) from May 1993 till December 1999.

On the Negenboerenpolder, a man made salt marsh along the Groningen coast of the Wadden Sea, not the number of floodings is determining the accretion rate, but the vegetation it self. In the pioneer zone the mean sedimentation in the *Salicornia* (annual species) vegetation is 5.7 mm, while in the perennial grass *Spartina* the accretion is 10 mm/y (Figure 6.2). In the lower marsh with *Puccinellia* as dominant species, the sediment seems to be fixed very well at an accretion rate of 19 mm/y. In the winters of 1994/1995 and 1998/1999 erosion occurred in the pioneer zone, but a high sedimentation was found in the lower marsh.

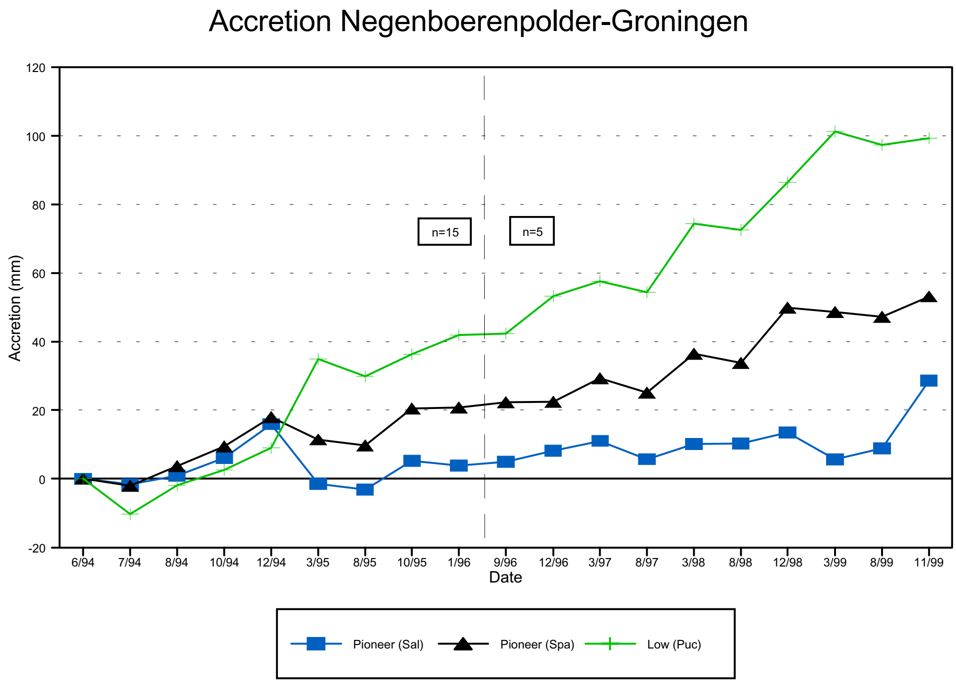

Figure 6.2. Cumulative accretion measured with as edimentation-erosion bar in three vegetation types in the Negenboerenpolder salt marsh (Groningen, The Netherlands) from June 1994 till November 1999.

In the Peazemerlannen, the difference in accretion at the lower marsh, which developed from a former summerpolder after the dike was breached, and the present summerpolder is very clear. (Figure 6.3) After almost 5 years, the average accretion in the lower marsh is ca. 7 mm/y, while the lack of floodings in the summerpolder caused an average shrinkage of the soil of 4 mm/y.

In the Schor van Waarde, a natural salt marsh in the Western Scheldt, the combined effects of flooding frequency, vegetation and creeks determines the accrtetion rate. In April 1994, after severe winter storms, an enormous accretion was measured for the *Puccinellia* stations as well as at the creek banks dominated by *Elymus*. Overall the average sedimentation after three years was 7-11 mm/y (Figure 6.4).

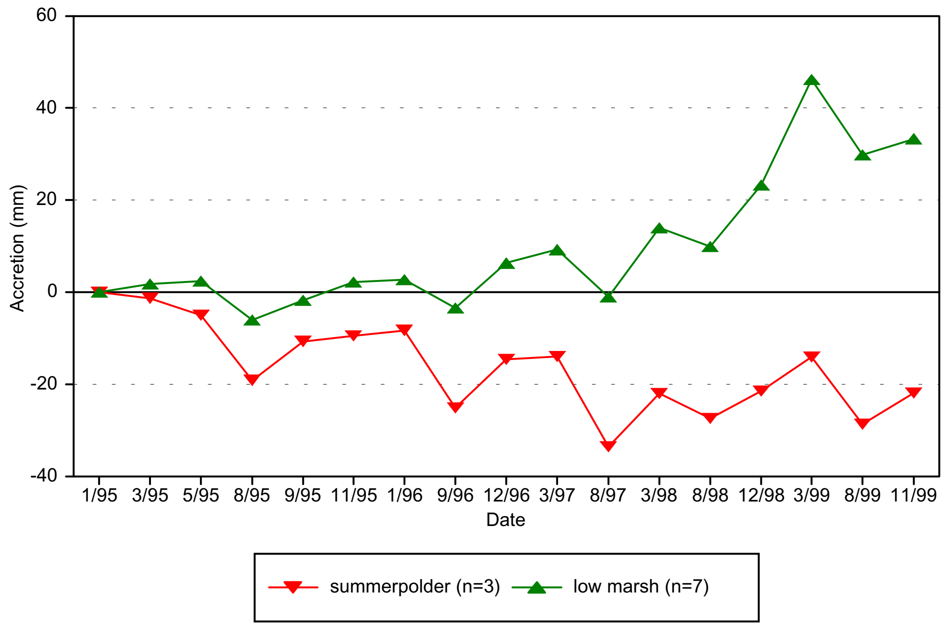

Figure 6.3. Average cumulative accretion measured with a sedimentation-erosion bar in the lower marsh (former summerpolder) and present summerpolder in the Peazemerlannen salt marsh (Friesland, The Netherlands) from January 1995 till November 1999.

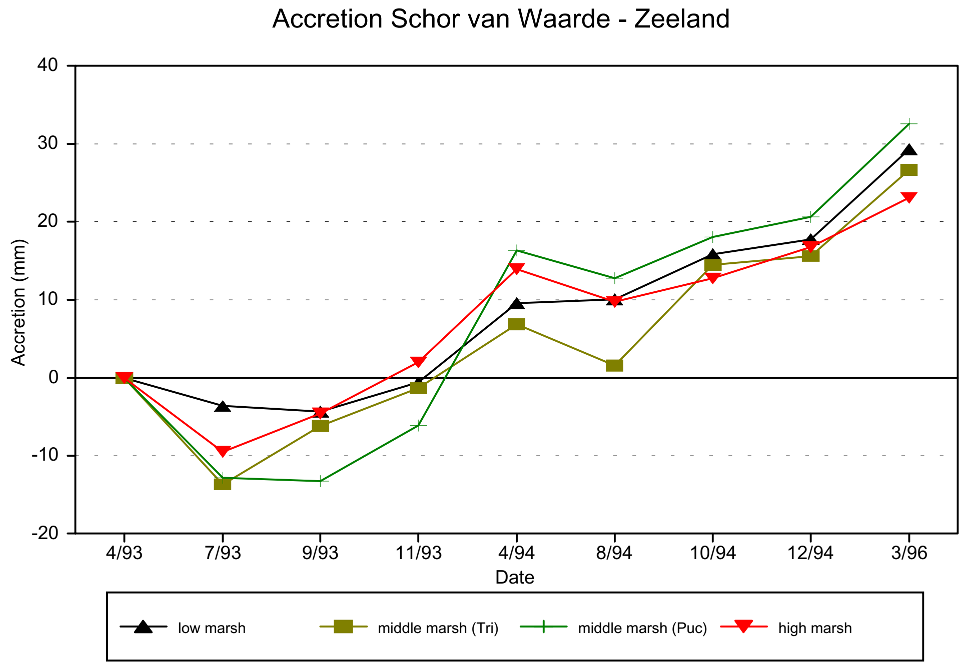

Figure 6.4. Average cumulative accretion measured with a sedimentation-erosion bar in four vegetation types in the Schor van Waarde salt marsh (Zeeland, The Netherlands) from April 1993 till March 1996.

7 Issues for further research

1. Scaling issues

The scaling issues have been intensely investigated both in the fields of biology and morphology and are thought to be understood partly though much mono-disciplinary research still has to be done. However the coupling of the scaling of the various physical and biological processes has not been studied as intensely and this is where we still have a large knowledge gap. By understanding this coupling better it should be possible to acquire a better understanding of the interrelationships between organisms and the physical forces. This should be an important focus for further research.

Understanding the scaling issues of the relevant phenomena and processes is not only essential for translating our knowledge into models, it is also required for the earlier stage of field campaign planning. Before designing and developing any modelling tools, *in situ* data is required and understanding the aspects of temporal and spatial scaling is essential for acquiring useable and accurate field data.

With the aim of adopting the same terminology in the course of the project we suggest to use a common classification for the temporal and spatial scales (see example):

Term of temporal scales	**Examples of processes operating at the different time-scales**	**Indicative duration**
daily-scale (short-term)	tide, storms, episodic events	days
monthly-scale	tidal cycles (neap to spring)	weeks
seasonal-scale (medium-term)	biological cycles, diseases	months
yearly-scale	annual weather	years
decennial-scale (long-term)	morphological evolution at the macro-meso scale, climate changes	tens of years
secular-scale	morphological evolution of entire estuary or large parts of it, climate changes	> hundreds of years

Table 7.1 Temporal scales

Term of spatial scales	**Dimensions in the Western Scheldt**	**Hierarchical ranking of ecosyst. at different levels of scale (Klijn, 1994)**	**Dimensions for a generic system**
mega-scale	tens of km	ecodistrict	whole estuary
macro-scale	kilometres	ecosection	whole meander
macro-meso-scale	hundreds of m	ecoseries	whole intertidal-flat
meso-scale	tens of metres	ecotope	homogeneous unit
micro-scale	metres and smaller	eco-element	microhabitat (bedforms)

Table 7.2 Spatial scales

Further elaboration of this classification should be a topic for further research.

The project has highlighted several important issues which need to be addressed in future research projects.

2. *Definition of ecotopes based on both abiotic and biotic factors, including time and* spatial scales.
   The biological definition of ecotopes should be based on biological indicators: presence of species (functional or taxonomic groups) selected for their preference of certain environmental characteristics.
   The abiotic definition of ecotopes should be based on a (large) number of parameters and their thresholds. The definition of the values distuiguishing between the different ecotopes (thresholds) should be assessed by means of exclusion laws (Crosato et al, 1999, de Jong, 2000, personal communication) and not by regression analyses. All values should be associated with their frequency (once per month, once per day etc.) and duration.

3. *Links between small and large scales:*
   From the point of view of ecomorphological interactions in estuarine and shallow coastal systems, the link between the small scales at which the ecological interactions operate, and the larger scale of the system or of considerable parts of it (e.g. one ebb-flood channel system in an estuary) is of particular importance. An important question to be raised is if the physical modifications of the habitat by the organisms has net carry-over effects from the small to the large scale. Is local fixation or mobilisation of mud by organisms important enough to modify the mud balance of the estuary ? Are similar effects to be expected for the sand balance? At what scale should one take into account the effects of organisms on the processes determining long-term morphological developments in the estuary ? Are organism effects 'hidden' in empirical relations used to describe and predict morphological evolution?

4. *Positive feedback*
   Even though studies of the dynamics of engineered habitats have not fully explored the range of possibilities, some consistent patterns emerge. On a small scale, the presence of co-operative ecosystem engineers, and therefore of positive feedback mechanisms, may lead to strongly non-linear relations between abiotic forcing and the presence-absence of particular habitat types or communities. This may be in the form of sharp habitat boundaries in environments forced by gradually changing conditions. It may even be in the form of randomly determined patches of one or the other of a set of stable states under a uniform abiotic forcing. In general, co-operative ecosystem engineering will lead to a decrease in the predictability of species-environment relations and, especially when the engineered habitat is subject to degradation, it will easily lead to unstable and constantly changing patterns of occurrence of the ecosystem engineer and its associated species. At the large (landscape to global) scale, ecosystem engineering may lead to an increase of the diversity of habitat and community type, and therefore lead to a higher biodiversity than would be possible without.

5. *Scales, hypotheses, questions for research regarding diatoms and sediment stabilisation:*
   Process scales at the micrometer-mm scale. At this small scale: Detailed models for growth and growth limitation of microphytobenthos are still lacking (but needed for predicting EPS production and biomass development). Process models for sediment binding and consequences for erodability are unavailable. There is no clear insight in loss processes of microphytobenthos: what determines their biomass (grazing? Erosion? Migration?) / what is the balance between growth and loss processes.

Scale of sediment patches as influenced by presence/absence of biofilm. 1m - 100m. Questions: how predictable is the pattern. Is there sufficient evidence of multiple stable states?
Scale of sediment storage / remobilisation: 10 km. Question: is silt storage as a consequence of sediment stabilisation really important for seasonal cycle of SPM in an estuary ? How does the silt stored/remobilised interfere with morphodynamics?

6. *Scales, hypotheses, questions for research regarding bioturbation:*
   Process scale: 1 cm - 10 cm. Most important question is how the different possible actions of macrofauna scale to one another, how forcing may determine which of the possible effects will dominate. Process modelling of bioturbation effects on sediment composition are also largely lacking (most modelling has concentrated on profiles of organic matter and/or of tracers).

   Patch scale: 100 m - 1km. How important are biotic interactions for establishing exclusive patches dominated by one or a few key species? Can the *Arenicola - Corophium* type of mutual exclusion be extrapolated to other assemblages. How important is this for the (non-linearity of the) relation between physical forcing and community composition? Is there influence of estuarine-scale processes (availability of food - availability of silt and SPM) on the local dynamics of bioturbating species and therefore on the forcing-community relation?

7. *Scales, hypotheses, questions for research regarding biodepositors and reef-builders:*
   In contrast to other processes discussed in chapter 6, the scale of the process (reef-building) is 100m - 1 km. The associated time scale is years to decades. The scale of the effect is 1km - 10 km. Ecological effects on phytoplankton and nutrients is at a scale of 10 km. Effect on silt dynamics is probably at a comparable scale.
   Interesting research questions are: the interaction of filtration and reef building with silt dynamics in the estuary. Influence of large-scale, long-term morphological changes on the development (and gradual change in position) of mussel banks and oyster reefs. Difference in dynamics between mussels and oysters. For these research questions both historical research (probably already done in the Wadden Sea - to be done for recent years in the Oosterschelde), field research, laboratory flume experiments and modelling are needed. The recent development of oyster reefs in the Oosterschelde seems to be an excellent study topic for this research.

8. *Scales, hypotheses, questions for research regarding vegetation:*
   Topics for research:
   - Seasonal interaction between mud storage on mud flats and sediment accretion in marshes. Is there a summer mud deposit that can be trapped on marshes during winter?
   - Cliff erosion of saltmarsh edges: how does it depend on the desequilibrium between hydrodynamical forces and height of the bed level ? Is there a critical difference where sedimentation is turned into erosion?
   - Relative importance of sand and mud availability in marsh development. Comparison between marshes in Delta region (mixed sand-silt) and Waddensea (clay deposits). Does this correlate with vegetation or is it only determined by sediment availability?
9. *Western Scheldt:*

For a proper assessment of sediment budgets to develop a long-term vision of the Western Scheldt estuarine morphological changes, the input of sediment from the North Sea, and to a lesser extend of the river Scheldt should be properly estimated, as well as the sediment budgets of the fine fractions (silt and clay).

The fate of salt marches (Saeftinge), intertidal mud flats, sandy shoals and gully systems is important. Siltation, erosion and sedimentation play an import role. Promotion or hindrance of these processes by ecological developments should be quantified in order to establish their importance. Vegetation will affect morphological development of intertidal flats and gullies.

10. *Eastern Scheldt:*
Mussels, oysters and cocklebanks are important for their economical value. The productivity of shell-fish is related to eco-morphological interactions. Biodeposion and reef-building are important for morphological developments and for their positive influence on the settling of young bivalves. One of the questions is: in which way are hydrodynamic processes and sediment transport affected by banks of shell-fish?

11. *Areas of interest for future research Haringvliet:*
Basic question in research on ecomorphology is related to the interactions between ecological processes and morphology. From morphological point of view it is interesting to know how diatom populations influence the morphodynamic behaviour of tidal flats. Is there a relation between ecologically important parameters like depth, bottom shear stresses, and the development of tidal flats? Are there seasonal fluctuations in tidal flat morphology due to fluctuations in diatom populations?

Most interesting areas in the Haringvliet in this respect are the silt depositing areas like West Plaat, Slikken van Voorne and Kwade Hoek. Also the protected foreshores in the inner Haringvliet with the returning tidal differences in future are areas of interest. These shores will graduately get shallower due to siltation and benthos can develop with time. What kind of benthos will develop in these shores and how will it influence the morphology (feedback mechanism)?

12. *Wadden Sea*
Eco-morphological interactions are expected to determine the robustness of the Wadden Sea area. It is important to disclose fundamental interactions that govern the survival of mussel beds, the formation and decline of salt marshes and the survival of eelgrass. Relations between the stability and composition of sediment and the occurrence of benthic algae, filter feeding bivalves, grazing of zoobenthos, as well as foraging of birds and fish have to be quantified.

It is not clear if the Wadden Sea will be able to compensate for both sea level rise (natural and antropogenically induced) and subsidence.

One of the opinions is that it is possible that the subtidal area will expand at the expense of the former flats and the salt marshes will disappear.

Another opinion is that no major changes are anticipated, unless the storm climate changes also. In the latter case additional erosion due to wave action can be expected along the edge of the salt marshes which, since in that case the development of their pioneer zone will be restrained, will most probably disappear. Also a steepening and retrogradation of the barrier-islands coastline is expected.

8 Summary and Conclusions

8.1 Summary

A summary is given of *managerial questions*, c.q. the problems of the end-users. Typical time horizons of these are of the order of 20 a 30 years.

Characteristic descriptions of the morphodynamic development of three typical systems: tidel lagoons (Wadden Sea), estuaries (e.g. Western Scheldt and Eastern Scheldt) and sea arms (mouth Haringvliet) are given. This considers the present state and expected future developments.

Also the ecological development of these systems is discussed, especially as a function of changes of water quality, i.e. from salt to fresh riverine water, and vice versa, and with respect to changed tidal regimes. Processes and factors governing the ecosystems are discussed. One of the most important issues in eco-morphology is addressed: spatial and temporal scales of ecological and morphodynamic processes.

The most important eco-morphological interactions are identified, specifically: diatoms and bio-stabilisation of sediment, bioturbation, biodepositors/reef-builders and vegetation. Also the role of positive feedback mechanism on the development of ecosystems is discussed. One example is the presence of alternate states: bimodal diatom distribution.

8.2 Conclusions

For management of the deltaic region it is important to consider eco-morphological interactions. Some examples of managerial issues that might be resolved by quantification of eco-morphological interactions are:

Western Scheldt:
The recent development is a strong diminishing of storage areas and salt marches. The proposed future development is a better planning of human activities to partially restore original dynamics.
The fate of salt marches (Saeftinge), intertidal mud flats, sandy shoals and gully systems is important. Siltation, erosion and sedimentation play an import role. Promotion or hindrance of these processes by ecological developments should be quantified in order to establish their importance. Vegetation will affect morphological development of intertidal flats and gullies.

Eastern Scheldt:
The recent development is a closure from river influences (dam + sluices) and storm-surge-barrier. The proposed future development is an increase of fresh water discharge to provide conditions closer to the original brackish intertidal character.

Mussels, oysters and cocklebanks are important for their economical value. The productivity of shell-fish is related to eco-morphological interactions. Biodeposion and reef-building are important for morphological developments and for their positive influence on the settling of young bivalves. In which way are hydrodynamic processes and sediment transport affected by banks of shell-fish?

Haringvliet:
The basin is closed from sea influences. The proposed future development is an appropriate opening of the sluices in order to provide again a brackish-tidal character to the basin. Several alternatives have been studied.
The proposed changes might for instance lead to morphological conditions similar to the Eastern Scheldt, but with much more river influence. One of the questions is: will salt marshes develop? Another question is whether the vegetation on intertidal flats might increase. How do banks of shell-fish respond to a different regime of siltation and sedimentation? How is morphological development affected by the (re)introduction of new species?

Wadden Sea
The long term development of mussel beds is an important ecological and economical factor. Mussel beds can survive for long periods. However strong declines have been recorded, both in area covered by mussel beds and biomass per unit area.
Also many of the salt marshes in the Wadden Sea need protection by brushwood groynes at present. It is desirable to enlarge the salt marsh area in the western part of the Wadden Sea.
A sharp decline in eelgrass vegetation has occurred, almost towards extinction. Eelgrass meadows affect water currents and may stabilise sediments. Successful recovery of eelgrass may be induced by protection of remaining eelgrass stands.
Further questions are related to the robustness of the Wadden Sea area with regard to human activities, such as fisheries, extraction of sand and shells, recreation and exploration of gas and oil.
It is not clear if the Wadden Sea will be able to compensate for both sea level rise (natural and antropogenically induced) and subsidence. If not, tidal flats will be lost.

Time-and length-scales
In evaluating these issues, it is very important to consider time- and length-scales of processes. Specifically the interaction of eco-morphological processes on intertidal flats and in gullies with respect to the estuarine processes as a whole.

Choices made with respect to research programme
It is not possible to study all interactions identified in the next two years. Therefore choices have to be made. This has been done on the basis of priorities in the management of the various Dutch systems and with respect to the scientific relevance, and a pragmatic argument, that is that the study should result in significant progress within the study period in our description and understanding of subject. It is for these reasons that it is proposed to study the generation, degeneration and behaviour of salt marshes.

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Zens, M., H. Michaelis, M. Herlyn, & M. Reetz 1997 Die Miesmuschelbestände der Niedersächsischen Watten im Frühjahr 1994. Ber. Forschungsstelle Küste, Norderney 41, 141-155

A ongoing Research Projects

Many multidisciplinary projects have been dealing or deal with the bio-geo-morphology of the dutch coast, they are:

- **BEON** (Beleidsgericht Ecologisch Onderzoek Noordzee/Waddenzee), internet site: *www.waterland.net/beon/index.html*. This project was carried out by a Dutch association of governmental and research institutes, with the aim of studying the ecology of the North Sea and Wadden Sea for the development of sustainable management policies. Project site within the Western Scheldt estuary: several intertidal flats.

- **ECOFLAT** (Ecometabolism of a tidal Flat), internet site: *www.nioo.knaw.nl/cemo/ecoflat/Ecoflat.htm*, contact person: carlo Heip (tel. 0113.577445). This project was funded by the European Commission in the framework of the ENVIRONMENT & CLIMATE programme and was part of the ELOISE project (European Land Ocean Interaction Studies). It was a multidisciplinary project aiming to understand the role of intertidal flats in forming the ecology of estuaries and to assist in the understanding of the upscaling of processes at the small scale to predictions relevant for management at the estuarine scale. Project site within the Western Scheldt estuary: the Molenplaat intertidal flat.

- **ECOMOR**, contact person B. Kornman (RIKZ, tel. 0118.672280). The project deals with the analysis of bottom dynamics including relations with benthos. Project site within the Western Scheldt estuary: Plaat van Baarland.

- **INGE** (Verkenning Inrichtsmaatregelen estuaria en kust), contact person: A. Smaal (RIKZ, tel. 0118.672230). The project dealt with the sea arms and the estuaries of the Netherlands with the aim of studying habitat availability for benthos and nursery areas for fish.

- **INTRMUD** (Intertidal Mudflats), internet site: *www.science.plym.ac.uk/KDYER*. This project was funded by the European Commission in the frame of the MAST III programme. The aims of the project were: to investigate the characteristics of several mudflats to establish a classification; to carry out experiments to quantify processes and interactions; to provide a basis for understanding which can be used for environmental management. Project site within the Western Scheldt estuary: the Molenplaat inter tidal flat.

- **LTV** (Long Term Vision), contact person H. Verbeek (RIKZ, tel. 0118.672225). This project has been commissioned by the Technical Scheldt commission to The National Institute for Coastal & Marine Management (RIKZ). The project aims at the development of a long term vision for the Western Scheldt estuary and to establish the quantitative indicators for shipping accessibility, safety from flooding and management of the natural system.

- **LWI-programme: EDSS** (Estuarium DSS Westerschelde), internet site: *www.lwi.nl*.. This projecs aim was the development of a Estuary Decision Support System (EDSS) with an interdisciplinary approach. The EDDS instrument was developed within the "Integraal Beheer Estuariene en Waddensystemen" project.

- **MARS**, contact person: L. Santbergen (RWS Directie Zeeland, tel. 0118.686402). The project deals with the restoration and maintenance of marshes along the River Scheldt.

- **MOVE** (Monitoring Verruiming Westerschelde), contact person: B. de Winder (RWS Directie Zeeland, tel. 0118.686200). This project has been commissioned by RWS Dir. Zeeland to the National Institute for Coastal & Marine Management (contact person: B. de Douwe, tel. 0118-672311) with the aim of monitoring and predicting the effects of deepening the navigation channel on physical, chemical and biological characteristics at the level of the whole estuary and at the level of large sections of it (mega-scale and macro-scale).

- **OOSTWEST**/verdiep, contact person: J. Vroon (RIKZ, tel. 0118.672232). This project deals with the analysis of the impact of human interventions, such as the creation of polders and the deepening of channels and dredging activities, on morphology, ecotopes and benthos of the Western Scheldt estuary.

- **RUIMTECOL**, contact person: J. Graveland (RIKZ, tel. 0118.672200). This project aims to determine the physical effects and their interrelationships that control the form and function of marine ecosystems. A methodology will be developed to aid in a better understanding of these parameters, which can then be used by policy makers to understand and mitigate the effects of human interventions on ecosystems, such as the Maasvlakte 2. The project considers the whole Dutch coast, including the estuaries, and focuses on benthos.

- **ZEEKENNIS**, contact person: H. van Pagee (RIKZ, tel. 0118.672298). Thiis This is a long-term research project (3-4 years) on the impact of interventions on the eco-morphology of the Western Scheldt estuary.

- **Research & Development program WL | Delft Hydraulics.** The functioning of the estuarine system of the Western Scheldt is analysed by studying the interrelations between all relevant abiotic and biological phenomena and processes, considering the spatial and temporal scales at which they operate. Internal report: Crosato, A., Vries, M. de and S. Tatman, 2000, Analysis Bio-geomorphological Interactions in the Western Scheldt.

Within the framework of GONZ (Graadmeter ONtwikkeling Noordzee) and LWI-Veerkracht a number of criteria (indicators) have been discussed and quantified that help the end-user to assess the quality of the North Sea ecosystem and the resilience of the Dutch coastal dunes. These criteria are defined as both physical and biological parameters; they reflect the current or future situation in relation to goals, trends and natural variability. Within the Westerschelde system, end-users are involved in discussing and describing the long-term quality status of the estuary (LTV). This exercise will produce a set of quality objectives that will be used to further define quality criteria.

Project DYSC, a four-year research initiative to be carried out at NITG-TNO, focuses on the DYnamics and Sediment Classification of the seabed. It is aimed at integrating existing geological and geophysical data and state-of-the-art models with repeated high-resolution multi-beam recordings. Data will be recorded at several sites that are characteristic of different seabed morphologies. DYSC is relevant to the present project because it contributes data for the morphological description of the closed coast.

In the Waddensea, Alterra is engaged in studies relating the distribution of suspension feeders (mainly mussels and cockles) to sediment characteristics and sediment budgets. Furthermore sediment budgets in relation to vegetation structure are being studied. These projects are embedded into the DLO research programs of the ministry of LNV, monitoring programs co-ordinated internationally by the Common Wadden Sea Secretariat and monitoring programs for NAM in relation to soil subsidence.

Currently, a project plan is being set up between Directorate Zeeland of RWS, RIKZ, NIOO and NIWA (New Zealand) for a scale-dependent study of macrobenthic distributions in estuaries. Within this project, the scale at which environmental variables (including morphological processes and characteristics) influence macrobenthos will be derived from statistical analysis of existing data. Statistical models will be improved by including process knowledge, e.g. about feeding ecology, interspecific interactions but also eco-morphological interactions. The derivation of ecological indicators for morphological changes is also one of the aims of the project.

B recent morphological studies - Wadden Sea

Many projects have been dealing or deal with the morphology of the Wadden Sea. The list below does not contain all works, but can be used as starting point for the study of the morphology of the Dutch Wadden Sea.

Effecten van landaanwinning Maasvlakte 2 op slibhuishouding, (on-going project WL | Delft Hydraulics). Contractor Project Mainpoortontwikkeling Rotterdam. This on-going project deals with the study of the effects of the Maasvlakte enlargement on suspended sediment transport along the Dutch coast, including the Wadden Sea. Water and suspended sediment discharges of the rivers Maas (Rhine), Thames, Senne and Scheldt are taken into account.

Morphology of the Wadden Sea, Impact of sand and shell borrowing (in Dutch). W.D. Eysink, WL | DELFT HYDRAULICS, Report R 1336 on literature study, May 1979. The morphology of the Dutch Wadden Sea has been studied in an extensive literature survey covering 149 articles and reports of different disciplines (geology, archeology, history, biology, sedimentology, hydraulics, etc.). This has resulted in a rather complete description of the morphological mechanisms responsible for the shaping of the Wadden Sea. The report presents a lot of characteristic data and the first empirical relationship between the tidal prism and the volume of tidal basins. Based on this study it was concluded that sand borrowing ultimately will have an impact on the North Sea coast of the Wadden Sea area and that the impact of shell borrowing on the sediment transport in the Wadden Sea is negligible.

Morphological response of tidal basins to changes. W.D. Eysink, 22nd ICCE, Delft, The Netherlands, 2-6 July, 1990, The Dutch Coast, paper No. 8. Presentation of empirical relations for channel cross section, depth and volume, for sand volume in outer deltas and for tidal flat area in the Dutch Wadden Sea and the Delta area and the possibility to apply them in coastal engineering.

Morphological stability of inlets and channels of the western Wadden Sea. F. Gerritsen, RWS-DGW, Report GWAO-90.019, October 1990. The report presents a number of empirical relationships for stable (in size) tidal channels and discusses the possibility of the use of empirical relationships, the “stability shear stress” approach, dimensionless parameters or numerical morphological modelling to solve the “stability equation” for a tidal channel. Further, forces causing channel migration are discussed and the possibilities of modelling morphological processes.

Coastal Genesis Project, Some considerations on tidal inlets, A literature survey on hydrodynamic and morphodynamic characteristics of tidal inlets with special attention to “Het Friesche Zeegat”. R.C. Steijn, WL | Delft Hydraulics, Report H 840.45 on literature survey, May 1991. In this report the interrelation between the different morphological units of the Wadden Sea is described based on the results of an extensive literature survey. It also discusses the possible impacts of human interference in the natural system and the applicability and restrictions in the validity of empirical relationships in literature.

GEOPRO Project, Inventory Field Data Wadden Sea (in Dutch). A.W. van Kleef, Univ. of Utrecht, Institute of Geographical Research, Vakgroep Fysische Geografie, Report

GEOPRO 1991.014 (Notitie AOFM-91.10.010, RWS-DGW). The report presents an overview of all historical field data of the Dutch Wadden Sea which are available in archives of RWS. This concerns discharge measurements (since 1948), soundings (1950-1985 in eastern part and 1930-1988 in western part), water level stations and records, station and records of wave measurements, Position of rows with ripple measurements, map with median sediment diameter, historic maps, titles and brief summaries of some brief reports of the Meet- en Adviesdienst Hoorn (period 1952-1982) and a list of documents about the Wadden Sea.

GEOPRO Project, Available sediment data of the Dutch Wadden Sea (Part I). J.J.P. Lambeek, Univ. of Utrecht, Institute of Geographical Research, Vakgroep Fysische Geografie, Report GEOPRO 1991.016A (Notitie GWAO-91.10090, RWS-DGW). The report presents an extensive literature survey on the sedimentology of the Dutch Wadden Sea. The results are describes in relation with the geology, morphology and hydrography of the Wadden Sea inclusive effects of land reclamation areas and the exploitation of sand and shells.

Coastal Genesis, Equilibrium relations in the ebb tidal delta, inlet and backbarrier area of the Frisian inlet system. E.J. Biegel, Univ. of Utrecht, Vakgroep Fysische Geografie, Report GEOPRO 1991.028 (GWAO-91.016, RWS-DGW), August 1991. Study on empirical relationships for the cross section of a tidal channel and the adaptation of the channels to the new conditions after closure of the Lauwers Sea.

ISOS*2 Project, Impact of sea level rise on the morphology of the Wadden Sea in the scope of its ecological function. This study focussed on the existence of empirical relationships between morphological units (such as tidal inlet and local channel profile, basin volume, sand volume of outer delta, height of tidal flats) and characteristic hydraulic parameters in the Wadden Sea based on data in literature and field data from the Dutch Wadden Sea (Phases 1, 2 and partly 4). The purpose was to look for the possibility to develop a concept for the development of mathematical models with a stable computational scheme for long-term morphological developments. Proposals for such schemes have been presented in the Phase 3 report. The Phase 4 report gives a more general description of the morphology of the Wadden Sea and additional empirical relations for the tidal flats in particular.

Morphological and ecological effects of sea level rise: An evaluation for the western Wadden Sea. E.B. Peerbolte, W.D. Eysink and P. Ruardij, In: Ocean Margin Processes in Global Change, edited by R.F.C. Mantoura, J-M. Martin and R. Wollast, © 1991 J. Wiley & Sons Ltd. Publication of a study on the building of the ISOS model for the Netherlands to support decision-making in the context of sea level rise. Part of the paper describes the principle of time lagging in the response of the bottom of the Wadden Sea and the effect on the tidal flat area. Another part describes the possible impact on the ecosystem.

The mystery of the wadden, How a tidal system reacts on sea level rise (in Dutch). T. Louters and F. Gerritsen, Ministry of Public Works, RIKZ, Report RIKZ-94.040, October 1994. This report is a final publication based on the results of the ISOS studies of which ISOS*2 concerned the morphological part. The report gives a clear picture of the genesis and the morphology of the Wadden Sea. It also describes the possible effects of increased sea level rise and human interference (like closure works, sand mining and bottom subsidence due to gas mining) on the morphology and ecology of the area.

Dutch "slufters", Tentative inventory of abiotic parameters (in Dutch). W.D. Eysink, A. IJ. Hoekstra and F.M.J. Hoozemans, WL | DELFT HYDRAULICS, Report H1465, March 1992. In the scope of maintenance and improvement of existing slufters and the possible development of new slufters or salt dune valleys there is a need for better knowledge on the morphological characteristics of slufters. This study was a start to find such characteristic relations.

Dynamics and sedimentary development of the Dutch Wadden Sea with emphasis on the Frisian Inlet, A study of the barrier islands, ebb-tidal deltas, inlets and drainage basins. A.P. Oost, Univ. of Utrecht, Fac. of Earth Science, Publ. No. 126 (Thesis). Extensive general description of historical developments and morphological processes in the Dutch Wadden Sea and the Frisian Inlet system in particular. A lot of historical data and information on bed forms.

Effects of future sea-level rise and subsidence on the Wadden Sea tidal system; Sediment dynamics and biology; What do(n't) we know? A.P. Oost, P.L. de Boer and W.J. Wolff (ed.), Proc. of Symposium, Wolfheze, 23/24 May 1996. Univ. of Utrecht and Groningen. Contributions of different institutes on different disciplines such as geology, morphology, subsidence, hydrodynamics, biology and modeling.

Study on the arrangement of the eastern part of the Western Scheldt, Analysis of the physical system (in Dutch). E. Allersma, WL | DELFT HYDRAULICS, Report Z 368, July 1992 (Report for Werkgroep OOSTWEST). Extensive literature survey on the morphology of the Western Scheldt estuary considering geology, geography, hydrography, morphology, sedimentology, impact of dredging and a conceptual model based on empirical relations.

The morphodynamics of the Wadden Sea on different space and time scales (in Dutch). T.T. Reijngoud, Waddenvereniging, Harlingen, January 1998. General description of the morphology of the Wadden Sea. The different units of the system are classified on different hierarchic levels with different times of response.

Prediction of coastline development 1990-2090, Phase 3, Subreport 3.1: dynamic model of the Dutch coastal system (in Dutch). M.J.F. Stive and W.D. Eysink, WL | DELFT HYDRAULICS, Report H 825, September 1989. The report presents a brief description of the history of coastal development of the Dutch coast and the impact of human interference particularly in the past 100 to 150 years. Further, it describes two conceptual models, i.e. one for a uniform coast and one for tidal inlets and estuaries. Based on these models and historic data an attempt was made to predict the development of the North Sea coast for the next 100 years.

Coastal defence Eierland (Texel), Hydraulic morphological impact study, Phase I (in Dutch). J.S. Ribberink and J.H. de Vroeg, Part I, Morphological analyses (main report), Hartsuiker, Part II, Detail model tidal flow, WL | DELFT HYDRAULICS, Report H 1241, June 1991. Preliminary study on the erosion problem of the northwestern coast of the island of Texel and investigations on possible coastal defence structures with emphasis on a solution with a long groyne.

Evaluation seaward coastal defence, Texel-Eierland groyne (in Dutch). H.D. Rakhorst, RWS, Dir. Noord-Holland, Dept. ANV, Haarlem, 18 March, 1999. The report describes the historical development of the northeastern coast of Texel and the actual development of the coast and the seabed after construction of a long groyne.

Evaluation of seaward coastal defence (in Dutch). Tj. Van Heuvel et al., RWS, RIKZ, Report RIKZ-99.009, April 1999. Description of the actual developments around recent coastal defence works in The Netherlands.

Gas extraction at East-Ameland, impact of bottom subsidence (in Dutch). R. Reinalda et al., WL | DELFT HYDRAULICS/RIN, Report H 114, April 1987. The report presents a prediction of hydraulic, morphological, ecological and economic impacts in the Wadden Sea and on Ameland caused by bottom subsidence expected due to gas extraction.

Monitoring impacts of bottom subsidence at East-Ameland, Evaluation after 13 years of gas extraction (in Dutch). W.D. Eysink et al., WL | DELFT HYDRAULICS/Alterra, Report H 841, March 2000. The report describes the impacts of bottom subsidence after 13 years of gas extraction. Until now hardly any effects could be found which actually are caused by bottom subsidence. Most of the changes are caused by the strong dynamic behaviour of the area.

Bottom subsidence due to gas extraction in the Wadden Sea, Effects on sand demand and tidal flats according to computations with the morphological response model MORRES (in Dutch). W.D. Eysink, WL | DELFT HYDRAULICS, H 1948, August 1993. In: Effects of bottom subsidence due to gas extraction in the Wadden Sea (in Dutch). A. P. Oost and K.S. Dijkema, IBN report 025, 1993. Study on the additional sand demand and loss of tidal flat area of the Dutch Wadden Sea due to gas extraction.

Integral Bottom Subsidence Study Wadden Sea, Geomorphology and Infrastructure (in Dutch). Effects of bottom subsidence due to gas extraction at the Wadden Sea, Morphological, infrastructure and economical aspects. W.D. Eysink, WL | DELFT HYDRAULICS, Report H 3099, December 1998. The impact of the total subsidence of all gas fields affecting the Dutch Wadden Sea was studied. Important aspects where the impacts on the tidal flat areas (reduction of level and area as a boundary condition for bird life in this natural reserve) and on the North Sea coasts of the islands. These impacts were studied for the Frisian tidal inlet with the models ESTMORF, ASMITA and MORRES. Further MORRES was used to extrapolate the ESTMORF and ASMITA results to the other tidal basins.