MORPHOLOGY AND MORPHODYNAMICS OF THE WADDEN SEA

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1. 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 1). These modes occupy different segments of the diagram and consist of transgression, regression, retrogradation and progradation (and combinations thereof).

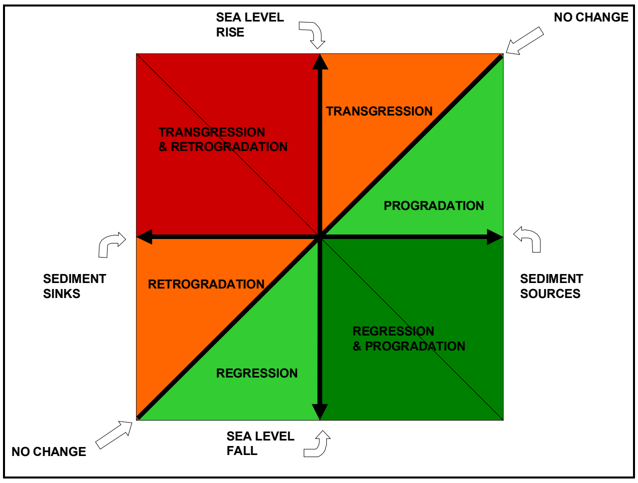

Figure 1

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. 2) 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: de 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 2 and 3).

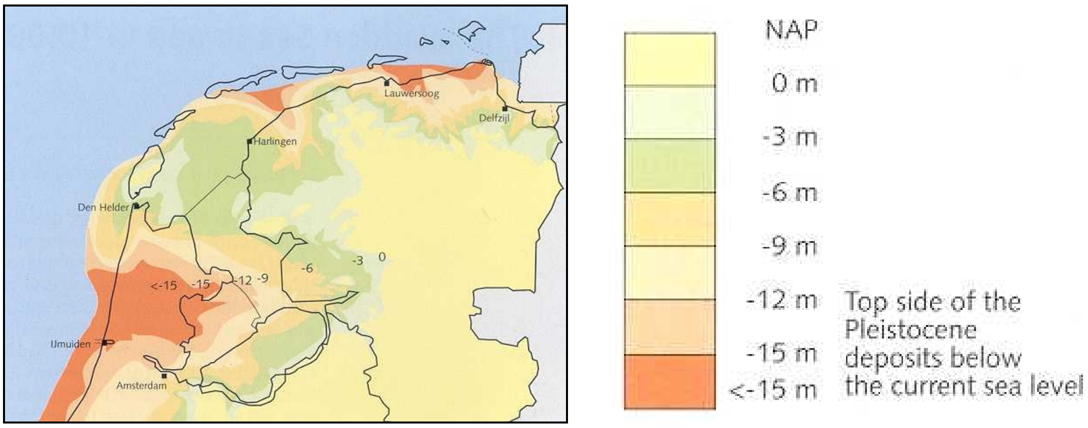

Figure 2. Irregular Pleistocene landscape with deep depressions (Figure from Louters & Gerritsen, 1994, after Zagwijn, 1986).

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 3a
Approximately 7000 (C14) years ago, that is 5800 B.C.

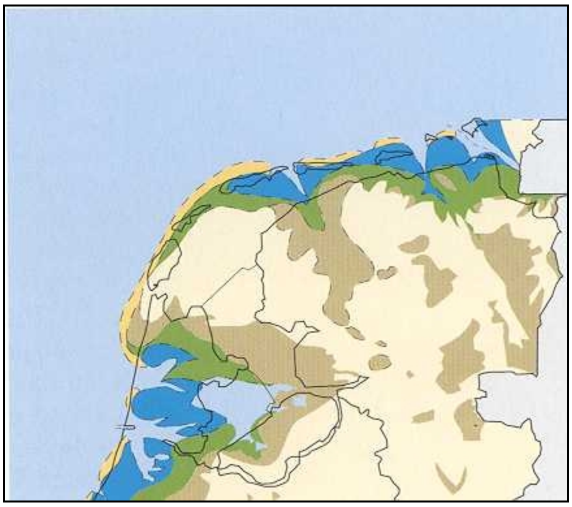

Figure 3b
Approximately 5300 (C14) years ago, that is 4000 B.C.

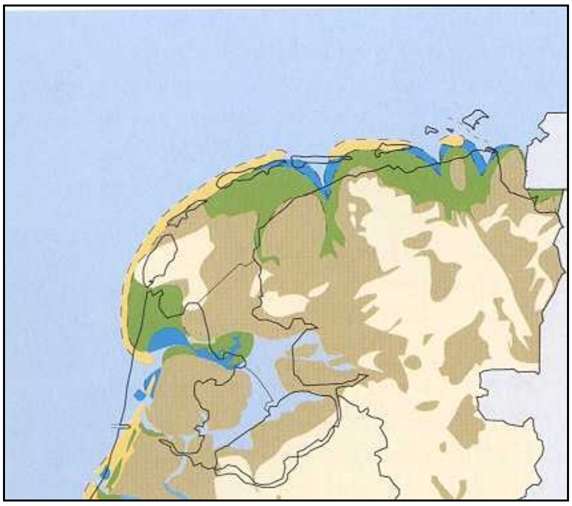

Figure 3c
Approximately 3700 (C14) years ago, that is 2100 B.C.

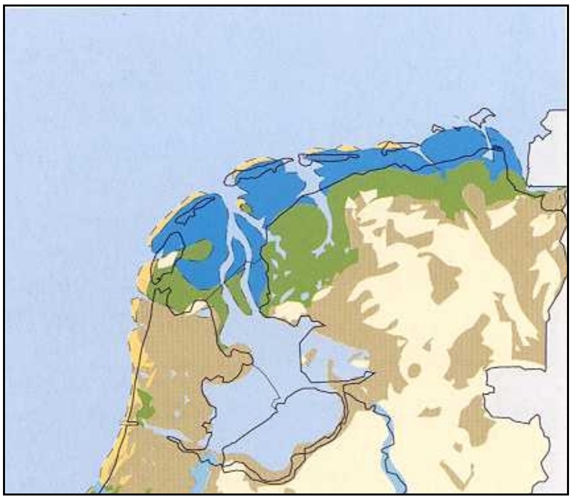

Figure 3d
Approximately 500-700 A.D.

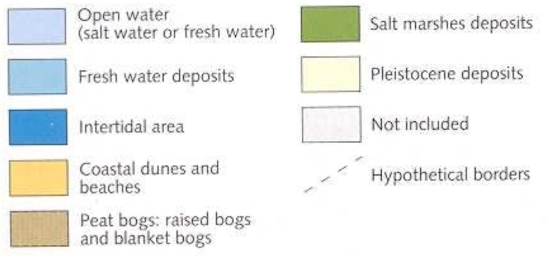

Figure 3.

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.

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.

2. 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.

The morphologically most dynamic area of the tidal basin system includes inlet throat and outer or ebb-tidal delta. Figure 4 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.

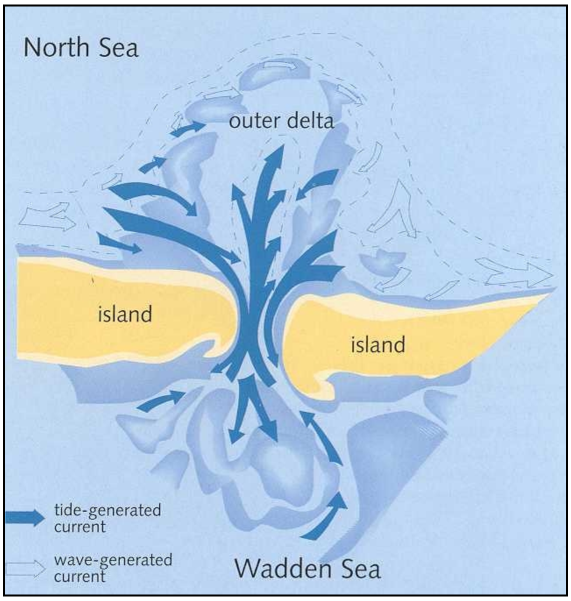

Figure 4
Schematisation of the interaction between the open sea and a typical Dutch Wadden Sea lagoon (Louters and Gerritsen, 1994).

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 5. 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.

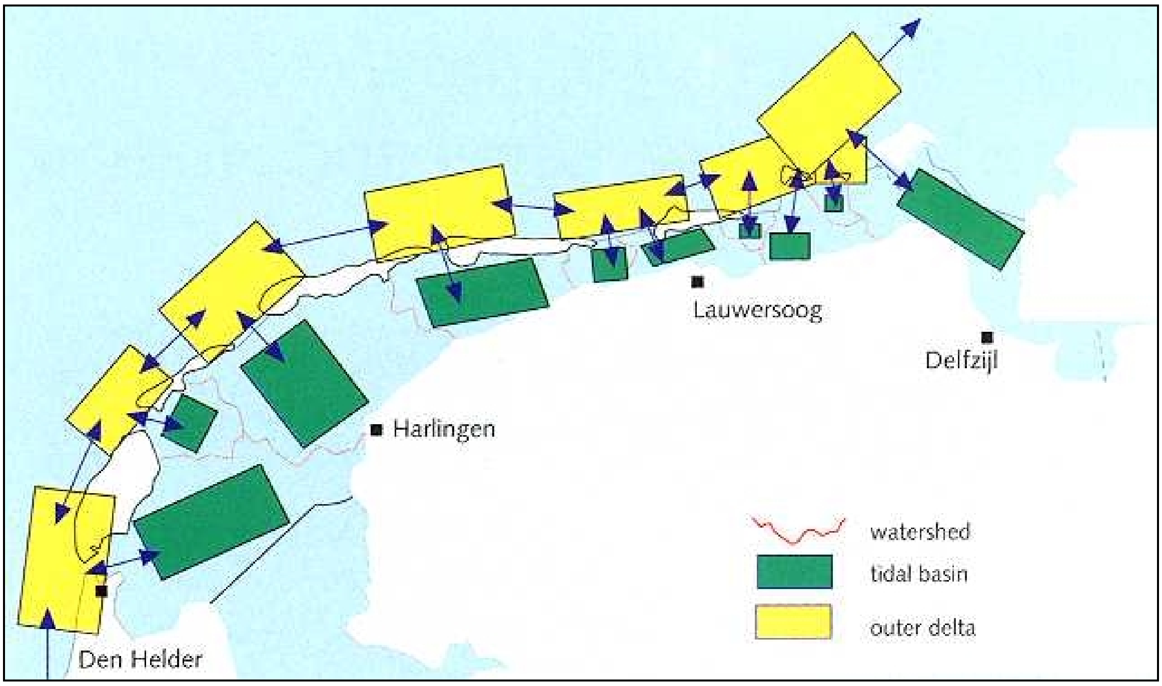

Figure 5. Sand sharing system. The sediment budgets are all interlinked (Figure from Louters & Gerritsen, 1994, modified after Stive and Eysink, 1990)

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).

Human interventions

- **Coastal protection works**. All the Dutch mainland Wadden Sea coast is protected by dikes and along parts of the barrier islands dikes protect the reclaimed areas. The salt marshes along the mainland coast are protected against erosion by brushwood groins perpendicular to the coastal line. 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, flatfish)**. 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 reduce the ability of capturing sediment in relation to the sea level rise phenomenon. Most shrimp fishery is carried out on the North side of the Wadden islands, where it is also allowed during the winter. 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 led to increased 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) has all been dumped within the estuary.
- **Extraction of sand and shells.** The yearly amounts of sand extraction have recently reduced to less than one million of cubic meters, while the average amount of shell extraction is 85,000 m^3. These activities lead to local lowering of the bed 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.

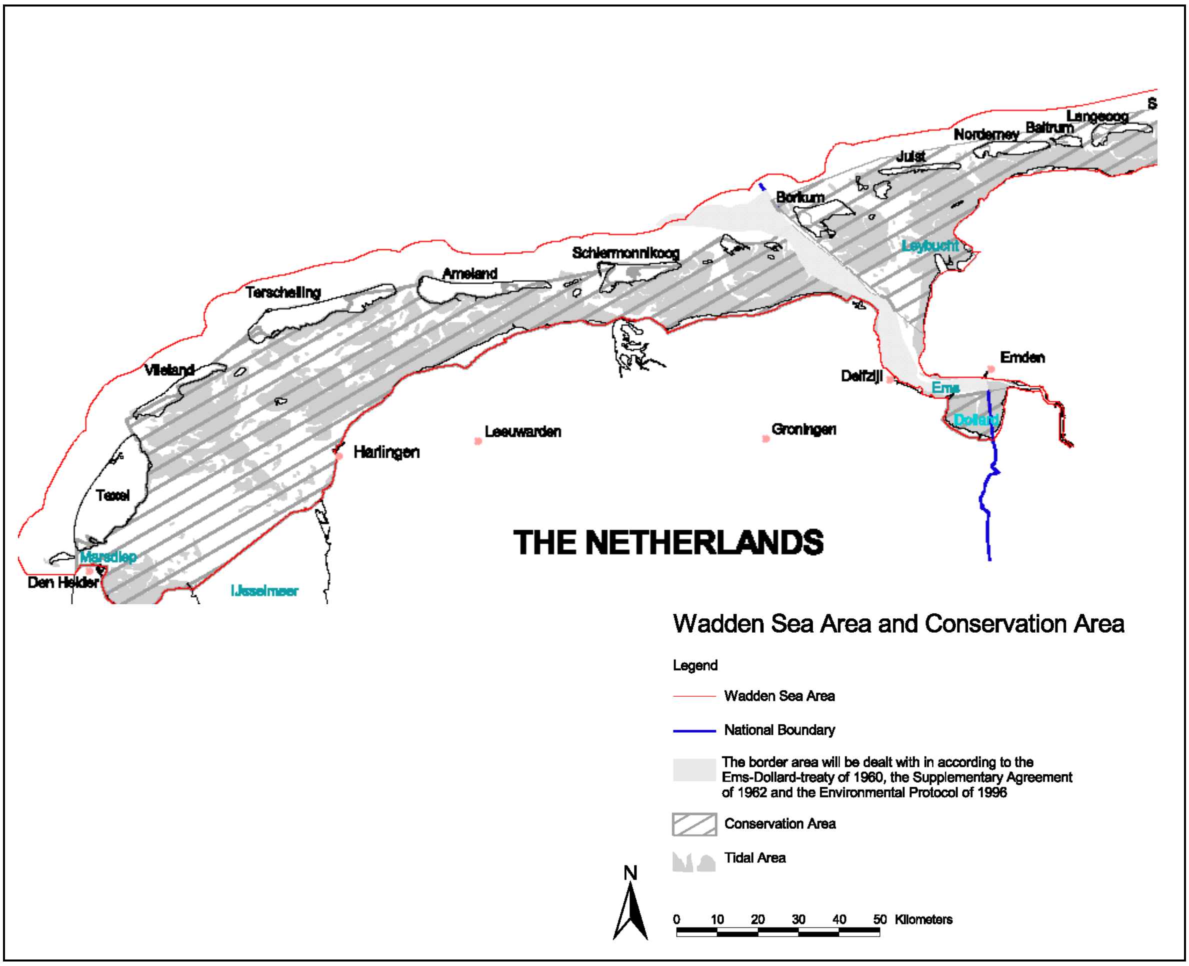

Figure 6. Conservation Areas in the Dutch Wadden Sea (RIKZ, CWSS, 1998)

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.

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