General introduction
Mud in the past, present and future

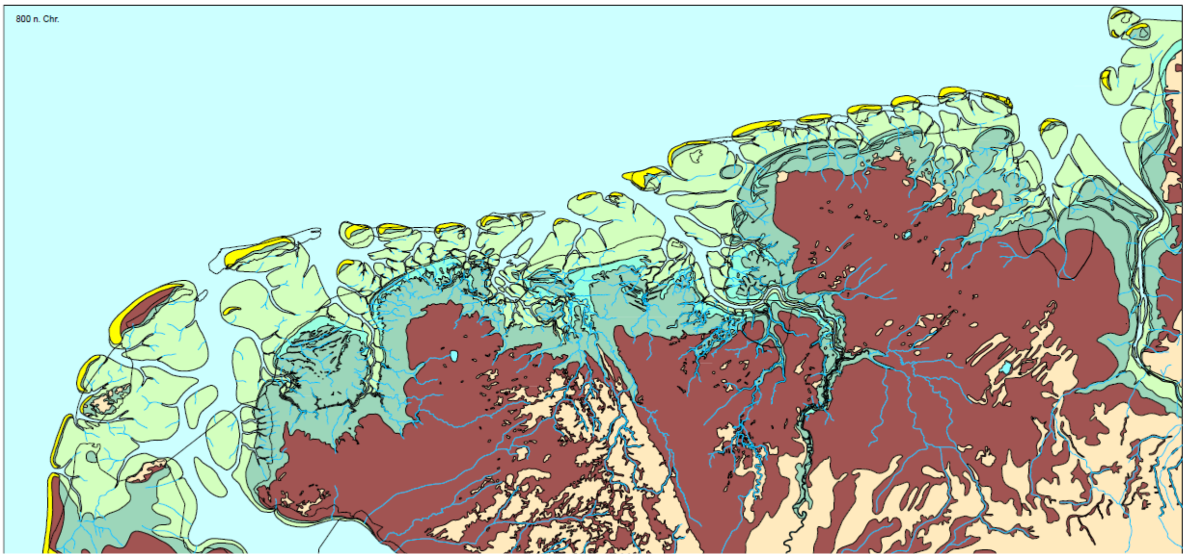
Figure 1; Jadebusen Photo A. Plesse

In the Wadden Sea there are two worlds: a “sand world” and a “mud world” which interact with each other. Due to their own typical sedimentary behavior, each of them cannot replace the other and provides its own natural values to the area. Compared to the natural situation, the muddy zone at the mainland has been shortened considerably by diking. At many places the clay deposits of the former muddy tidal flats are now lying tens of kilometers inland and have been subsiding relative to mean sea level, making these areas vulnerable to flooding and salt intrusion. Marine muddy embayments reaching for tens of km inland have been filled up and have disappeared. New entrances can no longer form and formation of new mud-rich environments has stopped. The mainland mudzone has changed strongly.

The first results of an inventory study indicate that at present a quite substantial part of the mud influx is deposited. As mud is transported from west to east, it is likely that mud sedimentation will decrease in that direction. For a future with accelerated sea-level rise this may prove detrimental for the resilience of the muddy systems. Wise mud management will play a major role to meet this challenge.

Two separated worlds
From measurements it has become clear that there is a relatively strong segregation between muddy sediments and sandy sediments, due to their different settling and resuspension behavior. In general, mud is deposited some 10 km from the inlets. Thus, the Wadden Sea can be thought of as consisting of a sand system and a mud system, which interact with each other. It implies that both are important for the functioning of the system and generating the natural values of the Wadden Sea area. Here we focus at mud transport and sedimentation and the role of mud management through time.

Past
The original landscape: extensive mud flats
Before humans started to influence the development of the mainland coastal zone, the Wadden Sea area was basically a flood-tide landscape. It consisted of high lying Pleistocene Boulder clays and sand deposits (Geest Grunden) surrounded by peat areas which had partially also filled in the old river valleys. This area merged into tidal marshes which gave way to higher tidal mudflats and to lower intertidal sandflats. Until the medieval dikes were built on a large scale the mud landscape formed about the half of the Wadden Sea area. Tidal marshes and tidal mudflats were up to several tens of kilometers wide.

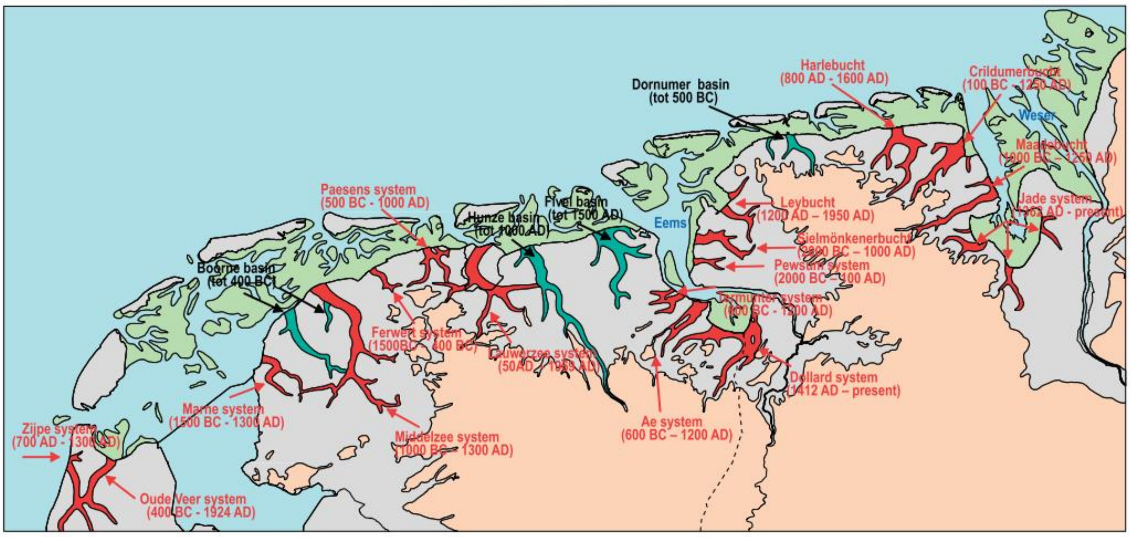


Reconstruction of the East and West Frisian Wadden Sea landscape in 800 AD. Orange = sandy areas; brown = peat; dark green = tidal marshes and mudflats; light green = mainly sandy tidal flats; yellow = sandy barrier islands (Vos & Knol, 2005).

Formation and infill of valleys: mud fills

When valleys or peat areas were flooded, the peat was eroded or compacted, and strong sedimentation of mud occurred. After the initial incursion of the sea, the area silted up and became land once again. The rapid infill of embayments such as the Dollart, the Middelzee and the Harlebay point to a very large availability of mud. For the Holocene deposits in the Dutch Wadden Sea it has been calculated that in total some 18,178*10^6 m^3 of mud was deposited. If it is assumed that the major part has been deposited during the past 5000 years that would be an average deposition of some 2.5 *10^6 m^3/yr for the Dutch Wadden Sea area up to Groningen. This is about twice as high as present-day values. The explanation is most likely two-fold:

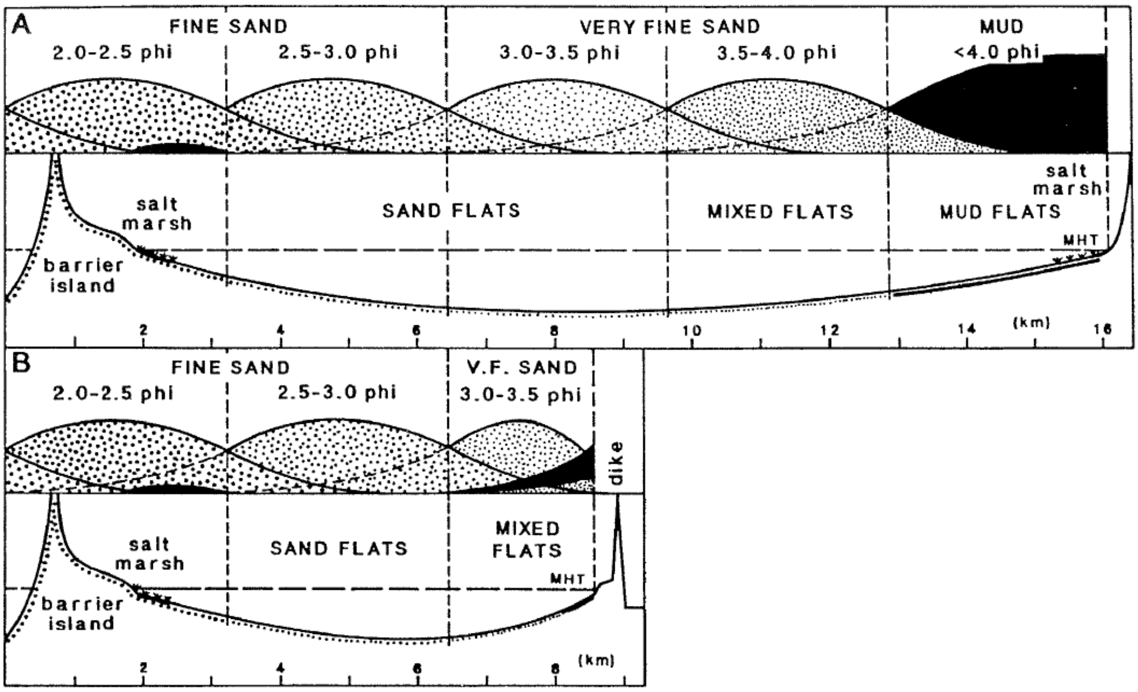
1) The incised valleys and embayments provided very quiet conditions for muds to be deposited.
2) The supply of mud might have been higher. Forest were cleared by man leading to stronger erosion and the sea bottom was still reacting on the rapid flooding after the last Ice Age, locally eroding the bottom. Also, coastal retreat has occurred over the past 5000 years in the West and East Frisian Wadden area and over the past 1000 years along the Holland coast and parts of the North Frisian Wadden area.



Locations of active tidal systems during the past 2400 years. Green: tidal channels of older tidal basins which were still active; red channels new ingressions (Vos & Knol, 2005).

Smoothening the coastline: no place for mud

On other parts, where energies became too high, the mainland coast eroded and retreated. Overall the mainland coast had a tendency to "smoothen out", with protrusions being eroded and indentation filled up. However, from time to time new valleys and low areas would open to flooding by the sea and so the history. At the same time the barrier islands and tidal inlets retreated in a landward direction, making the energy gradient steeper and locally leading to renewed erosion.



A: Hypothetical shoreward-fining grain size model for a natural backbarrier depositional system. B: Actual shoreward-fining grain size sequence observed in the backbarrier region of Spiekeroog Island. (From Flemming & Nyandwi, 1994).

Diking the landscape: no space for mud

For the longest part of the existence of the Wadden Sea the muddy zone has been quite broad: almost fifty percent of the area consisted of mudflats and tidal marshes. This long gradient made it possible for fines to settle according to grain size. Constructions of dikes to almost the outer rim of the muddy tidal flats is thought to have shortened the energy gradient.

Where the coast extended in a seaward direction by sedimentation this was followed by farmers, which took the new land and build dwelling hills (partially consisting of mud) on the higher ridges in the landscape. There are, however, clear signs that they may have helped the natural processes somewhat. Low dikes of several decimeters were built on lower tidal marshes from at least the first century BC onwards. These may have had the same function as the brushwood fences on the present-day foreland tidal marshes: enhancing sedimentation. On the middle tidal marshes, dikes of 0.9-1 m height and up to 5 m broad were built as early as 2nd Century BC. These dikes will in general have protected the area behind it from summer storms but will have been flooded one to a few times during the winter period. Thus, winter storms would bring in nutrients and kill of the nematods, whereas during summer fresh water conditions prevailed and agriculture was possible. In the centre of the area a dwelling hill was present, protecting the inhabitants from the higher storm surges.

Although systematic building of lines of dikes became the norm around the 10th – 11th Century, these were quite low. Even in the 16th Century one could stand behind the dike and look over it. As a result, flooding and bursting of the dikes was normal and the area behind it was flooded from time to time. Where flooded land could not be reclaimed immediately (subsidence, too much erosion of peat or top soil) the area became Waddensea. In exposed areas, such as the North Frisian area, the losses were permanent. In the sheltered areas, such as the Dollard area, sedimentation was rapid (2-3*10^6 m^3/yr). Furthermore, at many places, new areas of tidal marshes heightened sufficiently to become new polders. Due to this a large part of West and East Frisia was characterized by several lines of dikes: the Dreamer, the Sleeper and the "Waker" (Guardian). Due to their low heights these will many times have functioned as a double or even triple dike system. The increase in technical possibilities led to a tendency to "straighten" the coast line reducing dike lengths. Thus, many embayments and "dents" in the coast line were removed and the possibilities for fine grained sediment to settle permanently were strongly reduced.

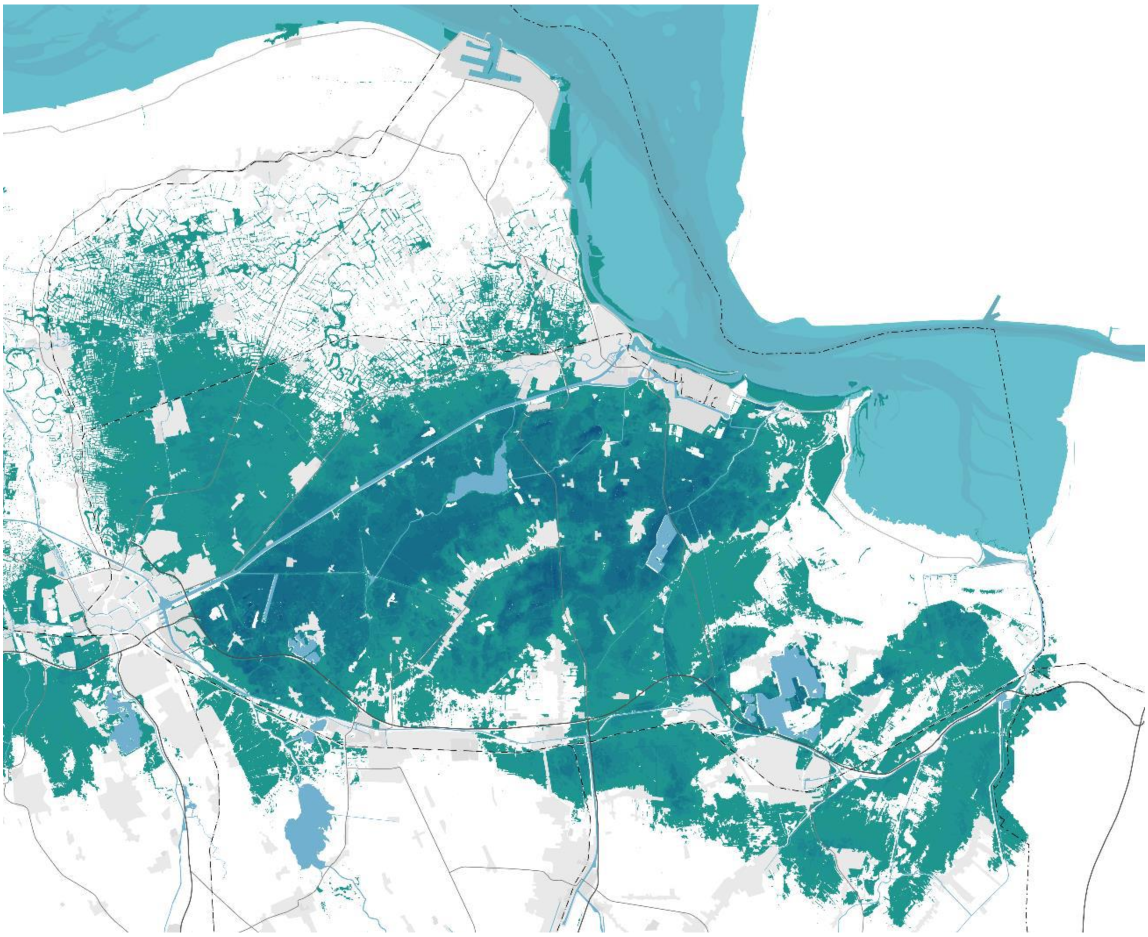
Present

Reclamation works stopped: maintaining the status quo of tidal marshes and mud flats

In the foreland tidal marshes mud deposition was furthered since at least the 16th Century via a system of ditches and brushwood groins. This practice became quite influential in the 19th and 20th century and huge areas were reclaimed. However, in the second half of the 20th Century, poldering of higher tidal marshes came gradually to an end. Centralization, the loss of natural values of tidal marsh areas and the costs to polder areas were important factors to bring expansion to a halt.

Strong separation Wadden area and mainland: former muddy flats subside

From then on, the dike line was mostly "kept". Several severe storm floods led the dike owners to increase in dike heights and widths. Dikes are nowadays up to around +10 m above MSL. Due to this heightening and the stabilization of the dike line positions, the area in front of the dike became almost completely separated from the area behind it. Ongoing sedimentation at the Wadden Sea side and subsidence at the landward side has at many locations resulted in lower elevation of the lands (below Mean Sea Level) with respect to the tidal marshes in front of the dike (above Mean High Water).



Height map with in color all areas in Groningen below Mean Sea Level (source: LAMA).

Managed realignment: restoring the mud landscape?
Locally, mainly around industrial and harbor complexes, areas were taken from the Wadden area and the estuaries for economic development. Since ca. 1990 managed realignment became important specially to compensate for loss of natural values. All in all, managed realignment resulted in some 18.5 km² of area becoming once more connected to the Wadden Sea and the major estuaries (Ems, Weser, Elbe, Varde Å). The way managed realignment was carried out differs strongly from site to site, so that - at present- strongly varying examples are present to compare.

Present-day mud sedimentation is of the same order of magnitude as the influx
The first results of ongoing research indicate that the annual influx (which does not all settle in the Wadden Sea) of mud is only slightly larger than the annual deposition including extraction. If these findings are correct, it implies that mud is a scarce commodity which should be managed with care.

Initial overview of net annual mud influx in the Trilateral Wadden Sea (Colina Alonso et al., in prep.)

Sources	Influx in 10^6 ton/yr
North Sea Continental Flow	10-14.4
Rivers	1.6
Local production & eolian dust	0,5
Subtotal:	**12.1-16.5**
East Anglia Plume (total 10-14.3*10^6 ton/year), reaching Wadden Area?	2*10^6 ton/year?

Initial overview of net mud sedimentation/year in the Trilateral Wadden Sea (Colina Alonso et al., in prep.)

		Sedimentation in 10^6 ton/yr	
Area	Period	Net mud sedimentation (= remaining sedimentation + extraction)	Extraction
Dutch Wadden Sea basins	1927-2015	1.2	- (only redistribution)
Ems Estuary	1990-2011	1.9 - 2.4	0.8
Lower Saxony	2000-2010	0.5	
Jade Bay	2000-2010	0.9	?
Weser Estuary	1998-2016	1.45	0.2
Elbe Estuary	1999-2016	1.3	0.8
Meldorf Bight	2000-2010	0.1	
Schleswig Holstein	2000-2010	1.5	
Danish Wadden Sea basins	Mainly: 1980–2003	0.2	- (only redistribution)
Tidal marshes		1.7-1.8	-
Total Trilateral Wadden Sea		**10.9-11.5**	

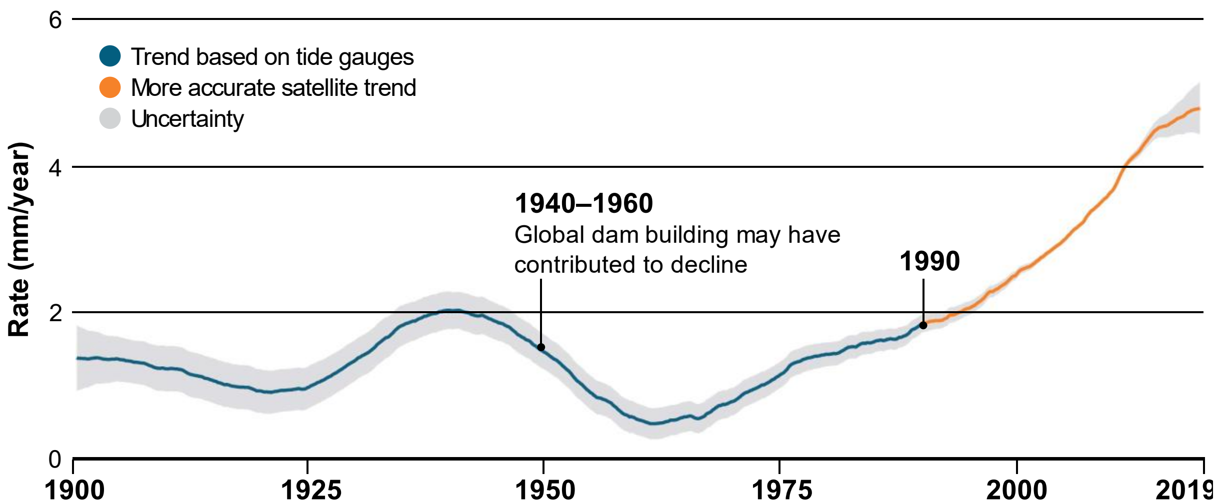
Careful mud management needed
If the initial findings of the mud balance are correct, this implies that we have to consider both the mud balance and the sand balance for the trilateral Wadden Sea and the estuaries carefully. Where the sedimentation of sand can be either limited by the supply (demand in the back-barrier basin is larger than the supply via the inlet) or limited by the demand in the basin, it is not clear if this functions in the same way with mud. Supply of mud mainly enters the area with North Sea Continental Flow from the

west. Where energy conditions and muddy sediments (which enhance mud sedimentation) make it possible, these muds may settle in relatively thick layers (locally up to several dm/yr) and suspended sediment concentrations in the water can be expected to become lower on average for the tidal basins and estuaries more to the east. What happens in terms of mud deposition in these basins is an open question: sedimentation rates might decrease with decreasing suspended sediment concentration (supply limited) or sedimentation will proceed at the same speed (demand limited). Most likely both are true: as long as suspended sediment concentrations are high enough sedimentation can proceed at its maximum rate; if it becomes too low sedimentation rates will also become lower.

Future
Climate change may complicate things further.

The role of increasing run-off: More mud available?
Already in the past century precipitation and evaporation patterns have been changing. Overall, runoff of rivers increased. However, during the summer period freshwater run-off is reduced strongly due to the increasing frequency of extremely hot periods. By contrast, during autumn/winter precipitation increased leading to strong run-off into the Wadden Sea system. At the moment it is unknown if this leads to an increase in suspended matter influx. In itself the increased outflow of fresh water will also enhance the estuarine circulation in the estuaries and the along the North Sea coast leading to a greater efficiency to trap mud in the currents. This might heighten the concentrations of mud in these waters and the availability of mud for the system.

The role of acceleration of sea-level rise: more mud needed
Global sea levels have been rising with some 1.8 mm/yr during the first half of the past century. Since 1960 global sea-level rise is accelerating. Presently, it is some 4.8 mm/yr. In large parts of the Wadden Sea sea-level rise is slower, most likely due to regional geological and glaciological effects. It is expected that global sea-level rise will continue for centuries to come and it is foreseeable that also in the Wadden Sea sea-level rise may proceed at a quicker pace. If sedimentation of the sandy flats can balance sea-level rise it would lead to a slight increase in average depth in the Wadden Sea with increasing velocity of sea level rise. The question is to what extent the hydrodynamic conditions will change and hinder sedimentation of mud? As long if that is not the case, and supply is sufficient, mud flats may keep up with sea level rise or even outgrow sea-level rise. But because more mud is needed to keep up with accelerated sea-level rise the eastward flow of mud will diminish more quickly, which might lead to deficits in the basins more to the east.



Measured rate of sea-level rise (in mm/yr) showing clear acceleration of the global rate since 1960 (after Dangendorf et al., 2019).

Above a critical limit it is expected that the sandy flats can no longer keep up with sea-level rise and start to drown gradually. Under such conditions the hydrodynamic energy will probably increase on the mudflats making lower deposition or erosion more likely. If no alternative sheltered areas are available mud flats and tidal marshes may become scarcer over time.

Saving the muddy tidal flats and marshes?
To heighten the chance of maintaining tidal muddy flats and tidal marshes in the coming centuries it is important to:

1) Develop wise mud management.

At the moment mud availability is still experienced as so high that it leads to problems. This is locally true, especially where fairways and harbors have an overdepth or where sluices are present. An example is the Ems where much effort is needed to keep shipping possible. Suspended matter concentrations within the estuary have increased leading to deteriorated conditions for primary production and fish migration. The increase of SPM is mainly attributed to the decreasing possibilities to settle permanently in the estuary. Thus, large-scale plans are currently being developed to extract the mud from the system, either by transporting dredged mud on the land or by getting it out of the local system via a “building with nature” solution. However, in the light of the likely increase in mud demand to maintain the muddy habitats in the system, a large-scale permanent retrieval might prove detrimental to the system on the long run. Prudent mud management, taking into account both spatial natural needs and mud-related problems, as well as the likely increase of mud demand in the future, will form a major challenge for this century.

2) Develop new areas for mud sedimentation

An important prerequisite for mud sedimentation is the availability of quiet hydrodynamic conditions, as present in sheltered embayments. Since the hydrodynamic energy in the present-day Wadden Sea could increase in the future, it will become increasingly important to develop new areas for mud sedimentation. Such areas might serve three goals: permanent deposition sites for uncontaminated muds; heightening the low-lying polder areas; compensating eventual losses in the future.

Double dykes as a solution?
Recently the double dike system (see factsheet) was proposed as a possible solution for the Dutch mainland coast of the Wadden Sea (Wadden Academy, WUR, Deltares). This might be extended to larger parts of the Wadden Sea coast. The central idea is that on many places the older inland dikes are still present or new inland dikes can be built in a relatively uninhabited landscape. The outer dike would serve to break the waves. The land behind it is in open connection to the Wadden Sea and will be flooded. The frequency of flooding will be determined by the height of the area. The flooding frequency will determine the exact usage of the area: nature, tourism, agriculture, mariculture, wind energy etcetera. Sedimentation in the area will heighten the area and can be used to enforce the dikes over time: a form of climate adaptation. The landward dike acts to prevent flooding but does not have to break the waves as this is already provided by the first dike. An additional benefit provided by the concept is that the double dikes give a longer time to flee an area than a single dike. What furthermore can be added to the concept are:

1) tidal marshes in front of the seaward dike, which provide nature values and breaking of waves.
2) broad green dikes which use less stone work and form a robust basis for coastal security.
3) connection with mud dredging activities in estuaries. The area can be “fed” with dredging sludge thus stimulating fast vertical sedimentation, as a way of climate adaptation.
4) seaward constructions around smaller habor towns to provide the extra dike in front of the present-day dike, taking in count not to interfere with the natural hydromorfological processes..

In this way a double dike system stimulating the development of a more diverse landscape, with larger natural values and a more diverse economy will help to enrich the mainland coast, while at the same time securing it against flooding.

Deep embayments as a solution?
Along the Dutch part of the Ems, several plans have been developed to realize the flooding and sedimentation of large areas of the former clay-rich Wadden Sea deposits which have been subsiding after diking (see factsheet managed realignment). Nature restoration, mariculture, agriculture and tourism

will all benefit from these plans. At the same time the land can grow with sea-level rise and dredged muds can find a new destination.

Outlook

Thus, perhaps in the future the circle will be round once more: the originally irregular, open and broad coastal zone with valleys incised into the mainland, will once more reappear.

Already now knowledge can be provided via the many managed realignment projects to study the feasibility of such an approach. New dedicated projects can be developed to help gain missing knowledge and built know-how. In the cause of this century larger parts of the straight coastline can thus be changed into a broad muddy coastal zone. On the longer run the broad dike zone of tidal marshes, present day dike, de-poldered zones and secondary dikes will form a sedimentation zone. It may provide the broad basis for the far future.

Lessons Learned

The typical behavior of mud differs strongly from that of sand leading to mud deposition areas which are largely separated from sand deposition areas. Under natural conditions muddy habitats such as muddy intertidal flats and tidal marshes used to constitute half of the original natural Wadden Sea landscape. Such landscapes were characterized by well-developed gradient of fines towards the coastline. Due to construction of dikes a large part of this landscape has been poldered. This part is now subsiding relative to mean sea level. The first results of the present-day mud balances learn that annual mud influx is 1-1.5 times larger than the net sedimentation. This implies that mud is a scarce commodity and that retrieval of mud may lead to unwanted effects elsewhere on the natural functioning of the muddy part of the Wadden system. For this century increases in mud demand are expected due to sea-level rise. This strengthens the need for prudent mud management. Possible solutions are found in large scale managed realignment over larger areas, such as rows of double dike systems or large-scale de-poldering measures. Such new nature, farming and tourism areas can store mud which is dredged from harbors and fairways and thus help reduce turbidity in the water column.

Stakeholder process

Locally in harbors and fairways mud causes problems and the stakeholders involved are looking for solutions which will be beneficial for man and nature. With it the discussion on wise mud management has started. For the present, the solution for local mud surpluses might be found in using these muds for nature development via the recreation of mud deposition sites via managed realignment or making the surpluses available to other stakeholders who are in need of mud for the natural functioning of the system. This can for instance be done via disposing dredged clean muds in such a way that it is taken by currents to other tidal basins. Such large-scale mud management is still in its infancy and much knowledge and know-how has to be developed, but it seems a promising way into the future.

Discussion points

- Are the initial balances correct? What are uncertainties and how can they be solved?
- How will mud sedimentation develop under conditions of higher run off and sea-level rise?
- What defines wise mud management?
- How much mud can we trap annually with realignment?
- Is it possible to use dredged mud to “feed” other tidal Wadden Sea basins?
- Is it not wiser to just heighten mainland areas with dredged mud to make the area more resilient against sea-level rise?

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