Increasing turbidity of the Dutch Wadden Sea*:* *The possible causes and consequences for the Wadden Sea and its salt marshes.*

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Abstract

To understand the dynamics and to make predictions for the future state of the Wadden Sea it is important to know what forces are participating. The increase in turbidity in the Dutch Wadden Sea is a topic where a lot of research is focused on and is expected to have a certain negative effect for the present state of the Wadden Sea and subsequently the associated salt marshes. Therefore this paper is giving an overview of factors that could have an effect on the increasing turbidity. Factors such as increased river discharge, dredging, fisheries, vanishing eelgrass beds and sea-level rise are subject to human activities. Many studies support this hypothesis, although indisputable evidence is hard to find because of the ecological interactions of the Wadden Sea. In general the present state of the Wadden Sea is a result of human activities in the past and the future state is depending on the human effort in preservation to remain or improve this present state.

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Introduction

1. General introduction

All the natural and human induced changes affect the Wadden Sea and its salt marshes. Numerous scientists have studied the complex ecological dynamics of the Wadden Sea, although in most studies not the whole system is taken in account. At present a lot of research is focused on the increase in turbidity of the Wadden Sea and the effects this can have for the Wadden Sea itself and the adjacent salt marshes (Cadée & Hegeman 2002). As will be explained later, the Wadden Sea is not in equilibrium (Elias *et al.* 2006 in: Herman *et al.* 2009) and the predictions for the future state of the ecosystem are unclear. A few possible factors can be selected that could explain the increasing turbidity. These are: human activities such as fisheries and dredging, planktonic and nutrient changes, and global warming. This paper gives an overview of what the major causes could be by answering the following questions:

- Which factor(s) could explain the increase in turbidity observed in the Wadden Sea?
- How will an increase in turbidity affect the Wadden Sea as a system?
- What are the possible effects for the development of salt marshes in the Wadden Sea?

2. The Wadden Sea

The Wadden Sea stretches from Den Helder in the Netherlands in the southwest, past the river estuaries of Germany to its northern boundary at Skallingen north of Esbjerg in Denmark. It is characterized by extensive intertidal mud flats, deep tidal trenches and the barrier islands that function as a barrier for the mainland against the North Sea. The Dutch part of the Wadden Sea with an area of approximately 3000 km², is situated between the North Sea and the mainland by seawalls (De Jonge 2000) and is known by its complex (ecological) dynamics. The functioning of the Wadden Sea depends on nutrient changes through fresh water flushing, mixing and transport of dissolved substances and particles by tidal frequencies, wind and varying temperature and day lenghts by seasonal cycles. In history human activities have influenced these dynamics massively. For example the Dutch made seawalls to protect inland areas against high tides and stormes (fig.1), and river flood plains and salt marshes have been reclaimed and transformed mainly into agricultural and residential areas (De Jonge & De Jong 2002a). Especially by creating seawalls influences were substantial. It caused a shortening of coastline which in turn negatively affects the sediment transport, the salt marshes and eelgrass beds, with the result that the Dutch barrier islands shifted to the east and south (De Jonge & De Jong 2002a).

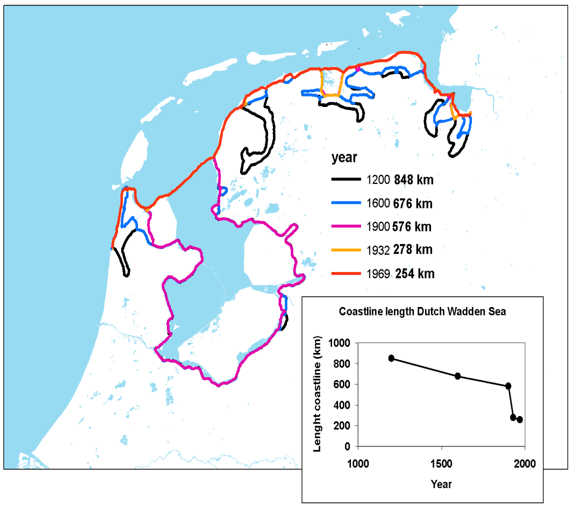

Fig. 1 The shortening of the Dutch coastline in the last 800 years (Olff 2009).

By embanking the Zuiderzee and creating Lake IJssel, the original functioning of local river basins changed even more dramatically and the Wadden Sea has not been able to recover from these interventions (Elias *et al.* 2006 in: Herman *et al.* 2009). Nowadays the Wadden Sea is still facing eutrophication effects, changed transport of dissolved substances and particles, global warming, fresh water flushing and changed wave velocity.

Natural borders of the Wadden Sea are the transitional intertidal areas between land and salty water called salt marshes. Salt marshes often develop where intertidal action and erosion is relatively gentle and there is enough light to allow vegetation to take hold. Salt marshes are considered as quite productive habitats, the plant species diversity is relatively low as the flora must be tolerant of salt and complete or partial submersion (Herman *et al*. 2009). A pioneer plant species is *Spartina sp.* which stabilizes the sediment thereby creating its own niche and enabling other plant species to establish succesfully. Sedimentation by the sea is very important for the development of the salt marsh. Over time salt marshes can grow due to sediment accumulation from the inundating seawater. These dynamics are a result of high tides that transport substances and particles to the salt marsh resulting in vertical accretion. As De Jonge and De Jong (2002a) nicely described: *In a sound estuary, salt marshes come and go, they silt up and erode. In a natural situation, all stages of salt marshes, primary salt marsh, low and mature salt marsh, are present somewhere in the estuary. When a salt marsh becomes too highly elevated, it becomes vulnerable to erosion and after erosion it gives way for new salt marsh formation.*

3. Turbidity and general Wadden Sea sediment transport clarification

Turbidity can be defined as the cloudiness of (sea)water caused by suspended and drifting particles where the measurement of turbidity gives an insight in attenuation of light as it passes through the water column. One way to measure turbidity is using a Secchi disk. This black and white disk is lowered into the water until it can no longer be seen. The depth (Secchi depth) is then recorded as a measure of the transparency of the water (inversely related to turbidity) and can provide a rough indication of the depth of the euphotic zone due to the amount of particles in the water. The distribution of particles and sediment, which are components of turbidity, are mainly driven by the tidal currents and wind-induced waves (fig. 2) (De Jonge 2000; Bartholomä *et al*. 2009).

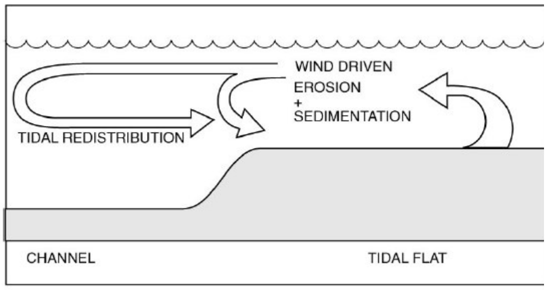

Fig. 2 Diagram illustrating the importance of resuspension by wind waves and redistribution by tidal currents (De Jonge 2000).

Grain sizes of suspended and drifting particles in the water of the Wadden Sea range from clay to medium sand. During flood phases, water from the North Sea enters the tidal inlet with speeds > 1 m s^{-1}. During the ebb phase, water enriched with suspended sediment flows out at generally higher flow velocities than during flood phase (Bartholomä *et al*. 2009). This is because the flood phase usually lasts longer than the ebb phase. Therefore the tidal basins are typified as being ebb-dominated (Bartholomä *et al*. 2009). The particle sizes of the suspended sediment in the water are smallest at maximum flow and biggest shortly after slack water (Bartholomä *et al*. 2009). The theory behind this is that all easily erodible material is respuspended after slack water and more consolidated cohesive sediments or bigger (sand) particles remain on the bed (Bartholomä *et al*. 2009). Sediments with a particle size around 180 µm have the highest mobility (Sanders 1958 in: Groenewold & Dankers 2004) because the cohesive forces of more fine sediment result in clustering of particles. Coarser particles are under average conditions often too heavy to be lifted from the sea bed. To lift sediment from the sea bed more energy is needed according to the increase of particle sizes. This is because the surface of particles increases times four, but the volume and weight times three (Seibolt 1974 in: Groenewold & Dankers 2004). Because fine sediment such as silt and clay cluster due to the cohesive forces, they are more reluctant to be transported and therefore particles sizes below 160 μm are normally transported in suspended condition (Groenewold & Dankers 2004). Bigger sediment sizes tend to be transported rolling over the sea bed, but at higher viscosity they can be transported gliding through the water column (Groenewold & Dankers 2004). The deposition of particles depends on different factors, but the main factor is, as described earlier, the current velocity. The current velocity needs a certain amount of energy to keep the particles in transport, otherwise they will sink. During spring and summer, when the energy conditions in the seawater are lowest, there is a net export of sediment from the Wadden Sea to the North Sea because the ebb phase contains more energy than the flood phase (Bartholomä *et al.* 2009). When the velocity increases due to more energy input during winter and during stormes, floc size increases significantly and particle transport changes resulting in the possibility that the tidal basin changes into a flood-dominated system which eliminates the net export.

Overview of factors that influence turbidity

Directly influencing human activities

For centuries the Dutch Wadden Sea has been used to exploit living resources. Since the early twentieth century public authorities have laid the foundation for more legislation. Nevertheless the increasing legislation during the following years, did not prevent the continuous habitat destruction and overexploitation. So far, this has already resulted in the extinction of at least 17 species (Wolff 2005). Although all overexploitations and other human factors do affect ecosystems, not all of them result in increasing turbidity.

1. Vanished eelgrass beds

Eelgrass used to be highly abundant in the western part of the Dutch Wadden Sea (up to 15,000 ha.) (Van Goor 1919 in: Giesen *et al.* 1990). Centuries ago it was already used as construction material for seawalls around this part of the Wadden Sea (Wolff 2005). Eelgrass is known as a sediment stabilizer (Giesen *et al.* 1989) and tolerates only a certain amount of turbidity because of the minimal needed amount of light penetration (Tutin 1942; Backman & Barilotti 1976; Dennison & Alberte 1982; Dennison & Alberte 1985 in: Giesen *et al.* 1990). When Eelgrass beds vanish from the ecosystem, subsequent erosion enhances and the formerly entrapped material will be redistributed within the system thereby increasing turbidity (Giesen *et al.*1990; Herman *et al.* 2009). The recognizable problems of vanishing eelgrass beds occurred already in the early twentieth century. Diseases and the enclosure of the Zuiderzee and Lauwerszee have lead to the eelgrass populations to become threatened and so far, the populations have not managed to recover (Giesen *et al.*1990; De Jonge & De Jong 2002a; Schouten 2004). The prominent effects of the enclosure of the Zuiderzee that caused the threats were changes in water currents and an increase of tidal amplitude (Giesen *et al.*1990; De Jonge & De Jong 2002a). This resulted in more wave energy, because the natural water current was forced to flow in an alternative direction, the ability of capturing the tidal water input decreased which changes the sedimentation flux and therefore with a combined result that turbidity increases (Giesen *et al.*1990; De Jonge & De Jong 2002a). Because of the higher turbidity, it prevents the development of new eelgrass populations (Fig. 3) (Giesen *et al.*1990; De Jonge & De Jong 2002a; Schouten 2004). So it seems that with the disappearance of the eelgrass populations, an illusive circle has started that prevent eelgrass beds recovery.

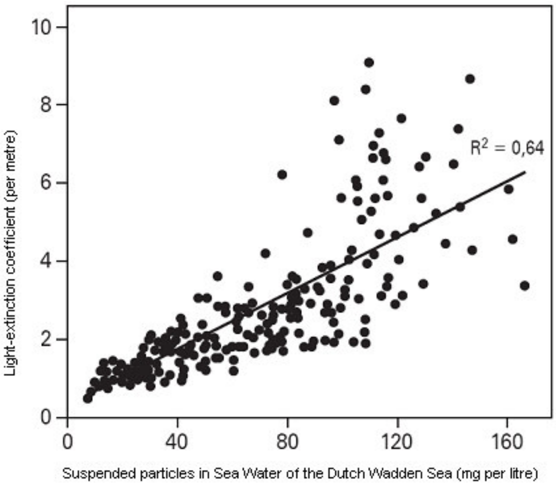

Fig. 3 Eelgrasses need clear water. The loss of eelgrasses lead to more turbidity which prevents new eelgrasses to colonize (Olff 2009).

2. Bottom-dredging fisheries

In the Wadden Sea several suspension feeders such as *Cerastoderma edule* (edible cockle) and *Mytilus edulis* (blue mussel) were massively fished as target species for human consumption in recent years (Wolff 2005). These suspension feeders are sediment stablizers and *Mytilus edulis* is besides that an autogenic engineer, meaning that in an interacting population it changes its environment by collectively creating their own physical populationstructures (mussel banks) which influences the whole system they live in (Piersma *et al*. 2001; Bouma *et al*. 2009; Brun *et al*. 2009; Reise *et al*. 2009). It produces feacal pellets (biodeposition) that positively influence the adhesion within the drifting particles in the seawater and therefore has a counteracting effect at turbidity (Piersma *et al*. 2001). This effect is a result of the turbidity diminishing mudlayer created by the biodeposition, that can cause a sediment accumulation up to 1 metre per year by the high adhesive forces (Fig. 4) (Piersma *et al*. 2001; Bouma *et al*. 2009; Herman *et al.* 2009).

Fig. 4 Biodepostion and mudlayer created by Mytilus edulis (Olff 2009).

Since the beginning of the twentyfirst century the mechanical cockle-dredging in the Dutch Wadden Sea has been prohibited, because of the damage it causes to ecosystems. Also the blue mussel fisheries have decreased due to the decreased populations caused by several different factors such as storms and diseases (Piersma *et al*. 2001; Wolff 2005; Herman *et al.* 2009). Because the decreasing populations of suspension feeders with their counteracting effects at turbidity, the Wadden Sea encountered a higher turbidity. A further intensifying negative effect is that organisms such as lugworms could increase because of the lower abundance of the *Cerastoderma edule* and *Mytilus edulis* (Fig. 5) (Reise 2002). These endobenthic deposit feeders tend to enhance the sediment mobility (Reise *et al*. 2009) in favour of their own fitness. Also the physical damage by bottom-dredging and trawling for shrimp creates more turbidity (Cadée & Hegeman 2002). The upper sediment layer is rummaged, which increases the suspension of fine particles and large particles are torn apart, resulting in more mobile particles. Consequently the bottom-dredging fisheries have changed the former ecosystem into an alternative state, with a higher turbidity as a result.

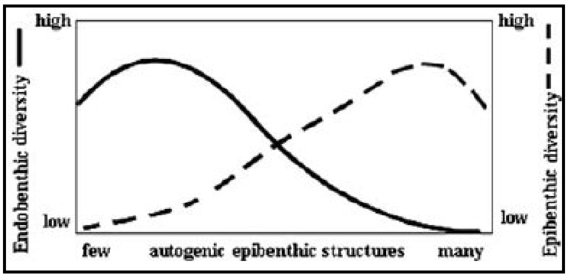

Fig. 5 The presence of epibenthic structures on soft- bottoms promotes the diversity of epibenthic organisms, whilst restricting the diversity of endobenthic ecosystem engineers (Bouma et al. 2009).

3. Dredging

Dronkers (2005) explained that dredging activities are often related to sand mining. Sand extraction in the western Wadden Sea amounted on average to an annual volume of around 2 million m^3 in the 1980s. Since then the sand mining volume decreased to an average of 1 million m^3 annually. The entrance channel of Rotterdam harbour is a major sediment sink in the Dutch coastal zone and the deposited sediment is mainly coming from other coastal areas and rivers. Due to the economic value of the Rotterdam harbour, the channel depth is maintained by dredging (Dronkers 2005). The dredged sediments are disposed at the Loswal (5 km northwest of Hook of Holland) and Dronkers (2005) describes that the increased sedimentation in the Wadden Sea by the disposal of the dredged sediment would be disappeared within a year. Groenewold and Dankers (2004) claim that an annual sediment deposition of 4 million tons in the last few years, coming from Rotterdam harbour, does have negative effects at turbidity in the Wadden Sea, whilst De Jonge (2000) suggests that a total amount of 6 million m^3 is dredged in Dutch coastal waters which would affect the turbidity in the Wadden Sea. Most of the disposed sediment is resuspended by action of waves and currents and transported in longshore direction, although a fraction of the disposed sediment would recirculate elsewhere (De Jonge 2000; Dronkers 2005). This means that it ends up in the Wadden Sea, because the Wadden Sea functions as a sediment sink due to geomorphological conditions. Apart from this extra input of suspended particles in the southwest of the Netherlands, are little dredging effects of more southern countries such as Belgium and France with contributing turbidity effects (Dronkers 2005). Due to the coriolis effect[1] and the Ekman spiral[2] (Fig. 6) the disposed sediments from dredging are transported in Northern longshore direction and also end up in Dutch coastal sinks and the Wadden Sea.

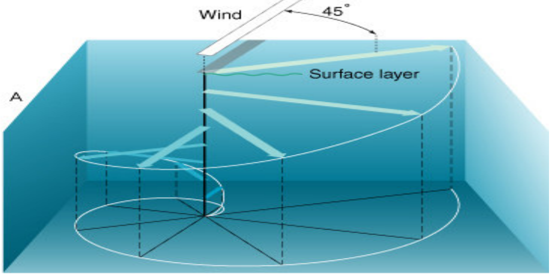

Fig. 6 The Ekman spiral describes how the horizontal wind sets surface waters in motion. As represented by horizontal vectors, the speed and direction of water motion change with increasing depth (anonymous without publishing year).

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[1] Named after French mathematician Gaspard Gustave Coriolis (1792-1843) and explained by Persson (1998) as: *On a rotating earth the Coriolis force acts to change the direction of a moving body to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. This deflection is not only instrumental in the large-scale atmospheric circulation, the development of storms, and the sea-breeze circulation (Atkinson 1981; Simpson 1985; Neumann 1984), it can even affect the outcome of baseball tournaments: a ball thrown horizontally 100 m in 4 s in the United States will, due to the Coriolis force, deviate1.5 cm to the right.*

[2] Named after Swedish oceanographer V.W. Ekman (1874-1954) and explained by Encyclopædia Britannica (2009) as: *The theoretical displacement of current direction by the Coriolis effect, given a steady wind blowing over an ocean of infinite depth, extent, and uniform eddy viscosity. According to the concept proposed by the 20th-century Swedish oceanographer V.W. Ekman, the surface layers are displaced 45° to the right in the Northern Hemisphere (45° to the left in the Southern Hemisphere), and successively deeper layers are further displaced so that at a given depth the water motion is opposite to wind direction. Current velocity decreases with depth because of the loss of momentum associated with the transference of motion from layer to layer.*

Therefore the outline is that although there are various data of the disposed dredged materials, there are short-term and long-term enhancing effects at turbidity.

Global warming changes

Since the industrial revolution in late eighteenth and early nineteenth century, the increasing emission of greenhouse gasses such as carbon dioxide, methane, nitrous oxide and ozone is overwhelming (Moore III *et al.* 2003).The gasses are found responsible for changing the atmospheric concentrations of (greenhouse) gasses and aerosols and are very likely to have caused most of the increase in global average temperatures since the twentieth century. This is also known as the Greenhouse effect, which means that the heating of the earth surface is due to the increase of gasses that absorb and emit infrared radiation. That global warming is changing ecosystems is a well-known certainty and a lot of changes can be linked to it. For example increased average windspeeds, increased storm events, increased temperature, increased precipitation and higher river discharge are climatological phenomena resulting from global warming (IPCC 1995 in: De Jonge & De Jong 2002b). Because most ecosystems are subordinated to provided solar energy, wind energy and tidal energy (De Jonge & De Jong 2002b), it is almost a certainty that the turbidity of the Wadden Sea is subject to global warming processes.

1. Planktonic organisms and changing nutrient availability

Based on Liebig's Law of the Minimum both nutrients and light are considered to be the limiting resources for phytoplanktonic organisms (Tilman 1977; De Baar 1994 in: Colijn & Cadée 2002). It means that the growth rate or nutrient uptake of phytoplanktonic organisms are limited by either one of these two resources. Dominant phytoplankton such as diatoms and *Phaeocystis* have annual life cycles with an accompanying major bloom, defined as a period with >1000 cells cm^3 (Cadée & Hegeman 2002), in spring and early summer, and a smaller bloom in autumn. The final size and rapid decrease of the first spring bloom is normally caused by a combination of successive nutrient limitations of Si, P and N and probably by grazing pressure of mesozooplankton (Fransz *et al.* 1992 in: Colijn & Cadée 2002). The decline of the bloom in autumn is normally due to limitation of light since the availability of light declines with declining daylight hours. Not only are they grazed by zooplanktonic organisms (Colijn & Cadée 2002), also are they a foodsupply for filterfeeders such as bivalves and several species of shrimps in the Wadden Sea. It is not easy to describe the abundance and distribution of phytoplankton because of the size of these organisms (as small as 0.2 µm). That is why flow cytometry is used (Olsen *et al.* 1985 in: Cadée & Hegeman 2002). This is a method to indicate the plant pigments in a phytoplankton biomass and the photosynthetic productivety that can express its result in a certain chlorophyll-a value (Harvey 1934 in: Cadée & Hegeman 2002). The increased flushing of terrestrial nutrients and the overall amount of freshwater input into the North Sea is expected to be a result of global warming. At the same time freshwater from the rivers was enriched with nutrients by industries that used the rivers for disposal during the 1970s (Cadée & Hegeman 2002). This lead to eutrophication and enabled the production of a certain amount of organic matter that also affected turbidity and sinks into the Wadden Sea and therefore resulted in very high annual average chlorophyll-a values of ~12 mg m^3 (Cadée & Hegeman 2002; Van Beusekom & De Jonge 2002). Since then industries had to decrease the disposal of nutrients into the rivers due to legislation and resulted in a slight decrease of chlorophyll-a values (Cadée & Hegeman 2002; Essink 2002). By cleaning the rivers, and especially the Rhine, eutrophication has consequently decreased, although concluded from measurements at the Marsdiep the decline of phytoplanktonic life did not decrease proportionally as expected (Cadée & Hegeman 2002). In terms of turbidity especially diatoms are counteracting turbidity by making biofilms (De Jonge & De Jong 2002b; Herman *et al.* 2009). The biofilm creates higher viscosity on top of the tidal beds so transport of particles will become more difficult.

2. Changing river discharge

The input of particles into the Wadden Sea is partly depending on the quantity and quality of freshwater and its containing nutrients and particles flowing into the sea through the rivers. Due to an increase of precipitation on land, more freshwater flows into the North Sea. An example source of fine sediment is the river Rhine with a yield of 1Mton/year (Dronkers 2005). De Jonge and De Jong (2002b in: Dronkers 2005) found a positive correlation between the mean annual Rhine discharge and the annual sediment disposal at the Loswal by dredging. The annual Rhine discharge and the suggested nitrogen load of the river boosts up the phytoplanktonic production in the Dutch coastal zone (Van Beusekom & De Jonge 2002). The waterlevel in rivers increases, which in turn increases the velocity and therefore the energy content in the rivers. More precipitation also has a flushing effects on the terrestrial nutrients and particles which results in an increased nutrient and particle availability that end up in the Dutch coastal zone. Because of the horizontal sediment current from south-west into north-east direction, the flushed particles, nutrients and produced organic matter end up in the Wadden Sea.

3. Sea-level rise

Another factor that is expected to have an effect on turbidity in the Dutch Wadden Sea is the sea-level rise. It is linked to other effects such as for example higher river discharge (IPCC 1995 in: De Jonge & De Jong 2002b). It is suggested that as a result of sea-level rise, the higher water levels will result in an increasing sediment deposition in the tidal basins of the Wadden Sea (Flemming 2002 in: Bartholomä *et al.* 2009). Due to this phenomenon it is therefore expected that the barrier islands will increase in shoreward direction due to their morphodynamic response (Bartholomä *et al.* 2009; Herman *et al.* 2009). When water level rises, it slows down the velocity under normal weather conditions which leads coarse particles to be transported more difficult, although a higher sea level comes with a possibility of higher waves and enhanced wave energy conditions (De Jonge & De Jong 2002b). This is important because enhanced wave energy can result in a temporarily flood-dominated Wadden Sea (Bartholomä *et al.* 2009). Untill now the alongshore sand transport has been large enough to maintain the present situation (De Jonge & De Jong 2002b) although there are various opinions about the future situation, because different water levels could influence other (benthic) organisms, and therefore influence the turbidity and transport of particles (Herman *et al.* 2009). It all depends on the ability of the Wadden Sea to adapt to a higher sea level, since it is connected to turbidity effecting aspects such as benthic organisms, increasing precipitation and higher groundwater levels through climatological changes, changing sedimentation dynamics and also salt-marsh developments (Herman *et al.* 2009).

Salt-marsh development

A significant shortening of the coastline in the last few centuries has resulted in the dissappearance of shallow and sheltered areas. As mentioned earlier one of the effects was the dissappearance of eelgrass beds (Giesen *et al.* 1989). Another consequence was the decline of shallow sheltered coastal areas such as the salt marshes (Dijkema 1987 in: De Jonge & De Jong 2002a). Salt marshes are ecological valuable wetland habitats and are essential for natural coastal and estuarine food chains apart from functioning as a protective barrier for the harsh North Sea influence and sedimantation sink (Nixon 1980; Gordon *et al*. 1985; Zedler & Callaway 2001 in: French 2006). The salt marsh is tidal-dominated and constrained and subordinated to the fine-grain sediment supplied by flood phases. The Dutch salt marshes are depending on surface elevation, tidal inundation and sedimentation fluxes (French 2006) apart from the need for vegetation to stabilize the sediment (Pedersen & Bartholdy 2007). These three factors influence the vertical growth time which can vary between 10 to 1000 years (French 2006). French (2006) suggests that a change in one of the three factors already alters the existing and developing salt marshes. For example when the tidal inundation changes in a lower or shorter submerged state of the salt marsh, the process of salt-marsh development alters, resulting in lower vertical growth or even erosion. The source of the sediment is mainly the North Sea, but other resources of fine-grained material include fluvial input (produced by the action of a river or stream), atmospheric deposition, internal erosion and primary production (Pedersen & Bartholdy 2007). The major part of the fine-grained material is deposited at the salt marsh (about 90%), resulting in accretion rates between 2 to 12 mm per year (Pedersen & Bartholdy 2006 in: Pedersen & Bartholdy 2007). It seems that the accretion of the salt marshes can keep up with the sea-level rise today at the barrier islands, but it is unclear if this will be the case in the future with ecological and hydromorphical changes. In order to form the salt marsh, it faces several succession stages of vegetation. It is suggested by Pedersen & Bartholdy (2007) that firstly *Spartina sp*. and *Salicornia europaea* colonize the tidal flat, resulting in increasing elevation, ultimately replaced by salt-marsh grass species, followed by species as *Suaeda maritima* and *Aster tripolium* and finally at highest levels *Artemisia maritima* and *Elytrigia sp* (Fig. 7).

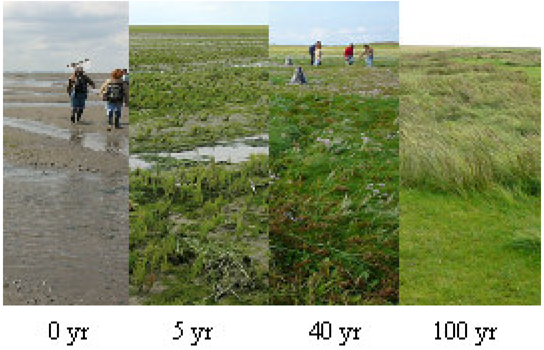

Fig. 7 The development of a salt marsh in 100 years (Olff 2009).

Flagrant is that salt marshes at the main-land especially in Groningen are decreasing rapidly, partly due to enclosing the Lauwerzee in 1969 (De Jonge & De Jong 2002a; French 2006). Through increased turbidity, the expectation is a changed sedimentation rate and changed salt-marsh dynamics but this will be discussed later in this paper. Normally, pioneer plant species and subsequently other species present at the salt marsh are capturing newly supplied particles but are subject to the light penetration. When turbidity increases it can negatively affect the photosynthetic processes of vegetation, resulting in changing colonization. Because of the threat of vanishing salt marshes, human activities are initiated to protect the existing salt marshes what results in an unusual growth of the salt marshes by counteracting the erosion (De Jonge & De Jong 2002a). Vanishing salt marshes mean that important sediment sinks are vanishing, affecting the whole sedimentation fluxes.

Synthesis

1. The Wadden Sea

After the inventarisation of possible causes of increased turbidity, it is usefull to keep in mind what effects the individual possible causes have on turbidity and each other (fig. 8 and fig. 9). When all the described factors of possible influences are evaluated, it gives an indication of the complexity and ecological dynamics that are present and affecting the state of the Wadden Sea and its turbidity. Eutrophication in rivers and lakes increases nutrient availability in the North Sea and Wadden Sea (Cadée & Hegeman 2002; Essink 2002; Van Beusekom & De Jonge 2002). Apart from the increased nutrient availability by more precipitation, higher groundwater levels positively affect the increased freshwater input to an increasing sediment mobility towards the North and Wadden Sea. The industries, which were a major eutrophication force situated at the river-banks, are reducing nutrient disposal since the 1980s (Cadée & Hegeman 2002; Essink 2002), but the effects can still be found in chlorophyll-a measurements. The enhanced sediment mobility and movement towards the Dutch coastal areas result in the need of dredging to sustain the economic value of the Dutch harbour areas (Groenewold & Dankers 2004; Schouten 2004; Dronkers 2005). The inconvenient and redundant sediment is disposed further at the North Sea and will partly sink in the Wadden Sea. So both by dredging and by freswater input turbation increases at the Wadden Sea. By high availability of nutrients, phytoplanktonic organisms make biofilms that restrain the turbation. Only by cleaning the rivers and especially the Rhine, chlorophyll-a values declined (Cadée & Hegeman 2002; Essink 2002), which results in a decline of biofilms. Due to the global warming consequences it is plausible that the net sediment export phenomenon of the Wadden Sea will be negatively affected by the higher energy contained and more frequent wind and storms which will result in more suspended and mobile particles and therefore turbidity. With the disappearance of eelgrass beds, salt marshes and suspension feeders sediment stabilizing forces have declined (Giesen *et al.* 1989).

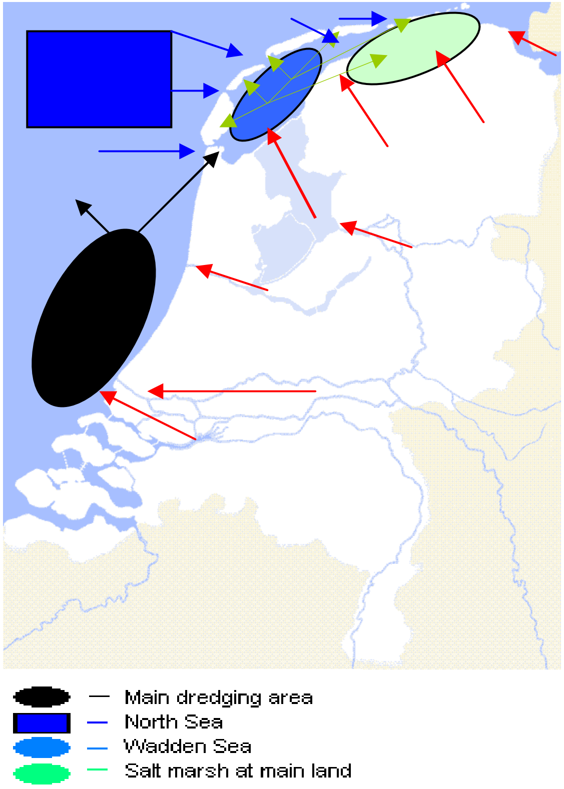

Fig. 8: An overview of affecting factors that is suggested to be influencing and increasing the turbidity in the Wadden Sea.

→ *Freshwater input of particles from rivers and lakes.*
→ *Dredging and disposal effects.*
→ *North Sea input with particles through tidal dynamics.*
→ *Sedimentation effects at salt marshes.*

Also the bottom trawling fisheries are negative for turbidity since their scrambling effect at the tidal beds (Piersma *et al.* 2001; Bouma *et al.* 2009). The high abundance of endobenthic organisms is also increasing turbidity, but the unnatural conservation of the salt marshes is counteracting turbidity since the sinked sediment at salt marshes is prevented of being eroded (De Jonge & De Jong 2002a; French 2006).

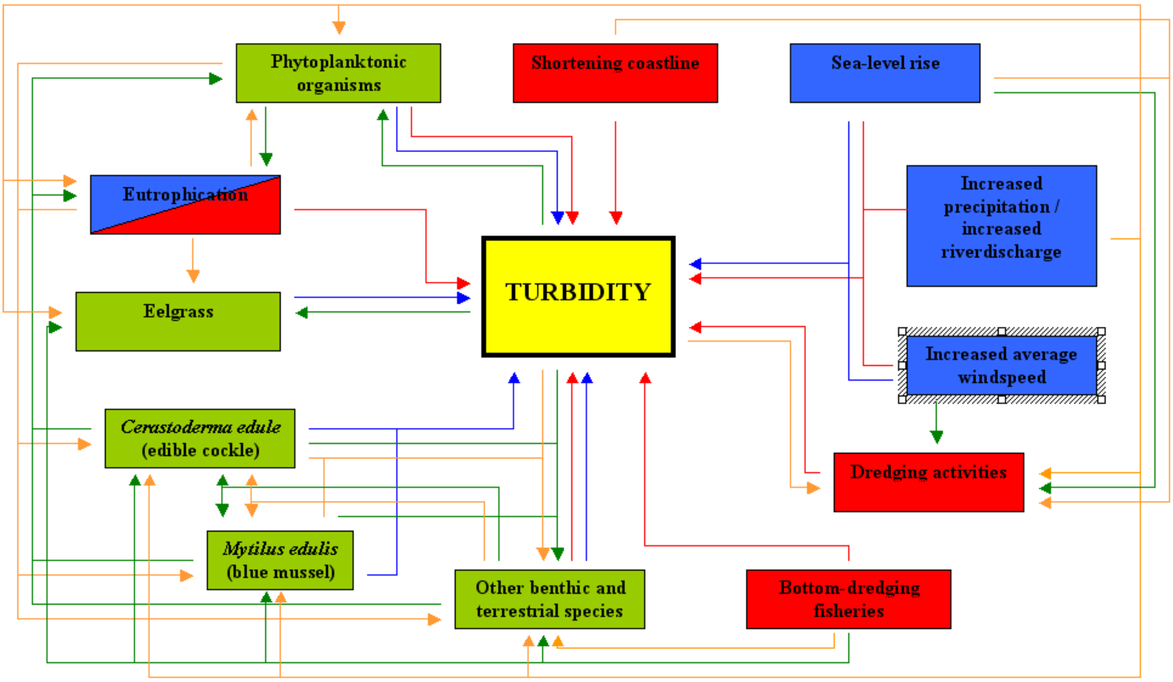

Fig. 9: Simplified interaction scheme of the Wadden Sea indicating the complex interactions between the components mentioned in this paper and their influences and effects on turbidity.

→ *Increasing turbidity.*
→ *Decreasing turbidity.*
→ *Stimulating effect.*
→ *Counteracting effect.*

🟥 *Direct human activities.*

🟦 *Global warming phenomenons.*

🟩 *Flora and fauna components.*

Figure 9 is a simplified interaction scheme that indicates the complexity of the Wadden Sea dynamics described in this paper. In reality there are even more interactive forces and effects between the components and other components as the North Sea sedimentation transport and biotic and abiotic factors such as storms and diseases are also influencing the Wadden Sea dynamics. Therefore figure 9 is usefull to give an impression of the forces participating in the complex dynamics but has no real scientific meaning because of the missing values per component. For most of the components the effects can be calculated but for some components, such as the global warming effects, it is not quite clear how much value of the varying effects will be due to unclear and varying ecological phenomena. That is why most of the specific data is kept out of this paper and will need to be studied for the entire system in the future. Obvious is the influence that human activities had in the past, at this moment and in the future on the Wadden Sea. Most of the turbidity components of figure 9 can be traced back to human interference and the overall picture is that the turbidity will further increase in the future (fig. 10). During reviewing the literature it became clear that most probably dredging, fisheries and the absence of sediment stabilizers such as eelgrass beds are major causes of the increased turbidity in the Wadden Sea, although precize percentages of suspended matter trapped or rummaged by the components are not researched sufficiently.

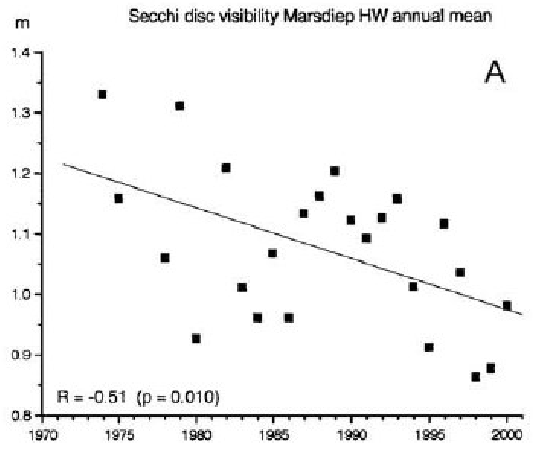

Fig. 10 Secchi-disc data for the Marsdiep that illustrates the annual mean high water visibility (Cadée & Hegeman 2002)

In this context long-term morphology changes in the Wadden Sea are definitely to be expected although the impact at the Wadden Sea is hard to predict (Herman *et al.* 2009). Without human assistance organic sediment stabilizers are not likely to return except for diatoms and other phytoplanktonic organisms. When due to sea-level rise the barrier islands shift more towards the mainland, the Wadden Sea loses its total surface area, volume and sedimentation dynamics. These events already became clear after the shortening of the coastline, which resulted in increasing and more shifting of the barrier islands (De Jonge & De Jong 2002a; French 2006). That the Wadden Sea is altered is an accepted perception, as it was always changing, but human interference has accelerated the changes. Nowadays the Wadden Sea can keep up in modifications with sea-level rise, but this is probably not the case in the future (Herman *et al.* 2009) and without preservation or reduced human influences the Wadden Sea will ecologically change quickly into an alternative state and most probably a retrenched state.

2. Salt marshes

The development of the Dutch salt marshes is depending on human activities. Whilst salt marshes at mainland areas are decreasing rapidly, salt marshes at the barrier islands are slightly increasing (De Jonge & De Jong 2002a; French 2006). The increase of salt marshes at the barrier islands is subject to preservation (De Jonge & De Jong 2002a). De Jonge and De Jong (2002a) suggest that there would not be as much sediment accretion without human interference such as artificial sanddikes. The main question arises whether this is a desirable situation. Overlooking the development of the salt marsh, it is subordinated to what changes will occur at the Wadden Sea. Since this is not completely certain due to the complexity of these systems, it is to be expected that the growth of salt marshes on the barrier islands will continue as most of the changing features that were mentioned in this paper such as higher turbidity and increase in light availabilty resulting from global warming, are extending the salt marshes if preservation continous.

Conclusion

1. The causes of increased turbidity

The search for the major cause for increasing turbidity in the Wadden Sea introduced an insight into the complex dynamics and influences of an open-ended ecosystem and the habitat functioning of the Wadden Sea. All the mentioned factors in this paper are enhancing or easening turbidity and affecting each other by ecological interactions. The indicated major causes of increased turbidity are most probably a collaboration of dredging activities, fisheries and global warming. Although these factors might explain the increase in turbidity, the interacting effects upon each other remain poorly understood.

2. Possible effects regarding the Wadden Sea

The Wadden Sea changes are confounding because of human influences (De Jonge & De Jong 2002a; Wolff 2005). In the last century human influences considerably changed the Wadden Sea and it is indispensable that the Wadden Sea should be protected for more increasing changes. Sediment stabilizers such as eelgrass beds are very hard to reintroduce just as epibenthic organisms and autogenic engineers (Giesen *et al.*1990; De Jonge & De Jong 2002a; Schouten 2004). The Wadden Sea will probably be in a completely altered and probably a less complex state within the future centuries with lost unique features such as salt marshes, specific bird populations, benthic species and habitats if not preserved (Herman *et al.* 2009).

3. Possible effects regarding salt-marsh development

During the research it became clear that the future of the salt marshes is uncertain. The possibility that the Dutch salt marshes will drown is present. The overall picture of decreasing salt marshes is that the decrease is counteracted by conservation and there is a hiatus in the desired state situation of the salt marsh (Herman *et al.* 2009). Therefore the development of the salt marshes is inseperable of human interference (De Jonge & De Jong 2002a). At the end the urge for a covering research is definitely needed because of the lack of interacting values.

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