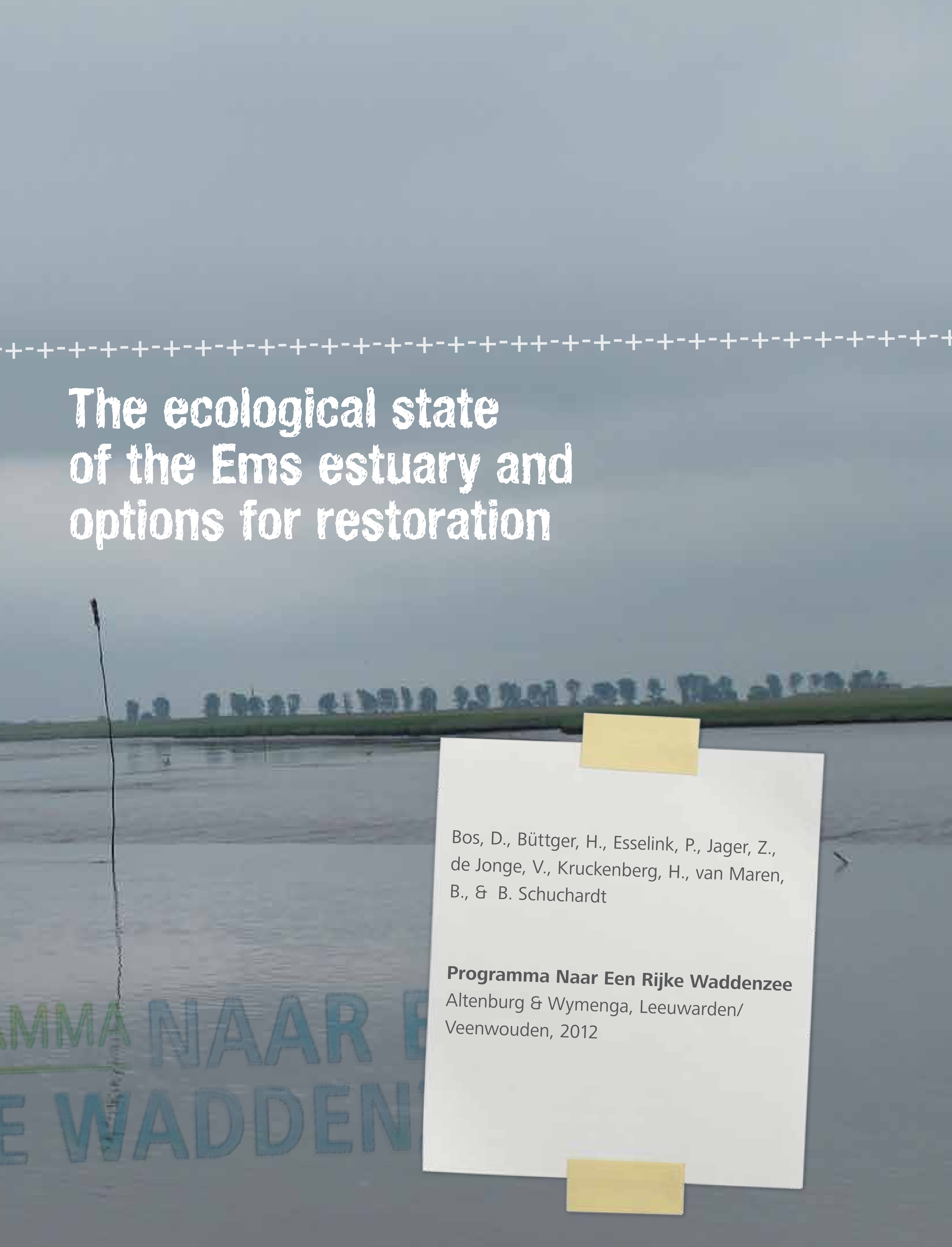
PROGRAMMA NAAR EEN RIJKE WADDENZEE

THE ECOLOGICAL STATE OF THE EMS ESTUARY AND OPTIONS FOR RESTORATION

PROGRAMMA NAAR EEN RIJKE WADDENZEE



The ecological state of the Ems estuary and options for restoration

Bos, D., Büttger, H., Esselink, P., Jager, Z., de Jonge, V., Kruckenberg, H., van Maren, B., & B. Schuchardt

Programma Naar Een Rijke Waddenzee
Altenburg & Wymenga, Leeuwarden/
Veenwouden, 2012

Abstract

This document has been written against the background of the Integral Management Plan that is under development in a co-ordinated initiative by Germany and The Netherlands. The document identifies the Ems estuary as a degraded ecological system, mainly because of a strongly artificial morphology, high levels of turbidity, extended periods of anoxy in certain zones and a limited quality and quantity of estuarine habitats. It offers stakeholders and policy makers an overview of the most relevant knowledge of the Ems estuary. The most important defined pathways leading to restoration of the system are presented along with their rationale.

Index

1 Introduction

There is currently a large and widely shared interest in the environmental state of the Ems estuary. For decades this state has been judged as alarming (de Jonge, 1983, 2000; van der Welle & Meire, 1999; Raad voor de Wadden, 2010). German and Dutch authorities have started to develop an Integral Management Plan (IMP) for this area. Under these circumstances, access to all relevant scientific information is of great importance. It is felt, however, that there is a strong disparity in the access to the information sources. This is to some extent caused by the fact that part of the available information is published in the so-called 'grey literature'.

The Dutch programme 'Naar een Rijke Waddenzee (PRW)' considered this a momentum to follow the suggestion by the Raad voor de Wadden (2010) and to write a summary paper on the most urgent problems, their causes and options for ecological restoration in the river Ems and its estuary. This summary provides an opportunity to synthesize the current state of knowledge and to disclose that information to the various stakeholders.

Fig. 1 Map of the Ems estuary with topographical names as mentioned in the text. For the purpose of this paper we distinguish four regions, the outer reaches, the middle reaches, the Dollard and the upper reaches or tidal river.

Hence, this paper deals with the following questions:

- what is known about the functioning of the Ems estuary?
- what are the main ecological problems in the Ems-estuary?
- what are their causes?
- what are the most feasible options for ecological restoration?
- what are essential knowledge gaps concerning causes and restoration options?

Given our objective of synthesizing and disclosing information to a wider audience, we cannot be exhaustive in our descriptions of facts, processes and developments. Whenever relevant we provide references to original sources or reviews, where the reader may find more details. All available electronic references are stored in a shared workspace on the internet (http://eems.pbworks.com).

STUDY AREA

Geographically the Ems estuary stretches from Borkum until the weir at Herbrum *(see fig. 1)*. From a hydraulic and hydrological perspective, the outer tidal delta, seaward from the barrier islands, the tributaries and the river upstream of the weir are also included. For the purpose of this paper we distinguish four seperate regions: the outer reaches, the middle reaches, the Dollard and the upper reaches (or tidal river, extending from circa Knock to the weir at Herbrum).

Reviews that describe, discuss and or summarize the structure and functioning of the Ems estuary are e.g. Stratingh & Venema (1855), Gerritsen (1952), Voorthuysen & Kuenen (1960), Wolf (1983), BOEDE publications (e.g. BOEDE 1985; Baretta & Ruardij 1988), Essink & Esselink (1998), van 't Hof (2006), de Leeuw (2006), de Jonge & Brauer (2006), Talke & de Swart (2006) and Schutttelaars et al. (2011). Papers describing perspectives on improving the physical boundary conditions of the Ems-estuary are Chernetsky et al. (2010) and Schuttelaars & de Jonge (accepted), those describing perspectives on improving the ecological status of the Ems-estuary are van der Welle & Meire (1999) and Schuchardt et al. (2009).

2 Elements of estuaries

Fairbridge (1980) defines an estuary as "an inlet of the sea reaching into a river valley as far as the upper limit of tidal rise, usually being divisible into three sectors: (a) a marine or lower estuary, in free connection with the open ocean; (b) a middle estuary, subject to strong salt and fresh water mixing; and (c) an upper or fluvial estuary, characterised by fresh water but subject to daily tidal action". The subdivision of the estuarine system into three regions is relevant to ecology.

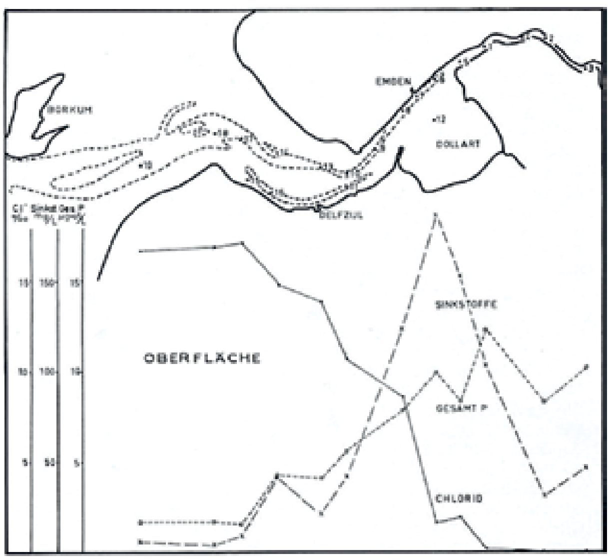


Fig. 2 Turbidity maximum in the Ems estuary, the Netherlands, nearly 60 years ago (Postma 1960). Observations were taken at the surface of the estuary at the stations indicated on the map. The suspended matter concentration is presented in the graph, as well as salinity (as chloride) and total phosphorus (sum of the particulate and the dissolved fraction).

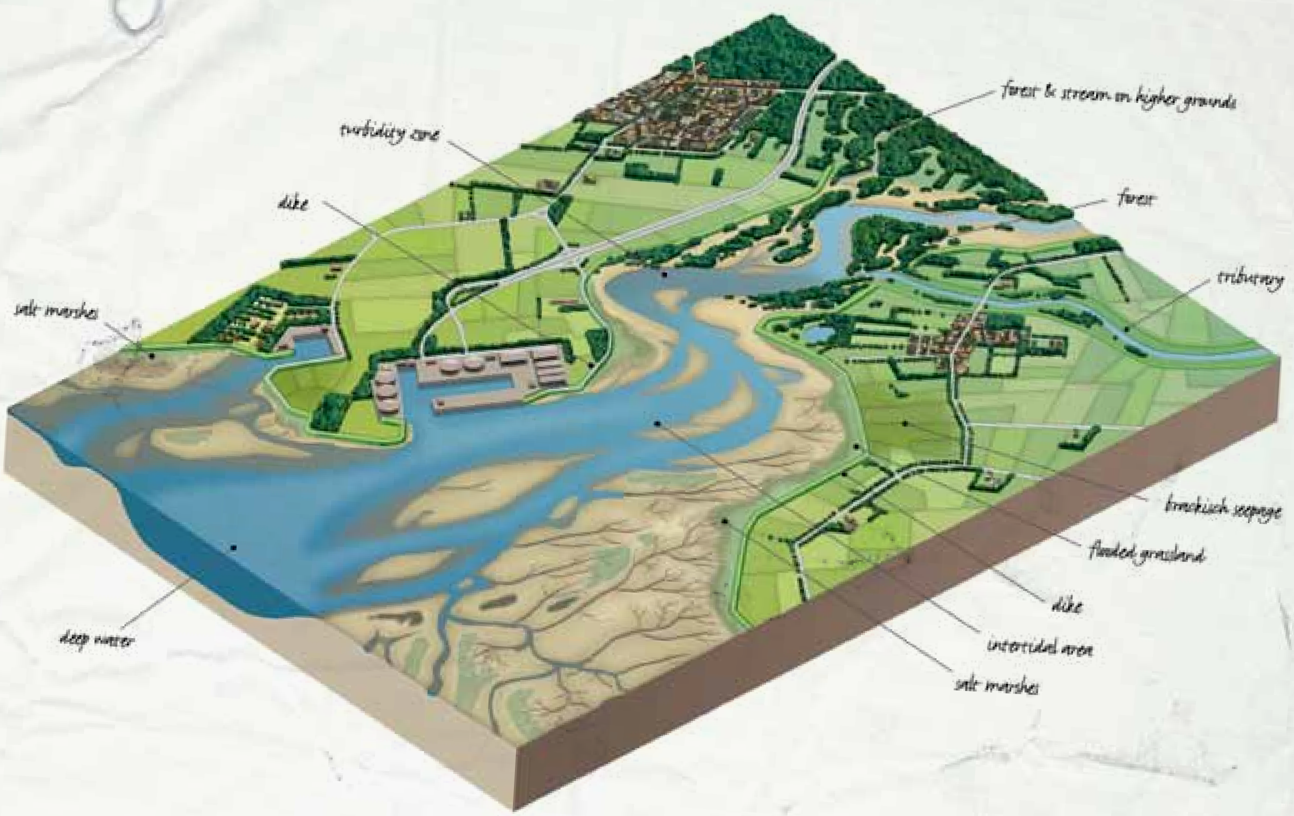
Detailed descriptions of the structure and functioning of estuaries are given in several text books, such as Belgrano et al.(2005), Dyer (1997), Levinton (2001) and McLusky & Elliott (2004). This particular paragraph aims to provide information at a more general level.

Estuaries are characterized by gradients in fresh- and sea water. There is diversity in habitats caused by combinations of different water bodies and intertidal areas with variation in salinity, current velocity (or turbulence) and elevation. These combinations lead to different habitats in different salinity zones (e.g. sand flats and mud flats at different elevations, shallow and deep water areas and tidal marshes). In tidal estuaries, the water flows in and out of the system in an oscillating mode via one single tidal inlet. Under natural conditions the water flows through well defined flood and ebb channels. Under the influence of the combination of oscillating tidal currents and local morphology, typical residual current patterns are detectable (de Jonge 1992) that significantly contribute to the tidal mixing (de Swart et al. 1997). Variation in fresh water discharge strongly contributes to the tidal mixing or dispersion of water and dissolved constituents (Helder & Ruardij, 1982).

The mixing zone is characterized by relatively turbid water and related poor light penetration. A part of this area is called the Maximum Turbidity Zone (MTZ) or the Estuarine Turbidity Maximum (ETM). The extent and location of the MTZ depends, amongst others, on the local morphology, tidal wave characteristics, water depth and discharge of fresh water. The turbidity maximum in the Ems estuary in the 1950s (Postma 1960) has been used as a classical textbook example by McLusky (1981, *see fig. 2*). Note the sharp (but low) peak in suspended matter near Emden, and the strong decline in salinity moving upstream.

Each zone along the salinity gradient is occupied by a specific community of organisms, consisting of a mix of marine, brackish and freshwater species. As an example, the macrozoobenthos in estuaries is generally characterized by relatively few species, which may be very abundant in terms of numbers (McLusky 1981).

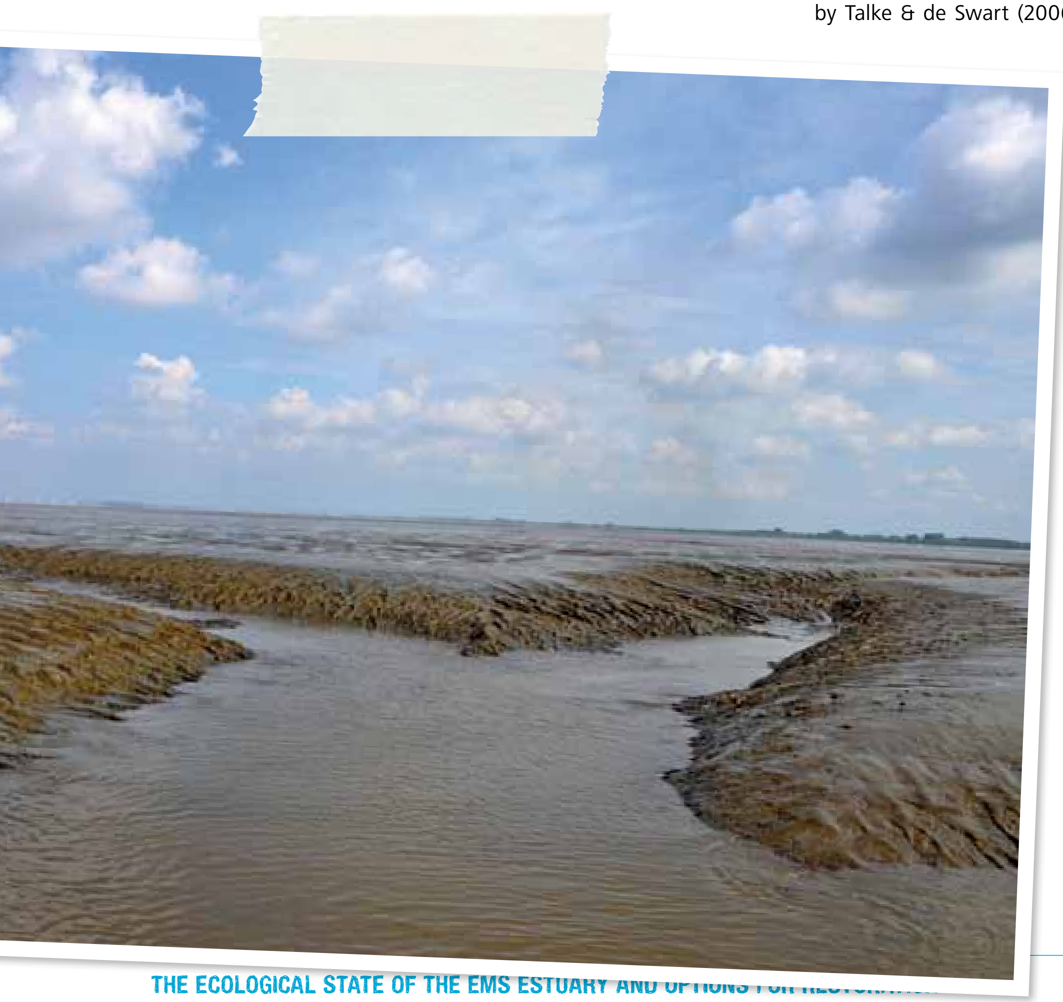
The high productivity of an estuary is an effect of a rich food supply, based on the import of particulate organic matter from the sea, the river and the local primary production which is fed by the nutrients discharged by rivers and other freshwater sources (Postma, 1954, de Jonge & Postma 1974).



Box 1 *A hypothetical estuary: characteristic elements of estuaries are the river, with its branches and meanders, a drowned river valley (the estuary census stricto) in free connection with the open sea, and its habitats in different salinity zones. There is a great diversity in these habitats caused by combinations of different waterbodies and intertidal areas with variation in salinity, current velocity and elevation. At many places man is impacting estuaries by land reclamation, infrastructure, channel deepening, dredging etcetera. There are parallels in the problems between the Ems estuary and other major estuaries in NW Europe and much can be learned from comparisons between them. In this paper, the knowledge derived from other estuaries has implicitly been taken into account.*

3 Functioning of the Ems ecosystem and knowledge gaps

To describe all relevant aspects of the Ems ecosystem we follow the structure of Deneudt et al. (2010) that was used to develop a monitoring plan for the Scheldt estuary. Four themes have been distinguished. Two of them (morphodynamics and water quality) describe the basis of the system. The other two themes focus on habitats and the species living in these habitats. In the following sections we will discuss what data are available with regard to these themes, what the essential trends are and, if present, what the essential problems are.



3.1 Hydro- and morphodynamics

The morphology of any estuary relates directly to its hydrodynamic and ecological functioning, but also to aspects of safety and its value for human use. A crucial characteristic of estuaries is water transport related sediment transport. The relative importance of sediment transport processes varies throughout the system. Strong human impact in the Ems estuary has affected the sediment (sand and mud) transport processes over time. We therefore introduce the morphology of the system, including an overview of the main anthropogenic influences, and give a review of dominant sediment transport processes.

Morphology

The morphological history and the more recent developments of the Ems estuary have been described by Gerritsen (1952) and van der Welle & Meire (1999) and more in depth reviewed by Talke & de Swart (2006) and Herrling & Niemeyer (2006). The present catchment area as a whole is defined and characterized in NLWKN (2010) and in the Water Framework Directive (WFD) management plan for the Ems catchment area (Geschaftsstelle Ems 2010). In order to understand the estuary from a hydromorphological perspective, it is important to note that sediment transport in various parts of the estuary is dominated by different processes.

Tab. 1 Historical record of the step-by-step deepening of the tidal river Ems upstream of Emden for shipping. Values refer to the depth below Mean High Water MHW (bron: WWF, 2006).

Period	Intervention
1958/ 1961	construction of the Geiseleitdamm leading to deepening of Emder Fahrwasser
1984/1985	5.7 m deepening pro Meyer-Werft ('Homeric-deepening')
1991	6.3 m deepening pro Meyer-Werft ('Zenith-deepening')
1993	6.8 m deepening pro Meyer-Werft
1994/1995	7.3 m deepening pro Meyer-Werft ('Oriana-deepening')
2001	Ems water barrage (Ems Sperrwerk) - ready in 2002

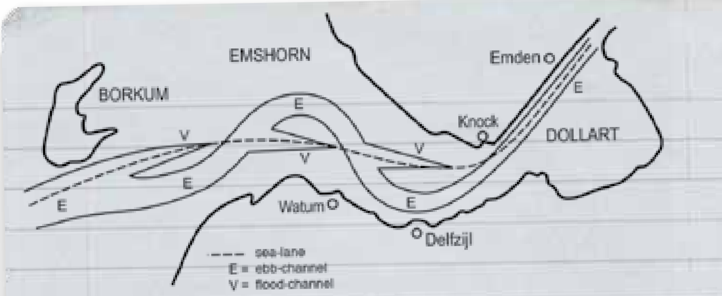


Fig. 3 Sketch of the natural flood and ebb-channels in the Eems middle and outer reaches (van Veen 1950). Van Veen predicted the current situation (indicated by a stippled line), as a consequence of dredging.

The outer and middle reaches and Dollard *(see fig. 1)* are strongly influenced by waves and tides. Together, these regions consist on average for 50% of intertidal flats (BOEDE, 1985). The remaing 50% is sub-littoral. The mud content of the bed, inventoried in 1990 (McLaren et al. 1998), increases from several percents in the sandy outer reaches to over 75 % near and in the Dollard bay (the section south of the Geiseleitdamm) and the tidal river. The Dollard bay consists of extensive muddy intertidal flats (covering 80% of the area). The area is intersected by two major tidal channels. The tidal flats and channels in the Dollard were probably accreting until 1984, but are alternatingly accreting and eroding since then (Esselink et al. 2011). The upper reaches or tidal river is the region between Knock (the entrance to the Emder Fahrwasser) and the weir near Herbrum *(see fig. 1)*. It includes the Emder Fahrwasser which is separated from the Dollard bay by the Geiseleitdamm. The sediment composition in the upper reaches (main channel) has shifted in the 1990s from predominantely sandy to mostly muddy (BfG 2008).

Herrling & Niemeyer (2006) give a full overview of anthropogenic changes to the morphology of the Ems estuary. Major changes in the tidal river were reductions in river length and width and an increase in channel depth. Reductions in river length were caused by the weir at Herbrum (1899) and the bypassing of river meanders. The width was squeezed by the construction of hard boundaries (dikes and break waters) for coastal protection and agricultural purposes (sluices). The channel depth has in a step by step mode increased by dredging *(see table 1)*, most effective between 1985 and 1995. Near Gandersum a storm-surge barrier has been constructed in 2001 - 2002 for coastal defence and shipping purposes. The Geiseleitdamm was initially constructed between 1930 and 1935, but was extended to a 12 km long training wall from 1958 to 1961. Continuous maintenance dredging is necessary between the North Sea coastal zone and the harbour of Emden; occasional dredging in the tidal river up to Papenburg is required if new vessels have to be transferred from the Meyer shipyard to the sea.

In the outer and middle reaches, the general changes can be characterized by a step by step removal of shallows in the navigation route to the Dutch and German harbours (started in 1898), turning the original flood-channels, which were straightly aligned, into the main navigation route, *see figs. 3 and 4*. The ebb channel 'Bocht van Watum', originally the main shipping lane, developed into a secondary channel with sills on both ends (Herrling & Niemeijer 2008) as predicted by van Veen (1950). These developments started already in the 1940s (Gerritsen, 1952). Nowadays, the tidal currents concentrate on the main channels and have increased in strength (Herrling & Niemeijer 2008). In order to maintain the shipping channels, there is continuous dredging (de Jonge, 1983, 2000; Mulder, 2004; BfG- Bundesanstalt für Gewässerkunde 2001).

In summary, the middle and outer estuary has changed from a two-channel system before the 1950s to essentially a one-channel system now *(fig. 4, Herrling & Niemeyer 2008)*. Over time there has been a strong loss of intertidal and supra-tidal areas *(see section 3.3)*. Some of these changes started hundreds of years ago and were caused by embankment activities and land reclamation along the Wadden Sea mainland coast and in the Dollard, following its formation in the 1600s (Groenendijk & Bärenfänger 2008). Of more recent origin is soil subsidence due to gas extraction, which amounts to some decimeters in parts of the estuary centred around Delfzijl (25 cm at maximum until 2009, NAM 2010). But strong sediment movements (of mainly mud) largely compensate for effects of this subsidence (Cleveringa 2008). The morphological changes (especially in the outer estuary) are very complex and not well understood. They are partly of anthropogenic and partly of natural origin. Changes continue over long spatial and temporal scales (Samu, 1979).

HYDRODYNAMICS AND SEDIMENT TRANSPORT IN THE TIDAL RIVER

The tidal range in the tidal river has increased significantly and the tidal curve has become more asymmetrical than before. These changes in the hydraulic characteristics have been reviewed by Talke & de Swart (2006) and van Maren (2010). Our understanding of the physics in the river Ems has improved substantially over the last years due to recent work by Talke & de Swart (2009a,b), Chernetsky et al. (2010), Winterwerp (2010), and Schuttelaars et al. (2011). We will first review the observed changes in both the hydrodynamics and the sediment concentrations, and then put forward explanations for the observed phenomena, as presented in the liteature mentioned above.

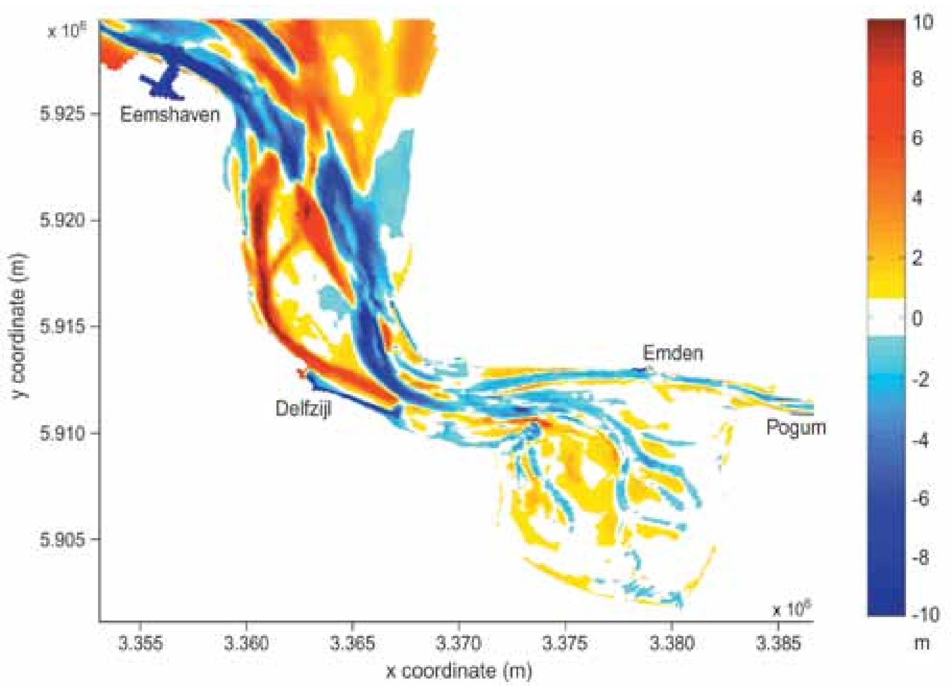


Fig. 4 *Net deepening (blue) and net accretion (red) between the bathymetrical states of 1937 and 2005 in the transitional waters between Pogum and Eemshaven (Herrling & Niemeijer, 2008). The current situation is essentially a one-channel system, in which the main navigation route follows the former flood-channels.*

A very strong increase in the tidal range has taken place in the tidal river upstream of Emden (Herrling & Niemeijer, 2008). Until the year 1940, the spatial variation in the tidal range was rather stable with a peak close to Emden (mean annual range -MAR- around 3 m), and then gradually decreased towards Herbrum (< 1 m). Since 1950 there has been an increase in the tidal range from Emden onwards. The tidal range now peaks at Papenburg (with MAR = 3.5 m, where it used to be 1.7 m in the 1930's; Herrling & Niemeijer 2008). Although partly a result from increased High Tide, this increase in tidal range primarily results from significantly lowered low tides (Herrling & Niemeyer, 2008). The increase in mean high water has made the upper parts of the Ems estuary more vulnerable to storm surges (Herrling et al. 2001; Talke & de Swart 2006) while the strong decrease in the mean low water level and the increase in high water level have had significant effects on e.g. the size and distribution of estuarine habitats (van der Welle & Meire 1999; Herrling & Niemeyer 2006; Schuchardt & Scholle 2009) and presumably on biological diversity (Schuchardt 1995).

Direct observations on changes in flow velocities are not at our disposal. Herrling & Niemeyer (2008) used the bathymetry of 1937 and 2005 to understand changes in the hydrodynamics. Their study suggests that flood velocities doubled during this period (whereas ebb-velocities did not), while in 1937 ebb and flood velocities were nearly equal. This is caused by an increase of the tidal amplitude and an increasing asymmetry of the tides.

The turbidity in the tidal river has dramatically increased over the past decades *(see fig. 5)*. The Ems estuary used to be a moderately turbid tidal estuary, with a turbidity peak near the water surface of ca. 150 mg of suspended matter (SPM) per liter, located at the transition from salt to fresh water (Postma 1960). Today concentrations up to several grams of SPM per liter are documented. The most pronounced increase took place in the period 1980-90 following the step by step increase of the water depth in the river Ems between Emden and Papenburg. Fluid mud was detected in the 1990s (Bezirksregierung Weser-Ems, 1998; Jager 1999; Schrottke & Bartholomä 2008): first episodically and later permanently. It only occurs in the tidal river. The cause of the appearance of the fluid-mud is not fully understood. There is, however, full agreement that the fluid-mud deposits strongly decrease the bottom roughness and that tides are subsequently significantly affected by the fluid mud. The feedback between the tidal current asymmetry and the sediment transport is complex, however, and several explanations have been given for the increase in turbidity. Overviews and analyses are given from different point of views by Talke & de Swart (2006), Winterwerp (2010) and Schuttelaars et al. (2011).

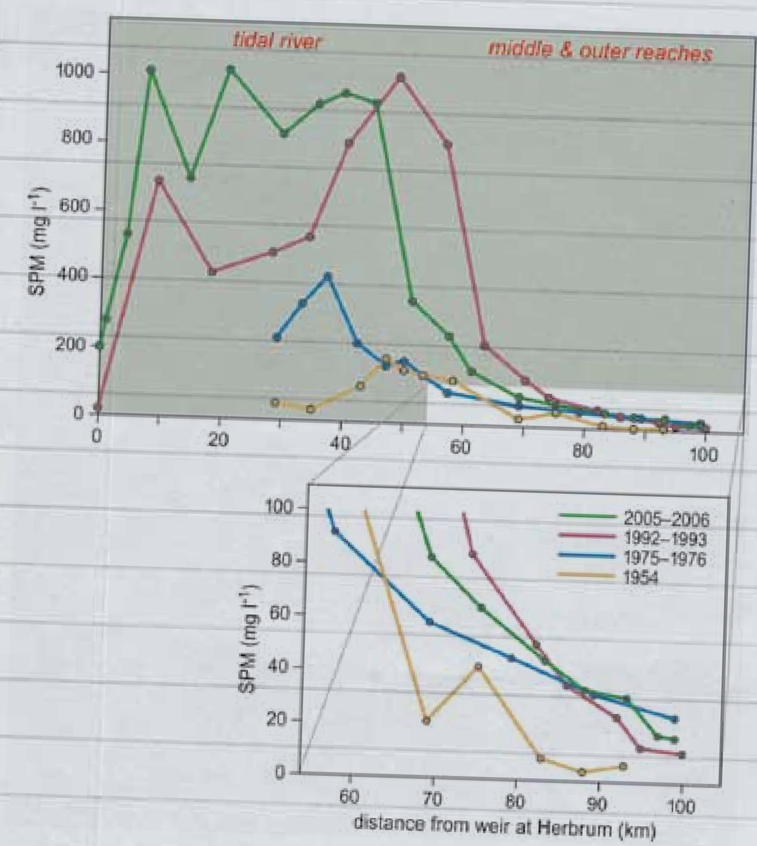


Fig. 5 Mean annual suspended matter (SPM) as function of the distance from the weir at Hebrun. Seperate lines are given for the years 1954, (Postma, 1960), 1975–1976 (de Jonge, 1983), 1992–1993 (measurements by van Beusekom & de Jonge) and 2005–2006 (measurements done by de Jonge) for the area between Herbrum and Borkum (upper panel) and in detail for the area between Emden and Borkum (lower panel). Paper in preparation by de Jonge et al.. The graph shows that the concentrations of suspended matter have increased, as well as the extent of the maximum turbidity zone (MTZ). The centre of the MTZ has shifted upstream.

How exactly the tidal river changed from the original situation to its current turbid state is unknown. Several mechanisms can result in an enhanced transport of sediment upstream. From the data in Fig. 5, it is clear that the dominant mud transport and accumulation processes in the tidal river have changed over time. Chernetsky et al. (2010) demonstrates that it is most likely that before the deepenings the upstream transport by tidal asymmetry and gravitational circulation balanced downstream transport by river flow. The highest turbidity occurred at the head of the saline intrusion in the 1950s (see fig. 2). Just before the main deepenings were started during the mid 1980s, the river bed was probably still dominantly sandy (BfG 2008). When this all changed is still highly unclear and under investigation. At present, and based on the work of Chernetsky et al. (2010), the current upstream sediment transport is most probably dominated by tidal asymmetry in the current velocities. Winterwerp (2011) further argues that the above process is further strengthened by an asymmetry in the size of mud-flocs (and hence settling velocity), which also depends on the current velocity.

Additionally, sediment-induced gravitational transport plays a role (Talke et al. 2009), which may distribute the sediment further into the upstream direction. Nowadays, the system is characterized by fluid mud layers of 2 m thick or more near the bottom, with a concentration in excess of 10 g/l (Talke et al. 2009a). These fluid mud layers travel upstream and downstream with the tides (Talke et al, 2009a) but also seasonally, with downstream flushing of the fluid mud layers during the highest river discharge (van Leussen 1994). Processes like the settling lag and scour lag, ideas of van Straaten & Kuenen (1957) and Postma (1961), also contribute to this net upstream transport.

In combination with deepening effects as described above, also the precise location of the weir at Herbrum strongly influences the system (Schuttelaars et al. 2011; Schuttelaars & de Jonge, accepted); the actual length, depth and hydraulic roughness of the tidal river are such that 'resonance' occurs, which strongly contributes to amplification of the tidal wave along the river. A recently developed idealized model for this situation by Chernetsky et al. (2010) and Schuttelaars et al. (2011) demonstrates that this resonance may have important consequences for the location as well as the extension of the zone with the highest turbidity (the MTZ).

HYDRODYNAMICS AND SEDIMENT TRANSPORT IN THE MIDDLE AND OUTER REACHES

Sediment transport processes in the middle and outer reaches as well as the Dollard depend on waves, tides, gravitational circulation, bioturbation and biostabilization (de Jonge 1995, de Jonge & van Beusekom 1995, Kornman and de Deckere, 1998), as well as anthropogenic processes such as dredging (de Jonge 1983) and dumping. For the outer reaches and the Dollard wind has a pronounced effect on the erosion-sedimentation balance and thus the SPM distributions in the water column (de Jonge 1995). The combination of these processes leads to clear variations in sediment concentrations over tidal, spring-neap and seasonal cycles (Habermann 2006) and differences in the mean levels of the SPM.

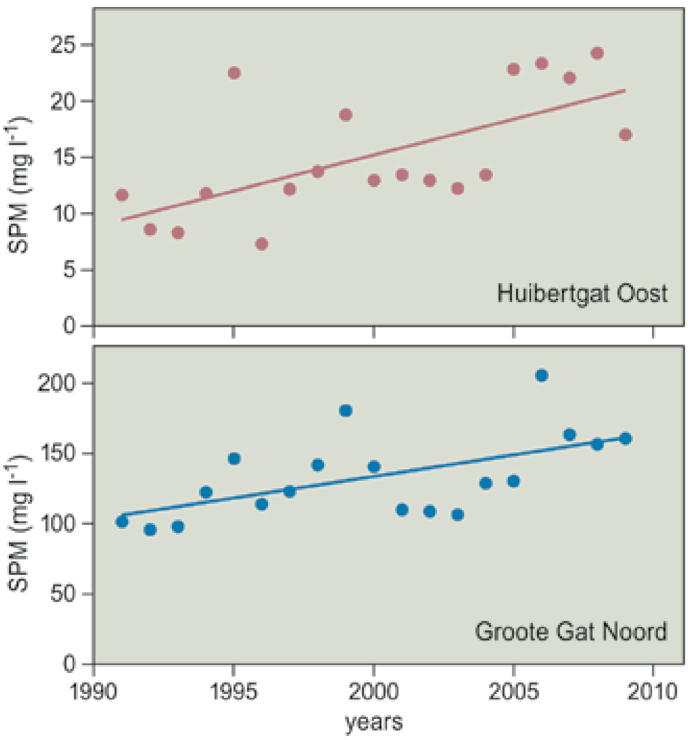


Fig. 6 Mean annual suspended matter near Borkum (Huibertgat Oost) and in the northern part of the Dollard (Groote Gat Noord) monitoringdata (DONAR) Rijkswaterstaat, 1991-2009. Annual mean values are based on monthly sampling at a standardized moment in the tidal cycle. Calculations from de Jonge.

Turbidity in the middle and outer reaches has increased during the years 1954-2008 *(see fig. 5)*. These findings are supported by the monitoring observation from Rijkswaterstaat *(Fig. 6)* and by observations from selected stations by van Maren (2010); Esselink et al. (2011) and Merkelbach & Eysink (2001). Merkelbach and Eysink (2001) estimated an increase of 30-60 mg/l over six stations from Oost-Friesche Gaatje to Groote Gat Noord. This is large, with respect to the average concentration of approximately 100mg/l at Delfzijl. Since 1991 measurements at these stations have been taken at the same moment relative to the tidal fase, and data for two of these stations are given in fig. 6. The processes for the above-mentioned increases in sediment concentration are not yet well-enough understood. The general opinion is nonetheless that the above-discussed anthropogenic effects, that have led to greater tidal volumes and stronger tidal assymetry, are most important.

From 1992 to 2009, 0.7 million m^3 of dredging material has been dumped on average in the Dollard area per annum (Esselink et al. 2011), which may also lead to higher sediment concentrations.The quantities are low however, in comparison with the longitudinal and lateral gross sediment transport rates in the area (de Jonge 1995; Mulder & Mijwaard 1997; Esselink et al. 2011).

3.2 WATER QUALITY

According to national and international standards relevant water quality parameters are: oxygen concentration, salinity, nutrients, organic load, light, temperature and toxic substances (Deneudt et al. 2010). Each of these is relevant for ecosystem functioning. Light and nutrients are essential resources for algal growth, temperature is a general parameter influencing process rate, salinity plays a role as boundary condition for species composition, toxic substances negatively influence structure and functioning of the ecosystem and organic loads form a substrate for aerobic bacteria to live in. Oxygen concentrations can decrease significantly if the re-aeration rate is lower than the rate of oxygen consumption by these bacteria, thus leading to oxygen concentrations which are too low for most organisms. The monitoring of these parameters is described in (NLWKN 2010; RWS 2009) and reviewed in Bakker et al. (2009); Becker & Dittmann, (2009); van Beusekom et al. (2009) and Schuchardt & Scholle (2009). According to the the standards of the WFD, the water quality was 'poor' in the tidal river and 'moderate' in the remainder of the estuary in 2009 (NLWKN 2010).

The increase of suspended matter in the tidal river Ems has dramatically changed the light penetration, especially in the freshwater reaches where normally the suspended matter concentrations are relatively low and consequently the primary production high per unit area (Schuchardt & Schirmer 1991). However, the changed SPM conditions further downstream in the outer reaches must have also significantly decreased the food supply to the overall estuarine system (as will be discussed in 3.4 on primary production). Apart from effects on primary production, increased suspended matter possibly affects organisms higher in the food chain directly, e.g. by blocking the filtration apparatus of molluscs, the gills of fish or reducing visibility.

There has been a decrease of the minimum oxygen levels from 8 mg/l in 1980 (van der Welle & Meire (1999) until 0 mg/l since the early 2000s between Papenburg and Leer *(fig. 7)*. Moreover, the oxygen deficiencies have since then further intensified in space and in time in this section *(see fig. 7 and Engels 2007)*. This negatively affects conditions for many species of biota (see below).

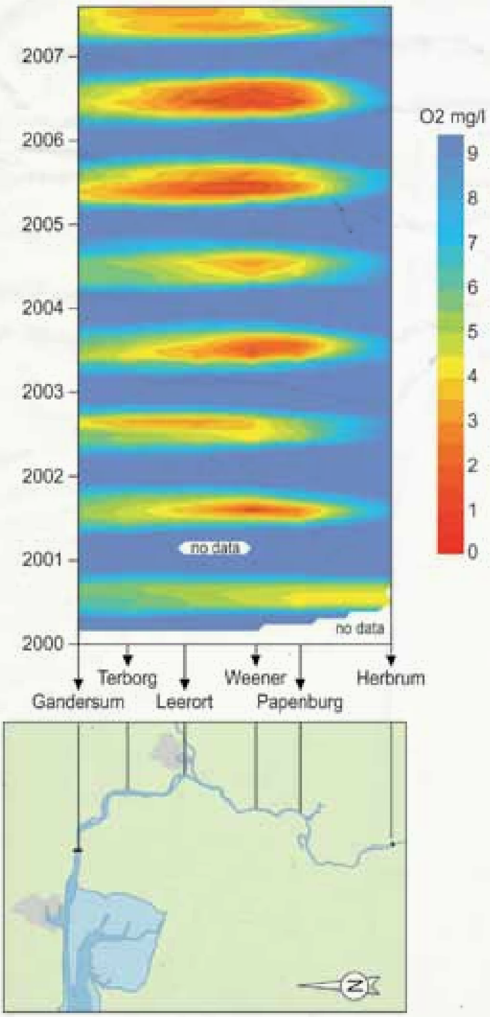


Fig. 7 Spatio-temporal plot of the oxygen concentration in the Ems estuary 2000-2007 between Herbrum and Gandersum (Harbasins project WP2, based on data of NLWKN Aurich).

For metals and macro-nutrients (nitrogen and phosphorus), riverine input is quantitatively most important. For particulate phosphorus there is significant input from the North Sea (25%, van Beusekom & de Jonge 1998). The input of metals, nitrogen and phosphorous in the Ems estuary has significantly reduced over the past decades, but concentrations are still above the natural background levels. The riverine input of hazardous substances has also strongly declined. Nonetheless, the concentrations measured in organisms (e.g. PCB and DDT in blue mussels, eggs of birds such as terns and Oystercatchers) are still relatively high, especially near Delfzijl. Several studies indicate that more attention is needed for emerging compounds (new types of chemicals) and ecotoxicological effects of mixtures of substances (Bakker et al. 2009; ten Hallers, 2006).

3.3 ESTUARINE HABITATS

The estuarine habitats provide the areas for communities of organisms to live and reproduce. There is often a close connection between the quality of the water (previous section) and the animals and plants (next section) that live in these estuarine habitats. Note that most of the flora and fauna contribute to the shape of the habitats as well. Some form massive reefs (blue mussel and Pacific oyster) or create shelter (seagrass meadows) while others stabilize (benthic diatoms) or destabilize (edible cockle, Corophium spp, shrimp, flounder) the sediments.

Relevant habitats are deep water, shallow water, tidal flats, marshes, reed beds, riverine forest and upland areas in zones influenced by marine, brackish and fresh water. There are various kinds of gradients, partly as a consequence of natural dynamics. Estuarine habitats are being mapped as ecotypes (Bouma et al. 2005; IBL 2009; Wijsman and Verhage 2004) in both countries, but there are also separate monitoring schemes for vegetation (Esselink et al. 2009), sea grass (Adolph 2010; van der Graaf et al. 2009a) and mussel beds (The Wadden Sea National Park Authoriy of Lower Saxony; Imares). In addition to this there is an urgent need for determining the functioning of these habitats apart as well as in relation to each other (de Jonge et al. 2003, de Jonge 2007, de Jonge et al. accepted) and the relevant boundary conditions and human activities.

Herrling & Niemeijer (2006), De Jong (2006) and Claus (1998) provide information that shows how the tidal river region has lost 35% of mudflats, 42% of the shallow water zones and 37% of the foreland areas between 1900 and 1990 (with some discrepancies between the authors). However, the magnitude of losses is similiar to those in the upper estuaries of Weser and Elbe (Schuchardt et al. 2007). Apart from land claim and coastal defence, the causes are mainly deepening due to shipping purposes and the disposal of sediments, filling shallow water areas. For the outer estuary and the middle reaches there have been large losses in intertidal and supra-tidal area until 1924, mainly due to land claim. This process already started in the 1600s, after the formation of the Dollard by a series of storm surges.

3.4 ESTUARINE SPECIES AND ECOSYSTEM FUNCTIONING

The most important groups of organisms in the food web are the algae and other primary producers, the zooplankton, hyper-benthos (crabs & shrimp), macrozoobenthos, fish, birds and mammals (Deneudt et al. 2010). The majority of the ecosystem fluxes (carbon, energy, N, P) takes place among organisms smaller than 1 mm (e.g. decomposers, algae bacteria, zooplankton), living in the water column as well as in the sediment. This is the reason why de Jonge et al. (accepted) call on the authorities which are responsible for the implementation of the EU Directives, to acknowledge eco-systems complexity by also stimulating the development of more functional indicators (see above).

PRIMARY PRODUCERS

Primary production is generated by algae living on the mudflats (mainly microphytobenthos, the role of macro algae and sea grasses is negligible) and by algae in the water column (phytoplankton). However, a significant part (on average 20 – 25%) of the microphytobenthos reaches the water column by natural resuspension phenomena (de Jonge 1995), where these algae contribute to the primary production by phytoplankton. Primary production is the basis of the food web and determines to a large extent the numbers of consumers at higher trophic levels. Nutrient availability and underwater light conditions are key factors affecting primary production.

A review of the available information for the Ems estuary (middle and outer reaches) is provided by de Jonge & Brauer (2006), relying heavily on data collected in the mid and late 1970s. The phytoplankton production varies as a complex function of the above mentioned conditions and thus over the year. River water carries nutrients and de Jonge & Essink (1991) found a strong positive correlation between the mean annual fresh water discharge and the annual primary production for the middle and outer reaches. The effect of higher river discharge was strongest in the outer reaches, indicating that the middle reaches and Dollard were in general light limited. This is not true for the primary production on the intertidal flats because here microphytobenthos is most active during exposure at low tide.

The main part of primary production takes place in the outer reaches. This is explained by the extensive surface in the outer reaches that is available for algal growth, in combination with lower turbidity. The contribution of the tidal river part to the total production is negligible (de Jonge & Brauer 2006), because of the limited surface and the extreme turbidity. Note, however, that the primary production in the freshwater reaches of less disturbed estuaries can be high on a per area basis (Schuchardt & Schirmer 1991).

Given the changes in turbidity between 1954 and present (previous section), the light conditions have deteriorated, especially in the tidal river. Direct field evidence for the effects of this deterioration on the primary production is not available because it has not been investigated. De Jonge and co-workers, however, explored the effects of climate change, dredging and river improvements on light conditions in several studies (DeGroodt & de Jonge, 1990; de Jonge & Brauer 2006; de Jonge unpubl), based on the historical measurements mentioned above and the models by Baretta & Ruardij (1988). They conclude that the effect of channel maintenance dredging and changes in river morphology is large. Relative to the undisturbed reference conditions de Jonge (unpubl) estimated a loss in primary production of more than 60% for the situation in 2005-2006, due to estuarine dredging and river improvements. Particularly the reduction in the outer reaches was responsible for the total decline of primary production in the total estuary. It is expected that the annual primary production could be significantly enhanced under improved light conditions, especially in the middle and outer reaches.

ZOOPLANKTON

There are a few publications on zooplankton in the Ems estuary from the late 1980's, reviewed in de Jonge & Brauer (2006). A study by de Jonge & van Beusekom (1992) showed that resuspended microphytobenthos may significantly contribute to the food of the fast developing copepod populations in the water column in early spring (March and April). During that period the concentrations of real phytoplankton are low and comparable to the amount of the resuspended microphytobenthos. Model calculations by Baretta and Ruardij (1988) indicate that among zooplankton the role of micro-zooplankton may be much more important than the copepods, although observed micro-zooplankton biomass only showed low values. Micro-zooplankton was, however, not an integrated part of the project Baretta & Ruardij (1988) reported about! Since zooplankton is an important link between primary producers and carnivores higher in the food web, there is a clear lack of knowledge with regard to this group.

HYPERBENTHOS

Until a decade ago, shrimp has been commercially fished in the entire estuary. The available data indicate sizeable stocks in the period 1946-1965, with an increasing trend in the amounts harvested. Results from the Demersal Fish Survey (DFS) point at decreasing densities in the outer, middle reaches and the Dollard, over the period 1970-2003 (van 't Hof 2006; Jager & Vorberg 2008). There is no clear insight in the causes of the recent decline (Jager & Vorberg, 2008). It should be noted that shrimp densities in the estuaries of the Ooster- and Westerschelde decreased as well over that period (van 't Hof 2006), while the trend for the Waddensea as a whole was unclear (Tulp et al. 2008). Systematic information on crabs is absent.

MACROPHYTES

Sea grass beds of the eelgrass *(Zostera marina)* are found in the outer Ems on the Hond-Paap (van der Graaf et al. 2009a; Adolph 2010). The presence of solitary plants was first recorded here in 1973 (Den Hartog & Polderman, 1975). Occurrence on the Hond-Paap was established in 1988 and eelgrass was regularly monitored ever since (Erftemeijer, 2005). The area covered by eelgrass increased in size between 1999 and 2004 to a maximum extent of 275 ha. After 2004, a strong decline ocurred in both area and coverage of the seagrass bed. By 2007 and 2008 the eelgrass had nearly vanished. Z. marina reproduces mainly through seeds and hardly by rhizomes, which makes it vulnerable and dependent on the production of sufficient seeds and on subsequent successful germination in the next spring (Erftemeijer, 2005). Dwarf eelgrass (*Z. noltii)* occurs sparsely on the opposite shore of the Hond-Paap in Germany. Increases of beds of Z. noltii were noted on the Randzel (south of Borkum, van der Graaf et al. 2009a; Adolph 2010). According to van den Hoek et al. (1979) it is unlikely that Zostera ever played a more important role in the Ems-Dollard estuary in the past, because it is neither mentioned by Stratingh & Venema (1855), nor by Voorthuysen et al. (1960).

It is not clear what has caused the decrease of seagrass at Hond-Paap. Van der Graaf et al. (2009a) noticed that the earlier increase of the eelgrass at Hond-Paap during the 1990s coincided with a parallel increase in suspended matter concentrations between 1990 and 2000 (Merckelbach & Eysink, 2001). In addition we like to notice that the area of maximum sea grass extension coïncides with the area of strongest bottom decrease due to gas exploitation. Although the contribution of eelgrass to the primary production in the Ems-estuary is insignificant (van den Hoek et al., 1979), the plants may provide a substrate for settlement and shelter for numerous organisms, including small fish (de Jonge et al., 1997).

Above the mean low water line there are vegetation zones that differ depending on salinity, soil level and grazing regime. A general overview is given in van der Welle and Meire (1999). Although there have been substantial habitat losses (see above) in the fresh water and brackish zone of the upper estuary there are still several hundreds of hectares of foreland (IBL 2008; 2009; 2010; van der Welle and Meire 1999). However, typical estuarine habitats such as riparian forests are lost. The majority of the remaining is mesophilic grassland, intensively used grassland and reed land. The conditions for these vegetation have deteriorated due to the human interventions described in 3.1. The impact of prolonged flooding is under study (NLWKN pers. comm.).

The majority of salt marshes in the estuary are found in the Dollard bay, with an area of nearly 1,000 ha. The development of areal extent of these salt marshes in the Dutch part of the Dollard has recently been analysed by Esselink et al. (2011). Another source is Esselink et al. (2009). Relevant processes on the salt-marsh are accretion (sedimentation), land reclamation, erosion, soil subsidence, succession of the vegetation and grazing management. Since about 1700 AD, salt marshes have artificially been developed and embanked in distinct episodes (Esselink 2000). In the Dutch part, accretion works were abandoned in 1953. The youngest part of the German salt marshes in the Dollard was artificially developed during the 1960s (Werkgroep Dollard 2001). The area of salt marshes in the German part of the Dollard is currently decreasing due to erosion. From 1997 to 2004, the salt marshes declined here by 95 ha to 249 ha (Esselink et al. 2011). Meanwhile in the same period, the erosion of salt marshes in the Dutch part was less than one hectare per year, circa 1-4 hectares in total.

MACROBENTHOS

Species diversity decreases from sea to the upstream parts of the estuary. This was illustrated by Ysebaert et al. (1998) who describe the changes in macrobenthic species composition over the estuarine gradient and show that the pattern in the Ems estuary resembles that in other estuaries (c.f. Wolff, 1983).

The blue mussel *(Mytilus edulis)* and cockle *(Cerastoderma edule)* mainly occur on tidal flats in the middle reaches in the Bocht van Watum (on the Hond-Paap and on the nearshore mudflats along the dike) and in the outer Ems on the German and Dutch side. Blue mussels have regularly been observed here since 1978. After a decline in 1998, the area covered by musselbeds on the Hond-Paap strongly increased towards the year 2000, and remained more or less stable around 200 ha until 2004 (Dankers et al. 2005). Information from Stratingh & Venema (1855) and data presented in Wolff (1983) indicate that mussels and cockles have not been common in the past in the middle reaches and Dollard. The pacific oyster *(Crassostrea gigas)* is a newcomer in the estuary and was first observed in 1998; it is still increasing in both numbers and biomass, and extending its range of distribution.

The Dollard bay received high amounts of organic waste water annually until 1990, mainly from the potato flour industry. This industry started in the 19th century. The problem was described as one of the biggest waste problems of the world (Ribbius, 1961). Waste water discharges continued to increase until the 1980s, when a sanitation scheme was introduced. During the years of pollution, extensive areas in the Dollard were completely anoxic in autumn. Because of that commercial fisheries disappeared from the bay shortly after World War II. The high loads of organic matter not only impacted the macrofauna, it also sustained high bird numbers (see bird chapter). The recovery of the Dollard after the sanitation of these discharges has been described in Essink & Esselink (1998).

Other available information on temporal development in macrobenthos has been summarized by van der Graaf et al. (2009b). The data are derived from the monitoring programme on the Heringsplaat, Dollard bay. The results should be interpreted with caution, since they do not yield any information about changes at a spatial scale, nor can they be representative for the estuary as a whole. Besides, the data series started at a moment when euthropication due to organic waste was still prominent. The number of species did not show a trend over the period 1987-2008, but biomass declined. The latter was a consequence of the strong decline in the alien species *Marenzelleria viridis*. In contrast to other parts of the Wadden Sea, *Macoma balthica* showed an increase over the last decades. The lugworm *(Arenicola marina)*, a characteristic species of sandy substrates, and a species that was not fully covered by the monitoring programme, appears to have vanished from the Dollard bay, including the Heringsplaat during recent years (Dollardrobben, pers. comm.).
In the tidal river there has been a very steep decline of benthic diversity, abundance and biomass during the last 20 years, mainly due to severe oxygen deficits, high SPM concentrations and fluid mud (Schuchardt et al. 1999; Bioconsult 2010).

Migratory fish encounter physical bottlenecks in the connectivity between the estuary and its tributaries and inland waters. Power plants along the borders of the estuary use large volumes of water for cooling. The use of cooling water may affect fish by impingement and by causing a temperature increaseof the water, but with the current information the impact of large-scale extraction of cooling water on fish populations cannot adequately be quantified (Jager 2010).

For the middle and outer reaches of the estuary, the ecological status of fish according to the WFD is considered moderate, for the upper reaches poor, compared with undisturbed reference conditions (Bioconsult 2009, 2010). In the upper reaches the species composition still resembles the reference conditions, but a number of diadromous species are missing and the abundance and biomass of most other species are severely reduced. The abundance of typical indicator species is at a very low level.

FISH

The functioning of the Ems estuary for the fish community has been reviewed by Jager (in: Essink & Esselink, 1998), Jager et al. (2009a), Schuchardt & Scholle (2009), Vorberg et al. (2005), Jager et al. (QSR 2009b), Bolle (2009). The Demersal Fish Survey has since 1970 been carried out in the Wadden Sea, including part of the Ems estuary, and since 2006 there is a systematic bi-annual fish monitoring for WFD requirements.

In the tidal river all species clearly encounter unfavourable conditions in summer (see also fig. 8). For the typical estuarine species such as Smelt *(Osmerus eperlanus)* and Twaite Shad *(Alosa fallax)* there is no successful reproduction, as was revealed by a pilot study on Smelt (Scholle et al. 2007). There is no suitable spawning habitat available and the conditions for larval survival are unfavorable. Poor water quality is the main problem (periods of anoxia, extremely high concentrations of suspended matter, fluid mud).

In the middle and outer reaches the situation is less deteriorated. Here is no temporal trend present in the number of species or ecological guilds, but there are negative trends in abundance for a selected group of species over the last two decades. The mechanisms behind these developments are only to some extent understood. Some species, such as Dab *(L.limanda)* and Common sole *(Solea solea)*, have decreased in the Ems estuary but also in other subareas of the Wadden Sea (Jager et al. 2009b).

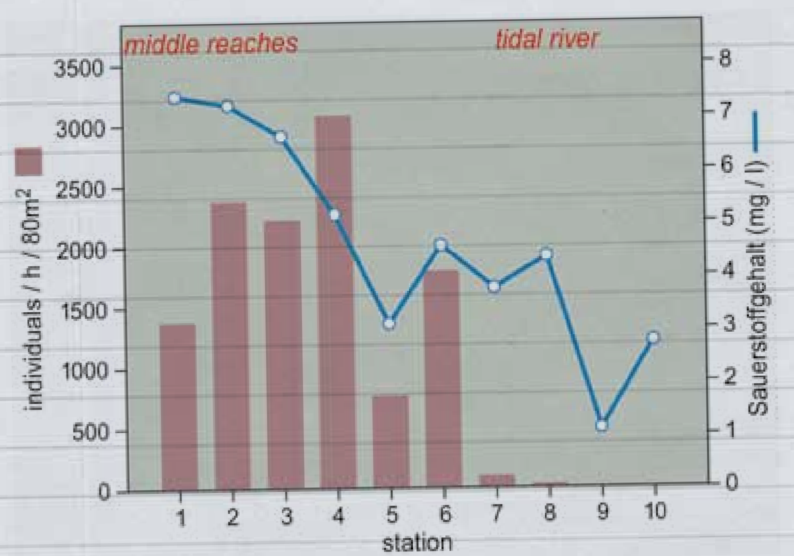
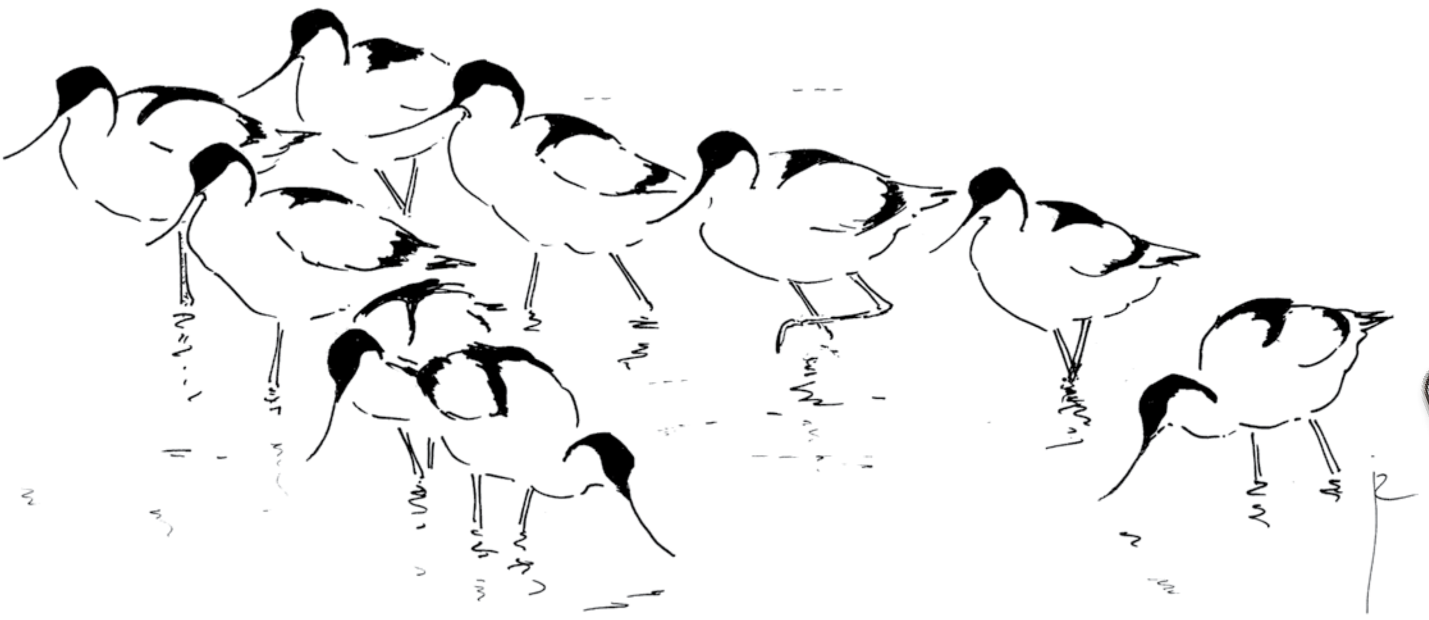


Fig. 8 Densitiy of fish (Individuals/hour/80m² net area) and mean concentration of oxygen [mg/l] in the Ems estuary (middle and upper reaches; (station 8: Leda, a tributary) in autumn 2006 (BIOCONSULT 2006). The stations 1 -10 are: Rysum, Wybelsum, Emden, Petkum, Terborg, Jemgum, Leer, Leda, Weener and Papenburg, respectively.



BIRDS

Recent information for numbers and trends of breeding and staging birds is given in Aarts et al. (2008) and Liefting et al. (2011) for the outer and middle reaches. Data for the Dollard and areas around the tidal river are given in Gerdes (2000) and Prop et al. (1999). Specific reviews with recent data for the Dollard are in preparation, but for the upper Ems estuary the available information is scattered in data reports (pers. comm. J. Prop and K. Gerdes).

In the outer Ems, as well as in the middle reaches, about three of the species with conservation objectives decrease, the remainder is stable or increases over the last 30 years until 2005 (Aarts et al. 2008). The problems for these species in decline are related to their food sources (Eider, Oystercatcher) or availability of suitable nesting habitat (Common tern). In general, birds do not require special concern in this part of the estuary.

A typical species for the Dollard, the Avocet *(Recurvirostra avocetta)*, declined until 1997 but increased again over the last decade (pers. comm. J. Prop and K. Gerdes). The trends in the Avocet population relate to the recovery of the Dollard after the sanitation, and present numbers may be more natural than those in the past. Interestingly, the Knot showed a marked increase as of 2005, in great contrast to the remainder of the Dutch Wadden Sea, but parallel to the observed local increase in *(M. balthica)*, its main food source. The Spotted redshank *(Tringa erythropus)* and Redshank *(T. totanus)* increased until 1995 because of the recovery to the more natural conditions in the Dollard (Prop et al. 1999). More recent figures indicate, however, that both species are currently in decline again (pers. comm. K. Gerdes).

The current problems in the tidal river estuary relate to the breeding birds in the foreland, such as harriers, passerines and meadowbirds. Part of the breeding habitat declined in quality because of intensive use by agriculture, not directly related to changes in the river. With regard to the changes in morphology and hydrology, there is concern for the effects of soil erosion, the disposal of dredged material, more frequent flooding and artificial prolonged flooding during the so-called 'Sommerstau' on the breeding success and the availability of suitable breeding habitat (pers. comm. K. Gerdes and H. Kruckenberg). The effect of 'sommerstau' needs to be judged in relation to the impact of storm tides. Storm tides may, in themselves, occur nowadays more frequently during the breeding season than in the past, given the current morphology and changes in sea level and climate. It is unclear to what extent these processes are currently being studied in the tidal river region, but van der Pol et al. (2010) showed that natural summer flooding is nowadays happening more often in the Wadden Sea.

MAMMALS

Available information on marine mammals in the Ems estuary is reviewed in Brasseur (2007), Reijnders et al. (2009) and Brasseur et al.(2010). Distribution and numbers of sea mammals are monitored annually by aerial counts during summer. In 2008 intensive additional monitoring of sea mammals started to evaluate the impact of the Eemshaven projects. The numbers of seals and harbour porpoises have increased over the past decades. The Ems estuary currently houses ca. 2000 Common seals *(Phoca vitulina)* and the main haul outs are on the Hond-Paap and in the Dollard. The harbour porpoise *(Phocoena phocoena)* is regularly observed in the Ems estuary, but no quantitative information is available. The Grey seal *(Halichoerus grypus)* recently colonised the Ems estuary and is mainly found near Borkum in the outer estuary. .The population developments may be hindered by human disturbance (dredging, construction, pile driving and recreation) and the limited availability of fish as a food source. Gaps in knowledge are identified in Brasseur (2007) and are related to the role of the Ems for Common seals, and the interaction between the Dollard and the remainder of the estuary.

Fish otters *(L. lutra)* have in the past inhabited the upper reaches of the Ems, but are absent now (Krüger 2006). Nowadays the river habitat has most likely become unsuitable for otters given their hunting technique. The local dissapearance, however, occured before the major changes in the upper reaches of the Ems took place and are assumed to be caused by general habitat destruction, environmental pollution and severe persecution in the past (Krüger 2006).

3.5 CURRENT & FURTHER RESEARCH

GAPS IN KNOWLEDGE

Almost every study identifies gaps in the knowledge, some at very detailed levels (Jager et al. 2009a; de Jonge & Brauer 2006; Talke & de Swart 2006), others more along general lines (NLWKN unpublished; RWS 2009; Oost & Lammerts 2007).

The most important gap is:

1) the lack of the precise quantitative understanding of the development of the estuary from the river in the 1950s to its current turbid state. This will also be a prerequisite for the planning of restoration measures (see below).

Other prominent gaps are, without being exhaustive:

2) What caused the decline of seagrass at the Hond-Paap after 2004?
3) What are the effects of sommerstau on breeding birds?
4) What are the changes of the macrobenthos distribution in the Dollard bay after the 1985 survey by Essink and co-workers; to what extent has the lugworm dissappeared from the bay and what is the possible explanation?
5) What is the relation between turbidity, functional composition of phytoplankton and primary production?
6) With regard to fish: the effects of cooling water extraction, the current functioning of the Dollard for reproduction and the population developments in shrimp, which is food for demersal fish.

CURRENT MONITORING AND RESEARCH

The available information is constantly being updated. Jager et al. (2009a) provide an entire chapter to describe the available data, ongoing monitoring and current research programmes per 2009. One recent study programme, that started after 2009, focusses on the above mentioned relationship between turbidity and primary production (van Maren pers. comm.). Additional data are currently collected within the framework of planning procedures for further deepenings. After a period of strong reductions in the Dutch monitoring efforts (de Jonge et al., 2006) the attention for it has been strongly increased over the last years. There is a lack of integrating the different programmes from an ecosystem perspective as e.g. suggested by de Jonge et al. (accepted). A comprehensive and integrated approach is required, in which proper hypotheses about the functioning of the ecosystem are tested, and state-of-the art models are developed, using carefully measured data. For this it is suggested to link the existing efforts in the area in order to optimise the results.

4 Summary of ecological constraints

In the above sections we have highlighted the essential trends with regard to ecology and hydromorphology. We have distinguished different regions within the estuary because they are ecologically and functionally different. We will now summarize the main problems, specifying to which region they mostly apply and confront these with what we described for the natural reference situation in chapters 2 and 3. This will allow us to focus in the next chapter on options for improvement.

4.1 TIDAL RIVER

Some of the ecological deficits are the most conspicuous in the upper reaches. This region showed strong degradation over the last 20 years, also in comparison to other estuaries such as Weser, Elbe and Eider (Schuchardt et al. 2007).

1) A large zone of the tidal river Ems is dominated by extremely high concentrations of suspended matter (and associated organic material), resulting in prolonged periods of severe oxygen deficiency over distances varying from 15 – 25 km;
2) The quantity and quality of estuarine habitats in the upper reaches is limited for several reasons;
3) Smelt, Twaite shad and related species of fish encounter no suitable spawning habitat and unfavorable conditions for larval recruitment in the upper estuary;
4) The benthic community is extremely deteriored with respect to species number, abundance and biomass;
5) Due to deteriorated light conditions, primary production per unit area is suppressed in the tidal freshwater reaches. At the estuary level this is a relatively small effect, since the surface area of the tidal freshwaterzone is small.

In a natural reference situation, the zone with high turbidity (MTZ) is much smaller and located closer to the mouth of the river, i.e. near Emden. In that reference state there are no oxygen deficiencies and fish can reproduce and migrate freely. The characteristic diadromous fish species would be present again and the area and quality of estuarine habitats is significantly higher than nowadays. We suggest a target state that closely approaches this natural reference.

4.2 MIDDLE REACHES AND DOLLARD

In the middle reaches there is much reason for concern about turbidity and a decreasing bed elevation due to gas exploitation, the vulnerability of the seagrass-beds, changes in the macrobenthos, and declining fish-stocks. The apparent disappearance of the lugworm from the Dollard bay may be related to the presence of large amounts of fine material in the system. Apart from the increased turbidity, there are several other threats that can be identified. For example, the large scale withdrawal of cooling water and discharge of warm effluent. The possibilities for migration between the Dollard and the catchment area are still far from optimal. It is also clear that hydrodynamic properties of the gullies have changed due to dredging. Essentially, the estuary is close to a one-channel system at the moment. The situation may not be as alarming as it is in the tidal river, but the problems are interrelated and need urgent attention and proper action.

In the natural reference situation there would be a multi-channel system, an open connection between Dollard and Westerwoldsche Aa, reduced turbidity (supposedly leading to a somewhat higher primary production plus increased biodiversity) and, as a result, improved conditions at higher trophic levels. The restoration of an open connection between Dollard and Westerwolsche Aa, however, must be considered unachievable, because of the past developments of land subsidence in the hinterland and rising water levels in the estuary. A realistic target for restoration could be an optimization of possibilities for fish migration at the outlet sluice.

4.3 OUTER REACHES

Although less severe than in the tidal river, the outer reaches have also been confronted with an increase in turbidity. But the surface of the outer reaches is much larger. And light is limiting the growth of algae in the outer reaches. Therefore, the predicted effects of increased turbidity on primary production are large. Also in the outer reaches there is large scale withdrawal of cooling water and discharge of warm effluent. The main problems in this region are therefore:

6) Reduced primary production due to increased turbidity.
7) The withdrawal of cooling water, which negatively affects fish.

The primary production in the natural reference state is suggested to be much higher (maybe 100 - 200% more, *see § 3.4*) than at present. If a target reference state is chosen by which light conditions in the outer region improve, this can be expected to have profound effects on the entire estuarine food-chain.

4.4 GENERAL ECOLOGICAL CONSTRAINTS

Some of the main ecological constraints are generally valid and have consequences for each of the regions. These are the following:

8) The input of nutrient loads and hazardous substances that are generally declining, but still above desired levels;
9) The diffuse and cumulative impact from disturbance by human activity; and
10) the barriers for migration between marine and fresh water

4.5 FOCUS ON FUNDAMENTAL PROBLEMS

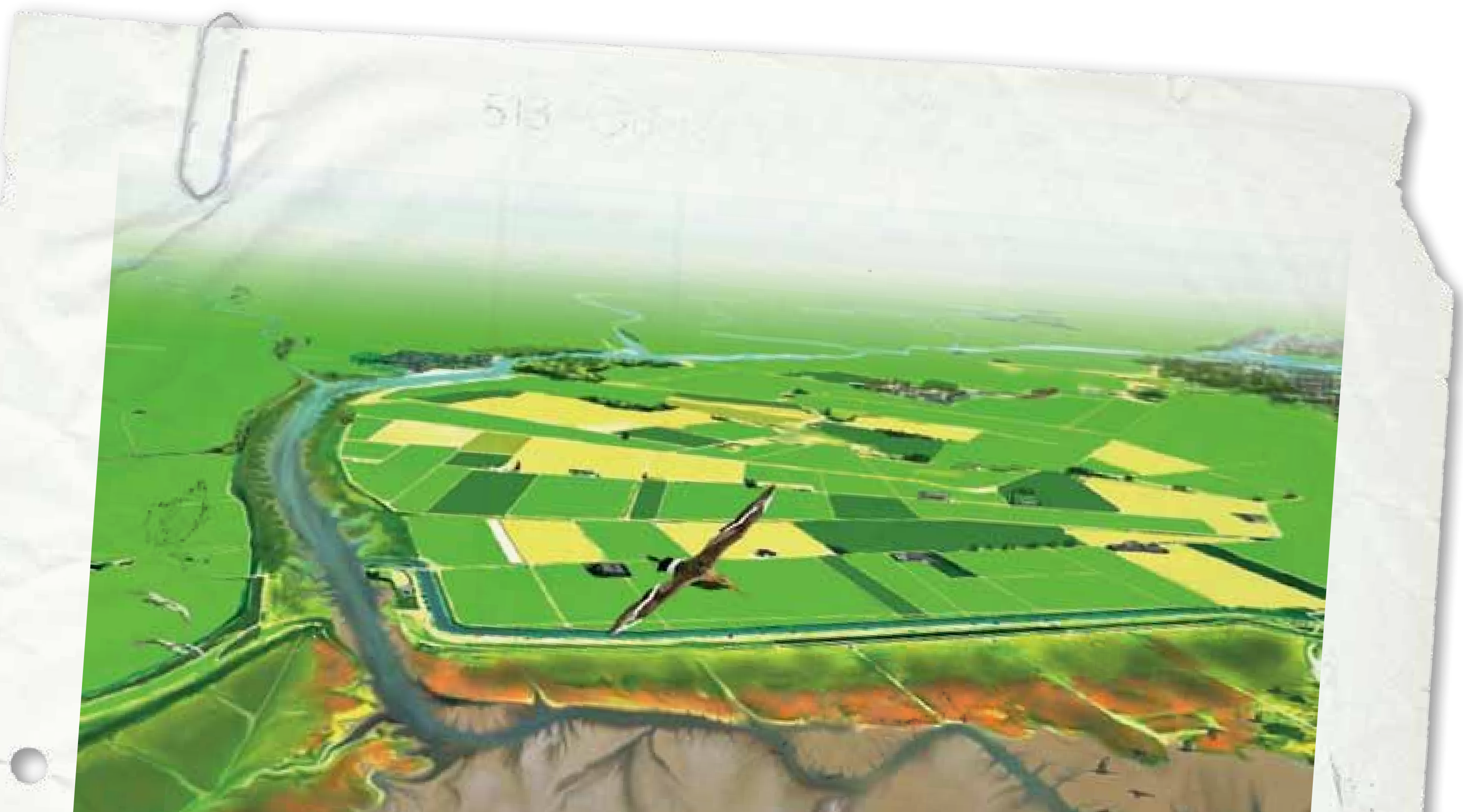
Although we have specified what problems apply to which region mostly, we need to emphasize that the regions are dependent on each other. As pointed out in the next chapter, it is considered feasible to act in one region in order to improve the ecological conditions in others. The ecological constraints are multicausal and require different sets of actions. Core problems however are the strongly artificial morphology of the estuary and the related phenomenon of 'tidal pumping'. They affect the water quality and the quality of the estuarine habitats in such a way that they can be considered as 'fundamental'. We will therefore limit our scope for restoration to options associated with these problems.

5 Current options for ecological improvement

The ecological state of the entire Ems estuary is poor and for the tidal river proper often being judged as 'alarming'. There are quite a number of planned developments in the region (listed in Jager et al. 2009a), meaning that the current trend of increased human impact is likely to continue. Various EU-Directives demand improvement of the Ems estuary ecosystem. These and other rationale to try and resolve, or mitigate, the constraints are discussed in de Jonge (2009). In this chapter we present measures that are expected to affect the essential symptoms of, or mechanisms behind, the ecological problems of the estuary. In the previous chapter we have argued that the core problems are found in the oxygen deficiencies (tidal river) and the increased turbidity (entire estuary). These are caused by the strongly artificial morphology of the estuary and the related phenomenon of 'tidal pumping'.

5.1 CURRENT OPTIONS

With regard to ecological restoration many options for intervention are at hand, put forward or reviewed Kuijper & Lentz (2011), Schuchardt et al. (2009), Schuttelaars et al. (2011), van der Welle & Meire (1999), with additional ideas put forward as personal comments by A. Oost, D. Post and W. Rodiek *(see table 2)*. For a thorough understanding of each of these, one needs to revert to the sources mentioned. The proposals listed in table 2 have all been selected to affect water quality. The mechanism by which they are expected to achieve this may differ in detail, but essentially they all affect the tidal characteristics. The majority of options mentioned require implementation in the upper estuary or beyond, but some have been formulated for the outer and middle reaches (options 4, 7 and 8). Some proposals seek to influence the ultimate cause, others mitigate the consequences. We decided to give each option an expert judgement (indicated with plusses and minuses) as an indication whether or not its implementation would bring the system in the direction towards of a more natural reference state and what the magnitude of the effect on the biological problem could be. However, for a proper assessment not enough is known about the different options and their consequences. For some of these options (and some others) in short time a detailed analysis and comparison shall be performed by German authorities (Claus, pers. comm).



There is a class of options that may have a considerably positive effect on the biological problem, but which push the system further away from a natural reference situation. For example the options which manipulate the tides upon entrance at the tidal river (table 2, options 1 and 2) or which block the tidal influence all-together (3). All three are strongly directed at the symptoms of the problem, but at the price of an even more altered estuary.

There are also options that try to influence essential processes, but which are not obviously consistent with the natural reference. They also do not interfere with the ultimate cause. These options are (4) creation of shallows in the North Sea coastal zone adjacent to Hohes Riff, (5) a tidal basin, (6) lowering of forelands and (7) a reduction of the width of the shipping lane.

Finally there is a class of options that act upon the real causes and these will thus most likely move the Ems estuary towards a more natural reference state. These are (8) restoration of a two gully system, (9) opening of summerdikes, (10) vegetation development, (11) moving backwards the main dike, (12) moving the weir upstream from Herbrum, (13) reconnecting old river meanders or tributaries, and (14) reduction of the depth of the waterway.

AN INVENTORY, NOT A CONCLUSION

For all of the proposals one need to realize that the magnitude of the effects will depend on the location and scale of implementation. Most options have consequences for the dimensions of the system. With regard to the length of the estuary (moving the weir up- or downstream) an appropriate scale would be ten(s) of kilometers and the same holds for narrowing the shipping lanes in the outer estuary. With regard to the enlargement of the estuary (moving dikes) the scale is probably hundreds of square kilometers (A. Oost pers. comm.). Finally, with regard to the depth, the changes in the system have occurred in response to a deepening of several meters. Such is therefore the scale over which a relevant restoration would take place.

Providing a clear definition of each measure with regard to these aspects of location and scale is beyond the scope of this document. Any attempt to quantitatively rank these options would thus be in vain. Criteria against which these options should be judged have been suggested by (Schuchardt et al. 2009). The relevant criteria for our purpose are: 1) the reduction in tidal pumping, 2) the improvement of the oxygen availability, and 3) the restoration of estuarine gradients. In order to make an integral objective assessment one also needs to consider 4) other effects on the aquatic ecosystem, 5) contribution to the objectives of Natura 2000 and Water Framework Directive plus the possible spin off to the Marine Strategy Framework directive, 6) climate robustness and 7) potential conflicts with implementation. Of course, 8) economical costs and benefits (estuarine goods and services) and 9) national safety regulations should not be disregarded. As yet, no such integral assessment of the effectiveness of each option in relation to these criteria has been made. But models for doing so are being constructed in research programmes by WWF-DE and RWS/Deltares (Dijkstra et al. 2011; WWF 2010). Clearly not all of these options can or should be worked out fully. We believe this expert judgment could be taken one step further. A further prioritization should be made using input from stakeholders and policymakers in public debate with scientists.

Number	Option	within or outside current estuary/river	Region	Source	Motivation and mechanism	Magnitude of effect on ecological problem (sediment & oxygen)	In the direction of a natural reference	Remarks
1	Manipulation of tides with the Ems storm surge barrier	in	upper	Post, pers. comm.	aims to reduce flood current speeds, withholds sediments	+ +	– –	
2	Construction of 'sohlschwelle'	in	upper	Rodiek, pers. comm.	Increase hydraulic roughness near the storm-surge barrier	+ +	– –	
3	Build a weir downstream (Dauerstau)	in	upper	Schuchardt et al. 2009	for example a sluice and a weir at kloster Muhde. Blocks tidal influence, shortens the river.	+ +	– –	
4	Creation of shallows in the North Sea coastal zone adjacent to Hohes Riff	out	outer	de Jonge, pers. comm.	Minor damping of the incoming tidal energy which will lead to amplified effects on the hydraulics of the river Ems	+	0	
5	Tidespeicherbecke/, tidal basin	out	upper	Schuchardt et al. 2009/ Winkel, pers comm.	Extra waterbody upstream, remove main dike and lower the ground level	+	0	
6	Lowering of forelands	in	upper	van der Welle & Meire 1999; Schuchardt et al. 2009	Increases tidal habitat that produces oxygen	+	0	
7	Reduce width of shipping lane	in	outer/middle	Oost, pers. comm.	Increase hydraulic roughness in outer estuary over multiple kilometers	+ +	0	
8	Restore two gully system	in	outer	Oost, pers. comm.	Increases hydraulic roughness	+	+	
9	Opening of summerdike	in/out	upper	Schuchardt et al. 2009; van der Welle & Meire 1999	reduce tidal pumping & enhance oxygen production	+	+	
10	Vegetation development	in	upper	Welle & Meire 1999	mudflats, marshes, galley forests increase hydraulic roughness	0	+	
11	Moving backwards the main dike	out	upper-middle	Schuchardt et al. 2009; Welle & Meire 1999	Enhance ebb currents, enlarge area of estuarine habitat	+ +	+ +	conflicts with present landuse
12	Move the weir upstream from Herbrum	out	upper	Schuttelaars et al 2011	Lengthens the River	+ +	+	conflicts with Natura 2000 upstream
13	Reconnect old river meanders or tributaries	out	upper	Schuchardt et al. 2009; Welle & Meire 1999	Increase hydraulic roughness, enlarge area of estuarine habitat	+ +	+ +	conflicts with shipping
14	Reducing depth of waterway	in/out	upper	Schuchardt et al. 2009; Hutzenlaub, 2009	With or without a parallel shipping channel, acts upon ultimate cause. The upper Ems can redevelop its natural dimensions.	+ + +	+ +	permanent solution at high economic cost

Tabel 2 List of current proposals for ecological improvement in the Ems estuary that affect the core problem of water quality. For each option it indicated whether it can be implemented within the boundaries of the current estuary or outside, to what region of the estuary it applies (see fig. 1), and what the motivation is behind the option. A quantitative ranking of options is beyond the scope of this paper, but we have tentatively indicated the expected relative magnitude of effect on the biological problem and to what extent it would bring the system towards a more natural reference state (+++ = strong effect, 0 = no effect, --- = strong negative effect).

5.2 SYNTHESIS

The current paper reviewed available knowledge about estuarine functioning of the Ems. The main ecological constraints have been indentified in chapters 3 and 4. The core problems are caused by the strongly artificial morphology of the estuary, that has developed under human influence over long temporal and and large spatial scale. These changes in morphology acted upon the water movements and the sediment transport and have resulted in severe changes in the functioning of this ecosystem. The current ecological situation differs strongly from what is known about a natural reference situation. Especially the high levels of turbidity, the regular oxygen deficiencies in parts of the tidal river and the limited quantity and quality of estuarine habitats provide reason to act.

There are gaps in knowledge, of course. They relate, for example, to detailed questions about the actual role of the different mechanisms behind the observed changes in tidal range, turbidity or species presence. However, gaps in knowledge should be no excuse to try and improve the ecological situation fundamentally in practice.

As mentioned, the past man-induced changes have resulted in strong shifts of the estuarine characteristics and related functioning. In order to accomplish serious ecological improvement, and arrive at a desired target state, the potential measures need to be of sufficient scale and impact. Options for ecological improvement, which are listed in this paper, thus almost necessarily affect the system properties. Most options have consequences for the dimensions of the system.

A crucial consideration is the question: "what can be changed to the boundaries of the system"?. The answer is: basically the length, the width and the depth. Those options that move the ecosystem in the direction towards a more natural reference state are preferred above others, from an ecological point of view.

6 Literature

Aarts, B. G. W., van den Bremer, L., van Winden, E. A. J., & Zoetebier, T. K. G. (2008). Trendinformatie en referentiewaarden voor Nederlandse kustvogels. WOT-rapport 79, Wageningen: pp. 1-108.

Adolph, W. (2010). Praxistest Monitoring Küste 2008. Seegraskartierung - Gesamtbestandserfassung der eulitoralen Seegrasbestände im Niedersächsischen Wattenmeer und Bewertung nach EG-Wasserrahmenrichtlinie. NLWKN Küstengewässer und Ästuare 2/2010. Norden: pp. 1-52.

Bakker, J., Lüerßen, G, Marencic, H. & Jung, K. (2009) Hazardous substances. In de Vlas, J., Marencic, H. (Eds.), Wadden Sea Ecosystem No. 25 Quality Status Report 2009 Thematic Report No. 6. Common Wadden Sea Secretariat Trilateral Monitoring and Assessment Group, Wilhelmshafen: p. 55.

Baretta, J.W. & Ruardij, P. (1988) Tidal flat estuaries: Simulation and Analysis of the Ems estuary. Ecological studies 71. Springer Verlag.

Becker, P. H., & Dittmann, T. (2009). Contaminants in Bird Eggs. In de Vlas, J., Marencic, H. (Eds.), Wadden Sea Ecosystem No. 25 Quality Status Report 2009 Thematic Report No. 6. Common Wadden Sea Secretariat Trilateral Monitoring and Assessment Group, Wilhelmshafen: p. 12.

Belgrano, A., Scharler U. M., Dunne, J. & Ulanowicz R. E. (2005). Aquatic food webs. An ecosystem approach. Oxford University Press. 262 pp.

van Beusekom, J. E. E., & de Jonge, V. N. (1998). Retention of phosphorus and nitrogen in the Ems estuary. Estuaries 21: pp. 527-539.

van Beusekom, J., Bot, P. V. M., Carstensen, J., Goebel, J. H. M., Pätsch, J., & Reise, K. (2009). Eutrophication. In de Vlas, J., Marencic, H. (Eds.), Wadden Sea Ecosystem No. 25 Quality Status Report 2009 Thematic Report No. 6. Common Wadden Sea Secretariat Trilateral Monitoring and Assessment Group, Wilhelmshafen: p. 22.

Bezirksregierung Weser – Ems (1998). Planfeststellungsbeschluss zum Emssperrwerk und Bestickfestsetzung vom14. August 1998 in der Fassung des Planergänzungsbeschlusses. VwVfG Oldenburg.

BfG- Bundesanstalt für Gewässerkunde (2001). Bagger- und Klappstellenuntersuchungen im Ems-Ästuar Klappstellen 1 bis 7. Bericht BfG-1329. BfG Koblenz.

BfG Bundesanstalt für Gewässerkunde (2008). Umweltrisikoeinschätzung (URE) und FFH-Verträglichkeitseinschätzung (FFH-VE) für Projekte an Bundeswasserstraßen, Ausbau der Außenems. BfG-Bericht 1538 i. A. Wasser- und Schifffahrtsdirektion Nordwest. pp 165.

Bioconsult (2006). Zur Fischfauna der Unterems. Kurzbericht über die Erfassungen 2006. Report prepared for LAVES, Hildesheim, IBL, Oldenburg, Ingenieurbüro Grote, Papenburg.

Bioconsult (2009). Stow net fishery Ems 2009. Fish fauna study within the framework of water status monitoring in accordance with WFD. Report prepared for Rijkswaterstaat.

Bioconsult (2010). Biologisches Monitoring des Sommerstaus in der Tideems 2009. Untersuchungsergebnisse Makrozoobenthos und Fische. Report prepared for NLWKN Aurich.

Bioconsult (2010). Kurzbericht: Hamenbefischung Unterems 2010. Fischfaunistische Untersuchung im Rahmen der Gewässerzustandsüberwachung nach WRRL. Report prepared for LAVES, Hildesheim.

Boede (1985). Biological research Ems-Dollard estuary by a survey of the ecosystem research during 1973 and 1982. Rijkswaterstaat communications 40: pp. 1-182.

Bouma, H., de Jong, D. J., Twisk, F. & Wolfstein, K. (2005). Zoute wateren Ecotopenstelsel (ZES.1) voor het in kaart brengen van het potentiele voorkomen van levensgemeenschappen in zoute en brakke Rijkswateren. RIKZ, Middelburg.

Bolle, L. J., Neudecker, T., Vorberg, R., Damm, U., Diederichs, B., Jager, Z., Scholle, J. Daenhardt A., Lüerben G. & Mranecic H. (2009). Trends in Wadden Sea Fish Fauna Part I: Trilateral Cooperation. Report nr C108/08, Wageningen Imares, IJmuiden.

Brasseur, S. (2007). Zeezoogdieren in de Eems, cumulatieve effecten van de activiteiten rond de ontwikkeling van de Eemshaven. Imares, Wageningen. pp. 1-44.

Brasseur, S., Polanen-Petel, T. V., Geelhoed, S., Aarts, G., & Meesters, E. (2010). Zeezoogdieren in de Eems; studie naar de effecten van bouwactiviteiten van GSP, RWE en NUON in de Eemshaven in 2009. Imares, Wageningen.

Chernetsky, A., Schuttelaars, H. M. & Talke, S. A. (2010). The effect of tidal asymmetry and temporal settling lag on sediment trapping in tidal estuaries. Ocean Dynamics 60: pp.1219–1241.

Claus, B. (1998). Landerübergreifendes Schutzkonzept für die Astuare Elbe, Weser und Ems. WWF/BUND Projekt, Berlin.

Cleveringa, J. (2008). Ontwikkeling sedimentvolume Eems-Dollard en het Groninger wad. Overzicht van de beschikbare kennis en gegevens. Alkyon, Emmeloord: p. 47.
Dankers, N. M. J. A., Dijkman, E., de Jong, M., Brasseur, S. & Reijnders, P. (2005). Aantal kaarten met verspreiding van habitats en soorten in de Waddenzee ten behoeve van de Passende Beoordeling en de Strategische Milieu Beoordeling PKB-Waddenzee. Interne notitie Alterra voor Min. VROM en Min. LNV.
Degroodt, E. G., & de Jonge, V. N. (1990). Effects of changes in turbidity and phosphate influx on the ecosystem of the Ems estuary as obtained by a computer simulation model. Hydrobiologia 195: pp. 39-47.
Deneudt, K., Eck BV, Bruens A, Kuijper K, Jeuken C, Oeveren CV, Maris T, Oosterlee L, Cox T, Meire P, Ryckegem GV, Bergh EVD & Speybroeck J (2010). Evaluatiemethodiek systeemmonitoring Schelde-estuarium.
Dijkstra, J., Kessel T van, Maren B van, Spiteri C, Stolte W (2011). Setup of an effect-chain model for the Eems-Dollard.
Dyer, K.R. (1997). Estuaries. A physical introduction. John Wiley & Sons, Chichester: pp. 195.
Engels, A. (2007). Seasonal and tidal variation of oxygen and salinity in the river Ems.- presentation Ems-Workshop at Emden 23.2.2007
Erftemeijer, P. (2005). Trend analyse van zeegrasverspreiding in de Nederlandse Waddenzee 1988-2003. WL| Delft Hydraulics, Delft: p. 94.
Esselink, P. (2000). Nature management of coastal salt marshes. Interactions between anthropogenic influences and natural dynamics. PhD thesis. University of Groningen, Groningen: pp. 256.
Esselink, P., Bos, D., Oost, A. P., Dijkema, K. S., Bakker, R., & Jong, R. D. (2011). Verkenning afslag Eems-Dollardkwelders. Puccimar-rapport 02. Puccimar, Vries/Veenwouden: p. 74.
Esselink, P., Petersen, J., Arens, S. J. P. B., Bunje, J., Dijkema, K. S., Hecker, N., Hellwig, U., Jensen, A.-V., Kers, A. S., Körber, P., Lammerts, E. J., Stock, M, Veeneklaas, R. M., Vreeken, M., Wolters, M. (2009) Salt Marshes. In: de Vlas, J., Marencic, H. (eds) Wadden Sea Ecosystems No. 25 Quality Status Report 2009 Thematic Report No. 8. Common Wadden Sea Secretariat Trilateral Monitoring and Assessment Group, Wilhelmshaven, pp. 27-30.
Essink, K., Esselink, P. (1998). Het Eems-Dollard estuarium: interacties tussen menselijke beïnvloeding en natuurlijke dynamiek. RIKZ, Haren.
Fairbridge, R. W. (1980). The estuary: Its definition and geodynamic cycle. In Olausson, E. & Cato, I. (eds.) Chemistry and Biogeochemistry of Estuaries. Wiley, New York: pp. 1–35.
Gerdes, K. (2000). Die Vogelwelt im Landkreis Leer, im Dollart und auf den Nordseeinseln Borkum und Lütje Hörn. Verlag Schuster, Leer.
Geschafststelle Ems & Ministerie van Verkeer en Waterstaat (2010). Internationaler Bewirtschaftungsplan nach Artikel 13 Wasserrahmenrichtlinie für die Flussgebietseinheit Ems. Bewirtschaftungszeitraum 2010-2015, Geschafststelle Ems, Meppen: pp. 266.
Gerritsen, F. (1952). Historisch-Hydrografisch onderzoek Eems. Rapport Studiedienst, Hoorn.
Gotje, W., Cleveringa, J., Steijn, R., & P. Esselink (2007). Restoration of estuarine habitats. What determines success or failure? CHAIN Partners in Water, Voorburg.
van der Graaf, S., de Vlas, J., Herlyn, M., Voss, J., Heyer, K. & Drent, J. (2009b). Macrozoobenthos. In de Vlas, J., Marencic, H. (Eds.), Wadden Sea Ecosystem No. 25 Quality Status Report 2009 Thematic Report No. 10. Common Wadden Sea Secretariat Trilateral Monitoring and Assessment Group, Wilhelmshafen: pp. 3-27.
van der Graaf, S., Jonker, I., Herlyn, M., Kohlus J., Vinther, H. F., Reise, K., de Jong, D., Dolch, T., Bruntse, G. & de Vlas, J. (2009a). Seagrass. In de Vlas, J., Marencic, H. (Eds.), Wadden Sea Ecosystem No. 25 Quality Status Report 2009 Thematic Report No. 2. Common Wadden Sea Secretariat Trilateral Monitoring and Assessment Group, Wilhelmshafen.
Groenendijk, H. & Bärenfänger, R.(2008). Gelaagd Landschap. Veenkolonisten en kleiboeren in het Dollardgebied. Archeologie in Groningen dl. 5. Profiel Uitgeverij, Bedum: pp. 96.
Habermann, C. (2006). Einfluss von Unterhaltungsbaggerungen auf die Schwebstoffdynamik der Unterems - Monitoring während eines baggerungsfreien Zeitraums. Bundesanstalt für Gewässerkunde, Bericht BFG-1488, Auftraggeber BfG-JAP-Nr. 3 Vol. 1. Emden: pp. 45
ten Hallers-Tjabbes, C. (2006). Impact and interaction of contaminants in the Ems-Dollard estuary ecosystem. Cato Marine Ecosystems, Kantens.
den Hartog, C. D., & Polderman, P. J. G. (1975). Changes in the seagrass populations of the Dutch Waddenzee. Aquatic Botany 1: pp. 141-147.
Helder, W. & Ruardij P (1982) A one-dimensional mixing and flushing model of the Ems-Dollard estuary: calculation of time scales at different river discharges. Neth. J. Sea. Res. 15: pp.293-312.

Herman, P. M. J., de Jonge, V. N., Dankers, N, Ens, B. J., Wolff, W. J., Brinkman, B. J., Baptist, M., van Leeuwe, M. A., Bakker, J. P., Philippart, C. J. M., Kromkamp, J., van Beusekom, J., van Katwijk, M. M., Piersma, T., van der Veer, H. W., Lammerts, E. J., Oost, A. P., van der Meer, J., Lindeboom Olff, H. H. J. & Jansen, G. (2009). (Natuur) behoud in een veranderende wereld. Position paper ecologie. Waddenacademie, Leeuwarden.

Herrling, G., Knaak, H., Kaiser, R. & Niemeyer, H. D. (2001). Evaluation of design water levels at the Ems-Dollard estuary considering the effect of a storm surge barrier. In Coastal Engineering 2010: pp. 1-10.

Herrling, G. & Niemeyer, H. D. (2006). Long-term Spatial Development of Habitats in the Ems-Dollard Estuary.

Herrling, G. & Niemeyer, H. D. (2008). Comparison of the hydrodynamic regime of 1937 and 2005 in the Ems-Dollard estuary by applying mathematical modeling. HARBASINS report.

van den Hoek, C., Admiraal, W. Colijn, F., de Jonge, V.N., (1979). The role of algae and seagrasses in the ecosystem of the Wadden Sea: A review, p. 9-118. In: W.J. Wolff (ed.) Flora and vegetation of the Wadden Sea, Stichting Veth tot steun aan waddenonderzoek, Leiden.

van 't Hof, P. M. J. (2006). Lange-termijn trends van fauna en biotopen in het Eems-Dollard gebied. Alterra, Texel.

Hutzenlaub, N., Baatar, U., Lasisz, K., Napiorkowski, M., Nielsen, J. K., Reijbroek, A., & Schuett, M. (2009). Spatial Planning at Sea: The Ems-Dollard Area Spatial Planning at Sea: The Ems-Dollard Area. Wageningen University.

IBL (2009). Lebenraumtypenerfassung und bewertung fuer die FFH-gebiete 173, 002 (nordlicher teil) und Erweiterungsflache 002 E.

Jager, Z. (1999). Visintrek Noord-Nederlandse kustzone. RIKZ, Haren: p. 37.

Jager, Z. & R. Vorberg (2008). Effecten van de door Nederland voorgenomen ontgrondingen en verspreiding van baggerspecie in de Eems op garnalen en vis. Literatuurstudie in opdracht van RWS Waterdienst. ZW Rapport 0801.

Jager, Z., van Maren, B., Spiteri, de Kok, van Weesenbeeck, Los & Nauta (2009a). Required modelling development to support the future management of the Ems-Dollard. Plan of activities. Deltares & ZiltWater Advies/Fotografie.

Jager, Z., Bolle, L., Dänhardt, A., Diederichs, B., Neudecker, T., Scholle, J. & Vorberg, R. (2009b). Fish. In de Vlas, J.& Marencic, H. (Eds.), Wadden Sea Ecosystem No. 25 Quality Status Report 2009 Thematic Report No. 14. Common Wadden Sea Secretariat Trilateral Monitoring and Assessment Group, Wilhelmshafen.

Jager, Z. (2010) Position paper on the sustainable use of cooling water from the Wadden Sea. Leeuwarden.

de Jong, J. (2006). Habitat Maps Ems Estuary and Historical Habitat Change HARBASINS report. Ecca advies, Assen: pp. 31.

de Jonge, V. N., (1983). Relations between annual dredging activities, suspended matter concentrations and the development of the tidal regime in the Ems estuary. Can. J. Fish. Aquat. Sci 40: pp. 289–300.

de Jonge, V. N. (1992). Tidal flow and residual flow in the Ems estuary. Estuarine Coastal Shelf Sci. 34: pp. 1-22.

de Jonge, V. N., (1995). Wind driven tidal and annual gross transports of mud and microphytobenthos in the Ems estuary, and its importance for the ecosystem. In Dyer, K. R. & D'Elia, C. F. (eds.). Changes in fluxes in estuaries: pp.29-40.

de Jonge, V.N., (2000). Importance of temporal and spatial scales in applying biological and physical process knowledge in coastal management, an example for the Ems estuary. Continental Shelf Research 20: pp. 1655-1686.

de Jonge, V. N., (2007). Toward the application of ecological concepts in EU coastal water management. Mar. Poll. Bull. 55: 407-414.

de Jonge, V. N., (2009). Water management in the Netherlands: development from a defensive to an integral water system approach. p. 17-46. In: Folmer, H. & Reinhard, S., (eds). Water Problems and Policies in The Netherlands. RFF-PRESS, Boca Raton, 257: pp. 17-46.

de Jonge, V.N., van den Bergs, J., de Jong, D.J., (1997). Zeegras in de Wadden¬zee, een toekomstperspectief. RIKZ-97.016; ISSN 0927-3980, 36 p.

de Jonge, V.N. & van Beusekom, J.E.E., (1992). Contribution of resuspended microphytobenthos to total phytoplankton in the Ems estuary and its possible role for grazers. Neth. J. Sea Res., 30: 91- 105.

de Jonge, V. N.& van Beusekom, J. E. E., (1995). Wind and tide induced resuspension of sediment and microphytobenthos from tidal flats in the Ems estuary. Limnol. Oceanogr. 40: pp. 766-778.

de Jonge, V. N. & Brauer, V. S. (2006). The Ems estuary - Changes in functioning and structure of a system under pressure.

de Jonge, V. N. & Essink, K. (1991). Long-term changes in nutrient loads and primary and secondary production in the Dutch Wadden Sea. In: Estuaries and coasts:spatial

and temporal intercomparisons. Olsen&Olsen International Symposium series. pp 307-316.
de Jonge, V. N., Kolkman, M. J., Ruijgrok, E. C. M. & de Vries, M. B., (2003). The need for new paradigms in integrated socio-economic and ecological coastal policy making. Proceedings of 10th International Wadden Sea Symposium. Ministry of Agriculture, Nature Management and Fisheries, Department North, Groningen: pp. 247-270.
de Jonge, V. N., Pinto, R. & Turner, R. K., (accepted). Integrating ecological, economic and social aspects to generate useful management information under the EU Directives. Ecosystem Approach. Ocean & Coastal Management (to be published in 2012).
de Jonge, V.N. & Postma H. (1974). Phosphorus compounds in the Dutch Wadden Sea. Neth. J. Sea Res. 8: pp. 139-153.
Kornman, B. A. & De Deckere, E. M. G. T. (1998). Temporal variation in sediment erodibility and suspended sediment dynamics in the Dollard estuary. In Sedimentary Processes in the Intertidal Zone (Black, K. S., Paterson, D. M. & Cramp, A., (eds)). Geological Society London Special Publications 139: pp. 231–241.
Kuijper, K., & Lentz, K. (2011). KPP: Deltaprogramma Wadden Quickscan Beïnvloeding Stormvloedhoogte Eems - Dollard Projectvoorstel. Delft: p. 32.
Krüger, H.-H. (2006). Fischotter Lutra lutra Der heimliche Rückkehrer. Ökoporträt 42 NVN/BSH: pp. 1-8.
de Leeuw, C. (2006). Verkenning van de ecologische problemen en knelpunten in het Eems estuarium. Een wetenschappelijke onderbouwing van de problematiek van het Eems-Dollard estuarium op het gebied van de ecologie. Rapport in opdracht van het Rijksinstituut voor Kust en Zee/RIKZ.
Levinton, J.S., (2001). Marine Biology. Function, biodiversity, ecology. Oxford University Press: pp. 515.
Liefting, M., Hallmann, C. & Ens, B. J. (2011). Trendontwikkeling van vogels in het referentiegebied Rottum en andere deelgebieden in de Waddenzee. Beek-Ubbergen.
Maren, D.S. van (2010). Eems-Dollard model setup: sediment transport module. Deltares report 1200739: p. 165.
McLaren, P., Steyaert, F. and Powys, R. (1998). Sediment transport studies in the tidal basins of the Dutch Waddenzee. Senckenbergiana maritima, 29 , pp. 53–61.
McLusky, D.S. (1981). The estuarine ecosystem. Blackie & son/Furnival House, Glasgow/London.
McLusky, D.S. & Elliott M, (2004). The estuarine ecosystem. Ecology, threats and management. Oxford University Press: pp. 214.
Merckelbach, L. M., & Eysink, W. D. (2001). Trendanalyse zwevend stof in Eems estuarium in relatie tot aanslibbing haven Delfzijl. WL Delft/Delft hydraulics, Delft: pp. 57.
Mulder, H. P. J. (2004). Dumping in the Ems estuary: an overview of effects and developments. RIKZ, Haren: pp. 10.
Mulder, H. P. J., & Mijwaard, B. (1997). Een methode om een twee-dimensionale sedimentbalans te maken, gebaseerd op meetgegevens met gebruikmaking van een GIS en toegepast op de Eems-Dollard voor de periode 1985-1990. RIKZ, Haren.
NAM (2010). Bodemdaling door Aardgaswinning. NAM-gasvelden in Groningen, Friesland en het noorden van Drenthe. Groningen.
NLWKN (unpublished). FGE-Ems Informations- und Anhörungs-dokument zu den wichtigen Wasserbewirtschaftungsfragen Die Ems.
NLWKN (2010). Flussgebietseinheit Ems Fördergebiet und Ökologische Bewertung der Wasserkörper nach WRRL.
Oost, A. & Lammerts, E. J. (2007). Het tij geleerd. achtergrondrapport. Gezamenlijke onderzoeksinstellingen en natuurorganisaties, Groningen/Utrecht.
van Leussen, W., 1994. Estuarine macroflocs and their role in fine-grained sediment transport, Ph.D. Thesis, Dept. of Earth Science, Utrecht University, 1994.
van de Pol, M., Ens, B. J., Heg, D., Brouwer, L., Krol, J., Maier, M., Exo, K.-M., Oosterbeek, K., Lok, T., Eising, C. M. & Koffijberg, K. (2010). Do changes in the frequency, magnitude and timing of extreme climatic events threaten the population viability of coastal birds? Journal of Applied Ecology, 47(4): pp. 720-730.
Postma, H., (1954). Hydrography of the Dutch Wadden Sea. Arch. Néerl. Zool. 10:pp. 405-511.
Postma, H., (1960). Einige Bemerkungen über den Sinkstofftransport im Ems-Dollard Gebiet. In JH van Voorthuysen: Das Ems-Estuarium. Verh. Kon. Ned. Geol. Mijnb.k. Gen. 19: pp. 103-110.
Postma, H., (1961). Transport and accumulation of suspended matter in the Dutch Wadden Sea. Neth. J. Sea Res. 1: pp. 148-190.
Prop, J., Esselink, P., Hulscher, J., Dollard, V. (1999). Veranderingen in aantallen vogels in de Dollard in relatie met lokaal en regionaal beheer. De Grauwe Gors 27.
Raad voor de Wadden (2010). Eems-Estuarium: van een gezamenlijk probleem naar een gezamenlijke oplossing = Ems-Ästuar: vom gemeinsamen Problem zur gemeinsamen Lösung. Leeuwarden.

Reuter, M. (2000): Brutvögel des Emsästuares zwischen Leer und Emden. in: Köppen, Hartwig & Ludwigkowski (ed) 2. Deutsches Seevogel-Kollogquium. - Seevögel 21 Sonderband 2-2: 33-38

Reijnders, P. J. H., Brasseur, S. M. J. M., Borchardt, T., Camphuysen, K., Czeck, R., Gilles, A., Jensen, L. F., Leopold, M., Lucke, K., Ramdohr, S., Scheidat, U. M.S. & Teilmann, J. (2009). Marine Mammals. In Marencic, H. & de Vlas, J. (Eds.), Wadden Sea Ecosystem No. 25 Quality Status Report 2009 Thematic Report No. 20. Common Wadden Sea Secretariat Trilateral Monitoring and Assessment Group, Wilhelmshafen.

Ribbius, F.J., (1961). The biggest waste problem in the world. Land en Water 5: p 24.

RWS, Ministerie van Verkeer en Waterstaat. (2009). Stroomgebiedbeheerplan Eems Den Haag: pp. 212.

Samu, G., (1979). Die morphologische Entwicklung der Außen-Ems von Dukegat bis zur See. Bundesanstalt für Wasserbau, Hamburg, 43 pp.

Scholle, J., Schuchardt, B, Schulze, S. & Veckenstedt, J. (2007). Situation of the smelt (Osmerus eperlanus) in the Ems estuary with regard to the aspects of spawning grounds and recruitment.

Schrottke, K., & Bartholomä, A. (2008). Detaillierte Einblicke in die ästuarine Schwebstoffdynamik mittels hochauflösender Hydroakustik. Tagungsband zum Seminar Ultraschall in der Hydrometrie: neue Technik; neuer Nutzen !?. Bundesanstalt fur Gewasserkunde, Koblenz: pp. 75-82.

Schuchardt, B. & Schirmer, M. (1991). Phytoplankton maxima in two coastal plain estuaries.- Est. Coast. Shelf Sci. 32: pp. 187-206.

Schuchardt, B. (1995). Die Veränderung des Tidehubs in den inneren Ästuaren von Eider, Elbe, Weser und Ems. Ein Indikator für die ökologische Verformung der Gewässer.- Naturschutz und Landschaftsplanung 27 (6): pp. 211-217.

Schuchardt, B., Schirmer M, Janssen G, Nehring G, Leuchs H., (1999) Estuaries and Brackish Waters.- In: F. de Jong et al. (eds.), Wadden Sea Ecosystem No. 9. Quality Status Report 2009. Common Wadden Sea Secretariat Trilateral Monitoring and Assessment Group, Wilhelmshafen: pp. 175-186.

Schuchardt, B., Scholle, J., Schulze, S. & Bildstein, T. (2007). Vergleichende Bewertung der ökologischen Situation der inneren Ästuare von Eider, Elbe, Weser und Ems: was hat sich nach 20 Jahren verändert? Coastline Reports 9: pp. 15-26.

Schuchardt, B. & Scholle, J. (2009). Estuaries. In Marencic H. & de Vlas J. (Eds.), Wadden Sea Ecosystem No. 25 Quality Status Report 2009 Thematic Report No. 16. Common Wadden Sea Secretariat Trilateral Monitoring and Assessment Group, Wilhelmshafen.

Schuchardt, B., Bachmann, F., Huber, A., Bildstein, T. & Scholle J. (2009). Aspekte der ökologischen Sanierung der Unterems. Brief report prepared for WWF, Hamburg

Schuttelaars, H.M., de Jonge, V.N. & Chernetsky, A. (2011). Influence of the length of an estuary on tidal motion and sediment trapping. Delft.

Schuttelaars, H.M. & de Jonge, V.N., (2012). Influence of the length of an estuary on tidal motion and sediment trapping and its relevance for estuarine management. Ocean & Coastal Management (to be published in 2012).

SDG Eems (2010). Internationaler Bewirtschaftungsplan nach Artikel 13 Wasserrahmenrichtlinie für die Flussgebiteseinheit Ems Bewirtschaftungszeitraum 2010-2015.

van Straaten, L. M. J. U. & Kuenen, Ph. H. (1957). Accumulation of fine grained sediments in the Dutch Wadden Sea. Geol. Mijnb. 19: pp. 329-354

Stratingh, G. A. & Venema, C. A. (1855). De Dollard of Geschied-, Aardrijks- en Natuurkundige beschrijving van dezen boezem der Eems (reprint 1979). Vereniging tot Behoud van de Waddenzee/Groninger Landschap, Harlingen/Groningen.

de Swart, H. E., de Jonge, V. N. & Vosbeek, M. (1997). Application of the tidal random walk model to calculate water dispersion coefficients in the Ems estuary. Estuarine Coastal Shelf Sci. 45: pp. 123-133.

Talke, S. A., de Swart H. E. (2006). Hydrodynamics and Morphology in the Ems/Dollard Estuary: Review of Models, Measurements, Scientific Literature, and the Effects of Changing Conditions. University of Utrecht. Institute for Marine and Atmospheric Research Utrecht (IMAU), Utrecht.

Talke, S. A., de Swart, H. E. & Schuttelaars, H. M. (2009a). Feedback between residual circulations and sediment distribution in highly turbid estuaries: an analytical model. Continental Shelf Research 29: pp. 119–135.

Talke, S. A., de Swart, H. E. & de Jonge, V. N. (2009b). An Idealized Model and Systematic Process Study of Oxygen Depletion in Highly Turbid Estuaries. Estuaries and Coasts 32 (4): pp. 602-620.

Tulp, I., Bolle, L. J., & Rijnsdorp, A. D. (2008). Signals from the shallows: In search of common patterns in long-term trends in Dutch estuarine and coastal fish. Journal of Sea Research 60(1-2): pp. 54-73.

van Veen, J. (1950). Ebb and flood channel systems in the Netherlands tidal waters. English translation of the original Dutch text with annotations. Originally published in: Journal of the Royal Dutch Geographical Society 67: 303-325.
van Voorthuysen, J. H. & Kuenen, Ph.H. (1960). Das Ems-Estuarium (Nordsee). Ein sedimentologisches symposium. Verh. Kon. Ned. Geol. Mijnb. Genootschap. 300 pp.
Vorberg, R., Bolle, L., Jager, Z. & Neudecker, T. (2005). Chapter 8.6 Fish. In: F. de Jong et al. (eds.), Wadden Sea Ecosystem No. 19 Quality Status Report 2009. Common Wadden Sea Secretariat Trilateral Monitoring and Assessment Group, Wilhelmshafen: pp 219-236.
Werkgroep Dollard (2001). Literatuurstudie over het storten van baggerspecie in de Mond van de Dollard. Nederlands-Duitse Eemscommissie, Rijksinstituut voor Kust en Zee. werkdocument RIKZ/AB/2001.615X. RIKZ, Haren. 154 pp.
van der Welle, J. & Meire, P. (1999). Levende Eems, herstelplan voor Eems en Dollard. Instituut voor Natuurbehoud, gezamenlijke natuurbeheersorganisaties, Groningen/Harlingen/Brussel.
Wijsman, J., & Verhage, L. (2004). Toepassing van het Zoute wateren Ecotopenstelsel (ZES) voor de Waddenzee met behulp van HABITAT. WL/Delft Hydraulics.
Winterwerp, J.C. (2010). Fine sediment transport by tidal asymmetry in the high-concentrated Ems River: indications for a regime shift in response to channel deepening. Ocean Dynamics 61: pp. 203-215.
Wolff, W. J. (ed.) (1983). Ecology of the Wadden Sea. Geomorphology/hydrography/flora and vegetation/invertebrates. Balkema, Rotterdam.
WWF (2006) Ausbau der Unterems. Eine Chronik der Maßnahmen seit 1984 mit einer Bewertung der Umweltfolgen. WWF, Frankfurt Main. 22 pp.
WWF (2010). Perspektive lebendige Unterems: Praxis- und umsetzungsnahes Konzept zur Renaturierung der Unterems als Impuls für eine nachhaltige Entwicklung der Region Ein Projektantrag von BUND, NABU, WWF sowie TU. Berlin.
Ysebaert, T., Meire, P., Coosen J. &Essink K. (1998). Zonation of intertidal macrobenthos in the estuaries of Schelde and Ems. Aquatic Ecology 32: pp. 53-71.

Acknowledgements

We have highly appreciated the constructive input by Karel Essink, Klaus Gerdes, Dick de Jong, Herman Mulder, Aechim Paetzold, Hein Sas, Jaap de Vlas, Leo Bruinzeel, Henk Schuttelaars, Wim Wolff and Eddy Wymenga. We thank Dick Visser, Jos Zwarts, Kees Nuijten and Ditmar Vroegindeweij for their carefully made illustrations.

Glossary

This glossary of terms is derived from www.coastalresearch.nl and Gotje et al. (2007)

Accretion: Accumulation of sediment through deposition – aangroei.

Benthos: Bottom-dwelling flora and fauna; from tiniest microbenthos (bacteria) to medium-sized meiobenthos (nematode worms) to the highly visible macrobenthos (clams, polychaete worms) - benthos of bodemleven.

Ecology: The study of the interrelationships of living organisms to one another and to their environment - ecologie.

Ecosystem: A community of living organisms interacting with one another and with their physical environment, such as a rain forest, pond, or estuary. Ecosystem is a concept applied to communities of different scale, signifying the interrelationships that must be considered – ecosysteem.

Erosion: The process where wind, water, ice, and other mechanical and chemical forces wear away rocks and soil, breaking up particles and moving them from one place to another - erosie.

Estuary: A semi-enclosed coastal body of water with one or more rivers flowing into it, and with a free connection with the open sea. – estuarium.

Fresh water: Water that is not saline (i.e. salinity below 0.5 ppt). – zoetwater.

Habitat: The sum of environmental conditions in a specific place that is occupied by an organism, population, or community – habitat, leefgebied of leefomgeving.

Hydrodynamics: The motion and action of water and other liquids, i.e., the dynamics of liquids, and the study thereof - waterbeweging.

Intertidal area: The area between high and low tide levels. The alternate wetting and drying of this area makes it a transition between land and water and creates special environmental conditions – intergetijdengebied.

Morphology or geomorphology: the study of landforms - geomorfologie.

Nutrients: Essential chemicals needed by plants or animals for growth. -nutriënten.

Restoration (Ecological -): (***1) (Strict sense):*** Restoring of something which was already there; creating an ecosystem with the same spcies composition and functional characteristics as a system which existed previously. - Natuurherstel. ***Restoration (Ecological -): (2) (Broader meaning):*** Creating an ecosystem with desirable functional characteristics - Natuurontwikkeling

Salinity: A measure of the amount of salts dissolved in water. Generally reported as " parts per thousand" (i.e., grams of salt per 1,000 grams of water) and abbreviated as "ppt" or ‰. Estuaries vary in salinity from 0 ppt to 36 ppt depending on the relative input of freshwater and seawater – saliniteit of zoutgehalte.

Salt marsh: may broadly be defined as area, vegetated by herbs, grasses or low shrubs, which is subject to periodic flooding (tidal or non-tidal) as a result of fluctuations in the level of the adjacent saline-water bodies (Adam 1990), and where saline water is defined as not being fresh, when the annual average salinity is greater than 0.5 g of solutes per kg of water - kwelder.

Seawall or dike: Solid coastal defence structure to protect the hinterland from flooding – dijk.

Sediment: Mud, sand, silt, clay, shell debris, and other particles that settle on the bottom of waterways -.sediment of afzettingen

Sedimentation: The deposition of suspended matter carried by water, wastewater, or other liquids, by gravity. It is usually accomplished by reducing the velocity of the liquid below the point at which it can transport the suspended material -afzetting.

Soil subsidence: the motion of the surface as it shifts downward relative to a datum such as sea-level – bodemdaling.

Subtidal: Below the ebb and flow of the tide. Used to refer to the marine environment below mean lower low tide – zone onder de gemiddeld laagwaterlijn.

Succession: Progressive replacement of one kind of community by another kind; the progressive changes in vegetation and animal life that may culminate in the climax. - successie.

Tidal range: Difference between high and low tide – getijverschil.

Tide: The alternating rise and fall of the ocean and estuary surface, caused by the gravitational pull of the sun and the moon upon the earth -getij.

Turbidity: A measure of how clear the water is; how much the suspended material in water results in the scattering and absorption of light rays. - troebelheid.

Tidal levels: Average water levels that result from the tides (so without the meteorological effects, like storm surges).

WFD: Water Framework Directive, an EU regulation.

Colophon

Bos, D., Büttger, H., Esselink, P., Jager, Z., de Jonge, V., Kruckenberg, H., van Maren, B., & B. Schuchardt, 2012.
The ecological state of the Ems estuary and options for restoration. A&W rapport 1759.
Programma Naar Een Rijke Waddenzee / Altenburg & Wymenga, Leeuwarden/Veenwouden.

Images and figures: , Kees Nuijten (page 7), Dick Visser (pages 5, 10, 11, 13, 14, 20),
Ditmar Vroegindewei (page 3, 26) and Jos Zwarts (page 21)
Photography: Michiel Firet (left front cover, pages 2, 12, 16, 22, 25), Teunis Haveman (page 18), Joop van Houdt | beeldbank.rws.nl (page 25),
Herman Verheij (right front cover, pages 7, 13, 22, 27, 29, 37), Zwanette Jager | ZiltWater Fotografie (page 17, 20),
Voß / Wattenrat (pages 12, 22, 24)
Design and layout: Groot Haar + Orth, communicatie en creatie, Leeuwarden

The previous (english) version of this document has been reviewed by the Dutch Waddenacademie. Their input is highly appreciated. The detailed comments may be downloaded by the interested reader from www.rijkewaddenzee.nl.

PROGRAMMA NAAR EEN RIJKE WADDENZEE

PROGRAMMA NAAR EEN RIJKE WADDENZEE