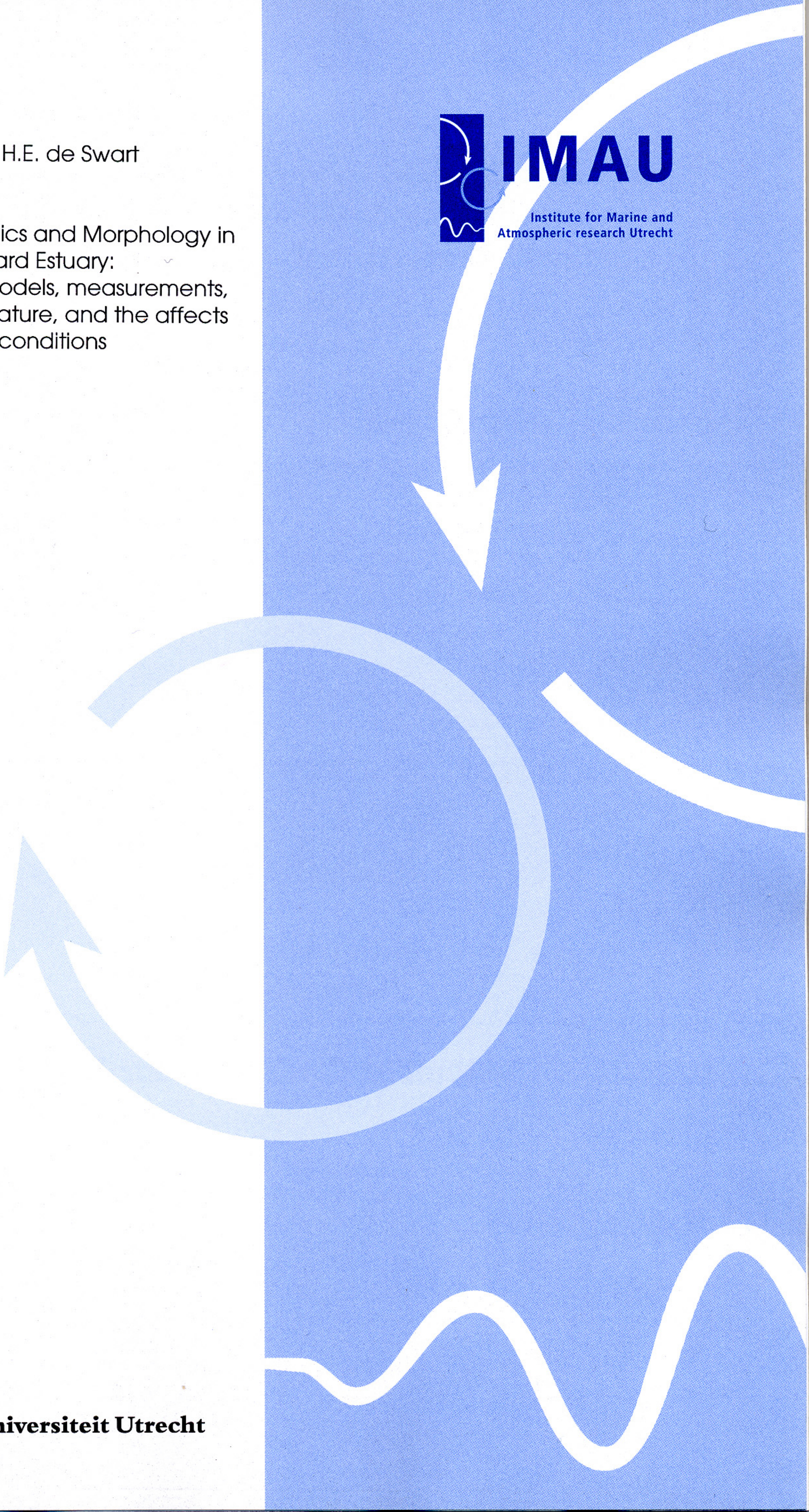
S.A. Talke en H.E. de Swart

Hydrodynamics and Morphology in the Ems/Dollard Estuary: Review of models, measurements, scientific literature, and the affects of changing conditions

R 06-01



IMAU
Institute for Marine and
Atmospheric research Utrecht

Universiteit Utrecht

Hydrodynamics and Morphology in the Ems/Dollard Estuary: Review of Models, Measurements, Scientific Literature, and the Effects of Changing Conditions

Stefan A. Talke
Huib E. de Swart

University of Utrecht
Institute for Marine and Atmospheric Research Utrecht (IMAU)
January 25, 2006

IMAU Report # R06-01

Executive Summary / Abstract

The Ems estuary has constantly changed over the past centuries both from man-made and natural influences. On the time scale of thousands of years, sea level rise has created the estuary and dynamically changed its boundaries. More recently, storm surges created the Dollard sub-basin in the 14th -15th centuries. Beginning in the 16th century, diking and reclamation of land has greatly altered the surface area of the Ems estuary, particularly in the Dollard. These natural and anthropogenic changes to the surface area of the Ems altered the flow patterns of water, the tidal characteristics, and the patterns of sediment deposition and erosion.

Since 1945, reclamation of land has halted and the borders of the Ems estuary have changed little. Sea level rise has continued, and over the past 40 years the rate of increase in mean high water (MHW) along the German coast has accelerated to 40 cm/ century. Climate has varied on a decadal time scale due to long-term variations in the North Atlantic Oscillation (NAO), which controls precipitation, temperature, and the direction and magnitude of winds. Between 1960 and 1990 the most intense variation in the NAO index on record was observed. As a result the magnitude and frequency of storm surges increased, and mean wave heights increased at 1-2 cm/year. Currently the NAO index—and therefore storminess—is trending downwards. Over the longer term, global warming models predict an average temperature rise of 2 degrees Celsius over the next century. A doubling of CO_2 is expected to increase sea level by 30 cm, while the significant wind speed and wave heights in the North Sea are predicted to increase by 50 cm/s and 50 cm, respectively.

Beginning in the late 1950's, dredging activity and construction measures in harbours and shipping channels greatly altered the physical processes in the Ems. Deepening and streamlining the Ems River and shipping channel between the 1960s and 1990s decreased the hydraulic roughness and increased the tidal range in the river above Emden by as much as 1.5 m. At the turbidity maximum between Emden and Papenburg, concentrations of sediment are currently between 1-2 orders of magnitude larger than in the 1950's, and fluid mud layers of several meters thickness occur. Other man-made changes, such as gas pipelines and the expansion of harbours, have often caused significant, but more localized, changes to the estuary.

Between the mid 19th century and the 1970's, dumping of organic waste—agricultural, industrial, and human—severely stressed the ecology of the Dollard sub-basin in particular. Since then the input of organic waste has been greatly reduced and anoxic conditions eliminated. However, the increase in turbidity at the turbidity maximum has caused depleted oxygen concentrations and periodic anoxia between Pogum and Papenburg during the summer months (personal communication, H. Juergens; Talke et al, 2005).

The Ems is a relatively well studied estuary. Significant research projects have included the BOEDE project in the 1970's --1980's and the BOA and INTRAMUD projects in the 1990's. These projects and other efforts have amassed a deep literature in the knowledge of tidal flats, fluid mud and flocculation, and mixing and dispersion processes. Projects currently underway are focusing on tidal dynamics and the affects of dredging in the high turbidity zone between Emden and Herbrum. Optimal management of the estuary is the goal of the HARBASINS project.

Many analytical and numerical models have been applied to the Ems estuary to estimate tidal range, storm surges, wave fields, sediment transport, and mixing and dispersion processes. Analytical models to estimate mixing of scalars and sediment fluxes (Sediment Trend Analysis) have been extensively used. Numerical models such as WAQUA, unTRIM, MIKE3, Telemac 2D, SWAN, Delft 3D –Sed, and

others have been applied to the Ems. While reasonable results are found for short term processes (order of days), long-term morphological change cannot yet be predicted. For the Ems catchement basin, the numerical models REGFLUD and FLUMAGIS are used to estimate nutrient inputs from diffuse sources and to visualize and evaluate the effects of land-use change.

Table of Contents

1.0 Introduction

The Dutch Ministry of Public Works, Infrastructure and Water Management (Rijkswaterstaat) requested information about the scientific state of the art in the Ems/Dollard estuary. Specific focus is given in this review to the natural variation (noise) in comparison to the effects caused by human activities (signal) during recent historic times in the past century (after 1900). This review is particularly important because the drainage basin of the river Ems covers Germany and the Netherlands and is subject to three very important EU Directives: the EU Habitats Directive, the EU wild birds Directive and the EU Water framework Directive.

The overview provided in this report will serve as background information for future joint German-Dutch restoration attempts within the Ems river drainage basin downstream of the weir at Herbrum, after further adaptations to the main system of channels have occurred.

1.1 The Ems/Dollard estuary

The Ems/Dollard estuary is defined as the semi-enclosed body of water stretching from the Island of Borkum to the end of the range of tidal influence at the weir in Herbrum. The dominant physical processes that affect the estuary are the tides, wind (both waves and shear), and freshwater inflow from the Ems River and Westerscholde Aa. The Ems River is the dominant source of freshwater, and drains a basin of ~ 12,600 square kilometres. Between Herbrum and approximately Papenburg the Ems River is freshwater. Between approximately Papenburg and Emden the river is classified as brackish, though the brackish zone migrates through a 30 km stretch of river depending on freshwater flow. Beyond Emden there is a significant increase in the width of the basin and water depths increase to about 30 m near Borkum. On the side of the channels and in the Dollard sub-basin are large tracts of intertidal mudflats that are exposed to air during low tide. A map of the Ems/Dollard estuary is shown below.

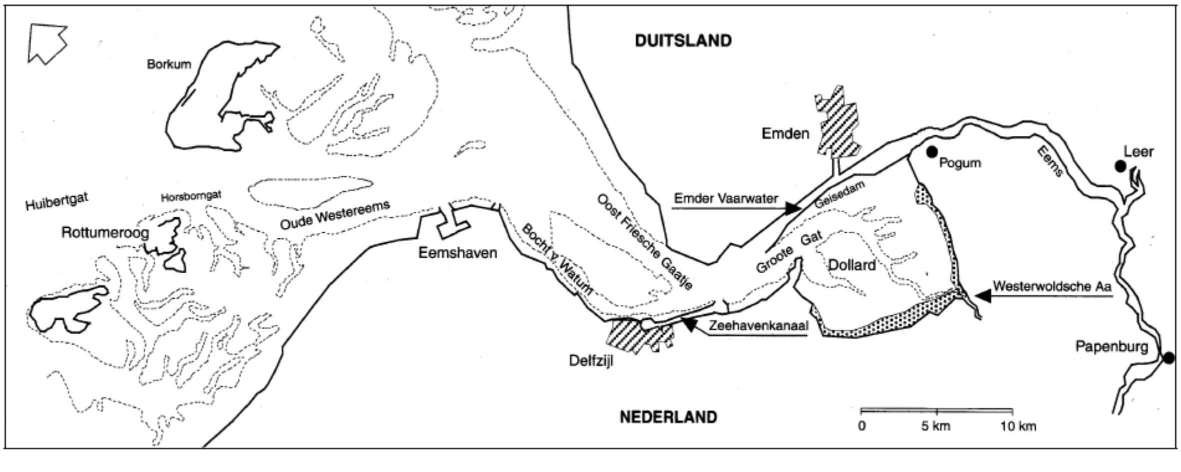


Figure 1.1 Map of the Ems/Dollard Estuary; from de Jonge, 1983.

1.2 Structure of the report

The report addresses the following questions:

- What climatalogical changes are predicted and what direct or indirect effects will they have on the Ems/Dollard Estuary?
- What anthropogenically caused changes have occurred in the Ems-Dollard over the past century (e.g., diking, damming, deepening of channels, dumping of dredging spoils, expansion of harbours, etc)?
- What scientific studies with field measurements have occurred concerning the morphology and hydrology of the Ems/Dollard estuary, and when did they occur?
- What models have been applied to the Ems/Dollard estuary, when were they made and for what purposes have they been used?
- Based on scientific literature, what changes can be reconstructed and inferred for the physics in the Ems/Dollard? Focus is on the tidal range and excursion, the turbidity maximum, turbidity, suspended matter, and erosion/sedimentation processes
- How much of the changes to the Ems estuary described in the scientific literature are due to anthropogenic changes to the estuary?
- What current research projects are occurring in the Ems/Dollard and what are their aims?

Each question is addressed separately in each of the succeeding chapters. This report specifically deals with processes affecting the Ems/Dollard estuary and its upstream and seaward boundary. An extensive review of scientific literature of the Ems/Dollard estuary and the Ems watershed has been performed. This literature will be made available in the form of a database that includes abstracts and searchable keywords.

Other reviews are available that are either more narrow or broader in scope. The Wadden Sea Council has published an excellent review of physical and biological processes affecting the Wadden Sea from the Netherlands to Denmark (Wadden Sea QSR 1999, Wadden Sea QSR 2004). On a smaller scale, Rijkswaterstaat (RWS) has published an extensive literature review dealing with sediment transport and dispersion in the Dollard, with a focus on the affect of dredging (RWS report RIKZ/AB/2001.615x).

2.0 Climate change

Climate in the North Sea and the Ems Estuary varies on yearly, decadal, and longer time scales. Changes in local and global climate are currently causing sea level rise in the North Sea and the Ems estuary, and may contribute to increasing tidal range. Wind magnitudes, wave heights, and the frequency and magnitude of storm surges steadily increased from the 1950's to the 1990's, but have trended downwards since. These variations occur because of changes to the average winter storm track across Europe, which is set by pressure changes in the North Atlantic (the North Atlantic Oscillation, or NAO). Global warming models predict additional sea level rise as CO_2 levels increase, as well as slight increases in wind speed and wave height. Precipitation is expected to increase. The relationship between the NAO and global warming is not yet known.

2.1 Sea level rise

The Ems estuary was formed by rising sea levels after the last ice age ended 10,000 years ago. Streif and Kostet (1978) discuss sea level rise in the North Sea during the Holocene era (last 10,000 years), focussing on the coast between the Ems, Elbe, and the Danish border. Brandt (1980) uses the pattern of settlements in the Ems as a proxy for sea level rise over prehistoric and early historic times. Early coastal development and settlement patterns and the long-term effect of sea level rise in the Holocene era are also described by Behre (2004). A geochemical and microfacies study by Gerdes et al (2003) investigated climate induced sea level rise during the Holocene. Vos and Van Kesteren (2003) describe the evolution of mudflats in the Ems estuary and Wadden Sea coast over the past 7500 years, looking at the change of tidal range, sea level rise, and more recently anthropogenic change. Rohde (1975) describes the history of tidal measurements in the German estuaries (including the Ems) since the middle of the 19th century. The rate of sea level rise has not been constant since at least the 16th century (Rohde, 1975). A reconstructed history of the mean high water for the Frisian Islands (including Borkum) is shown in figure 2.1. The sea level is reconstructed from sub-fossil records of deposits on mudflats and marshlands (Freund & Streif, 2000). Note that the observed dip in the mean tidal height between 600-700 B.P. (before present) was probably caused by the flooding of inland areas such as the Dollard (Freund & Streif, 2000).

Over the past 100 years, global sea level has risen ~ 18 cm, though estimates vary from 10-20 cm; over the next century, estimates for global sea level rise vary from 9 cm to 88 cm (IPCC report, 2001). Along the German coast from 1855-1990, the mean tidal level (MTL) increased at a rate of 15 cm/century (Töppe, 1993). More recently, the rate of mean tidal level (MTL) change has increased slightly to about 19 cm/century between 1965 and 2001 (Jensen and Mudersbach, 2005). In the Ems estuary, the mean sea level rise has remained constant at about 10-12 cm/100 years since 1901 ((Jensen and Mudersbach, 2005). Subsidence of the ground along the North Sea Coast between 2 cm/century to 8 cm/century and distortion of the tide due to intertidal mudflats make the MTL difficult to compare directly to global sea level trends (Jensen et al, 2003). However, they are in qualitative agreement.

(Freund, 2000).

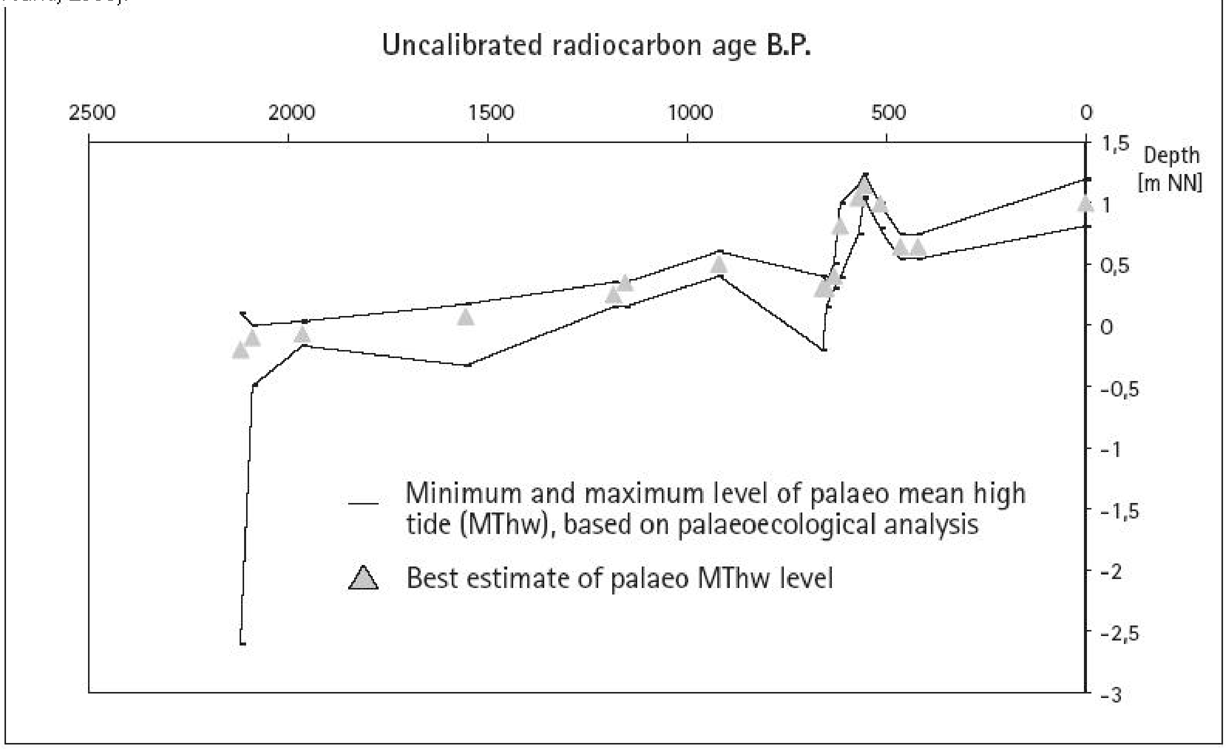


Figure 2.1: Reconstructed changes in the mean high water level over the past 2000 years, reconstructed from mudflat and marshland deposits on North Sea islands. Adapted from Freund & Streif, 2000.

2.2 Tidal range.

Between 1855-1990, the mean tidal range (MTR) increased by 13 cm/century (Töppe, 1993). However, over the past 40 years the tidal range along the German coast and barrier islands has dramatically increased (Jensen and Mudersbach, 2005). Between 1965 and 2001, the mean tidal range increased at a rate of 51 cm/100 year. Jensen et al (2003) suggest that the accelerated increase in tidal range may reflect accelerated sea level rise due to climate change. However, the influence of long-term natural cycles on the increase in mean tidal range growth is still unknown (Töppe, 1993, Jensen et al, 2003).

2.3 Temperature increase

The average temperature in the Wadden Sea is expected to rise over the next century by an average of 2 degrees Celsius, with a range of 1-6 degrees (IPCC 2001, Verbeek 2003). Potential biological effects are documented in the Wadden Sea QSR, 1999. The direct affect of increasing temperature on hydrodynamics and morphology in the Ems estuary is unknown, but may be coupled to biological changes. For example, the erosion resistance of mud is quite dependant on the density of diatoms on its surface (Kornman and de Deckere (1998)). In turn, the diatom concentrations depend greatly on the timing of the spring bloom, and predator/prey dynamics (Kornman and de Deckere, 1998). Staats et al, 2001 found that cold winters reduce erosion by armouring the mudflats with ice. Increasing temperatures will decrease the likelihood of such armouring.

2.4 Wind

The magnitude and direction of wind—and therefore the magnitude of storm waves and storm surge—greatly depends on the North Atlantic Oscillation Index, a pressure gradient between the Azores and Iceland. This pressure gradient varies on the decadal time scale and longer time scales, as is shown in figure 2.2. During years in which the NAO index is greater than 1, there is increased rainfall and greater freshwater flow in the Ems estuary. This leads to a decrease in salinity. Cold, dry winters occur when the NAO index is negative, as occurred during 1979/1980 (Wadden Sea QSR,1999). Between 1960 and 1990, the largest long-term amplitude variation on record was recorded. It is yet unclear how much global warming contributes to the strength of these oscillations. Current trends show the NAO index decreasing downwards again (see for example http://www.cru.uea.ac.uk/~timo/projpages/nao_update.htm).

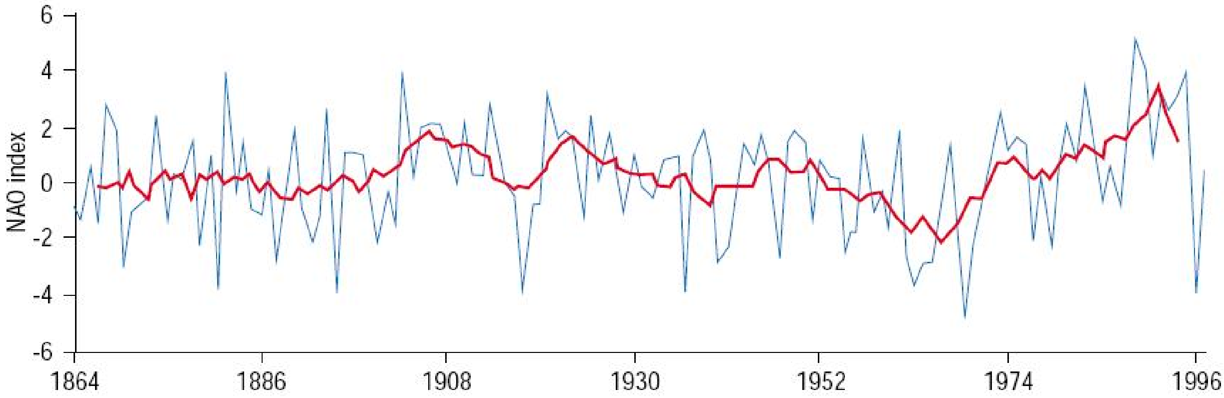


Figure 2.2. The NAO index from 1864 to 1995. The solid red line is a running 5 year average. Adapted from Hurrel, 1995.

Over the past 120 years, the geostrophic wind speed measured along the coastline (Figure 2.3) varies on yearly and decadal time scales (Schmidt and van Storch, 1993). A normalized measure of geostrophic wind records (figure 2.4) or 'storminess' reconstructed from air pressure measurements in the North Sea shows the same trends as figure 2.3 (Alexandersson et al, 1998, Alexandersson et al, 2000). The largest storminess is observed in the late 19th century, while the calmest period is observed around 1960. After 1960, a measurable increase in North Sea storminess occurs, but appears to decrease again after 1995. Overall, present conditions are not significantly different from a century ago (WASA, 1998).

Simulations of global warming (doubling of CO_2) predict slightly increased wind speeds at the North Sea: the 90th percentile of wind speed is predicted to increase by about 0.5 m/s along the North Sea coastlines if carbon dioxide doubles (WASA, 1998). The increased wind speeds and storminess during winter months (Nov.-March) are simulated to cause a rise in mean High water on the order of 10-15 cm along the Wadden Sea coastline (Kauker and Langenberg, 2000). In addition, sea level rise on the order of 10 cm is predicted due to thermal expansion of the ocean (Cubasch et al, 1995, Kauker and Langenberg, 2000). Under the same scenario (CO_2 doubling), significant wave heights in the North Sea are predicted to rise by as much as 50 cm (Günther et al, 1998).

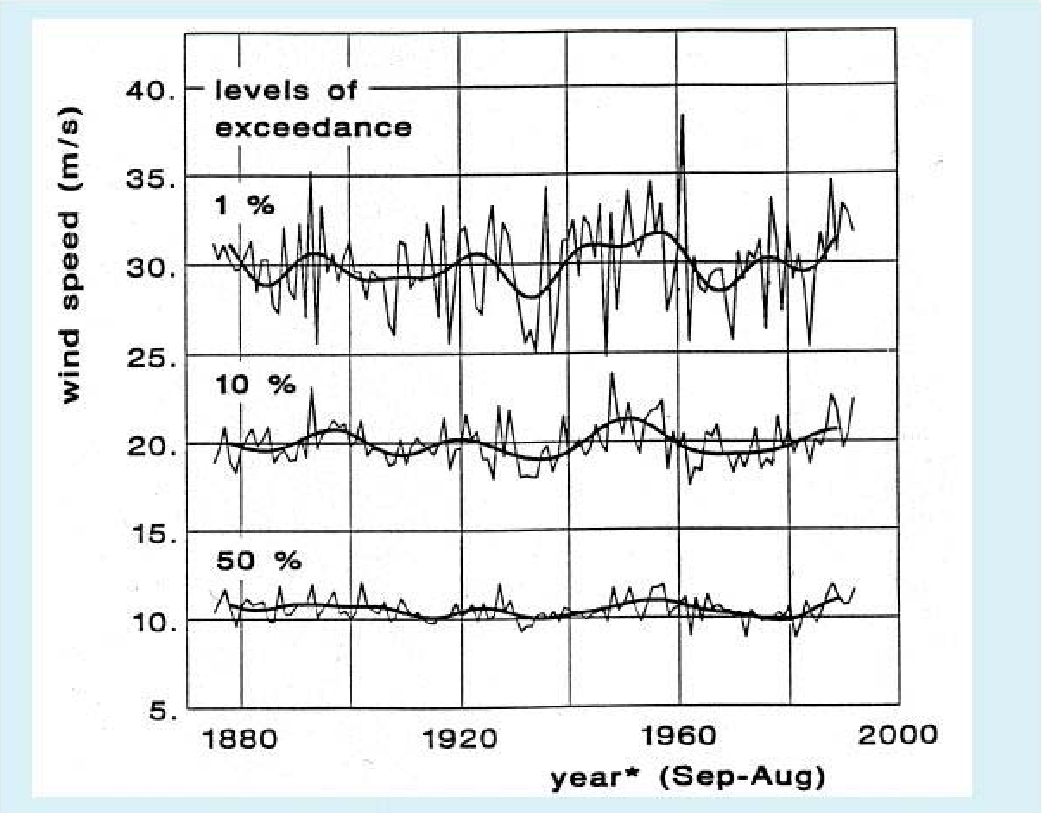
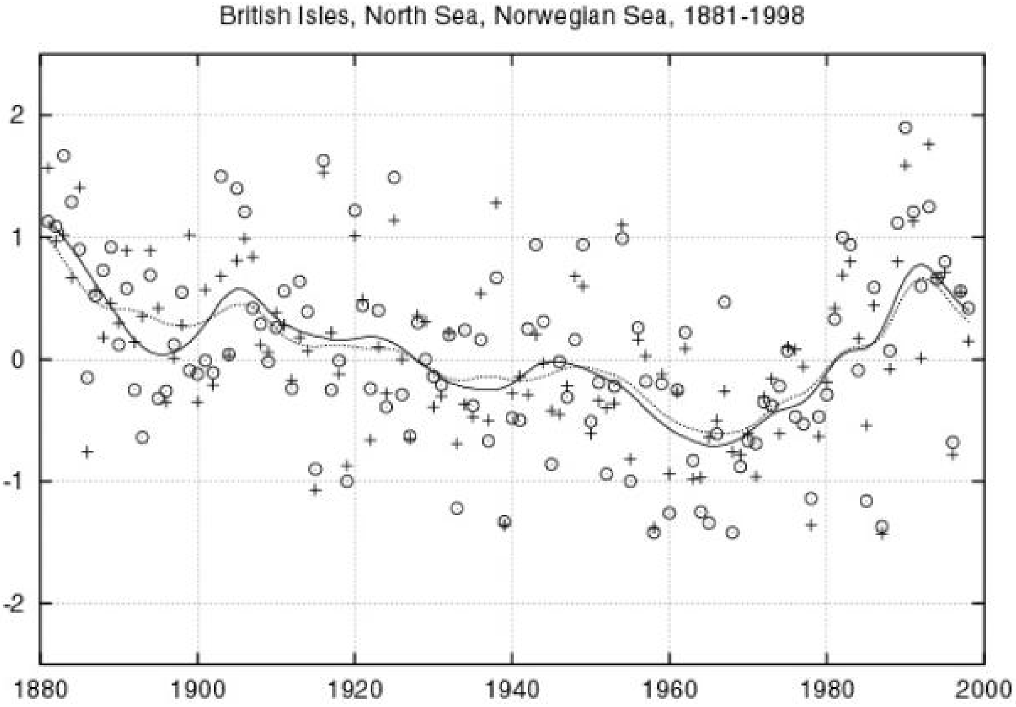


Figure 2.3: Wind speed in the German Bight between 1876 and 1995, separated by the level of exceedence. Adapted from Schmidt and van Storch, 1993.



2.4: A normalized index of storminess over the North Sea over the past 120 years, based on daily geostrophic wind measurements. Figure obtained from Alexandersson et al, 1998, Alexandersson et al, 2000.

2.5 Storm surge

In the early 1950's, a storm surge barrier was erected at Leda and successfully resisted storm surges of up to 45 cm between 1954 and 1963 (Gursch, 1966). Seifert and Lassen (1986) note that the height of storm surges in the North Sea outpaced sea level rise (35 cm increase vs. 5 cm increase) after 1940. A 50 % increase in the frequency of storm surges occurred over a 3 decade span. However, data from Rijkswaterstaat shows no clear long-term (100 + year) trend in the frequency of storm surges in Delfzijl over the last century, though larger decadal fluctuations are apparent and an increasing trend occurs from the mid 1950's to 1990 (see figure 2.5).

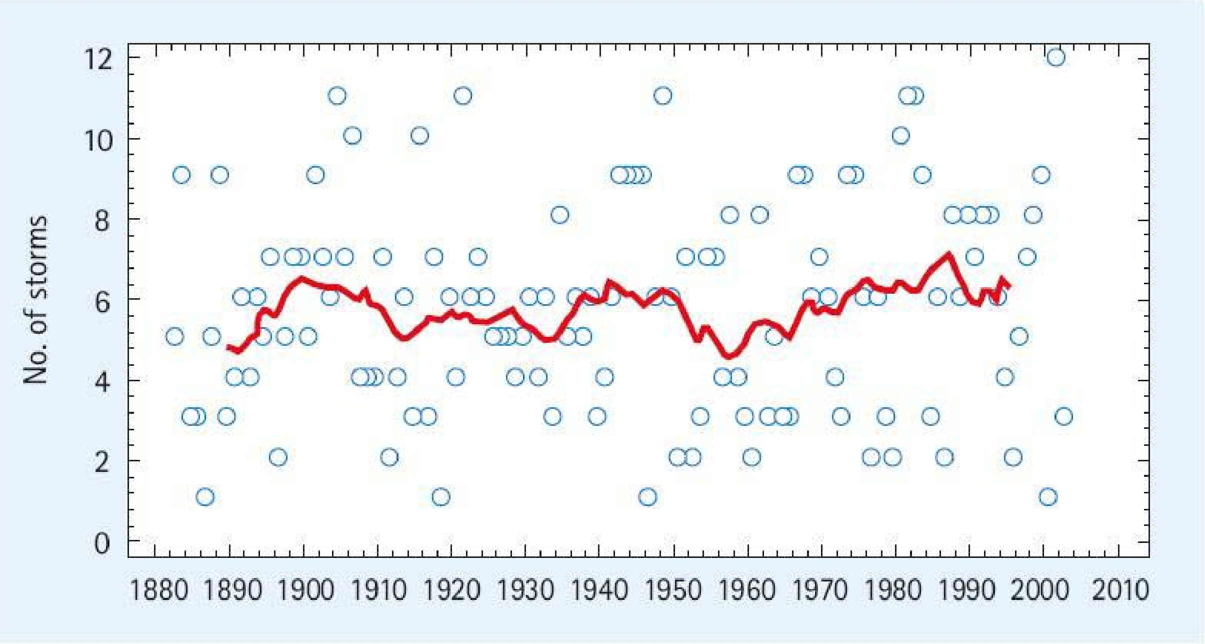


Figure 2.5: Number of storms which cause a storm surge that is 90 cm greater than the astronomical high tide measured in Delfzijl. Rijkswaterstaat data, from Wadden Sea QSR, 2004 .

The frequency of storm surges depends not only on the magnitude of wind, but the direction from which it is coming. Storm surges along the German coast and Ems estuary are primarily caused by winds originating from the northwest. Large decadal variations in the frequency of wind from the northwest occur, and are associated with changes in the NAO index (see figure 2.6). An NAO index of greater than 1 implies more wind from the west and northwest, and therefore increases the likelihood of storm surge.

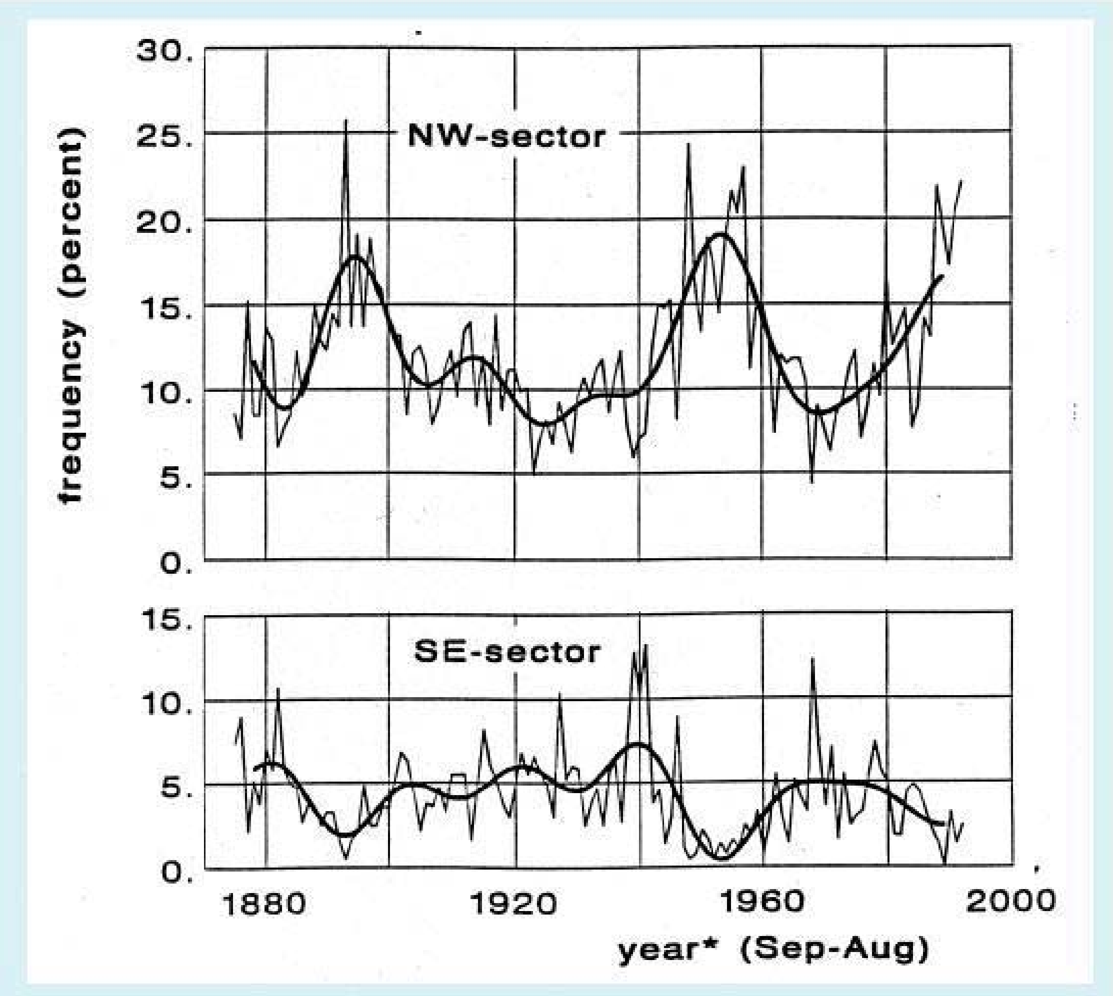


Figure 2.6. The frequency of large wind events greater than 15 m/s occurring from the Northwest and from the Southeast from 1876 to 1992. From Wadden Sea QSR, 1999.

Deepening of river channels has caused dramatic changes to the tidal ranges and mean high water (MHW) in the German estuaries, including the Ems. As a result of both processes (local and North Sea), storm surge water levels are increased and many dykes between Emden and Herbrum no longer fulfilled design requirements (Niemeyer & Kaiser,2002). To protect against storm surges and enable large ships to navigate the Ems from the Meyer Shipyard in Papenburg, a storm surge barrier was built near Gandersum and opened in 2001 (Niemeyer & Kaiser,2002).

Modelling shows that the water level increase and intensity of storm surge corresponds to the duration of the largest winds in various parts of the estuary (between 15 m/s and 25 m/s (Pluess et al, 2001). Global warming models predict a slight increase in the intensity of storm surges on the order of several centimetres (for a doubling of CO_2). However, this prediction is with-in currently measured natural variability (Kauker and Langenberg, 2000).

2.6 Wave heights

Wave heights in the North Sea and coastline areas are coupled strongly to changes in wind patterns. A hindcast numerical model of wind speeds and wave heights at the North Sea platform K13 shows increasing wind and wave heights from 1960 to 1990, after which a decreasing trend begins (Soares, 2002). As shown in Figure 2.7 the 99th percentile of wind speed increased from 17 m/s to over 20 m/s in 1990, while the 99th percentile of wave heights increased from 4 m to nearly 5.5 m. Despite this increase, the wave climate now is similar to the wave climate a century ago (WASA, 1998). This is due to long term variability in the wind climate.

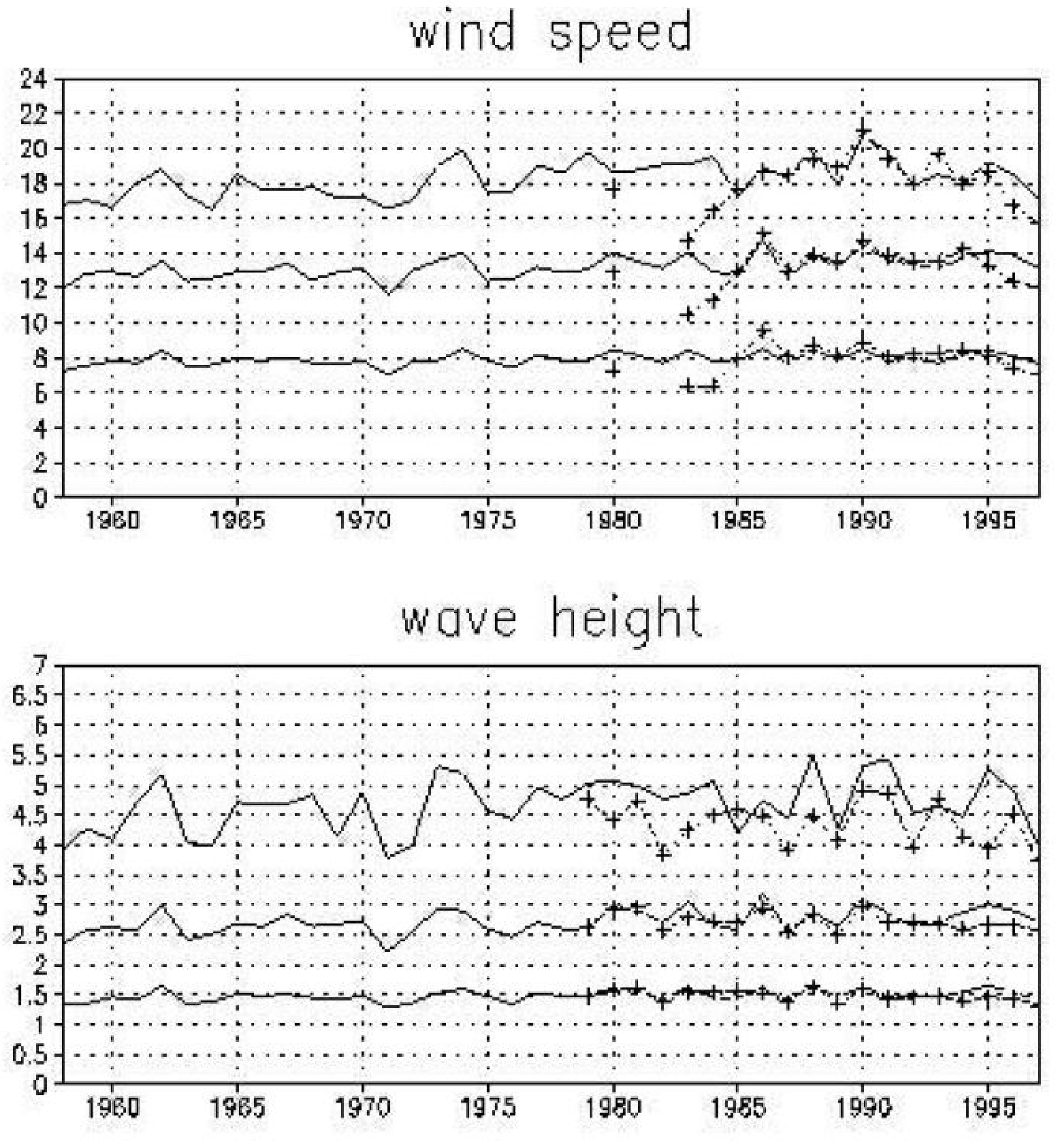


Figure 2.7 : The 99th , 90th, and 50th percentile of wind speed and wave heights at station K13 in the southern North Sea. The solid line denotes the hindcast model, while symbols denote data. Only data after 1985 is considered accurate. Adapted from Soares, 2002.

2.7 Increased freshwater discharge

Global warming models predict greater rainfall in northern Europe and therefore increased freshwater discharge (http://www.grida.no/climate/ipcc_tar/wg1/408.htm). Between 1900 and 2000, rainfall in the Netherlands increased by ~ 12% (Können, 1999). Over the next 100 years, precipitation is expected to increase again by 12 %, with-in a range from 6% to 25% (Verbeek, 2003). The 10 day average rainfall is expected to increase by as much as 40%, with an average expected increase of 20% (Verbeek, 2003). Similar estimates are made for Germany (Wadden Sea QSR, 2004). As a result, decreased salinity is expected in the Wadden Sea, particularly during episodic rain events (Wadden Sea QSR, 2004).

The effects of varying discharge conditions in the Ems River, as understood in current literature, are described below. From this analysis the likely changes in the Ems due to increased freshwater discharge can be inferred. The movement of salinity in the Ems River depends greatly on the measured discharge (Schulze & Spingat, 1991). During high discharge, the brackish zone is moved downstream. The turbidity maximum and sediment move through a range of ~30 km as river discharge changes from low flow to high flow conditions, and small changes to the freshwater flow can cause large changes in sediment concentration (Spingat and Oumeraci, 2000). Therefore, increased rainfall due to global warming likely leads to a downstream migration of the brackish water zone (at least during the spring and winter rains), while the increased variability of river flow (due to increased 10 day average rainfall) may cause greater variations in the magnitude and location of the turbidity maximum.

Jensen et al (2003) show that the mean low water in Herbrum is linearly related to the freshwater discharge of the Ems. Therefore, another indirect effect of increased rainfall due to global warming would be an overall increase in water level in the Ems River, particularly in winter and spring (see figure 2.8).

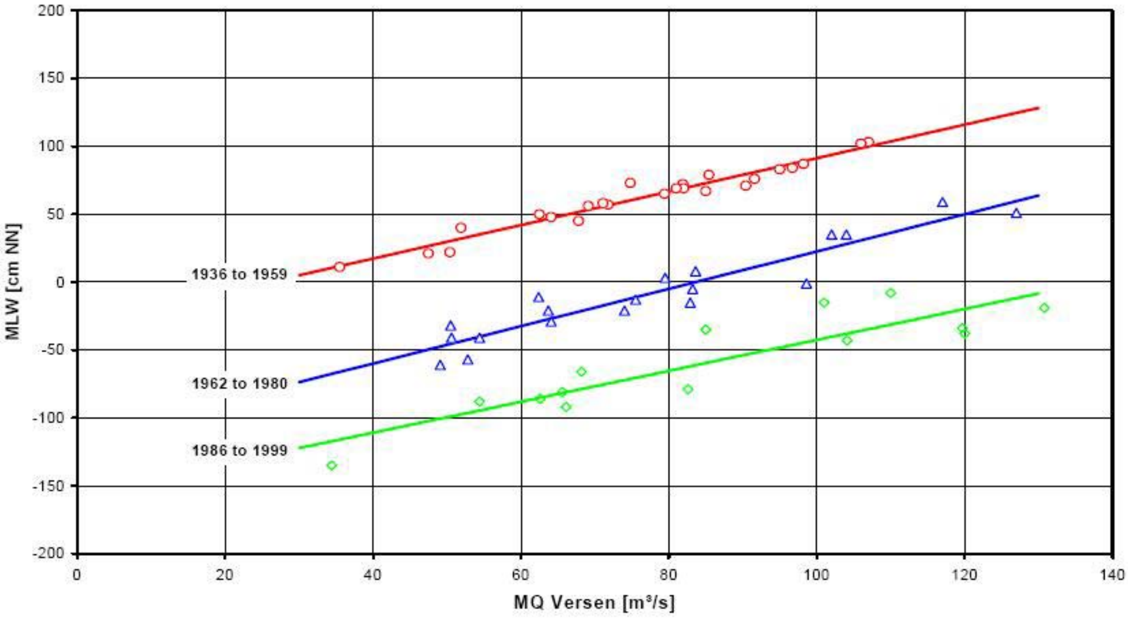


Figure 2.8: Increase in the mean low water at Herbrum as a function of the mean fresh water flow measured in Versen. Note that the mean low water (MLW) for a given flow has decreased due to anthropogenically induced changes in the tidal range. Adapted from Jensen et al, 2003.

3.0: Anthropogenic changes to the Ems estuary

Beginning in the 16th century, humans have had a large affect on the form and functioning of the Ems estuary. From the 16th century to the middle of the 20th century, the most profound changes occurred due to diking, land reclamation and polderization. After WW II, the largest affects have been dredging and construction efforts to maintain, develop and deepen shipping channels and harbours. Other developments include gas extraction and transport efforts, and the building of a power plant. In this section the various anthropogenic influences are described.

There is some literature which gives an overview of anthropogenic influence on the estuary. Schubert (1970) gives a history of the Ems estuary and discusses historical measures which may have affected morphology and economic worth. Anthropogenic effects on the Wadden Sea and the German estuaries (including the Ems) are detailed in the Wadden Sea Working Group (Dijkema et al, 1980). Anthropogenic influence on the river Ems is described by Gienapp (1983). Physical changes—and proposed changes that never occurred-- to the Dollard basin are described in Steen (2003).

3.1 Historical land reclamation

During the middle ages, the Westerscholde Aa discharged into the Ems Estuary near the Punt van Reide. Beginning in 1362, a series of storm surges flooded over the natural banks of the Ems, creating a large shallow sea that extended as far as Winschoten in 1509 (Stratingh and Venema, 1855, Dollardzijlvest 1992). Beginning in the 16th century, the Dollard basin has been gradually shrinking due to polderization, or diking, of forelands. The history of these land reclamations is shown in figure 3.1, which also shows additional land reclamation efforts near Emden and in the outer estuary north-west of Delfzijl. Additional land was reclaimed from the Ems River between Emden and Papenburg (Schumacher, 2003). The Dollard region, at about 100 square kilometres, is about 1/3 the size of its greatest historical extent. Between 1912 and 1924, the channels and mudflats between Knock and Emden were diked off. By doing so, it was hoped to increase the depth of the river to 7 m below low water and eliminate the need for dredging (Gerittson, 1952). Since 1922, about 21 square kilometres of land have been lost from the Ems/Dollard region (Schuchardt et al, 1993). After World War II, only 63 hectares have been reclaimed from the Dollard basin. Some additional (small) surface area was lost due to dyke stabilization measures and the growth of forelands in front of the dykes (Steen 2003).

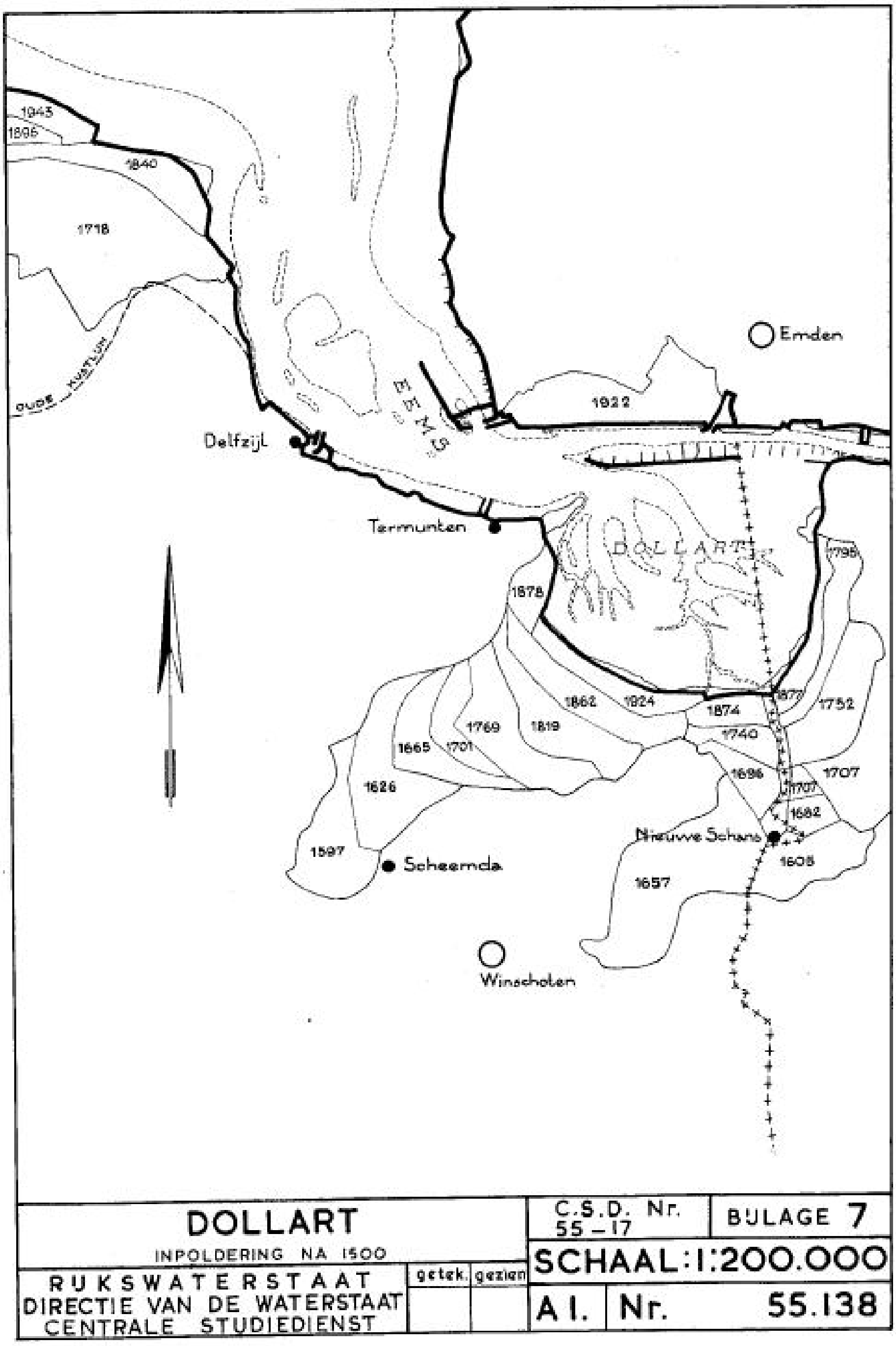
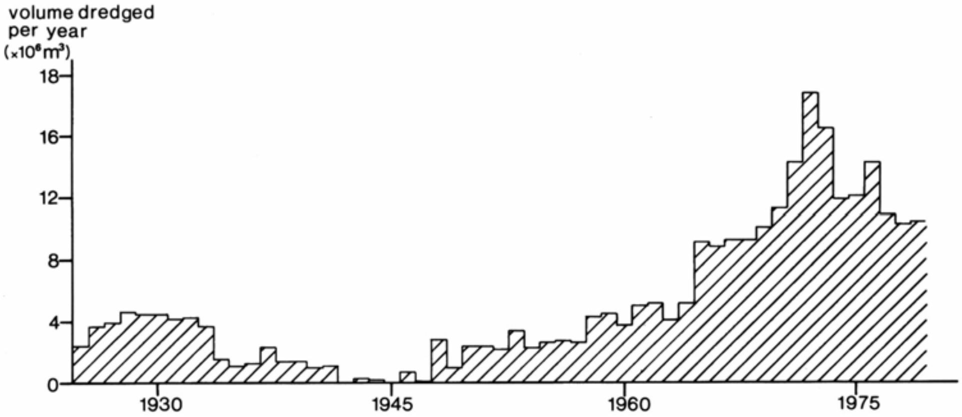


Figure 3.1: Land Reclamation ('Poldering') after 1500 in the Ems Estuary. Adapted from Gerritsen, 1955.

3.2 Maintenance dredging of channels and harbours

As is shown in figure 3.2, significant volumes of sediment were being dredged in the Ems estuary even in the 1930's (de Jonge, 1983). However, dredging volume greatly increase during the 1960's through 1980s. Before 1960, dredging occurred exclusively using bucket-type dredgers; by 1973, all dredging was done by suction dredgers. Between 1954 and 1972, the length of the channel between Emden and Borkum that was dredged increased from 8 km to 53 km. Dredging changes the morphological and hydrodynamic regime and the system tends to search for a new equilibrium; this results in erosion in some locations and siltation in others (de Jonge, 1983).

The dredging in the Ems is driven both by increasing ship traffic and size, and by the fast siltation rate of harbours and channels. Nasner (1992, 1997) analyzed sounding data and theoretical and hydraulic models and determined that the harbour of Emden was silting up at the rate of 2-3 m per year. Garrelts et al (1973) describe strategies and measures taken to control sand transport in German estuaries including the Ems. Harten (1979) describes how increasing ship traffic has necessitated deepening of shipping channels in the Ems, Jade, Elbe, Weser, and Eider rivers. The method of deepening the channels is described.



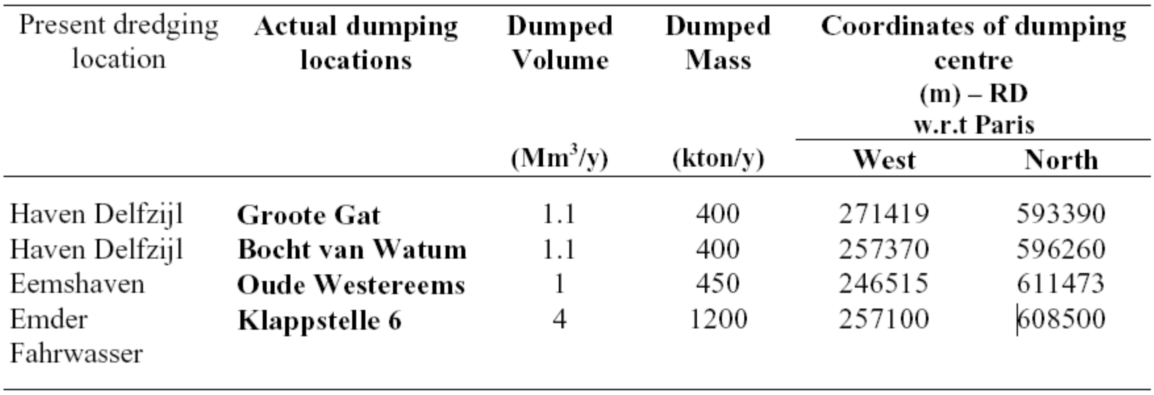
(de Jonge, 1983)

Figure 3.2: Historical dredging volumes in the Ems estuary. Adapted from de Jonge, 1983.

Current estimates of yearly dredging from the Emder Fahrwasser and the harbours at Delfzijl and Eemshaven are shown in Table 3.1 (Rijkswaterstaat estimates, from Boon et al, 2002). About 7.2 Mm^3/y , corresponding to ~ 2450 ktons per year, are dredged from these locations. The majority of the dredging spoils are dumped into the outer Ems estuary at Klappstelle 6 (Germany) or the Oude Westereems and Bocht van Watum (Netherlands). An additional 2.5 Mm^3/y of sandy material is dredged from the main shipping channel from Knock to the North Sea.

Investigations of Klappstelle 1-7 are reported in a 2001 report from the Bundesanstalt fuer Gewaesserkunde (BfG). Turbidity is increased in the short term, and mud is introduced in an otherwise sandy area. According to Steen (2003) and Boon et al (2002), most of the dumped spoils are dispersed away from the dumping location. Wind waves stir up the deposited sediments, which are then carried to other locations by residual currents (Boon et al, 2002). A RWS review (2001) therefore found no correlation between long term sedimentation in the Dollard and dredging/dumping activities. The biota and ecology of the Ems estuary are likely very sensitive to the amount of dumping that occurs, as well as the time of year that it occurs (personal communication, Victor de Jonge). The effect of dredging on the Ems estuary is also described by Essink et al, 1992. Franzius (1986) describes the dredging required to maintain the shipping channel in the brackish water of the Ems River, and discusses implications of turbidity to the water quality and ecology.

Table 3.1: Estimates of Dredging in the Ems Estuary. An additional 2.5 Mm^3/y of sandy material is dredged from the main shipping channel from Knock to the North Sea. Adapted from Boon et al, 2002.



Present dredging location	**Actual dumping locations**	**Dumped Volume**	**Dumped Mass**	**Coordinates of dumping centre (m) – RD w.r.t Paris**	
		(Mm^3/y)	**(kton/y)**	**West**	**North**
Haven Delfzijl	**Groote Gat**	1.1	400	271419	593390
Haven Delfzijl	**Bocht van Watum**	1.1	400	257370	596260
Eemshaven	**Oude Westereems**	1	450	246515	611473
Emder Fahrwasser	**Klappstelle 6**	4	1200	257100	608500

Note that dredged volumes from the port of Emden greatly decreased after 1990 and are therefore not shown in table 3.1. Wurpts (2003, 2005) describes the novel method used to eliminate dredging and yet maintain nautical depth in the outer Emden Harbour. Rather than dredging and removing material, the dredging authorities (Niedersachsen Ports GmBH) now simply stir and oxygenate the fluid mud at appropriate intervals (perhaps every 3-6 months). Stirring changes the viscosity of the fluid mud, allowing ships to pass through the fluid mud as if it were water. Oxygenation causes bacteria in the fluid mud to produce slime, which preserves the matrix structure of the fluid mud (a web of carbohydrates and inorganic material with interstitial spaces filled with water). Thus, the consolidation of fluid mud into impassable mud (‘shlick’) is slowed (Wurpts, 2003, 2005).

Periodic dredging is also required between Emden and Pappenburg (Wadden Sea QSR, 1999), and has greatly increased after deepening of the channel in 1985 (see figure 3.3, from Habermann, 2003). After 1990, dredging appears to vary between 0.5-1 Mm^3/y. Because dredged material is dumped on land, the cost is high: each year, 24 million euros are spent to maintain the navigable depth, with 2 million euros spent for each ship delivered from Pappenburg (personal communication, H. Juergens). The cost of dredging the Emder Fahrwasser is 7 million euros per year. Meesenburg et al (1999) describe dredging in the Emder Fahrwasser.

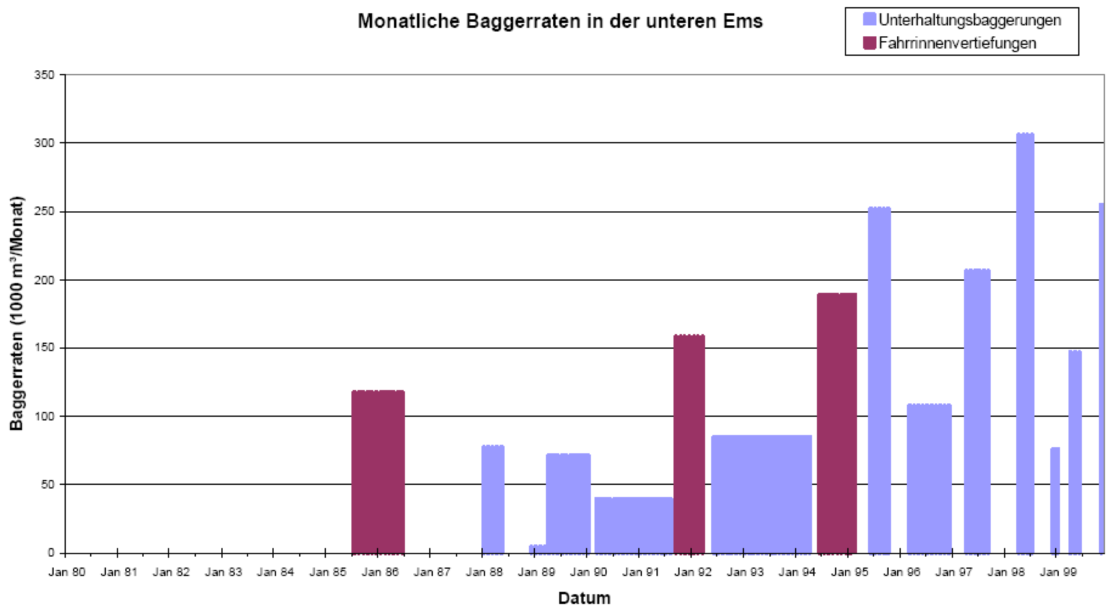


Figure 3.3: Monthly dredging rates in the Ems between Emden and Pappenburg between 1980 and 2000, in units of 1000 m³/month. The magenta refers to deepening of the channel, while the blue denotes maintenance dredging. Adapted from Habermann, 2003.

3.3 Expansion of harbours

Wroz (1978) describes an expansion of the Emden harbour in the 1970's. Carsiens and Wurpts (1987) and Franzius (1986) describe plans to build a canal from Emden to Knock that would bypass the Emdener fairway; however, the so-called Dollart-Dock ('Dollart-hafen') project has never been built (Steen 2003). Due to its increasing use as a shipping harbor for automobile export, the harbour of Emden is currently being expanded (Clasmeier et al, 2004). A review of seaport development in the Ems-Dollard region is given by Van Den Bremen (1992). Focus is given to historical changes in political point of view on how to solve economic, infrastructure, and environmental problems. Van Den Bremen (1992) notes that conflicts over responsibilities and development often occurs on border areas in estuaries, leading to delayed or stifled regional development in the economy, infrastructure, and environmental management.

The Eemshaven, a harbour in the outer Ems estuary (see figure 1.1), was developed in the 1960's and officially opened in 1973 (de Jonge, 1983). The dredging of a new shipping channel in 1976 near Eemshaven led to morphological changes in the nearby vicinity and the shifting of sandbar locations in the late 1970's (de Jonge, 1983). In 1976, the Eemscentrale power plant operated by Electrabel came online with a 650 MW capacity, and was expanded to 1675 MW in the mid 1990's. This comprises about 15% of total power demand in the Netherlands. The water used by the power plant leads to fish kills and increases the temperature of the water (Hadderingh and Jager, 1995). Though harbour use has not met expectations, construction of a malting plant and a biodiesel factory with a capacity of 80 million liters per year by 2007 is expected to increase use. Another planned project is the building of a 5 billion cubic meter shipping terminal by Essent and ConocoPhillips, which is currently under environmental review and is planned to be operation by 2010. The project would entail dredging, which Groningen Seaports and Rijkswaterstaat have agreed to do (see e.g. the Platts.com newsletter, issue 471, March 2006). Eemshaven is also being mentioned as a finalist for a multifuel, 1200 MW power plant by Nuon. Finally, there is currently some discussion of building a nuclear power plant at

Eemshaven and using estuarine water for cooling (see for example ttp://www.ulricianumtimes.de/no20/article.php?ID=52).

3.4 Maintaining and developing shipping channels

In 1899, the weir at Herbrum and the Ems-Dortmund canal were built to improve shipping (Steen, 2003). Though this likely changed the tidal dynamics of the Ems estuary by restricting tidal propagation past Herbrum (Habermann, 2003), no records of this change are available. The primary measures taken in the past 50 years to enhance shipping channels in the Ems river and estuary have been the construction of the Geiseleitdamm, the deepening and streamlining of the shipping channel from Borkum to Papenburg, and the construction of the Emssperwerk.

3.4.1 Geiseleitdamm

Beginning in 1873 and continuing in 1900 and 1930, measures were taken by the German government to shore up the ‘Geiserucken’ which separated the Ems River from the Dollard sub-basin. This effectively made the ‘Dollard Mund’ the drain of the Dollard basin and increased flow speeds and depth in the Emder Fahrwasser. Between 1958 and 1961 a 12 km long dam called the “Geiseleitdamm” was constructed along a 12 km stretch of river westward of Pogum. In addition, a 2.2 km long ‘Leitdamm Seedeich’ was built in the outer estuary (Steen ,2003). By again reducing the width of the river, the Geiseleitdamm succeeded in further deepening the Emder Fahrwasser to a depth of 9 m SKN (mean low water mark for spring tides). After 1972, the Geiseleitdamm was not maintained, in part because of the planned ‘Dollarthafen’, which was never built (Steen 2003). Built to the MHW mark in 1960, the Geiseleitdamm has become increasingly porous due to an increase in MHW, subsidence of the western Dollard (due partly to gas extraction) and general weathering. As a result the Dollard basin is becoming more brackish, and during high water the Dollard is emptying into the Ems (Steen, 2003, personal communication, H. Juergens).

3.4.2 Channel deepening and streamlining

Over the past 20 years, the Ems river between Emden and Papenburg has been deepened several times, to 5.7 m in 1985/1986, to 6.8 m in 1991/1992, and to 7.3 m in 1994 (Jensen et al, 2003). In addition, a bend in the river was streamlined in 1984/1985 (the ‘Weekeborger Bucht’), reducing the river length by nearly a km (personal communication, H. Juergens; Habermann, 2003).

The driving force behind these changes is the Meyerwerft ship factory in Pappenburg. The deepening of the river has changed the tidal dynamics (lower hydraulic friction) and increased the tidal range in the Ems River (Jensen et al, 2003). The shipping channels between Knock and Borkum have also been streamlined and deepened starting in the 1960’s (de Jonge, 1983).

3.4.3 Emsperwerk

The increased tidal range has made the Ems River more vulnerable to storm surges (Seifert and Lassen, 1986). To protect against storm surges and enable increasingly large passenger ships to navigate the Ems from the Meyerwerft shipyard in Papenburg, a storm surge barrier was built near Gandersum and opened in 2001 (Niemeyer & Kaiser,2002). A photo of a large passenger ship being floated down the Ems River is shown in figure 3.4, while the Emssperwerk is shown in figure 3.5. The Emssperwerk is typically closed about twice a year for several days to allow large ships to navigate downstream. To allow ships to pass, a train bridge must be deconstructed. Saline water from the downstream side of the Emssperwerk is pumped to the upstream side in order to increase the water depth (personal communication, Andreas Engels). Model runs show that the density driven currents caused by saline water can intrude about 10-20 km upstream over the time scale of several days (personal communication, Andreas Engels). After the Emssperwerk is reopened, no affect is seen in the tides after several days (personal communication, Andreas Engels). The politics, planning, and management of the Emssperwerk project are described from the point of view of the project leader in Starke (2002).

3.5 Gas pipeline and gas extraction

The Gas World Gas Journal (1975) describes plans for placing a natural gas pipeline in the Ems estuary. Swiss (1975) details the difficulties in laying the pipeline in the Ems estuary, particularly through the mudflat areas. De Winton (1977) describes the start-up of this pipeline, which transports gas from the Norwegian sector of the North Sea to the Ems Estuary. Alma (1984) describes the Ems as a dumping ground for oil producers. Approximately 3 decades later, De La Motte (2004) describes how soil erosion at the Paapsand mudflat reduced the soil cover of the pipeline. Spiekhout & Russ (2000) described safety evaluation and monitoring of the exposed and threatened 800 m of pipeline.

De La Motte (2004) further describes the gradual westward movement of the main shipping channel in the Ems due to morphological changes. Measures over the past 3 decades such as sandbagging, using sediment and silt fences, and dumping rocks on the pipeline altered the local hydrodynamics and caused scour holes. To protect the pipeline and return the area to a more natural bathymetry, the pipeline was lowered 12 m into a dredged trench, and the underwater dam (sandbags, rocks) removed. The effects of deepening the oil gas pipeline are discussed in a Delft Hydraulics report (2003). Currently, the pipeline is again exposed and further measures are being considered to monitor and protect the pipeline (personal communication, H. Juergens).

Hockert & Chromik (1982) describes the construction of a natural gas platform built at Emshoern in the Ems estuary. Pipelines and cables were laid through tidal flats. Hess (1985) describes the design of the gas extraction plant and platform. Hadderingh and Jager (2002) describe the seasonal variation of the yearly impingement of greater than 10 million fish of 35 different species at the Eemshaven power station. In addition, they compare impingement before and after moving the cooling water intake from the shoreline to the edge of a tidal channel.

Between 1993 and 2000 natural gas was extracted from the ‘Groothuisen’ area (Wadden Sea QSR, 2004). It is yet uncertain whether extraction will resume. Finally, subsidence of up to 20 cm has occurred in the Dutch portion of the Ems Estuary do to natural gas extraction in the province of Groningen (Wadden Sea QSR, 1999).

Figure 3.4. A large passenger ship is floated down the Ems River. Unknown date.

Figure 3.5. Photograph of the Emssperwerk in March, 2005. Note the turbid water in the foreground.

3.6 Anthropogenic inputs

Beginning in the mid 19th century, large amounts of organic material were input into primarily the Dollard, causing oxygen depletion particularly during the autumn months (Essink, 2003).
Bouwman and Kop (1979) , Laane et al (1983), Van Es et al (1980), and Vanes (1980) described and investigated the effect of organic waste on the Dollard tidal basin (e.g., on benthic populations). Oxygen levels lower than 20% were measured by Van Es et al (1980). In the autumn, sulphide reducing bacteria were present during times of sewage disposal, and large fauna were non-existent. A standard for acceptable oxygen levels in the Ems estuary and methods for reducing the organic load were suggested by a panel of German scientists (Rincke (1973). The German panel recommended stopping the dumping of raw sewage and the simultaneous construction of a pressure pipe to transport treated sewage. Subsequent sanitation measures in the 1970's and 1980's reduced the organic load and the Dollard estuary has returned to a condition more typical of estuaries (Essink, 2003). Species diversity increased, while the number of Nematodes (which flourish under adverse conditions) decreased (Essink & Keidel, 1998, Essink & Romeyn, 1994, Peletier, 1996). Species of diatom less resistant to sulphides and ammonium became dominant, and oscillations in the dominant species of diatoms ceased (Peletier, 1996). The effects of dredging and anthropogenic eutrophication are analyzed by de Jonge (2000), and the implications for management of the estuary are discussed. A decrease in mercury emissions shows up as a decrease in bioavailable Hg in the Ems estuary (de Kock, 1986).

4.0 Scientific measurements of the Ems estuary

Beginning in the 1950's, a multitude of measurement campaigns have occurred on the Ems/Dollard estuary. Many have resulted in scientific literature which is described below. In addition, long term monitoring of the estuary is being performed by German and Dutch governmental agencies. The large-scale projects that have occurred in the past and the currently running monitoring programs are described in section 4.1, and the scientific product of the large scale, small scale, and monitoring is described in section 4.2.

4.1.1 Long term monitoring by NLWKN, WSA Emden, and RWS

Long term measurements are occurring at 9 locations on the Ems River stretching from Knock to Rhede (near Herbrum) through a cooperation of NLWKN and WSA Emden. Measurements occur continuously in intervals between 3 and 30 minutes. Physical measurements such as velocity, turbidity, salinity, temperature, tidal stage, sediment concentration, pH, and oxygen concentration are measured. In addition, meteorological data is measured in Gandersum.

At approximately 2 week to 1 month intervals throughout the year (except winter), RWS is sampling the Ems estuary at Borkum and in the Dollard. Biological and chemical parameters are being measured.

4.1.2 The BOA project

The BOA project, funded by NWO, ran from 1995 to 1997. Its aim was to better understand the physical and biological processes affecting mud in shallow water and intertidal areas, and the time scales over which these processes act (de Deckere, 2003). The main feature of the experiment was the BOA bridge across a tidal channel in the Dollard, from which meteorological and hydrodynamic instrumentation was deployed (see figure 4.1). Other measurements were made at various intertidal mudflats nearby. Much scientific literature resulted from this project and is discussed in the following sections.

Figure 4.1 Picture of the BOA bridge

4.1.3 INTRMUD

INTRMUD, which stands for "The Morphological Behaviour of Intertidal Mudflats" was a European Community initiative whose aim was to improve the scientific understanding of mudflat processes. Led by K. Dyer, the project investigated many mudflats in Europe. In the Dollard, research occurred in conjunction with the BOA project. For more information, see http://www.hrwallingford.co.uk/projects/INTRMUD/ .

4.1.4 Emssperwerk baseline measurements

On March 13, 2001, synoptic measurements were carried out in order to create a baseline dataset of the Ems/Dollard estuary before the Emssperwerk became operational. Multiple profiles where made with ADCP, while an array of probes set up along the Geiseleitdamm and in the Dollard measured velocity, salinity, and at selected stations turbidity and oxygen. In addition, the long-term measurements in Gandersum and Emden were used. The overall goal of the project was to make synoptic measurements over a tidal cycle. The measurements were a made through a cooperation of WSA Emden, BAW, NLWKN-Aurich, Meetdienst Noord-Nederland, Delfzijl, and the Forschungsstelle Wasserwirtschaft und Umwelt an der Universität Siegen. Conference papers by Blasi et al (2001) and Jensen et al (2002) came out of these measurements. For more information, see http://univis.uni-siegen.de/formbot/dsc_3Danew_2Fresrep_view_26rprojs_3Dfachber10_2Fwasser_2Fwasser_2_2Funters_5F39_26dir_3Dfachber10_2Fwasser_2Fwasser_2_26ref_3Dresrep

4.1.5 BOEDE project

The BOEDE project, which stands for Biological Research Ems-Dollard Estuary, was research that investigated primarily the biological consequences of organic pollution in the Dollard sub-basin during the 1970's and early 1980's (see for example BOEDE, 1983). Some publications with a physical slant occurred, for example Van Es and Ruardij (1982).

4.1.6 BIOGEST

As part of a project investigating the emissions of biogases from European estuaries, the BIOGEST program measured the Ems estuary in July 1997. Papers coming from the survey can be found at http://www.ulg.ac.be/oceanbio/biogest/publis.htm, and focus on the concentrations and emissions of gases such as carbon dioxide, nitrogen, methane, and volatile gases from surface water.

4.2 Field experiments—descriptions and major results

The studies presented here are divided into field studies of flocculation and settling velocity, field studies of intertidal mudflats, and field studies of fluid mud in the port of Emden.

4.2.1 Measurements in intertidal areas—sediment erosion, deposition, and flux

Most of the intertidal studies described below came out of research for the BOA and INTRMUD projects.

Christie et al (1997) describe measurements on an intertidal mudflat in the Dollard estuary and conclude that three factors influence the resuspension of sediments: wind driven waves, tidal currents, and the biofilm. Sediment fluxes are the highest just after wetting and just before drying. Dyer et al (2000) show that sediment flux is shoreward during calm conditions, despite the ebb dominance of currents. During windy conditions sediment is exported from the flat, except when diatom productivity is high. Sediment eroded during wetting has a larger organic component. Highest settling velocities occur during slack.

Kornman and de Deckere (1998) and Staats et al (2001a,b) investigate the effect of biological activity on sediment erodibility in the Dollard. Resistance to erosion from waves and currents greatly increased during a diatom bloom in April 1996 (Kornman and de Deckere (1998). By June, sediments began to erode again as the amphipod Corophium volutator decreased diatom concentrations significantly. Staats et al (2001 a) show that changes in floc size do not bias the measured sediment concentration downward during algae blooms. Instead, benthic algae produce extracellular carbohydrates which increase bed strength and reduce resuspension. However, high mud content (90%) at the margins of intertidal mudflats varies little throughout the year and is caused by hydrodynamic, not biotic, factors (Staats et al, 2001 b).

Lucas (2003) investigated the concentration of diatoms at the turbid tidal edge at the Hond mudflat in the Dollard and determined that the concentration of diatoms is greater at the end of the ebb than during the beginning of the flood. Because local resuspension is posited to be the major source of diatom concentrations, Lucas (2003) concludes that the supply of diatoms during the flood is reduced because diatoms resuspended during the ebb are carried away to deeper channels. De Jonge and van Beusekom (1995) similarly concluded that biota and sediment is exported to channels during sustained (several day) windy conditions. Van Duyl et al (1999, 2000) look at the affects of tidal immersion and emersion, as well as eroded and non-eroded mats, on the growth of algae, bacteria, and the production of sugars. De Jonge and van den Bergs (1987) used a laboratory experiment to investigate the resuspension of diatoms and sediment due to changing water flow conditions.

De Haas and Eisma (1993) measure current velocities on tidal flats and channels. High suspended sediment concentrations occur during the flood tide. Shoreward transport of sediment during fair weather is larger than seaward export during storms, leading to a net increase in deposition of 1-2 mm (and as much as 8 mm) per year. Ridderinkhof et al (2000) use a long term record (> 6 months) of suspended sediment concentration to analyze the variation in SSC and the flux of suspended sediments in a channel/flat system. The large intertidal flats in the Dollard force ebb dominance in the currents. Winds affect SSC much more on the tidal flats than in the channel, where SSC is limited by the availability of fine-grained sediments. During fair weather a small net flux occurs towards the tidal flats. Net transport over a tide increases dramatically when the wind speed increases, but can be either onshore or offshore.

Staats et al (2001a) show that the length of time ice covers tidal flats in the Dollard tidal basin affects the suspended particulate matter later in the year. In particular, suspended particulate matter was lower in 1996 than either 1995 or 1997 due to the long duration of ice cover. Ice cover enhances consolidation of the sediment and protects against the occurrence of large waves.

4.2.2 Measurements of particle size distribution and flocculation processes

Bernard et al (1986) classified estuarine particles from different stations on the Ems Estuary using an electron microprobe X-ray microanalysis and an automatic image analysis system. Eleven different elements were analyzed and 13 different particle types were defined. Eisma (1983) analyzed suspended matter and made observations on macro-aggregates, particle size and organic composition. Eisma (1991) measured the size of particles along the Ems estuary and concluded that particle size does not depend on salinity, organic matter, or the bulk composition of the particle. Therefore, there is no consistent evidence that flocculation due to salinity is an important process in the Ems.

Eisma & Li (1993) showed that variations in floc size are related to settling during slack tide, resuspension during early ebb and flood, and flocculation over most of the tide. Large flocs are broken into smaller flocs during or after settling to the bottom. The largest flocs are formed during periods of high suspended sediment concentrations. Eisma et al (1994) show that the floc size varies with particle concentration and is larger near the bed than at the surface. The size of flocs also likely depends on the flow onto and off of the mudflats in the Dollard, but not on organic composition or salinity. In situ measurements of floc size with a camera are described in Eisma & Kalf (1996).

Mikkelsen and Pejrup (1998) used settling tubes and a laser diffraction analyzer to determine the smallest floc size from samples taken in the Dollard estuary. They determined a linear relationship between suspended sediment concentration (SSC) and floc size: the greater the SSC, the smaller the smallest floc size. This is attributed to the effect of increasing velocity, which tends to increase SSC but shear the flocs. The settling velocity of the smallest flocs is related exponentially to the SSC. Van Leussen & Cornelisse (1993, 1996) describe an in-situ underwater video camera for measuring floc size and settling velocity. Large flocs of up to 1 mm are observed, and settling velocities between 0.5 mm/s and 8 mm/s are measured. Further, Van Leussen (1998) investigated how biological processes affect floc sizes and settling velocities on a longitudinal transect in the Ems Estuary.

Van Der Lee (1998) compares the size of flocs in a tidal channel and mudflat for similarly energetic conditions. On the mudflat, high shear at the bed causes floc break-up and decreases floc size. Therefore, floc size is controlled by fluid shear on the mudflat. In the channel, the concentration of suspended sediment is the dominant predictor of floc size. Van Der Lee (2000 a) investigates the temporal variation of floc size using an under water camera. The settling velocity of flocs shows only a small dependence on floc size. This occurs because larger flocs are shown to have much smaller effective densities than smaller flocs. Settling velocity and floc size are correlated with SSC over a tidal time scale, but this relation changes with time and location. Over a season, the properties of the sediment affect floc size.

Van Leussen (1999) compared flocs in the Ems estuary and found that that settling velocities vary by several orders of magnitude even when sediment concentrations are the same. Therefore, other factors besides sediment concentration are important, including physical-chemical and biological effects. During the decline of a spring bloom, Van der Lee (2000) shows that floc sizes increased. He concluded: “Biological cohesion of flocs is probably more dependent on the ‘glue’ quality of the biopolymers than on the absolute quantity. The quantity as well as the quality of the biopolymers may depend on the species composition, concentration and physiological state of phytoplankton and bacteria”.

4.2.3 Measurements of fluid mud and organic matter

Wurpts (2003 a,b, 2005 a,b) describes measurements of fluid mud made in the harbour of Emden. Fluid mud is neither a fluid nor a solid, but rather acts like a solid at low shear stress and as a fluid at higher shear stress. The transition between fluid and solid is the yield point. Viscosity then varies with the applied shear stress. Wurpts (2003, 2005) presents measurements of the yield stress as a function of fluid mud density for samples from the Emden harbour. Shipping is found to be possible with fluid mud densities of up to 1.25 t/m^3, above which the mud becomes more clay-like. Fluid mud is thixotropic, and regains its firmness after a rest period (much like paint). In practice, fluid mud remains navigable as long as it is aerobic, allowing bacteria to produce slime that keep particles in the fluid mud suspension. In anaerobic conditions, methane producing bacteria cause particles to settle. The high organic content of fluid mud in the Emden Harbour and the Ems River (22%) leads to a lower yield stress and decreased viscosity. Whereas an anorganic sample with a density of 4.0 mass % has a yield point of 1000 Pa and a viscosity of 0.3 kPa*s, Emden harbour mud has a yield point of 30 Pa and a viscosity of 0.08 kPa*s.

Rechlin (1996) discusses how to measure the nautical depth in areas with muddy bottom and fluid mud. Wurpts (2003, 2005) proposes using an appropriate yield point of fluid mud at the nautical depth. Dasch and Wurpts (2001) describe using isoviscs as a means for estimating sedimentation of fluid mud. Merckelbach (2000) measured the consolidation of Dollard mud in a settling tube, measuring density, pore water pressure, and strength (shear stress). Merckelbach and Kranenburg (2004) describe a simple, low-cost method of determining the constitutive equations of soft mud from settling column experiments. Using mud from the Dollard estuary, they determine the vertical effective stress and permeability and show their new method compares well to conventional methods.

Van Heemst (2000) shows that most organic matter in the Ems estuary is not new in origin. Megens and Van der Plight (1998) and Megens et al (2002) use spectrometry and carbon isotope analysis to determine that most particles of less than 20 microns found in the Ems/Dollard estuary are from the North Sea. Most coarse particles (> 20 microns) are of terrestrial origin. Dankers et al (1984) described the flux of water, particulate and organic matter between a salt marsh and the estuary. They conclude that coarse organic debris, carbon, ammonia, phosphate and silica are exported while nitrate is imported. Van Beusekom and De Jonge (1994,1996) show a relation between the maximum of dissolved inorganic phosphate, iron and aluminium and the transition between marine and riverine sediments upstream of the turbidity maximum in the Ems.

4.2.4 Hydrodynamic studies

Between 1993 and 1996 extensive biological and physical measurements were undertaken at selected cross sections in the Ems and Dollard estuary. The overall goal of the program was to measure the flux of scalars such as sediment and biota (e.g., fish larvae) through the cross sections. Various scales of deployment occurred. The highlight of the program were measurements taken with 10 boats across a cross-section—5 to measure biology, and 5 to measure physical parameters. Such a large contingent required the cooperation of WSA Emden and RWS. More information can be found in the thesis of Jaeger (1999).

Nasner (2004) describes measurements taken both with-in and outside the harbour of Emden with Aanderaa probes, made in order to better calibrate hydrodynamic and morphodynamic models in brackish water harbours. This was part of KFKI-Projekt 63- 03KUIS019 .

Partenscky & Barg (1977) estimate damping and energy dissipation in estuaries using the method of damped, co-oscillating tides, and compare German tidal rivers including the Ems to North American estuaries. Jürges & Winkel (2003) describe tidal hydrodynamics in the lower Ems River.

4.2.5 Morphodynamics and sediment transport

Hoselmann and Streif (2004) analyze the pattern of deposits and accumulation during the Holocene sea level rise along the low-lying areas from the Ems to the Weser estuaries. Borehole records, hydrographic soundings and topographic surveys are used to map the pattern of deposition over the previous 7500 years. Only 10% of the sediments are of riverine origin (peat), and 90% of the sediments are of marine origin (clastic). Niebuhr (1952) analyzes the westward migration of the mouth of the Ems since 1833 and traces morphology change to changing flow conditions, sand transport and meteorological conditions.

Schubert (1970) summarizes the morphology, geology, geographic, and hydrodynamics of the Ems estuary and evaluates the effect of human changes on the morphology and economic worth of the region. Niebuhr (1955) measures sand transport at the mouth of the Ems and details particle sizes for ebb and flood. Bed forms and sediment transport are discussed in Garrelts et al (1973). Dijkema et al (1980) describe the geomorphology of the Wadden Sea and the German estuaries, including the Ems, and describe controlling factors such as climate, waves, currents, sediments and dynamic processes. Kempe et al (1981) describe erosion rates along the middle European coastline.

Van De Kreeke and Robaczewska (1993) derive an analytical expression for the tidally averaged bed load transport in a tidal channel. Transport is proportional to some power of the local current speed, and depends on the amplitudes and phases of the tidal current constituents. Ridderinkhof (1997) investigates the effect of residual currents from tidal asymmetries on sediment transport in the Ems.

Van de Kreeke (1997) measures sediment concentration at 4 heights over 8 tidal cycles, and decomposes the resulting sediment concentration measurement into M2, M4, M6, M8 and M10 tidal frequencies. The ebb tide carried more sediment past the sensors than the flood, resulting in an M2 component of sediment concentration. At higher elevations above the bed, the M4 component dominates. Energy at the M4, M6, M8, and M10 frequencies is caused by variations in vertical mixing as well as nonlinear interactions between settling velocity, time dependant mixing and concentration. Variations in concentration and mixing strength are stochastic at time scales less than 2 hours. Sediment flux of similar magnitudes occur at M2, M4, M6, and M10 frequencies.

De Jonge (1992) describes the residual current patterns in the Ems along different cross-sections of the Ems. De Jonge and Van Beusekom (1995) describe the erosion and transport of sediment and microphytobenthos in the Ems estuary. They show that the concentration of sediment and microphytobenthos in the channels is critically dependant on the wind conditions during several tides before a measurement is made. Wind driven waves erode sediment and microphytobenthos, which are then transported off the tidal flats to the main channels.

Bergmann et al (1978) describes velocity measurements and iron, copper and manganese concentrations and fluxes over a partial cross-section in the Ems estuary over several tidal cycles. Jager (1999) and Jager (2002) describes extensive hydrodynamic measurements and flux calculations that occurred from 1993-1995 at various locations in the Ems and Dollard.

4.2.6 Satellite and radar measurements—sediment Concentrations and bathymetry

Niedermeier et al (2001) used SAR (synthetic aperture radar) images to track the land/water boundary of mudflats in the Ems (and other) estuaries, and transforms these images to isolines of bottom topography using available tide-gages. Over a long time period, changes in topography can be monitored by comparing isolines.

Lehner et al (2004) used an algorithm that combines Modular Optoelectronic Scanner (MOS) data and SPOT satellite imagery to estimate the suspended sediment concentration in the Ems (and other) estuaries. Concentrations of 6 mg/L to 60 mg/L are estimated, and compared to in-situ measurements and transport models in figure 4.2.

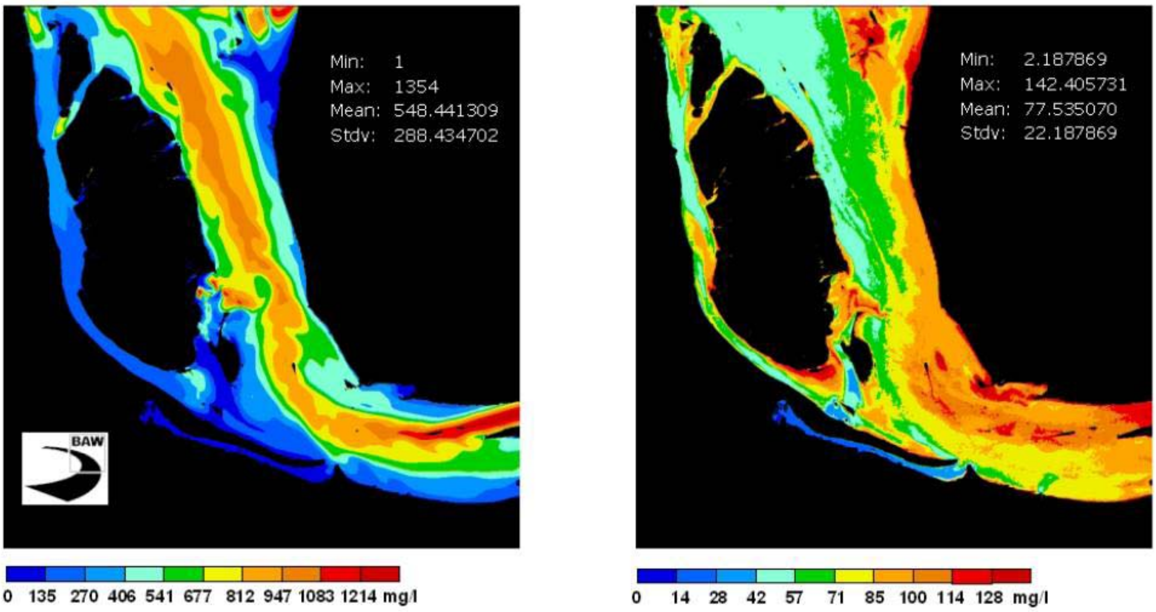


Figure 4.2 Comparison of surface sediment concentrations modelled by the numerical model TRIM (left) and sediment concentrations measured by satellite imaging (right). There is a general correlation between the models, though the magnitudes of the numerical model are much higher. Adapted from Lehner et al, 2004.

5.0 Models of Ems estuary

A number of analytical and numerical models of varying complexity and scope have been developed for the Ems-Dollard Estuary. These are described below:

5.1 Hydrodynamic models

Hydrodynamic models simulate fluid flow in the Ems/Dollard estuary and the affects of bathymetry, tidal motion, and longer time scale residual flows. Geise et al (1975) describe a scale model of the Ems developed at the BAW in Hamburg. Harten and Vollumers (1977) describe hydraulic models run to simulate flow conditions in the East Friesian Gatje, Gatjebogen and the Emdener fairway, which often require maintenance dredging. Hydrological data from the area is also reported. Flow conditions are particular complex in the Gatjebogen, with lateral flow occurring over the fairway. The Ems hydraulic model no longer exists (personal communication, C. Maushake). As early as 1979, a 3D numerical model and a vertically averaged model of the Ems is described in the journal Kueste (Vol. 34; anonymous author), with the goal of modelling the tides and salinity intrusion. Wubs (1987) describes an explicit numerical model to solve the shallow water equations and model flow on large tidal flats.

Currently used numerical models of the hydrodynamics in the Ems/Dollard estuary are:

5.1.1 WAQUA

Van de Kreeke & Robaczeswka (1993) describe the use of the depth-averaged numerical model WAQUA in the Ems Estuary. Boon et al (2002) use WAQUA to model the entire Ems estuary, as part of a project to model the affect of different scenarios for dumping dredged material. A parameterization is used to estimate density driven flows due to salinity differences between fresh and salt water. An example of the maximum flood velocity field calculated by WAQUA is given in figure 5.1.

5.1.2 MIKE21 and MIKE3

The MIKE suite of numerical models is developed by DHI Software, Denmark http://www.dhisoftware.com/). Geils et al (2001) and Stoschek et al (2003) from the Franzius Institute at the University of Hannover describe efforts to model the Ems estuary with MIKE21 and MIKE3D, focussing on the Emdener Fahrwasser and the port of Emden. Their model shows good agreement with the measured tidal data at Emden. Velocity is measured with an average error of 10 cm/s and 5 cm/s, though graphs show significant outliers of greater error. Strong stratification of up to 10 psu is predicted downstream of Emden during the ebb tide, while residual circulation into and out of the harbour is particularly apparent during flood tides due to salinity induced density differences. Fresher harbour water is modelled to flow out on the surface, while more saline water intrudes the harbour at the bottom (Stochek et al, 2003).

5.1.3 unTRIM 3D

The Bundesanstalt fuer Wasserbauw (BAW) in Hamburg uses an implicit finite difference numerical model (unTRIM 3D) for its estuarine and coastal modelling. This model was developed by Vincenzo Casulli, Ralph Cheng, and Guenther Lang. For more information, see
http://www.baw.de/vip/en/departments/department_k/publications/pkb/trim3d/trim3-en.html
According to Holgar Weilbeer at BAW-Hamburg, the Ems modelling effort of the BAW is still in basic form with many unanswered questions but will receive increasing attention in coming years (personal communication).

Interesting results of TRIM 3D on the Ems estuary include animations on the tidally averaged salt and velocity field from Borkum to Gandersum and over a cross section at the Ostfriesische Gatje Nord. (http://www.baw.de/vip/en/departments/department_k/methods/animate/ausems/aems-en.html) .

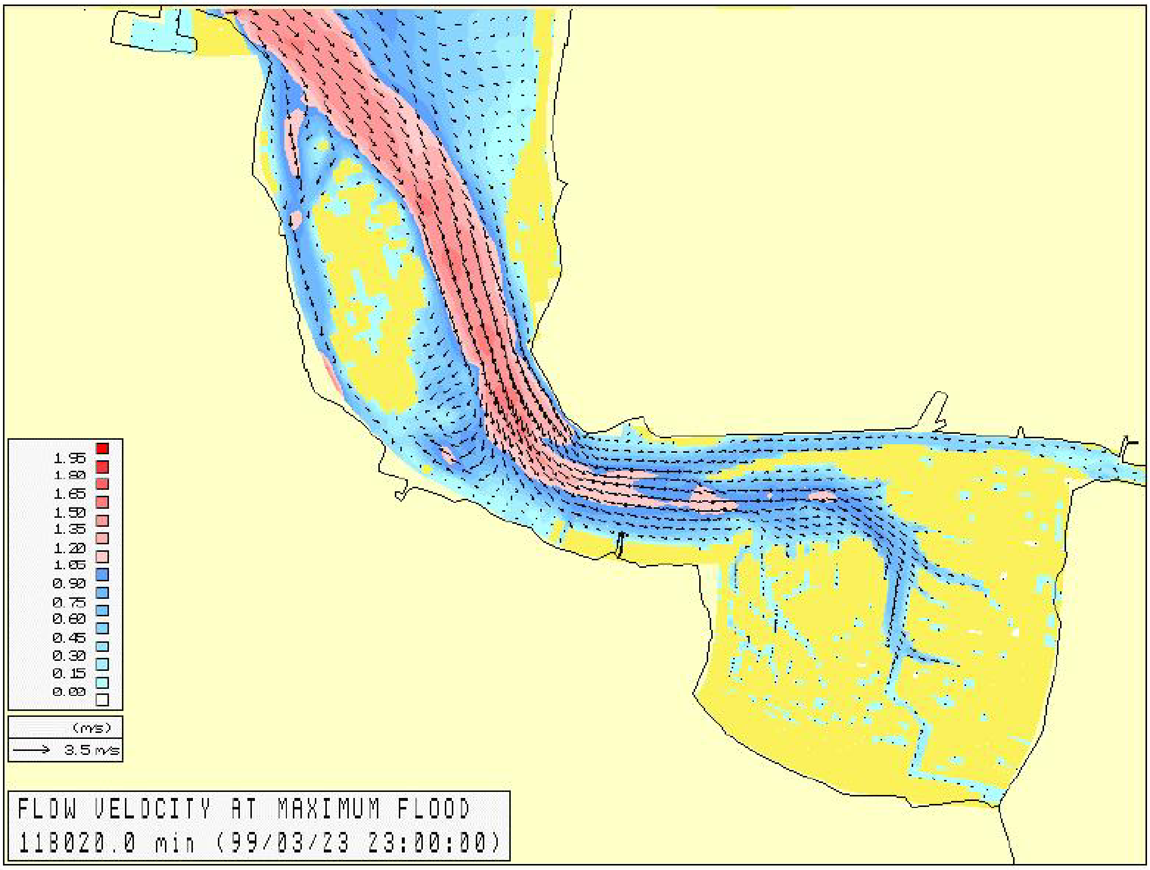


Figure 5.1: Flow velocity at maximum flood in the Ems/Dollard calculated by the WAQUA model. Adapted from Boon et al, 2002.

5.1.4 GETM—General Estuarine Turbulence Model

GETM, devised by Hans Burchard and Karsten Bolding, is a publicly available 3D numerical model that includes the state of the art GOTM (General Ocean Turbulence Model) turbulence modelling framework. Though not applied to the Ems itself, Stanev et al (2003 a, b) describe use of the numerical model GETM to the tidal inlets of the Wadden sea islands from Nordeney northwards to the Elbe inlet. As such, this model covers a small portion of the outer Ems estuary and forms the boundary condition that affects the larger Ems/Dollard estuary.

5.1.5 Telemac 2D

The numerical model Telemac 2D was used by Pleuss (2001) to model the effect of wind on the hydrodynamics of the Ems.

5.2 Sediment transport models

In the Ems estuary, both analytical and numerical models of sediment transport have been applied. These are described below.

5.2.1 Analytical models

McLaren et al (1998) describe the results of a Sediment Trend Analysis (STA) model used to estimate patterns of net sediment transport by investigating relative changes to the grain size distribution of bottom sediments and bottom bathymetry. The erosion, deposition, and dynamic equilibrium of bottom sediments is also estimated. Tidal basins in the Netherlands, including the Ems/Dollard, follow similar patterns. Sediment is transported up a network of dendritic tidal channels to intertidal mudflats, where net deposition occurs. Convergence zones are defined by fine sediments, and separate tidal basins from each other. The STA analysis can be used to define locations for dredging spoils, design channels, analyze the effect of coastal structures, and estimate the dispersal of contaminants. Mulder and Mijwaard (1997) applied STA analysis to the Ems/Dollard. Results are shown in figure 5.2 Merckelbach and Eysink (2001) use trend analysis of suspended sediments in the Ems estuary to understand the sedimentation occurring in the harbor of Delfzijl.

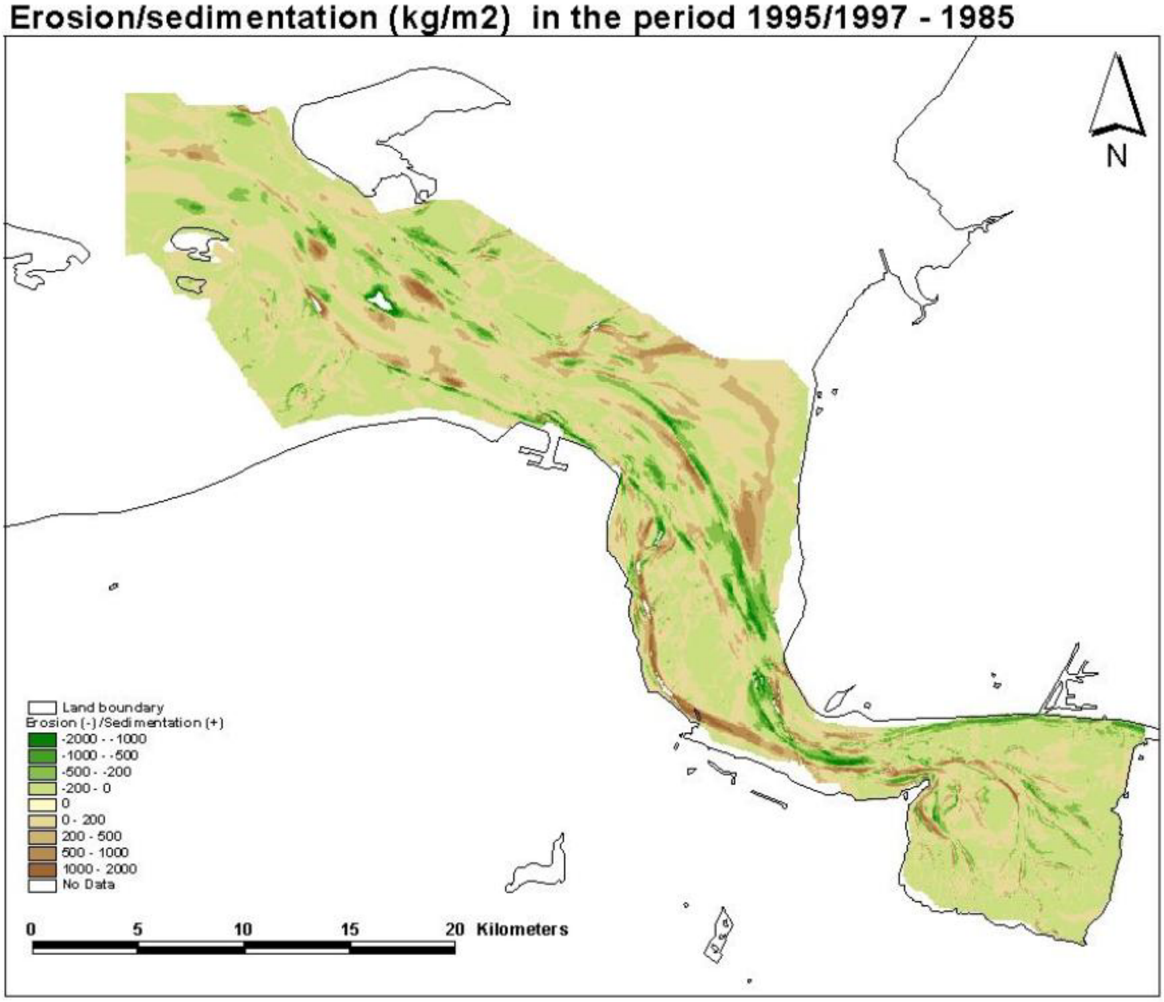


Figure 5.2 Erosion and Sedimentation found using STA analysis between 1985 and 1990, adapted from Mulder and Mijwaard (1997). Green denotes erosion, while brown depicts sedimentation.

5.2.2 Numerical models

Boon et al (2002) describes how Delft3D-Sed is used to model sediment transport and the affect of alternative sediment disposal in the Ems/Dollard sites with-in the SIMONA framework of models. The study concludes that all the proposed alternative dumping sites would increase sedimentation rates in the harbours of Delfzijl and Emden. On the order of 4% and 7% of total dumped sediment, respectively, would end up in the harbours. The BAW in Germany uses the SEDIMORPH model to simulate sediment transport and morphological changes. Sediment transport is coupled to the unTRIM3D model, and the differential settling and transport of 5 different size classes of particles can be modelled.

5.3 Flocculation and consolidation models

The flocculation of cohesive sediments is critical for estimating the settling velocity of particles, and therefore estimating long-term patterns of sediment transport and consolidation. Various analytical models have been developed based specifically on measurements in the Ems/Dollard estuary.

Van Leussen (1999) compared flocs in the Ems estuary and found that that settling velocities vary by several orders of magnitude even when sediment concentrations are the same. Therefore, other factors besides sediment concentration are important, including physical-chemical and biological effects. The concept of flocculation ability is introduced to explain the large differences in settling velocity of flocs. Combining data from the Dollard, the Gironde, and the Tamar, Manning (2004 a) created a statistical regression model between settling velocity and both the turbulent shear stress and the suspended particulate matter concentration. The regression shows that flocculation and hence settling velocity increase up to a shear stress between 0.36 N/m^2 and 0.42 N/m^2, at which point turbulence tends to break up flocs and decrease the settling velocity.

Merckelbach (2000) devised an analytical model to simulate the consolidation of mud flocs under quiescent conditions. The modelled density, pore water pressure, and strength (shear stress) were compared to measurements of Dollard mud in a settling tube. The constitutive equations were modelled using a scale-invariant, fractal bed structure consisting of clay. The modelled density evolution matched well with the measured densities. A partial segregation that occurred in the Dollard mud was also predicted. A criterion for mud failure (onset of flow) was developed and indicates that the critical shear stress is related linearly to the clay volume fraction and to the effective stress. Above 100 Pa, effective stress dominates

Winterwerp (2002) developed a model to estimate the settling velocity of cohesive sediments and applied the model to the Ems estuary. The model accounts for the aggregation and break-up of mud flocs by turbulence. The canonical formula (Stokes law) for the settling of spherical particles is modified by the fractal dimension of the mud flocs. At high concentrations, the model accounts for hindered settling; as concentration increases, settling velocity approaches zero and the suspension becomes fluid mud. The model for the settling velocity of flocs was implemented into a 1 dimensional turbulence model, and was applied to the turbidity maximum of the Ems river. The model results compared well to measurements of the vertical suspended concentration, floc size, and fluid-mud concentration. Large temporal variations in settling velocity and the time needed to flocculate were predicted by the model.

5.4 Dispersion and mixing processes

Modelling mixing and dispersion processes in an estuary is essential for analyzing the fate and transport of sediment, nutrients, contaminants, and biota. A number of analytical and numerical models have been used to estimate both horizontal and vertical mixing In the Ems and Dollard, and are described below.

5.4.1 Longitudinal mixing

Dorrestein and Otto (1960) estimate dispersion coefficients in the Ems using a box model. Helder & Ruardij used a box model and salinity distributions from 1970 to 1977 to estimate flushing times and predict dispersion. Results suggest that the Dollard is flushed on average in 14 days, and the Ems estuary in 38 days. Turnover times and residence times vary with freshwater discharge. Zimmerman (1988) estimated the residence time of the Ems estuary using box models over the entire estuary and using local time scales that vary with position. Beerens (1995) applied a 2D numerical model to the Ems estuary to estimate the chaotic mixing of residual eddies numerically. De Swart et al (1997) calculated dispersion coefficients for the Ems using the chaotic mixing model of Zimmermann, finding coefficients that were a factor of 3 or 4 greater than previous studies using a box model. De Swart concludes that mixing by residual circulation patterns around sand banks is much greater than mixing from shear dispersion.

Van Es and Ruardij (1982) use a mixing and flushing time model to calculate the dispersal of organic waste in the Dollard and its effect on oxygen levels. Reaeration proved to be the dominate source of oxygen, though primary production was important in the summer. During high discharge of waste, the oxygen demand in the mouth of the Dollard was up to 4x background levels. Louisse et al (1986) use a fluorescent tracer to track the spread of cohesive sediments after the dumping of dredging spoils. Mulder (1999) applies a model to investigate resuspension and dispersion of dredging spoils from the Eemshaven harbour.

5.4.2 Vertical mixing

Van der Ham et al (2000 a,b) made in-situ measurements of velocity and suspended sediments in a tidal channel over several tidal cycles. In unstratified conditions, turbulence characteristics behaved similarly to experiments in laboratory flumes. Sediment induced stratification occurred during low flow conditions or during times of high suspended sediment concentration (Van der Ham et al ,2000 a). The ensuing vertical density gradients cause a decrease in correlation between streamwise and vertical velocity fluctuations. The measured time series of velocity, suspended sediment concentration, and turbulence properties were then compared to the results of a 1D k-epsilon turbulence model applied in the vertical direction. The rapid settling of sediment around slack water is caused by density stratification and a reduction in mixing (Van der Ham et al, 2000 b). During high velocities, sediment concentrations are limited by the supply of sediment. A sediment settling velocity of 0.5 mm/s is estimated, though no algebraic dependence of settling velocity on SSC or turbulent energy is found (Van der Ham et al, 2000 b).

5.5 Storm surge and waves models

Storm surge and waves are both caused by the stress applied by wind to the surface of the North Sea and Ems estuary, and are greatly affected by bathymetry. Models of storm surge and waves therefore require knowledge of both local wind fields and local bathymetry.

5.5.1 Wave models

The numerical wave model SWAN is implemented into several numerical modelling packages. Boon et al (2002) use SWAN as part of the SIMONA suite of models to determine the feasibility of various proposed dumping sites. Using the wave model SWAN, Berkhahn and Mai (2004) investigate the effect of differing mesh types on the simulated propagation of waves in the Ems estuary. Niemeyer & Kaiser (2002) use the wave model SWAN to help model storm surge in the Ems river.

5.5.2 Storm surge models

Pluess et al (2001) present a coupled meteorological/ hydrodynamic model to simulate storm surge in the Ems, Jade-Weser, and Elbe estuaries. For the wind field they use a potential flow wind field with Mass Consistent Wind forcing (MCW). In the Ems, they use the Telemac 2D numerical model to simulate the effect of wind on the hydrodynamics. Wetting and drying of intertidal flats is included in the model. The effect of storm surge varies locally with hydrographical structures, bathymetry, exposure to wind, and fresh water discharge. In the Ems, the storm surge of January, 1994 is well represented by the model (see figure 5.3) The duration of the largest winds in various parts of the estuary (between 16 m/s and 25 m/s) is critical for the ensuing elevation of storm surge. The maximum storm surge was reached in Leerort.

Niemeyer & Kaiser (2002) use a statistical model as well as the wave model SWAN to model storm surge on the Ems River between Emden and Herbrum. They conclude that the increased tidal range in the river due to deepening has left many dykes below design requirements and therefore vulnerable to storm surge. They note that this study was part of the rationale for building the Emssperwerk storm surge protection barrier, and formed the technical part of the legal justification for building the Emssperwerk.

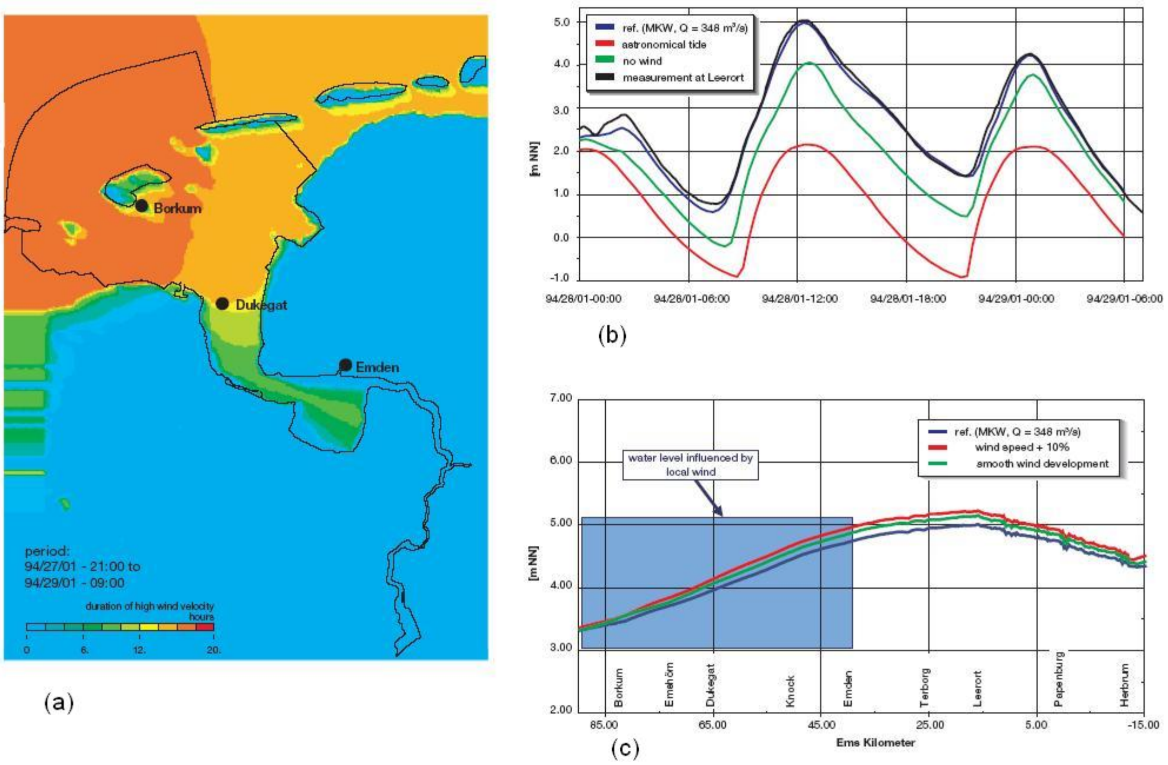


Figure 5.3: Results adapted from the Pluess et al (2001) storm surge model. Panel (a) shows the length of time wind exceeded 16 m/s during a large storm in January 1994. Panel (b) shows the agreement between the modelled and measured tidal heights at Leerort (blue and black lines), and presents the astronomical tide (red line). Panel (c) shows the maximum rise in water level over the longitudinal axis of the estuary.

5.6 Hydrological and land-use models

Two primary models are currently used by German scientists to estimate the input of nutrients to the Ems estuary and to evaluate the affect of changing policies, land use, and management techniques.

5.6.1 REGFLUD

The model REGFLUD, which stands for "Management regionaler Flusseinzugsgebiete in Deutschland" (Management of regional river catchments in Germany), is an aggregation of 3 hydrological and land-use models: an agricultural sector model (RAUMIS), a water balance model (GROWA) and a residence time/denitrification model (WEKU). This model essentially models the upstream boundary condition of nutrient fluxes into the Ems estuary. The REGLUD project aims to reduce pollution from diffuse agricultural sources (Kunkel et al, 2003, Kunkel et al 2005 a,b).

REGFLUD is extensively used by a consortium of German scientists (see http://www.faa-bonn.de/proj1.htm) to model the hydrology and nutrient inputs of the Ems catchement area.
For example, Bogena et al (2004) use CORINE land cover data and REGFLUD to estimate water and nitrogen fluxes in the Ems region. Tetzleff and Wendland (2004 a, b) evaluate the aggregate effect of diffuse sources of Phosphorous from ground water, overland flow, cities, drainage, and soil erosion, focussing on the effect of raised bogs used for agricultural purposes (livestock). An example of simulated phosphorous export is given in Figure 5.4. Goemann et al (2003) and Goemann et al (2005) use the REGFLUD model to investigate the effects of policy options on reducing diffuse pollution from agriculture in the Ems catchment. Similarly, Kunkel et al (2003, 2005 a,b) uses REGFLUD to estimate nitrogen surpluses in the Ems catchment, and analyze the impact of different policies such as a nitrogen tax or the density of livestock. For more information on the REGFLUD project, see http://www.faa-bonn.de/proj1.htm or http://www.bw.fal.de/Projekte/LR/kreins-p2.htm).

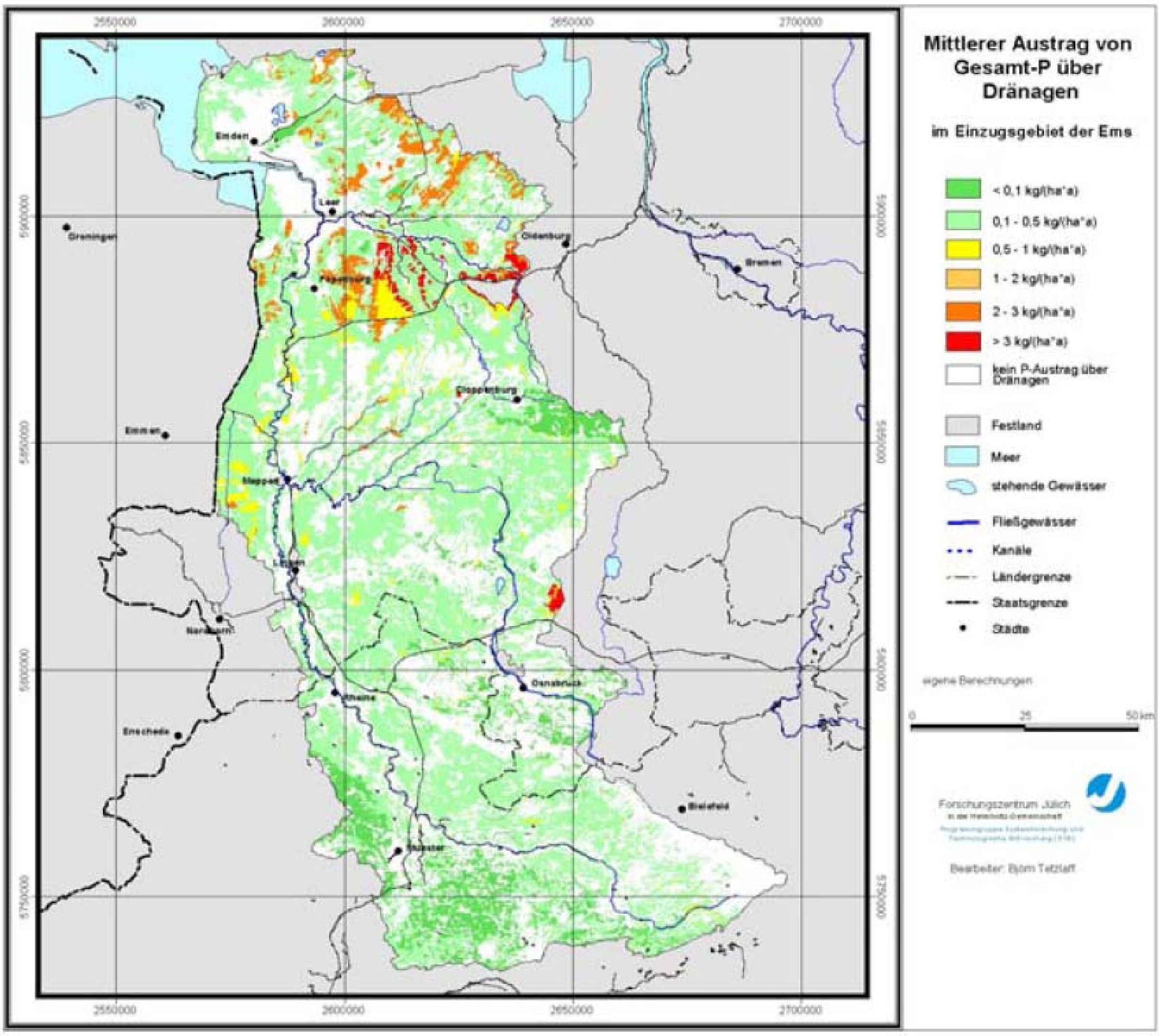


Figure 5.4 Simulated export of phosphorous from the Ems catchment basin using REGFLUD. Red coloration indicates high phosphorous concentrations in the drainage water, while green indicates low phosphorous concentrations. Figure adapted from Tetzleff and Wendland (2004 a).

5.6.2 FLUMAGIS

The FLUMAGIS project is a consortium of German scientists (in the fields of limnology, landscape ecology, hydraulic engineering, hydrology, geoinformatics and socioeconomy) that work on the development of methods and 3D visualization tools to help with the planning and management of river basins. The FLUMAGIS project has developed an interactive tool for the evaluation and 3D visualization of the upper (non-navigable) Ems river, with a focus on the landscape ecology and the mass balance of water and scalars (Möltgen et al, 2004 a,b). Through 3D visualization, the effects of various planning scenarios become transparent and can be discussed and experienced in a participatory planning process (see Möltgen et al, 2004 a,b). More information on the FLUMAGIS project can be found at their website, www.flumagis.de .

The FLUMAGIS project led to the development of a Spatial Decision Support Systems (SDSS) model for the upper Ems basin termed FLUMAGIS-SDSS (see Möltgen et al, 2004 a,b). This model basically combines GIS software, knowledge modelling, and hydrological and socio-economic models. Water balances and matter fluxes are modelled with imbedded models at different scales, for example NASIM (micro to meso scale), ArcEGMO (micro to macro scale), SWAT (meso to macro scale) and ABIMO (macro scale; see Möltgen et al, 2004 a,b). In addition, the BEMO model is used for socioeconomic modelling and the software 'Protégé' is used for knowledge base and decision modelling. As shown in figure 5.5. The results can be viewed in 2D or 3D (see Möltgen et al, 2004 a,b).

Bohn (2004) describes the importance of the alluvial plain in the Ems catchement for making policy decisions to fulfil EC Water Framework directives. The ecological health of surface waters in the upper Ems river basin is evaluated by Poepperl and Meyer (2004). Other references can be found at www.flumagis.de .

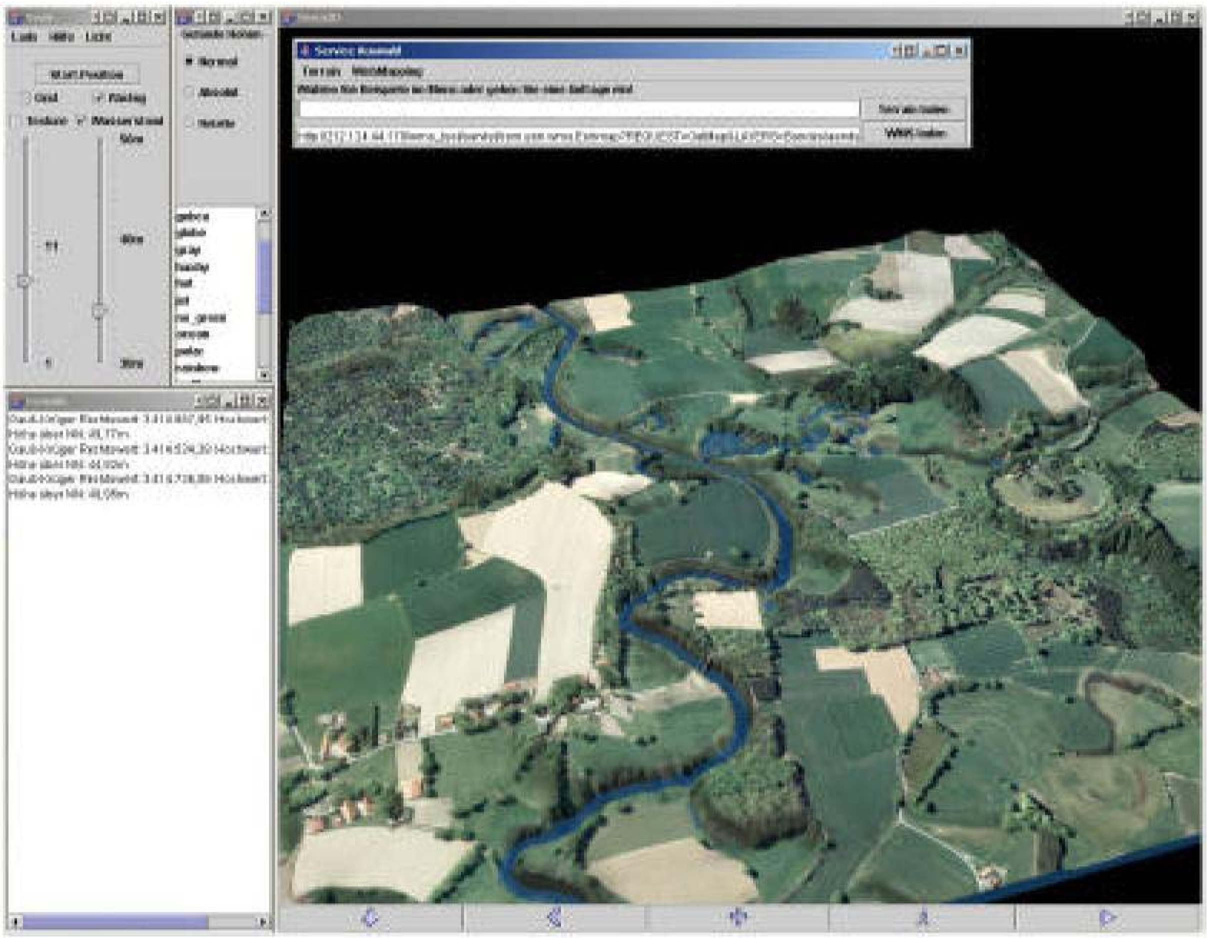


Figure 5.5: Example of the 3D visualizion software FLUMAGIS-SDSS applied to the upper Ems (non-navigable) watershed. Adapted from Möltgen et al, 2004a.

6.0. Changes in the physics of the Ems

Over the past 50 years both the tidal range and the turbidity in the Ems estuary has increased, changing the hydrodynamics and morphodynamics of the system. The changes are described below.

6.1 Tidal range

Harten (1979) describes how deepening of rivers has changed the tidal dynamics in German estuaries including the Ems. Jensen et al (2003) determine that the tidal range in the Ems river is increasing both due to sea level rise and deepening of the navigable channel.

Between the years 1855-2001, the mean tidal range (MTR) increased by about 13-15 cm/century along both the German coast and barrier islands (Töppe, 1993 & Jensen and Mudersbach, 2005). However, between 1965 and 2001 the rate of change in tidal range dramatically increased. Along the barrier islands, the MTR is now increasing at 32.8 cm/ 100 yr. As shown in figure 6.1, the rate of increase in the mean tidal range at the coast was even larger, at 51 cm/100 years between 1965 and 2001 (Jensen and Mudersbach, 2005). Most of the change occurs from an increase in the mean high water (MHW) of 40 cm/ 100 years (see figure 6.2). These trends are echoed in the Ems estuary. Between 1944 and 1999, tidal range increased by 25.3 cm/100 yr in Borkum, but 57.2 cm/100 yr in Emden (Jenson et al, 2001). Overall, mean low water in Emden has decreased at an average rate of 24 cm/100 y after 1944, while the mean high water has increased at a rate of 33.2 cm/ 100 yr, for a combine 57.2 cm/100 yr (Jensen et al, 2001).

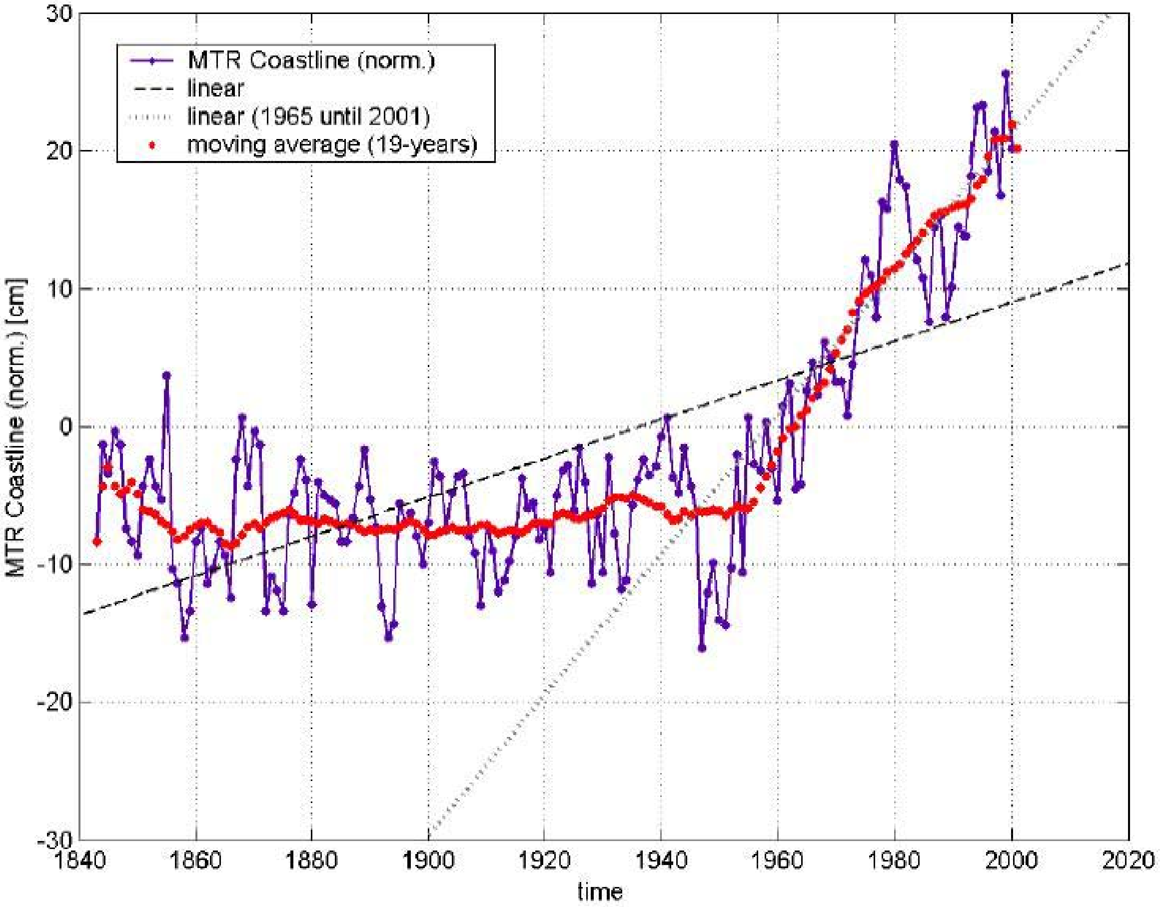


Figure 6.1 Mean tidal range observed at tidal gauges along the German coastline. The red line is an 18.6 year average. Adapted from Jensen and Mudersbach, 2005.

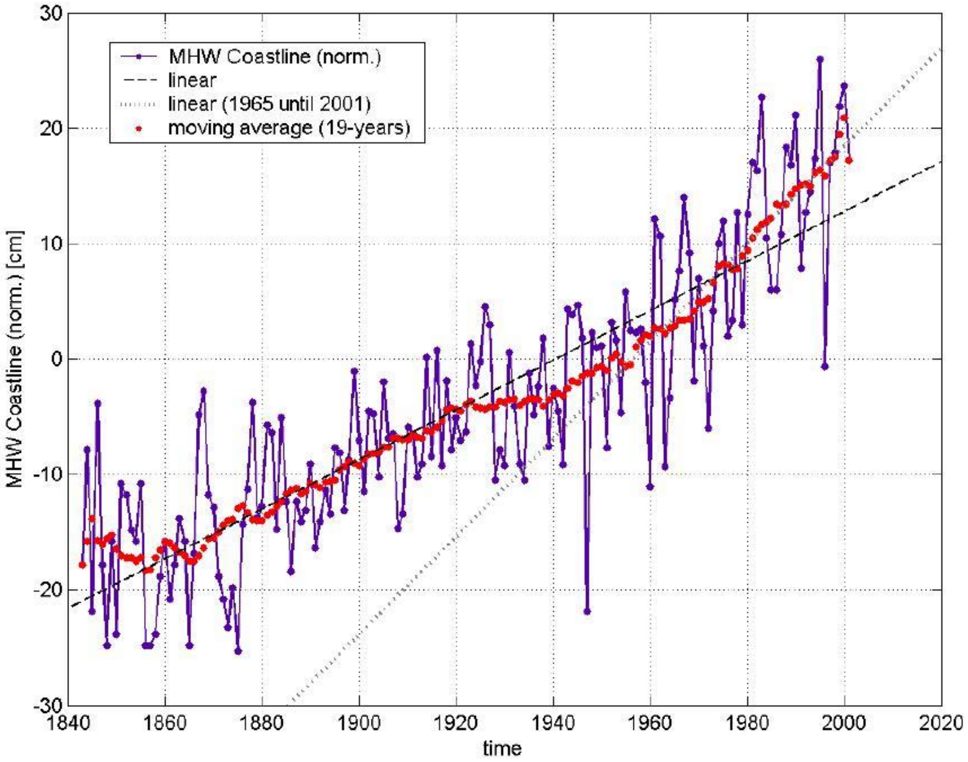


Figure 6.2: Increase in the mean high water level along the German North Sea coast, adapted from Jensen and Mudersbach (2005). The red line represents an 18.6 year moving average.

Further upstream, Jensen et al (2003) determine statistically that the tidal range in the brackish region of the Ems River is increasing both due to sea level rise and deepening of the navigable channel. Changes in the mean high water (MHW) in Borkum are amplified upstream. Currently, a 1 cm increase in mean high water at Borkum results in a 1.7 cm increase in MHW in Papenburg and a 1.2 cm increase at Herbrum (Jensen et al, 2003). Before 1960, changes to the mean low water (MLW) in Borkum were not coupled to changes in MLW in Herbrum (Jensen et al, 2003). This has been changing recently as the river is deepened and the hydraulic roughness decreases (Jensen et al, 2003). Currently, a 1 cm decrease in MLW at Borkum results in a 1 cm decrease in MLW in Herbrum (Jensen et al, 2003). However, the data used for this trend appears to be somewhat scattered and inconclusive.

Deepening and streamlining the channel between Knock and Pappenburg has greatly reduced the mean low water in Herbrum and Pappenburg, but has only slightly influenced the mean high water (Jensen et al, 2003). The difference between the mean low water (MLW) elevation in Borkum and Herbrum has decreased from ~2.1 m to ~ 50 cm since the 1940's, as can be seen in figure 6.3. Between 1959 and the present there have been two distinct downward shifts in the mean low water at Herbrum (figure 6.4). The shifts correspond to the deepening of the Emder Fahrwasser by the construction of the Geiseleitdamm between 1958-1961 and the deepening of the channel between Emden and Pappenburg starting in 1985/1986. Overall, the tidal range in Papenburg has been increased by about 1.5 m (Jensen et al, 2003).

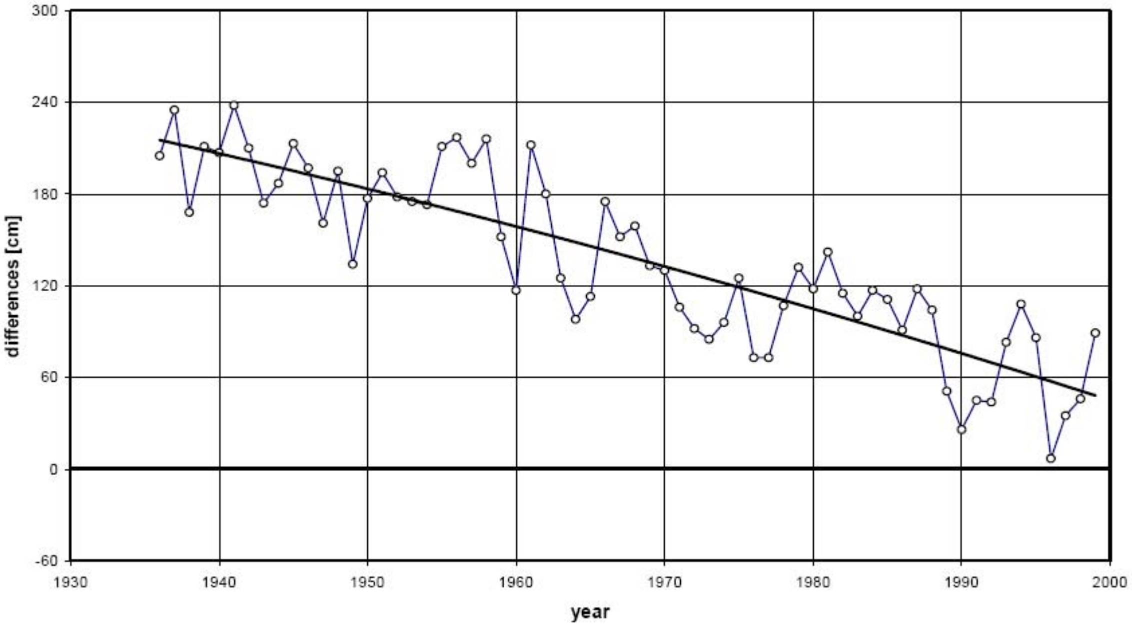


Figure 6.3: Decrease in the elevation difference of the mean low water (MLW) between Herbrum and Borkum. Adapted from Jensen, 2003.

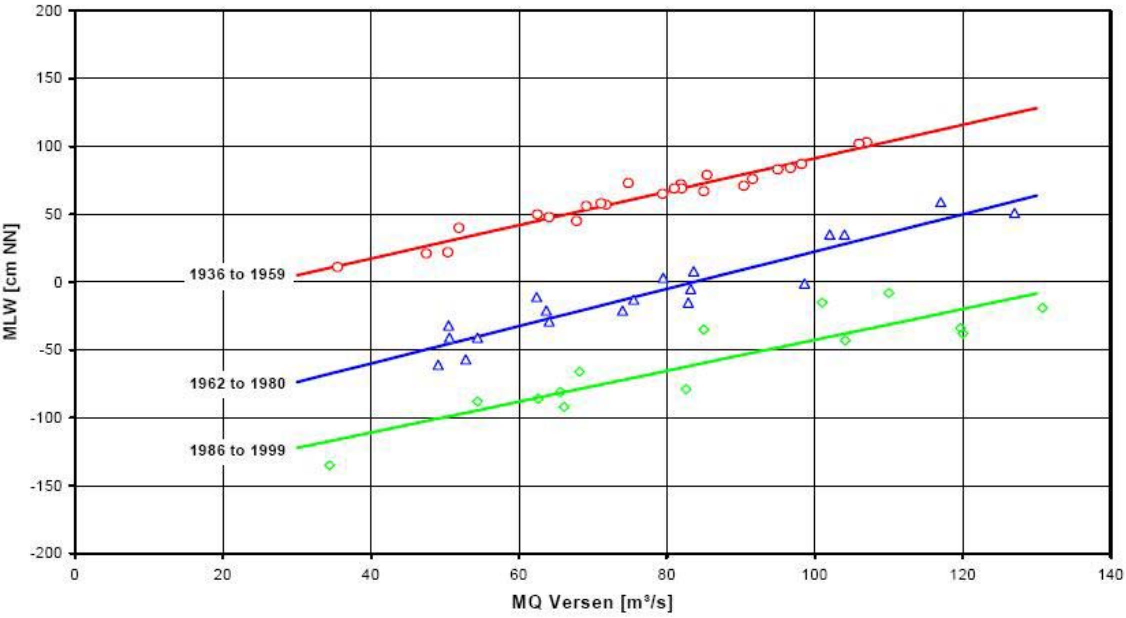


Figure 6.4: Increase in the mean low water at Herbrum as a function of the mean fresh water flow measured in Versen. Note that the mean low water (MLW) for a given flow has decreased due to anthropogenically induced changes in the tidal range. Adapted from Jensen et al, 2003.

The deepening of the Ems River and estuary has caused a decrease in the hydraulic roughness of the river, and lessened the affect of friction on tidal propagation (de Jonge, 1983, Jensen et al, 2003). A regression analysis by Jensen et al (2003) shows that the tidal range in the Ems River has become more sensitive to changes in the North Sea tidal range. Moreover, a decrease in the time lag between the high tide and slack water in Knock (see figure 6.5) further suggests that friction in the main channels of the estuary has decreased (de Jonge, 1983). Therefore, more tidal energy reaches the weir in

Herbrum and tidal velocities are increased (Habermann, 2003). Rising sea levels over the entire estuary may similarly decrease hydraulic roughness. Since deepening the shipping channels and the change in mean sea level and tidal range causes changes to the morphology of the entire system, it is possible that elevations increase in other parts of the estuary (see e.g. De Jonge, 1983), causing a localized decrease in velocity and increased friction. This is true at the dumping sites like the Bocht of Watum, which have been silting up (Boon et al, 2002). In any case, the tidal dynamics are distorted by changes to the morphology of the system. A further consideration is the import and export of sediment. If the estuary is losing sediment, then the mean depths must decrease; similarly, a net import of sediment increases the mean depth. The Dollard is known to be slowly silting up (Mulder, 2004), which presumably counteracts the effects of hydraulic changes caused by the rise in mean sea level to some extent. More research is necessary.

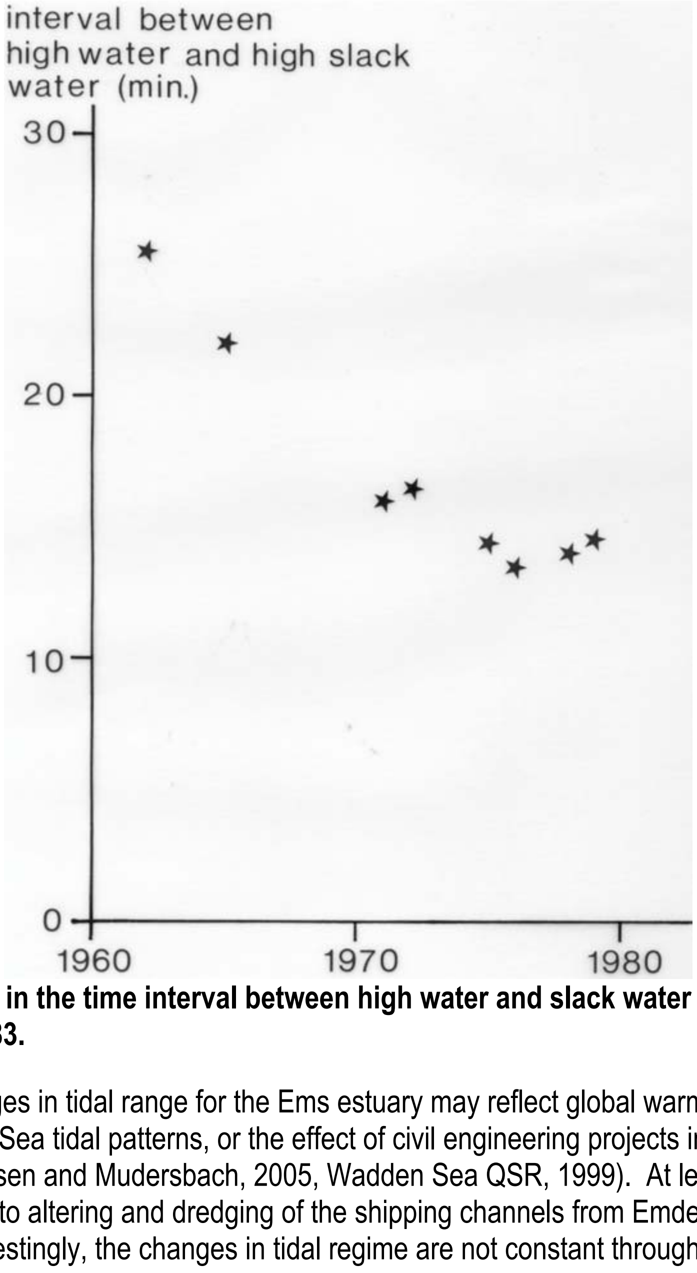


Figure 6.5 Change in the time interval between high water and slack water at Knock. Adapted from de Jonge, 1983.

The observed changes in tidal range for the Ems estuary may reflect global warming trends, natural oscillations in North Sea tidal patterns, or the effect of civil engineering projects in the German estuaries (Töppe, 1993 & Jensen and Mudersbach, 2005, Wadden Sea QSR, 1999). At least some of the change in tidal range is due to altering and dredging of the shipping channels from Emden to the North Sea (de Jonge, 1983). Interestingly, the changes in tidal regime are not constant throughout the estuary. Changes are smallest in Borkum, larger in Emden, and most evident in Herbrum. The change of the tidal range in the upper reaches of the tidal Ems is dominated by the lowering of the mean low water. The reverse is true in Emden and the outer Ems estuary, where an increase in the mean high water dominates. Historically, the tidal range in Emden and Borkum follow each other. The current decoupling of that trend clearly suggests that deepening and altering the shipping channel has changed tidal behaviour in the Ems.

The changes in tidal range alter the tidal velocities and change the morphodynamic equilibrium of the estuary (de Jonge, 1983). Lowering the MLW also lowers the groundwater table, which has a negative impact on marshes fringing the estuary (Wadden Sea QSR, 1999). The changes in tidal asymmetry due to deepening of channels are unknown. Curiously, however, the high water in Pappenburg begins decreasing while tidal levels in Leerort, further downstream, are still increasing.

6.2 Turbidity, turbidity maximum, and sediment concentrations

The Ems river and estuary is much more turbid that in the past. De Jonge (1983) shows that sediment concentrations in the turbidity maximum in the Ems changed from about 100 mg/L in 1954 to about 300-400 mg/L in the 1970's and 1980's. At the same time, visibility decreased as the water became 5-10 times more turbid (Kuehl & Mann, 1973). De Jonge (1983) shows that the increase in turbidity and sediment concentration correlates with an increase in dredging activity and the length of the shipping channel that is dredged. In the 1950's average sediment concentration for the estuary was less than 50 mg/L (de Jonge, 1983). Between 1973 and 2000, the average increase in sediment concentration at Dutch monitoring stations in the Dollard and outer Ems appears to be 1-2 mg/L/ year (Merkelbach and Eysink, 2001), for a total change of 30-60 mg/L. This is significant compared to the average concentration of 100 mg/L in the Dollard over that time period (Merkelbach and Eysink, 2001). Raised turbidity is also observed immediately following the dumping of dredging spoils (Bfg, 2001).

Over the last 15 years, an increase in the depth of the shipping channel between Emden and Pappenburg is correlated with a large increase in the maximum sediment concentrations in the Ems river. Moreover, the turbidity maximum has moved upstream (Habermann, 2003, Wurpts, 2005). Surface water concentrations of nearly 5 g/L have been measured during the summer months (Stefan Talke, unpublished data) compared to a maximum of ~ 300-400 mg/L in the early 1980's (de Jonge, 1983). Data from fixed measurements located between 1-2 m above the bed or floating about 1 m beneath the surface indicate that concentrations sometimes exceed 25 g/L during the late summer (personal communication, H. Juergens). At these concentrations, sediment is no longer suspended in water but forms fluid mud that can be more than 2 meters thick. Even during a period when dredging ceased for a year, measured sediment concentrations remained high (Habermann et al., 2006). Therefore, the increase in sediment concentration and turbidity is likely related both to the changing physics of the system as well as individual dredging events.

The grain size distribution in the turbidity zone consists of about 50% clay ('Klei'), 20% sand, 10% sand/clay mixtures, and another 20% organic material or 'schlick' (Dette et al, 1994). Dette et al (1994) report that this distribution holds from Emden to Leerort. Between Leerort and Pappenburg, Dette et al report that sediment is mostly fine to medium grained sands (70-80%).

Since the early 1990's, however, two factors appear to have altered the distribution of sediments. First, the turbidity maximum has moved upstream (Habermann et al, 2003, Wurpts, 2005). Second, in contrast to other estuaries, the high turbidity zone in the Ems now extends into the freshwater zone to Pappenburg and even Herbrum (Habermann, 2003). Spingat and Oumeraci (2000) and Habermann (2003) suggest that this is due to asymmetry between flood and ebb tidal motions. Talke et al (2005) suggest that turbidity currents caused by high sediment concentrations may also contribute to sediment flux into the freshwater zone.

The zone of high turbidity in the Ems is asymmetrical. On the seaward size of the turbidity maximum, sediment concentrations sharply increase from background concentrations to the maximum over a range of 5-10 km (Talke et al, 2005). On the upstream side of the turbidity maximum, sediment concentrations gradually decrease to background levels over a distance of 10-20 km. Depending on freshwater flow conditions, the turbidity maximum changes location (Habermann, 2003, Dette et al, 1994). Currently, the turbidity maximum may occur around Pogum during large flow events in the winter and is typically found near Leerort in the summer (personal communication, H. Juergens). Oxygen concentrations are greatly decreased by the high turbidity during the summer months, and the minimum oxygen concentration is measured upstream of the turbidity maximum (personal communication, H. Juergens; Talke et al, 2005). There is a strong spring-neap variation in the oxygen signal (personal communication, H. Juergens).

6.3 Erosion/sedimentation processes.

The increase in turbidity and fluid mud over much of the Ems River has important consequences for the erosion and deposition of particles. The entrainment of fluid mud into the water column is quite different than the erosion of sandy sediments (e.g., Winterwerp, 2002). Sand is eroded above a critical stress and tends to form ripples and dunes along the bed which increase roughness (see e.g., Habermann, 2003). Fluid mud is entrained by shear instabilities between fluid mud and water, both of which may be moving (e.g., Mehta & Maa, 1986). The fluid mud also causes density stratification in the water column, which alters the distribution of velocity and therefore tidal propagation (van der Ham & Winterwerp, 2001; Gabioux et al, 2005). Tidal friction characteristics in the Ems may have changed due to the upward migration of the turbidity zone (Habermann, 2003). Moreover, the settling velocity of cohesive sediments (described in chapter 4) depends critically on biological and turbulence processes. Because sediment concentrations are large enough to significantly affect the vertical mixing of water and the turbulence in the water, large variations in settling velocity are observed over a tide (van der Ham & Winterwerp, 2001). As much as 30 cm of sediment are observed to settle in Pappenburg between the flood slack tide and the ebb slack tide (Habermann, 2003). There is likely a seasonal difference in floc formation and settling velocity, as biological activity changes (Van Leussen,1999). It is possible that the depleted oxygen over the summer months in large parts of the river Ems also have an affect on the physical properties of fluid mud.

The construction of a pipeline in the 1970's and subsequent attempts to protect it from erosion actually led to greater scouring in the area of the Paapsand (De La Motte, 2004). The dredging of a new channel near Eemshaven in 1976 caused a redistribution of the 12.5 m isobaths and altered the location of local sand bars (de Jonge, 1983). Restoration attempts also lead to changes in hydrodynamics and therefore erosion and settling characteristics. Esselink et al (1998) show that the vertical accretion in an abandoned man-made salt marsh was closely correlated to the distance from water channels. Abandoning the drainage system led to the formation of natural levees throughout the marsh and may have contributed to a slower accretion (between 6.6-11.4 mm per year) than observed in other salt marshes. Giani and Landt (2000) describe the initial growth of salt marshes from brackish water sediments.

7.0 Effects of anthropogenic changes

The greatest changes in the last 50 years in the physical functioning of the Ems estuary have been the increased sea level and tidal range, the increased amplitude and frequency of storm surge, and greatly increased turbidity and sediment concentrations (particularly near the estuarine turbidity maximum) Much of the changes can be traced directly or indirectly to anthropogenic influence.

Indirect anthropogenic influence is often attributed to Global Warming. Global Warming models predict that anthropogenically induced $C0_2$ emissions will increase temperature, precipitation, wind velocity, and wave heights along the North Sea Coast. Current increases in the intensity of the North Atlantic Oscillation and the rate of sea level rise are consistent with anthropogenically induced climate change. However, the available literature also suggests other explanations for the observed fluctuations in sea level and climate. Therefore, more study is needed to understand the observed variations.

7.1 Tidal characteristics

The rate of sea level rise in Emden and Borkum showed little variation between 1901 and 2001 (Jensen and Mudersbach, 2005). However, the rate of change in the tidal range has more than tripled in Emden, from 20.4 cm/100 year to 66.8 cm/100 year (Jensen and Mudersbach, 2005). Mean low water is decreasing at -25.4 cm/100 year while mean high water is increasing at 41.3 cm /100 yr. By comparison, the rate of change in tidal range in Borkum has altered from 22.1 cm/100 year to 32.3 cm/100 years (Jensen and Mudersbach, 2005). The differences observed between Borkum and Emden suggest that anthropogenic changes to channel morphology are the cause.

Indeed, increasing the depth of the shipping channels clearly has reduced hydraulic roughness and decreased the propagation time of the tidal wave into the estuary by decreasing friction (de Jonge, 1983). More tidal energy reaches the weir in Herbrum, causing a greater reflection of the tidal wave and increased tidal range (Habermann, 2003). The sharp decrease in mean low water in the brackish reaches of the Ems is clearly related to the construction of the Emder Fahrwasser and deepening of the main channel between Emden and Pappenburg from 1985-1994 (Jensen et al, 2003). The increase in MHW in the Ems estuary is not as clearly correlated to deepening of the shipping channels (Jensen et al, 2003). This is likely because decreasing hydraulic friction results in a lowering of the mean water level as well as an increase in tidal range; put together, that amplifies changes to mean low water and decreases changes to mean high water (Habermann, 2003). Jensen and Mudersbach (2005) suggest that decreased hydraulic roughness or amplification of the tidal wave by resonance (in the manner of a standing wave) may explain the increase in the mean high water and tidal range over the entire estuary. Increased resonance may be caused by increasing mean water levels (Jensen and Mudersbach, 2005), or by deepening of the main shipping channels.

The observed changes to the tidal regime alter the hydrodynamics and morphodynamic equilibrium in the estuary, drive patterns of sedimentation and erosion, and affect biota (de Jonge, 1983). Schuchardt (1995) analyzed the increase in tidal range in the Ems over the last century from civil engineering projects, and shows that tidal changes are an indicator of ecological distortion. The ecological disturbance of changes to high and low tide levels, areas of open water and mud flats, hydrodynamics, submersion times, ground water, and the salt gradient are examined. Lowering the MLW decreases the groundwater table, which has a negative impact on marshes fringing the estuary (Wadden Sea QSR, 1999). An effect of deepening the shipping channel of the Ems river is that storm surges have become a greater danger than floods, and that dikes have required reinforcing (Wadden Sea QSR, 1999). Waves from passing ships and increased tidal currents have required shoreline reinforcement projects (Wadden Sea QSR, 1999)

On the western boundary of the Ems, long-term sea level rise causes the Wadden Sea islands to migrate towards the coast (Wadden Sea QSR, 2004). Because the coastline is fixed by dykes, natural erosion processes along the coast are halted and the distance between the islands and the mainland decreases. The resulting 'coastal squeeze', coupled with sea level rise, has reduced intertidal mudflats in the Wadden Sea by as much as 58% from pre-dyke levels along the Wadden Sea coast (Delafontaine *et al.*, 2000). Some literature suggests that intertidal mudflats may eventually disappear in the Wadden Sea (Flemming and Nyandwi, 1994).

7.2 Increased Turbidity and Sediment Concentration

Changes to the turbidity and sediment concentration in the Ems are related both to dredging and dumping activities and to the changed tidal dynamics due to deepening of channels. Therefore, anthropogenic changes dominate the increase in turbidity. In order to maintain and deepen shipping channels, periodic dredging occurs over virtually the entire estuary, from Borkum to Pappenburg. De Jonge (1983) shows that dredging results in increased sediment concentrations and turbidity. He suggests that a cessation of dredging would allow sediment concentrations to return to the level of the 1950s. Habermann (2003) echoes this conclusion, hypothesizing that time is needed for bedforms and ripples to reform, which in turn would increase hydraulic roughness and nudge the system towards pre-dredging conditions. However, a recent year without dredging between Emden and Pappenburg did not decrease sediment concentrations appreciably (Habermann et al., 2006). Therefore, the physics of the system and the natural erosion and sedimentation processes have been altered. It is possible that changes to the residual circulation in the Ems river – perhaps because of tidal asymmetry or turbidity induced currents (Spingat and Oumeraci, 2000, Talke et al, 2005) – have altered both the longitudinal extent, and magnitude of the turbidity maximum. Wurpts (2005) also notes that the turbidity maximum has migrated upstream in past years.

Essink (1999) investigates the effect of dredging and dumping sediments in the Ems-Dollart estuary on local ecology. Increased turbidity affects primary production, impairs visual predators such as fish and birds, and impacts the survival of benthic organisms. Filter feeding mussels are stressed at sediment concentrations greater than 250 mg/L. Nematodes can survive burial of up to 10 cm, while mussels and oysters can only cope with a change of 1-2 cm. Recovery of an ecosystem depends on the interval between dumping. Eggens and Bakker (2001) investigate whether HCB (Hexachlorobenzene) resuspended by dredging is harmful to organisms. Because mud/sand mixture from the Emder Fahrwasser (2/3 mud, 1/3 sand) is being dumped in a sandy environment, BfG (2001) reports that both biomass and species composition is being altered at Klappstelle 1-7. In the short term, local turbidity is also increased (BfG, 2001). Near Delfzijl, the concentration of suspended matter has increased between 1970 and 2000 (Merkelbach and Eysink, 2001). In the near future, an alternative dumping site to the Bocht of Watum needs to be found due to siltation and reduction in the navigational depth (Boon et al, 2002). Mulder (2004) gives an overview of the dumping of dredged material in the Ems estuary and its effects.

7.3 Storm surge

The increased frequency of storm surges during the second half of the 20th century occurred in large part because of oscillations in the North Atlantic Oscillation (NAO), as can be noted by comparing figure 2.2 and figure 2.4. The NAO oscillation is not affected by anthropogenic changes to the Ems, though indirect effects from global warming cannot be discounted.

However, the risk of storm surge is also increasing because of rising mean sea level and mean high water. The available literature agrees that deepening of shipping channels is one of the primary reasons for the increasing tidal range (de Jonge, 1983, (Seifert and Lassen, 1986, Niemeyer & Kaiser,2002). Man-made changes to estuarine bathymetry also change storm-surge characteristics (Pluess et al, 2001). It is possible that the decrease in hydraulic roughness and increased wave propagation velocity on the shipping channels could enhance storm surge amplitudes in much the same way as tidal range is increased.

8.0 Current research projects

The current research projects occurring on the Ems Estuary are described below.

8.1 BfG (Bundesanstalt fuer Gewaesserkunde) monitoring project

The Bfg recently monitored the Ems River between Emden and Papenburg during a year in which no dredging occurred (2004), and is continuing to periodically monitor the river after dredging resumed (personal communication, C. Habermann). The overall goal of the project is to better understand the sources of variability in the turbidity signal, and to determine the direct effect of dredging on variations in sediment concentration. To further this goal, 4 cruises have been taken along the longitudinal transect of the Ems with continuous measurements of turbidity, salinity, and temperature. The tidal stage and boat speed are chosen to make the measurements synoptic. In addition, use is being made of the long-term monitoring stations from NLWKN and WSA Emden. Starting in 2006, oxygen measurements will be made along with ADCP measurements for backscatter and velocity distributions. The contact person at Bfg for this project is Christine Habermann (habermann@bafg.de).

8.2 Dynamics of estuarine turbidity maxima (ETM): Coupling of morphology and biology

The LOICZ project is a cooperation between the coastal group of the IMAU institute at the University of Utrecht (Stefan Talke and Huib de Swart), Victor de Jonge from the University of Groningen, and various German and Dutch agencies. The goal of the project is to investigate biological and hydrodynamic processes and feedbacks at the Estuary turbidity maximum of the Ems river, from both an experimental and modelling standpoint. Both short term change on the scale of the tidal cycle and longer term change (years) due to sea level rise, increased dredging, and other natural or anthropogenic changes are being investigated. An extensive field measurement campaign began in February, 2005 and will continue through the summer of 2006. Measurements occur over longitudinal transects of the Ems estuary from Borkum to Herbrum, with selected cross sections near the Estuary Turbidity Maximum. Cruises occur at monthly intervals with ships of RWS (outer Ems) and either WSA Emden or NP GmBH from Emden to Herbrum. Measurements include velocity, salinity, turbidity, and biological parameters such as algae, fluorescence, oxygen, nitrogen, phosphates, and silicates. Contact person for this project is Stefan Talke (s.a.talke@phys.uu.nl). For more information, see http://www.phys.uu.nl/~talke/Ems/Ems_ETM_research.htm.

8.3 Measurements of fluid mud

A team from the University of Bremen, A. Kopf and A. Seifert, are currently starting a project to measure fluid mud on the Ems river. They have devised in-situ instruments to measure fluid mud density and pore-pressure and will begin testing their instruments in 2006. The goal of the project is to obtain a better understanding of the processes that affect fluid mud.

8.4 KFKI Hannover: high resolution turbulence measurements

A team of scientists from the KFKI institute in Hannover led by Prof. Dr.-Ing. Friedrich-Wilhelm Bach is investigating fluid flow around hydraulic structures, with the specific aim of both measuring and modelling fluid flow and turbulence around the Emssperwerk. A high resolution 3D turbulence instrument using particle image velocimetry (PIV) has been developed and will be deployed on the Emssperwerk. Moreover, a numerical model is being developed to simulate the flow conditions.

For more information, see http://kfki.baw.de/fileadmin/newsletter/20050623-kfki-aktuell-en.pdf or http://kfki.baw.de/KFKI-Projekte.7.0.html?tx_kuddelprojects_pi1%5Bproject_id%5D=132&tx_kuddelprojects_pi1%5Bdisplay_project%5D=yes.

8.5 Dispersal of dredging material

WSA Emden recently made extensive measurements in February 2005 to measure the advection and dispersal of sediments in the Dollard after the dumping of dredged material. Measurements were made with multiple ships and fixed instruments, and hydrodynamic variables such a water velocity, turbidity, salinity were measured. As part of the measurements, as many as 600 bottom samples were taken. For more information, contact Helge Juergens or Martin Krebs of WSA Emden.

8.6 HARBASINS-- Harmonised River Basins Strategies North Sea

The HARBASINS project, directed by Hermann Mulder, aims to “enhance the compatibility of the Water Framework Directive and international cooperation on integrated management of estuaries and costal waters in the North Sea Region”. Moreover, it aims at “harmonisation of management strategies leading to estuarine ecosystem restoration in the river basins of the North Sea Region and exchange of knowledge and experiences in successful implementation of the Water Framework Directive between the North Sea partners involved”.

Out of this project “ a network of public authorities and scientific institutions” will be assembled, which will “enable communication required for establishing optimum management, monitoring and assessment techniques”. In addition, the project also aims to “standardise scientific parameters, e.g. a fish-based index for assessing ecosystems”.

Five different work groups are being set up, 3 to deal with scientific issues such as ecology, chemistry, and hydrodynamics, and 2 work groups to deal with management issues. This project began on Nov. 30, 2004 and runs until June 30, 2008. For more information, see http://www.interregnorthsea.org/project-details.asp?id=1-16-31-7-61-04

8.7 Fluid mud transport in estuaries

A group of scientists from the University of Bremen and the Senckenberg Institut led by A. Bartholomae and D. Hebbeln is investigating the sediment dynamics of fluid mud in the Weser and Ems estuaries. Current research includes investigating the variability of suspended sediment and the affect of tides, the spring neap cycle, and seasons on the fluid mud complex. The overall goal is to better understand the variability of fluid mud over time and from that devise strategies for maintaining the nautical depth. Field measurements were made in the Ems Estuary and river in 2005, and another field campaign is scheduled for September 2006. Measurements are being made with ADCP, CTD, and a sediment-echosounder (to measure the formation of fluid mud layers). For more information, see http://www.rcom.marum.de/Projekt_D2_-_Slicktransport_in_Aestuaren.html. Contact person for this project is Dr. Kerstin Schrottke (shrottke@rcom-bremen.de).

8.8. Properties and processes of fluid mud in brackish water harbours

The Research and Education Ministry of Germany (Bundesministerium für Bildung und Forschung, BMBF) is funding several projects to look into the hydrodynamic and sediment transport processes in brackish water harbours, including Emden. The overall goal is to better understand the siltation of harbours and to devise strategies to minimize maintenance costs. As part of KFKI-Projekt 03 KIS 019, field measurements are being performed by Professor H. Nasner to investigate the hydrodynamic and morphological properties. These investigations have then served as the basis for numerical simulations (MIKE 2D and MIKE 3D, see section 5.1.2) by the Franzius Institute in Hannover for the related project 03 KIS 020. In Emden, field measurements of velocity, salinity, oxygen concentration, temperature, sediment concentration, and nautical depth have been made in collaboration with Niedersachsen Ports GmBH. Research is also being focused on the properties of fluid mud, including its chemical and biological content, the particle size distribution and settling velocity, and rheological parameters. For more information, see http://www.hs-bremen.de/Deutsch/Seiten.asp?SeitenID=11491 .

9.0 Conclusions

Many physical changes have occurred to the Ems estuary during the past centuries and millennia. Before the 16th century, the river and estuary changed primarily due to natural processes. This led to the creation of the Dollard region in the 14th and 15th century. From the 16th century until the middle of the 20th century, diking and reclaiming land from the sea increasingly altered the natural equilibrium and was the primary anthropogenic influence. Beginning in the late 19th century, however, efforts to maintain and improve shipping channels and harbours became increasingly important. After WW II, these efforts dominated the anthropogenic influence on the estuary, though other measures such as gas extraction are also important. Anthropogenic developments include deepening and straightening channels and the construction of barriers such as the Geiseleitdamm and the Emssperwerk. Natural changes to the estuary are still large, particularly through yearly and decadal variations in climate conditions. Changes to the North Atlantic Oscillation (NAO) on the yearly and decadal time scale change the storm track through Europe and cause either wet, windy winters or cold, dry winters. The second half of the 20th century saw a large increase in wind, wind driven waves, and storm surge due to an upward trend in the NAO index, though this trend has recently reversed.

The scientific literature available for the Ems has greatly increased scientific knowledge about intertidal mudflats, interactions between biological and physical processes, cohesive sediments, fluid mud, and flocculation, and defines the current ‘state of the art’ in these fields. A rich literature is also available for processes such as estuarine mixing and residence time and the historical reconstruction of tidal range and sedimentation processes. The current literature, however, does not adequately explain the physical mechanisms behind the greatly increased sediment concentrations and fluid mud reaches near the turbidity maximum. The resulting problems such as oxygen depletion are also poorly understood, as are the consequences to the biology and ecology of the Ems. Long term morphological changes and their dependence on human activity are also not adequately understood.

Working numerical and analytical models of the Ems estuary exist for many physical processes considered important: wind and wave propagation, storm surge, tidal variation, mixing and dispersion of scalars such as salt, residual circulation, and sediment transport. Upstream and downstream boundary conditions are also well modelled. Improvements can certainly be made; in particular, the effects of fluid mud and transport processes at the turbidity maximum are not well parameterized. In general, long term morphological change throughout the estuary is not well predicted. However, the currently available models could be effective tools for investigating and diagnosing how man-made changes to bathymetry (such as past or future deepening of the shipping channel) affect tidal propagation and tidal range, storm surge, wave climate, and other short term processes. The output from global climate models can be—and is—used to predict the affects of climate change on the North Sea and Ems estuary.

Past field campaigns have focussed on perceived problem areas. In particular, the eutrophication and oxygen depletion in the Dollard region through the 1970’s led to extensive research through the Boede project. Field campaigns in the 1990’s also focussed on the Dollard. Currently, field research into two current problem areas—the dumping of dredging spoils and the high turbidity in the brackish water Ems—is receiving increasing attention.

Many scientific questions about the functioning of the Ems estuary, and the effects of natural and anthropogenic changes, are still open and unanswered. However, the available evidence and scientific literature seems to point to the following conclusions about physical changes to the Ems estuary, and their causes:

1. The mean sea level in the Ems estuary has increased on the order of 10 cm in the last century. Over the last 50 years, however, the tidal range has begun increasing at a much faster rate than previously. The change in tidal range is largest in the freshwater and brackish regions (e.g., 1.5 m in Pappenburg), and decreases towards the island of Borkum (rate = 32.3 cm/ 100 years).
2. Deepening and streamlining of the shipping channels between Borkum and Pappenburg has increased the rate of tidal propagation into the Ems estuary and decreased the hydraulic roughness. The large fluid mud reaches upstream of Knock may also decrease the friction felt by the tide, though more research is needed. The changes to the channel depth likely explain much of the increase in tidal range.
3. Construction of the Geiseleitdamm from 1958-1961 and the deepening of the Ems River between 1985 and 1994 caused step-changes in the mean low water (MLW) in Pappenburg and Herbrum. The MLW in Herbrum is now only ~ 50 cm above the MLW in Borkum, compared to about 2.1 m in the 1940's.
4. The increase in the MHW has made the Ems estuary more vulnerable to storm surge. Climatic oscillations (NAO index) caused an increase in storminess between the 1950's and early 1990's. The frequency and intensity of storm surges increased. However, wind velocities and wave heights are currently trending downwards.
5. Historical diking and land reclamation, as well as long term sea level rise, likely changed the tidal characteristics of the Ems over the past 500 years (see figure 2.1).
6. Sea level rise has caused the barrier islands of the Wadden Sea to migrate towards the coast. Because the coastline is fixed by dykes, the resulting 'coastal squeeze' has greatly reduced the area of mudflats in the Wadden Sea. In a natural state, the coastline would also erode and the distance to the barrier islands would remain greater. More study is needed in this area, however.
7. Dredging and construction activities in the past 50 years has greatly increased turbidity in the Ems Estuary, particularly near the turbidity maximum in the brackish water portion of the river. Sediment concentrations at the turbidity maximum have increased by more than an order of magnitude. This corresponds to a likely increase in the amount and longitudinal extent of fluid mud, though more research is necessary.
8. Unlike other estuaries, the region of increased turbidity extends far into the freshwater zone. Deepening of the channel and changed tidal characteristics have pushed the turbidity maximum upstream. Overall, the region of enhanced turbidity is as much as 30-40 km long. Potential reasons include tidal asymmetry and currents due to the high turbidity and fluid mud. Again, more research is needed.
9. The biological oxygen demand in the fluid mud layer causes oxygen depletion in the summer months and sometimes forces completely anoxic conditions. The biological and physical reasons and consequences are poorly understood.
10. The port of Emden has introduced a novel method to maintain the navigable depth in Emden: Rather than continuously dredge sediment, the port now oxygenates and stirs the fluid mud in the harbour at 3-6 month intervals. These actions reduce the viscosity of fluid mud and allow ships to pass through as if driving through water. The overall affect of this changed technique on the Emder Fahrwasser and the entire estuary is not well researched.
11. Dredging spoils are harmful to the local ecology, particularly when dumped in the outer estuary. The time of year when dredging spoils are dumped is essential. In this sense, the greatly reduced dredging in the port of Emden is likely positive.

12. In addition to a temperature increase, Global Warming models also predict slightly increased wind, waves, and precipitation in the North Sea Area. While probably important in the long run (century time scale) other variability in climate (such as NAO) appears to dominate over anthropogenically induced climate change in the short term (1-2 decades). The relation between the NAO and global warming is unknown, however.

In the near future, the increasing frequency and size of ships seems likely to continue to drive anthropogenic changes to the form and functioning of the estuary and harbours. Yearly and decadal variations in the NAO index also drive significant variations in fresh water flow, storm surge, and wave heights. Thus, the Ems estuary is constantly changing. Over the long term (100 years), changes to the tidal range, sea level rise, and global warming affects are likely to become more apparent, particularly to the morphology of mudflats and to the estuarine tidal characteristics.

Acknowledgements

Many thanks to the LOICZ project for helping to fund our research on the Ems and to the support of RIKZ, WSA Emden, and Niedersachsen Ports for their expertise and help in carrying out our field experiments on the Ems estuary.

References

(1979). "Numerische Modelle für Tide und Salzgehaltsverteilung im Mündungsbereich der Ems." Kueste **34**.

(1990). "Goose counts in The Netherlands and Belgium in 1987/88 [Ganzentellingen in Nederland en Belgie in 1987/88]." Limosa **63**(2): 71.

(2003). "Stirring up mud - No problem? Ecological effects of the deepening of a gas pipeline in the Ems-Dollard estuary." Hydro Delft(92): 8.

Abril, G., M. Nogueira, et al. (2002). "Behaviour of organic carbon in nine contrasting European estuaries." Estuarine, Coastal and Shelf Science **54**(2): 241.

Ackermann, F. (1980). "A procedure for correcting the grain size effect in heavy metal analyses of estuarine and coastal sediments." Environmental Technology Letters **1**(11): 518.

Admiraal, W. (1977). "Influence of various concentrations of orthophosphate on the division rate of an estuarine benthic diatom, Navicula arenaria, in culture." Marine Biology **42**(1): 1.

Admiraal, W. (1977). "Tolerance of estuarine benthic diatoms to high concentrations of ammonia, nitrite ion, nitrate ion and orthophosphate." Marine Biology **13**(4): 307.

Admiraal, W. (1984). "The ecology of estuarine sediment-inhabiting diatoms." Progress in Phycological Research **3**: 269-322.

Admiraal, W., E. D. De Ruyter van Steveninck, et al. (1989). "Environmental stress in five aquatic ecosystems in the floodplain of the River Rhine." Science of the Total Environment **78**: 59.

Admiraal, W., H. Peletier, et al. (1984). "The seasonal succession patterns of diatom species on an intertidal mudflat: an experimental analysis." Oikos **42**(1): 30.

Admiraal, W., H. Peletier, et al. (1982). "Observations and experiments on the population dynamics of epipelic diatoms from an estuarine mudflat (Ems-Dollard estuary, Netherlands)." Estuarine, Coastal & Shelf Science **14**(5): 471.

Aerts, B. A., P. Esselink, et al. (1996). "Habitat selection and diet composition of greylag geese Anser anser and barnacle geese Branta leucopsis during fall and spring staging in relation to management in the tidal marshes of the Dollard." Zeitschrift fur Okologie und Naturschutz **5**(2): 65.

Alexandersson, H., T. Schmith, et al. (1998). "Long-term trend variations of the storm climate over NW Europe." Global Atmospheric. Oceanic. System **6**: 97-120.

Alexandersson, H., T. Schmith, et al. (2000). "Trends of storms in NW Europe derived from an updated pressure data set." Climate Research. **14**: 71-73.

Alma, C. (1984). "The Eems as a dumping ground for national oil producers." Waddenbulletin **19**(1): 44.

Andersen, T. J., O. A. Mikkelsen, et al. (2000). "Deposition and mixing depths on some European intertidal mudflats based on 210Pb and 137Cs activities." Continental Shelf Research **20**(12-13): 1569.

Anon (1975). "HOW EKOFISK GAS WILL BE BROUGHT TO EMDEN." Gas World Gas J **180**(4676).

Anon (2001). Literatuurstudie over het storten van baggerspecie in de Mond van de Dollard (Literaturstudie ueber das Verklappen von Baggergut in den Dollartmund). Werkdocument RIKZ/AB/2001.615x. W. D. Nederlands-Duitse Eemscommissie and A. D. Deutsch-niederlaendische Emskommission.

Baird, D., J. M. McGlade, et al. (1991). "The comparative ecology of six marine ecosystems." Philosophical Transactions - Royal Society of London, B **333**(1266): 15.

Baird, D. and R. E. Ulanowicz (1993). "Comparative study on the trophic structure, cycling and ecosystem properties of four tidal estuaries." Marine Ecology Progress Series **99**(3): 221.

Baretta, J. W. (1988). "Distribution and abundance of the zooplankton of the EMS Estuary (North-Sea)." Netherlands Journal of Sea Research **22**: 69.

Baretta, J. W. and P. Ruardij (1987). "Evaluation of the Ems Estuary ecosystem model." Continental Shelf Research **7**(11-12): 1471.

Baretta, J. W. and P. Ruardij (1988). Tidal Flat Estuaries: Simulation and Analysis of the Ems Estuary (Ecological Studies).

Battermann, G., B. Boehm, et al. (1977). "Grundwassermodell Ems - Jade. Hydrologische und hydrogeologische Voruntersuchungen." Wasser und Boden **29**(2): 53-56.

Beerens, S. P. (1995). Mixing by Chaotic Advection in Tidal Areas, University of Utrecht. **PhD**.

Behre, K. E. (2004). "Coastal development, sea-level change and settlement history during the later Holocene in the Clay District of Lower Saxony (Niedersachsen), northern Germany." Quaternary International **112**: 37-53.

Bergmann, H. and B. Hoffmann (1976). "Heavy metals in the Ems estuary: proposals for an investigative program" [SCHWERMETALLE IM EMSASTUAR - EIN DISKUSSIONSBEITRAG ZUR GESTALTUNG EINES MESSPROGRAMMS]." DTSCH.GEWAESSERKUNDL.MITT. **20**(2): 43.

Bergmann, H., O. Lehnen, et al. (1978). "Investigations on the transport of heavy metals in the Ems estuary. I. Methodology and first results [UNTERSUCHUNGEN ZUM TRANSPORT VON SCHWERMETALLEN IM EMSASTUAR. I. METHODIK UND ERSTE ERGEBNISSE]." DTSCH. GEWASSERKUNDL. MITT. **22**(4): 106.

Berkhahn, V. and S. Mai (2004). Numerical Wave Modeling based on Curvilinear Element Meshes. 4th Int. Symp. on Environmental Hydraulics (ISEH), Hong Kong.

Bernard, P. C., R. E. Van Grieken, et al. (1986). "Classification of estuarine particles using automated electron microprobe analysis and multivariate techniques." Environmental Science and Technology **20**(5): 467.

BfG (2001). Bagger- und Klappstellenuntersuchungen im EmsÄstuar. Klappstellen 1 bis 7. BfG-1329, BfG-Koblenz, WSA-Emden.

Blasi, C. and J. Jensen (2001). Identification and Management of Hydrological System Parameters of the Ems-Estuary. Proceedings of the 5. International MEDCOAST-Conference, Tunisia, Middle East Technical University, Ankara.

Blasi, C. J. (1998). Statistical Investigations of Hydrological and Water Quality Data in the Ems Estuary. 3rd International Conference on Hydro-Science and -Engineering, Brandenburg University of Technology at Cottbus/Berlin.

Blome, D. (1996). "An inventory of the free-living marine nematodes of the East Frisian Wadden Sea including the estuaries of the Rivers Ems, Jade, and Weser." Senckenbergiana Maritima **26**(3-6): 107.

Boddeke, R., R. d. Clerck, et al. (1970). "Young fish and Brown Shrimp survey in the North Sea." Annals of Biology **27**: 183-187.

Boddeke, R., N. Daan, et al. (1969). "A census of juvenile demersal fish in the Dutch Wadden Sea, the Zeeland nursery ground, the Dutch coastal area and the open sea areas off the coasts of The Netherlands, Germany and the southern part of Denmark." Annals of Biology **26**: 269-275.

BOEDE-groep (1983). Biologisch onderzoek Eems-Dollard estuarium. Texel, Netherlands, Nederlands Instituut voor Onderzoek der Zee, NIOZ.

Bogena, H., H. Goemann, et al. (2004). Use of CLC data for modelling water balance and nitrogen fluxes in Ems and Rhine. In. Workshop CORINE Land Cover 2000 in Germany and Europe and its use for environmental applications, Berlin.

Bohn, C. (2004). Die Bedeutung der Auen für die Umsetzung der Ziele der EU-Wasserrahmenrichtlinie. Interdisziplinäre Methoden des Flussgebietsmanagements, Universität Münster, IfGIprints, Institut für Geoinformatik, Universität Münster.

Boon, J. G., L. Dardengo, et al. (2002). Alternative Dumping Sites in the Ems Dollard Estuary, Delft Hydraulics.

Bouwman, L. A. (1981). "A survey of nematodes from the Ems estuary: Part 1." Systematics. Zool. Jahrb. (Syst. Oekol. Geogr. Tiere) **108**: 335-385.

Bouwman, L. A. (1983). "A survey of nematodes from the Ems estuary: Part 2. Species assemblages and associations." Zool. Jahrb. (Syst. Oekol. Geogr. Tiere) **110**: 345-376.

Bouwman, L. A. and A. J. Kop (1979). "Effects of effluent input on the ecosystem in the Dollard area (Netherlands)." NATUUR TECHN. **47**(12): 668.

Bouwman, L. A., K. Romeijn, et al. (1984). "On the ecology of meiofauna in an organically polluted estuarine mudflat." Estuarine, Coastal and Shelf Science **19**(6): 633.

Brandt, K. (1980). "(The elevation of prehistoric and early historic habitation in the marshlands of northwestern Germany as height indicators of former water levels) [Die Hohenlage ur- und fruhgeschichtlicher Wohnniveaus in nortwestdeutschen Marschengebieten als Hohenmarken ehemaliger Wasserstande.]." Eiszeitalter und Gegenwart **33**: 161.

Cadee, G. C. (1987). Organic carbon in the Ems River and Estuary: a comparison of summer and winter conditions. Transport of Carbon and Minerals in Major World Rivers, Pt. 4. E. T. Degens, S. Kempe and G. Weibin, Mitt. Geol.- Paläont. Inst. Univ. Hamburg. **Sonderbd. 64 SCOPE/UNEP:** 359-374.

Cadée, G. C. and R. W. P. M. Laane (1983). Behaviour of POC, DOC and fluorescence in the freshwater tidal compartment of the River Ems. Transport of Carbon and Minerals in Major World Rivers, Pt.2. E. T. Degens, S. Kempe and H. Soliman, Mitt. Geol.-Paläont. Inst. Univ. Hamburg, SCOPE/UNEP Sonderbd. **55:** 331-42.

Carsiens, R. and R. Wurpts (1987). "DOLLART-DOCK PROJECT EMS BYPASS AND A NEW ACCESS TO THE PORT OF EMDEN." Bulletin of the Permanent International Association of Navigation Congresses **59**: 56.

Chmura, G. L. and D. Eisma (1995). "A palynological study of surface and suspended sediments on a tidal flat: Implications for pollen transport and deposition in coastal waters." Marine Geology **128**(3-4): 183.

Christie, M. C., K. R. Dyer, et al. (1997). Erosion response of estuarine mudflats to tidal currents and waves. Coastal Dynamics - Proceedings of the International Conference.

Clasmeier, H.-D., D. Bennje, et al. (2004). "Neubau der Emspier im Aussenhafen in Emden." Hansa International Maritime Journal.

Clason, B. and G. P. Zauke (2000). "Bioaccumulation of trace metals in marine and estuarine amphipods: Evaluation and verification of toxicokinetic models." Canadian Journal of Fisheries and Aquatic Sciences **57**(7): 1410.

Colijn, F. (1982). "Light absorption in the waters of the Ems-Dollard Estuary and its consequences for the growth of phytoplankton and microphytobenthos." Netherlands Journal of Sea Research **15**: 196-216.

Colijn, F., W. Admiraal, et al. (1987). "Primary production in a turbid estuary, the Ems-Dollard: field and model studies." Continental Shelf Research **7**(11-12): 1405.

Colijn, F. and G. C. Cadée (2003). "Is phytoplankton growth in the Wadden Sea light or nitrogen limited?" Journal of Sea Research **49**(2): 83.

Colisv, F. (1983). Primary production of phytoplankton in the Ems-Dollard Estuary. BOEDE-Publicaties en Verslagen, University of Groningen. **PhD:** 123.

Coquery, M. and D. Cossa (1995). "Mercury speciation in surface waters of the North Sea." Netherlands Journal of Sea Research **34**(4): 245.

Cubasch, U., Hegerl,C.C., Hellbach, A., Hoeck, H., Mikolajewicz, U., Santer, D.B., Voss, R., 1995. A climate change simulation starting from 1935. Clim. Dyn. **11**, 71-84.

Dankers, N., M. Binsbergen, et al. (1984). "Transportation of water, particulate and dissolved organic and inorganic matter between a salt marsh and the Ems-Dollard estuary, The Netherlands." Estuarine, Coastal & Shelf Science **19**(2): 143.

Dasch, W. and R. Wurpts (2001). "Isoviscs as useful parameters for describing sedimentation." Terra et Aqua **82**: 3-7.

De Brouwer, J. F. C., L. J. Stal, et al. (2003). "Distribution of extracellular carbohydrates in three intertidal mudflats in Western Europe." Estuarine, Coastal and Shelf Science **56**(2): 313.

De Deckere, E. M. G. T. (2003). Faunal influence on sediment stability in intertidal mudflats, Rijksuniversiteit Groningen.

De Haas, H. and D. Eisma (1993). "Suspended-sediment transport in the Dollard Estuary." Netherlands Journal of Sea Research **31**(1): 37.

De Jong, F., Bakker, J.F., van Berkel, C.J.M., Dankers, N.M.J.A., Dahl, K., Gätje, C., Marencic, H. and Potel, P. (1999). 1999 WADDEN SEA QUALITY STATUS REPORT. Wadden Sea Ecosystem No. 9. Folkert de Jong, J. F. Bakker, C. J. M.et al. Wilhelmshaven, Germany, Common Wadden Sea Secretariat, Trilateral Monitoring and Assessment Group, Quality Status Report Group.

De Jonge, V. N. (1983). "Relation between annual dredging activities, suspended matter concentrations, and the development of the tidal regime in the Ems estuary." Canadian Journal of Fisheries and Aquatic Sciences **40**: 289-300.

De Jonge, V. N. (1992). "Tidal flow and residual flow in the Ems estuary." Estuarine, Coastal & Shelf Science **34**(1): 1.

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**(12-13): 1655.

De Jonge, V. N. and F. Colijn (1994). "Dynamics of microphytobenthos biomass in the Ems Estuary." Marine Ecology Progress Series **104**(1-2): 185.

De Jonge, V. N. and H. Postma (1974). "Phosphorus compounds in the Dutch Wadden Sea." Netherlands Journal of Sea Research **8**(2-3): 139.

De Jonge, V. N. and J. E. Van Beusekom (1995). "Wind- and tide-induced resuspension of sediment and microphytobenthos from tidal flats in the Ems estuary." Limnology and Oceanography **40**(4): 766.

De Jonge, V. N. and J. E. E. Van Beusekom (1992). "Contribution of resuspended microphytobenthos to total phytoplankton in the Ems Estuary and its possible role for grazers." Netherlands Journal of Sea Research **30**(1-4): 91.

De Jonge, V. N. and J. Van Den Bergs (1987). "Experiments on the resuspension of estuarine sediments containing benthic diatoms." Estuarine, Coastal & Shelf Science **24**(6): 725.

De Jonge, V. N. and L. A. Villerius (1989). "Possible role of carbonate dissolution in estuarine phosphate dynamics." Limnology & Oceanography **34**(2): 332.

De Kock, W. C. (1986). "Monitoring bio-available marine contaminants with mussel (Mytilus edulis L) in the Netherlands." Environmental Monitoring and Assessment **7**(3): 209.

De La Motte, J., J. Spiekhout, et al. (2004). "Lowering a 42-in in-service pipeline in an estuary crossing." Pipeline World(3 JUNE): 9.

De Swart, H. E., V. N. De Jonge, et al. (1997). "Application of the Tidal Random Walk Model to Calculate Water Dispersion Coefficients in the Ems Estuary." Estuarine, Coastal and Shelf Science **45**(1): 123.

De Winton, C. (1977). "EKOFISK COMPLEX COMMISSIONED." Gas World Gas J **182**(4708): 588.

De Wolf, P. (1975). "Mercury content of mussels from West European coasts." Marine Pollution Bulletin **6**(4): 61.

Degens, E. T. and e. al. (1982). VALDIVIA Cruise October 81 (Elbe, Weser, Ems, German Bight). Transport of Carbon and Minerals in Major World Rivers, Pt. 1. E. T. Egens, S. Kempe and J. E. Richey. Mitt. Geol.-Paläont. Inst. Univ. Hamburg, SCOPE/UNEP Sonderbd. **52:** 585-749.

Degroodt, E. G. and V. N. De Jonge (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**: 39.

Delafontaine, M. T., B. W. Flemming, et al. (2000). The Wadden Sea squeeze as a cause of decreasing sedimentary organic loading. Muddy coast dynamics and resource management. B. W. Flemming, Delafontaine, M.T. and G. Liebezeit, Elsevier Science**:** 273-286.

Dette, H., A. Raudkivi, et al. (1994). Anpassung des Ems-fahrwassers an ein 7,30 m Tiefgehendes Schiff. Leichtweiss-Institut, Bericht 770.

Dijkema, K. S., H. E. Reineck, et al. (1980). Geomorphology of the (estuarine) Wadden Sea area: final report of the section 'Geomorphology' of the Wadden Sea working group: Report 1.

Dollardzijlvest (1992). Dollardzijlvest, gepeild en aagekaart: een kartografisches kijk op de geschiedenis van land en water van Oost-Groningen en Drenthe.

Dorrestein, R. and L. Otto (1960). On the mixing and flushing of the water in the Ems-estuary. Das Ems-Estuarium (Nordsee). J. H. v. Voorthuysen and P. H. Kuenen, Verh. K. Ned. Geol.-Mijnb.k. Genoot., (Geol. Ser.). **19:** 83-102.

Dyer, K. R., M. C. Christie, et al. (2000). "An investigation into processes influencing the morphodynamics of an intertidal mudflat, the Dollard Estuary, the Netherlands: I. Hydrodynamics and suspended sediment." Estuarine, Coastal and Shelf Science **50**(5): 607.

Eckhold, J.-P., H.-H. Jürgens, et al. (2000). "Unterhaltunskonzept Ems." HANSA **137**(6): 66-69.

Eggens, M. and J. Bakker (2001). Toxicity of Dredged Material Polluted with Hexachlorobenzene (HCB) - Is there a Risk of Organisms in the Ems-Dollard Estuary? Wadden Sea Newsletter 2001-2.

Eisma, D. (1991). "Suspended-matter particle size in some west-European estuaries; part I: particle-size distribution." Netherlands Journal of Sea Research **28**(3): 193.

Eisma, D., P. Bernard, et al. (1985). Loss of particulate organic matter in estuaries as exemplified by the Ems and Gironde Estuaries. Transport of Carbon and Minerals in Major World Rivers, Vol. 3. E. T. Degens, S. Kempe and R. Herrera, Mitt. Geol. Paläont. Inst. Univ. Hamburg, SCOPE/UNEP Sonderbd. **58:** 397-412.

Eisma, D., Bernard, P., Boon, J. J., Van Grieken, R., Kalf, J. and Mook, W. G. (1985). Loss of particulate organic matter in estuaries as exemplified by the Ems and Gironde Estuaries. Transport of Carbon and Minerals in Major World Rivers, Pt.3. E. T. Degens, S. Kempe and R. Herrera, Mitt. Geol.-Paläont. Inst. Univ. Hamburg, SCOPE/UNEP Sonderbd. **58:** 397-412.

Eisma, D., J. Boon, et al. (1983). Observation on macro-aggregates, particle size and organic composition of suspended matter in the Ems Estuary. Transport of Carbon and Minerals in Major World Rivers, Vol. 2. E. T. Degens, Mitt. Geol. Paläont. Inst. Univ. Hamburg, SCOPE/UNEP Sonderbd. **55:** 295-314.

Eisma, D., S. Chen, et al. (1994). "Tidal variations in suspended matter floc size in the Elbe River and Dollard Estuaries." Netherlands Journal of Aquatic Ecology **28**(3-4): 267.

Eisma, D. and J. Kalf (1996). "In situ particle (floc) size measurements with the NIOZ in situ camera system." Journal of Sea Research **36**(1-2): 49.

Eisma, D. and A. Li (1993). "Changes in suspended-matter floc size during the tidal cycle in the Dollard Estuary." Netherlands Journal of Sea Research **31**(2): 107.

Esselink, P., L. F. M. Fresco, et al. (2002). "Vegetation change in a man-made salt marsh affected by a reduction in both grazing and drainage." Applied Vegetation Science **5**(1): 17.

Esselink, P., G. J. F. Helder, et al. (1997). "The impact of grubbing by Greylag Geese (Anser anser) on the vegetation dynamics of a tidal marsh." Aquatic Botany **55**(4): 261.

Esselink, P., S. Reents, et al. (1998). "Vertical accretion and profile changes in abandoned man-made tidal marshes in the Dollard estuary, The Netherlands." Journal of Coastal Research **14**(2): 570.

Esselink, P., J. Van Belkum, et al. (1989). "The effect of organic pollution on local distribution of Nereis diversicolor and Corophium volutator." NETH. J. SEA RES. **23**(3): 323.

Esselink, P., W. Zijlstra, et al. (2000). "The effects of decreased management on plant-species distribution patterns in a salt marsh nature reserve in the Wadden Sea." Biological Conservation **93**(1): 61.

Essink, K. (1988). "Decreasing mercury pollution in the Dutch Wadden Sea and Ems Estuary." Marine Pollution Bulletin **19**(7): 317.

Essink, K. (1998). "Dispersal and development of Marenzelleria spp. (Polychaeta, Spionidae) populations in NW Europe and The Netherlands." Helgolander Meeresuntersuchungen **52**(3-4): 367.

Essink, K. (1999). "Ecological effects of dumping of dredged sediments; Options for management." Journal of Coastal Conservation **5**(1): 69.

Essink, K. (2003). "Response of an estuarine ecosystem to reduced organic waste discharge." Aquatic Ecology **37**(1): 65.

Essink, K. and A. H. Bos (1985). "Growth of three bivalve molluscs transplanted along the axis of the Ems estuary." Netherlands Journal of Sea Research **19**(1): 45.

Essink, K. and R. Dekker (2002). "General patterns in invasion ecology tested in the Dutch Wadden Sea: The case of a brackish-marine polychaetous worm." Biological Invasions **4**(4): 359.

Essink, K., Dettmann, C., Farke, H., Laursen, K., Lüerßen, G., Marencic, H. and Wiersinga, W. (Eds.), (2005). Wadden Sea Quality Status Report 2004. Wadden Sea Ecosystem No. 19. Wilhelmshaven, Germany, Trilateral Monitoring and Assessment Group, Common Wadden Sea Secretariat.

Essink, K., J. Eppinga, et al. (1998). "Long-term changes (1977-1994) in intertidal macrozoobenthos of the Dollard (Ems estuary) and effects of introduction of the North American spionid polychaete Marenzelleria cf. wireni." Senckenbergiana Maritima **28**(4-6): 211.

Essink, K. and H. Keidel (1998). "Changes in estuarine nematode communities following a decrease of organic pollution." Aquatic Ecology **32**(3): 195.

Essink, K. and H. L. Kleef (1988). "Marenzelleria viridis (Verrill, 1873) (Polychaeta: Spionidae): a new record from the Ems estuary." Zoologische Bijdragen **38**: 1-13.

Essink, K., H. L. Kleef, et al. (1989). "On the pelagic occurrence and dispersal of the benthic amphipod Corophium volutator." Journal - Marine Biological Association **69**(1): 11.

Essink, K. and K. Romeyn (1994). "Estuarine nematodes as indicators of organic pollution: an example from the Ems Estuary (the Netherlands)." Netherlands Journal of Aquatic Ecology **28**(2): 213.

Essink, K., F. H. I. M. Steyaert, et al. (1992). "Effects of dredging activities in the Ems estuary and Dutch Wadden Sea." Publ. Ser. Neth. Inst. Sea Res. **20**: 243-246.

Evers, E. H. G., H. J. C. Klamer, et al. (1993). "Polychlorinated dibenzo-p-dioxin and dibenzofuran residues in estuarine and coastal North Sea sediments: Sources and distribution." Environmental Toxicology and Chemistry **12**(9): 1583.

Flemming, B. W. and N. Nyandwi (1994). "Land reclamation as a cause of fine-grained sediment depletion in backbarrier tidal flats, southern North Sea." Neth. J. Aquat. Ecol **28**: 299-307.

Fowler, S. W. (1990). "Critical review of selected heavy metal and chlorinated hydrocarbon concentrations in the marine environment." Marine Environmental Research **29**(1): 1.

Franzen, R. and R. Turik (1974). "NUCLEAR POWER STATIONS IN THE NORTH SEA."

Franzius, O. (1986). "SUSPENDED SEDIMENT PROBLEMS IN THE BRACKISH TRANSITION OF THE TIDAL EMS RIVER." Bulletin of the Permanent International Association of Navigation Congresses(53): 37.

Freund, H. and H. Streif (2000). Natural Sea Level Indicators Recording the Fluctuations of the Mean High Tide Level in the Southern North Sea. Wadden Sea Newsletter 2000.

Gabioux, M., S. B. Vinzon, et al. (2005). "Tidal propagation over fluid mud layers in the Amazon Shelf." Continental Shelf Research **25**: 113-125.

Gaedke, U. (1990). "Population-dynamics of the calanoid copepods eurytemora-affinis and acartia-tonsa in the EMS-Dollard-Estuary - a numerical simulation." Archiv Fur Hydrobiologie **118**(2): 185-226.

Garrelts, E., H. Harten, et al. (1973). "Structures on the stretches at the mouths of the German tidal rivers and their action on the movement of sand." IN: PROC. 23RD. INT. NAVIGATION CONGRESS, (OTTAWA, CANADA, 1973), SECTION(II, Ocean Navigation, subject 2, Means of controlling littoral drift to protect beaches, dunes, estuaries): 49.

Geils, J., O. Stoschek, et al. (2001). MIKE21/MIKE3 for Modeling Hydrodynamics in a Brakish Tidal Environment. DHI Software Conference, Helsingoer, Denmark.

Gerdes, G., B. M. Scholz-Böttcher, et al. (2003). "The record of climatic change in the geological archives of shallow marine, coastal, and adjacent lowland areas of Northern Germany." Quaternary Science Reviews **22**(1): 101.

Gerdes, K. (1994). "Long-term and short-term changes of geese numbers (Anser fabalis, A. albifrons, A. anser and Branta leucopsis) near the Dollart and their ecological correlations" [Lang- und kurzfristige Bestandsanderungen der Ganse (Anser fabalis, A. albifrons, A. anser und Branta leucopsis) am Dollart und ihre okologischen Wechselbeziehungen]." Vogelwarte **37**(3): 157.

Gerritsen, F. (1952). Historisch geogafisch onderzoek eems, Internal report Rijkswaterstaat.

Gerritsen, F. (1955). Enige opmerkingen over het ontstaan van de dollart, Internal report Rijkswaterstaat.

Giani, L. and A. Landt (2000). "Initial marsh soil development from brackish sediments." Journal of Plant Nutrition and Soil Science **163**(5): 549-553.

Gienapp, H. (1983). "(Marine optical investigations in the Ems estuary, Germany)" [Meeresoptische Untersuchungen in der Emsmundung.]." Deutsche Hydrographische Zeitschrift **36**(4): 157.

Giese, E., H. Harten, et al. (1975). "Erfahrungen mit dem Betrieb von Tidemodellen mit beweglicher Sohle." Die Küste **27**.

Gömann, H., P. Kreins, et al. (2005). "Model based impact analysis of policy options aiming at reducing diffuse pollution by agriculture - a case study for the river Ems and a sub-catchment of the Rhine." Environmental Modelling and Software **20**(2): 261-271.

Gömann, H., P. Kreins, et al. (2003). Management of regional German river catchments (REGFLUD) - general conditions and policy options on diffuse pollution by agriculture of the rivers Rhine and Ems. Proceedings of the 7th International Conference on Diffuse Pollution, Dublin, Ireland.

Gresikowski, S., N. Greiser, et al. (1996). Distribution and activity of nitrifying bacteria at two stations in the Ems estuary. Suspended particulate matter in rivers and estuaries: Proceedings of an International Symposium held at Reinbek near Hamburg, Germany. Kausch, Hartmut, Michaelis and Walfried. **VIII:** 65.

Günther, H., W. Rosenthal, et al. (1998). "The wave climate of the Northeast Atlantic over the period 1955-1994: The WASA wave hindcast." Global Atm. Oc. System **6**: 121-163.

Gursch, P. (1966). "Das Leda-Sperrwerk in Ostfriesland." Kueste **14**(2).

Habermann, C. (2003). Morphologischer Nachlauf nach Baggermaßnahmen in Tideästuaren. Diplom Arbeit, Institut für Wasserbau und Wasserwirtschaft Fachgebiet Wasserbau Technische Universität Darmstadt.

Habermann, C., et al., 2006. Einfluss von Unterhaltungsbaggerungen auf die Schwebstoffdynamik der Unterems- Monitoring während eines baggerungsfreien Zeitraums. Report, Bfg, Koblenz.

Hadderingh, R. H. and Z. Jager (2002). "Comparison of fish impingement by a thermal power station with fish populations in the Ems Estuary." Journal of Fish Biology **61**(SUPPL. A): 105.

Harten, H. (1979). "Ausbaumassnahmen in Tideästuarien der deutschen Nordseeküste und die Auswirkungen auf das Tidegeschehen." Die Küste **34**.

Harten, H. and H. J. Vollumers (1977). "Investigations on model in connection with structural measures on German tidal rivers."

Heijnis, H., G. W. Berger, et al. (1987). "Accumulation rates of estuarine sediment in the Dollard area - comparison of PB-210 and pollen influx methods." Netherlands Journal of Sea Research **21**(4): 295-301.

Heip, C. H. R. and P. M. J. Herman (1995). "Major biological processes in European tidal estuaries." Hydrobiologia **311**(1-3).

Helder, W. (1983). "Estuarine nitrite maxima and nitrifying bacteria (EMS-Dollard Estuary)." Netherlands Journal of Sea Research **17**(1).

Helder, W. and R. T. O. De Vries (1983). "Estuarine nitrite maxima and nitrifying bacteria (Ems-Dollard estuary)." Netherlands Journal of Sea Research **17**(1): 1.

Helder, W. and R. T. P. De Vries (1986). "Dynamics of dissolved silicium and nitrogen-nutrients at low temperature in the Ems-Dollard estuary." Netherlands Journal of Sea Research **20**(2-3): 277.

Helder, W. and P. Ruardij (1982). "A one-dimensional mixing and flushing model of the Ems- Dollard estuary: calculation of time scales at different river discharges." Netherlands Journal of Sea Research **15**(3-4): 293.

Hess, H. (1985). "Emshoern Z1A Production Platform with Gas Drying Plant of the BEB in the Ems Estuary Stahlbau **54**(5): 129.

Hiddink, J. G. and Z. Jager (2002). "Abundance and reproduction of Nilsson's pipefish on tidal flats." Journal of Fish Biology **61**(SUPPL. A): 125.

Hockert, W. and P. Chromik (1982). "Connection of the EMSHORN 2 1 A Well - Laying of Pipelines in the Tidelands GWF, Gas - Erdgas **123**(4): 145.

Hoffmann, N., H. Jödicke, et al. (2001). "The distribution of pre-westphalian source rocks in the North German Basin - evidence from magnetotelluric and geochemical data." Geologie en Mijnbouw/Netherlands Journal of Geosciences **80**(1): 71.

Hoogweg, P. H. A. and F. Colijn (1992). "Management of Dutch estuaries the Ems-Dollard and the Western Scheldt." Water Science and Technology **26**(7-8): 1887.

Hoselmann, C. and H. Streif (2004). "Holocene sea-level rise and its effect on the mass balance of coastal deposits." Quaternary International **112**(1): 89.

Hurrel, J. (1995). "Decadal trends in the North Atlantic Oscillation regional temperatures and precipitation." Science **269**: 676–679.

IPCC (1995). Climate Change 1995, the science of climate changes. Cambridge, Cambridge Univ. Press.

IPCC (2001). A report of working group I of the Intergovernmental Panel on Climate Change. Summary for Policymakers.

Jager, Z. (1998). "Accumulation of flounder larvae (Platichthys flesus L.) in the Dollard (Ems estuary, Wadden Sea)." Journal of Sea Research **40**(1-2): 43.

Jager, Z. (1999). Processes of tidal transport and accumulation of larval flounder (Platichthys flesus L.) in the Ems-Dollard nursery, Amsterdam University. **PhD**.

Jager, Z. (1999). "Selective tidal stream transport of flounder larvae (Platichthys flesus L.) in the Dollard (Ems estuary)." Estuarine, Coastal and Shelf Science **49**(3): 347.

Jager, Z. (2001). "Transport and retention of flounder larvae (Platichthys flesus L.) in the Dollard nursery (Ems estuary)." Journal of Sea Research **45**(2): 153.

Jager, Z. (2002). "Across-channel distribution of flounder larvae (Platichthys flesus L.) in the Eems-Dollard estuary and its effects on larval transport estimates." ICES Journal of Marine Science **59**(6): 1187.

Jager, Z., H. L. Kleef, et al. (1993). "The distribution of 0-group flatfish in relation to abiotic factors on the tidal flats in the brackish Dollard (Ems Estuary, Wadden Sea)." Journal of Fish Biology **43**(Suppl. A): 31.

Jager, Z., H. L. Kleef, et al. (1995). "Mortality and growth of 0-group flatfish in the brackish Dollard (Ems Estuary, Wadden Sea)." Netherlands Journal of Sea Research **34**(1-3): 119.

Jager, Z. and H. P. J. Mulder (1999). "Transport velocity of flounder larvae (Platichthys flesus L.) in the Dollard (Ems estuary)." Estuarine, Coastal and Shelf Science **49**(3): 327.

Jathe, B. and M. Schirmer (1989). "Chlorinated hydrocarbons and toxic heavy metals in the Weser estuary [Chlorierte KW und toxische Schwermetalle in und an Unter- and Aussenweser]."

Jensen, J., F. Bender, et al. (2001). Analysis of the Water Levels along the German North Sea Coastline. Proceedings of the fifth conference MEDCOAST 01, Tunesia.

Jensen, J., T. Frank, et al. (2002). Synoptic field measurements in the context of hydrological changes in the Ems estuary. Low-lying Coastal Areas – Hydrology and Integrated Coastal Zone Management (International Symposium Bremerhaven 9.-12.9.2002), Koblenz, Deutsches IHP/OHP Nationalkomitee.

Jensen, J. and C. Mudersbach (2005). Recent Sea Level Variations at the North Sea and Baltic Sea Coastlines. ICEST, USA.

Jensen, J. and C. Mudersbach (2005). Zeitliche Änderungen in den Wasserstandszeitreihen an den Deutschen Küsten, Forschungsstelle Wasserwirtschaft und Umwelt (fwu) an der Universität Siegen.

Jensen, J., C. Mudersbach, et al. (2003). Hydrological changes in tidal estuaries due to natural and anthropogenic effects. 6th International MEDCOAST 2003 Conference, Ravenna, Italy.

Jürges, J. and N. Winkel (2003). Ein Beitrag zur Tidedynamik der Unterems. Mitteilungsblatt der Bundesanstalt für Wasserbau**:** 29-31.

Kauker, F. and H. Langenberg (2000). "Two models for the climate change related development of sea levels in the North Sea. A comparison." Climate Research. **15**: 61-67.

Kempe, S. (1982). Valdivia Cruise, October 1981: carbonate equilibria in the estuaries of the Elbe, Weser, Ems, and in the Southern German Bight. Transport of Carbon and Minerals in Major World Rivers, Vol. I. E. T. Degens, Mitt. Geol. Paläont. Inst. Univ. Hamburg, SCOPE/UNEP Sonderbd. **52:** 719-742.

Kempe, S., B. Mycke, et al. (1981). "Flußfrachten und Erosionsraten in Mitteleuropa 1966-1973." Wasser und Boden **1981**(3): 126-31.

Kerstan, M. (1991). "The importance of rivers as nursery grounds for 0- and 1-group flounder (Platichthys flesus L.) in comparison to the Wadden Sea." Netherlands Journal of Sea Research **27**(3-4): 353.

Kettel, D. (1982). "EAST GRONINGEN MASSIF - DETECTION OF AN INTRUSIVE BODY BY MEANS OF COALIFICATION." Geologie en Mijnbouw **62**(1): 203.

Knickmeyer, R. and H. Steinhart (1988). "The distribution of cyclic organochlorines in North Sea sediments." Deutsche Hydrographische Zeitschrift **41**(1): 1.

Können, G. P. E. (1999). De toestand van het klimaat in Nederland 1999. De Bilt, KNMI**:** 64.

Kornman, B. A. and E. M. G. T. De Deckere (1998). "Temporal variation in sediment erodibility and suspended sediment dynamics in the Dollard estuary." Geological Society Special Publication(139): 231.

Kronberg, B. I., U. Lammerz, et al. (1982). Valdivia Cruise October 1981: mineral nutrients in the Elbe, Weser, and Ems Rivers and the German Bight. Transport of Carbon and Minerals in Major World Rivers, Vol. I. E. T. Degens, Mitt. Geol, Paläont. Inst. Univ. Hamburg, SCOPE/UNEP Sonderbd. **52:** 655-666.

Kruckenberg, H., J. Jaene, et al. (1998). "Mut oder Verzweiflung am Straßenrand? Der Einfluß von Straßen auf die Raumnutzung und das Verhalten von Bleß- und Nonnengänsen am Dollart, NW-Niedersachsen." Natur und Landschaft **73**(1): 3-8.

Kuehl, H. and H. Mann (1973). "Untersuchungen zur Hydrobiologie der Unteren Ems." Arch. Fischereiwiss. **23**: 243-268.

Kunkel, R., H. Bogena, et al. (2003). MANAGEMENT OF REGIONAL GERMAN RIVER CATCHMENTS (REGFLUD) IMPACT OF NITROGEN REDUCTION MEASURES ON THE NITROGEN LOAD IN THE RIVER EMS AND THE RIVER RHINE. Diffuse Pollution Conference, Dublin, Ireland.

Kunkel, R., H. Bogena, et al. (2005). "Management of regional German river catchments (REGFLUD) impact of nitrogen reduction measures on the nitrogen load in the River Ems and the River Rhine." Water Science & Technology **51**(No 3-4): 291 - 299.

Kunkel, R., H. Bogena, et al. (2005). Coupling of Hydrological and Agro-Economical Models to Assess the Impacts of Nitrogen Reduction Measures on the Nitrogen Load in Rivers. ICID 21st European Regional Conference 2005, Frankfurt (Oder) and Slubice - Germany and Poland.

Laane, R. W. P. (1981). "Composition and distribution of dissolved fluorescent substances in the EMS-Dollard Estuary." Netherlands Journal of Sea Research **15**: 88.

Laane, R. W. P. (1982). "The relation between fluorescence and dissolved organic-carbon in the EMS-Dollard Estuary and the Western Wadden Sea." Netherlands Journal of Sea Research **15**: 217.

Laane, R. W. P. M. (1980). "Conservative behaviour of dissolved organic carbon in the Ems-Dollart estuary and the western Wadden Sea." Netherlands Journal of Sea Research **14**(2): 192.

Laane, R. W. P. M. (1980). "Some observations on the lipid concentration in the Ems-Dollart estuary and the Western Wadden Sea." Estuarine & Coastal Marine Science **10**(6): 589.

Laane, R. W. P. M. (1982). "Sources of dissolved organic carbon in the Ems- Dollard Estuary: the rivers and phytoplankton." Netherlands Journal of Sea Research **15**(3-4): 331.

Laane, R. W. P. M. and V. Ittekkot (1983). Behaviour of dissolved organic waste in a part of the Ems-Dollart Estuary: the Dollart. Transport of Carbon and Minerals in Major World Rivers, Pt.2. D. E. T., S. Kempe and H. Soliman, Mitt. Geol.-Paläont. Inst. Univ. Hamburg, SCOPE/UNEP Sonderbd. **55:** 343-52.

Laane, R. W. P. M. and V. Ittekkot (1985). Dissolved and particulate carbohydrates in the Ems-Dollart Estuary. Transport of Carbon and Minerals in Major World Rivers, Pt.3. E. T. Degens, S. Kempe and R. Herrera, Mitt. Geol.- Paläont. Inst. Univ. Hamburg, SCOPE/UNEP Sonderbd. **58:** 385-95.

Langenberg, H., A. Pfizenmayer, et al. (1999). "Storm related sea level variations along the North Sea coast: natural variability and anthropogenic change." Continental. Shelf Research **19**: 821-842.

Lehner, S., I. Anders, et al. (2004). "High Resolution Maps of Suspended Particulate Matter Concentration in the German Bight." EARSeL eProceedings **3**(1).

Louisse, C. J., R. J. Akkerman, et al. (1986). A fluorescent tracer for cohesive sediment.

Lucas, C. H. (2003). "Observations of resuspended diatoms in the turbid tidal edge." Journal of Sea Research **50**(4): 301.

Luten, J. B., W. Bouquet, et al. (1986). "Trace metals in mussels (Mytilus edulis) from the Waddenzee, coastal North Sea and the estuaries of Ems, Western and Eastern Scheldt." Bulletin of Environmental Contamination and Toxicology **36**(5): 770.

Manning, A. J. (2004). "Observations of the properties of flocculated cohesive sediment in three western European estuaries." Journal of Coastal Research(Special Issue 41): 70-81.

Manning, A. J. (2004). "The observed effects of turbulence on estuarine flocculation." Journal of Coastal Research(Special Issue 41): 90-104.

McLaren, P., F. Steyaert, et al. (1998). "Sediment transport studies in the tidal basins of the Dutch Waddenzee." Senckenbergiana Maritima **29**(1-6): 53.

Meesenburg, S., H. Meyer, et al. (1999). "Baggern im Emder Fahrwasser - Ein neues Konzept." HANSA **136**(2): 39-45.

Megens, L., J. Van der Plicht, et al. (2002). "Stable carbon and radiocarbon isotope compositions of particle size fractions to determine origins of sedimentary organic matter in an estuary." Organic Geochemistry **33**(8): 945.

Megens, L., J. D. Van Der Plight, et al. (1998). "Molecular, radioactive and stable carbon isotope characterization of estuarine particulate organic matter." Radiocarbon **40**(2): 985.

Mehta, A. J. and P. Y. Maa (1986). Waves over mud: Modeling erosion. Proceedings 3rd International Symposium on River Sedimentation, Univ. of Miss.

Merckelbach, L. (2000). "Consolidation and strength evolution of soft mud layers." Communications on Hydraulic and Geotechnical Engineering **100**(2): 1.

Merckelbach, L. M. and W. D. Eysink (2001). Trendanalyse zwevend stof in Eems estuarium in relatie tot aanslibbing haven Delfzijl., WL | Delft Hydraulics.

Merckelbach, L. M. and C. Kranenburg (2004). "Determining effective stress and permeability equations for soft mud from simple laboratory experiments." Geotechnique **54**(9): 581.

Meurs, H. G. and G. P. Zauke (1988). "Regional and temporal distribution of euryhaline gammarus species (crustacea, amphipoda) within the Elbe Estuary, Weser Estuary and EMS Estuary." Archiv Fur Hydrobiologie **113**(2): 213-230.

Middelburg, J. J. and J. Nieuwenhuize (2000). "Uptake of dissolved inorganic nitrogen in turbid, tidal estuaries." Marine Ecology Progress Series **192**: 79.

Middelburg, J. J., J. Nieuwenhuize, et al. (2002). "Methane distribution in European tidal estuaries." Biogeochemistry **59**(1-2): 95.

Mikkelsen, O. and M. Pejrup (1998). "Comparison of flocculated and dispersed suspended sediment in the Dollard estuary." Geological Society Special Publication(139): 199.

Möltgen, J., G. Schmidt, et al. (2004). An interdisciplinary SDSS for planning and controlling in river management. Proceedings of 6th AGILE 2004 conference on Geographic Information Science, Heraklion, Greece.

Möltgen, J. u. S., U. (2004): " März 2004, (2004). Interdisziplinäre Methoden- und Werkzeuge zur Planung und Kontrolle für das Flusseinzugsgebietsmanagement mit GIS. Interdisziplinäre Methoden des Flussgebietsmanagements, Universität Münster, IfGIprints, Institut für Geoinformatik,Universität Münster.

Mouny, P., J. C. Dauvin, et al. (2000). "Benthic boundary layer fauna from the seine estuary (eastern English Channel, France): Spatial distribution and seasonal changes." Journal of the Marine Biological Association of the United Kingdom **80**(6): 959.

Mulder, H. P. J. (1999). "Model application to the resuspension and dispersion of dumped sediment from the Eemshaven harbour (Ems Estuary)." Senckenbergiana Maritima **29**(SUPPL.): 99.

Mulder, H. P. J. (2004). Dumping in the Ems estuary: an overview of effects and developments. Haren, National Institute for Coastal and Marine Management/RIKZ**:** 10.

Mulder, H. P. J. and B. Mijwaard (1997). Een methode on een twee-dimensionale sedimentbalans te maken, gebaseerd op meetgegevens, met gebruikmaking van GIS en toegepast op de Eems-Dollard voor de periode 1985-1990. Werkdocument RIKZ/OS-97.609X.

Nasner, H. (1992). "Sedimentation in Tidehäfen." Die Küste: 127-169.

Nasner, H. (1997). Sedimentation in Tidehäfen, Phase 2. Die Küste**:** 63-114.

Nasner, H. (2004). "Hydrodynamic and morphological processes in brackishwater zones - in situ measurement [Hydrodynamische und morphologische Vorgänge in brackwasserbeeinflussten Vorhafen. - In situ Messungen -]." Kuste(68): 1.

Nehring, S. (2000). "On the occurrence of Rhithropanopeus harrisii (Gould, 1841) in German aquatic habitats: The successive spreading of an American neozoon (Crustacea: Decapoda) [Zur bestandssituation von Rhithropanopeus harrisii (Gould, 1841) in Deutschen gewassern: Die sukzessive ausbreitung eines Amerikanischen Neozoons (Crustacea: Decapoda: Panopeidae)]." Senckenbergiana Maritima **30**(3-6): 115.

Nehring, S. and H. Leuchs (1999). "The BfG-monitoring in the German North Sea estuaries: Macrozoobenthos." Senckenbergiana Maritima **29**(SUPPL.): 107.

Niebuhr, W. (1952). "Über die neüre Entwicklung der Aussenems und ihre vermutlichen Ursachen." Die Küste **1**(1).

Niebuhr, W. (1955). "Beobachtungen über den Sandtransport in der unteren Ems." Die Küste **4**.

Niedermeier, A., S. Lehner, et al. (2001). Monitoring big river estuaries using SAR images. International Geoscience and Remote Sensing Symposium (IGARSS).

Niemeyer, H. D. and R. Kaiser (2002). Evaluation of Design Water Levels and Design Wave Run-up for an Estuarine Coastal Protection Master Plan. Conference Proceedings Coastal Engineering 200.

Niemeyer, H. D. (1999). Untersuchungen zur Deichsicherheit an der Unterems. Hannover.

Nienhuis, P. H. (1993). "Nutrient cycling and foodwebs in Dutch estuaries." Hydrobiologia **265**(1-3): 15-44.

Nyenhuis, H. (1997). "For population dynamics and migration phenology of wild ducks (Anatidae) in the territory of Weser-Ems." Allgemeine Forst und Jagdzeitung **168**(5): 89-95.

Partenscky, H. W. and G. Barg (1977). "Energy dissipation in tidal estuaries." In: Proc. 15th Coastal Engineering Conference (Hawaii Univ., USA, 1976). 4, New York, U.S.A., American Soc. Civ.Engng., 1977: 3312.

Peletier, H. (1996). "Long-term changes in intertidal estuarine diatom assemblages related to reduced input of organic waste." Marine Ecology Progress Series **137**(1-3): 265.

Plüß, A., E. Rudolph, et al. (2001). "Characteristics of storm surges in German estuaries." Climate Research **18**(1-2): 71.

Poepperl, R. and E. I. Meyer (2004). Bewertung des ökologischen Zustandes der Fließgewässer im Einzugsgebiet der Ems. Interdisziplinäre Methoden des Flussgebietsmanagements, Universität Münster, IfGIprints, Institut für Geoinformatik.

Poremba, K., U. Tillmann, et al. (1999). "Distribution patterns of bacterioplankton and chlorophyll-a in the German Wadden Sea." Helgoland Marine Research **53**(1): 28.

Radford, P. J. and P. Ruardij (1987). "The validation of ecosystem models of turbid estuaries." Continental Shelf Research **7**(11-12): 1483.

Rechlin, D. (1996). "Bestimmung der nautischen Tiefe in Hauptschlickgebieten." HANSA **133**(7): 76-83.

Remerie, T., T. Bourgois, et al. (2005). "Morphological differentiation between geographically separated populations of Neomysis integer and Mesopodopsis slabberi (Crustacea, Mysida)." Hydrobiologia **549**(1): 239.

Reuss, N., D. J. Conley, et al. (2005). "Preservation conditions and the use of sediment pigments as a tool for recent ecological reconstruction in four Northern European estuaries." Marine Chemistry **95**(3-4): 283.

Ridderinkhof, H. (1997). "The effect of tidal asymmetries on the net transport of sediments in the Ems Dollard estuary." Journal of Coastal Research **25**: 41-48.

Ridderinkhof, H., R. Van der Ham, et al. (2000). "Temporal variations in concentration and transport of suspended sediments in a channel-flat system in the Ems-Dollard estuary." Continental Shelf Research **20**(12-13): 1479.

Rincke, G. (1973). "The pollutant loading capacity of the Ems estuary in the judgment of the German referee " Ingenierur **85**(35): 680.

Ritterhoff, J., G. P. Zauke, et al. (1996). "Calibration of the estuarine amphipods, Gammarus zaddachi Sexton (1912), as biomonitors: Toxicokinetics of cadmium and possible role of inducible metal-binding proteins in Cd detoxification." Aquatic Toxicology **34**(4): 351.

Rohde, H. (1975). "Wasserstandsbeobachtungen im Bereich der deutschen Nordseeküste vor der Mitte des 19. Jahrhunderts." Die Küste **28**.

Rolinski, S. and G. Eichweber (2000). "Deformations of the tidal wave in the Elbe estuary and their effect on suspended particulate matter dynamics." Physics and Chemistry of the Earth **25**(4): 355-358.

Ruardij, P. and J. W. Baretta. (1982). "The EmsDollart Ecosystem Modelling Workshop." **2**.

Rutgers Van Der Loeff, M. M., F. B. Van Es, et al. (1981). "Sediment water exchanges of nutrients and oxygen on tidal flats in the Ems-Dollard estuary (Heringsplaat)." Netherlands Journal of Sea Research **15**(1): 113.

Rybarczyk, H. and B. Elkaïm (2003). "An analysis of the trophic network of a macrotidal estuary: The Seine Estuary (Eastern Channel, Normandy, France)." Estuarine, Coastal and Shelf Science **58**(4): 775.

Salomons, W. and R. G. Gerritse (1981). "Some observations on the occurrence of phosphorus in recent sediments from Western Europe." Science of the Total Environment **17**(1): 37.

Schiedek, D. (1997). "Marenzelleria viridis (Verrill, 1873) (Polychaeta), a new benthic species within European coastal waters: Some metabolic features." Journal of Experimental Marine Biology and Ecology **211**(1): 85.

Schmidt, H. and H. v. Storch (1993). "German Bight storms analysed." Nature **365**: 791.

Schoer, J. and D. Eggersgluess (1982). Chemical forms of heavy metals in sediments and suspended matter of Weser, Elbe and Ems Rivers. Transport of Carbon and Minerals in Major World Rivers, Vol. 1. E. T. Degens, Mitt. Geol. Paläont. Inst. Univ. Hamburg, SCOPE/UNEP Sonderbd. **52:** 667-685.

Schoer, J., U. Nagel, et al. (1982). Metal contents in sediments from the Elbe, Weser, and Ems Estuaries and from the German Bight (Southeastern North Sea): grain size effects. Transport of Carbon and Minerals in Major World Rivers, Vol. 1. E. T. Degens, Mitt. Geol. Paläont. Inst. Univ. Hamburg, SCOPE/UNEP Sonderbd. **52:** 687-702.

Schroder, H. G. J. and F. B. Van Es (1980). "Distribution of bacteria in intertidal sediments of the Ems-Dollard estuary." Netherlands Journal of Sea Research **14**(3-4): 268.

Schubert, K. (1970). "Ems und Jade." Die Küste **19**.

Schuchardt, B. (1995). "Changes in the tidal level in the inner estuaries of the Eider, Elbe, Weser and Ems: an indicator for the ecological distortion of the water area [Die Veranderung des Tidehubs in den inneren Astuaren von Eider, Elbe, Weser und Ems: ein Indikator fur die okologische Verformung der Gewasser]." Naturschutz und Landschaftsplanung **27**(6): 211.

Schuchardt, B. and M. Schirmer (1991). "Phytoplankton maxima in two coastal plain estuaries." Estuarine & Coastal Shelf Science **32**: 187-206.

Schuchardt, B., M. Schirmer, et al. (1999). Estuaries and Brackisch Waters. Wadden Sea Quality Status Report. F. d. Jong, J. Bakker, C. van Berkelet al. Wilhelmshaven, Germany, Common Wadden Sea Secretariat, Trilateral Monitoring and Assessment Group, Quality Status Report Group**:** 175-186.

Schuchardt, B., M. Schirmer, et al. (1993). "Vergleichende Bewertung des ökologischen Zustands der tidebeeinflußten Flußunterläufe Norddeutschlands." Natursch. Landschaftspfl **48**: 137-152.

Schulze, M. (1988). Über die Abhängigkeit zwischen elektrischer Leitfähigkeit und Salzgehalt am Beispiel von Untersuchungen im Ems - □96?stuar. Mitteilungen des Leichtweiss-Instituts für Wasserbau der TU Braunschweig**:** 231-249.

Schulze, M. (1990). "Dynamics of suspended matter in brackish water of Ems Estuary[Zur Dynamik des Schwebstoffhaushaltes in Brackwassergebieten am Beispiel des Ems-Astuars]." Mitteilungen - Leichtweiss-Institut fur Wasserbau, Braunschweig **108**: 1.

Schulze, M., W. Fritzsche, et al. (1990). "Time series of conductivity measurements of water at station Terborg/Ems by capacity and induction measurements [Zur kapazitiven und induktiven Leitfahigkeitsmessung am Beispiel von Messreihen der Gewassergutemessstation Terborg/Ems]." Mitteilungen - Leichtweiss-Institut fur Wasserbau, Braunschweig **108**: 155.

Schulze, M., W. Puls, et al. (1989). Schwebstoff-Sinkgeschwindigkeitsmessungen in der Ems, Vergleich mit Messungen in der Elbe. GKSS - Forschungszentrum Geesthacht GmbH. Geesthacht**:** 28.

Schulze, M. and D. Rupert (1989). Über Aufgaben und Ziele von Messungen in der Unterems an der Radioaktivitäts- und Gewässergütemeßstation Gandersum. Mitteilungen des Leichtweiss-Instituts f52?r Wasserbau der TU Braunschweig**:** 319-342.

Schulze, M. and F. Spingat (1991). "Investigation of salinity in the Ems Estuary between Terborg and Gandersum [Untersuchung zum Salzgehaltsregime in der Tide-Ems zwischen Terborg und Gandersum]." Mitteilungen - Leichtweiss-Institute fur Wasserbau (Braunschweig) **111**: 411-444.

Schulze, M. and J. M. D. Vries (1991). "Analysis of suspended matter and sediments in the Ems Estuary [Analyse der Schwebstoffe und Sedimente im Brackwassergebiet der Ems]." Mitteilungen - Leichtweiss-Institut fur Wasserbau (Braunschweig) **111**: 447-486.

Schwarzbauer, J. and R. Littke (2004). "Quantitative evaluation of Elbe River-derived organic marker compounds in sediment samples from the German Bight." Journal of Soils and Sediments **4**(3): 177.

Siefert, W. and H. Lassen (1986). Development and Course of Storm Surges in the Ems, Weser and Elbe (Final Report of a KFKI Project) [ENTWICKLUNG UND ABLAUF VON STURMFLUTEN IN EMS, WESER UND ELBE (ABSCHLUSSBERICHT EINES KFKI-PROJEKTES).].

Sindern, J. and H. Gohren (1979). "(The storm surges of January 1976: water levels and tide curves)[Die Sturmfluten im Januar 1976 Wasserstande und Tidekurven.]." Kuste **33**: 214.

Soares, C. D., R. Weisse, et al. (2002). A 40 year hindcast of wind, sea level and waves in European waters. Proceedings of the 21st International Conference on Offshore Mechanics and Artic Engineering, Oslo, Norway.

Spiekhout, J. and W. Russ (2000). Safety evaluation and monitoring of an exposed estuary crossing [Evaluation de securite et surveillance d'une traversee destuaire a decouvert]. International Gas Union World Gas Conference Papers.

Spingat, F. and H. Oumeraci (2000). "The Dynamics of suspended matter in the Ems Estuary - Application 1 A concept for processing and evaluating data obtained from High Resolution Measurements [Schwebstoffdynamik in der Trubungszone des Ems-Astuars - Anwendung eines Analysekonzeptes fur hoch aufgeloste und dauerhaft betriebene Gewassergutemessungen -]." Kuste(62): 159-219.

Staats, N., E. De Deckere, et al. (2001). "Observations on suspended particulate matter (SPM) and microalgae in the Dollard estuary, the Netherlands: Importance of late winter ice cover of the intertidal flats." Estuarine, Coastal and Shelf Science **53**(3): 297.

Staats, N., E. M. G. T. De Deckere, et al. (2001). "Spatial patterns of benthic diatoms, carbohydrates and mud on a tidal flat in the Ems-Dollard estuary." Hydrobiologia **448**: 107.

Stanev, E., G. Floser, et al. (2003). Dynamical control on water exchanges between tidal basins and the open ocean. A case study for the East Frisian Wadden Sea. Ocean Dynamics, PECS 2002 Special Issue.

Stanev, E., J.-O. Wolff, et al. (2003). "On the circulation in the East Frisian Wadden Sea: Numerical modelling and data analysis." Ocean Dynamics **53**: 27-51.

Starke, W.-D. (2002). "Projektteam Emssperrwerk." Hansa International Maritime Journal.

Steen, D. (2003). Planungen und eingriffen im Dollartraum nach 1945. Zwischer Weser und Ems. Aurich, WSD. **Heft 37**.

Stoschek, O., J. Geils, et al. (2003). 3D-Strömungen und Sedimenttransport in tide- und brackwasserbeeinflussten Häfen. FZK-Kolloquium "Küsten - Morphodynamik und Küstenschutzwerke", Hannover.

Stratingh, G. A. and C. A. Venema (1855, Reprint 1979). De Dollard of Geschied-, Aardriks- en Natuurkundeige beschrijving van dezen boezen der Eems. Groningen, Vereinging tot Behoud van de Waddenzee, Harlingen en Stichting Het Groninger Landschap.

Streif, H. and R. Kostet (1978). "Zur Geologie der deutschen Nordseek□52?ste." Die Küste **32**.

Stroh, M., Kratochwil, A., Remy, D., Zimmermann, K. & Schwabe, A. (2003). Rehabilitation of alluvial landscapes along the River Hase (Ems river basin, Germany). Lowland River Rehabilitation Conference, Wageningen, The Netherlands.

Stronkhorst, J. (1992). "Trends in pollutants in blue mussel Mytilus edulis and flounder Platichthys flesus from two Dutch estuaries, 1985-1990." Marine Pollution Bulletin **24**(5): 250.

Swiss, M. (1975). "LARGE DIAMETER PIPELAYING IN THE EMS ESTUARY." CIV. ENGNG. (LONDON)(824).

Talke, S., V. N. de Jonge, et al. (2005). Measuring and modelling biological and physical parameters at the Estuary Turbidity Maximum on a river with high sediment concentrations (Ems estuary). Estuarine Research Federation, Norfolk, VA.

Tetzlaff, B. and F.-I. e. Wendland, 2004): Vol. 1, S. (2004). The Contribution of Agriculturally used Raised Bogs to the total-P Input from Diffuse Sources to Surface Waters - the River Ems Case Study (NW-Germany). Wise Use of Peatlands, Proceedings of the 12th International Peat Congress.

Tetzlaff, B. and F. Wendland (2004). Entwicklung eines GIS-gestützten Modells zur flächendifferenzierten Analyse des Phosphataustrags aus diffusen Quellen in großen Flusseinzugsgebieten - das Beispiel Ems. Interdisziplinäre Methoden des Flussgebietsmanagements., Workshopbeiträge, Institut für Geoinformatik, Münster, Germany, IfGI-prints.

Thomas Schumacher, H. (2003). Grenzenlos an Deich und Dollart, Das Reise- und Lesebuch für die Ems-Dollart-Region.

Töppe, A. (1993). Longtime cycles in mean tidal levels. Proceedings Int. Workshop Workshop SEACHANGE □80?93, Koblenz, BfG, IHP/OHP-Sekretariat.

Uncles, R. J., P. E. Frickers, et al. (2000). "Concentrations of suspended particulate organic carbon in the tidal Yorkshire Ouse River and Humber Estuary." Science of the Total Environment **251-252**: 233.

Van Beusekom, J. E. E. and V. N. De Jonge (1994). "The role of suspended matter in the distribution of dissolved inorganic phosphate, iron and aluminium in the Ems Estuary." Netherlands Journal of Aquatic Ecology **28**(3-4): 383.

Van Beusekom, J. E. E. and V. N. De Jonge (1996). Seasonal cycle in the interaction of suspended matter with dissolved aluminium and iron in the Ems estuary. Suspended particulate matter in rivers and estuaries: Proceedings of an International Symposium held at Reinbek near Hamburg, Germany. Kausch, Hartmut, Michaelis and Walfried. **VIII**.

Van Beusekom, J. E. E. and V. N. De Jonge (1998). "Retention of phosphorus and nitrogen in the Ems estuary." Estuaries **21**(4 A): 527.

Van Beusekom, J. E. E. a. d. J., V.N. (2002). Long-term changes in Wadden Sea nutrient cycles: importance of organic matter import from the North Sea. Nutrients and eutrophication in estuarine and coastal waters, Hydrobiologia 475/ 476. M. E. V. N. d. J. E. Orive**:** 185-194.

Van Damme, D., C. Heip, et al. (1984). "Influence of pollution on the harpacticoid copepods of two North Sea estuaries." Hydrobiologia **112**(2): 143.

Van de Kreeke, J., C. M. Day, et al. (1997). "Tidal variations in suspended sediment concentration in the Ems estuary: Origin and resulting sediment flux." Journal of Sea Research **38**(1-2): 1.

Van De Kreeke, J. and K. Robaczewska (1993). "Tide-induced residual transport of coarse sediment; application to the Ems Estuary." Netherlands Journal of Sea Research **31**(3): 209.

Van Den Bremen, W. J. (1992). "Seaport development and state boundaries: the Ems-Dollart Region and the Scheldt-Antwerp region on Dutch frontiers." Ocean & Coastal Management **18**(2-4): 197.

Van der Ham, R., H. L. Fontijn, et al. (2001). "Turbulent exchange of fine sediments in a tidal channel in the Ems/Dollard estuary. Part I: Turbulence measurements." Continental Shelf Research **21**(15): 1605.

Van der Ham, R. and J. C. Winterwerp (2001). "Turbulent exchange of fine sediments in a tidal channel in the Ems/Dollard estuary. Part II. Analysis with a 1DV numerical model." Continental Shelf Research **21**(15): 1629.

Van Der Lee, W. T. B. (1998). "The impact of fluid shear and the suspended sediment concentration on the mud floc size variation in the Dollard estuary, The Netherlands." Geological Society Special Publication(139): 187.

Van Der Lee, W. T. B. (2000). "The settling of mud flocs in the Dollard estuary, the Netherlands." Nederlandse Geografische Studies(274): 1.

Van der Lee, W. T. B. (2000). "Temporal variation of floc size and settling velocity in the Dollard estuary." Continental Shelf Research **20**(12-13): 1495.

Van der Lee, W. T. B. and (2000) (2000). Parameters affecting mud floc size variation on a seasonal time scale: the impact of a phytoplankton bloom in the Dollard estuary, The Netherlands. Coastal and estuarine fine sediment transport processes. W. H. McAnally and A. J. Mehta.

Van Duyl, F. C., A. J. Kop, et al. (1999). "Tidal coupling between carbohydrate concentrations and bacterial activities in diatom-inhabited intertidal mudflats." Marine Ecology Progress Series **191**: 19.

Van Duyl, F. C., A. J. Kop, et al. (2000). "Consequences of diatom mat erosion for carbohydrate concentrations and heterotrophic bacterial activities in intertidal sediments of the Ems-Dollard estuary." Continental Shelf Research **20**(10-11): 1335.

Van Es, F. B. and P. Ruardij (1982). "The use of a model to assess factors affecting the oxygen balance in the water of the Dollard." Netherlands Journal of Sea Research **15**(3-4): 313.

Van Es, F. B., M. A. Van Arkel, et al. (1980). "Influence of organic pollution on bacterial, macrobenthic and meiobenthic populations in intertidal flats of the Dollard." Netherlands Journal of Sea Research **14**(3-4): 288.

Van Es, F. R. and R. W. P. M. Laane (1982). "The utility of organic matter in the Ems- Dollard estuary." Netherlands Journal of Sea Research **16**: 300.

Van Heemst, J. D. H., K. J. Dria, et al. (1999). "Characterization of dissolved organic matter from the Ems-Dollart estuary and the North Sea using ramp-CPMAS C-13-NMR." Abstracts of Papers of the American Chemical Society **318**: 30-GEOC Part 1.

Van Heemst, J. D. H., L. Megens, et al. (2000). "Nature, origin and average age of estuarine ultrafiltered dissolved organic matter as determined by molecular and carbon isotope characterization." Organic Geochemistry **31**(9): 847.

Van Leussen, W. (1996). Erosion/sedimentation cycles in the Ems estuary. Suspended particulate matter in rivers and estuaries: Proceedings of an International Symposium held at Reinbek near Hamburg, Germany. Kausch, Hartmut, Michaelis and Walfried. **VIII:** 179-193.

Van Leussen, W. (1998). The effect of biological processes on the longitudinal variation of floc sizes and settling velocities of fine-grained sediment in the Ems Estuary. Geographical developments in coastal morphodynamics**:** 83-101.

Van Leussen, W. (1999). "The variability of settling velocities of suspended fine-grained sediment in the Ems estuary." Journal of Sea Research **41**(1-2): 109.

Van Leussen, W. and J. M. Cornelisse (1993). "The determination of the sizes and settling velocities of estuarine flocs by an underwater video system." Netherlands Journal of Sea Research **31**(3): 231.

Van Leussen, W. and J. M. Cornelisse (1996). "The underwater video system VIS." Journal of Sea Research **36**(1-2): 77.

Van Zon, H., J. Abrahamse, et al. (1974). Dollard, portrait of a landscape (Dutch).

Vanes, F. B. (1980). "Influence of organic pollution on bacterial, macrobenthic and meiobenthic populations in inter-tidal flats of the Dollard." Netherlands Journal of Sea Research **14**: 288.

Vanes, F. B. (1982). "Community metabolism of Inter-tidal flats in the EMS-Dollard Estuary." Marine Biology **66**: 95.

Verbeek, K. (2003). De toestand van het klimaat in Nederland. De Bilt, KNMI.

Vollmers, H. "Harbour inlets on tidal estuaries."

Vos, P. C. and W. P. Van Kesteren (2000). "The long-term evolution of intertidal mudflats in the northern Netherlands during the Holocene; natural and anthropogenic processes." Continental Shelf Research **20**(12-13): 1687.

Voslamber, B., M. Zijlstra, et al. (1993). "Migration of different populations of greylag geese Anser anser through the Netherlands: differences in area preference and timing in 1988 [De trek van verschillende populaties grauwe ganzen Anser anser door Nederland: verschillen in gebiedskeuze en 1988]." Limosa **66**(3): 89.

WASA (1998). "Changing waves and storms in the Northeast Atlantic?" Bull. Amer. Met. Soc. **79**: 741-760.

Winterwerp, J. C. (2002). "On the flocculation and settling velocity of estuarine mud." Continental Shelf Research **22**(9): 1339.

Wroz, W. (1978). "Das Dollarthafenprojekt (Seehafen Emden)." Zeitschrift für Wirtschaftsgeographie **22**(5): 141-148.

Wubs, F. W. (1987). "Shallow-water flow computations by an explicit method on the Cyber 205."

Wurpts, R. (2003). "Bestimmung der nautischen Sohle durch Anwendung rheologischer Parameter - 15 Jahre Erfahrung mit fluid mud, Teil 1." HANSA **140**(9): 64-72.

Wurpts, R. (2003). "Bestimmung der nautischen Sohle durch Anwendung rheologischer Parameter - 15 Jahre Erfahrung mit fluid mud, Teil 2." HANSA **140**(10): 74-79.

Wurpts, R. (2005). "Hyperconcentratred flow: Reduzierter Unterhaltungsaufwand bei Berücksichtigung der Fließfähigkeit des Baggergutes." HANSA.

Wurpts, R. and P. Torn (2005). "15 Years Experience with Fluid Mud: Definition of the Nautical Bottom with Rheological Parameters." Terra et Aqua **99**.

Ysebaert, T., P. Meire, et al. (1998). "Zonation of intertidal macrobenthos in the estuaries of Schelde and Ems." Aquatic Ecology **32**(1): 53.

Zauke, G. P., S. Kunze, et al. (1985). Biological Monitoring of Cd, Pb, Ni, Zn, and Cu in the Elbe-, Weser-, and Ems-Estuary (NW-Germany). Heavy Metals in the Environment. T. D. Lekkas. **1:** 536-538.

Zimmerman, J. T. F. (1988). Estuarine residence times. B. Kjerfve, CRC Press. **1:** 75-84.