Mud dynamics in the Eems-Dollard, research phase 1

literature review mud and primary production

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Title

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Client	Project	Reference	Pages
Rijkswaterstaat Waterdienst	1204891-000	1204891-000-ZKS-0012	83

Summary

The Water Framework Directive (WFD) obliges the EU member states to achieve good status of all water bodies (rivers, lakes, transitional and coastal waters) by 2015. In the management plan for the implementation of the WFD (and Natura 2000) in the Netherlands , the context, perspectives, targets and measures for each designated water body (also including the Eems-Dollard) have been laid out. The WFD obliges to improve our knowledge on the mud dynamics in the Ems-Dollard, and before 2015 the reasons for the apparent increase in turbidity must be established. Therefore Rijkswaterstaat Waterdienst has initiated the project “Onderzoek slibhuishuiding Eems-Dollard”. The first phase of this project aims to setup a modelling and monitoring plan, supported by stakeholders and scientific experts. This phase consists of (a) identification of the current system knowledge and knowledge gaps related to KRW, water turbidity and primary production, (b) a modelling and monitoring plan, and (c) workshops with specialists and stakeholders. This report reviews the current system knowledge and knowledge gaps related to WFD, water turbidity and primary production. This report serves as the basis for the modeling and monitoring plan (part b), described in an accompanying report

References

Offerteaanvraag RWS/WD-2011/1032, offerte 1204891-000-ZKS-003, toekenning RWS/WD-2011/1509

Version	Date	Author	Initials	Review	Initials	Approval	Initials
	Aug. 2011	dr. D.S. van Maren		dr. T. van Kessel		T. Schilperoort	
				dr. F.J. Los			
	Oct. 2011	dr. D.S. van Maren				T. Schilperoort	

State

final

Contents

1 Introduction

The Water Framework Directive (WFD) obliges the EU member states to achieve good status of all water bodies (rivers, lakes, transitional and coastal waters) by 2015. It also introduces the principle of preventing any further deterioration of the status and maintaining good status through a number of measures. This forms the basis of the River Basin Management Plans (RBMP) set up by the Member States for each identified river basin.

The management plan for the implementation of the WFD (and Natura 2000) in the Netherlands is described in the "Bijlage Programma Rijkswateren 2010-2015" (Rijkswaterstaat, 2009). Herein, the context, perspectives, targets and measures for each designated water body (also including the Eems-Dollard) have been laid out. The measures and targets necessary for improving the chemical and ecological quality, as requested by the WFD, are grouped under 3 main themes: Clean water ("Schoon water"), Biotope ("Leefgebied") and Connections ("Verbindingen").

Under the theme Clean water, three goals (and corresponding measures) have been defined:
1) reduction in chemical loads
2) reduction of eutrophication
3) improvement of the water transparency/reduction of water turbidity

As part of goal 3), the WFD obliges to improve our knowledge on the mud dynamics in the Ems-Dollard, and before 2015 the reasons for the apparent increase in turbidity must be established. Therefore Rijkswaterstaat Waterdienst has initiated the project "Onderzoek slibhuishuiding Eems-Dollard". This project should answer the following questions:
- What are the effects of the current dredging and dumping strategies on the mud dynamics in the Ems-Dollard?
- What are the effects of mud dynamics on ecology, and the water quality elements of the WFD?
- Which solutions and measures exist to improve or restore the ecological quality?

To answer these questions, the project is divided in three phases:
1) Setup of a modelling and monitoring plan, supported by stakeholders and scientific experts. This phase consists of (a) identification of the current system knowledge and knowledge gaps related to KRW, water turbidity and primary production, (b) a modelling and monitoring plan, and (c) workshops with specialists and stakeholders.
2) Monitoring and model setup, to enhance understanding of system functioning with respect to sediment transport and distribution and other affected processes, namely primary production
3) Scenario studies in which instruments developed in phase 2 are used to quantify mitigation measures.

The sediment dynamics in the Ems-Dollard and its relation to primary production are complex, and therefore Rijkswaterstaat Waterdienst has commissioned research institutes Deltares and Imares to carry out phase 1. This report covers activity a) of phase 1 and reviews the current system knowledge and knowledge gaps related to WFD, water turbidity and primary production.

It is intended to relate the knowledge and available data and information to the monitoring and modelling work proposed in the project. Activity b) of phase 1 will be reported in a separate document, called “Working plan”, in which also a plan for phase 2 en 3 will be presented.

In this report, the Water Framework Directive and its implications for the Ems-Dollard is reviewed in chapter 2. The hydrodynamics, turbidity, and changes in turbidity in the Ems-Dollard are analysed in chapter 3. Primary production, and human-induced changes therein, are evaluated chapter 4. The available data and models for the area are described in chapter 5, and results are summarized in chapter 6.

2 The Water Framework Directive

2.1 Classification of status

The implementation of the Water Framework Directive (WFD) requires the protection of the ‘structure’ and the ‘functioning’ of aquatic ecosystems by 1) optimizing water quality 2) optimizing the habitat providing conditions and 3) evaluating the effect of the restoration measures (WFD, 2000/60/EC). The enhanced protection and improvement of the aquatic environment necessitates the achievement and/or maintenance of “good status” by 2015. For surface waters, “good status” is defined by both “ecological” and “chemical” status. The ecological status of a water body (lakes, rivers, coastal and transitional, groundwater) can be described by five ecological status classes: high (= nearly undisturbed conditions), good (= slight change in composition, biomass), moderate (= moderate change in composition, biomass), poor (= major change in biological communities) or bad (= severe change in biological communities). This classification is based on a number of biological quality elements (BQEs), supported by determinants for general physico-chemical elements (nutrients, temperature) and specific pollutants, as depicted in the schematic diagram below (Figure 2.1). The BQEs set for coastal and transitional water bodies are based on the composition, abundance of: a) phytoplankton, b) other aquatic flora (angiosperms), c) benthic invertebrate fauna (macrofauna), and d) fish fauna (in case of transitional waters, including Ems-Dollard). The overall status of a water body is determined by the 'one-out, all-out' principle, which implies that all parameters/categories must fulfil the targets in order to achieve overall good status.

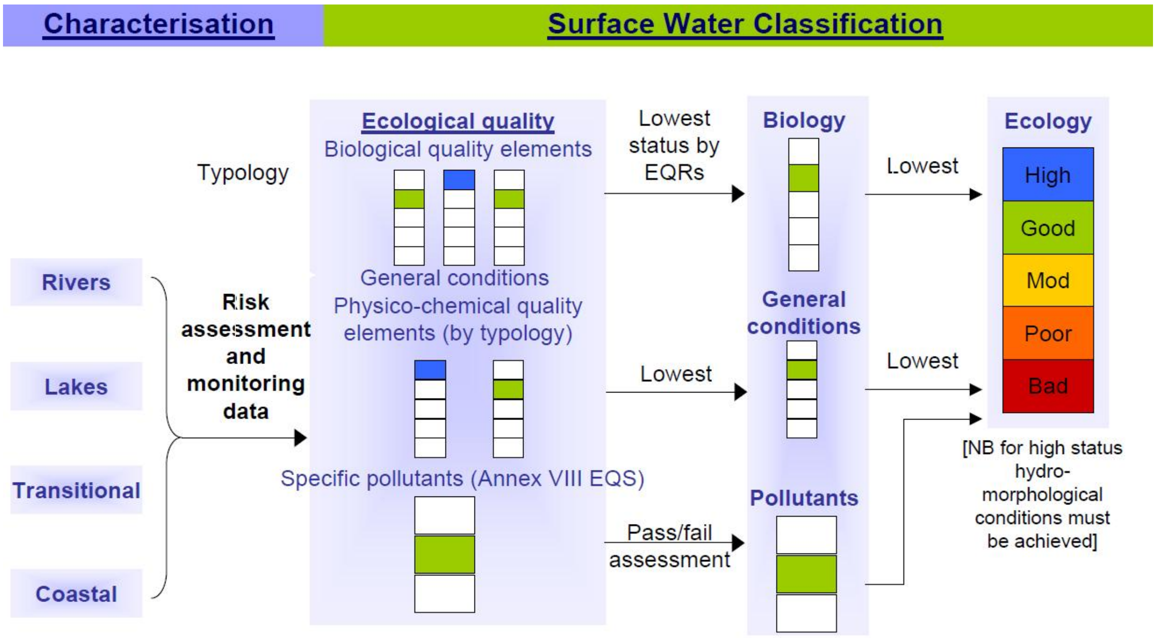


Figure 2.1 Schematic representation of the quality elements used in the determination of “ecological status” in the context of WFD

The WFD classification of water bodies in relation to type-specific reference conditions enforces the view of eutrophication as a process, where nutrient enrichment through human activities causes adverse changes in the aquatic environment, rather than as a particular level of productivity or trophic state. The definition of good ecological status for the BQEs ‘Phytoplankton’ and ‘Macrophytes and Phytobenthos’ uses very similar wording as the definition of eutrophication used in the UWWT and Nitrates Directives and by OSPAR. Good status includes an absence of eutrophication problems.

The Dutch assessment of the BEQ “phytoplankton” is based on the 90 percentile of chlorophyll-a concentration during the growing season (March 1 – September 30; 7 months period). For species composition, only the frequency of *Phaeocystis* blooms is considered, where a bloom is defined if concentrations exceed > 10^6 cells.l^{-1}..

The Netherlands has assessed the current situation with regard to phytoplankton as being ‘good’; for abundance the score is good, and for species composition the score is very good. Germany however considers phytoplankton not to be an appropriate quality element for transitional waters, because of the high concentrations of suspended matter. This parameter is therefore excluded from the assessment of the ecological status. Due to the high turbidity in the area, the result of the assessment does not give a unambiguous description of the eutrophication status and is therefore defined as a (methodological) bottleneck for the ecological functioning (Brondocument KRW, 2009).

2.2 Measures

In the Netherlands, the pragmatic “Prague Approach” is used for the determination of policy objectives for water quality within the WFD. The Ems-Dollard is, as almost all Dutch water bodies, characterized as a heavily modified water body, on the bases of hydromorphological changes by humans. Therefore, the principle policy objectives for WFD compliance will be set according to the “Maximal Ecological Potential”, lowered by those measures that will have little or no effect in terms of improvement of the ecological or chemical status. Moreover, according to the “Prague Approach”, measures that are relatively costly will be postponed or left aside, and the policy target remains for the first WFD management cycle (Figure 2.2).

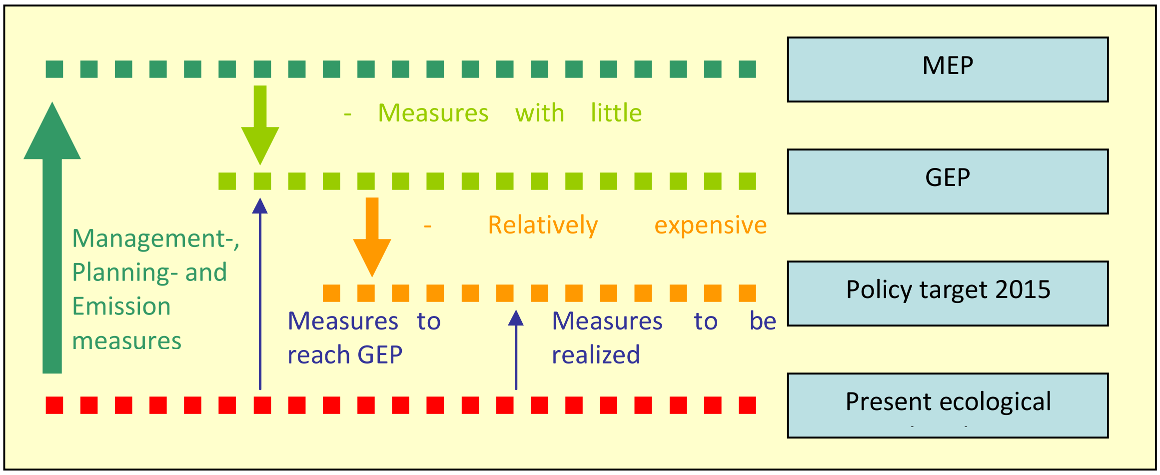


Figure 2.2 Methodology for derivation of GEP and policy targets according to the Prague approach (adapted from Rijkswaterstaat 2009)

2.3 The Ems Dollard

The Ems-Dollard estuary, located on the border of the Netherlands and Germany, is a semi-enclosed body of water stretching from the Island of Borkum to the weir in Herbrum, the end of the range of tidal influence. Four main subareas can be identified (Figure 2.3): the outer area or lower reaches, the inner estuary of middle reaches, the Dollard, and the Ems River (upstream of Emden). This definition of water bodies is based on physical processes (see section 3), and will therefore be used throughout the current report.

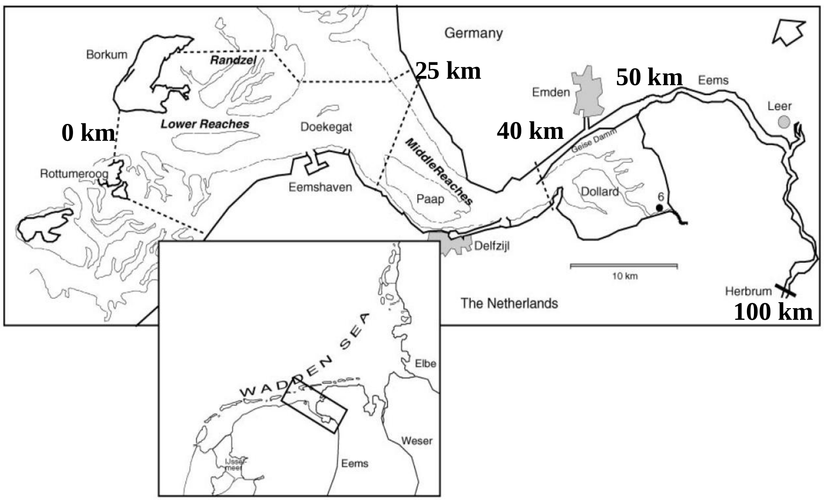


Figure 2.3 Map of the Ems-Dollard estuary showing the three sub-areas Lower (0-25 km), Middle (25-40 km) and Dollard (40-50 km) Reaches and Ems River (50-100 km) (Source: De Jonge et al., 2000)

The Dutch River Basin Management Plan (RBMP) of the Ems defines the waterbodies differently. The river basin is subdivided in three water bodies (Figure 2.4): the Ems-Dollard (transitional water body with code NL81_2), the Ems-Dollard coast (coastal water body; NL81_3) and the Ems coast (part of territorial water; coastal water body; NL95_5B). The water body NL81_2 is comprised of the Dollard and the Middle Reaches while NL81_3 covers a large area of the Lower Reaches.

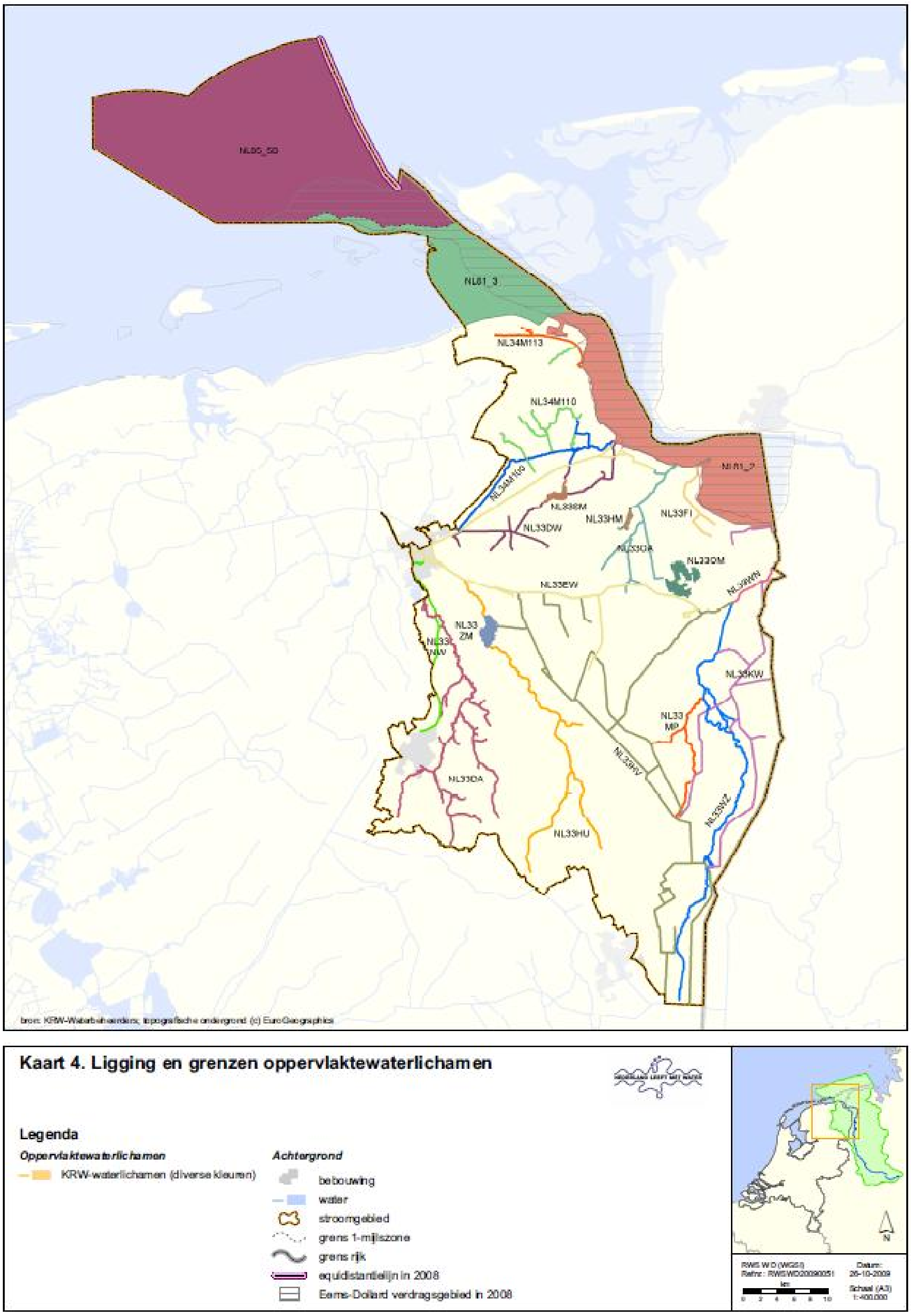
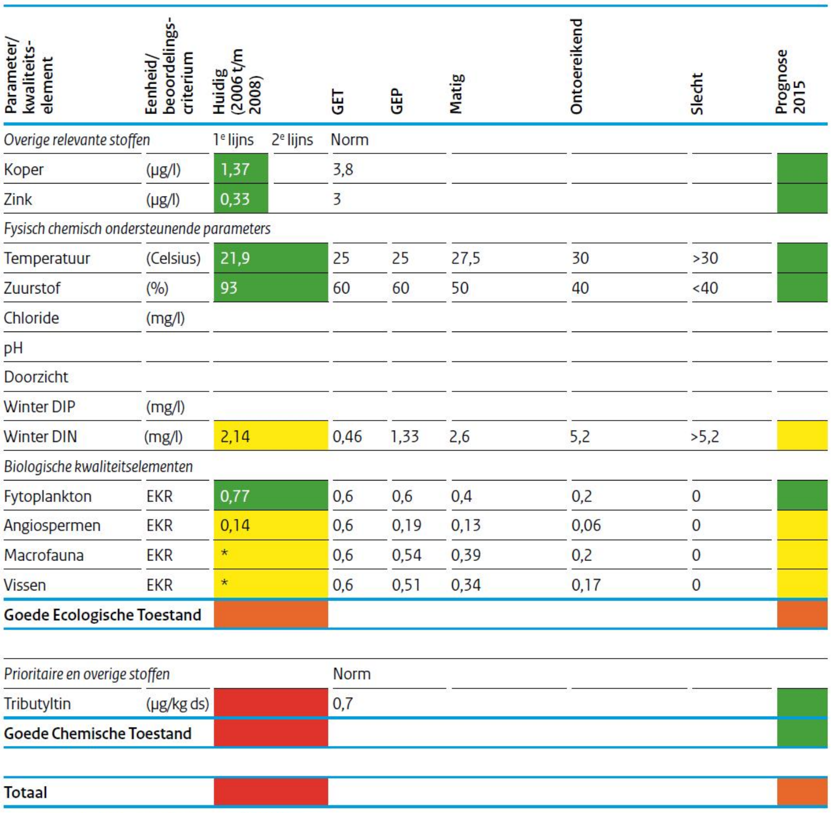


Figure 2.4 Map showing the delineated water bodies according the WFD RBMP for the Ems

Based on the Programme Rijkswateren 2010-2015 (Rijkswaterstaat, 2009), the ecological status of the Ems Dollard (NL81_2) is classified as “poor” (Table 2.1). The overall status is classified as “bad”, as a result of “bad” chemical status due to too high concentrations of tributyltin and octylphenole. This assessment is based on values averaged over 2006 to 2008. The ecological status of Ems Dollard is affected by the quality elements macrophytes (angiosperms), macrofauna and fish, and the supporting element dissolved inorganic nitrogen

(DIN), all of which are classified as “moderate”. The BQE “phytoplankton” is judged to be “good”, despite the fluctuating concentrations of chlorophyll-a from year to year.

Table 2.1 Overview of the current ecological status for the Ems Dollard and policy targets for the first WFD cycle ending in 2015 (Rijkswaterstaat 2009).



Parameter/ kwaliteits-element	Eenheid/ beoordelings-criterium	Huidig (2006 t/m 2008)		GET	GEP	Matig	Ontoereikend	Slecht	Prognose 2015
Overige relevante stoffen		1ᵉ lijns	2ᵉ lijns	Norm					
Koper	(µg/l)	1,37		3,8					🟩
Zink	(µg/l)	0,33		3					🟩
Fysisch chemisch ondersteunende parameters									
Temperatuur	(Celsius)	21,9		25	25	27,5	30	>30	🟩
Zuurstof	(%)	93		60	60	50	40	<40	🟩
Chloride	(mg/l)								
pH									
Doorzicht									
Winter DIP	(mg/l)								
Winter DIN	(mg/l)	2,14		0,46	1,33	2,6	5,2	>5,2	🟨
Biologische kwaliteitselementen									
Fytoplankton	EKR	0,77		0,6	0,6	0,4	0,2	0	🟩
Angiospermen	EKR	0,14		0,6	0,19	0,13	0,06	0	🟨
Macrofauna	EKR	*		0,6	0,54	0,39	0,2	0	🟨
Vissen	EKR	*		0,6	0,51	0,34	0,17	0	🟨
Goede Ecologische Toestand		🟧							🟧
Prioritaire en overige stoffen				Norm					
Tributyltin	(µg/kg ds)	🟥		0,7					🟩
Goede Chemische Toestand		🟥							🟩
Totaal		🟥							🟧

* Gezamenlijk oordeel van Nederland en Duitsland

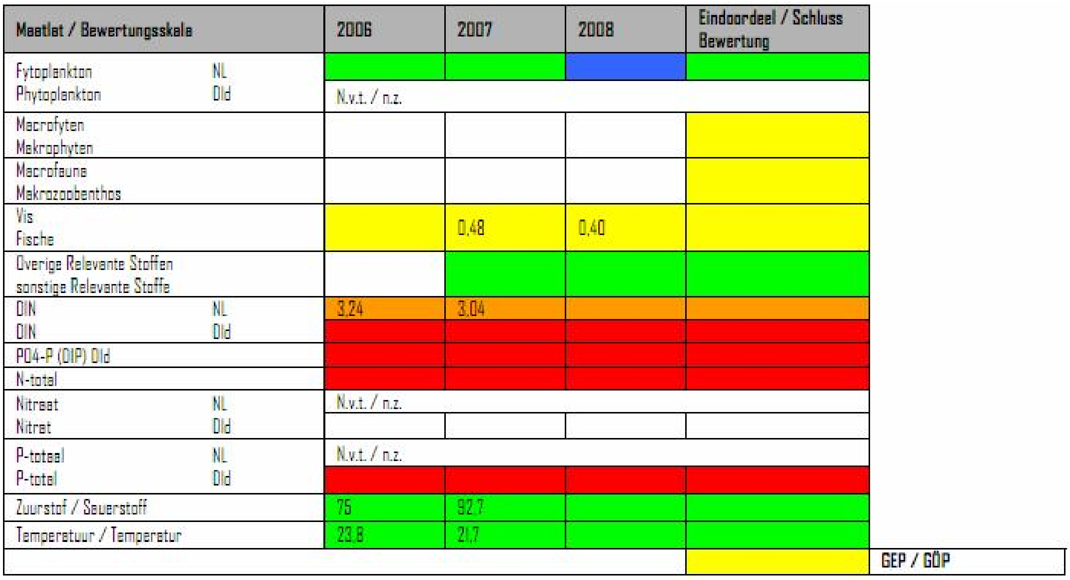
Winter DIN concentrations generally exceed the threshold for GEP due to high riverine loads from the Ems, Rhine, Meuse and Scheldt. Excess nitrogen may contribute to eutrophication, the cause of extensive algal blooms. Eutrophication changes the plankton composition, especially due to periodic blooms of *Phaeocystis*. The death and decomposition of algae blooms may lead to anoxic conditions, affecting ecosystem functioning. However, the fact that “Winter DIN” exceeds the threshold whereas at the same time “phytoplankton” scores as “good” implies that primary production is light-limited due to high turbidity. High sediment concentrations result from extensive dredging and dumping in the Ems-Dollard for maintenance and deepening of navigation channels. Although high turbidity may suppress the occurrence of severe eutrophication resulting in a deceptive “good” phytoplankton qualifier, dredging activities have a negative affect on “macrofauna”, “angiosperms” and “fish”. “Macrofauna” are affected by disruption of the sediment bottom through dredging and sedimentation due to dumping. Deepening of shipping lanes leads to increasing flow velocity, and thereby probably turbidity, while loss of shallow intertidal mudflats reduces the potential habitat for marine angiosperms. The formation of a continuous layer of fluid mud in upstream Ems, in combination with the sharp increase in upstream turbidity, gives rise to anoxic conditions that affect ecosystem functioning, including fish. Fish ecological status is classified as “moderate”, mostly based on low fish abundance and species composition of diadromous fish species. Further, migration of fish along the estuarine gradient is disrupted by the locks and dams in the mouth of the river. The identified bottlenecks for each BQE determining the ecological status are summarized in Table 2.2.

Table 2.2 Overview of the identified bottlenecks for each BQE used to assess the ecological status (Rijkswaterstaat 2009).

Water body	**Phytoplankton**	**Angiosperms**	**Macrofauna**	**Fish**
Ems-Dollard NL81_2	Effect of eutrophication partly suppressed by turbidity	Causes of low seagrass quality is unclear Possibly related to declining area of saltmarshes due to poldering	Fishing and navigation channel-deepening/maintenance dredging	Physical barriers to migrating fish and upstream turbidity (formation of fluid mud)
Ems-Dollard coast NL81_3	Landborne nutrient loads		Fishing and channel-deepening/maintenance dredging	

Unfortunately, the Dutch and the German evaluation of the quality elements gave different results. This is because the two countries adopted a different methodology for assessing the status which does not take into account the same quality element (Table 2.3). Germany does not evaluate the element “phytoplankton”, while The Netherlands do not evaluate “P-total” as quality elements for ecological status. So far there is no agreement between The Netherlands and Germany on the reference value (and therefore the targets) for chlorophyll-a in the Ems-Dollard, which currently deviates by a factor of 3.

Table 2.3 Comparison between the Dutch and German evaluation of the ecological quality elements (Brondocument KRW, 2009) for the years 2006, 2007 and 2008. Note that the status of the quality elements deviates from that presented in Table 2.1 in which values are averaged over the 3 years based on the updated methodology (Rijkswaterstaat, 2009).



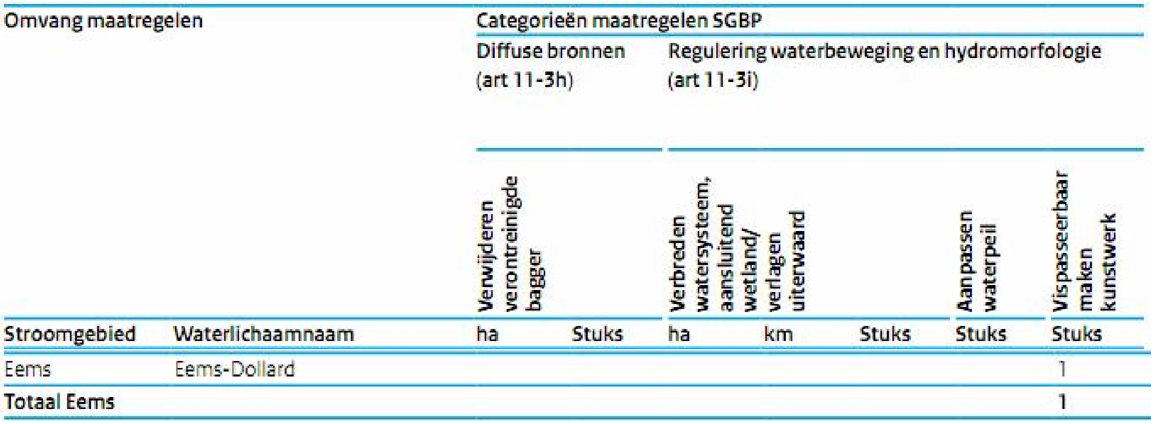
Maatlat / Bewertungsskala		2006	2007	2008	Eindoordeel / Schluss Bewertung	
Fytoplankton	NL	🟩	🟩	🟦	🟩	
Phytoplankton	Dld	N.v.t. / n.z.				
Macrofyten Makrophyten					🟨	
Macrofaune Makrozoobenthos					🟨	
Vis Fische		🟨	🟨 0,48	🟨 0,40	🟨	
Overige Relevante Stoffen sonstige Relevante Stoffe			🟩	🟩	🟩	
DIN	NL	🟧 3,24	🟧 3,04	🟧	🟧	
DIN	Dld	🟥	🟥	🟥	🟥	
PO4-P (DIP) Dld		🟥	🟥	🟥	🟥	
N-total		🟥	🟥	🟥	🟥	
Nitraat	NL	N.v.t. / n.z.				
Nitrat	Dld					
P-totaal	NL	N.v.t. / n.z.				
P-total	Dld	🟥	🟥	🟥	🟥	
Zuurstof / Sauerstoff		🟩 75	🟩 92.7	🟩	🟩	
Temperatuur / Temperatur		🟩 23.8	🟩 21,7	🟩	🟩	
					🟨	GEP / GÖP

2.4 Proposed measures for the Ems-Dollard

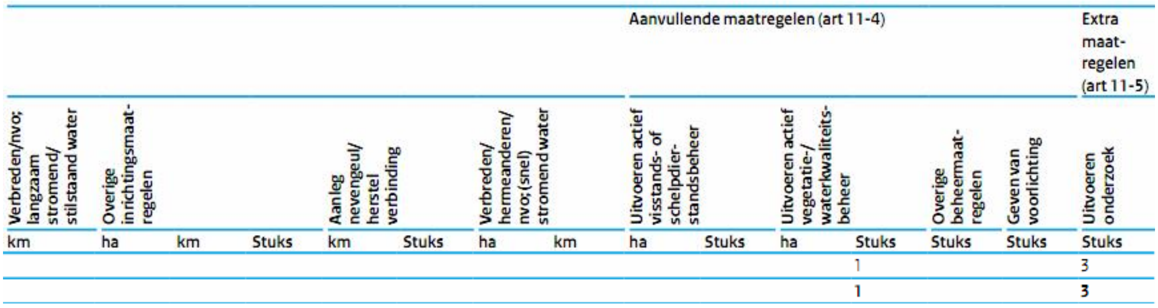
Based on the current status, a number of measures have been proposed in Rijkswaterstaat (2009) for the period 2012-2015. The effect of the implementation of these measures on the ecological status will then be re-evaluated, possibly leading to new or revised measures.

Some of the proposed measures for the Ems-Dollard focus on addressing the problem of high nutrient loadings and high turbidity (Rijkswaterstaat, 2009). Both factors are intertwined and relate directly to the target conditions for optimal phytoplankton growth, in terms of species and compositions. The reduction of nutrient loadings is identified as a major challenge, requiring not only local measures but international agreements on the reduction of transboundary nutrient inputs. For the Ems-Dollard area, a 20-40 % reduction in nitrogen is envisaged. The second priority measure concerns the reduction of turbidity in the Ems Dollard caused by dredging and dumping activities. The effects of these current activities on the sediment transport and distribution will be assessed in the research study “Onderzoek slibhuishuiding Ems-Dollard” of which this review is part. This study will also evaluate how changes in sediment will influence primary production and thus the ecological status as described by the BQEs, in particular “phytoplankton”.

Table 2.4 Overview of the measures proposed for 2010-2015 for the water body Ems-Dollard (Rijkswaterstaat 2009)



Omvang maatregelen		Categorieën maatregelen SGBP						
		Diffuse bronnen (art 11-3h)		Regulering waterbeweging en hydromorfologie (art 11-3i)				
		Verwijderen verontreinigde bagger		Verbreden watersysteem, aansluitend wetland/ verlagen uiterwaard			Aanpassen waterpeil	Vispasseerbaar maken kunstwerk
Stroomgebied	Waterlichaamnaam	ha	Stuks	ha	km	Stuks	Stuks	Stuks
Eems	Eems-Dollard							1
Totaal Eems								1



								Aanvullende maatregelen (art 11-4)						Extra maat-regelen (art 11-5)
Verbreden/nvo; langzaam stromend/ stilstaand water	Overige inrichtingsmaat-regelen			Aanleg nevengeul/ herstel verbinding		Verbreden/ hermeanderen/ nvo; (snel) stromend water		Uitvoeren actief visstands- of schelpdier-standsbeheer		Uitvoeren actief vegetatie-/ waterkwaliteits-beheer		Overige beheermaat-regelen	Geven van voorlichting	Uitvoeren onderzoek
km	ha	km	Stuks	km	Stuks	ha	km	ha	Stuks	ha	Stuks	Stuks	Stuks	Stuks
											1			3
											1			**3**

Other measures for improving ecological status of the Ems Dollard include the re-introduction of continuity in waterways leading to improved fish migration into fresh water streams, and improved abundance of diadromous fish species. Furthermore, research is planned to improve the scientific base for determination of effects of human activities and measures on ecological status. An active sediment and water quality management is implemented to facilitate best possible (cost-effective) measures for the improvement of chemical and ecological status. An overview of measures for improving the status of the Ems-Dollard is given in Table 2.4. The expected effect of these measures on the status in 2015 is indicated in Table 2.1.

3 Suspended Sediments

3.1 Introduction

This chapter presents a preliminary description of fine sediment behavior in the Ems-Dollard estuary. This behavior and the observed turbidity increase are the result of long-term evolutions of the estuary. Our understanding of the current system is based on analyses of (historic) data and numerical modeling studies. For didactic reasons, we choose to present first a brief summary of the relevant historical developments, followed by a physical description of the current system and changes in hydrodynamic and sedimentary processes. After that, we present a summary of data and model requirements and availability. Phase 1 work is mainly meant to sustain the definition of a detailed monitoring program, and is not complete because of time constraints. In a next phase of the work, the Phase 1 overview will be completed.

3.2 Historical developments in the estuary

A few bathymetrical maps are available for the entire estuary. Figure 3.1 presents maps of 1937 and 2005, showing a convergence of the multiple channel system of 1937 into one deeper channel. The Westerems (West of Borkum) becomes more separated from the Oosterems (East of Borkum), and as a result the larger part of the Ems Estuary is drained only by the Westerems. SImultaneously, the Oost Friesche Gaatje (east of Paap island, see Figure 2.3 for names) is becoming more dominant in relation to the Bocht van Watum (west of Paap Island). The major changes, though, are found along the German coast, where large land reclamation works took place. The bathymetrical maps of Figure 3.1 suggest that these reclamations must have had a considerable effect on the hydrodynamics, morphodynamics and sediment transports in the outer estuary.

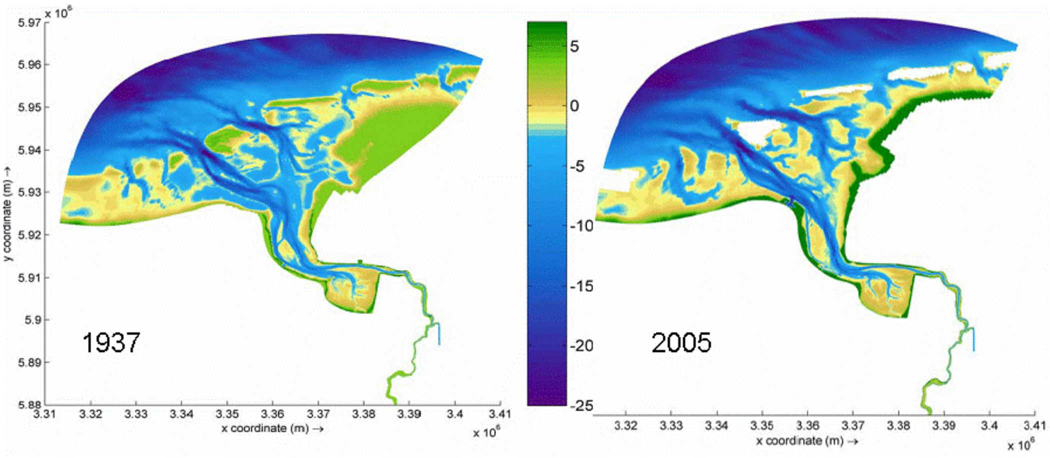


Figure 3.1 Evolution of bathymetry outer estuary (units in m; after Herrling, 2009).

Figure 3.2 presents an overview of the historic evolution of the Ems-Dollard estuary over a period of about three and a half century, showing a dramatic reduction in tidal volume of the estuary. As the morphodynamic time scale of the estuary is measured in centuries, the current bathymetry may not yet be in equilibrium with the current tidal volume. The closing of the Bocht van Watum may be the response to these decreases in volume.

Figure 3.3 and particularly Figure 3.4 show that also the Ems River has undergone large morphological changes. The plan view of the Dollard region from around 1800 suggests that the mouth of the Ems River was characterized by a number of islands, and possibly a multiple channel system. The large reduction in river width must have had a profound effect on the evolution of the tide within the river – this is elaborated a bit further in Section 3.4.

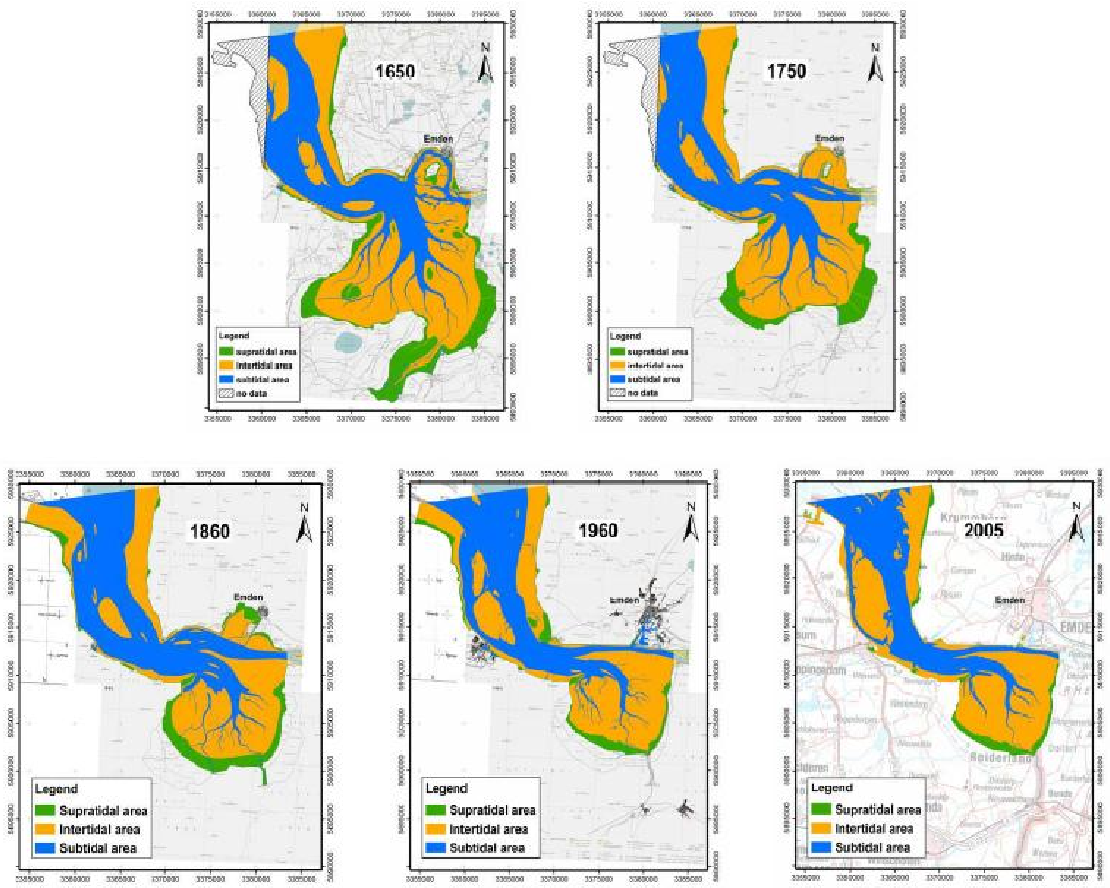


Figure 3.2 Reconstruction of historical evolution of Ems-Dollard estuary (after Herrling, 2009)

Next to these large scale changes in the estuary, a large number of smaller interventions have been realized, some of which have (had) a profound effect on the hydrodynamics and sediment dynamics within the estuary:

1. Large scale land reclamation works in and along Dollard and Ems River, and rectification and alignment of the Ems River.
2. The construction, maintenance and exploitation of a number of ports in the region (Eemshaven, Delfzijl and Emden), and their fairways. The maintenance of these basins and fairways (dredging and dumping) is subject of ongoing discussions.
3. The construction of the Geiseleitedam regulating the hydrodynamics in the fairway to Emden ("Emder Vaarwater".
4. The exploitation of the Meyer Shipyard in Papenburg and the navigable depth in the Ems River, including its maintenance through dredging.

However, one should realize that also non-local interventions may have had, or still have an effect on the sediment dynamics in the estuary, be it only through changes in the supply of fine sediment to the estuary:

1. Erection, maintenance and possibly negligence of the salt marsh works along the Groninger, and possibly Frisian Wadden coast – these salt mars works may catch large amounts of fine sediments.
2. Closure of the Zuiderzee and Lauwerszee through which large catchment basins for fine sediment have been lost. Possibly, the effect of a closure of the Afsluitdijk on the hydrodynamics may have an impact in the eastern part of the Wadden Sea, and/or Ems-Dollard estuary as well through changes in tidal elevation and propagation.
3. Even the remote Deltaworks may have had their impact through their effect on the outflow of the Rhine River, and the width of its coastal plume, responsible for the northward transport of fine sediment towards the Wadden Sea and beyond.
4. Sand mining and sand nourishments along the Dutch coast and the Wadden Islands may have an effect on the availability of fine sediments in the Ems-Dollard estuary.

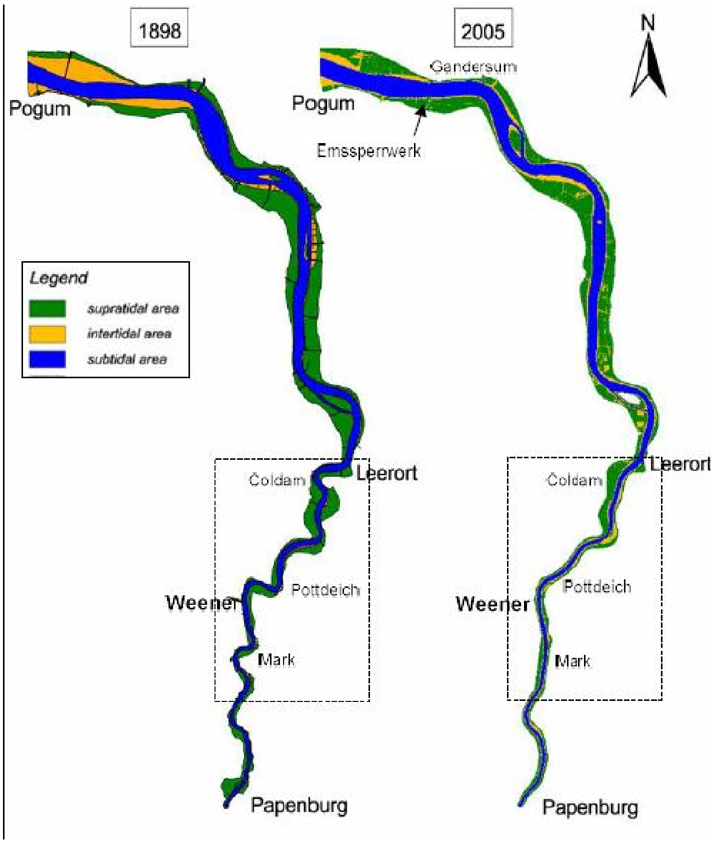


Figure 3.3 Reconstruction of historical evolution of the Ems River (after Herrling, 2009)

Finally, there are a number of “autonomous” developments important for our understanding of the hydrodynamics and sediment dynamics in the Ems-Dollard estuary:

1. Ongoing, and possibly accelerated sea level rise.
2. An increase in tidal amplitude on the North Sea (see below) – this increase is not understood, but has been observed along the entire North Sea coast.
3. The 18.6 year cycle in tidal amplitude – though this cycle has always existed, it is listed here as measurements in the estuary should be projected against the phase of this cycle.

4. The morphodynamic response of the estuary to all these changes in the system. Though this response is not subject of the current study, one should realize that this response does define boundary conditions for the hydrodynamics and thus fine sediment dynamics.

It is not part of the objective of the current study to elaborate on the role of all the interventions listed above. However, we should be aware of the fact that the estuary may not be in equilibrium with large scale changes in the system, and that data measured to day may reflect conditions from the past, and sometimes really long ago. In the next phase of the study, we will detail these interventions further, line them up along a time axis, and assess their role for the Ems-Dollard estuary through expert judgment.

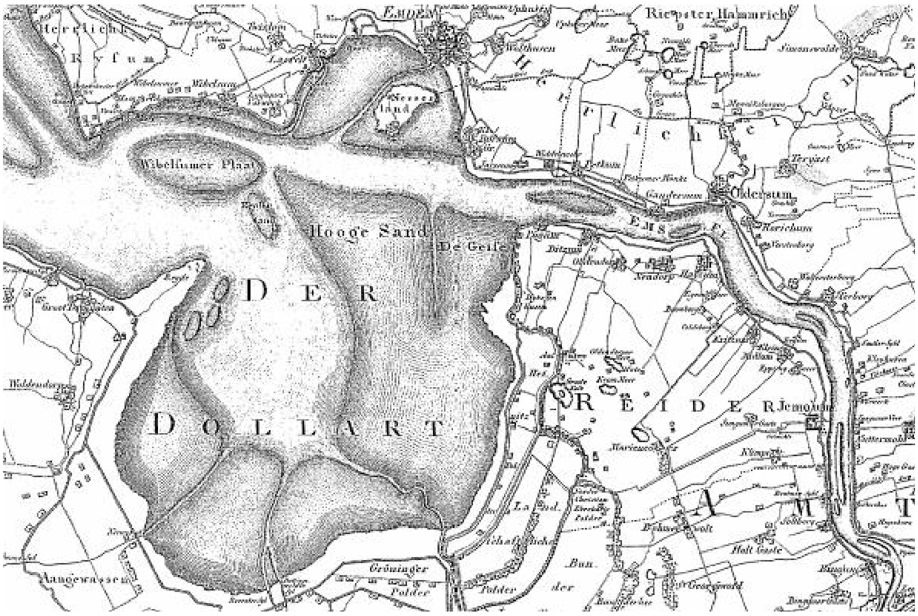


Figure 3.4 Map of historical bathymetry of Dollard, from Camp and Le Coq (1802) – after Krebs (2009).

3.3 A physical description of the current estuary

We will briefly describe the most essential hydrodynamic and sediment transport processes required for definition of knowledge gaps and modelling approach, relevant for the current project. For a more detailed review of hydrodynamic and sediment transport processes, see van Maren, 2010 (focus on whole system) or Talke and de Swart (2006) and Winterwerp (2011), both biased to the Ems River.

Figure 2.3 presents an overview of the Ems-Dollard estuary, including some of the more important geographical places, whereas Figure 3.1 (right panel) shows the current bathymetry of the estuary. The fraction of fine sediment (“slib percentage”) in the bed of the estuary is depicted in Figure 3.5. The sediments in the outer estuary are mainly composed of sand with median grain sizes between 95 and 155 µm. The clay content (grain size <2 µm) varies, depending on the degree of exposure to currents and waves, between 0.3 to 3.5%; near shore the clay content is higher. In the middle part of the estuary the clay content on the embankments increases to values of 9 to 18% with an accompanying decrease in the median grain size to values of 16-75 µm, while the sediments on the tidal flats are sandy with a clay content from 0.1 to 5.5% and a median grain size from 105-150 µm. In the Dollard clear

gradients in the clay content are present. In the central part it is less than 5% and increases towards the shore (Maschhaupt, 1948) to 35% near the salt marshes.

Figure 3.6 contains some characteristic numbers of the estuary, and definition of a series of sub-domains. Here, we prefer another subdivision, based on the relevant hydrodynamics and bed composition, e.g. Figure 3.5:

1. The inner and outer estuary consists for about 50% of tidal flats. The tidal channels and some of the tidal flats are fairly sandy, and the suspended sediment concentration increases slowly in the landward direction. The hydrodynamics are governed by tide and waves. Fine sediment concentrations are so small (in relation to the transport capacity of the flow) that the hydrodynamics are not affected, but fine sediment transport itself is affected by the salinity distribution.
2. Around 80% of the Dollard is covered with mudflats. The tidal flats are muddy, and the suspended sediment concentrations are fairly high – these concentrations are so large that they affect the hydrodynamics, in particular vertical mixing. Hydrodynamics and sediment transport are governed by the tide, waves, and salinity and suspended sediment induced density currents and stratification.
3. The Ems River, including the fairway to Emden, which is characterized by a muddy bed and hyper-concentrated conditions. There is a strong feedback between hydrodynamics (tide and river flow), suspended sediment and fluid mud in the river. Waves are not relevant.

These regions do overlap. However, this subdivision is important, as it defines where which processes are dominant / relevant, and need to be quantified with numerical models and possibly measurements.

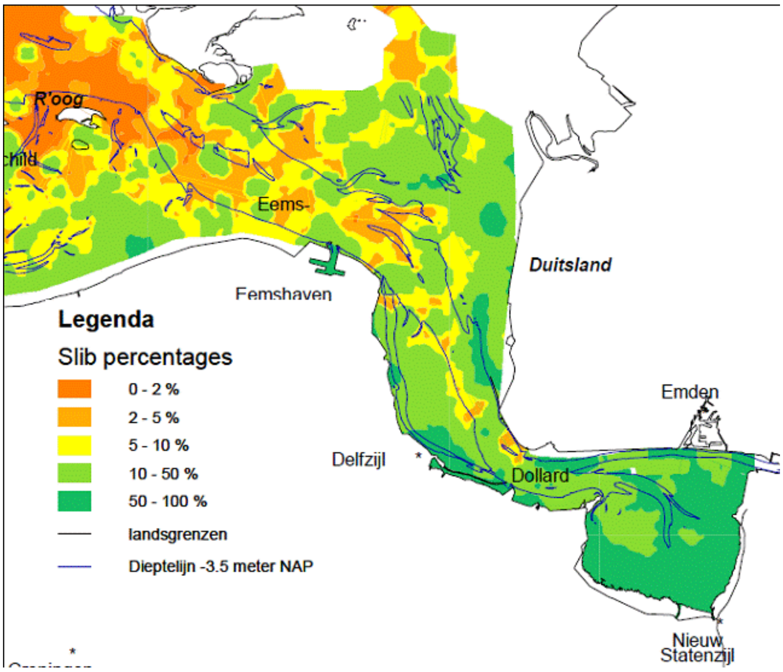


Figure 3.5 Fine bed sediment (< 63 μm) composition in Ems-Dollard estuary (after the Sedimentatlas Waddenzee, containing sediment information from grab samples taken from 1989 – 1997). Note that the values in the legend of upper panel should be divided by a factor 3, according to de Jonge and Brauer.

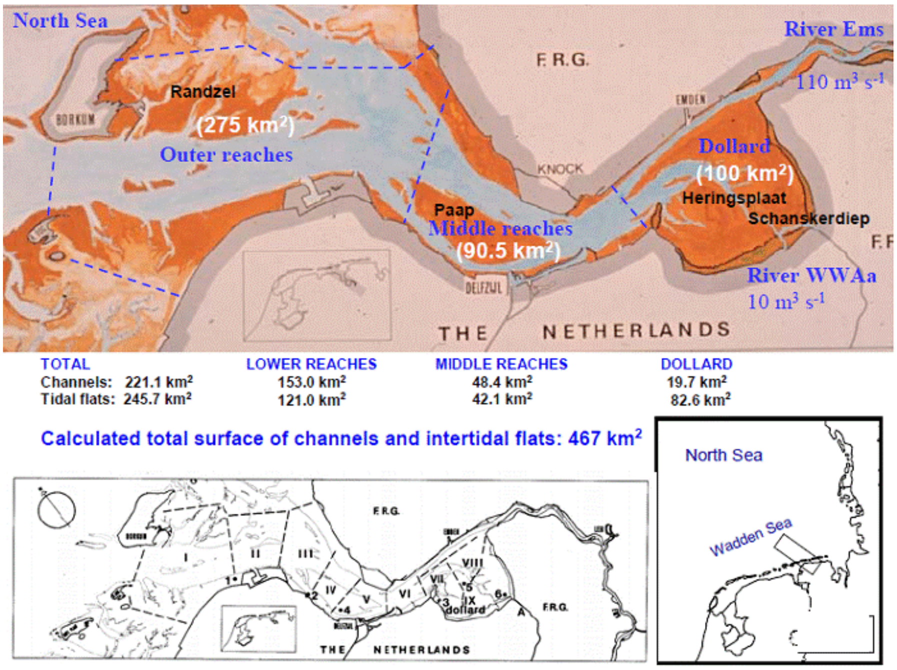


Figure 3.6 Some characteristic numbers for Ems-Dollard estuary (after de Jonge and Brauer, 2006)

In the following, we elaborate a bit further on the relevant hydro-sedimentological processes in Ems-Dollard estuary. We distinguish between the outer estuary and the inner estuary. The inner estuary is funnel-shaped, shallow, with one main channel and a secondary channel (Bocht van Watum), which seems to degenerate though. Figure 3.7 suggests that the channel bed is almost entirely sandy, whereas the fine sediment fraction (< 63 μm) in the intertidal areas is a bit higher. If we assume cohesive behavior at fine sediment fractions > 40%, Figure 3.5 suggests that the majority of the bed of the inner estuary has a granular structure, i.e. the bed is sandy, but with a variety of fines content.

The Ems-Dollard estuary is forced by semidiurnal tides, with a tidal range increasing from 2.3 m at the inlet to ~3.5 m in the river. Fresh water enters the Ems estuary by different sources of which the most important is the river Ems with a yearly average of 80–110 m^3/s. The average freshwater discharge varies from 10 to 40 m^3/s during the summer months to a maximum of ~600 m^3/s during wet winter periods. The second most important fresh water source is the Westerwoldsche Aa, which makes part of the canal system of the northern Dutch provinces and therefore has no well-defined watershed. The water discharge of the Westerwoldsche Aa is roughly 10% of that of the river Ems. Despite the low discharge, the inner estuary is characterized by substantial horizontal gradients in salinity (see Figure 3.7 for long-term timeseries and Figure 3.8 for the spatial distribution measured in 1977). Given the small fresh water inflow and large tidal effects, one does not expect any vertical stratification in the inner estuary, and this has not been reported either.

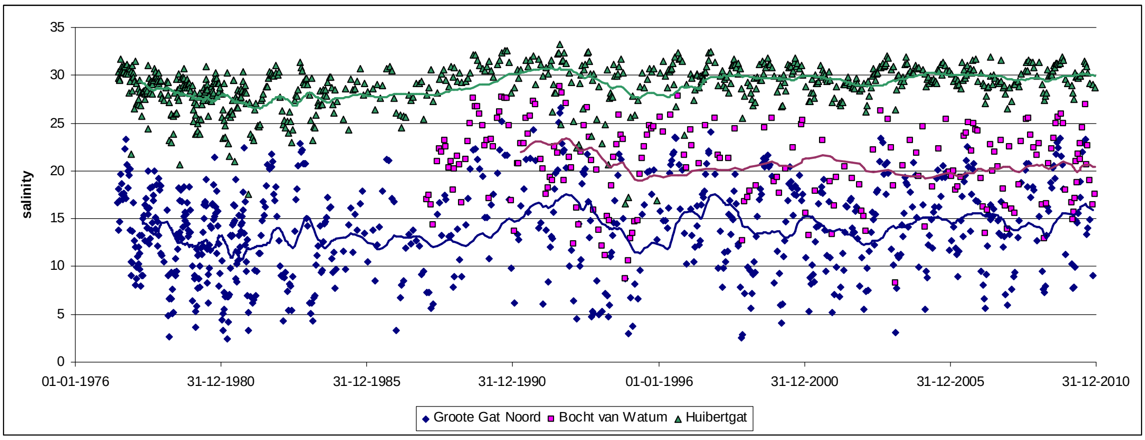


Figure 3.7 Salinity at the seaward side of the Outer Estuary (Huibertgat, average salinity 28.9), the Inner Estuary (Bocht van Watum, average salinity 20.7) and the Dollard (Groote Gat Noord, average salinity 13.9). MWTL measurements (near surface), with yearly trendline.

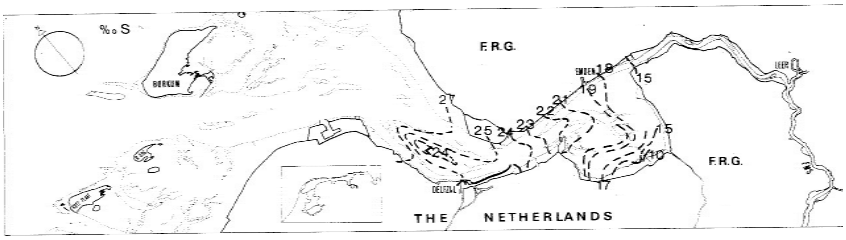


Figure 3.8 Salinity distribution based on measurements in September 1977 before HWS (after de Wolf et al., 1979).

Because of its shallowness, locally generated waves play a major role in the sediment dynamics. As the wind climate is characterized by a seasonal cycle, also fine sediment dynamics are characterized by a seasonal variation, reinforced by the effects of biota (bio-stabilization and bio-destabilization – see also processes in the Dollard).

The outer estuary is characterized by processes similar to those in other parts of the Wadden Sea, though the tidal volume through the tidal inlet is much larger than elsewhere in the Wadden Sea because of the Ems-Dollard estuary. The bed is predominantly sandy, apart from a stretch along the mainland coast where large mud flats (salt marsh works) are found. Physical processes in inner and outer estuary are very similar, though flow velocities and waves will be different. The border between the inner and outer estuary is arbitrarily set at the cross section Eemshaven – Greetsiel. The main reason to distinguish between inner and outer estuary is that the inner estuary domain is well defined, whereas the outer estuary domain is not – areas west of the Rottemeroog watershed and east of Borkum are likely to affect the hydro-sedimentological processes in the outer estuary, in particular under storm conditions. Though the larger gradients in salinity occur in this part of the estuary (Figure 3.7 and Figure 3.8), estuarine circulation plays a marginal role in the fine sediment dynamics. Van de Kreeke (1991) computed density-induced current magnitudes around 0.5 cm/s from horizontal salinity gradients, agreeing with in situ observations (residual flows of 0.7 cm/s).

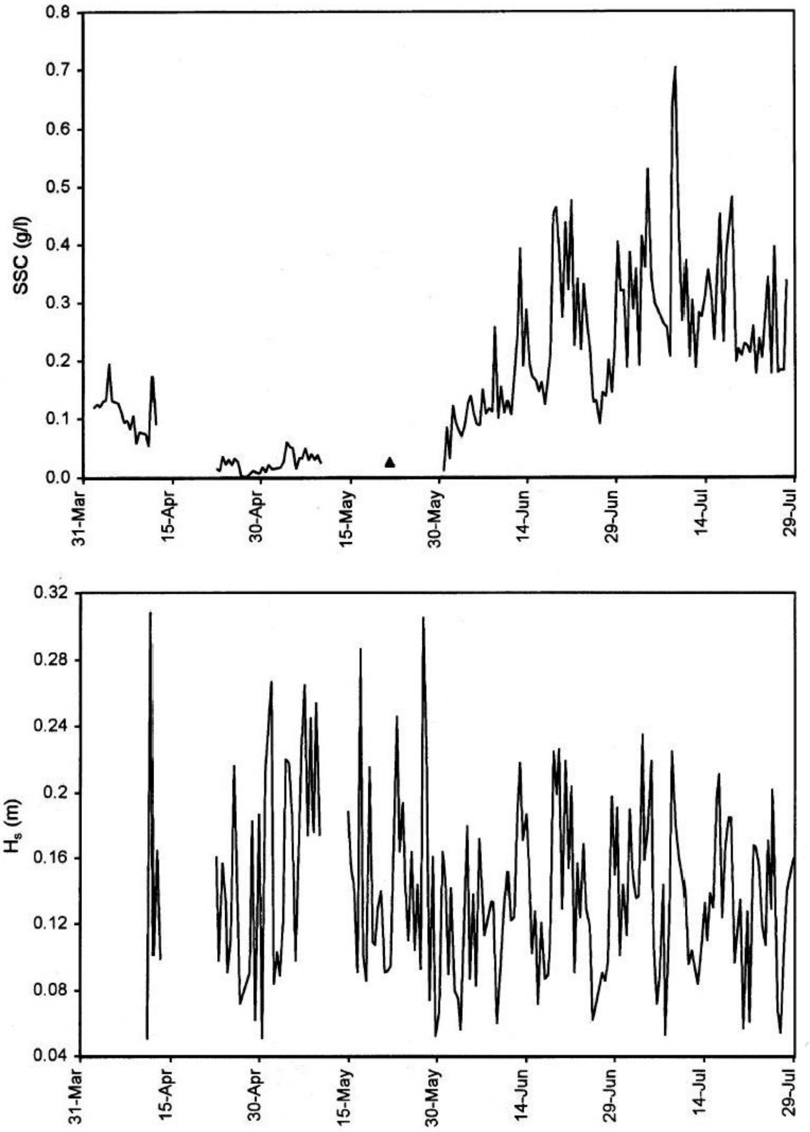


Figure 3.9 Mean suspended sediment concentration measured 5 cm above the bed (top) and the wave height (bottom), both measured on the Heeringsplaat, Dollard, in 1996. From Kornman and de Deckere, 1998.

The semi-enclosed Dollard basin is situated at the head of the Ems-Dollard estuary. The bed consists of large amounts of cohesive sediments, apart from Groote Gat channel, where a more sandy bed is expected. Because of its open nature and shallow depth, waves are expected to be important. Hence fine sediment dynamics are governed by tide, waves, and some estuarine circulation. Suspended sediment concentrations can become so large that sediment-induced stratification effects can have a profound effect on the vertical mixing (e.g. Van der Ham and Winterwerp, 2001). This is an important observation with respect to modeling and monitoring, as this sediment-induced stratification should be accounted for.

On a seasonal time scale, the effects of biota are important, as shown in Figure 3.9. Early spring, SPM concentrations are low because micro-phytobenthos (algae) stabilize the sediments – this benthos may occur in thick mats on the intertidal areas. Then, early June, grazing by Meiofauna decreases sediment stability largely, as a result of which SPM concentrations increase again. A second micro-phytobenthos peak occurs at the end of summer, probably by bird feeding on the meiofauna.

Esselink et al. (2011) analyze bathymetrical data since 1985 and concluded that the Dollard slowly erodes. Over the period 1985 – 2008 the total change in volume amounted to about $(0.2 - 1.5)\cdot 10^6$ m^3, which amounts to an erosion rate of 0.1 – 0.6 mm/yr. It is obvious that such erosion rates are difficult to assess from bathymetrical surveys, as pointed out by Cleveringa (2008): small (erroneous) vertical variations in bed level lead to large mass variations. However, if the numbers on erosion are more or less correct, an interesting question arises on whether this erosion is related to the "sediment starvation" of the Ems River, as the trapping efficiency of the Ems River has largely increased over the last few decades.

The Ems River can be considered as a hyper-concentrated system, with very high suspended sediment concentrations up to 30 – 40 g/l, e.g. Figure 3.10. The bed consists of cohesive sediments and profound occurrences of fluid mud. Suspended sediment dynamics are mainly governed by tidal asymmetry, both with respect to vertical mixing and peak flow velocities, mobilizing fine sediments from the bed (fluid mud layer), e.g. Winterwerp (2011). Waves do not play a role. Sediment-induced vertical stratification and intense flocculation and floc break-up yield very high trapping efficiency, accumulating large amounts of fine sediments in the Ems River. Most likely, no equilibrium has yet been attained.

Figure 3.10 presents time series of SPM concentrations in the Ems River (see Figure 5.3 for the location of the measuring stations). Figure 3.10a shows a profound neap-spring variation SPM values; spring tide SPM values are almost an order of magnitude larger than neap tide values. Figure 3.10b suggests that at river flows beyond ~70 m^3/s, fluid mud is flushed in the downstream direction (higher fresh water flow rates in December through April), though a similar response can be obtained through a reduction in vertical mixing as well(1). Interpretation of long-term changes in SSC (suspended sediment concentration) is complex because the observations have been cut off at magnitudes which vary through time. Weener Station appears to have been cut off at 20 g/l until 2001, followed by 2 years of maximum observed SSC of 30 g/l, and at 50 g/l after 2003. Papenburg Station is always cut off at 20 g/l. Nevertheless, Figure 3.10c shows that SPM values increased rapidly after ~2000, in particular further upstream in the river.

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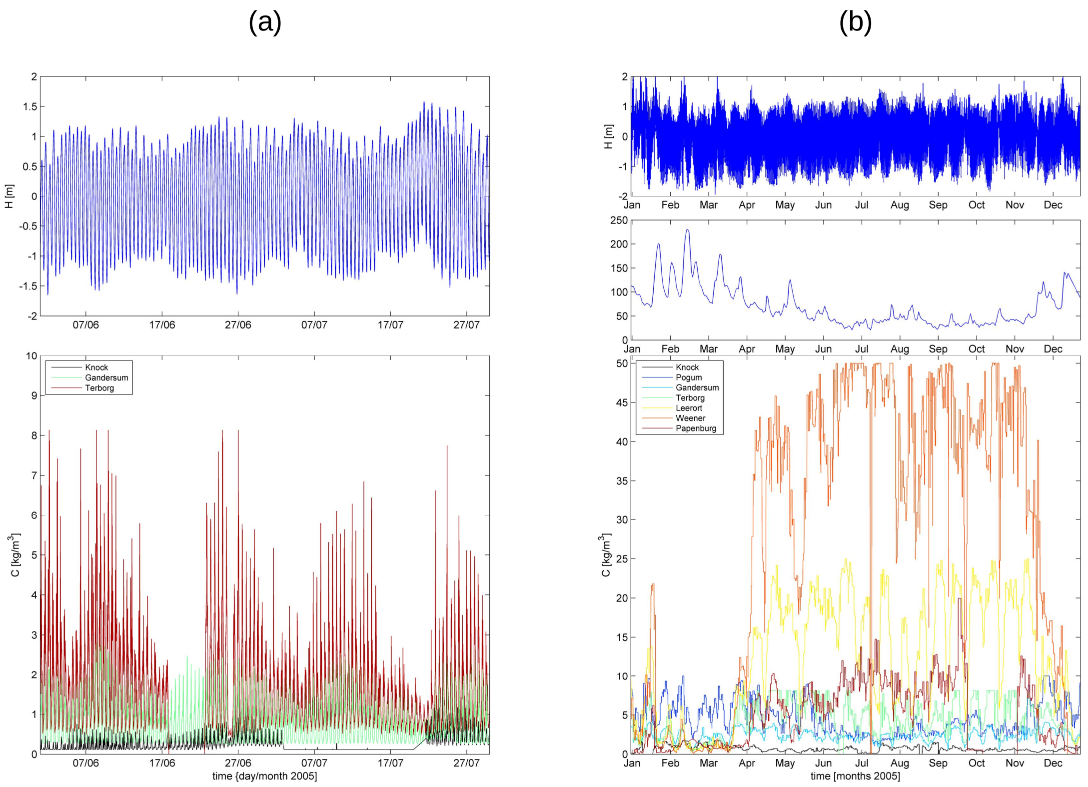
(1) *Note that peak flood velocities in River Ems are much larger than ebb velocities. Hence, an increase in river flow will enhance peak ebb velocities, but decrease peak flood velocities, as a results of which tidal mean vertical mixing may decrease.*


(a)

(b)

(c)

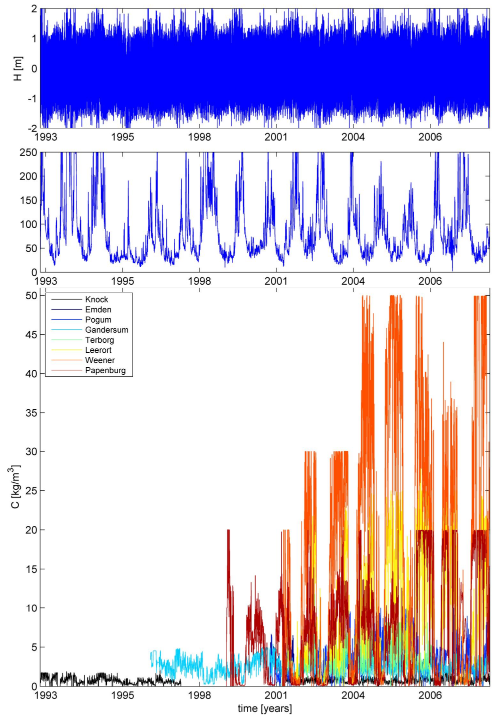


Figure 3.10 Suspended sediment (SPM) concentrations measured in the Ems River (for stations, see Figure 5.3): (a) Daily variations in SPM show a pronounced spring-neap signal, (b) seasonal variations in SPM show a large reduction in upstream SPM at higher river flows, and (c) long term variations in SPM show a spectacular increase in upstream SPM around 2000

3.4 Changes of physical processes

The long-term evolution of mean sea level and tidal amplitude on the North Sea should be taken into account when evaluating long-term variations in behavior of the Ems-Dollard estuary. Figure 3.11 shows a considerable increase in tidal amplitude over the last 50 years on the North Sea. This increase has been observed at all tidal stations along the North Sea – this increase is not well-understood at present, though. Figure 3.11 also shows the effects of the 18.6 year cycle on the tidal amplitude, though a harmonic analysis would visualize this effect better. Anyway, Figure 3.11 demonstrates that tidal data are available for a period well over 150 years.

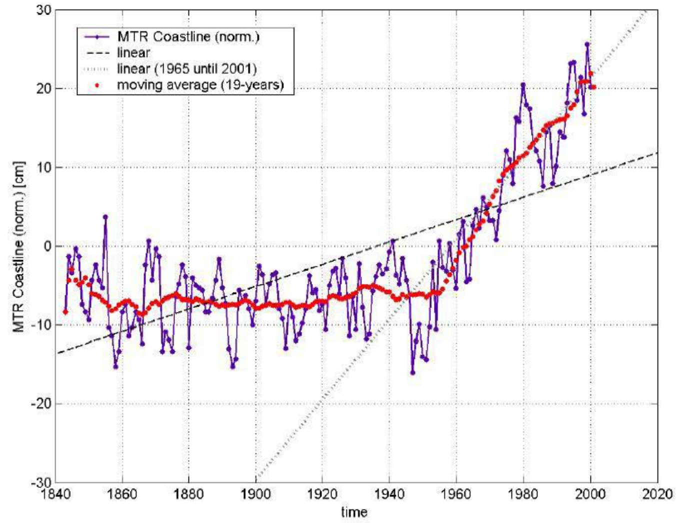


Figure 3.11 Mean tidal range observed at tidal gauges along the German coastline. The red line is an 18.6 year average. Adapted from Jensen and Mudersbach, 2005 (after Talke and de Swart, 2006).

Differences between the 1937 and 2005 bathymetry in the inner estuary and Dollard are given in Figure 3.12, showing the degeneration of the Bocht van Watum, and a substantial increase in the main channel, the Oost Friesche Gaatje. This increase is not understood, as the increase in tidal volumes seems too small to explain the increase completely. Possibly, also the increase in tidal amplitude on the North Sea and/or the land reclamation works along the German coast may have had an effect as well.

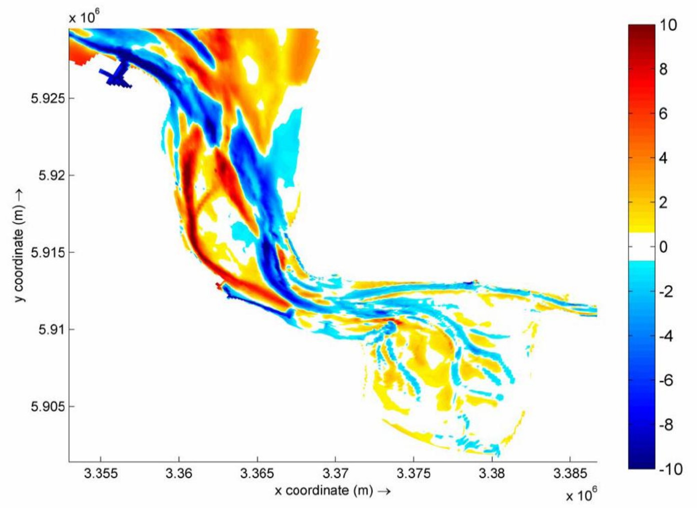


Figure 3.12 Difference of 1937 and 2005 bathymetry in the inner estuary and Dollard (after Herrling, 2009).

Figure 3.13 shows that also further upstream, in the middle reaches of the Ems River considerable changes, in particular deepening of the river occurred. Its effect on the hydro-sedimentology will be discussed elsewhere in this report.

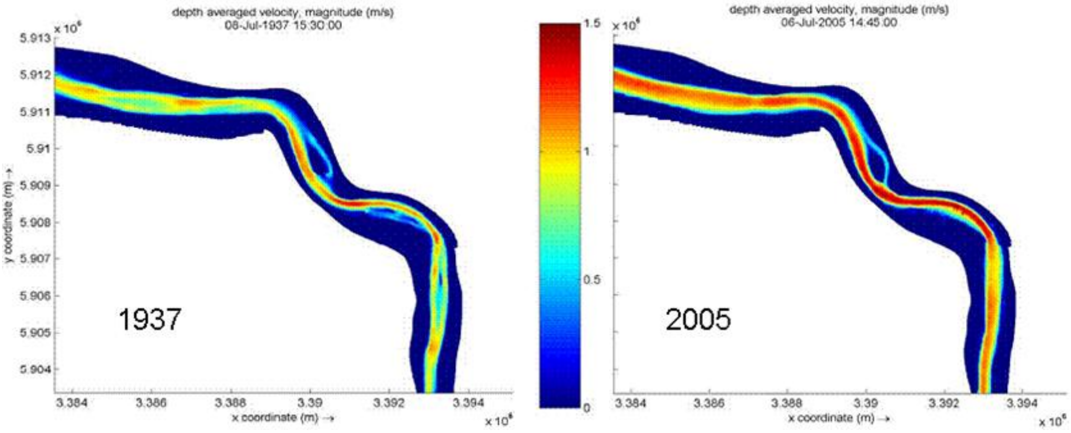


Figure 3.13 Evolution of bathymetry middle reaches Ems River (units in m; after Herrling, 2009).

Figure 3.14 presents the results of numerical simulations of the hydrodynamics for the 1937 and 2005 bathymetry. These simulations show that currents have become more concentrated in the deeper channel in the inner estuary, and that maximum current velocities increased largely.

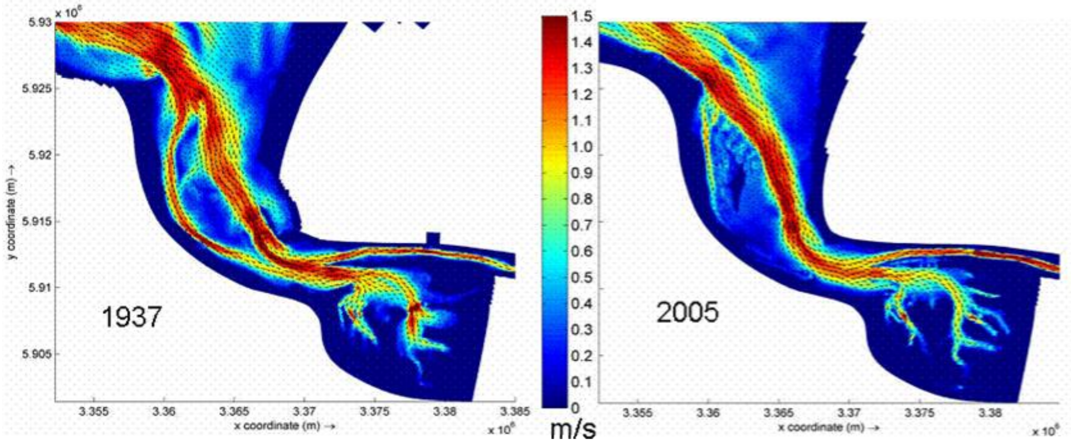


Figure 3.14 Differences in computed flow velocities and patterns between 1937 and 2005 (after Herrling, 2009).

We have no information on the current detailed spatial distribution of salinity in the Ems-Dollard estuary, but we do not expect too many changes in inner and outer estuary and in the Dollard, apart from some enhanced salinity intrusion through the deeper Oost Friesche Gaatje, the main channel in the inner estuary. This is supported by the timeseries presented in Figure 3.7. Note that more changes in salinity patterns are expected to have occurred in the Ems River itself, owing to the ongoing deepening.

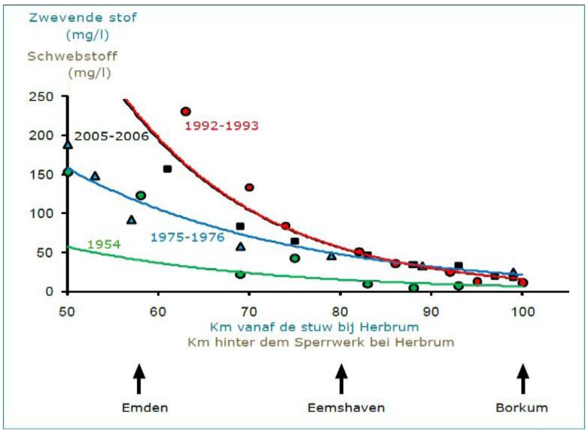


Figure 3.15 Evolution of SPM values in Ems-Dollard estuary (Raad voor de Wadden, 2010).

Longitudinal variations of characteristic SPM values over time are shown in Figure 3.15, suggesting highly elevated SPM values in the entire estuary, and an increasing gradient towards the head of the estuary. Figure 3.16 suggests that SPM values in the tidal inlet of the outer estuary have decreased, whereas elsewhere in the estuary, SPM values increased. The MWTL data should be interpreted with care because of changes in sampling methods (see Dronkers, 2005). Until 1982, sampling was done randomly within the tidal cycle, but afterwards more or less constant per station. In 1984, the number of measurement transects and measurement frequency was reduced. In 1995, the research vessel was replaced with a survey vessel, which was no longer able to operate at open sea at wind speeds exceeding 6 Bft, leading to less observations with high sediment concentrations. However, the effect of this replacement may be less prominent in the relatively sheltered Ems/Dollard estuary. Because of these uncertainties, we re-analyse the MWTL data, focussing on data collected since 1982 (Figure 3.17). To minimise the effect of sampling frequency, we first average the data per year, followed by linear regression. The trend in increase is similar to Figure 3.15 and Figure 3.16, with more or less constant sediment concentrations at the North Sea, but with concentrations increasing towards the head of the estuary. Halfway the estuary (Bocht van Watum Noord) the SSC increase is already 2.4 mg/l/year, peaking at 3.2 mg/l/year in the Dollard (Groote Gat Noord). An exception is the Bocht van Watum, where the increase is only 0.7 mg/l/year: this may also be due to the rapid siltation and therefore loss of tidal discharge in the Bocht van Watum.

Note that the rate of change is strongly influenced by the sampling period. The rate of change in Figure 3.17 is much larger than that in Figure 3.16. Re-analysing the data from 1990 onwards results in even larger increases in the suspended sediment concentration.

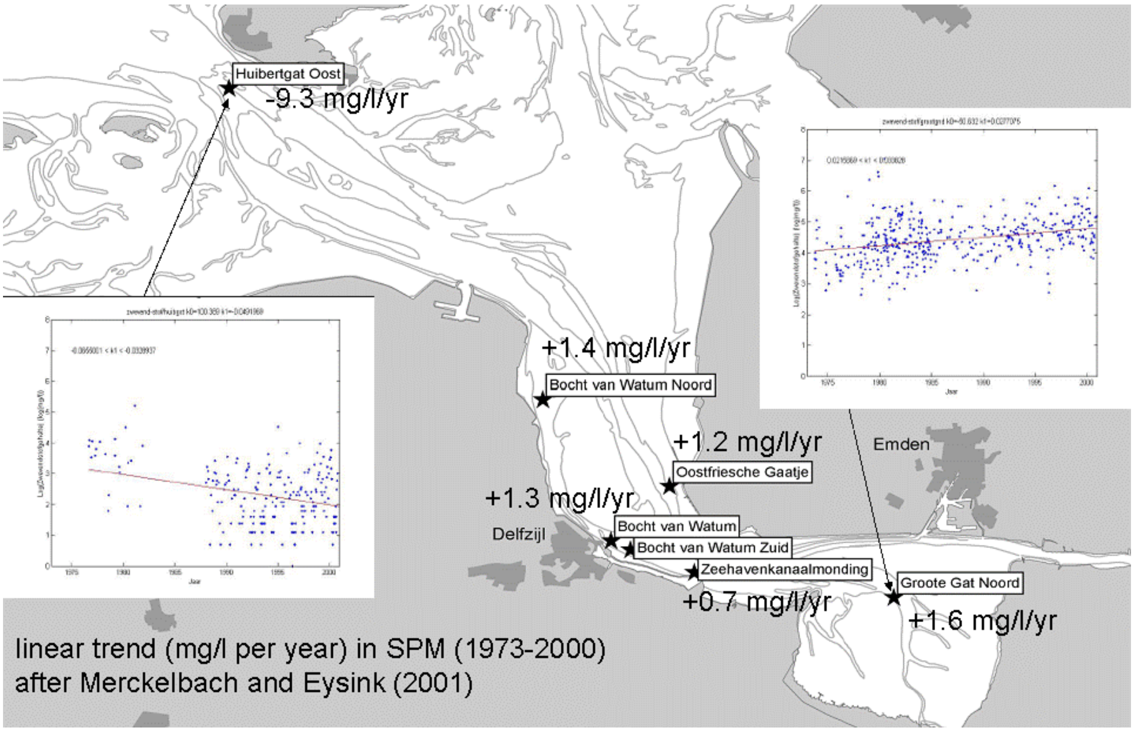


Figure 3.16 Long term changes in SPM values measured in Ems-Dollard estuary (after Mulder, 2011a).

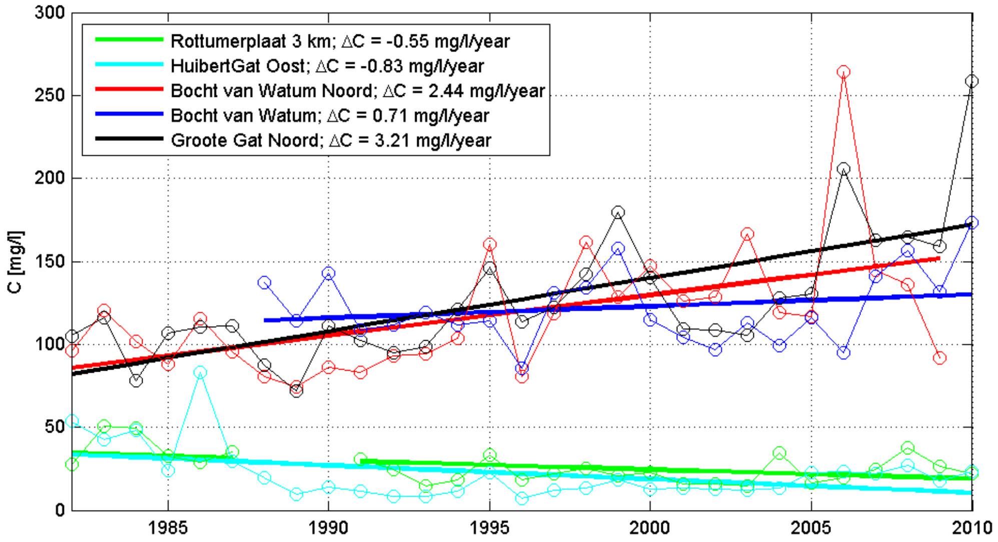


Figure 3.17 Long term changes in SPM values from 1988 until present, measured at stations in or near the Ems-Dollard Estuary where sampling continued until present (or until 2009; Bocht van Watum Noord). circled line: yearly averages, solid thick line: regression.

As discussed in Section 3.3, analyses of bathymetrical data suggest an erosion of the Dollard. Though the overall changes are small, Figure 3.18 suggests a consistent trend. Note that Figure 3.18 also suggests that intertidal area levels increase, whereas the channels deepen. This could be a response to an increase in tidal amplitude. Moreover, the channels are expected to be ebb-dominant with respect to residual (fine) sediment transport, which may explain a (small) reduction in mean bed level with increasing tidal amplitude. Figure 3.21, however, shows that also significant channel migration took place in the Dollard. We have no information whether this migration is cyclic, or forms part of a trend in the system.

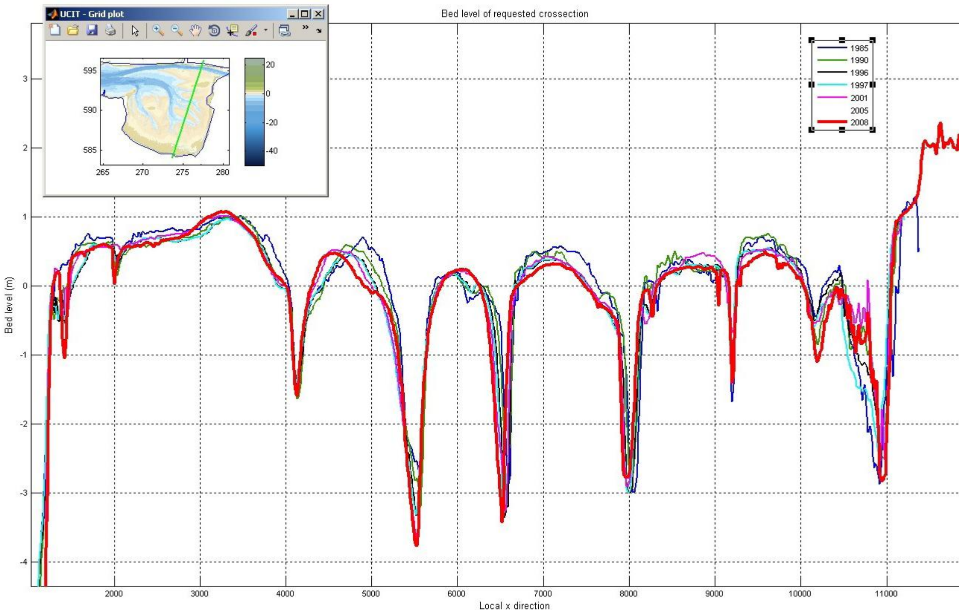


Figure 3.18 Evolution of Dollard bathymetry along cross section near the head of the estuary (after Esselink et al., 2011).

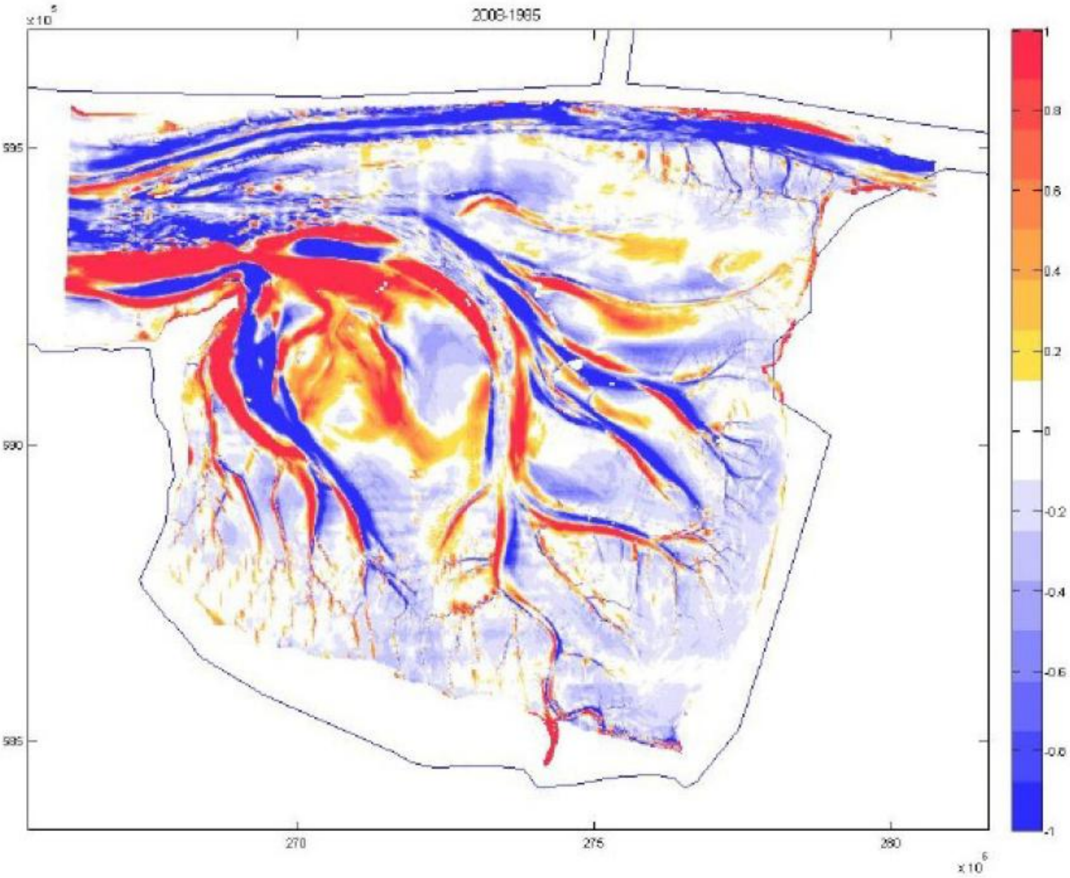


Figure 3.19 Differences between 1985 and 2008 bathymetry of the Dollard (after Esselink et al., 2011

The larger changes in the estuary, however, are found in the Ems River, and its approaches. As discussed above, the river has been deepened and rectified considerably, and large areas of intertidal flats were lost. Probably, the tide is the first to respond to these interventions. Figure 3.20 shows that the tidal range in the Ems River almost doubled near Papenburg, and even almost tripled near Hebrum. As also mean water levels lowered, high waters in a major part of the Ems River increased by almost 0.5 m, whereas the low water levels decreased by about 1.5 m, e.g. Figure 3.21.

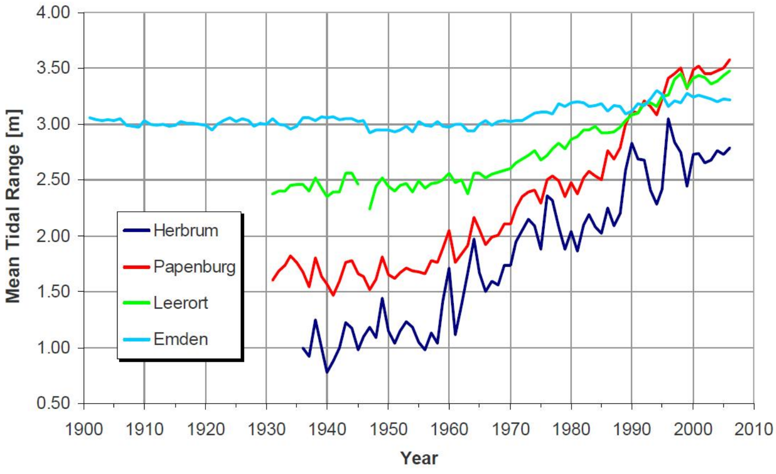


Figure 3.20 Long tidal evolution of tidal range in Ems River (after Herrling, 2009).

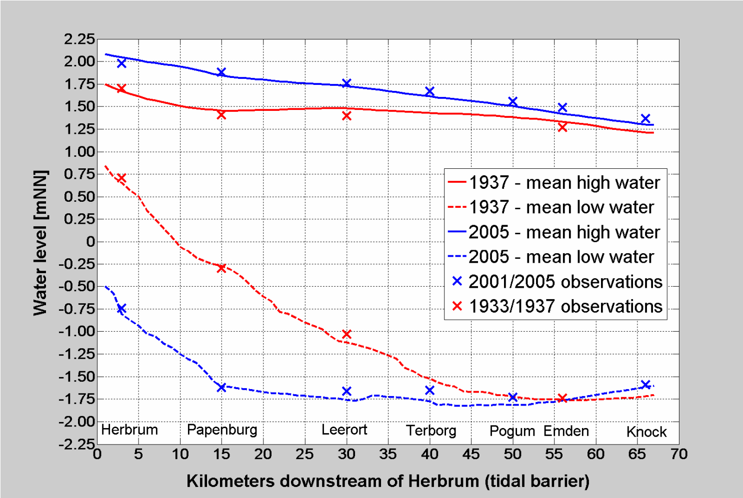


Figure 3.21 Evolution of high and low waters in Ems River (after Herrling, 2009).

The large changes in tidal range and mean water level have resulted in large changes in flow velocities in general, and in a very profound asymmetry in the tide. This is shown in a number of ways in Figure 3.22 through Figure 3.24. At present, peak flood velocities are at least 50% larger than peak ebb velocities, with a substantial longer ebb period to compensate for the water balance. As vertical mixing scales with U^2, and the transport rate of fine sediment under these hyper-concentrated conditions scales with U^4, this asymmetry has had a profound effect on the fine sediment dynamics in the Ems River.

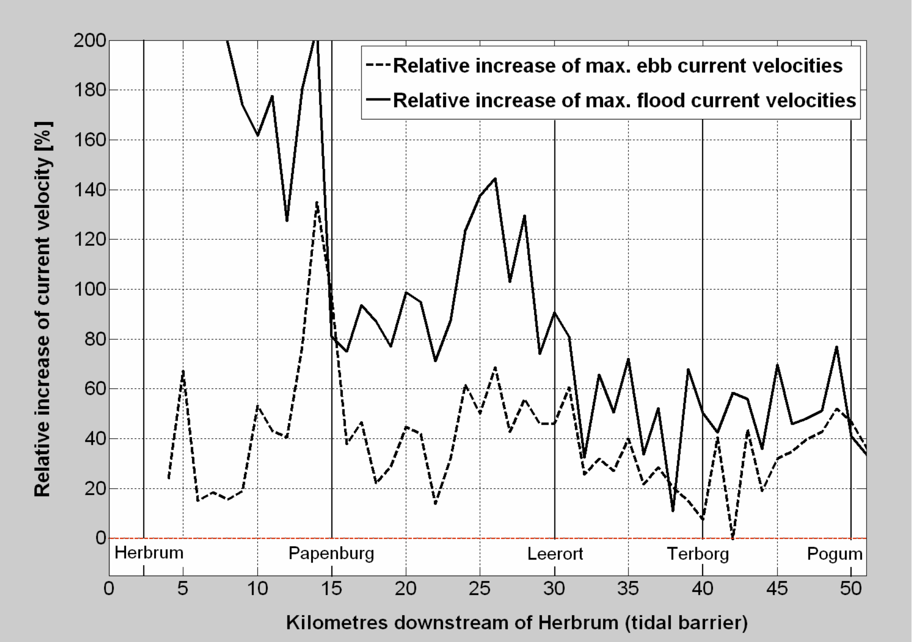


Figure 3.22 Evolution of maximal ebb and flood velocities from 1937 to 2005 (after Herrling, 2009).

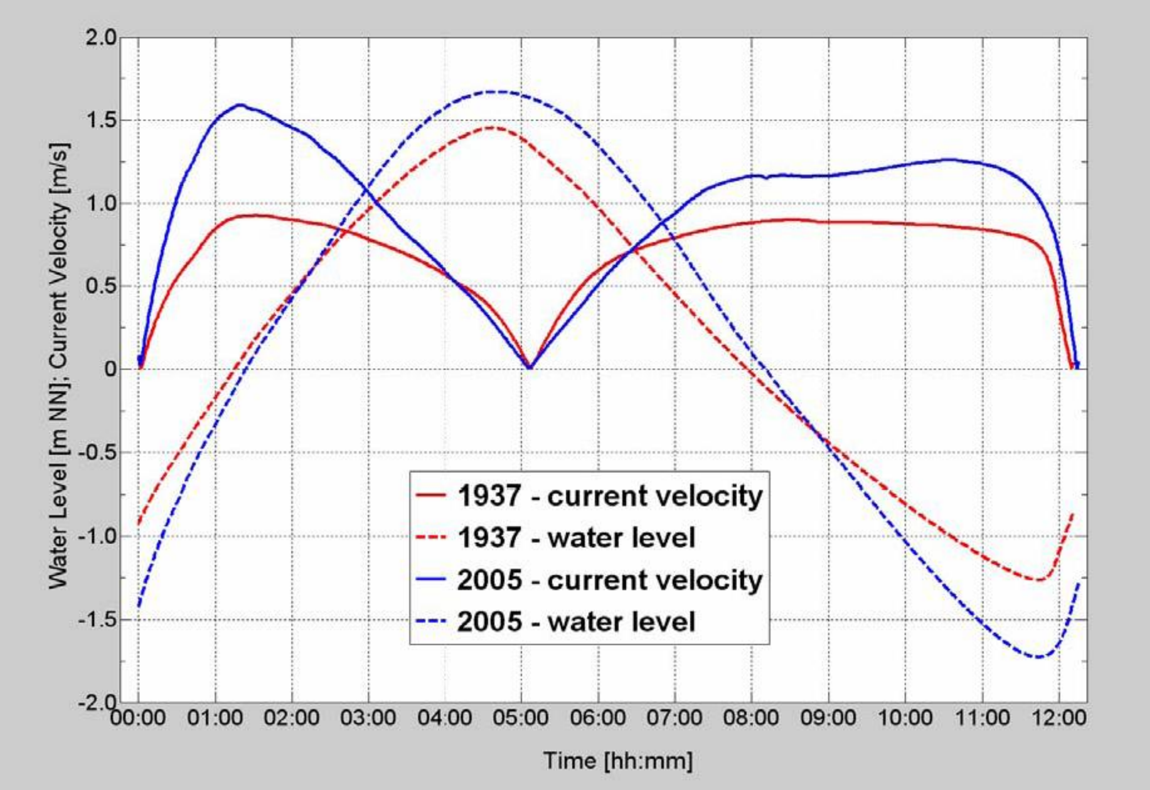


Figure 3.23 Evolution of asymmetry in tidal velocities at km 35, south of Jemgum (after Herrling, 2009).

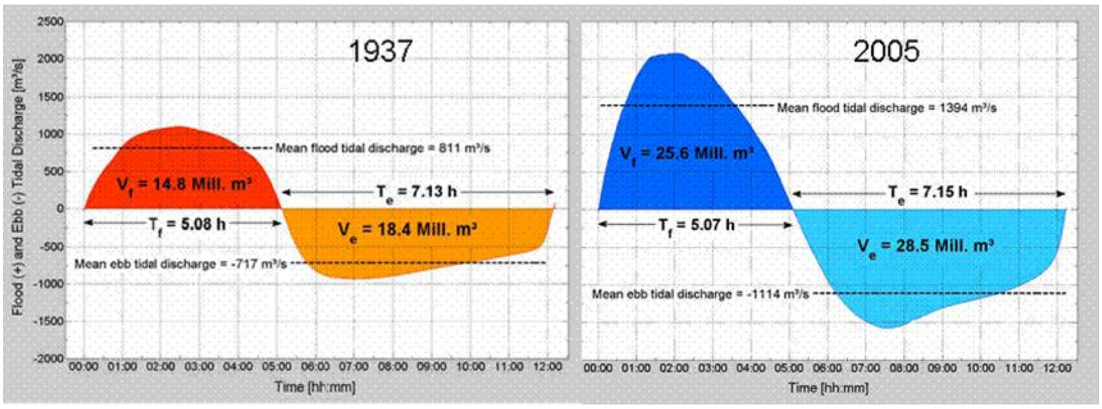


Figure 3.24 Evolution of asymmetry in tidal volume at km 35, south of Jemgum (after Herrling, 2009).

Indeed, near surface values of SPM presented in Figure 3.25 show a large increase in suspended sediment concentrations over the last 50 years. Maybe even more important is the observation that the elevated levels of turbidity are no longer related to the position of the salinity front, as depicted in Figure 3.26. The reasons for the increase in SSC, however, are not fully understood. It is well known that the tidal asymmetry has changed due to deepening and dam construction, promoting upstream transport of sediment. There is also agreement that the fluid mud deposits significantly influence bottom roughness and that tides are subsequently affected by this fluid mud layer. However, the feedback between the tidal asymmetry and the sediment transport is very complex, and therefore a large number of interpretations exist explaining the increase in turbidity. Possibly the most complete overview and analysis is given by Winterwerp (2011).

Winterwerp (2011) hypothesizes that the present-day upstream sediment transport is the result of asymmetry in vertical mixing (internal tidal asymmetry). The sediment is vertically mixed during the high flood currents, but not by the weaker ebb currents, leading to upstream transport. This is strengthened by an asymmetry in the floc size (and hence settling velocity), which also depends on the current velocity. However, Winterwerp (2011) also concluded that the dominant mud transport processes in the Ems River have changed through time. Before deepening, the system behaved as a normal estuary where upstream transport by gravitational circulation and tidal asymmetry balanced downstream transport by river flow, with the highest turbidity occurring at the head of the saline intrusion. The first response of the river to deepening of the river Ems was a decrease in river flushing and an increasing gravitational circulation, both leading to increasing upstream transport. During these conditions, the river bed is still dominantly sandy, and therefore the pronounced asymmetry in the flow velocity is still of minor influence. In addition to deepening, the construction of the weir at Herbrum (constructed in 1899) may have also influenced the system: Schuttelaars et al. (in prep) argue that the construction of the weir instantly changed the tide from a progressive wave into a standing wave. Probably, the settling lag (Straaten & Kuenen, 1957 and Postma, 1961) also substantially contributes to upstream transport (van Maren, 2010, Chernetsky et al., 2010) during this period.

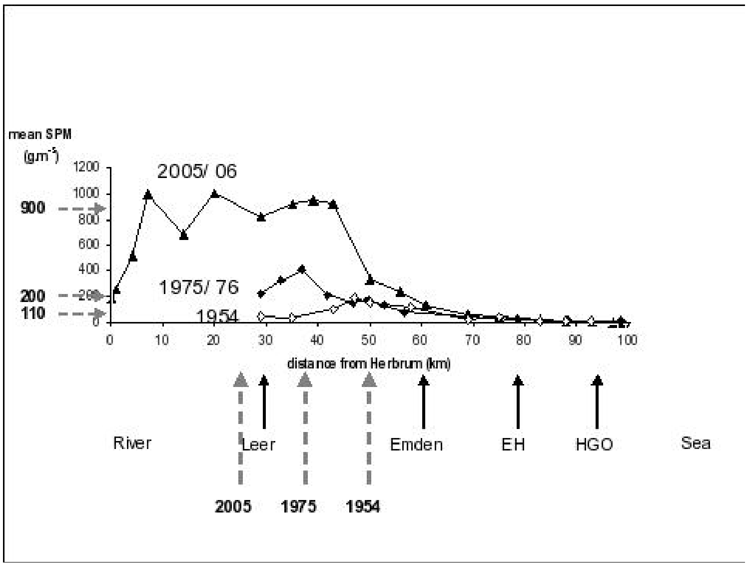


Figure 3.25 Historic development of turbidity levels (SPM) in Ems-Dollard estuary (after de Jonge, 2007)

A regime shift occurs when the river bed becomes permanently muddy, and tidal asymmetry becomes dominant. At present, this is mainly due to asymmetry in vertical mixing and flocculation (described above). Additionally, sediment-induced gravitational transport plays a role (Talke et al., 2009), which may distribute the mud further in the upstream direction. At present, the system is characterized by fluid mud layers of 2 m thick or more, with a concentration in excess of 10 g/l (Talke et al., 2009, see Figure 3.26). These fluid mud layers travel upstream and downstream with the tides (Talke et al, 2009) but also seasonally, with downstream flushing of the fluid mud layers during the highest river discharge (van Maren, 2010). Figure 3.27 shows the results of multi-frequency echo-soundings during four phase of the tide. As the tide in the Ems River behaves as a standing wave, high water corresponds to high water slack conditions. The acoustic images show a 1 to 2 m thick fluid mud layer, which interface dissolves during accelerating tide as a results of vertical mixing (entrainment).

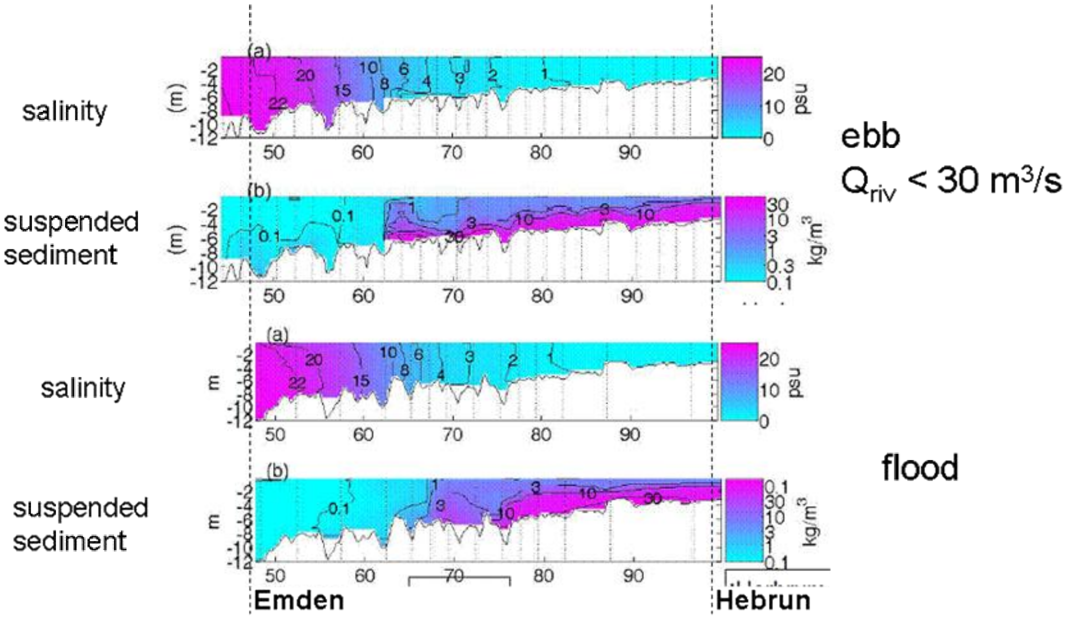


Figure 3.26 Mobility of fluid mud in Ems River, measured by Talke et al. (2009)

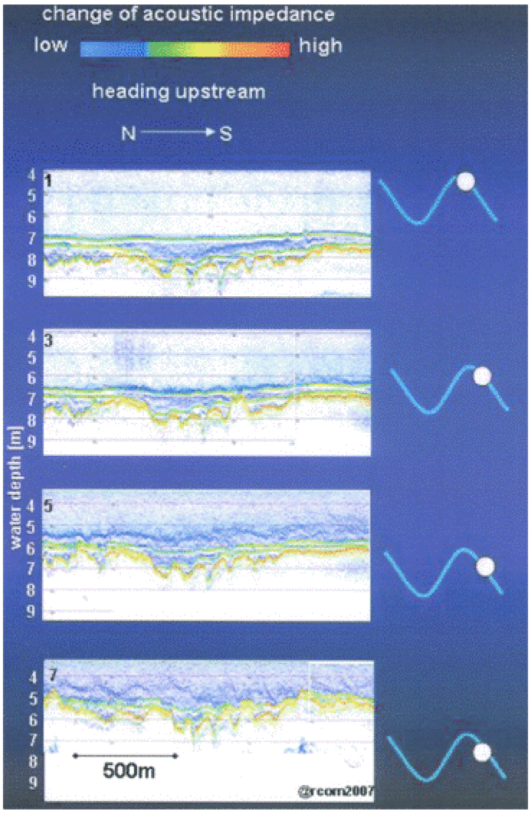


Figure 3.27 Evolution of fluid mud interface in Ems River during accelerating flow (ebbing – the sinusoidal cure represents water levels) (after Schrottke and Bartholomä, 2008)

The evolution of maintenance dredging volumes in the estuary is shown in Figure 3.28. Although the dredging volumes increased substantially in the 1960’s and 1970’s, they appear to have become constant afterwards. De Jonge (1983, 2000) concludes dredging to significantly increase the turbidity in the estuary, depending more on the spatial scales of the dredging activities than on the dredging volume. The evolution of dredging volumes and dredging-dumping strategies, and its consequences on turbidity, will be evaluated in more detail in Phase 2 of this project.

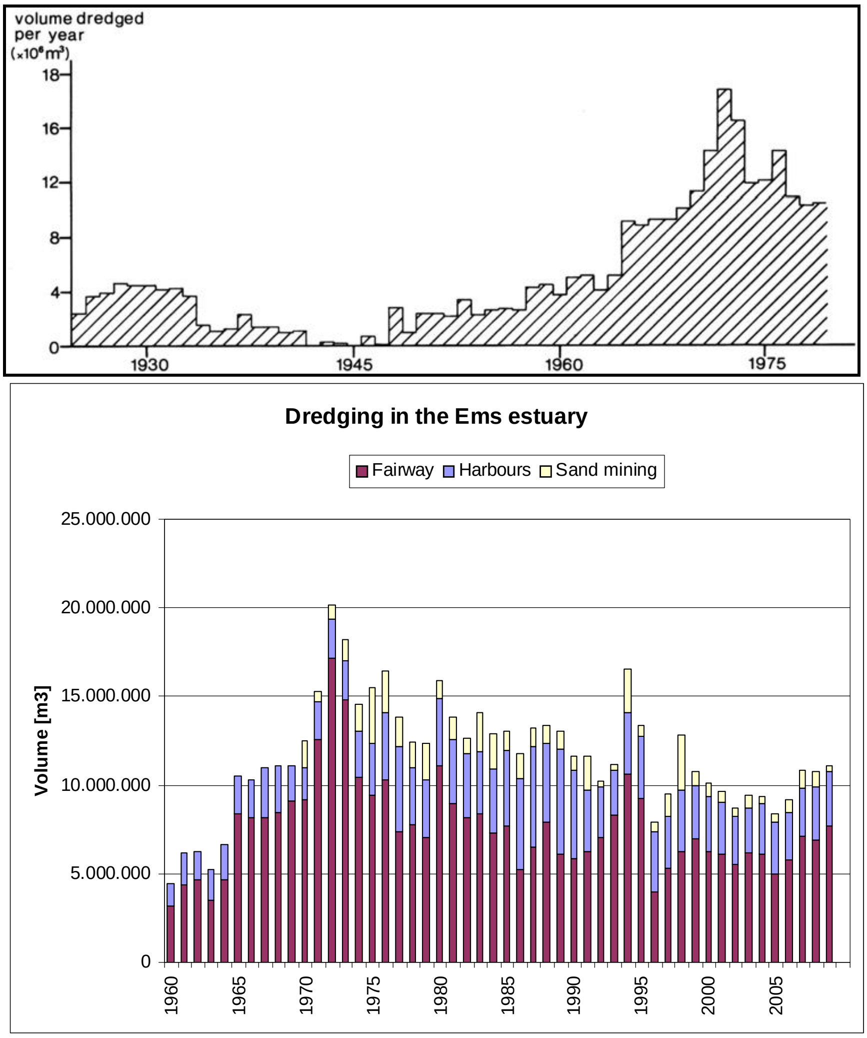


Figure 3.28 Evolution of dredging volumes. Top: from 1925 to 1980, after de Jonge, 1983. Bottom: from 1960 to 2009, from Mulder, 2011b.

3.5 Knowledge gaps

The main issues to be addressed for the WFD are to (1) quantify the apparent increase in turbidity in the Ems-Dollard, and (2) explain the processes leading to this increase in turbidity. Any historic increase in turbidity can only be assed through measurements. The main existing databases, the MWTL measurements in the Netherlands and the NLWKN measurements in Germany, both suggest an increase in turbidity. Both datasets have, however, important shortcomings. The MWTL measurements are carried out only once every 2 weeks, under restricted weather conditions, and sampling methods have changed through time. The NLWKN measurements are cut off at a certain sediment concentration which varies through time. These data restrictions inhibit a direct full quantification of changes in turbidity. An alternative is to combine the data with models. If numerical models exist which can reproduce the observed SSC, then model results can be used to interpolate and extrapolate observations, leading to a relatively accurate prediction of changes in turbidity.

The mechanisms for the increase in turbidity in the Ems – Dollard estuary are still unknown. It is often assumed that this increase is due to

1. Dredging and release of dredge spill. The dredged volume has increased dramatically in the 1960's, but stabilised in the 1970's. Several studies exist to quantify the effect of dredging on turbidity, but although these studies may reveal the short-term effects of dredging, the long-term effects are more difficult to quantify. A potential effect is that continues dredging activities may lead to a slow but progressive increase in SSC due to persistent stirring and preferential removal of sand, leading to a fining of the seabed. This increase may be linear or stepwise: a constant increase may lead to regime shift which results in a dramatic increase in turbidity (Winterwerp, 2011). Additionally, even though dredging volumes may remain constant, dredging and dumping strategies may have changed leading to increasing sediment dispersal. The effect of dredging and dumping will be assessed in more detail in Phase 2 of this study.
2. There is general agreement that the hydrodynamic regime in the Ems – Dollard has changed due to (a) deepening of the Ems River, (b) reduction of the intertidal area, and (c) changing ebb-flood channel morphology due to channel deepening in the middle and lower reaches of the estuary. This has led to a more asymmetric tide, which has led to an increasing sediment import. However, the relative importance of these 3 man-induced morphologic changes is poorly known. In addition, other processes may play a role, such as increased settling lag effects in the Ems, flocculation asymmetry (also mainly Ems River), and increased estuarine circulation due to deepening.
3. Reduction of sedimentation rates on the (former) intertidal area. Large amounts of fine sediments accumulate in intertidal areas, but the surface of the intertidal areas has been strongly reduced in the past centuries. Reclamation of these areas was traditionally done using wooden constructions ('rijswallen') in which large amounts of fine sediments accumulate. This method was abandoned in the 1990's, and the resulting reduction in sedimentation may have led to increased turbidity levels.

The turbidity of the Ems River has dramatically increased, following from data (Figure 3.10, Figure 3.25), but to what extent this is the result of changes in turbidity in the Dollard or vice versa is unknown. The inter-annual variation reveals that during high discharge events, this turbid water is flushed seaward. It could therefore be that changes in hydrodynamics have led to a constant accumulation of sediment in the Ems River (through processes described above), which is episodically flushed (Figure 3.25) into the middle and lower estuary. The relative importance of this episodic flushing is unknown.

The questions can be answered using long-term and high-frequency observation stations at relevant locations (in the Dollard, in the middle estuary, and in the Ems River), and possibly with well-calibrated and advanced numerical models. The availability of data and the availability and capability of numerical models will be discussed in section 0

4 Primary production

4.1 Introduction

Primary production, measured in units of gC/m^2/y, is the conversion of inorganic material into organic compounds by organisms via photosynthesis using energy from sunlight. In aquatic systems, algae are the main primary producers/autotrophs, forming the base of the food chain. These algae encompass a diverse range of organisms ranging from single floating cells (phytoplankton), single cells living in and on the sediment (microphytobenthos) to attached seaweeds and higher plants (Eelgrass and salt marsh vegetation). Primary production from salt marshes reaches the estuary mostly as dead organic material. For the aquatic food web, phytoplankton is regarded as the most important food source. The type and species of phytoplankton determine the quality of food available to higher trophic levels, such as grazers. Particular focus is given to those algal blooms that may present potential health problems to humans due to the production of toxins that end up in consumable products, such as mussels.

Primary production is controlled by an interplay between nutrient and light availability. Both ‘flushing rates’ that determine the rate at which chemical compounds, e.g. nutrients, enter the estuary and water residence times influence primary production. A distinction is made between pelagic and benthic primary production, carried out by free-living phytoplankton in the water column or (micro)phytobenthos attached to the sediments, respectively.

4.2 Aim of this literature study

The last measurements of primary production in the Ems-Dollard were performed about 30 years ago (BOEDE group). Since then, the areas has been subject to many changes. The decline in eutrophication and increase of dredging activities have an impact on the functioning of the estuarine ecosystem. These impacts will be assessed by means of ecosystem modelling (elaborated during the 2nd phase of this research). These models need to be calibrated and validated with actual measurement data considering light, nutrients and algae. A monitoring program needs to provide the required information and will also directly give input to the information needed for the specific management targets related to the WFD. Considering the international support that is needed, it is important to increase the basis of this project by means of a substantial monitoring programme.

As a first step, an insight is needed in the information that is available on the primary production in the Ems-Dollard, and which data are needed and lacking. On the basis of a brief literature study, data-based research and expert opinion, the most critical and steering factors will be determined that drive the balance of the total primary production in the entire Ems-Dollard (including the coastal zone).

The aims of this literature study are to:

- Provide a coherent overview of the trends in primary production in relation to turbidity and underlying factors;
- To identify gaps in knowledge regarding the species composition and primary production by phytoplankton;
- To assess the relevance of primary production by phytobenthos for the other quality elements of the ecosystem;
- To identify gaps of knowledge relevant for the Monitoring and Modelling Plan (Work Package 2).

Due to the relatively high turbidity in the estuary, light is often the limiting factor for primary production. However, because of the presence of intertidal areas, covering around 50 % of the area in Ems Dollard, benthic primary production by microphytobenthos contributes to ~25 % of the total annual primary production in this area. Primary production by microphytobenthos will be covered in a separate section.

In fig.2 3 an overview has been presented. Characterstics of the three parts of the estuary are given in table Table 4.1

Table 4.1. Contribution of tidal flats in relation to other characteristics of defined zones within the Ems-Dollard area (data from de Jonge & Brauer, 2006), and computed (Lower reaches mean water depth)

	Total	**Lower reaches**	**Middle reaches**	**Dollard**
Total area (km^2)	467	275	90.5	100
Area of channels (km^2)	221.1	153.0	48.4	18.7
Area of Tidal Flats (km^2)	245.7	121.0	42.1	82.6
% Tidal Flats	53%	44%	45%	98%
Mean water depth (m)		6	3.5	1.2
Volume of water at mean high tide (m^3)		1300x10^6	460X10^6	220x10^6

The lower reaches are strongly influenced by the Wadden Sea and coastal North Sea. The middle section is subject to strong salt and fresh water mixing, and the upper section is heavily affected by freshwater input and tidal action.

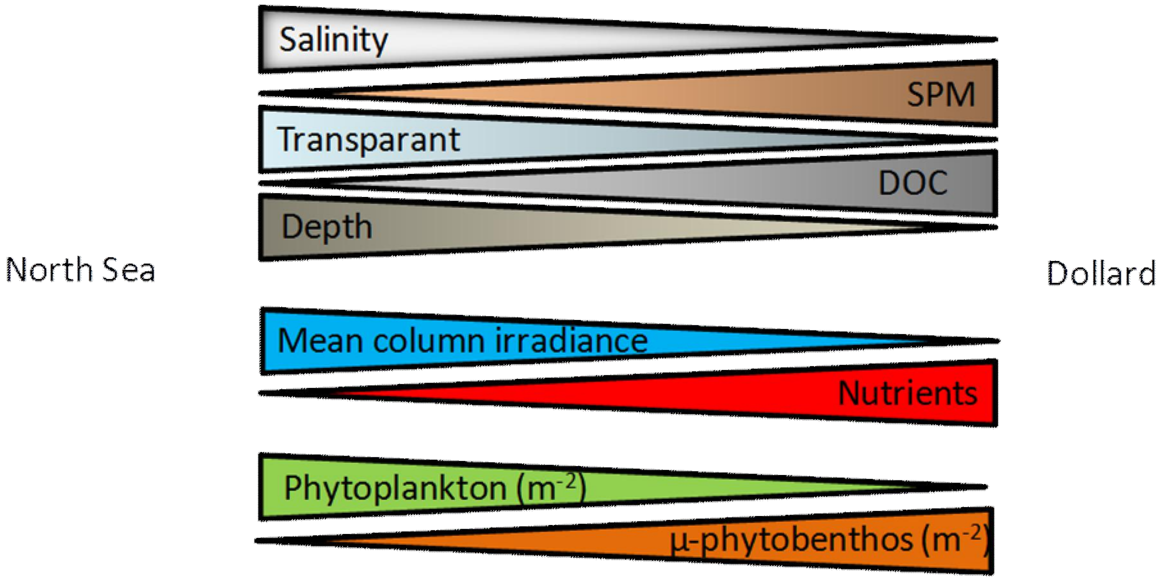


Figure 4.1. Simplified scheme indicating the direction of gradients of properties in the estuary. Vertical cross section of each symbol symbolises the magnitude of the parameter, dependent of the location in the estuary.

The Ems-Dollard estuary is characterised by the presence of strong gradients. Seawards there is a strong increase in salinity (from 5 to 28 ‰). Summer suspended matter concentrations vary between 20 and more than 200 mg/l. Consequently, the shallow waters of the Dollard (mean depth of channels is 1.2 m) are very turbid (attenuation coefficients up to 6 m^{-1}). In the outer regions the average depth of the channels is 5.8 m and the light absorbance is much less (attenuation coefficients up to 1.2 m^{-1}) (Colijn 1983; de Jonge & Brauer, 2007).

In the Ems Dollard, annual primary production is highest in the outer Lower Reach, reaching 600 $gC/m^2/y$ (Figure 4.2). Lower rates, around 50 $gC/m^2/y$, are measured in the Dollard and Middle Reach. The differences in measured rates result from different light climate and nutrient availibility in the three areas. As explained in more detail below, the landward gradient of increasing nutrient concentrations and seaward gradient of decreasing turbidity can result in an optimum zone for phytoplankton growth in the Lower Reach. The high water turbidity in the upper estuary and the Dollard may limit primary production in these areas, despite the elevated nutrient concentrations. The rates presented in Figure 4.2 are based on primary production measurements and eutrophication status in the mid and late 1970s (Colijn, 1983), part of a long term proramme (1973-1982) on the Biological Research of Ems-Dollard Estuary (BOEDE) related to the ecosystem functioning and water quality issues in this area (Baretta and Ruadij, 1988). No further primary production measurements have been carried out in the last years. This implies that the current situation might be different from that presented in Figure 4.2, in particular as a result to changes in nutrient loadings over the years Unfortunately, this period was characterised by an extreme load of organic matter, as a consequence of untreated waste water discharge from strawboard and potato flour factories in the southeast of the province Groningen (The Netherlands) (for detailed information: see de Jonge & Brauer 2007). The maximum of these discharges was reached in 1977. This caused large parts of the Dollard estuary to suffer from anoxia. In the early nineties, oxygen levels had been restored to normal, as a consequence of large scale waste water treatment of industrial plants.

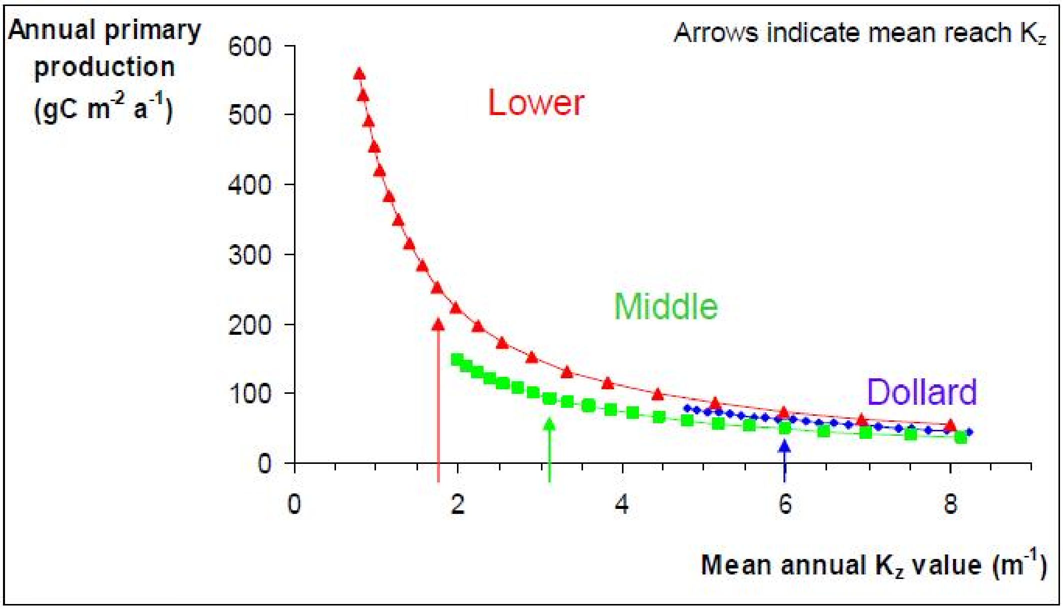


Figure 4.2Annual primary production (based on primary production measurements and eutrophication status during the period 1972-1980) in the three reaches of the Ems estuary as a function of changes in the light extinction coefficient (Source: de Jonge and Brauer, 2006)

4.3 Controlling factors for algal growth

The estuary receives nutrient-rich water from the drainage basin, which, depending on river discharge, may result in enhanced annual primary production, (Baretta and Ruardij, 1988; De Jonge and Essink, 1991). Although discharges of nutrients affect the annual primary production in different ways in the three subareas, the response is generally linear (Figure 4.3 based on the limited number of primary production measurements taken in the mid and late 1970s). In general, an increase in the river discharge (and therefore in nutrient inputs) results in an increased primary production in especially the Lower Reach which is primarily nutrient-limited and not light-limited as the Middle Reach and the Dollard. (de Jonge & Brauer, 2007) At the lower reaches, where the suspended matter is much lower than in the Dollard, nutrients are considered to be limiting the primary production. Based on the regression equation derived from Figure 4.3, the effect of variable discharge rates on primary production rates in the three areas was further investigated (de Jonge and Brauer, 2006). The results show that in general a 5-fold increase in river discharge (from 50 to 250 m^3 s^{-1}) gives rise to a nearly 9-fold increase in the pelagic primary production in the entire estuary.
However, in reality high turbidity in the Dollard area and the lower river Ems limit the increase in primary production stimulated by increased nutrient loads (via riverine discharge) (de Jonge & Essink, 1991). Morover, it should be noted that high discharges also increase the flux of humic substances that limit the light availability.

Until now, no direct evidence, based on measurements on the physiological state of the algal cells (e.g. (Riegman and Rowe 1994) is available. More recently, indirect evidence for the growth rate limiting factor of phytoplankton in the Wadden Sea and coherent areas reveals light, silicate and phosphate the most controlling factors (Loebl et al. 2009). The same authors conclude that the control of phytoplankton biomass in turbid areas of the Wadden Sea seem to be more closely related to light and nitrogen. Thus, the relation between annual discharge and primary production rates is not only affected by the influx of nutrients carried by the river but is also inherently subject to interannual variations in weather conditions, including fluctuations in temperature and flushing rates, as well as changes in turbidity/light climate as a result of dredging activities.

Direct measurements on the growth rate limiting factor by means of nutrient uptake experiments (e.g. Riegman et al. 1990) have not been carried out in the Ems-Dollard estuary.

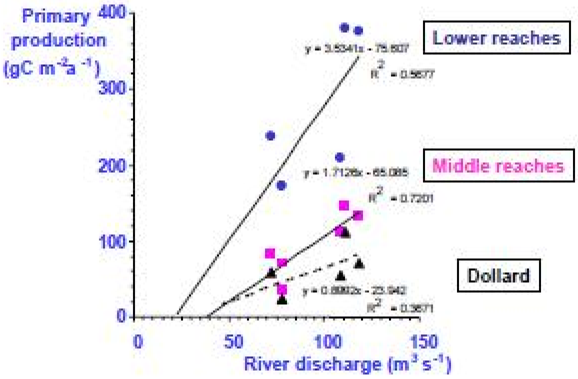


Figure 4.3 Mean annual primary production in different reaches of the Ems estuary as a function of the mean annual freshwater discharge (de Jonge & Essink, 1991)

In absence of primary production measurements, chlorophyll-a concentrations are often used as a surrogate for algal primary production and algal biomass. Chlorophyll-*a*, however, does not represent any process in itself but is rather an indicator of various processes related to primary production, primary consumption by grazers and mortality and degradation of algae. Further, chlorophyll-a concentrations vary seasonally, interannually and even periodically (longer time periods) as a result of changes in nutrient conditions, turbidity, wind and grazer intensity.

4.4 Characteristics of phytoplankton and (possible) controlling factors

4.5 Biomass trends

Phytoplankton biomass (measured as chlorophyll-a) distribution is only known in detail from data collected in the late seventies (Colijn 1983; De Jonge & Brauer 2007). Annual average chlorophyll-a varied in the period 1976-1980 between 4 and 12 µg.l^{-1}. Generally, higher values were observed in the outer region (9.49 µg.l^{-1}) than in the inner region (7.5 µg.l^{-1}). Relatively higher concentrations are found near the Eemshaven, and somewhat lower concentrations next to Dollard inlet. Concentrations increase to around 10 mg/m^3 and higher going from Dollard basin towards the Ems River.

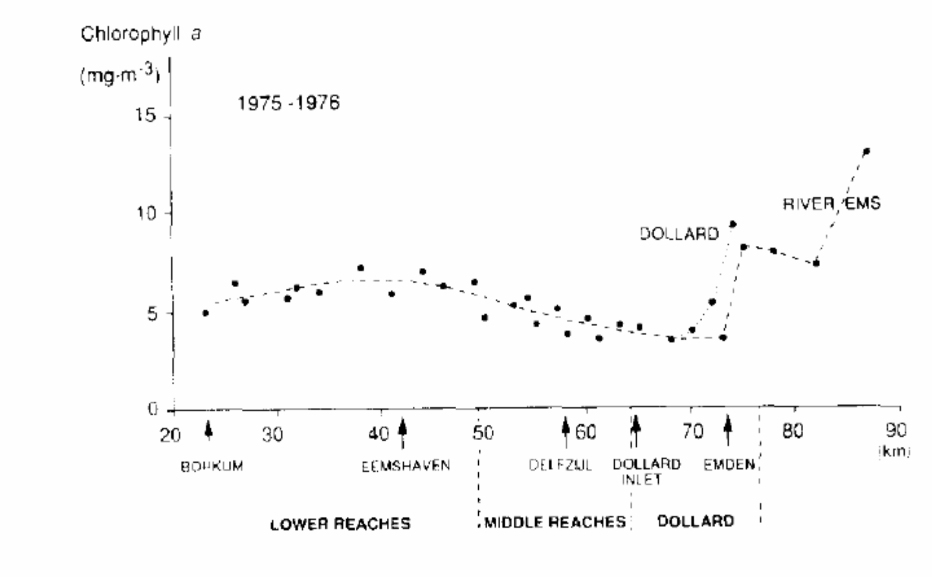


Figure 4.4 Mean annual chlorophyll-a concentrations for the period 1975-1976 along the estuary axis (Source: De Jonge and Beuserkom, 1992)

Long term monitoring at three locations (Huibertgat, Oost Friesche Gaatje and Groote Gat Noord) during the period 1976 – 1997 did not reveal any remarkable trend (de Jonge & Brauer, 2007) although these authors noticed a correlation between annual averaged values for dissolved inorganic phosphorus and chlorophyll-a.

A strong longitudinal SPM gradient is also observed from high concentrations at the upper estuary (~ 6000 mg/l) down to close to 0 mg/l in the lower estuary, coinciding with the chlorophyll peaks as a result of sufficient light (low SPM).

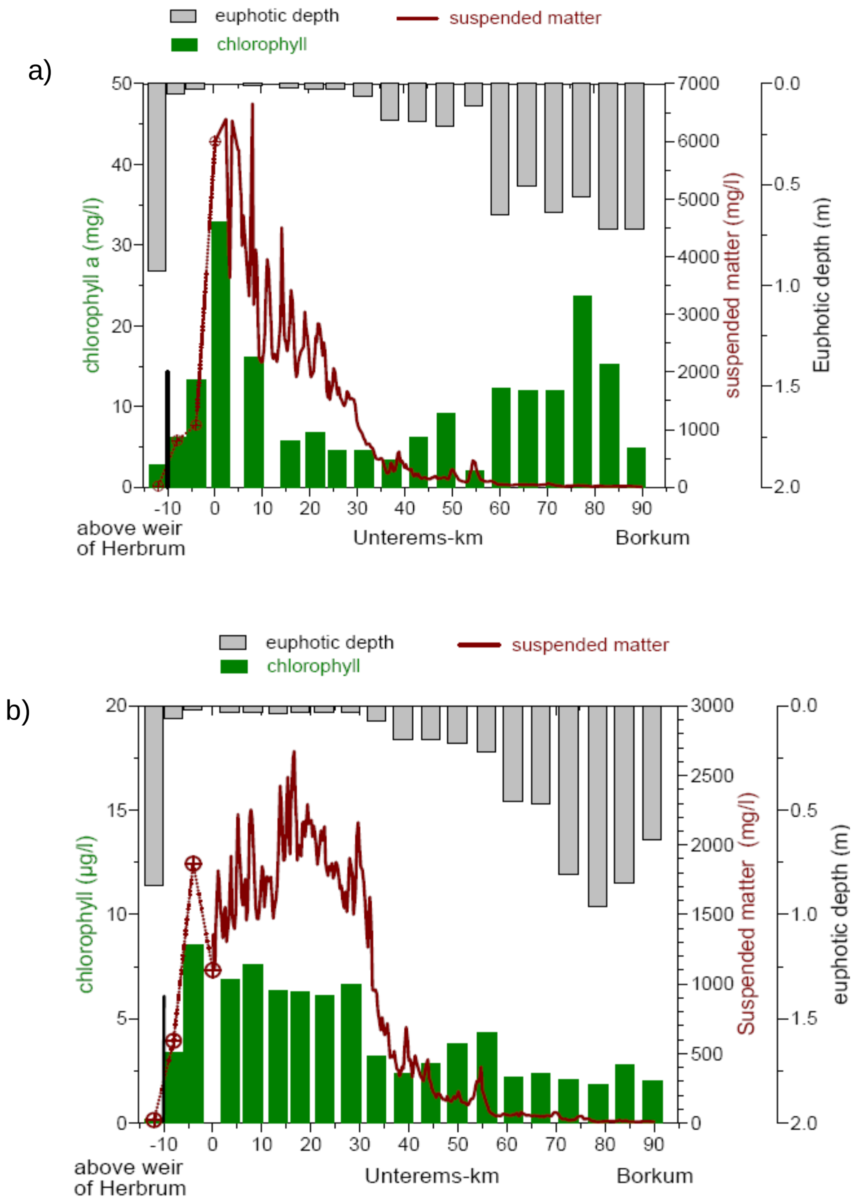


Figure 4.5 Longitudinal estuarine profiles of suspended matter, chlorophyll-a concentrations and depth of euphotic layer measured in a) May 2007 and b) September 2007. Data from Bfg, presented by Andreas Schoel Emden workshop, 2008- accounted for the fact that the km 0 here is at Hebrum

Figure 4.6 shows a time series of the chlorophyll-a measurements at the three monitoring stations Groote Gat Noord, Bocht van Watum and Huibertgat Oost. Note that during 1975 to1985, the analysis of chlorophyll-a was carried out by a different technique and therefore direct comparison with now recent measurements should be made with caution. During this monitoring period, three eutrophication events (1976, 1984 and 1996) have been recorded in Groote Gat Noord in the middle of the Dollard basin with chlorophyll-a concentrations reaching 180 ug/L. After 1996, chlorophyll-a concentrations fluctuated between 5 and 15 ug/l. In the Middle and Lower Reaches (Bocht van Watum and Huibertgat Oost, respectively), phytoplankton blooms occur more frequently, yet the maximum chlorophyll-a concentration does not exceed 100 ug/L. Although a general decrease in chlorophyll-a is observed in the recent years (Figure 4.6), a distinct chlorophyll-a peak of 90 ug/L was recorded in Bocht van Watum in 2005.

The monthly-average time series for the same three locations (Figure 4.8) shows a distinct chlorophyll-a peak in the month of May in both Groote Gat Noord and Bocht van Watum, with concentrations around 20-30 ug/l. The annual chlorophyll-a peak in the Huibertgat Oost is less pronounced and lasts over the summer months (April-August). Most likely, this is the result of lower light limitation in the Lower Reach due to lower suspended sediment concentrations.

Brinkman (2008) published a trend analysis study on Rijkswaterstaat monthly monitoring data for chlorophyll-a concentrations, available for the period 1976-2005 (). Summer values (April-September) were log-transformed and the relationship was analysed using a generalized additive model (gam). Next to the analysis, also the 95% confidence interval for each estimate has been computed following a bootstrap procedure. The confidence intervals are shown by the bars in the same figures.

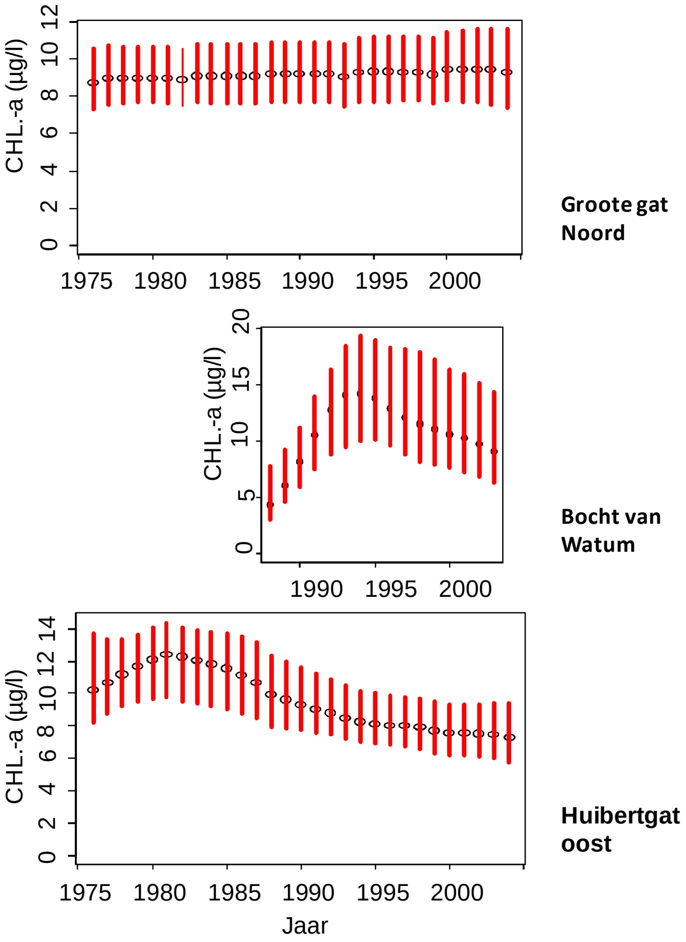


Figure 4.6 Long term trends in summer averaged chlorophyll-a in the water column at three sites in the estuary: Groote Gat Noord (Dollard), Bocht van Watum (middle region) and Huibertgat Oost (lower region). Source: Brinkman, 2008.

In the Dollard (at Groote Gat Noord) there is hardly any interannual variation in summer chl.-a values. This may imply that the phytoplankton in this area is mainly acting as if it is in a turbidostat. Variations in incidental inputs of chlorophyll-a from the microphytobenthos are buffered by light control of the biomass of the pelagic algae.
At the middle region (Bocht van Watum) less data have been collected in the past. Within the period from 1998 to 2003 there has been a maximum in the middle nineties. In the regions closest to the Wadden Sea and coastal area of the North Sea (Huibertgat oost) maximum summer chlorophyll-a concentrations were present in the early eighties. From then on a gradual reduction in algal biomass (reflecting the reduction in nutrient discharges from the European continent) can be observed. It is unclear why the middle region shows a pattern that deviates from the other regions. An explanation might be that especially the middle region has been subject to morphological changes due to dredging activities. If watermasses have altered their major flow patterns in the middle region, chlorophyll variations at one particular site, such as the Bocht van Watum, are to be expected.
Since from 1997 onward there has been a further reduction in nutrients in Dutch coastal waters, it is likely that also chlorophyll-a may have been reduced during the past decade, especially in the outer compartment where nutrients are limiting for algal growth rates during summer. This trend has been observed in the Wadden Sea (Phillipart et al. 2007).
This is in agreement with De Jonge et al. (1998) who presented the correlation between chlorophyll-a concentrations (annual and summer) and annual loads for TotP and DIP at Huibertgat Oost in the Lower Reach (Figure 4.7). Despite the low number of data, results show that the good correlations in both the summer half year and the entire year. However, the regression coefficients obtained were lower than those for primary production and river discharge rates, indicative of nutrient fluxes (Figure 4.3).

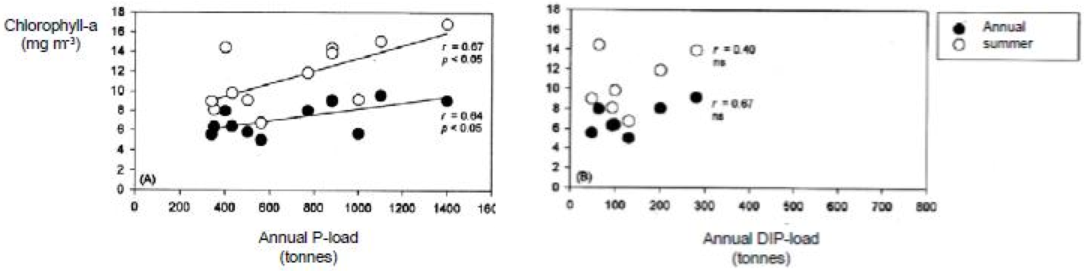


Figure 4.7 Correlations between annual and summer chlorophyll-a and phosphorus (TotP and DIP) loads. Source: De Jonge et al., 1998

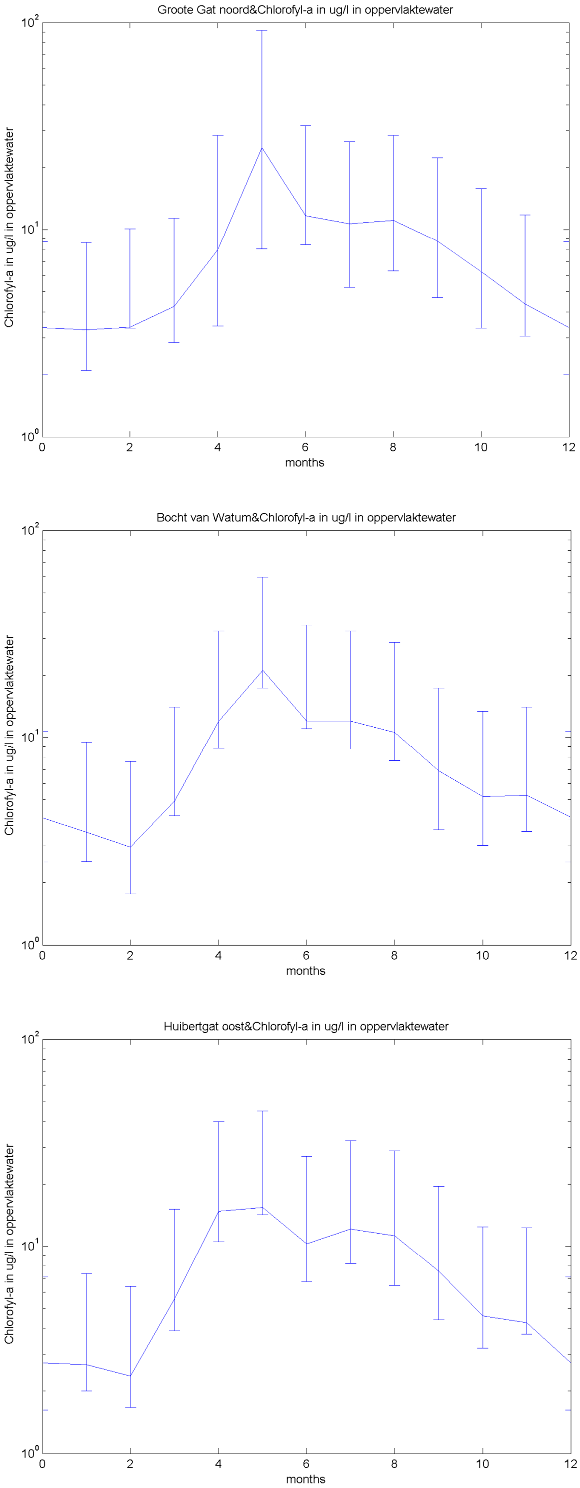


Figure 4.8 Monthly-averaged chlorophyll-a concentrations at
a) Groote Gat Noord (1976-2008)
b) Bocht van Watum (1988-2008)
c) Huibertgat Oost (1976-2008)

4.6 Species composition

Species composition of phytoplankton is recorded from scattered data collections (van der Werff 1960; van de Hoek et al., 1979). De Jonge (1985) presents information on resuspended benthic diatoms (mainly penate species). This phenomenon of resuspension of microphytobenthos was originally demonstrated elsewhere (Bailly & Welsch 1980) and recognized as an important issue for the Dollard (Admiraal 1984). Most informative are the calculations showing that micro-algae resuspend into the water column after heavy wind periods (De Jonge 1992, De Jonge & van Beusekom 1992,1995). This process dominates the species biomass and composition of phytoplankton in the channels of the Dollard. De Jonge & Brauer (2007) distinct three groups of micro-algae in the estuary: ‘real phytoplankton’, resuspended microphytobenthic algae, and the microphytobenthos. In datasets where chlorophyll-a or primary production measurements in the water column of the channels where collected, there is always a percentage of micro-algae present that originate from the surrounding banks. Occasionally, this contribution of microphytobenthos to the plankton community may reach values up to 50% or more (Figure 4.9; from De Jonge & van Beusekom, 1992).

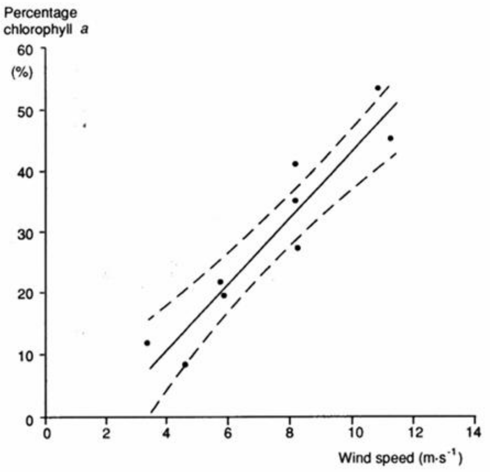


Figure 4.9. Relation between the fraction (as % of pelagic chlorophyll-a) of resuspended benthic chlorophyll-a in the water column and the effective wind speed (fig. copied from de Jonge & van Beusekom 1992).

4.7 Photosynthesis and primary production

The most recent data on primary production in the estuary originate from the late seventies in the previous century (Colijn 1983, Colijn & de Jonge 1984, Colijn & Admiraal 1987). Colijn used an incubator method where the photosynthetic properties of phytoplankton sample were measured by ^{14}C uptake. In combination with measurements on daily photosynthetic irradiation (PAR) and underwater light attenuation (Kd), a daily (or annual) primary production was calculated. Comparison with another method demonstrated that results from the incubator method deviate less than 10% from the more classical in situ method (Riegman and Colijn 1991). The observed annual primary production (in comparison with chlorophyll-a) is presented in Table 4.2:

Table 4.2. Regional differences in the primary production and chlorophyll-a in the estuary. Data calculated as annual averages in the period 1976-1980. Data from Colijn (1983).

Annual average (1976-1980)	unit	Region Outer	Middle	Dollard
Chlorophyll-a	mg/m^2	55	27	9
Phytoplankton biomass	gC/m^2	1.4	0.7	0.2
Primary production	gC/m^2	263	85	49

With respect to the extrapolation of this information to more recent years, at least two different serious drawbacks have to be mentioned. For the primary production calculations, Colijn used an empirically established relationship between suspended matter and light attenuation coefficient which revealed a “background” attenuation of 0.4 m^{-1}. This is due to the light absorption by dissolved components. The observed value of 0.4 m^{-1} is very high, compared to the usual value of 0.1 that is observed in for example the Wadden Sea (Riegman, unpubl. results). The high background, indicating additional light absorbance by dissolved matter, may have been related to the extended discharge of untreated sewage water, being rich in undegradable humic acids. It is very likely that the background attenuation has improved significantly after sewage treatment was applied on a large scale in the eighties.

The second drawback concerns the measured photosynthetic parameters. Extraction of these parameters from the data presented by Colijn (1983) shows a typical seasonal pattern (Figure 4.10).

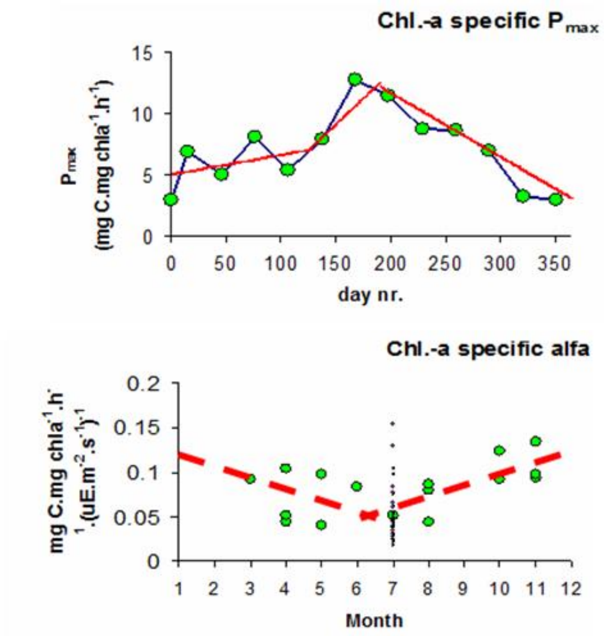


Figure 4.10. Seasonal pattern of the chlorophyll-a specific photosynthetic parameters Pmax and alfa, extracted from the data presented by Colijn (1983).

Alfa, a measure for the affinity of photosynthesis for light, shows a slight decrease during summer. This parameter is relatively more sensitive to the availability of light in the growth environment than to temperature. For P_{max}, here defined as the chlorophyll-a specific maximum photosynthetic rate, a reverse pattern is observed. This photosynthetic parameter is mainly determined by chemical processes, rather than physical processes in the algal cells. Higher in situ water temperatures explain why especially during summer high P_{max} values are found. Comparison with data from the Oosterschelde estuary (Malkin et al., in prep.) shows that the observed P_{max} values of the Ems-Dollard phytoplankton anno the late seventies were about 20% higher than the values that have been measured the last decennium in the Oosterschelde. A possible explanation may be a difference in species composition between the different regions. It is known that photosynthetic performance of algal communities is not only regulated by external factors such as nutrients or light, but also is related to the species composition of the community since photosynthetic parameters are species specific properties. The lack of recent data on background light absorption, algal species composition, biomass and productivity, makes a quantitative extrapolation of the findings of Colijn on primary production in the Ems Dollard estuary towards more recent years by definition inadequate.

Additionally, several environmental factors have been altered since the late seventies. Changes in human activities such as wastewater treatment, dredging, dumping and dredging or the use of water for cooling purposes all will have their impact on the primary producers in the ecosystem. Here, the major impacts are generally recognized to be mediated by changes in nutrients, organic- and suspended matter, and processes that trigger the resuspension of microphytobenthos in the estuary.

Reflection on the various ecological targets as defined by European and National statements by law urgently needs an updated input of data on the present role of the primary producers in the estuary. A detailed research programme designed to re-evaluate the former findings, to establish the present situation, and to provide modelling efforts with updated information in order to predict more adequately the potential impacts of various human activities, is presented in the “Field Monitoring Program” section.

4.8 Light regime

The light conditions in the water column are determined by the combination of day length, meteorological conditions and water turbidity. In the Northwestern Europe, there is a seasonal cyclic variation in light energy depending on the changing day lengths over the year, well as the angle of light incidence. Both factors influence the annual variations of surface radiation (Figure 4.11).

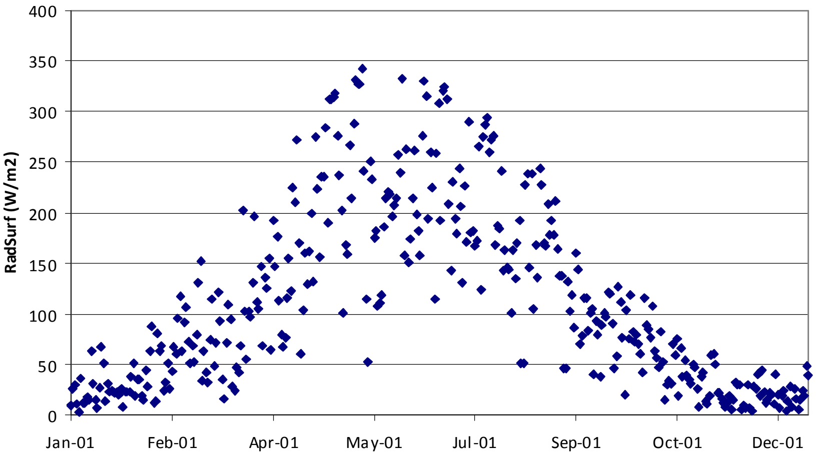


Figure 4.11 Measured daily averaged irradiance, calculated from surface irradiance at station "Nieuw Beerta".

Turbidity is closely linked to the suspended sediment concentrations. The mean annual suspended matter gradient varies from approximately 20 g m^{-3} near the tidal inlet to approximately 400 g m^{-3} in the most turbid part of the estuary (Figure 2.3 & Figure 4.12). The mean concentration of suspended matter in the Dollard is roughly 200 g m^{-3}. In the Ems-Dollard estuary sedimentation amounts to about 5 x 10^6 t suspended matter per annum. This amount cannot be transported into the estuary by the Ems River alone, which only discharges some 0.1 x 10^6 t/a. In fact, import of suspended matter from the North Sea and sedimentation of marine particulate material predominates in the Ems estuary resulting in particles of marine origin within the turbidity maximum.

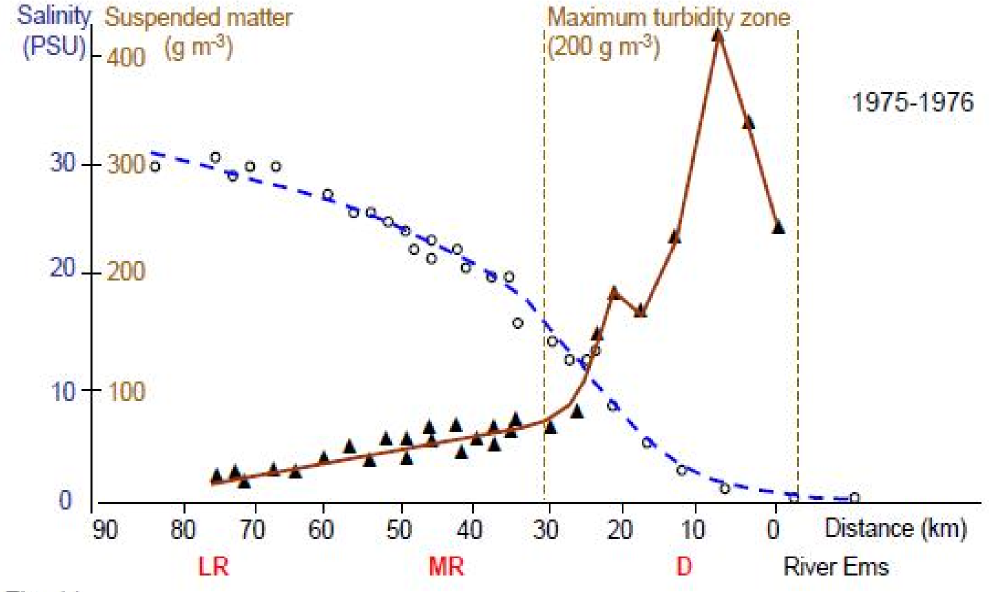


Figure 4.12 Distribution of suspended matter (g m^{-3}) and salinity along the estuarine longitudinal axis.

4.9 Nutrient dynamics

Nutrient concentrations: Time series plots of NH_4^+ and PO_4^{3-} concentrations at Groote Gat Noord in the Dollard area show a decreasing trend in concentration from 1976 onwards (Figure 4.13). This decreasing trend is the result of reductions in nutrient loads, mainly of phosphorus from point sources and the discontinuation of discharges of labile organic waste from, for example, potato floor factories into the Dollard. The trends in NO_3^- and SiO_2 are less pronounced (Figure 4.14) implying that either their concentration is determined by biogeochemical reactions (such as through nitrification) or their input sources have not changed over the years.

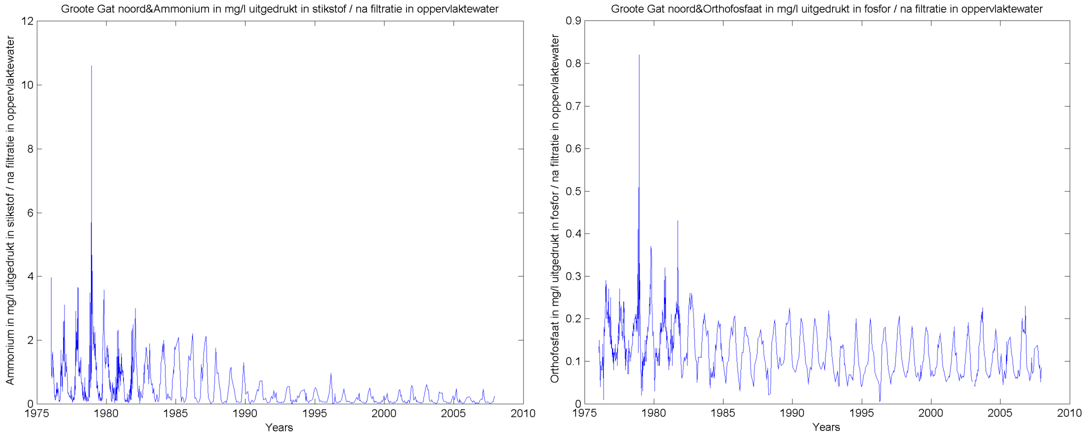


Figure 4.13 Time series of NH_4^+ (l) and PO_4^{3-} (r) concentrations measured at Groote Gat Noord over the time period 1976-2008.

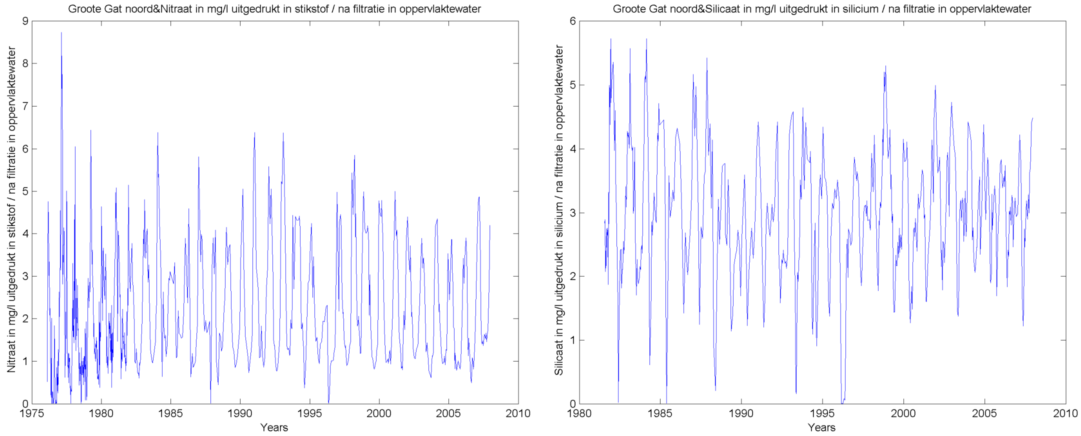


Figure 4.14 Time series of NO_3^- (l) and SiO_2 (r) concentrations measured at Groote Gat Noord over the time period 1976-2008.

In general, nutrient concentrations are low (NO_3^-: 3 mg/l; NH_4^+: 0.5 mg/l; PO_4^{3-}: 0.15 mg/l; SiO_2: 3 mg/l), although concentrations vary along the longitudinal axis of the estuary. Nitrate makes up 85 % of the dissolved inorganic nitrogen (DIN), whereas ammonia, the nitrogen fraction that is more readily taken up for primary production, contributes to 15 % of DIN. The longitudinal nutrient profiles (Figure 4.15) show that the concentrations of NO_3^-, PO_4^{3-} and SiO_2 decrease gradually from the peak concentration at km 20 located in the Ems River towards the lower estuary. A peak PO_4^{3-} concentration occurs in mid-estuary (km 30-60), between the mouth of Ems River and the Dollard basin (Figure 4.15). Such a mid-estuary dissolved phosphate maximum was also observed by van Beusekom and de Jonge (1998). In general, nutrient gradients in the Ems estuary during summer are strongly influenced by biological processes like uptake by phytoplankton and remineralisation whereas during winter these processes are at a minimum. Phosphorus concentrations change seasonally due to uptake by phytoplankton resulting in relatively high DIP concentrations in winter and lower concentrations in spring. The shift in DIN and DIP concentrations could imply that DIP concentrations are potentially limiting in spring, whereas DIN concentrations might be limiting during mid-summer. These potential nutrient limitations may result in reduced primary production and possible shifts in species composition.

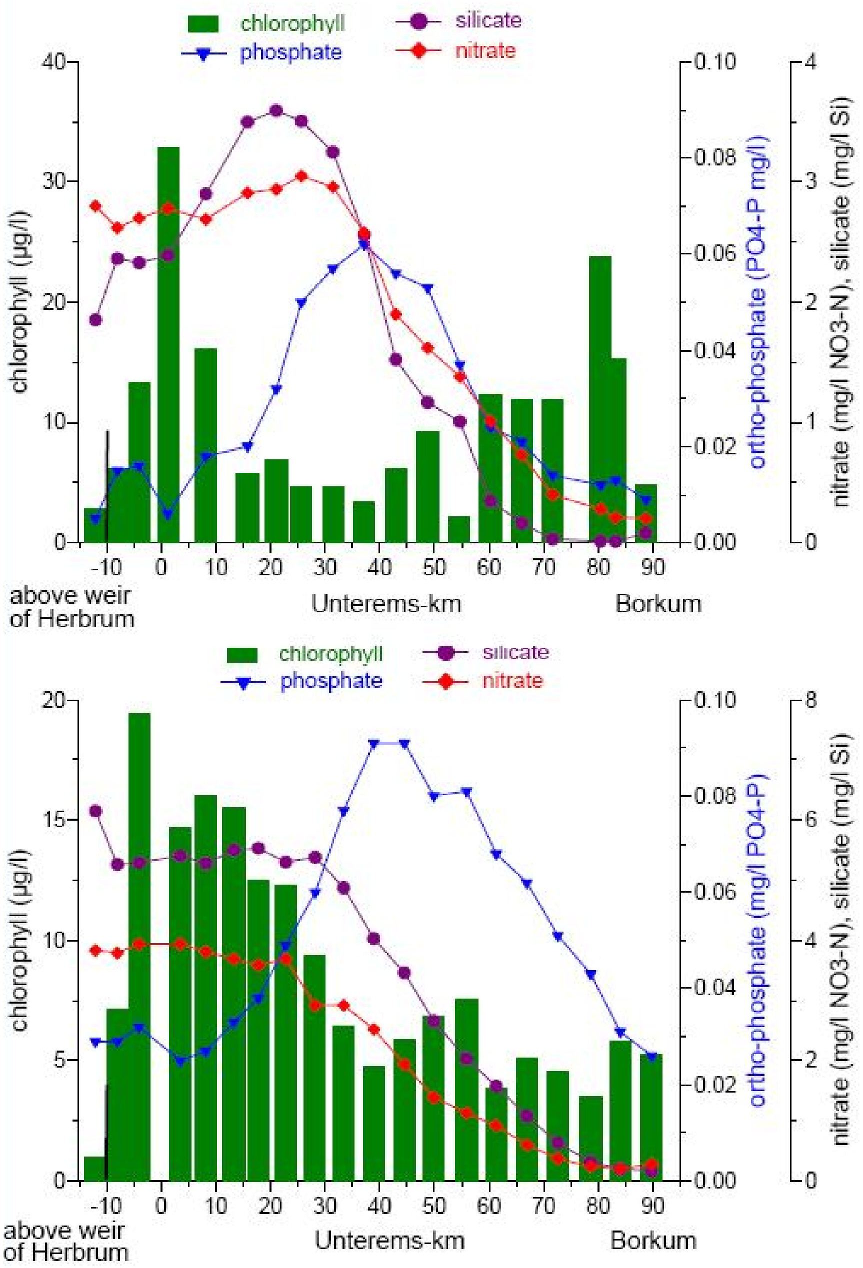
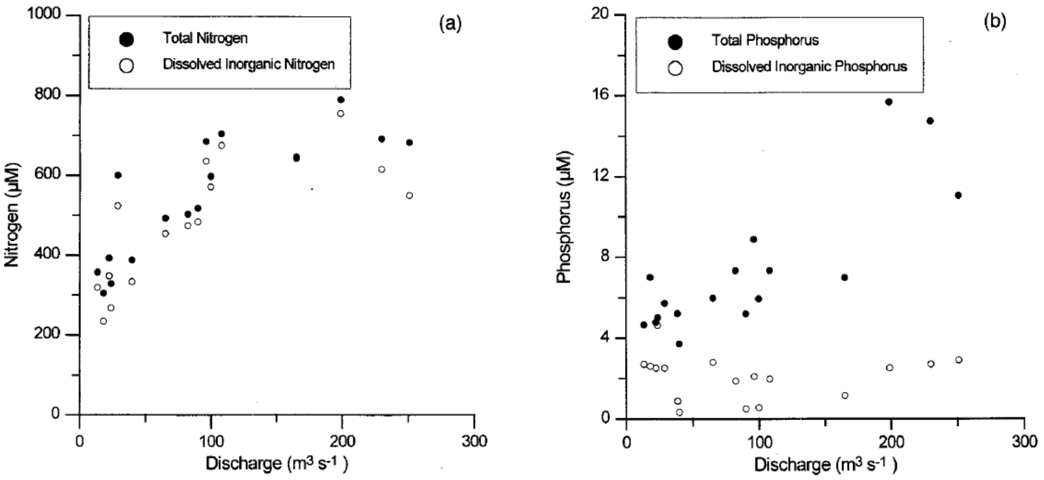


Figure 4.15 Longitudinal estuarine profiles of chlorophyll-a and nutrient concentrations measured in a) May 2007 and b) September 2007 (Source: A. Schoel presentation- Emden 2008)

In a study by van Beusekom and de Jonge (1998), the TotN was found to increase with riverine discharge until 100 m^3/s, after which no further increase in concentration is observed with increasing discharge. Total phosphorus (TotP) increased linearly with discharge, although it showed more scatter than TotN (Figure 4.3). However, the form in which both nutrients are transported into the estuary and, hence, the relations between the nutrient concentrations and water discharge were different. Dissolved inorganic N (DIN) contributed

90% to the TotN while only 3 % was in the particulate form as Particulate Nitrogen (PN). On average DIP contributed only 26% of the TotP, whereas the major fraction (61 %) was

composed of particulate phosphorus (PP), associated to organic and inorganic suspended material. *Nutrient input:* The Ems River carries a significant fraction of the land-borne nutrients to the Ems-Dollard estuary. The total N (TotN) and total P (TotP) load of the Ems depend on the river discharge (Figure 4.16), with maximum loads during high discharge periods (Figure 4.17). For example, the average annual discharge rate in 2001 was 85 m^3/s, resulting in average TotN and TotP loads at the mouth of Ems River of 53 t N/d and 1.4 t P/d. At times of high discharge rates, TotN load reached as high as 250 t N/d, 5 times higher than the annual average, while the maximum measured TotP load was 10 t P/d, almost one order of magnitude higher than the annual average. These nutrient loads are lower than the average nutrient fluxes in other estuaries in the Netherlands such as Scheldt and Rhine (Scheldt- TotN: 126 t N/d, TotP: 4 t P/d; Rhine- TotN: 464 t N/d, TotP: 15 t P/d for 2001). The average river discharge of the Ems is, however, also considerably lower than that of the



Scheldt (around 100 m^3/s) and Rhine (1600 m^3/s).

Figure 4.16 Concentration of Total N, DIN, Total P and DIP as a function of riverdischarge (Source: van Beusekom and de Jonge, 1998)

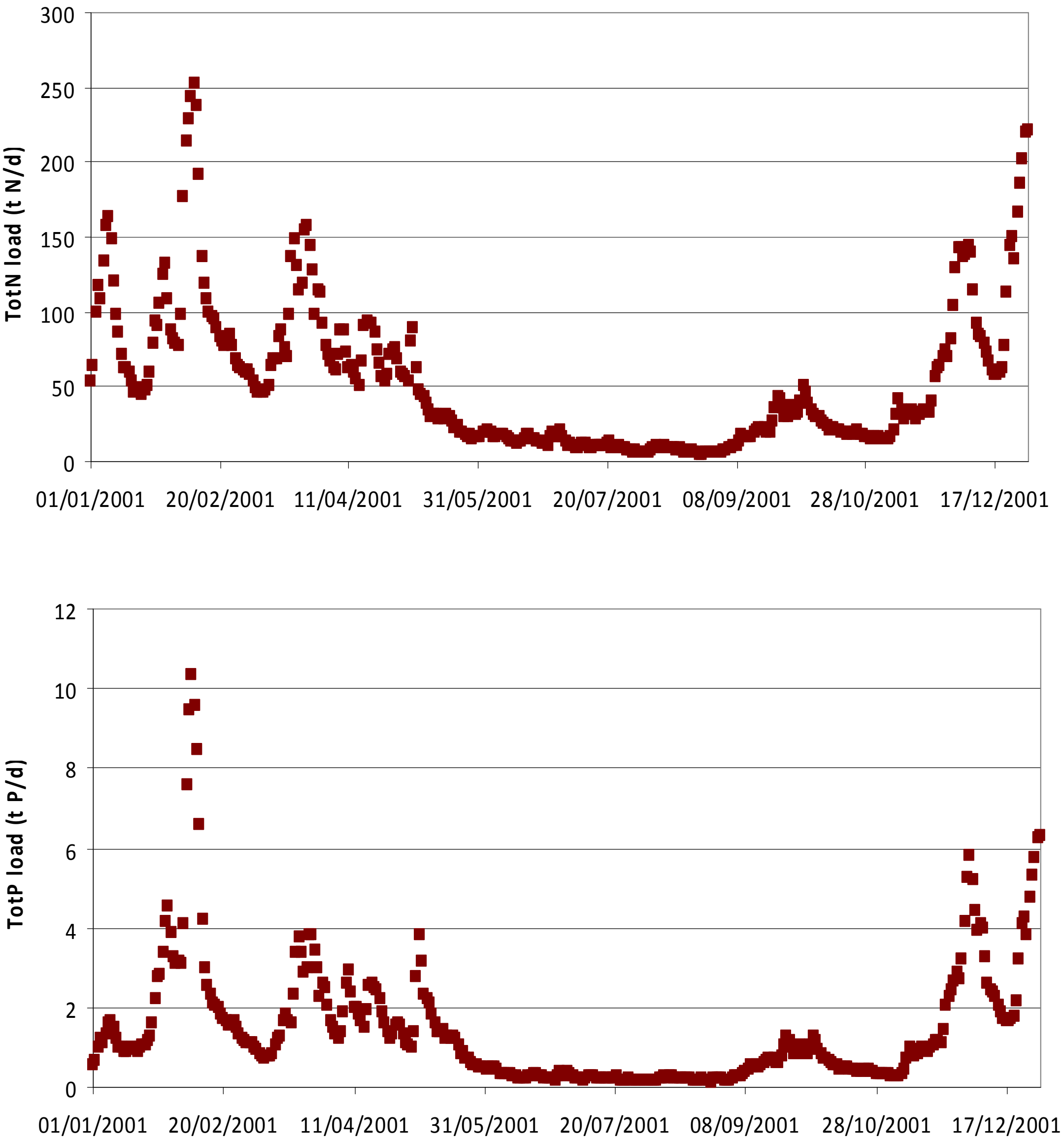


Figure 4.17 Time series for Total Nitrogen and Total Phosphorus loads measured at the mouth of Ems River in 2001

Nutrient geochemcial behaviour: Analysis of field data (2000-2002) of DIN and total nitrogen at Groote Gat Noord (Dollard basin), Bocht van Watum (Middle Reach) and Huibertgat Oost (Lower Reach) shows near conservative behaviour of nitrogen with salinity during the winter months (Figure 4.18). Extrapolation of the trendline along the data points to both salinity extremes (0 and 35) gives an indication of the concentration of total nitrogen and DIN at the freshwater endmember (also known as the effective concentration) and at the seaward boundary. Nutrient-salinity plots shown in van Beusekom and de Jonge (1998) also indicate that the Total Dissolved Nitrogen (TDN) behaves largely conservatively. The annual variation in nitrogen fluxes from the estuary to the North Sea indicate that 75 % of N input is transported to the North Sea. Denitrification is probably the major loss factor (19% of N input) whereas burial explains 3%.

These N fluxes are dominated by DIN transport. The nitrogen demand of phytoplankton in the outer Ems estuary is largely covered by recycling of organic matter.

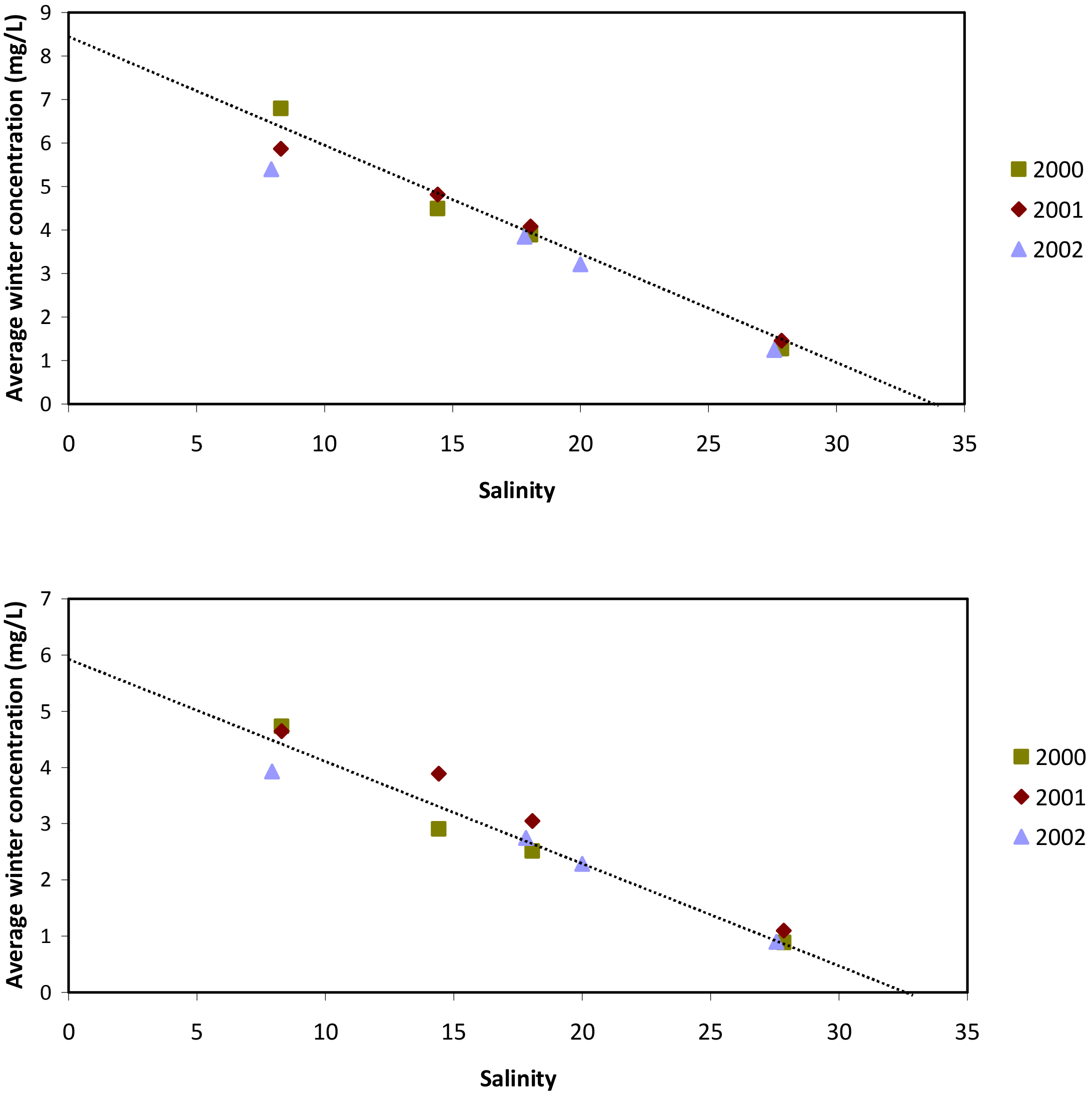


Figure 4.18 Nutrient-salinity plots for average winter TotN and DIN concentrations measured along the Ems estuary in during 2000-2002 in measuring stations Groote Gat Noord, Bocht van Watum and Huibertgat Oost

In contrast to nitrogen, Total Dissolved Phosphorus (TDP) behaved non-conservatively during estuarine mixing with a marked mid-estuary maximum (van Beusekom and de Jonge, 1998; Figure 4.19). This dynamic behaviour of dissolved phosphorus is probably due to the release of DIP through desorption from sediments and suspended matter or through remineralization of particulate organic P (van Beusekom and de Jonge, 1998). The comparison of seasonal phosphate-salinty profiles along the estuary shows that the increase in phosphate concentration is higher in the summer months (Figure 4.20) as a result of higher phosphate sediment return fluxes.

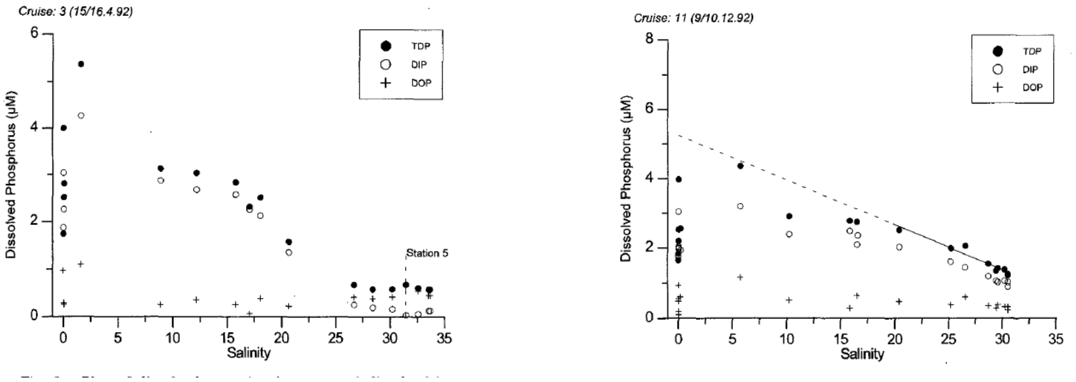


Figure 4.19 Dissolved phosphate concentrations as a function of salinity during April and December 1992 (Source: van Beusekom and de Jonge, 1998)

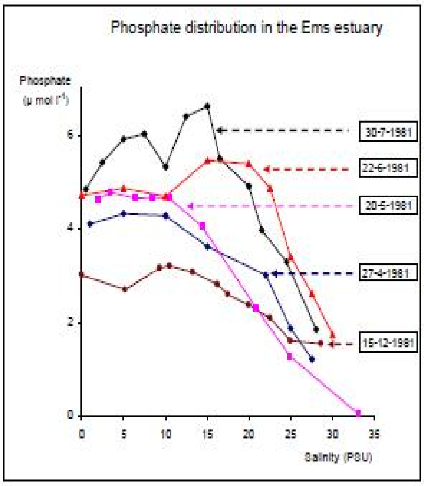


Figure 4.20 Seasonal difference in phosphate distribution along the main axis of the estuary, excluding the Dollard. (Source: de Jonge & Villerius, 1989)

4.10 Flushing rate and wind

Apart from nutrient and light availability, the flushing rate and wind conditions as determined by weather conditions are other important factors controlling primary production. The impact of wind on the estuary is threefold: a) the wind direction and speed influences water levels and therefore determine the mixing and flushing rates within the estuary b) wind generates drift currents which also modify the mixing and flushing rates and thus the water exchange with the Wadden Sea at the sea boundary and c) wave action modifies the sediments of the tidal flats and of the shallow subtidal inducing resuspension of mud and diatoms. The latter influences directly benthic production by microphytobenthos and the variation in turbidity. The Ems estuary is a highly wind-dominated system with an intense interaction between the benthic and the pelagic parts of the ecosystem. Therefore, wind action, rather than tidal dynamics is a dominant factor in determining water turbidity, which in turns controls the occurrence of primary production.

4.11 Microphytobenthos

Primary production by microphytobenthos occurs at the sediment water interface. Due to the relatively high turbidity in most of the estuary, benthic primary production therefore only occurs at the sediment of intertidal areas. In such areas, diatoms dominate microphytobenthos (Figure 4.21).

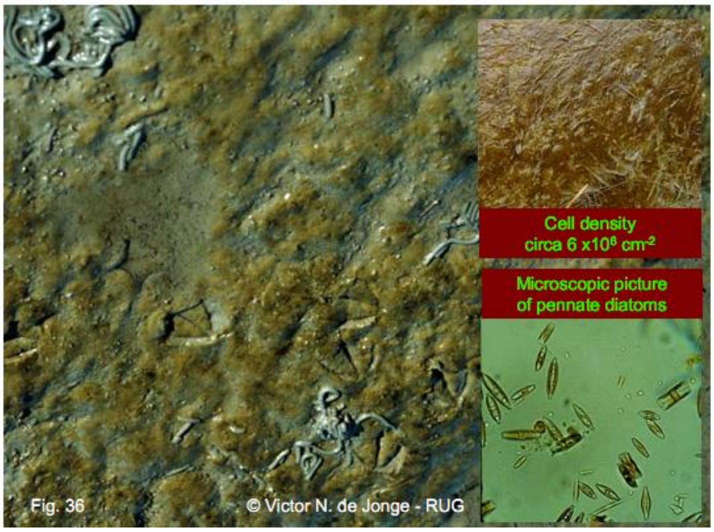


Figure 4.21 Example of a microphytobenthos assemblage in the Dollard area. The inserts represent a very dense layer and a microscopic picture of pinnate diatoms, (Source: De Jonge & Brauer, 2006)

Since the Ems-Dollard area is covered for 53% by tidal flats (Table 4.1.), a substantial part of the primary production takes place on the sediment. During periods of high wind speed, up to 50% of the total chlorophyll-a in the water column can be made up by resuspended microphytobenthos species (see Figure 4.9). Most of the microphytobenthos data in the Ems-Dollard were collected at six stations (Figure 4.22), sampled for biomass (de Jonge & Colijn, 1994; de Boer, 2000) and primary production (Colijn & de Jonge, 1984).

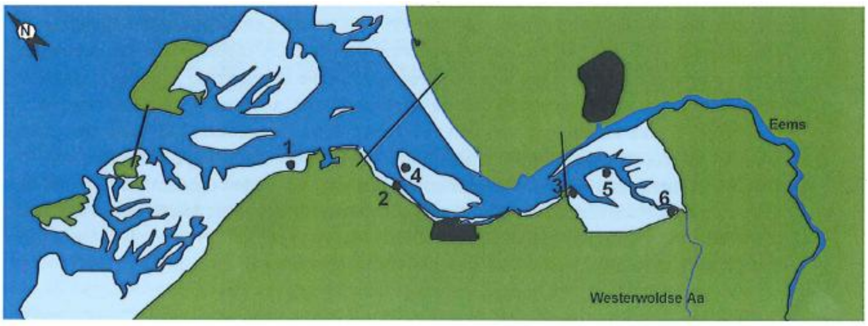


Figure 4.22. Locations sampled for microphytobenthos in the periods between 1976 and 1978, and between 1992 and 1999 (from de Boer, 2010).

Microphytobenthos is a descriptive term for the diverse assemblages of photosynthetic diatoms, cyanobacteria, flagellates, and green algae that inhabit the surface layer of sediments in marine systems (Underwood, 2001). Algal species living on a muddy substrate are called epipelic. Main species of phototrophs in the epipelic community belong to the group of Diatoms (Bacillariophyta) with genera such as *Navicula*, *Gyrosigma*, *Diploneis* and *Nitzschia* (Underwood, 2001). These algae live at the boundary layer between the sediment and the water column, and are able to actively move upward and downward through the sediment.

In the Dollard, close to the outlet of the Westerwoldse Aa, the species composition of the microphytobenthos has been studied by Peletier (1996) in 1976-1977, 1987 and 1993. Data were also used from Admiraal & Peltier (1980), Admiraal et al (1982), and Admiraal et al (1984). During the period covered in the study by Peletier (1996), organic waste inputs from the Westerwoldse Aa, resulting from the regional potato flour and cardboard industries (Essink, 2003), declined from high levels (observed before 1980) to reduced levels (1987-1993). The epipelic community was dominated by only a few species and changed during the course of the study period. Under high organic loads, *Navicula salinarium* and *N. pygmaea* were dominating, but these were replaced by *N. phyllepta* and *N. flanatica* when organic loads were reduced. The latter species showed lower tolerance to high ammonium and sulphide concentrations.

The dynamics of microphytobenthos biomass at six stations in the Ems estuary (Figure 4.22) was studied by de Jonge & Colijn (1994) in the period 1976-1978 and de Boer (2000) between 1992 and 1999. Peletier studied the microphytobenthos in the Dollard in 1987 and 1993 close to the discharge point of the river Westerwoldse Aa. Furthermore, Staats (2001) sampled four transects on the Heringsplaat in the Dollard 1995 an 1996.

In general, the seasonal trend shows higher concentrations of chlorophyll during summer than during winter (de Jonge & Colijn; de Boer, 2000). During summer, irradiance, photoperiod and temperature are higher, and also lower wind speed may result in higher chlorophyll concentrations in the sediment. Mean chlorophyll concentrations (acetone extraction) range from about 30 to 400 mg.m^{-2} (de Jonge & Colijn; de Boer, 2000). A seasonal trend was also observed by Staats et al (2001) at the Heringsplaat in the Dollard, with high chlorophyll-a concentrations (in top 5 mm of sediment) of up to 90 mg.kg^{-1} sediment in June, and low values of less than 10 mg.kg^{-1} sediment in March, October and December. When averaged, the Dollard sediment contains about 70 mg chla m^{-2}, the mid reaches (Hond & Paap) about 15-20 mg chla m^{-2} and the lower reaches (that is including the tidal flats of Borkum and Zuid-OostLauwers) about 40 mg chla m^{-2}). Since the latter tidal flats cover a large area, phytobenthos (and phytobenthic production) in this area is important for the whole system.

Staats et al (2001) found that chlorophyll-a in the sediment did not show a clear depth distribution, except in the zone of high chlorophyll-a concentrations in the peak period (June) when almost all chlorophyll was restricted to the top 5 mm of the sediment. De Jonge & Colijn (1994) also conclude that most of the vital chlorophyll-a is present in the upper 0.5 cm of the sediment, however vital cells can be found down to 3 cm in the sediment. The ratio between the 0.5-2cm sediment layer and the 0 to 2 cm layer was fairly constant, and between 0.40 and 0.47, suggesting a fairly constant depth profile. Next to vital algae, chlorophyll-a can also be present in detrital material (dead cells) that may be buried deeper in the sediment. De Jonge & Colijn (1994) report mean total chlorophyll-a concentrations down to at least 12 cm depth. In contrast to the findings of Staats et al (2001) de Boer found a clear extinction curve of chlorophyll-a, and constructed curves for the six stations sampled between 1992 and 1999 (Figure 4.23).

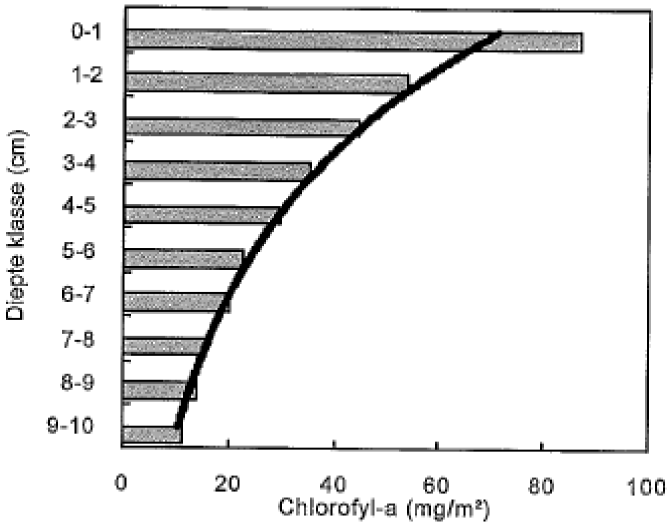


Figure 4.23. Mean chlorophyll-a concentrations related to depth, on the basis of samples from six stations during different times of the year (from de Boer, 2000).

In relation to the depth distribution, it is worth mentioning that the euphotic layer in the sediment is at most 3 mm thick (Colijn, 1982). Only vital cells in the top few mm, i.e. only a small fraction of the total chylorophyll-a in the sediment, contributes to the primary production.

4.12 Primary production

The primary production of the microphytobenthos in the Ems estuary has been measured at six stations (Figure 4.22) from 1976 through 1978 (Colijn & de Jonge, 1984). During the period about 16 measurements were performed at each station, and measurement included the chlorophyll-a concentration, primary production (by ^{14}C carbon fixation), environmental parameters and sediment characteristics. De Boer (2000) calculated primary production rates for the period between 1992 and 1999 on the basis of chlorophyll-a concentrations and an empirical relationship established by De Jong & De Jonge (1995). It should be noted, however, that there may be a high variability between the production rates at a certain chlorophyll-a concentration (Colijn & De Jonge, 1984).

The time series of primary production measurements (Figure 4.24) published by Colijn & de Jonge (1984) form the basic data set (collected in the late seventies) that has been used for several succeeding publications by de Jonge c.s. An assessment of the total primary production of both phytoplankton and microphytobenthos was made by de Jonge (1995). It shows that the microphytobenthos production is relatively more important in the Dollard region, but in absolute values is more important in the lower reaches of the estuary (Figure 4.26). In the lower reaches, production by microphytobenthos takes place in the water column rather than on the tidal flats, whereas in the Dollard production it is more important on the tidal flats. Microphytobenthos biomass makes up a considerable part of the total algal biomass in the estuary (Figure 4.25). The biomass of the microphytobenthos is both present on the tidal flats and in the water column of the estuary. Therefore, also production in the water column by microphytobenthos contributes substantially to the overall primary production in the estuary. Overall, the microphytobenthos production makes up about a quarter of the total primary production in the estuary (Figure 4.27), and in the shallow Dollard almost 70 %.

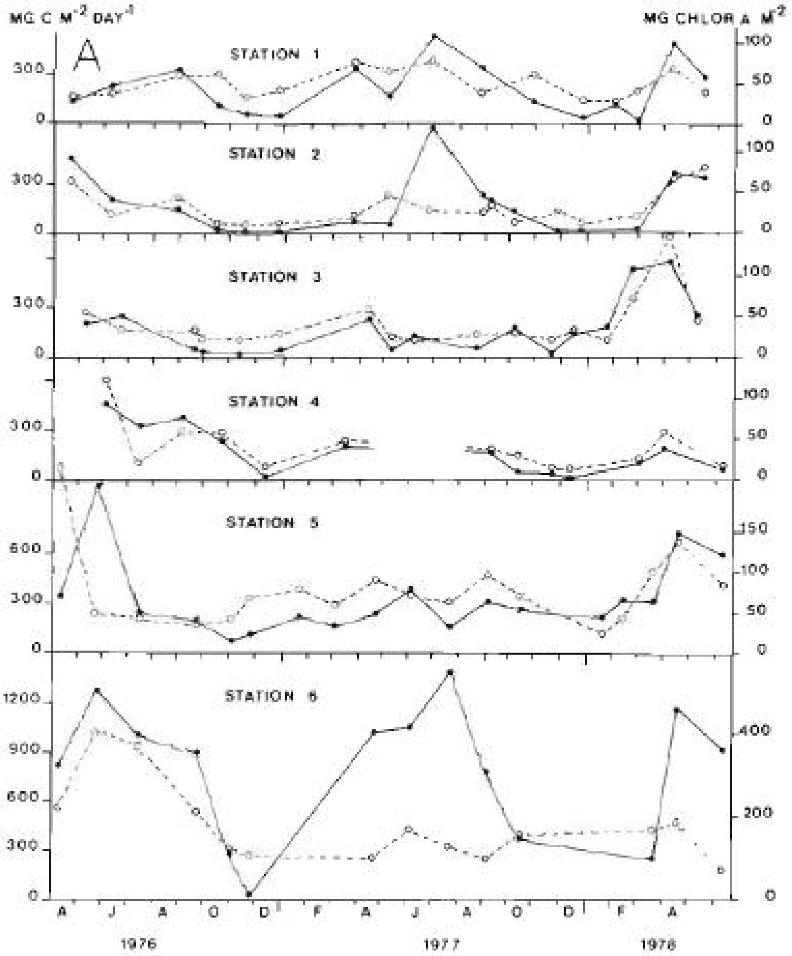


Figure 4.24. Daily primary production rates (solid circles) and chlorophyll-a (open circles) at the six stations as presented in Figure 4.22 (Source: Colijn & de Jonge, 1984).

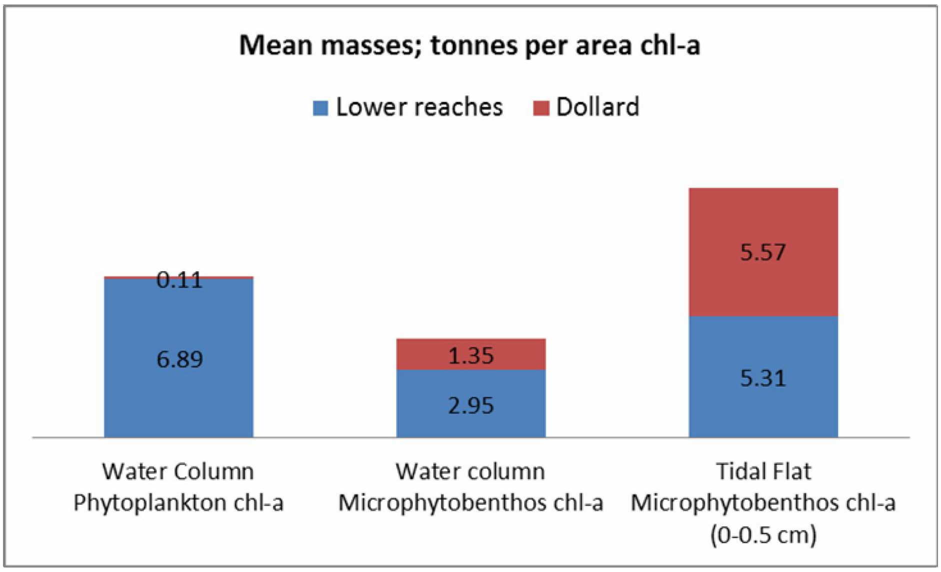


Figure 4.25. Chlorophyll-a (biomass) of phytoplankton and microphytobenthos in the Lower reaches and Dollard in the year 1977 (based on de Jonge, 1980). The values given have a considerable uncertainty, because they are based on measurements on just a few sites.

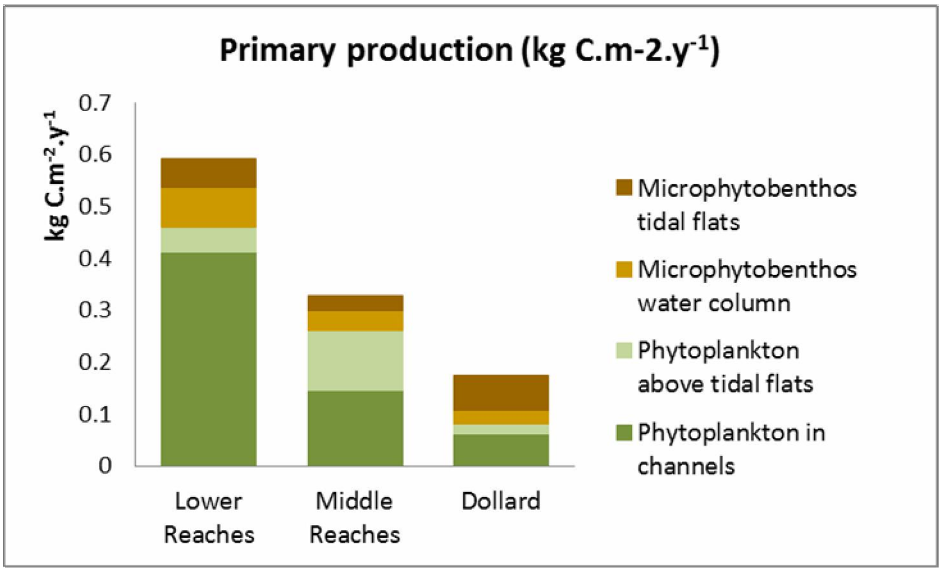


Figure 4.26. Mean annual primary production figures for different reaches of the Ems-Dollard estuary over the period 1976-1980 for phytoplankton (excluding excretion) and microphytobenthos (after de Jonge, 1995).

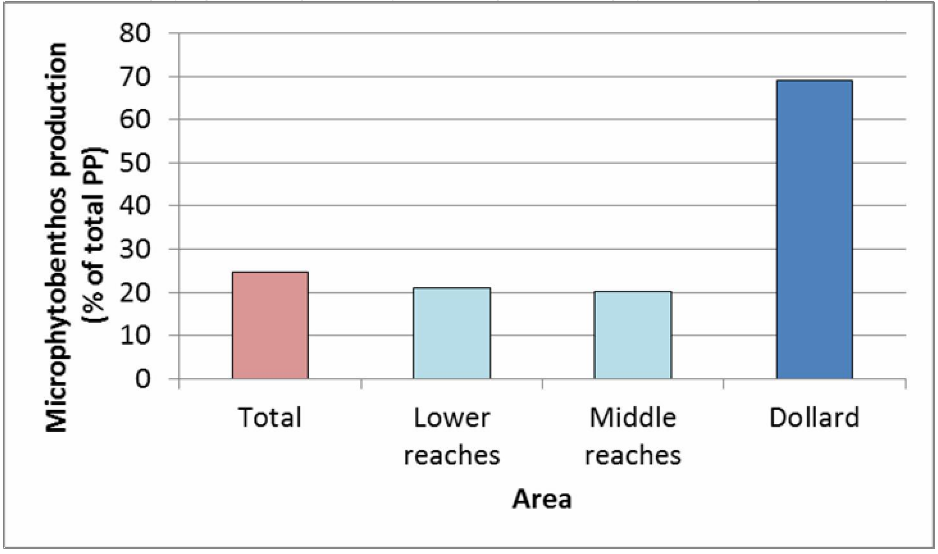


Figure 4.27. Percentual contribution of microphytobenthos production to the total production in the total estuary and for the distinguished zones within the estuary (based on data by de Jonge, 1995).

4.13 Factors controlling biomass

Factors influencing microphytobenthos biomass include irradiance, resuspension, nutrients, grazing, exposure, desiccation and others (Underwood, 2001). De Boer (2000) found significant relationships between the chlorophyll concentration and sediment composition, emersion period, climate variables and water quality parameters.

In the Ems estuary, the microphytobenthos is mainly present on the tidal flats. The period of emersion is most important for algal growth on the sediment, and is determined by the level of elevation of the flats and the tidal range. During submersion, the turbid water above the tidal flats limits growth at the sediment surface, and is usually assumed to be zero.

Since maximum chlorophyll-a levels in the sediment are of the order of hundreds milligram chla m^{-2} (see below) against about 10 mg m^{-3} in the water column, it is obvious that resuspension will strongly affect the content of phytopbenthos in the water column, and that on the other hand the phytobenthos content in the sediment will only be slightly affected.

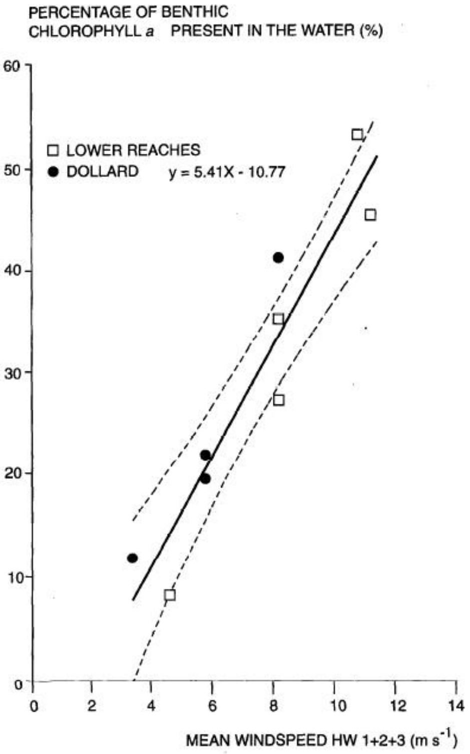


Figure 4.28. Relation between the fraction of resuspended chlorophyll-a and mean windspeed during the three preceding high water periods in the lower reaches and the Dollard (de Jonge & van Beusekom, 2005).

Hence, the contribution of microphytobenthos to total primary production is the sum of the processes in the sediment and the contribution of originally benthic microphytes in the water column.

Integrated analyses from measurements during 1976-1980 show that up to almost 50 % of the total primary production in the estuary came from microphytobenthos (Table 4.3). Furthermore, it was shown that benthic primary production per unit of area was relatively independent of the position in the estuary, as opposed to production by phytoplankton. This is explained by the fact that benthic production is restricted to the dry periods on tidal flats, thus being relatively uninfluenced by the turbidity of the estuarine water. Therefore, although high turbidity in the estuary is the main cause of the restriction of phytobenthos to the higher intertidal areas, it does not cause any spatial differences in production by phytobenthos. Moreover, changes in species composition and biomass of microphytobenthos could be related to changes in grazing by zooplankton over the years. There are no recent measurements of benthic primary production that would show the possible effect of changed nutrient loads in the estuary and grazing pressure on benthic primary production and its contribution to total production.

Whereas the temporal and seasonal biomass levels appear to be affected by a range of factors, in between years variation appears to be closely correlated with the average temperature (de Boer, 2000; *Figure 4.29*).

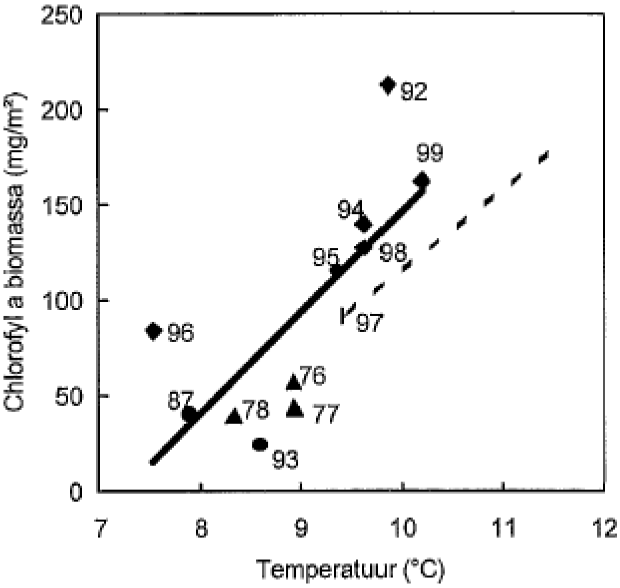
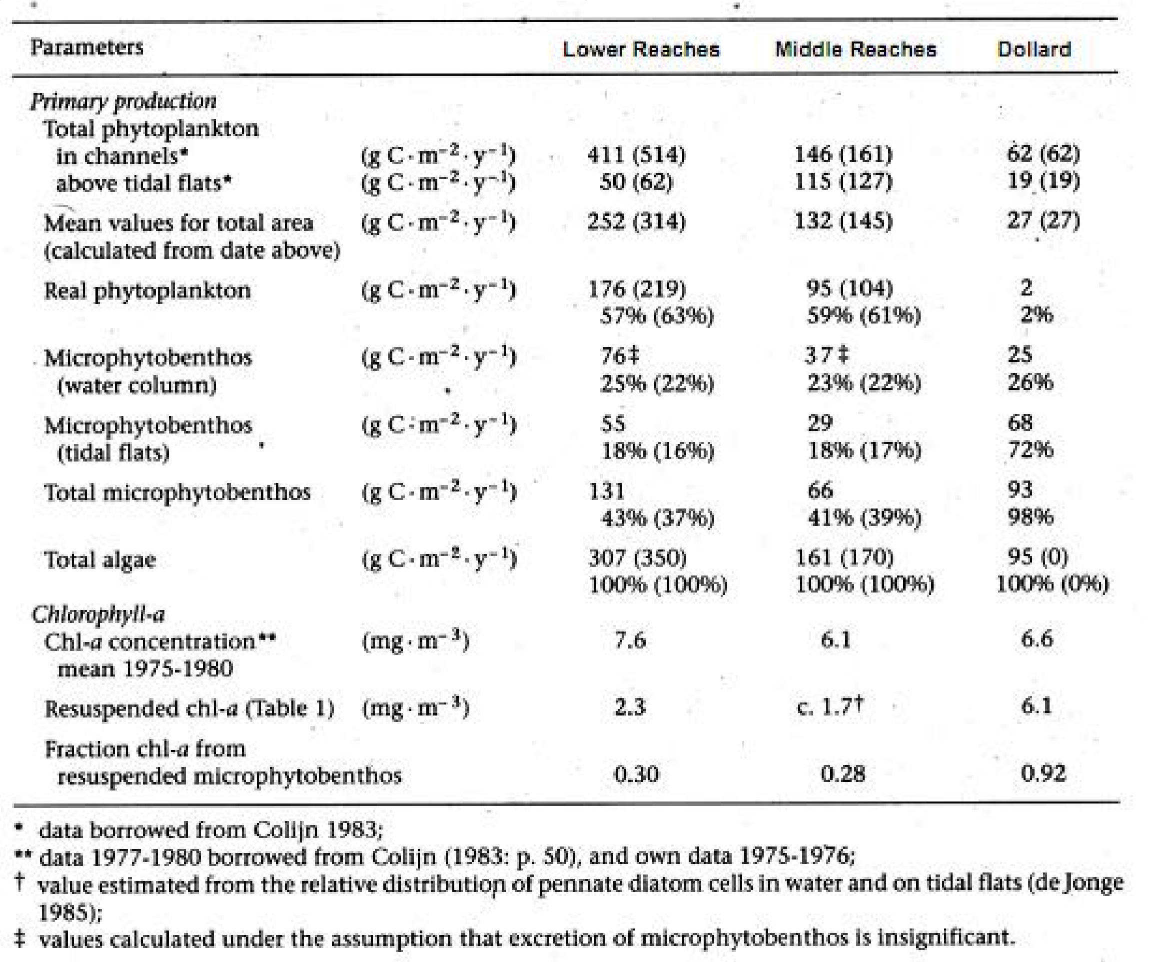


Figure 4.29. Relationship between yearly averaged chlorophyll-a concentrations (on the basis of HPLC corrected values) and average temperature, based on data from Colijn & de Jonge (1984) for 1976-1978 (triangles), Peletier (1996) for 1987 and 1993 (circles), and de Boer (2000) for 1992, 1994-1999 (diamonds). The solid line represents the equation for the Ems-Dollard, the broken line the relationship found in the Oosterschelde (see de Boer, 2000).

Primary production in mg C m^{-2} h^{-1} correlates well with the benthic algal biomass in mg chlorophyll-a m^{-2} almost uninfluenced by location and/or season (Figure 4.30). Indeed, the maximum light availability at the higher points in the tidal area is for most of the year enough to saturate the growth of the abundant benthic diatom species. Only at some stations in the Dollard area, chlorophyll-a specific production was lower than expected as compared to other areas. This may be due to self-shading due to high biomass of benthic algae, or high organic loads to the sediments, increasing the extinction coefficient of PAR in the top layers of the sediment.

Table 4.3 Mean annual primary production and chlorophyll-a for different reaches of the Ems estuary over the period 1976 – 1980. Values between brackets are including excretion.



Parameters		Lower Reaches	Middle Reaches	Dollard
Primary production				
Total phytoplankton				
in channels*	($g \cdot C \cdot m^{-2} \cdot y^{-1}$)	411 (514)	146 (161)	62 (62)
above tidal flats*	($g \cdot C \cdot m^{-2} \cdot y^{-1}$)	50 (62)	115 (127)	19 (19)
Mean values for total area (calculated from date above)	($g \cdot C \cdot m^{-2} \cdot y^{-1}$)	252 (314)	132 (145)	27 (27)
Real phytoplankton	($g \cdot C \cdot m^{-2} \cdot y^{-1}$)	176 (219) 57% (63%)	95 (104) 59% (61%)	2 2%
Microphytobenthos (water column)	($g \cdot C \cdot m^{-2} \cdot y^{-1}$)	76‡ 25% (22%)	37‡ 23% (22%)	25 26%
Microphytobenthos (tidal flats)	($g \cdot C \cdot m^{-2} \cdot y^{-1}$)	55 18% (16%)	29 18% (17%)	68 72%
Total microphytobenthos	($g \cdot C \cdot m^{-2} \cdot y^{-1}$)	131 43% (37%)	66 41% (39%)	93 98%
Total algae	($g \cdot C \cdot m^{-2} \cdot y^{-1}$)	307 (350) 100% (100%)	161 (170) 100% (100%)	95 (0) 100% (0%)
Chlorophyll-a				
Chl-*a* concentration** mean 1975-1980	($mg \cdot m^{-3}$)	7.6	6.1	6.6
Resuspended chl-*a* (Table 1)	($mg \cdot m^{-3}$)	2.3	c. 1.7†	6.1
Fraction chl-*a* from resuspended microphytobenthos		0.30	0.28	0.92

* data borrowed from Colijn 1983;
** data 1977-1980 borrowed from Colijn (1983: p. 50), and own data 1975-1976;
† value estimated from the relative distribution of pennate diatom cells in water and on tidal flats (de Jonge 1985);
‡ values calculated under the assumption that excretion of microphytobenthos is insignificant.

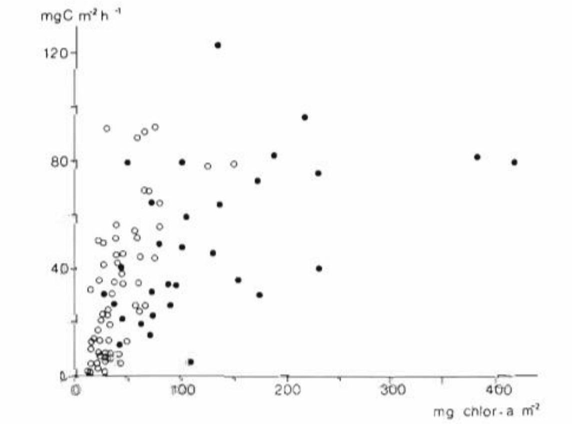


Figure 4.30 Relation between chlorophyll-a concentration and production rate at different stations (Source: Colijn & de Jonge 1984)

It is generally assumed (e.g. Colijn & de Jonge, 1984) that nutrients are not limiting microphytobenthos growth at the water-sediment interface, since nutrients are probably taken

up from the porewater of the sediment and not from the water column. However, no data on sediment nutrient concentrations are available for the Ems-Dollard (de Boer, 2000).
De Boer (2000) performed a limited study of the impact of macrofaunal grazing, by comparing chlorophyll biomass at Heringplaat with the average biomass and density of five diatom consuming species (*Hydrobia ulvae*, *H. ventrosa*, *Corophium volutator*, *Macoma balthica* and *Scobicularia plana*). No impact of grazing pressure on chlorofyll could be detected, however. In fact, there was a positive relationship between the density of *Macoma balthica* and chlorophyll biomass, showing a bottom up rather than a top down control.
The biomass (in the upper 5 mm of the sediment) close to the outlet of the Westerwoldse A showed a decreasing trend during the period of decreasing loads of organic material (Peletier, 1996). Chlorophyll-a levels reached highest levels in May-June with peak levels of ca 400 mg.m^{-2} in 1976, ca 200 mg.m^{-2} in 1977 and 1987, and ca 70 mg.m^{-2} in 1993. The difference in the development of microphytobenthos biomass was probably caused by the increasing numerical densities of the macrofaunal diatom grazers *Nereis diversicolor* and *Corophium volutator*, caused by the reduction of the organic waste. However, de Boer (200) could not detect a relationship between the macrofaunal grazing pressure and the chlorophyll concentration.

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4.14 Human-induced changes in primary production

Certain human activities may influence those factors that determine primary production rates, namely by changing the availability of nutrients and light, in relation to turbidity. These effects are superimposed on top of natural variations in, for example, weather conditions that act as a forcing for estuarine mixing. Over the last years, the Ems estuary has been subject to changes in nutrient inputs and dredging activities, including channel deepening and disposal of dredged material. Others disturbances have been caused by land reclamation and land subsidence due to gas exploitation.

Changes in nutrient loadings: Historically, the Ems estuary has been subject to strong eutrophication as a result of extensive potato flour and strawboard production industry and the more recent application of artificial fertilizers and detergents. The discharge of high loads of untreated waste rich in organic matter from potato flour and strawboard factories into the Dollard has led to high phosphate and nitrogen concentrations, oxygen depletion and an impoverished benthic fauna. Following the discontinuation of these untreated discharges in mid- to late 1970s, the area has seen ecological improvements, the return of oxygen saturation values to ‘normal’ levels and the nutrient concentrations, particularly ammonia and phosphate resulting from organic matter decomposition, decreased steadily since later 1970s (Figure 4.13).

Changes in light availability: There is enough indication the dredging is the most prominent human factor that affects turbidity and the functioning of the ecosystem of the Ems estuary. As shown in Figure 4.2, the different areas respond differently to changes in turbidity, as indicated by the light extinction coefficient (Kz). Primary production in the Dollard is less sensitive to a reduction in light extinction than the two other areas. The strongest response is expected in the Lower Reach with its relatively less favourable light conditions, assuming primary production is not nutrient-limited. There is no information about the effects of turbidity changes on the phytoplankton species composition in the Ems estuary. However, it is envisaged that changes in the light climate influences competition among algal species for light and therefore lead to different algal diversity.

4.15 Conclusions

Historical trends in primary production in the Ems-Dollard estuary are hampered by a lack of data. The most recent measurements on primary production have been carried out in the late seventies of the previous century. There are strong indications that environmental factors, having an impact on primary production, have been changed since then.

In the Dollard area, light absorbing humic acids may have decreased, whereas suspended matter has increased due to hydromorphological changes as a consequence of dredging activities. In the lower regions a reduction of nutrient load may have reduced the primary production in the water column.

Microphytobenthos biomass and production were higher in the nineties than in the late seventies. Important factors for the microphytobenthos are the water temperature and the effective wind speed. Indirectly, recent changes in hydromorphology of the estuary may also have had its effect on the habitat of benthic algae. Resuspension of microphytobenthos is found to be a key factor for algal biomass and production in the Dollard.

5 Data and Models

5.1 Data

5.1.1 Available data

There exists two series of long-term monitoring stations within the Ems-Dollard estuary. Series 1 consists of the Rijkswaterstaat measurements program MWTL, whereas series 2 consists of the German NLWKN measurements. In addition, several relevant monitoring campaigns have been carried out in the past 20 years.

MWTL ('Monitoring Waterstaatkundige Toestand des Lands') is a measurement network to monitor the physical, chemical, and biological properties of Dutch waters. As part of the MWTL, shipborne surface sediment samples are, or have been taken in the past, for a large number of stations in the Ems-Dollard region (Figure 5.2). The measured data contains a number of physical and water quality parameters (such as salinity, transparency, extinction, nutrient concentrations, oxygen, chlorophyll, suspended sediment concentration), and is stored in the DONAR database (www.waterbase.nl). Additional measurements of algal counts are also available (Figure 5.1). The frequency and duration of the measurements vary considerably. Most stations have been abandoned within one year of operation while others have been operational for nearly 40 years. Long-term water quality data has been collected at three main stations since 1976; these are Groote Gat Noord, Bocht van Watum and Huibertgat Oost located in the Dollard, Middle and Lower Reaches, respectively. The initial measurement frequency was bimonthly, later reduced to monthly. Additionally, the sampling method, depth and tidal phase have changed through time. Time series (original and smoothed) as well as monthly averaged sediment concentrations measurements of stations with more than 5 years of data are available.

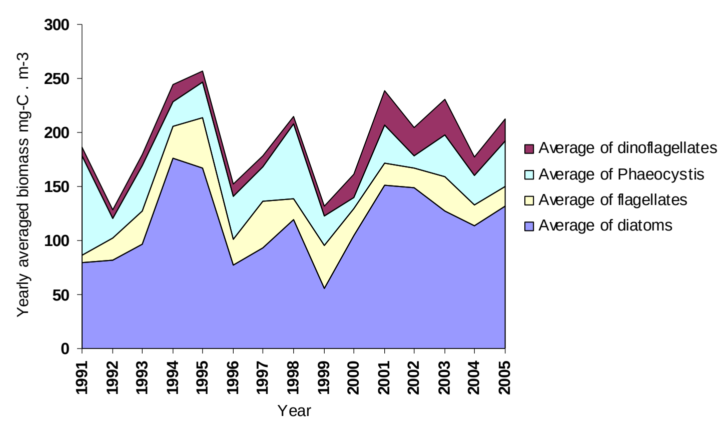

Figure 5.1 Yearly average biomass of main phytoplankton groups at station Huibertgat oost. Source: MWTL monitoring Rijkswaterstaat.

The NLWKN database contains measurements of salinity, water level, oxygen content, and sediment concentration on 8 fixed stations in the Ems River (Figure 5.3). This data is available at 30-minute intervals, for a period since instrument deployment through 2008. In addition to these fixed stations, monthly cruises along the Ems River are done to measure turbidity, DOC, TOC, Ammonium, Nitrate, Chlorophyl-*a*, Temperature, Conductivity, Phosphate, and suspended sediment concentration.

1	**Bocht van Watum**	18	Mond van de Dollard
2	Bocht van Watum midden oost	19	Mond van de Dollard noord
3	Bocht van Watum midden west	20	Nieuwe Statenzijl buiten
4	Bocht van Watum noord	21	Oosterhoofd
5	Bocht van Watum zuid	22	Oostfriese Gaatje
6	Delfzijl buitenhaven	23	Oostfriese Gaatje midden
7	Doekegat	24	Oostfriese Gaatje noord
8	Eemscentrale	25	Oude Westereems
9	Emden vaarwater	26	Oude Westereems noord
10	Emshornplate	27	Paap
11	Gaatje Bocht noord	28	Ra
12	Gaatje Bocht noordwest	29	Ranselgat
13	Gaatje Bocht west	30	Ranselgat zuid
14	**Groote Gat noord**	31	Robbenplaat
15	Groote Gat zuid	32	Westerhoofd
16	Huibertgat noordoost	33	Zeehavenkanaal monding
17	**Huibertgat oost**		

Figure 5.2 Map of the Ems-Dollard estuary showing the locations of the monitoring stations, including Groote Gat Noord in Dollard basin (station 14), Bocht van Watum in Middle Reach (station 1) and Huibertgat oost in Lower Reach (station 17).

Long-term measurements of velocity and sediment concentration were conducted in the Oost Friesche Gaatje (in the Ems estuary), using a measurement pole located at the transition between the tidal channel and tidal flat (depth 5 m below NAP) and a near-bed velocity meter (NBA) in the centre of the channel. Results have been published in several Hydrest reports (see e.g. van de Kreeke 1991, 1993, 1996) and Van de Kreeke et al. (1997). Unfortunately, the suspended sediment sensors suffered from biofouling during periods with temperatures exceeding 15 ^{o}C. A comparable dataset is the Groote Gat measurements (1991), also measuring velocity at three point in the vertical and sediment concentration at 4 points in the vertical, of which 7 weeks of accurate data (October – December 1991) exists.

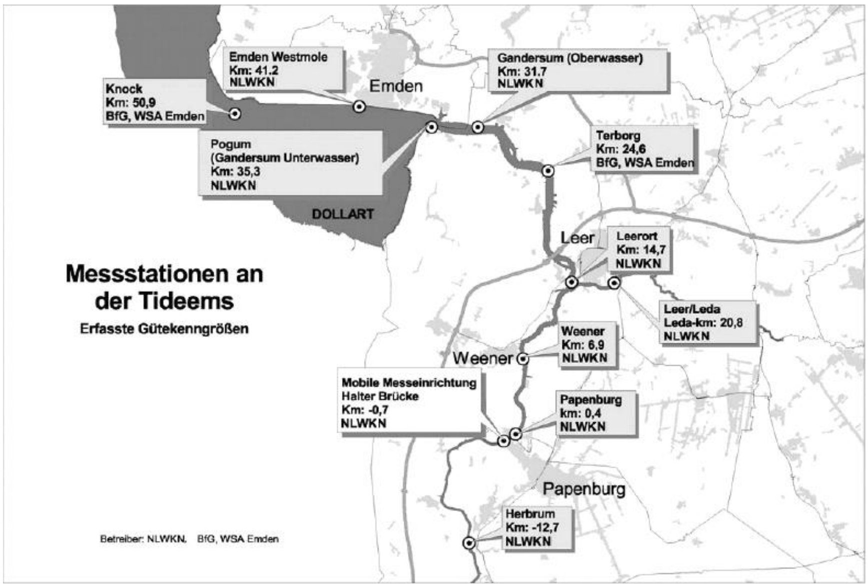

Figure 5.3 NLWKN stations in Ems River (and some in ED-estuary).

Current velocities and sediment concentrations were measured in the Groote Gat and adjacent Heeringsplaat (Dollard estuary) from 1995 to 1997. The measurements consisted of a measurement pole (RWS208) in the tidal channel, a measurement bridge (BOA) on the adjacent tidal flat (Heeringsplaat), a frame (INTRMUD) on the more landward tidal flat, and ship-borne through-tide measurements. The measurement pole measured from spring 1995 to autumn 1996 (not in winter). Two frames were attached to the measurement pole: a Rijkswaterstaat frame for long-term turbidity and velocity measurements, and a frame for turbulence measurements. The measurements were strongly influenced by biofouling. Results are presented in van der Lee et al. (2000), in van der Ham et al. (2001a, 2001b), and Ridderinkhof et al. (2000). The measurement bridge was equipped with 6 velocity sensors and several turbidity sensors. The periodic drying of the instruments prevented biofouling; results are presented in Ridderinkhof et al. (2000) and in Dyer et al. (2000).

Flocculation properties have been measured in the 1990's in the Dollard and the Ems River. Through-tide measurements (13 stations) were carried out in the Dollard estuary in the winter and summer of 1990, reported in de Haas and Eisma (1993). Through-tide measurements were done at 5 locations in the Ems River and estuary on sediment concentration, flow velocity and floc size to determine sediment transport rates. A comprehensive overview is presented in van Leussen (1994).

Hydrological and biological surveys were conducted between 1977 and 1982 as part of the BOEDE (Biologisch Onderzoek Eems-Dollard Estuarium) research programme. The BOEDE biological monitoring programme included the collection of both water quality (e.g. nutrients, oxygen, organic carbon) and ecological data (phytoplankton, primary production including microphytobenthos, zooplankton and nekton (fish, shrimps and crabs)). These measurements taken more than 30 years ago are the most recent data available on primary production and algal populations. Other data collection takes place within the Trilateral Wadden Sea program (TMAP) that however covers the entire Wadden Sea.

5.1.2 Data requirements

The MWTL measurements lack the temporal detail to be used for process analysis. Therefore, they cannot be used to address the relevant importance of the Ems and dredging activities on SSC variation. Additionally, they are unsuitable to calibrate numerical models. Hence, there is no data available to analyse current sediment transport mechanisms in the Ems-Dollard Estuary.

Measurements carried out in the 1990’s are useful for analysis of the relevant importance of transport processes. However, since there are strong indications that the sediment dynamics have profoundly changed, these observations may no longer be representative for present-day processes. This discrepancy may also serve as an opportunity. Monitoring the hydrodynamics but especially sediment dynamics in the Ems Estuary at locations close to the observations in the 1990’s provides an opportunity to compare absolute changes in SSC level, but also on changes in the relative importance of sediment transport processes. This will be addressed in more detail in the monitoring plan.

Primary production measurements are required for the calibration/validation of the water quality/ecological model. Given the importance of benthic production in the tidal flats, measurements of production by microphytobenthos is also required. Due to the changes in the system behaviour during the past decades, current information on algal type distribution in space and in time is also needed. In addition to nutrient data in the water column as well as in nutrient discharges, measurements of organic carbon concentrations, both in the dissolved and particulate form are also necessary for model validation. Additional measurements include light intensity at the water surface PAR, which supplement the (total) radiation values collected on a daily basis by KNMI.

5.2 Numerical models

5.2.1 Available sediment transport models

A number of models exist for the Ems-Dollard region. In the framework of applied research for RWS (TO /KPP), two sediment transport models have been developed, covering the Ems-Dollard Estuary, a substantial part of the North Sea, and the Ems River. Both use a cohesive sediment transport approach. One is implemented in sed-online, with the advantage that sediment-induced density effects are implemented. Another model is developed within the Delft3D WAQ environment, with the advantage that sand-mud interactions are better simulated at substantially faster computational times. The WAQ model allows full-year simulations, which is not possible with the Sed-online model. A disadvantage of the WAQ model is that sediment-induced density effects are excluded, which may be problematic in the Dollard, but especially in the Ems River.

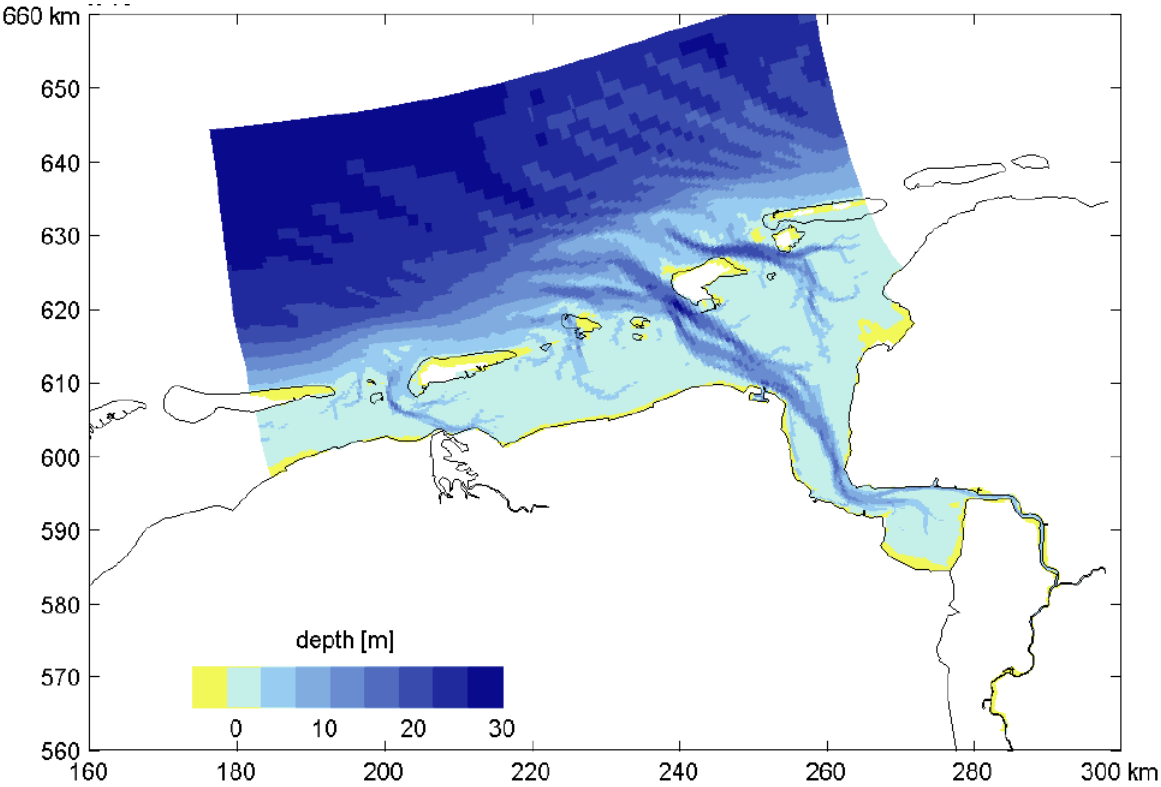

Figure 5.4 Water depth of the Delft3D-based sediment transport models: the sand/silt transport model developed by Alkyon (2008), the online sediment mud transport model by van Maren (2010), and the WAQ mud transport reported in Dijkstra et al. (2011).

The hydrodynamics of the TO/KPP models is from Alkyon's model (Alkyon, 2008). For this model, also a sand/silt transport model was developed, using van Rijn (2007a,b) unified transport formula. Additionally, BAW developed a transport model on an unstructured grid (Untrim and Mudsim, Weilbeer, 2008) which has been extensively used to model dredge plume dispersal. In this model, fluid mud is modelled with a more experimental bed module (Knoch, 2009). Detailed process analysis can be done with a 1DV model in which all relevant processes are implemented (i.e. Winterwerp, 2011).

The hydrodynamics in the Ems Estuary and the Dollard Estuary are well reproduced by the Delft3D model. Alkyon's sand-silt model reasonably simulated sedimentation rates on the mudflats and typical concentrations in the estuary, but failed to correctly model the exchange between the Ems-Dollard and the Ems River. The sed-online cohesive sediment transport model reasonably simulated the exchange between the Ems River and the Ems-Dollard estuary. However, this model still needs to improve siltation on the mudflats and lacked a wave model. The WAQ model underestimated transport into the Ems River, probably resulting from the lack of the sediment-induced density coupling. The main advantages of the WAQ model are that it allows long-term simulations, reproduces typical tidal flat sedimentation rates and patterns, and better reproduces seasonal variability. Preferably, the strong points of both model concepts should be combined into one model. A possibility for this is a new modelling framework under development within Building with Nature that does combine these two, and will be available in the course of 2011. This new model also has a sophisticated bed level module to compute the spatial and vertical segregation of sand and mud. Still, also in this model a choice has to be made whether to simultaneously model sediment and water. Simultaneous simulation is more accurate in turbid environments, but results in such long computational times that seasonal variations become difficult to realise. This issue will be addressed in the Plan van Aanpak (task 2 of phase 1 of this study).

5.2.2 Available ecosystem models

An ecosystem model of the Ems-Dollard estuary was first developed as part of the BOEDE progamme. This model incorporated the important biological components and spatial differentiation and was constructed from 4 sub-models: a physical sub-model that simulated transport processes and 3 sub-models that simulated the biological system: a benthic model, a pelagic model and an epibenthic model (organisms that live in the water but feed on the sediment, e.g. flatfish, crabs, etc.). All biological entities were expressed as biomass with units of organic carbon per area or volume. The Ems-Dollard estuary was divided into 5 regions based on biological criteria such as species composition and biomass.

A more advanced water quality model is now being developed by Deltares and implemented in Delft3D-WAQ within the framework of applied research (TO /KPP). This module is directly coupled to the hydrodynamics and sediment transport model referred to above. The ecological model used is the Generic Ecological Model (GEM) for estuarine and coastal waters, which includes the processes and substances as shown in Figure 5.5. The module BLOOM within GEM is used to model the competition between species and the adaptation by species to limiting factors such as nutrients and light (e.g. Los and Wijsman, 2007). In this module, the maximum net growth is optimized, which is done by selecting a combination of species groups that uses the limiting factor (nutrient or light) most efficiently and reaches the highest net growth rate. The list of modules/processes included in the current model set-up are given in Table 5.1 (Dijkstra et al., 2010).

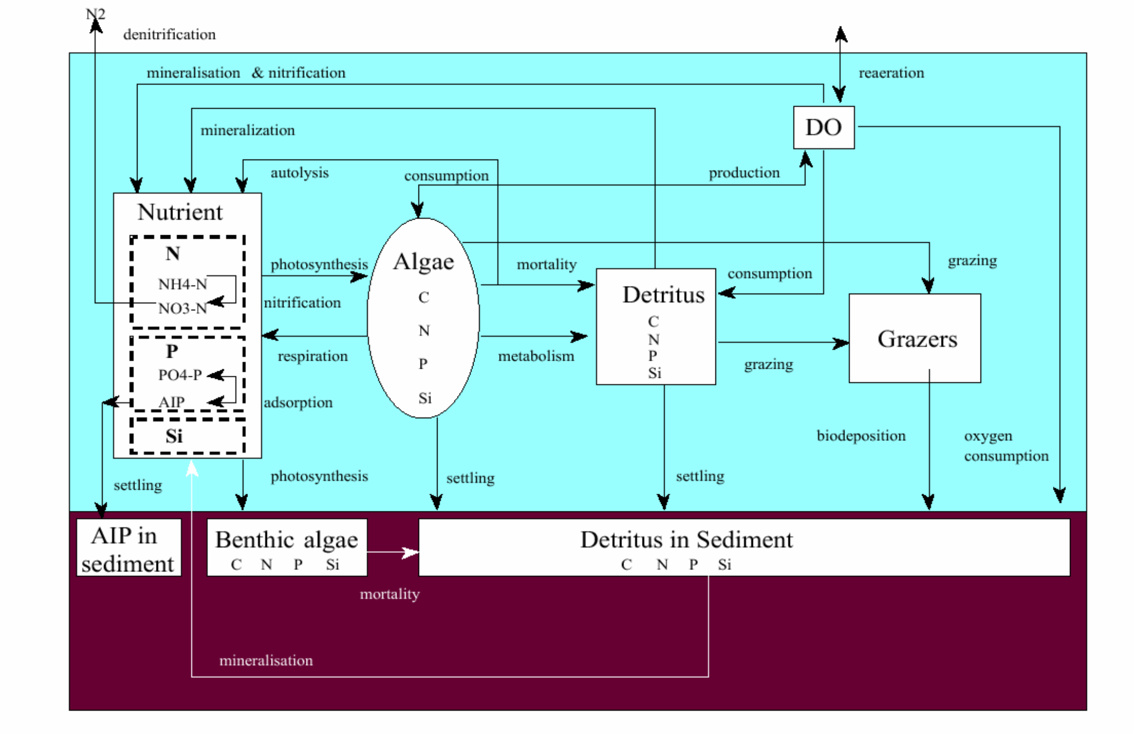

Figure 5.5 Schematic overview of the substances and processes incorporated in GEM

Table 5.1 An overview of the main processes in the model. Entries in grey indicate those processes which are not implemented in the current set-up.

Process	**GEM**	**BLOOM**	CONSBL	S1/S2	DELWAQ-G
sedimentation and resuspension	**x**			x	x
Re-aeration of oxygen	**x**				
aerobic decomposition of organic substances	**x**				x
Denitrification	**x**				x
Nitrification	**x**				x
phosphorus sorption/desorption	x				x
light extinction	**x**				
Phytoplankton growth/respiration/mortality		**x**			
atmospheric deposition	**x**				
microphytobenthos		x			
grazing			x		
sediment diagenesis					x

5.2.3 Sediment transport model requirements

A number of physical processes described in the review should be numerically reproduced in order to capture the essential sediment transport processes in the Ems-Dollard estuary. These include (1) channel shoal interactions, (2) fluid mud formation in the Ems River, (3) dredging and dumping, and (4) biota effects

(1) Channel shoal interactions

Sediment is exchanged between mudflats and tidal channels through net tide-induced upflat transport, and net transport towards the channels under storm conditions. The tide-induced transport is primarily resulting from settling lags, requiring 3D models and a detailed bathymetry: sediment is transported between flats and main tidal channels through an intricate network of tidal channels. Modelling channel-shoal interactions with a detailed bathymetry requires either a very detailed numerical grid, or using more advanced subgrid modelling techniques. These sub-grid modelling techniques are presently being developed, and may not become compatible with existing sediment transport models within the course of this project. Accurate modelling of the mudflat sedimentation further requires an equilibrium bed level module (such as the sand buffer model developed by van Kessel et al., 2010), distinguishing zeroth and first-order erosion, rather than standard Partheniades and Krone deposition / erosion. At concentrations as high as in the Dollard, sediment-induced buoyancy effects may substantially influence sedimentation rates, requiring simultaneous simulation of hydrodynamics and sediment transport. Computing sediment-induced buoyancy effects is not yet possible with the previously mentioned sand-buffer model. Finally, channel-shoal interactions requires modelling of waves. This can be done through complex wave models (i.e. SWAN), or more simple fetch-length approaches.

(2) Fluid mud formation in the Ems River

Sediments are transported upstream into the Ems River through a variety of transport processes. As indicated by Winterwerp (1999, 2011), the upstream transport results from a combination of sediment-induced buoyancy destruction and flocculation; probably also the settling lag plays a prominent role (Chernetsky et al., 2010, van Maren, 2010). As fine sediment accumulate within the river, the sediment concentrations increase, until hindered settling, consolidation, and mud entrainment also become important processes. Full 3D modelling of fluid mud formation and entrainment are being developed (i.e. van Maren et al., 2007) and Knoch, 2008), but are not yet operational. They also have two important drawbacks. Although these models are valuable tools for process analysis, they are not very predictive, and therefore not and even more, are still far from predictive tools. Secondly, due to the complex processes and the required high resolution in time and space, these models are not yet suitable for the long timescales the modelled processes typically operate on. For process analysis, 1DV consolidation tools may be preferred, as used e.g. by Winterwerp (2011). Such a tool can be used to generate boundary conditions for a model of the Ems-Dollard area without the Ems River.

(3) Dredging and dumping

Sediment is spilled during both dredging and dumping. On short timescales, fine sediment is released, leading to a local increase in the suspended sediment concentration, for a relatively short period. These effects can be modelled with relatively straightforward modelling tools. However, dredging and dumping probably also leads to a more slow increase in turbidity on the longer term. This may be the result of release of fines that exceeds the capability of the system to store sediment e.g. in the sandy bed substrate or on muddy tidal flats, or by a change in the composition of the bed sediment (with a relatively higher amount of sand than mud being extracted from the seabed. Both these effects are extremely challenging for numerical models. Partly because of the difficulties of monitoring this (possible) effect, little or none of such modelling studies on long-term dredging effects have been carried out.

(4) Biota
The erosion rates of mudflats, and therefore the turbidity in the water column, decreases as a result of biostabilization (i.e. algae mats). Vice versa, the turbidity increases again when these algae mats are destroyed by bioturbation. Therefore, there is a seasonality in mud dynamics related to biotic effects. Research tools exist to model these effects to a certain degree. These models are, similar to consolidation models, valuable research tools, but they are not yet sufficiently predictive to use as operational tools.

An important issue for modelling sediment transport in the Ems-Dollard estuary, is that a large number of complex processes play an important role, most of which require long simulation times and high spatial resolution. On the other hand, the questions to be addressed are frequently on the level of inter-annual light climate variability and changes in turbidity on even longer timescales.

5.2.4 Ecosystem model requirements

The current water quality/ecological model in Delft3D reproduces the salinity, dissolved oxygen and nitrogen compounds reasonably well. However, improvements are necessary to describe chlorophyll-a and phosphorus dynamics more realistically. Primary production (and thus chlorophyll-a) is one of the most important output parameters. Light, which is the most important limiting factor for primary production in this estuary, is highly influenced by suspended sediments and to a lesser extent by nutrient concentrations and salinity.

Therefore future model requirements demand for an improved simulation of the suspended sediment concentration. Moreover, field measurements of primary production are useful to calibrate/validate the performance of the model.

Further model requirements include the coupling of GEM/BLOOM modules with the explicit simulation of the suspended and fixed fractions of microphytobenthos (primarily as diatoms), as well as the interactions between them.

In order to improve the overall model performance of primary production, it may be necessary to adjust some of the phytoplankton and/or phytobenthos physiological parameters. However, it should be noted that this step needs to be carried out only if this is indicated by available biological data for algal physiological parameters in this specific area.

6 Summary

6.1 WFD

The Water Framework Directive (WFD) obliges the EU member states to achieve good status of all water bodies (rivers, lakes, transitional and coastal waters) by 2015. It also introduces the principle of preventing any further deterioration of the status and maintaining good status through a number of measures. This forms the basis of the River Basin Management Plans (RBMP) set up by the Member States for each identified river basin. For surface waters, “good status” is defined by both “ecological” and “chemical” status. The ecological status of a water body can be described by five ecological status classes (high, good, moderate, poor or bad) based on a number of biological quality elements (BQEs) and supported by determinants for general physico-chemical elements (nutrients, temperature) and specific pollutants. The BQEs set for coastal and transitional water bodies are based on the composition, abundance of: a) phytoplankton, b) other aquatic flora (angiosperms), c) benthic invertebrate fauna (macrofauna), and d) fish fauna (in case of transitional waters, including Ems-Dollard).

In the Dutch RBMP of the Ems, the river basin is subdivided in three water bodies: the Ems-Dollard (NL81_2), the Ems-Dollard coast (NL81_3) and the Ems coast (NL95_5B). According to the Programme Rijkswateren 2010-2015 (Rijkswaterstaat, 2009), the ecological status of the Ems Dollard (NL81_2) is classified as “poor”. The overall status is “bad”, as a result of “bad” chemical status due to too high concentrations of tributyltin and octylphenole. The ecological status of Ems Dollard is affected by the quality elements macrophytes (angiosperms), macrofauna and fish, and the supporting element dissolved inorganic nitrogen (DIN), all of which are classified as “moderate”, whereas the BQE “phytoplankton” is judged to be “good”. However, it can be argued that the BQE “phytoplankton” on its own does not serve as a suitable indicator for ecological status as high water turbidity in transitional water bodies may have a negative effect on the growth of phytoplankton. For this reason, “phytoplankton” is not taken into account in the RBMP set up by Germany for the same area.

The proposed measures for the Ems-Dollard focus on addressing the problem of high nutrient loadings and high turbidity. Both factors are intertwined and relate directly to the target conditions for optimal phytoplankton growth, in terms of species and compositions, and the reduction of nutrient loadings (in particular nitrogen) by 20-40 %. The latter demands for local measures as well as international agreements on the reduction of transboundary nutrient inputs. The second priority measure concerns the reduction of turbidity in the Ems Dollard. The implications of changes in sediment on primary production, and thus the ecological status as described by the BQE “phytoplankton” will be evaluated in this study as described in more details in the “Plan van Aanpak”.

6.2 Suspended Sediments

The Ems River has become significantly more turbid in the past decades. From a tidal river with an Estuarine Turbidity Maximum of several 10’s to 100’s of mg/l it evolved into a hyperconcentrated tidal river with concentrations of several 10’s of g/l. The sediment concentration is also no longer at the head of the salt intrusion, but spread throughout the river. The mechanisms for the upstream transport are related to a strong asymmetry in the tides, which has also increased in the past decades. This increase is mostly the result of

deepening of the Ems River. Therefore, the deepening of the Ems River is an important, and probably the most important reason for the increase of turbidity. However, more developments may have played an additional role.

The sediment concentration in the Ems-Dollard has probably increased in the past decades. The reason for this increase is less straightforward than for the Ems River. It may be related to changes in hydrodynamics in the Ems-Dollard Estuary itself (acting on timescales up to several 100’s of years) or in the Ems River, result from changes in land use of and therefore sedimentation rates on the intertidal areas, dredging and dumping, or the effect of the Ems River on the Ems Dollard Estuary. This needs to be quantified through analysis of data and numerical models.

Models that are able to address all these issues with sufficient accuracy do not yet exist, and it is also not likely that they will be completed within the coming years, However, models do exist do reproduce some of the most essential processes. Two models developed within the applied research of Deltares are of particular interest for this study; presently a framework is being developed in which these models may be merged.

6.3 Primary production

Primary production is controlled by an interplay between nutrient and light availability. Both ‘flushing rates’ that determine the rate at which chemical compounds, e.g. nutrients, enter the estuary and water residence times influence primary production. A distinction is made between pelagic and benthic primary production, carried out by free-living phytoplankton in the water coloumn or (micro)phytobenthos attached to the sediments, respectively. In the Ems Dollard, benthic primary production by microphytobenthos contributes to ~25 % of the total annual primary production that takes place on intertidal areas.

Available field measurements include physical and water quality parameters, such as nutrients, as well as algal counts which will be analysed in the next phase of the project. Clear decreasing trends in nutrient concentrations, in particular in NH_4^+ and PO_4^{3-}, can been observed since the mid 70s as a result of the discontinuation of wastewater effluent sources and discharges of labile organic waste from potato floor factories into the Dollard. The most recent measurements of primary production in the Ems Dollard were taken 30 years ago by the BOEDE group, at that time when the estuary was subjected to high nutrient loads. Other controlling factors, namely light conditions have also changed in the last decades due to changes in sediment concentrations. For this reason, these primary production measurements are no longer representative of the current situation. In absence of primary production measurements, chlorophyll-a concentrations are often used as a surrogate for algal primary production and algal biomass. However, chlorophyll-*a* is merely an indicator of multiple processes and does not represent any process in itself.

Benthic production by microphytobenthos, predominately diatoms, contributes significantly to the total annual primary production. Microphytobenthos are partly resuspended into the water depending on depth, wind conditions and sediment integrity. The relative abundance of benthic algal chlorophyll-a in the water column can be up to 50 %.

The currently available ecological model of the Ems-Dollard estuary is implemented in Delft3D-WAQ and considers nutrients, oxygen and primary production. The module BLOOM is used to model the competition between species and the adaptation by species to limiting factors such as nutrients and light. Delft3D-WAQ is coupled directly to the Delft-3D hydrodynamic and sediment model. Near future model developments include the addition of the microphytobenthos and grazing modules. However, proper validation of these modules is only possible once more recent field measurements become available.

7 Literature

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