Ems-Dollard primary production research Concise summary

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Summary

The Water Framework Directive (WFD) requires EU member states to achieve good ecological and chemical status of all designated water bodies (rivers, lakes, transitional and coastal waters) by 2015. Therefore Rijkswaterstaat Waterdienst has initiated the project 'Research mud dynamics Ems Estuary' (*Onderzoek slibhuishouding Eems-Dollard*). The aim of this project, carried out by Deltares and IMARES, is to (1) improve our knowledge on the mud dynamics in the Ems Estuary (Figure 1.1), (2) to identify the reasons for the increase in turbidity and (3) to quantify measures to improve the ecological status of the estuary.

The whole research consists of an analysis of available data, the collection of new data as well as the improvement and application of numerical models.

The IMARES task, reported in this document, is to provide the numerical models with ecological data, and to answer a number of primary production related questions which are important for reaching aim (3).

The last detailed research on ecological characteristics of the Ems-Dolard estuary has been performed between 1976 and 1980. IMARES performed new research on phytoplankton presence and primary production in 2012 and 2103, and on phytobenthos presence and primary production in 2013. Beside this, concentrations of nutrients, suspended matter and a number of associated variables were measured.

This report provides a summary of the main findings. A detailed report containing an overview of the applied methods, the analytical procedures and the results is provided as 'Full data report' (Brinkman et al, 2014).

Rijkswaterstaat asked a number of research questions:

- *What is the pelagic primary production (PP) at present and are there differences between present primary production and primary production in the late seventies?*

Primary production values computed for the channels in 2012 and 2013 are of the same order of magnitude as for 1978, but much lower than those measured in 1979 and 1980. Largest absolute differences are found for the two outer stations (1 and 2), where present results are 60% of the values in 1979-1980. In the Dollard stations (5-6) we found no difference. In station 3 (in the Oostfriese Gaatje) we found values of the same order as in the late seventies. Largest differences are found at station 4, where primary production found in 2012 is 40-50%, and in 2013 60-70% of the late seventies values.

System average primary production, including both the channels and the tidal flats for 2012 and 2013 was 120 and 125 g C m^{-2} y^{-1}, respectively. Colijn (1984) found an average value of 165 gC m^{-2} y^{-1}.

- *What is the benthic PP at present, and what are differences between now and the late seventies?*

We did not succeed in finding precise benthic primary production data. We computed a minimum benthic primary production of 11-14 g C m^{-2} y^{-1}, and a maximum of 80 g C m^{-2} y^{-1}. Based on a number of arguments, we believe that 40-80 g C m^{-2} y^{-1} is a most likely estimate. These values include the submersion period of the tidal flats.

The uncertainty thus is large and mainly determined by the benthic attenuation coefficient used and the assumptions on benthic diatom motility. Consequently, primary production values computed for 2013 can hardly be compared with the ones found for 1976-1978 by Colijn & De Jonge (1984) (93 g C m^{-2} y^{-1} for the tidal flats alone, including the submersion period).

- *What is the impact of suspended matter (SPM) on pelagic primary production?*

Assuming non-limiting nutrient concentrations, a 50% increase in light attenuation (corresponding to an increase in almost 50 % in suspended solids) would result in a 25% lower pelagic primary production at the inner stations (i.e. in the Dollard and nearby regions) according to our calculations. For the outermost stations (i.e. Huibertgat and Oude Westereems), a similar increase in light attenuation results in a 35-40% reduction of primary production. A 50% lower light attenuation coefficient (e.g. a 50% lower suspended solid concentration) would increase primary production about 40% in the Dollard and 60-65 % at the outermost stations. During times when nutrient availability rather than light is limiting primary production, the changes due to a decrease in suspended matter might not be as large as suggested. In the Ems-Dollard estuary, nutrient limitation might occur at the two outer stations in (late) spring. During that period, an increase in light penetration (less suspended matter) may not result in such an increase in primary production. Thus, at the outer stations changes probably will be smaller.

- *What is the impact of suspended matter (SPM) on benthic primary production?*

We did not study the relationship between suspended matter and benthic primary production. Since benthic primary production mainly takes place during emersion, we assume that a change in suspended matter content of the water column has a minor effect on benthic primary production.

- *What is the impact of suspended matter (SPM) on the start of the growing season?*

Light attenuation might also affect the start of the phytoplankton growing season. Although we did not specifically investigated this, it can be argued that especially at the beginning of the phytoplankton growing season, light is the most important limiting component, more than temperature and nutrients. Especially then, changes in light conditions will have the largest effect on algal biomass development.

- *Are there factors, other than SPM, that have affected the water column irradiances in the last decades?*

Next to suspended solids, also coloured organic carbon (CDOM) cq Yellow Substance (mostly consisting of humic-like organic matter) contribute to the light attenuation. This is especially the case in the more inner stations, where, next to high concentrations of suspended solids occur, also high concentrations of Yellow Substance/CDOM can be found. In those areas, these components account for about 40% of the light attenuation.

- *What is the relationship between the light attenuation coefficient K_d and suspended matter now and in the late seventies*

The relationship found here between K_d and suspended matter (without regarding the role of coloured organic carbon (CDOM) or yellow Substances) is similar to the relationship reported by Colijn (1982) (Colijn did not distinguish CDOM or Yellow Substance).

- *To what extent is primary production by planktonic or benthic algae limited by nutrients or light?*

Pelagic primary production in both outer stations (1 and 2) is possibly limited in spring time by low phosphorus and silicate concentrations, but we could not prove this. Nitrate concentrations do not seem to have an impact on primary production. The three most inner stations (4 - 6) most likely did not suffer from nutrient deficiency.

There was no indication that nutrients play an important production limiting role for phytobenthos.

- *What is the effect of declining nutrient concentrations since the late seventies*

Primary production in 2012 and 2013 for both outer stations was about 10-20% below the 1978-values, and almost half of the 1979-1980 values. This could not be attributed to solar radiation conditions: applying 1978-1980 radiation conditions to the present setting revealed roughly the same results.

Alternative explanations for the lower pelagic production in 2012 and 2013 compared to the late seventies might be the lower nutrient concentration at present, an increased turbidity, a changed phytoplankton species composition and lower phytoplankton concentrations.

Nutrient concentrations, especially ortho-phosphate, dropped down to about 50% of the concentrations in the late seventies resulting in a lower primary production. Since we found a better water column light climate at the outer stations and still a lower production, a nutrient effect remains a plausible explanation. But, as said before, we could not prove nutrient limitation.

At the inner stations, light is limiting algal growth rates and also, we did not find a primary production decrease.

What we did find were lower chlorophyll-a concentrations in the outer parts of the estuary and a much lower presence of highly productive *Phaeocystis* algae as compared to the late seventies. Since this genus is commonly associated with a bad eutrophication status, a de-eutrophication effect is likely.

- *Are there geographical variations and/or temporal variations in the limitation of the growth of algae within the estuary?*

Nutrient limitations are most likely at both outer stations at the end of spring, beginning of summer while for the inner stations, nutrient limitation is less likely. With regard to light limitation, this occurs throughout the estuary. However, at the outer stations it is most prominent at the beginning of the phytoplankton growing season and in late summer/autumn, while at the inner stations, light limitations occurs throughout the year.

- *What is the contribution of the phytobenthos to the total volume of pelagic phytoplankton?*

At the outer stations, benthic algae make up 15 (summer)-40 (winter) % of the total algae volumes; in the inner area this fraction is around 50%.

The report concludes with a couple of recommendations for improving procedures for sampling and analyses and for additional measurements.

1 Preface

The report presented here is a summary of the research conducted by IMARES in the Ems-Dollard area in 2012 and 2013.

The IMARES research was part of the research project 'Research mud dynamics Ems Estuary' (*Onderzoek slibhuishouding Eems-Dollard*), commissioned by Rijkswaterstaat. The aim of this project, carried out by Deltares and IMARES together, is (1) to improve our knowledge on the mud dynamics in the Ems Estuary, (2) to identify the reasons for the increase in turbidity and (3) to quantify and judge measures to improve the ecological status of the estuary.

This report briefly describes i) what was done and where, ii) why has it been done, iii) what are the main results and iv) what have we concluded.

The IMARES research has fully been described in a data reference report (Brinkman et al, 2014).

2 Introduction

The Water Framework Directive (WFD) requires EU member states to achieve good ecological and chemical status of all designated water bodies (rivers, lakes, transitional and coastal waters) by 2015. The ecological condition of the Ems-Dollard estuary is subject to many discussions, mostly related to an increased turbidity and its ecological implications. These discussions take place in both The Netherlands and Germany. To identify the problem and to quantify the effect of proposed solutions, the present project was carried out.

The research project 'Research mud dynamics Ems Estuary' (*Onderzoek slibhuishouding Eems-Dollard*) consists of a detailed analysis of available data, the collection of new data as well as the improvement and application of numerical models.

The IMARES task, reported in this document, is to a) provide the numerical models with ecological data, and b) to answer a number of primary production related questions. Therefore, IMARES performed a separate research on phytoplankton and -benthos primary production, including a number of associated variables. All details on what was sampled, how it was analysed, what the results where and what conclusions have been drawn, have been described in detail in Brinkman et al (2014).

3 The research project, and what was measured

3.1 The whole research project

For more information on the background of the whole research project, see Spiteri et al (2011) and Van Maren et al (2012). An analysis of existing data is described by Vroom et al (2012). The hydrological model is reported by Van Maren et al (2014a), and the sediment transport model by Van Maren et al (2014b).

3.2 The IMARES research questions

Rijkswaterstaat asked a number of research questions:

- *What is the pelagic primary production (PP) at present and what are differences between the present situation and the late seventies?*
- *What is the benthic PP at present, and what are differences between present situation and the late seventies?*
- *What is the impact of suspended matter (SPM) on pelagic and benthic primary production?*
- *What is the impact of suspended matter (SPM) on the start of the phytoplankton growing season?*
- *Are there factors, other than SPM, that have affected the water column irradiances in the last decades?*
- *What is the relationship between Kd and suspended matter now and in the late seventies*
- *To what extent is primary production by planktonic or benthic algae limited by nutrients or light?*
- *What is the effect of changing nutrient concentrations since the late seventies?*
- *Are there geographical variations and/or temporal variations in the limitation of the growth of algae within the estuary?*
- *Is there a substantial contribution of phytobenthos to the number and/or volume of algae in the water column?*

3.3 The IMARES-research

All questions asked can be summarized in two tasks:

- Find out what the current primary production is in the system (pelagic and benthic) and how it is compared to the results previously obtained by Colijn (1982, 1983) and Colijn & De Jonge (1984) for the late seventies.
- Collect necessary data for tuning the Deltares primary production model.

The research on pelagic primary production was conducted in 2102 and 2013, the benthic primary production research was only conducted in 2013.

3.3.1 Pelagic primary production

Since the results of the present research have to be compared with Colijns data (1938), the same methods were applied. To measure primary production in the system, water samples were taken at six sites in the estuary and brought to the laboratory. Twenty cruises were performed in 2012 and nineteen in 2013. In the laboratory, PI-curves were measured to find the relationship between primary productivity (as carbon uptake rate) and light intensity. At each sampling site also the light attenuation in the water column was measured. Hourly natural solar radiation was taken from the data series of the Royal Netherlands Meteorological Institute. Thus, at each site the gross primary production at each depth of the water column could be computed for each hour of the day. Summed, it yielded total gross primary production per m^2 on the day of the sampling.

In order to come to an estimate for the whole year, the data obtained were inter- and extrapolated in time (to estimate the situation on other days of the year).

Finally, it was assumed that each sampling site was representative for a part (compartment) of the estuary. With known morphological data (depth, area, fraction tidal area, and submersion times of the tidal areas) primary production for each compartment could be computed. Adding up the primary production per compartment then yields the total primary production for the whole estuary.

3.3.2 Benthic primary production

To measure benthic production in the system, sediment samples were taken at five sites in the estuary and brought to the laboratory. Eleven cruises were performed in 2013. In the laboratory, a sub-sample was taken, and it was measured how primary productivity (as carbon uptake rate) depended on light intensity, and what the benthic chlorophyll-a content was. Solar light also penetrates into the sediment, and light attenuation characteristics were estimated based on sediment composition. We also investigated the effect of a 50% lower light attenuation coefficient.

Benthic diatom are capable of migrating vertically, finding optimal positions with respect to the benthic light climate. We assumed a number of migration distances to estimate the effect of such behaviour.

With the hourly natural solar radiation taken from the data series of the Royal Netherlands Meteorological institute, at each site the gross primary production at each depth in the sediment could be computed for each hour of the day.

Summed, it gave the total gross primary production per m^2 on the day of the sampling.

Also these benthic results were assumed to be representative for a part of the system. As for the pelagic primary production, values were inter- and extrapolated to produce an estimate for the whole year, and thus, for the whole system.

3.3.3 Additional pelagic variables measured during the cruises at each sampling site

Nutrient concentrations in the water column: these data were needed for the Deltares model, but also to estimate whether phytoplankton growth might be limited by nutrients or by light availability.

Salinity: was needed to know the proportion of fresh water in each water sample.

Temperature: a standard variable.

Oxygen: tells us whether the system suffers from oxygen deficiency, plus it reflects the primary production intensity.

Suspended solids: to serve as input to the Deltares model and to determine a relationship between light attenuation and dissolved and suspended matter in the water column.

3.3.4 Additional pelagic variables measured continuously during the cruises

During all the 40 cruises performed in 2012 and 2013, a so-called PocketBox was installed, measuring continuously several variables and thus largely improving the spatial resolution of these data. Most important were, next to temperature, salinity and oxygen concentrations: turbidity, light attenuation and chlorophyll-a. Also, yellow substance and coloured dissolved matter was recorded continuously.

3.3.5 Additional results from the measurements

The data made it possible to find relationships between the light attenuation in the water column and the amount of suspended solids and dissolved coloured organic matter in the water column, and between the turbidity data and the amount of suspended solids. Thus it became possible, each time a sampling cruise was performed, to estimate suspended matter concentrations in the whole estuary from turbidity data and from light attenuation data.

Table 1 List of questions asked and what pelagic measurements were performed to answer these questions.

Topic / theme	Variable	Remarks
Supply to Deltares ecosystem model	Temperature	Continuous measurements
	Salinity & conductivity	Continuous measurements
	Oxygen concentration	Oxygen electrode. Continuous measurements
	Oxygen saturation	
	SPM	Several methods, local and Continuous measurements, find relationship extinction coefficient, turbidity and suspended matter concentration (SPM)
	Turbidity	
	CDOM (Coloured dissolved organic matter)	Gives an idea of dissolved organic matter
	Yellow substances	Gives an idea of yellow substances (dissolved humic and fulvic acids)
Supply to Deltares ecosystem model / computation primary production	Light extinction	Needed to compute primary production in the field
Supply to Deltares ecosystem model / computation primary production	Chlorophyll	Compare to end '70-'s results. Several methods
Supply to Deltares ecosystem model / computation primary production	Primary production	Compare to end '70-'s results. ^{14}C incubations
Computation primary production	Inorganic C	Needed to interpret ^{14}C-measurements
Are nutrients or is light growth phytoplankton limiting?	[P], [NO3], [NH4], [Si]	Concentrations
	Growth limitation	Pigment absorption ratios
Algae species distribution / Supply to Deltares ecosystem model	Diatoms	Continuous measurements, and some algal cell counts
	Cryptophytes	
	Blue-greens	
	Green algae	

Table 2 List of questions asked and what benthic measurements were performed to answer these questions.

Topic / theme	Variable	Remarks
Supply to Deltares ecosystem model	Sediment temperature	Only at sampling site
Supply to Deltares ecosystem model / computation primary production	Sediment chlorophyll-a	Only at sampling site
Supply to Deltares ecosystem model / computation primary production	Benthic Primary production	Only at sampling site

4 The Ems-Dollard area

4.1 Introduction

In this chapter a number of characteristics of the Ems-Dollard area are given, plus the sites where the pelagic and benthic samples were taken.

4.2 The area

The Ems-Dollard area (Figure 1) is characterised by its large spatial differences from the North Sea side down to the Dollard area. At the North Sea side, water is clear (the light attenuation coefficient is about 1.2 m^{-1}), salinity is high (about 28‰), suspended matter content is low (about 20 mg l^{-1}) and nutrient concentrations are relatively low. In the Dollard area, the water is very turbid (the light attenuation coefficient is up to 10 m^{-1}), suspended matter content is high (up to a few hundred mg l^{-1}), the area is highly influenced by fresh water input from the rivers Ems and, to a lesser extent, the Westerwoldse Aa (salinity is about 5‰), and nutrient contents are relatively high (Colijn 1983; De Jonge & Brauer, 2006; Brinkman et al, 2014).

Figure 1 Ems-Dollard area, with meteorological stations Lauwersoog en Nieuw-Beerta mentioned. Source: Google Earth

The average mean high water depth of the compartments decreases from slightly over 5 m in the outer areas to about 1 m in the Dollard area; low water channel depths decrease from about 10 m in the outer areas to less than 1 m in the Dollard area. In the Dollard, almost the complete area runs dry at low water, with an average emersion period of 43%. Close to the North Sea, the sediment has a low silt content (grain size <63 µm); this is up to 100% in the Dollard.

4.3 Changes in the last decades

As stated in the introduction, the reason to perform the research is the increased turbidity in the estuary, its supposed consequences for ecosystem functioning and the relationship of these changes with intensified dredging activities to secure the accessibility of the Meyer shipyard in Papenburg, the Emden harbour and the Groningen Seaport (Eemshaven). The first requires dredging the Ems river, the two last require dredging shipping channels in the estuary.

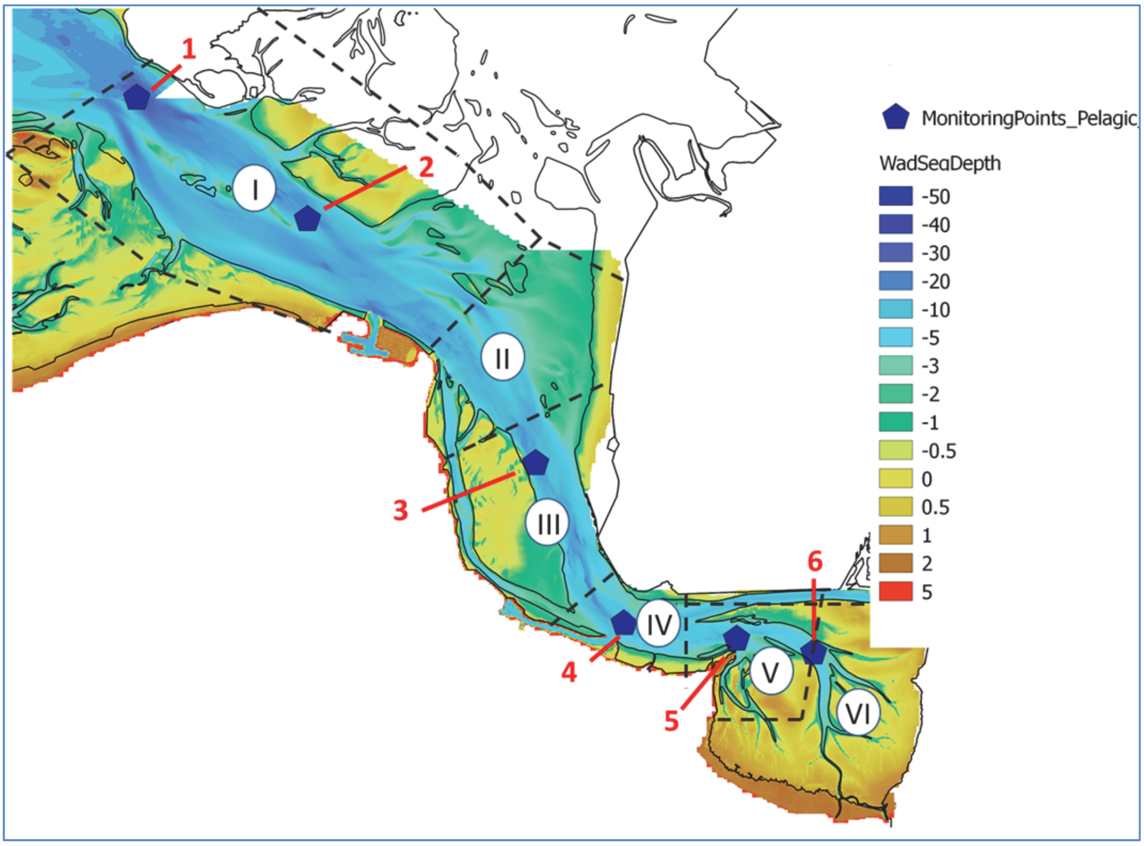


Figure 2 Depth map of the Ems-Dollard area, with pelagic sampling stations (1-6) and compartments (I-VI) as distinguished in the present study.

5 IMARES sampling sites

5.1 IMARES sampling sites

We want to characterise the ecological conditions of the whole system. Thus, data for the whole estuary are needed and therefore, sampling sites along the axis of the whole estuary are chosen, preferably at the same sites as chosen by Colijn (1983). Pelagic sampling sites are presented in Figure 2–plotted on a depth map based on Rijkswaterstaat depth soundings- and benthic sampling sites in Figure 3–plotted on a silt map from RIKZ (1998)-.

5.2 IMARES sampling tracks

As written in section 3.3.5, continuous measurements were performed while sailing from sampling site 1 up to site 6 (Figure 4). Based on sailing speed, it was identified when doing the survey (speed <8.5 km h^{-1}), when sampling took place (speed < 3 km h^{-1}), and when sailing between harbour and first and last survey site (speed>8.5 km h^{-1}). The last type of data, gathered between harbour and survey track, were skipped; they were unreliable because of the high sailing speed.

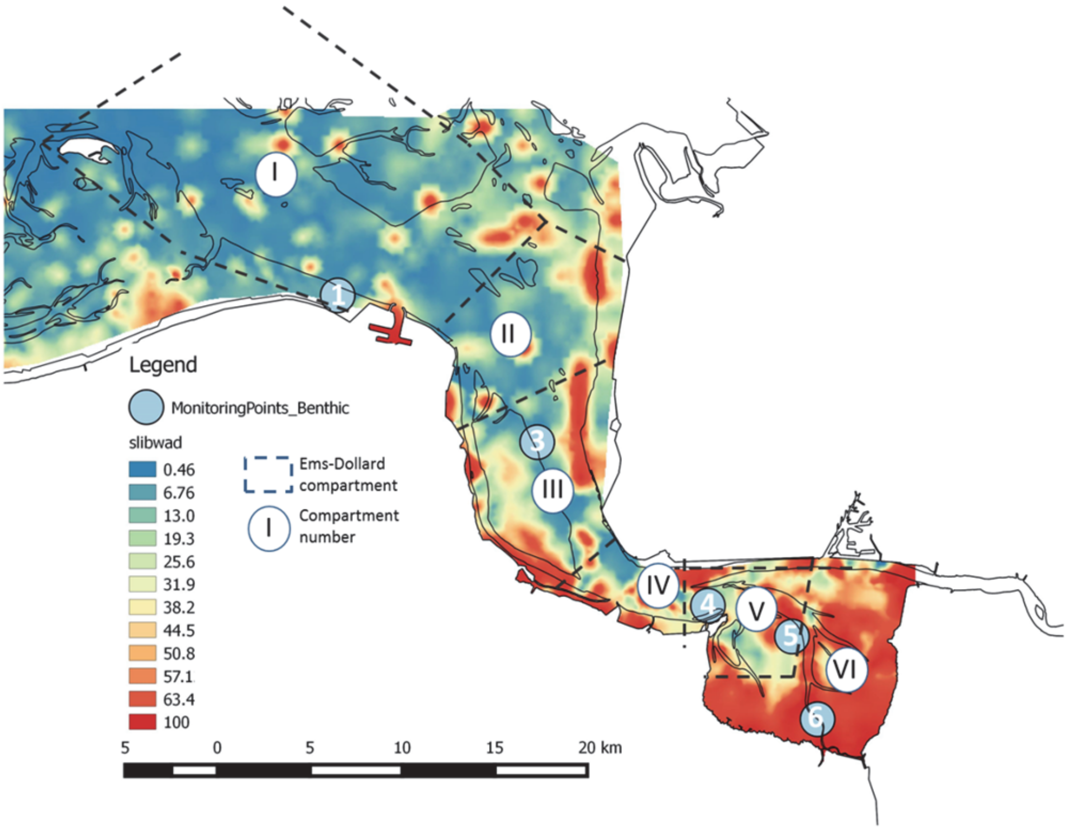


Figure 3 Silt map of the Ems-Dollard area (after the Rijkswaterstaat Wadden Sea sediment map; RIKZ 1998), with benthic sampling stations (1-6) and compartments (I-VI) as distinguished in the present study. Sampling point 2 is lacking, since it was visited only once.

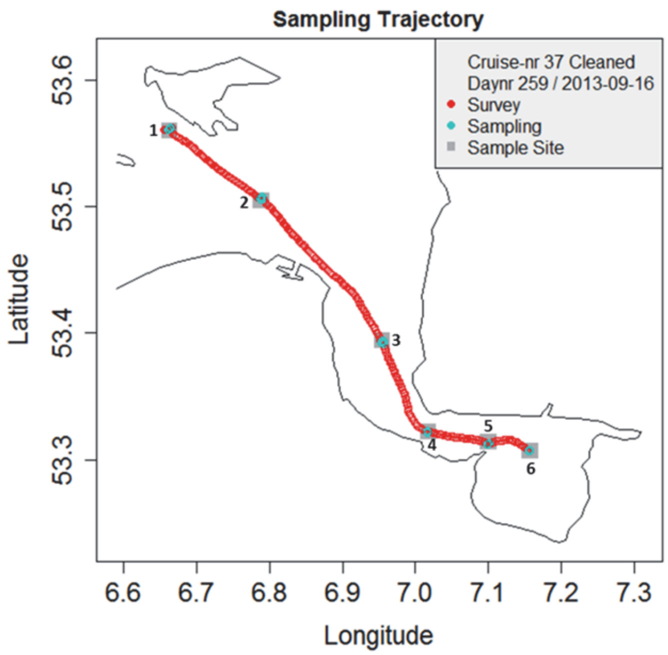


Figure 4 Continuous measurements while sailing from site 1 (most North-western site) up to site 6 (most South-eastern site), sampling trajectory as registered by the PocketBox. Example for day 259 in 2013 (September 19th). Sampling is only assumed to be reliable when sailing speed is < 8.5 km h^{-1}.

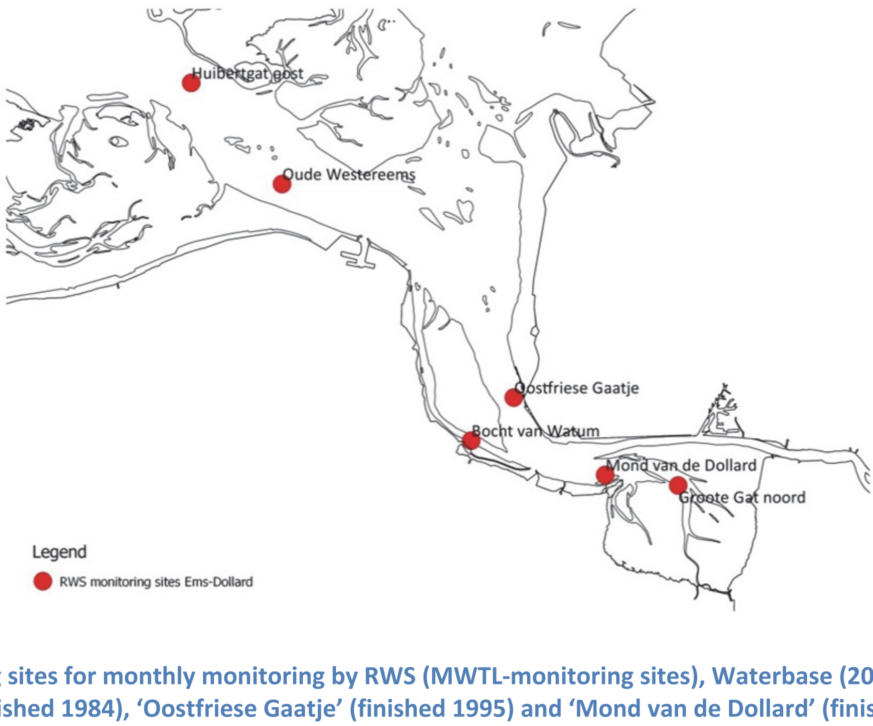


Figure 5 Sampling sites for monthly monitoring by RWS (MWTL-monitoring sites), Waterbase (2014). Sites 'Oude Westereems' (finished 1984), 'Oostfriese Gaatje' (finished 1995) and 'Mond van de Dollard' (finished 1987) are not monitored anymore; 'Bocht van Watum' became a monitoring site in 1984.

5.3 Rijkswaterstaat sampling sites

Next to our own data, those from the monthly Rijkswaterstaat monitoring programme (MWTL) are available (Figure 5). More stations have been sampled in the past, but these are omitted here.

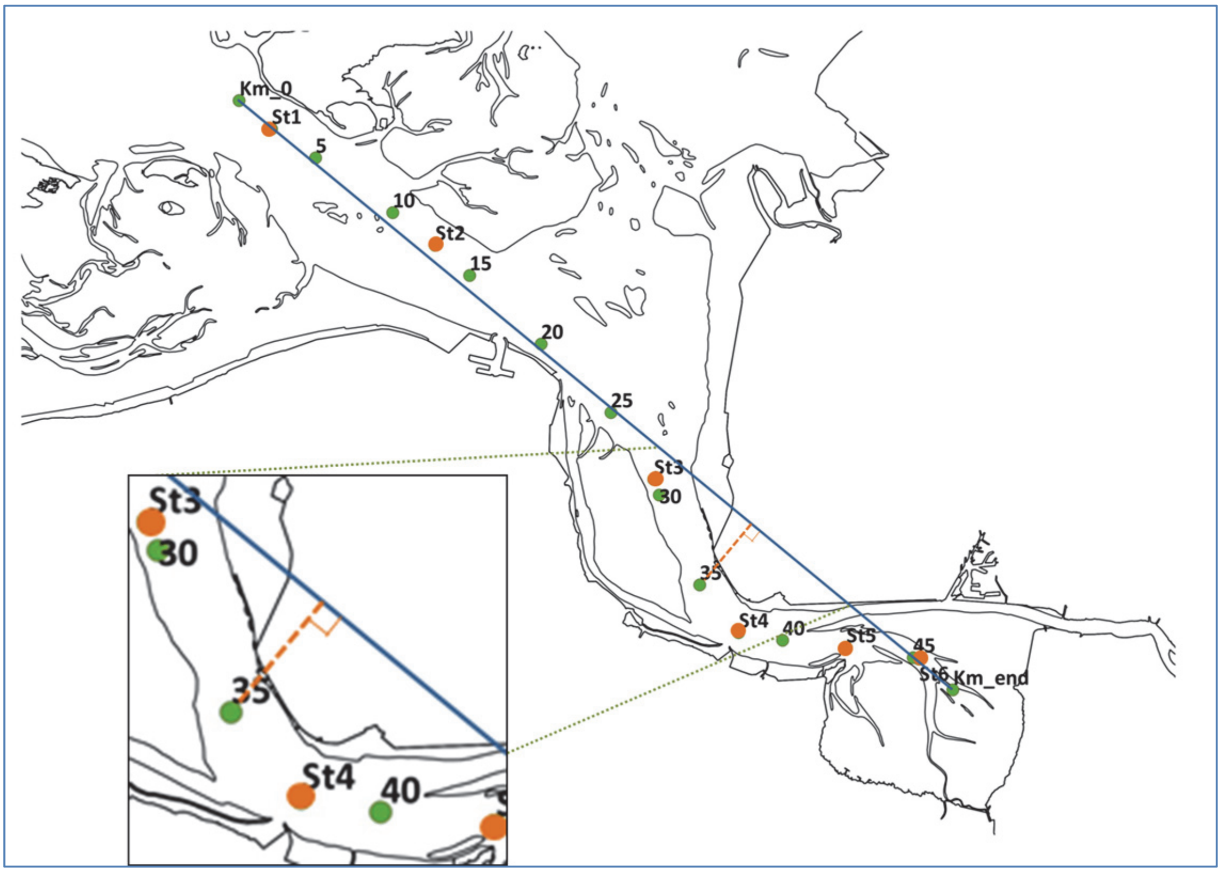


Figure 6 Cruises in the Ems-Dollard estuary: positions of the sampling sites (stations 1..6, orange dots) plus distances from starting point (0,0) (green dots). For all cruises, 'distances from starting point' were computed along the straight line from Km_0 to Km_end using perpendicular lines as sketched by the dashed orange line in the insertion.

Note that partly the Herbrum river weir upstream in the Ems river has been taken as (0,0); Station 6 then is at km 56, and Station 1 at 98 km. This is the case for all level plots (chapter 6).

5.4 Distances from the 'beginning' of the estuary, positioning of continuous measurements

All sampling sites are at a certain position from the 'beginning' of the estuary. In Figure 6 this is presented. In order to come to a uniform estuary scale, all sampling sites and continuous monitoring points were projected on the straight line between Km_0 and Km_end (Figure 6).

Other publications (e.g. De Jonge & Brauer, 2006; De Jonge et al, 2014) however, start with the Herbrum weird in the Ems river as beginning, which is about 100 km upstream from Km_0. This scale is used for all level plots in chapter 6; our station 6 then is at km 56, and station 1 at km 98.

6 Results

6.1 Introduction

All results are presented briefly, in the same order as the questions asked in section 3.2.

6.2 Abiotic characteristics of the water column

6.2.1 Temperature and oxygen content

6.2.1.1 Results

Temperature and oxygen concentration plus saturation percentages are presented as contour plots in Figure 7 and Figure 8.

Temperature is almost uniform in the whole system, with only small differences between the outer and inner areas. Close examination of Figure 7 reveals that temperature increase in spring and decrease in autumn starts a bit earlier in the inner areas, and maximum values are a bit higher there.

With regard to the oxygen concentration and saturation values the most important conclusion is that saturation values dropped below 60% only on a few occasions in the Dollard area and only during a short period. Highest saturation values are observed in those periods where primary production is at its top (see section 6.10), and lowest saturation values occur later in summer when temperatures are high, and breakdown processes (with oxygen consumption) become important.

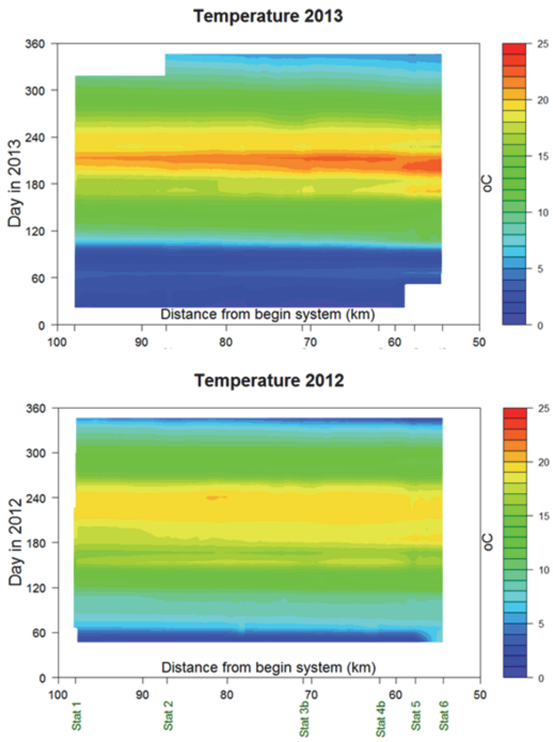


Figure 7 Temperature in the system. Left: 2012, right: 2013. Distances mentioned are from Herbrum (DE). Sampling stations 1-6 are indicated.

Although measurements were done just below the surface only, it is believed that, due to the vertical mixing, these data are also representative for the whole water column. During 2013 and 2014 (so, the year after the present study), vertical profiles of salinity, oxygen and temperature were recorded by Rijkswaterstaat at site Groote

Gat Noord (see Figure 5; local depth is about 5m), showing that temperature and dissolved substances are well-mixed at that site (solids do show at vertical gradient). For details see section 8.19 in the full-data report

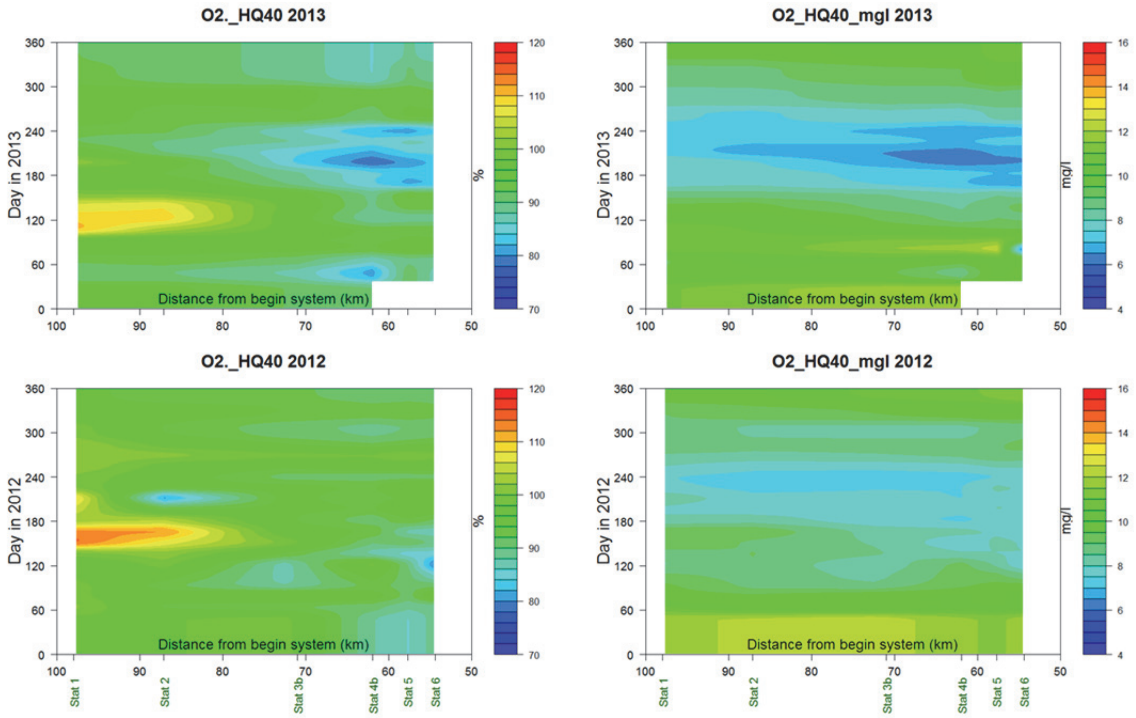


Figure 8 Oxygen concentrations (right, mg O2 l^{-1}) and saturation percentage (left) in the system, taken from the HQ40-handheld results. Distances mentioned are from Herbrum (DE). Sampling stations 1-6 are indicated.

6.2.1.2 Gradient along the estuary axis

Year-average gradients of oxygen saturation values for 2012 and 2013 along the estuary axis are p presented in Figure 12. Both patterns show a steady decrease from the outer areas towards the Dollard. In both years there is minimum around km 40 (Figure 6), which is close to spot where the Ems river flows into the estuary.

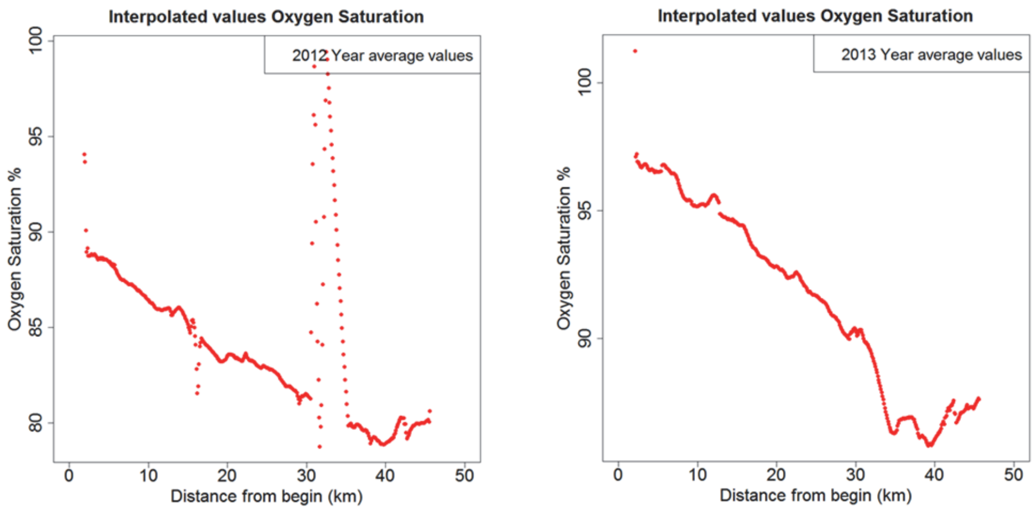


Figure 9 Year-average gradient of oxygen saturation value along the estuary axis. For distances (starting at the outer station 1), see Figure 6. Sudden peak in 2012 at km 32 probably is an error that was not filtered out by the applied routines.

6.2.2 Nutrients in the system

All nutrient results are summarized as level plots in Figure 10. Characteristic pattern is that all concentrations are highest in winter and in the Dollard area. Otho-phosphate and silicate have lowest values in late spring, nitrate has lowest values in summer. These patterns are clear in both years, in 2013 a bit more than in 2012. These patterns are common in the Wadden Sea, North Sea coastal zone and Lake IJssel (Brinkman, 2008; Grunwald et al, 2010).

Ortho-phosphate shows a bit typical pattern since after spring values increase rapidly in the Dollard-area, causing higher summer averages (April-September) than winter averages (November-February). Lower values in late spring only last for a short period.

Low ortho-phosphate and silicate values in late spring at the outer stations support the possibility of nutrient depletion and thus limitation of algae growth, but this was not tested in the laboratory. The higher nutrient concentrations in the Dollard area possibly support the *absence* of nutrient limited algal growth. This is discussed further after the primary production measurements (section 6.8).

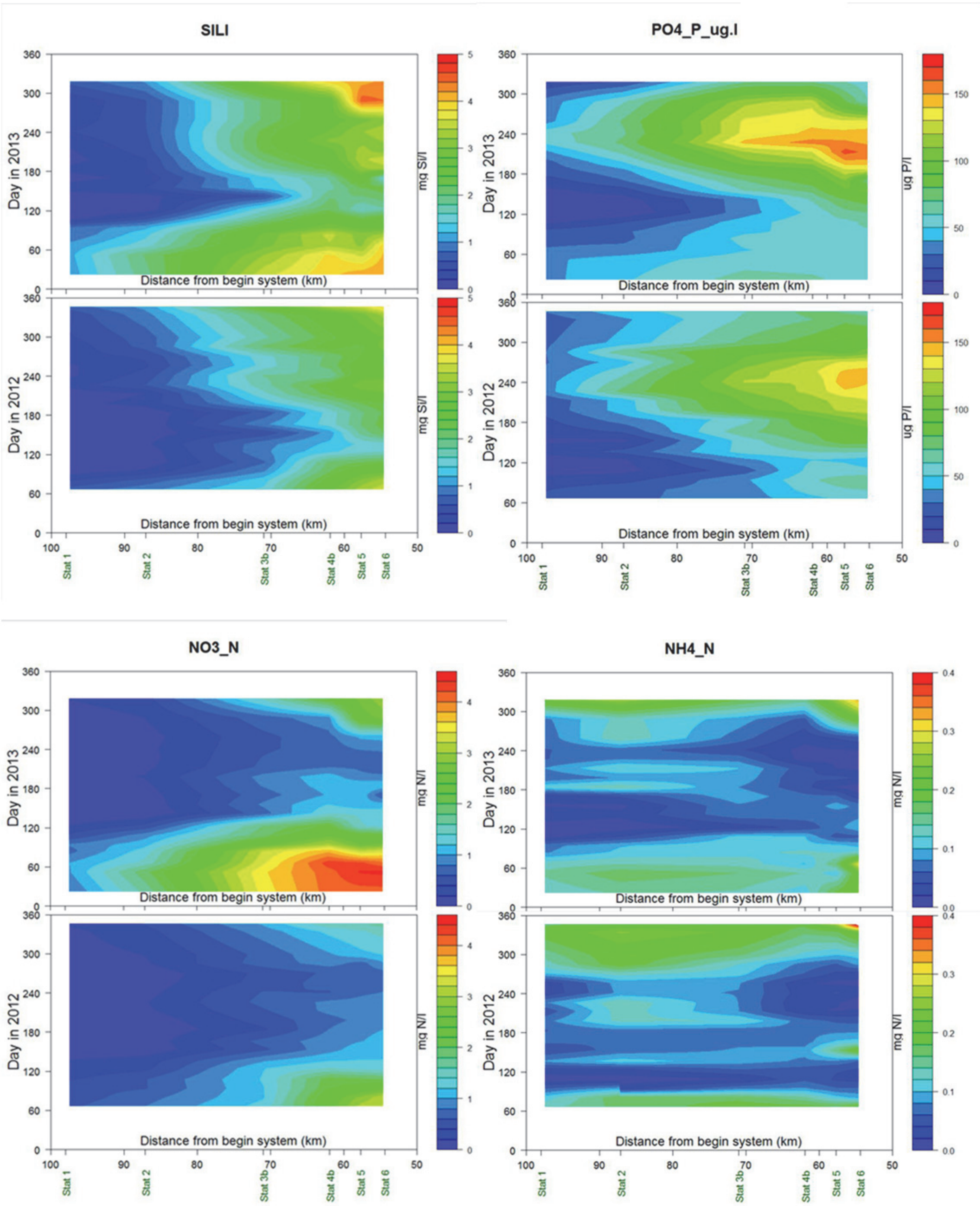


Figure 10 Level plots for silicate (mg Si l^{-1}), ortho-phosphate (mg P l^{-1}), nitrate (mg N l^{-1}), ammonium (mg N l^{-1}) for 2012 and 2013. Distances mentioned are from Herbrum (DE). Sampling stations 1-6 are indicated.

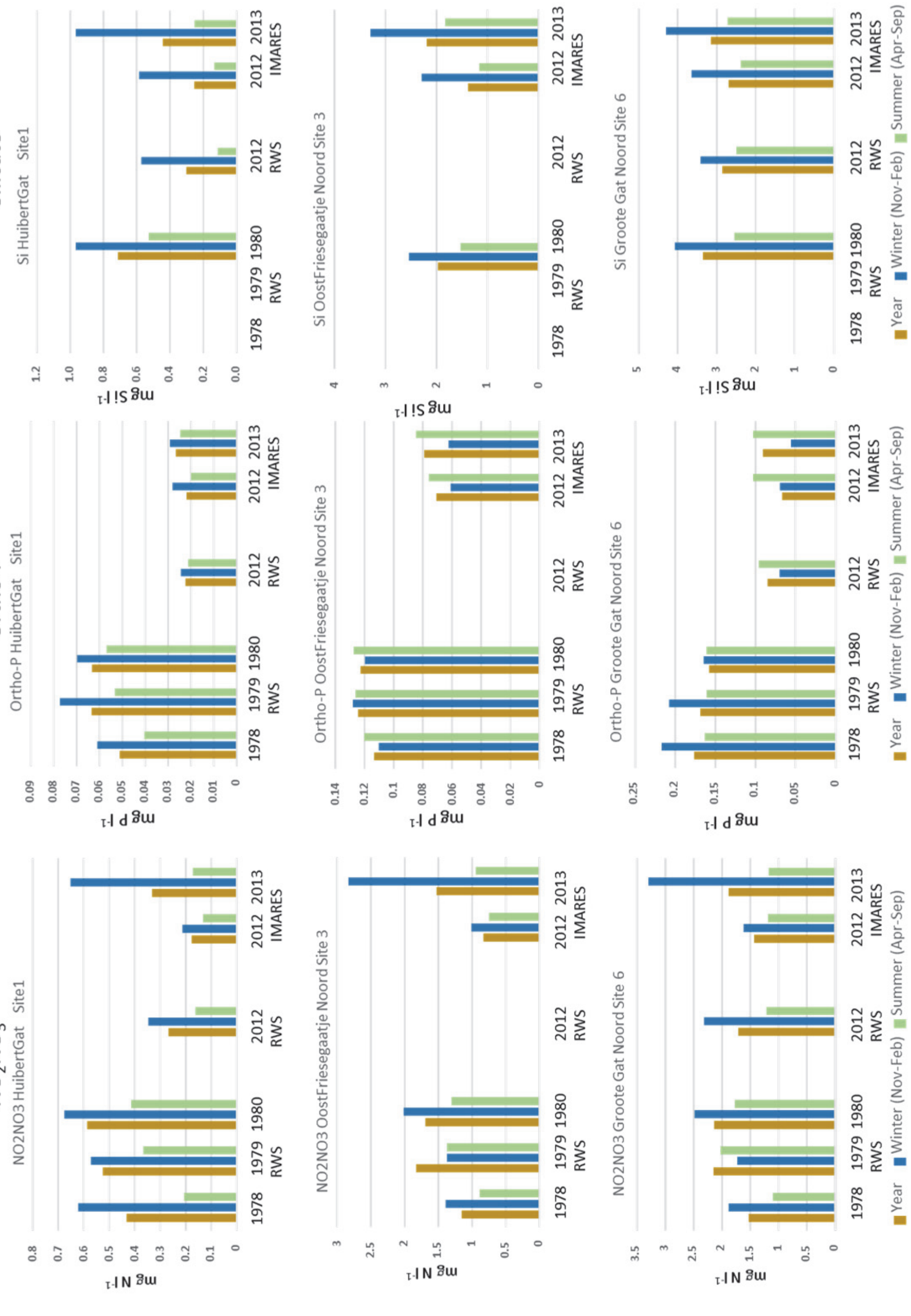


Figure 11 Summary of concentrations of nitrate+nitrite, ortho-phosphate and dissolved silicate as measured by RWS (RWS 2014), and IMARES for sites 1,3 amd 6, in 1978-1980, 2012 (RWS) and 2012 & 2013 (IMARES). Year, winter (months 1,2,11,12) and summer (months 4-9

6.2.3 Suspended matter in the water column and light attenuation coefficients

6.2.3.1 Gradient along the estuary axis

Year-average suspended solids gradients for 2012 and 2013 along the estuary axis are presented in Figure 12. For both years, suspended solid concentrations show a steady increase from the outer areas towards the Dollard. In 2013, there is a clear dip around km 30; that is close to our sampling site 3. This pattern is not (so) obvious in 2012.

6.2.3.2 Interpolated results

Suspended matter contents for both years and the whole estuary are shown in Figure 13 and Figure 14; as a result of direct measurements, as values computed after the relationship found with turbidity and as values after the relationship found with continuous light attenuation measurements.

Highest values found are above 300-400 mg DW l^{-1}, up to an occasional 700 mg DW l^{-1}. Summer values are considerably lower than winter values. For backgrounds on suspended sediment dynamics, see Van Maren et al (2014[b, c]).

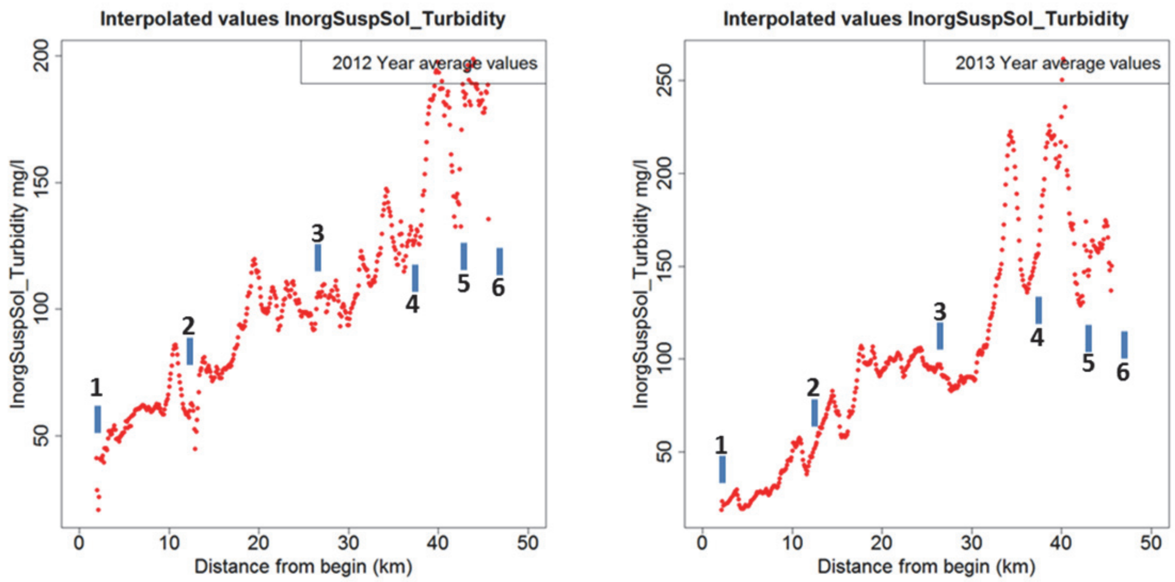


Figure 12 Year-average suspended solids gradient along the estuary axis, based on turbidity data. Left: 2012, right: 2013. Station nrs mentioned; also see Figure 6. Note the different Y-scales.

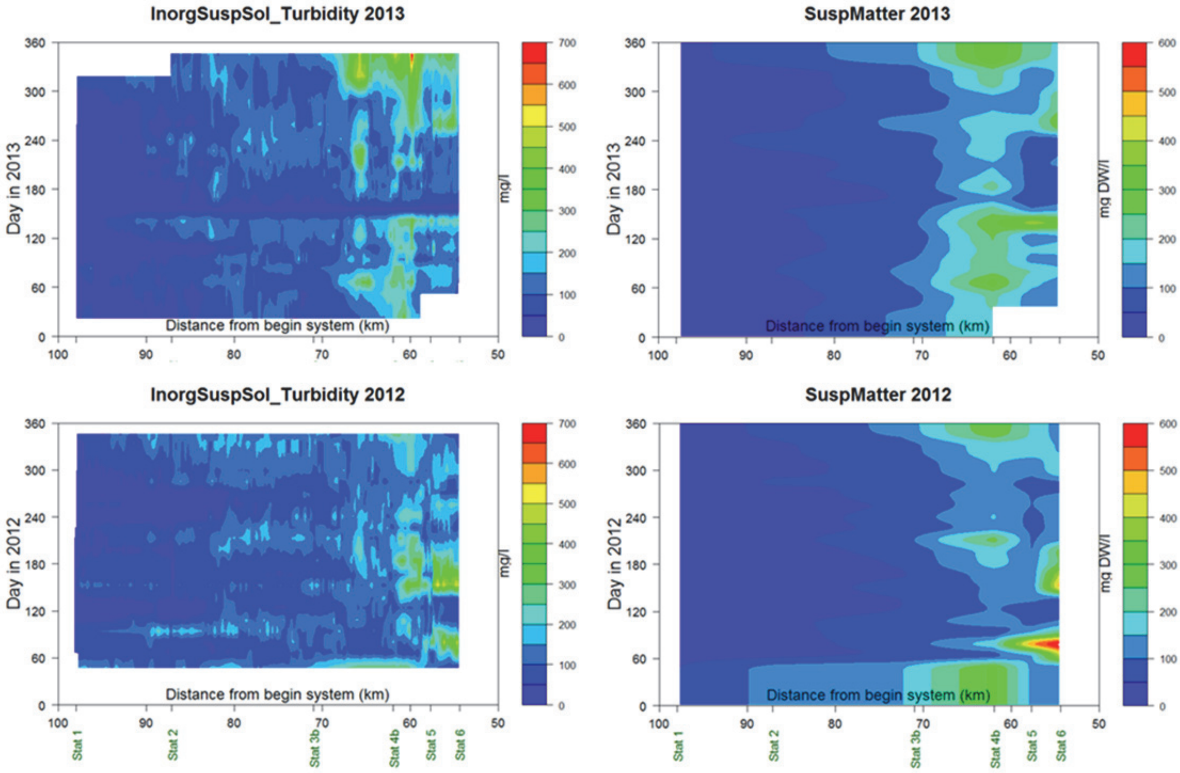


Figure 13 Inorganic suspended solids in the system. Upper: 2012, lower: 2013. Right: as measured at the sampling sites only. Left: as estimated from continuous PocketBox-turbidity data. Distance=0 at Herbrum (DE). Presence of ice in the beginning of 2012 highly affected the interpolated results for the first two months.

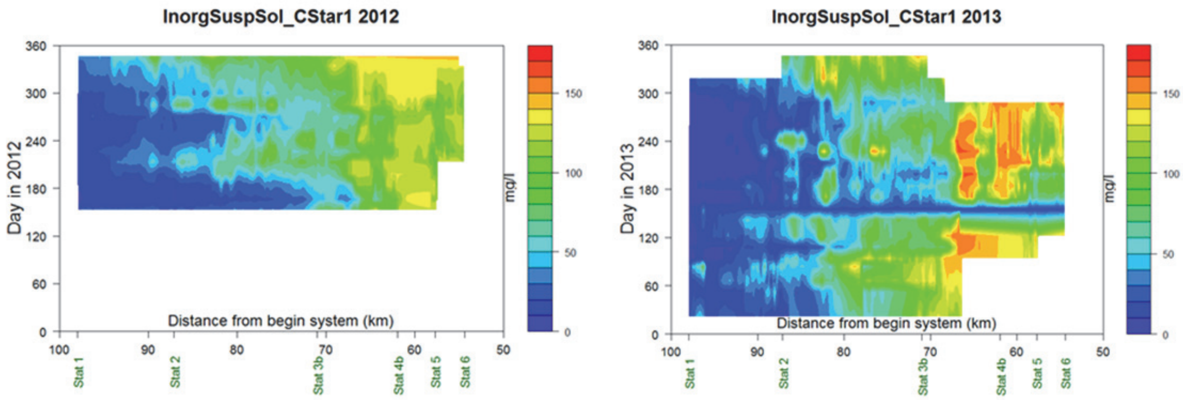


Figure 14 Inorganic suspended solids in the system. Left: 2012, right: 2013. Lower: as estimated from C-Star1 attenuation data (see 4.4.6 & 7.12). Especially C-Star1 –data are missing in the most turbid regions of the system because the sensor reached its upper limit. Mind the different scales. Distance=0 at Herbrum (DE).

6.2.3.3 Comparison with other monitoring data

Suspended matter results compared to older data available are presented as average values in Figure 15.

From our results, the RWS-dataset and Colijns results (Colijn 1984) a few conclusions can be drawn (not trends, but just differences between the data then and those found now):

Site 1 (*Huibertgat Oost*): Suspended matter values found now are slightly lower than Colijns values, and clearly below the 1976-1980 RWS-monitoring values. RWS-2012 values are much lower than IMARES-values. De Jonge et al (2014) mention values of 10 g DM m^{-3} for 1992-1993 and 15-25 g m^{-3} for 2005-2006 and 1975-1976, respectively.

Site 2 (*Oude Westereems*): Suspended matter values found now are slightly higher than values found by Colijn (1984), and in 1992-1993 and 2005-2006 (De Jonge et al (2014): 40 g m^{-3}.

Site 3 (*Oostfriese Gaatje Noord*): Suspended matter values now are above the 1976-1980 values of RWS and Colijn, both the latter have the same value. At the site *Oostfriese Gaatje*, which is between sites 3 and 4, a clear increase could be observed between the ’70-s to the last monitoring year 1995 (RWS-monitoring data, Figure 17). Figure 12 also shows that between site 3 and 4 large differences may occur, and suspended solid concentrations may vary between 100 and 200 g m^{-3}.

Site 4 (*Gaatje Bocht Noord*): the site with the largest differences found. Suspended matter values found (varying between 100 and more than 250 g m^{-3}) now are almost twice of the values found in 1976-1980 (both by Colijn and by RWS); De Jonge et al (2014) mention values up to 200 g m^{-3} in 1992-1993 and about 100 g m^{-3} in 2005-2006. Again, these data indicate that large variations occur.

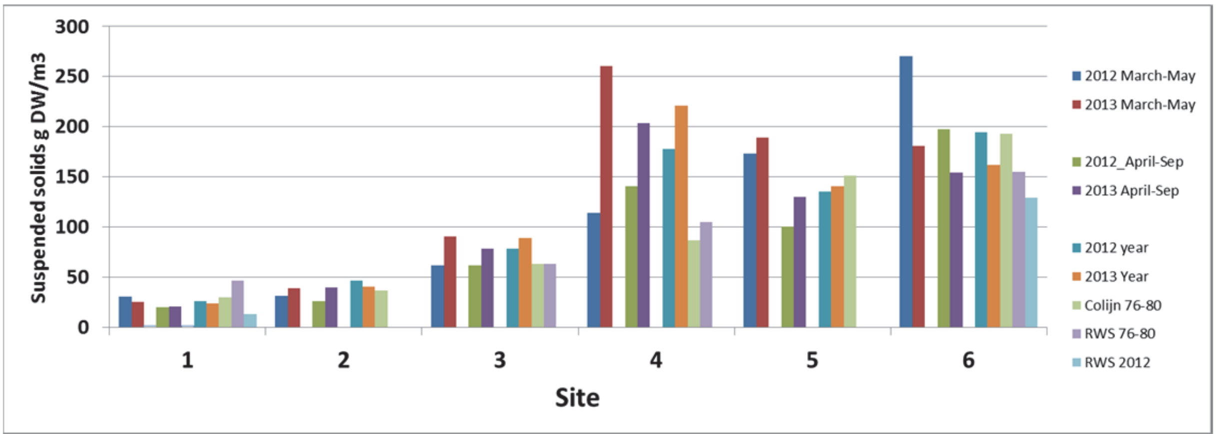


Figure 15 Suspended solids in the estuary. Mean values for the period March-May (MM), April-September (AS) and whole year (Y) for 2012, 2013 and Colijn (1983) results for 1976-1980 (whole period only). RWS monitoring results are included: 2012-data only for the present situation, 1976-1980-data for site 1, 3 and 6, and 1976-1978-data for site 4.

Site 5 (*Mond van de Dollard*): Suspended matter values now are almost the same as those found by Colijn.

Site 6 (*Groote Gat Noord*): Suspended matter values now are almost the same as those found by Colijn and RWS; present RWS-values are lower than the 1976-1980 values.

A seasonal trend can be observed in the RWS-data for Huibertgat Oost, but this trend has disappeared more or less at *Oostfriese Gaatje* and *Groote Gat Noord* (the Dollard site). This phenomenon appears in our data as well (not shown here, see Brinkman et al (2014), section 8.7).

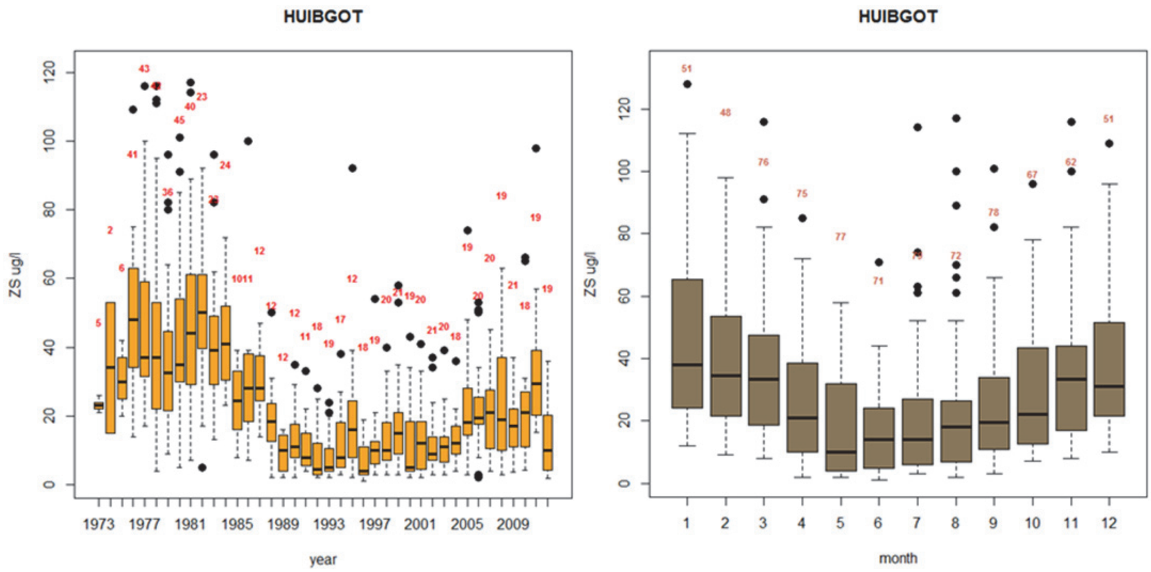


Figure 16 Suspended solids in the estuary at Huibertgat Oost, yearly (left) and monthly (right) averages as boxplots for the period 1975-2011. All data are in mg Dry Matter l^{-1}. See site nr in Figure 5

6.2.3.4 Conclusions

Present suspended matter estuary gradients are well in line with results from Rijkswaterstaat, and show a clear increase from the most North Sea site (Huibertgat Oost) to the Dollard site (Groote Gat Noord).

Compared to observations in the period 1976-1980, very clear differences are found at site 4 (Gaatje Bocht Noord) where the Ems river enters the Ems-Dollard: from 1976-1980 to now suspended matter contents almost doubled there from below 100 mg DM l^{-1} to 170 – 220 mg DM l^{-1}. Comparison with other data (e.g. De Jonge et al, 2014) shows that large variations occur. At site 3 (Oostfriese Gaatje) suspended matter has increased since the 1976-1980 period, but to a lesser extend compared to site 4. At Huibertgat, values now are more or less the same as (or a bit lower than) those found by Colijn, and considerably lower than the 1980 RWS-data. In the Dollard area, changes are much smaller, and it is seems that values are more or less the same as those in the Colijn-period.

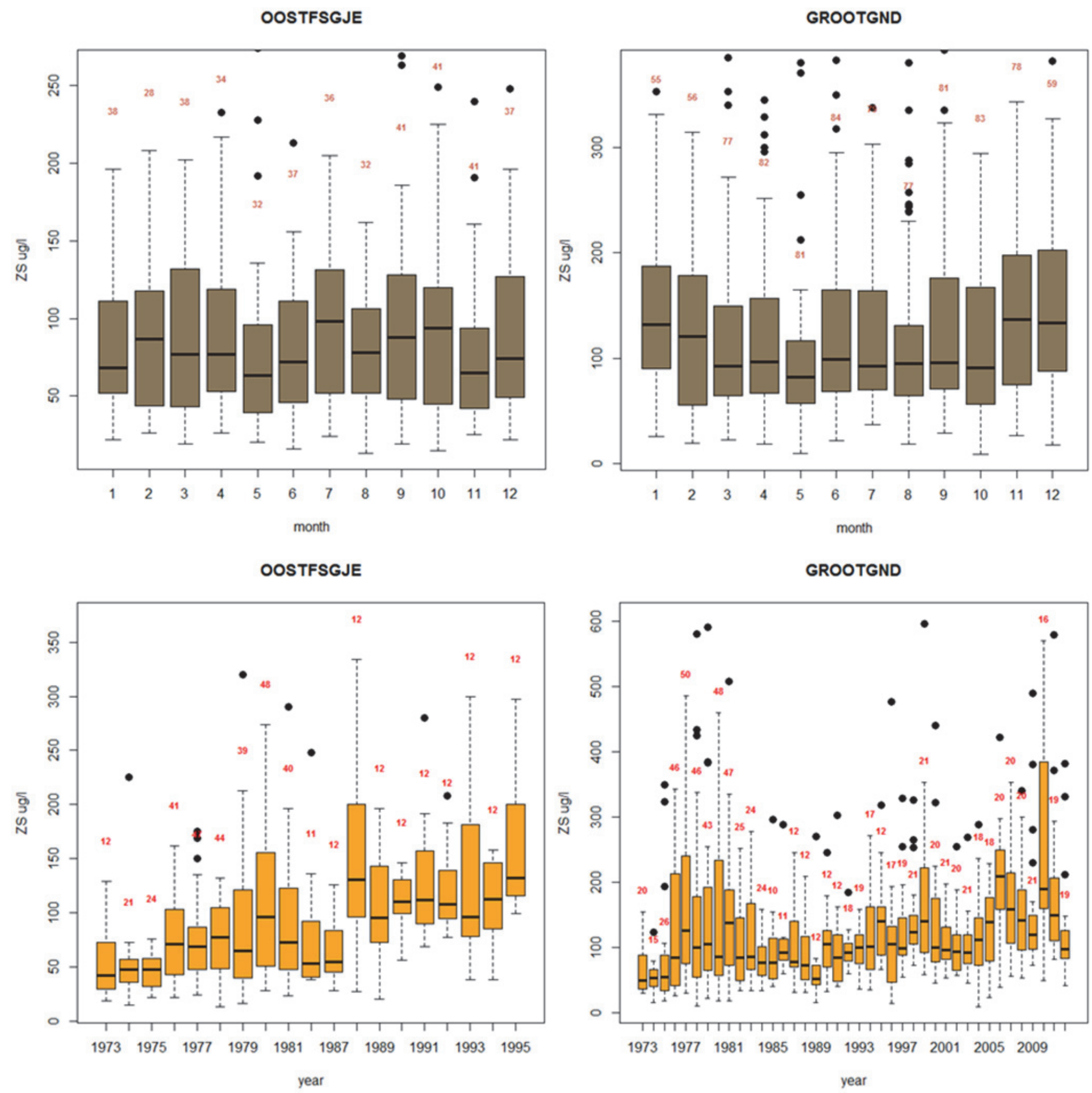


Figure 17 Suspended solids in the estuary, monthly (upper) and yearly (lower) averages as boxplots for the period 1973-1995 (Oost-Friese Gaatje, left) and 1975-2011 (Groote Gat Noord, right, site = station 6). Mind the different Y-axis scales. Source: Waterbase (2014). Nrs give the nr of observations. All data are in mg Dry Matter l^{-1}. Position of the left graphs is roughly between sites 3 & 4 with the left graph closest to the Dollard. Exact sites: see Figure 5.

6.2.4 Light attenuation coefficient in the water column

6.2.4.1 Results

Light attenuation coefficients in the water column determine primary production for a large part. Average values are shown in Figure 18, for all sites and for both years 2012 and 2013. Highest values are found around site 4, which is close to the spot where the Ems river flows into the estuary. Also at this site, differences with values found by Colijn (1983) are largest. Extinction values found now are

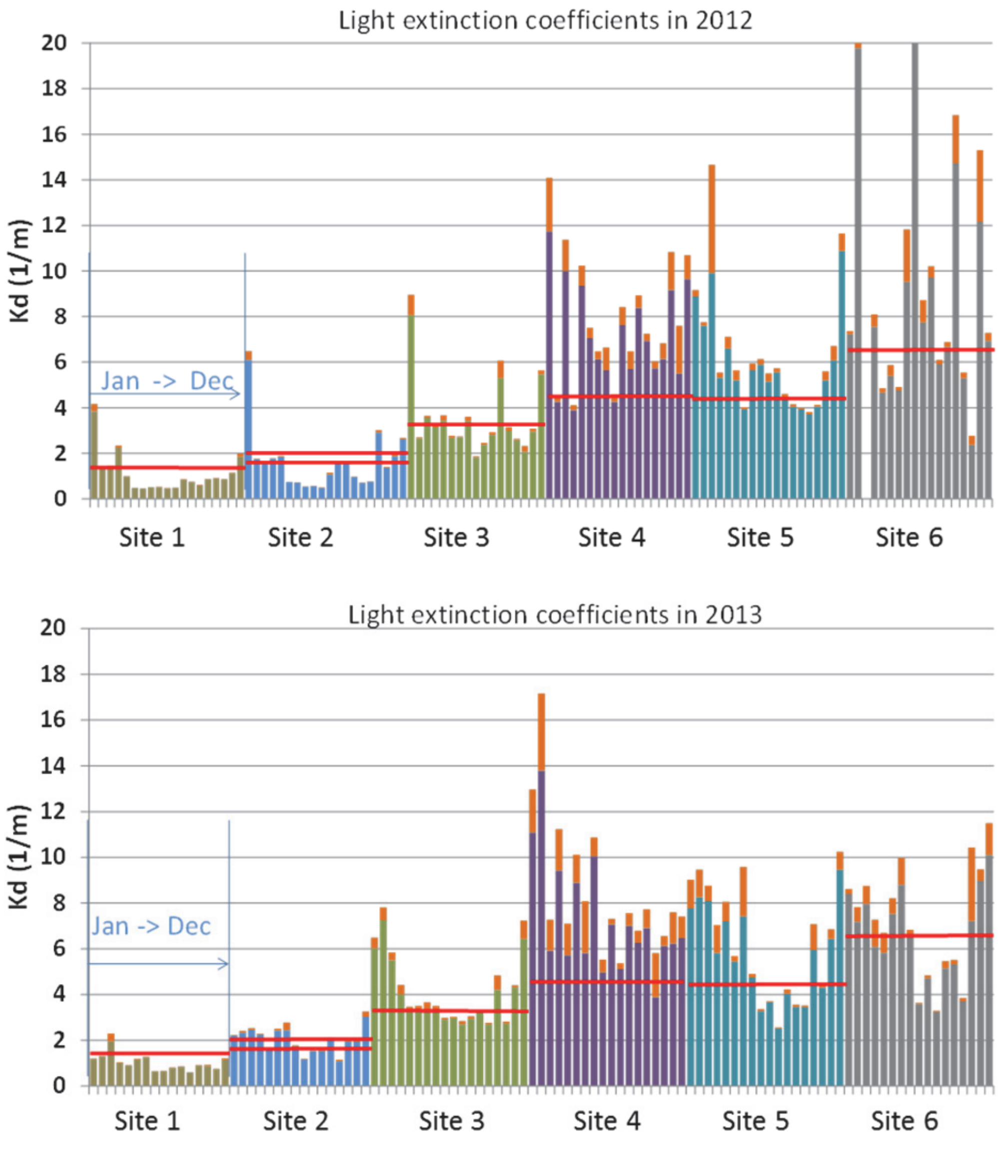


Figure 18 Summary of light extinction coefficients found in the Ems-Dollard area. Upper: 2012, lower: 2013. Data are grouped per station (1->6), and from January (most left per station), to December (most right). Orange bars denote standard deviation of the results (follows from the parameter fit procedure). Red horizontal lines show average values as found by Colijn (1983).

larger than Colijns values. At the outer station (1 (and to a lesser extend also station 2) extinction coefficients found now are lower than those reported by Colijn (1983).

6.2.4.2 Gradient along the estuary axis

Gradients of the light attenuation coefficient along the estuary axis are shown in Figure 19. A maximum is reached around km 35-40, that is half-way between sites 3 and 4 until site 4 (Figure 6).

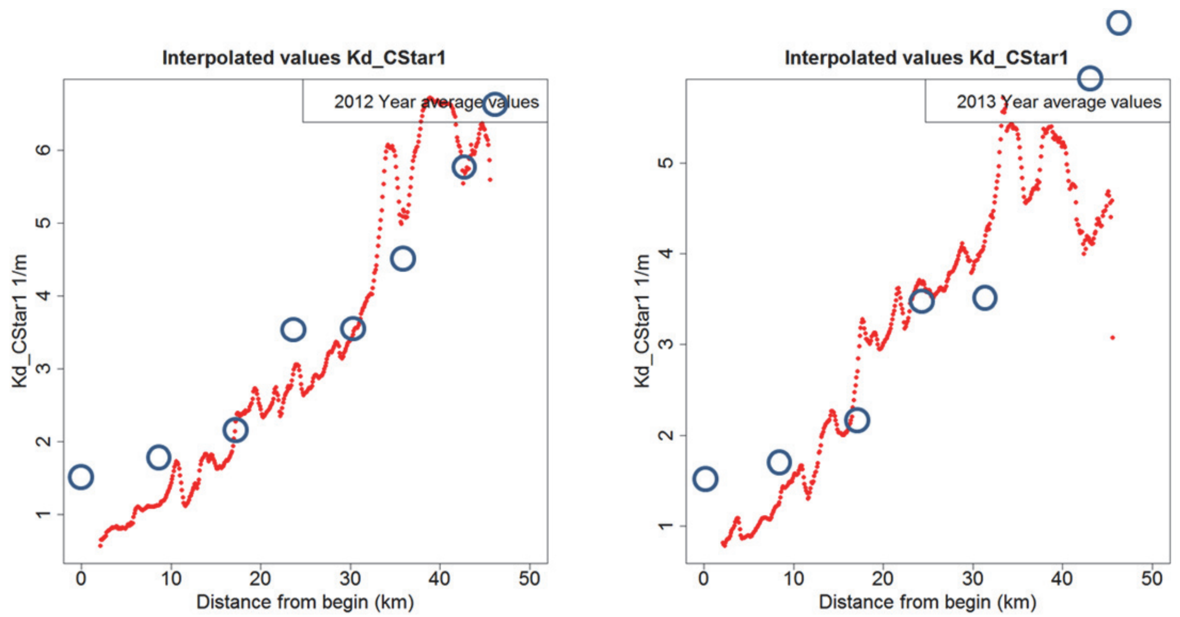


Figure 19 Year-average gradient of the light attenuation coefficient k_d along the estuary axis, based on C-Star1 data (continuous light attenuation monitoring, see sections 7.11 and 8.17 of the full data report (Brinkman, 2014). Circles denote results by Colijn (1983) as average for the years 1976-1980. For distances (starting at the outer station 1), see Figure 6.

Suspended matter is the most important factor determining light attenuation, together with yellow substance; the latter is especially important in the inner areas. Thus, these results are similarly shaped as those for suspended matter (Figure 12).

6.2.4.3 Comparison with Colijns data

Results reported by Colijn (1983) are plotted as averages for the years 1976-1980 in Figure 19. If a structural difference exists, then it is in the outer areas, where Colijn found a larger light attenuation than we did now. This is in agreement with the RWS –data on suspended matter, their monitoring results gave higher values for the end 70's than for the present years (Figure 16).

Colijn (1983) found a relationship between suspended matter content (SPM) and the light attenuation coefficient (k_d), giving $k_d = 0.4 + 0.04 \cdot SPM$. We checked this relationship as well, and found $k_d = 0.044 \cdot SPM$ in 2012 and $k_d = 0.037 \cdot SPM$ in 2013. With an intercept allowed, it followed that $k_d = 0.73 + 0.038 \cdot SPM$ and $k_d = 0.99 + 0.031 \cdot SPM$ in 2013. Since most k_d-values are far above 1, the differences in intercept found are not striking. This relationship changes a bit if we include yellow substance in this relationship; and it appeared that yellow substance (as did coloured organic matter) explained better the k_d-values at high contents of suspended matter. See section 7.9 of the full data report (Brinkman 2014).

6.2.4.4 Conclusions

The relationship we found between suspended matter and light attenuation coefficient appears to be similar to the one Colijn (1983) found. This is as expected since the relationship depends on the properties of suspended matter, which most likely did not change since the seventies. Most light attenuation values we found in the estuary (the transect from sea side up to the Dollard) are comparable to those described by Colijn (1983). Colijn found higher values for station 1 (North Sea side), and around the 35 km site (Figure 19) values were higher in 2012 and 2013 compared to the seventies. This is in line with the elevated suspended solid concentrations mentioned in the previous section.

6.3 Abiotic characteristics of the sediment top layer

6.3.1 Light attenuation in the sediment

To compute benthic primary production it was necessary to compute the light profile in the sediment top layer. This was done based on the relationship between light attenuation in the water column and the silt content (section 6.5.3). Next, sediment composition (silt, sand, water) was estimated based on the Rijkswaterstaat Wadden Sea sediment atlas (RIKZ, 1998), a few corrections based on Zwarts (2004) and complementary data from Brinkman & Van Raaphorst (1983). This procedure is completely described in section 8.18 of the full data report. Estimated values are presented in Table 3.

Table 3 Sediment attenuation coefficients kd (m^{-1}) computed from sediment composition data (Malvern-data, converted following the equations of Zwarts (see section 8.18 in the full data report). Solids= total density of sediment; Silt= contribution of Silt (<63 µm) to total density, Sand= contribution of Sand (>63 µm) to total density, Kd silt = contribution of Silt to total extinction coefficient kd_all, Kd sand= contribution of sand to kd-all. Kb_min Colijn, Kd_max Colijn and Kd_avg Colijn give min, max and average of Colijns estimates.

Station	Solids g/cm3	Silt g/cm3	Sand g/cm3	Kd silt m^{-1}	Kd sand m^{-1}	kd_all m^{-1}	Kd_min Colijn m^{-1}	Kd_max Colijn m^{-1}	Kd_avg Colijn m^{-1}
1	1.53	0.038	1.5	1707	5969	7677	5470	5600	5535
2	1.51	0.045	1.5	2040	5863	7903	7230	25270	15580
3	1.56	0.026	1.5	1152	6145	7297	9090	9090	9090
4	1.45	0.067	1.4	3008	5546	8554	15480	15480	15480
5	1.15	0.161	1.0	7253	3970	11223	5800	5800	5800
6	0.56	0.224	0.3	10099	1328	11428	32050	32640	32345

6.4 Chlorophyll-a and primary production in the water column

6.4.1 Chlorophyll-a

6.4.1.1 Present 2012-2013 data

Chlorophyll-a content was measured in different ways, which gave a possibility to check the quality of the results. Chlorophyll-a values for each site and sampling day were inter- and extrapolated to cover the whole system and the whole year, results are presented in Figure 20. Chlorophyll-content was substantially higher in 2013 than in 2012; in both years highest values were recorded in late spring (around day 120 = end of April).

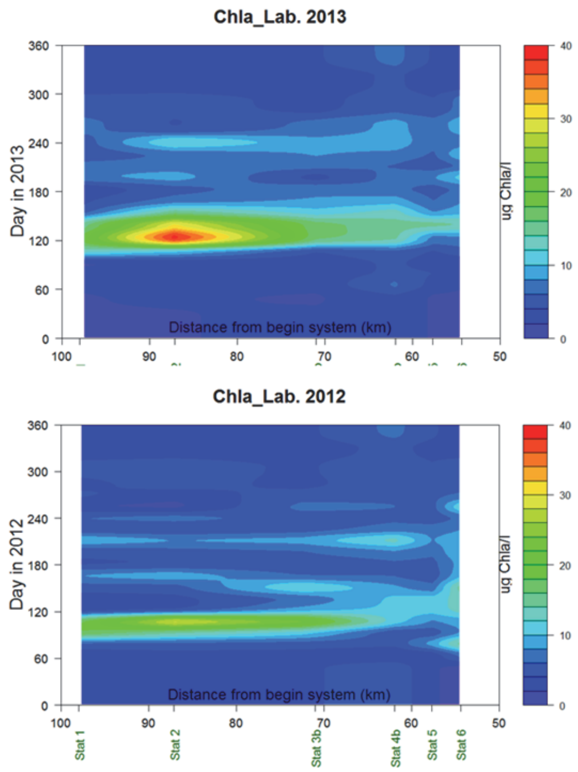


Figure 20 Chlorophyll-level plots. Results from laboratory fluorometer analyses. Distance=0 at Herbrum (DE).

6.4.1.2 Gradient along the estuary axis

The average chlorophyll-a gradient along the estuary axis is presented in Figure 21. For both years 2012 and 2013 an increase in chlorophyll content towards the Dollard area was found. There is a clear dip around km 30 in 2013; that is close to our sampling site 3. This pattern is not present in 2012. It is also clear from Figure 21 that in 2012 chlorophyll-a content especially is low at the outer side of the estuary, between km 0 and 20-25 from sampling site 1 at Huibertgat.

6.4.1.3 Previous RWS data

Monthly monitoring data for three sampling sites (Waterbase, 2014) are shown in Figure 22, including present year-average values. For *Groote Gat Noord* (Dollard area), values in 2012 and 2013 are not very different from those in previous years. At *Huibertgat Oost* values are below most of the previous years, although the last few years (and 1991) values are about the same. For *Oostfriese Gaatje*, values now are below those found in the period 1975-1995, with years 1987-1989 as exception.

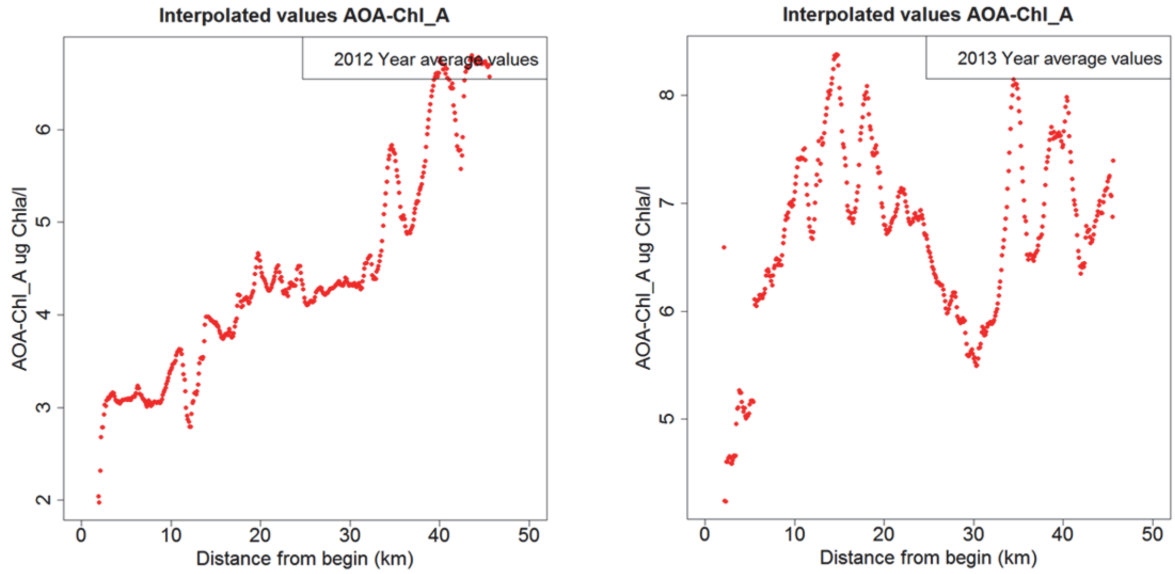


Figure 21 Year-average chlorophyll-a gradient along the estuary axis, based on continuous AOA-measurements. For distances (starting at the outer station 1), see Figure 6.

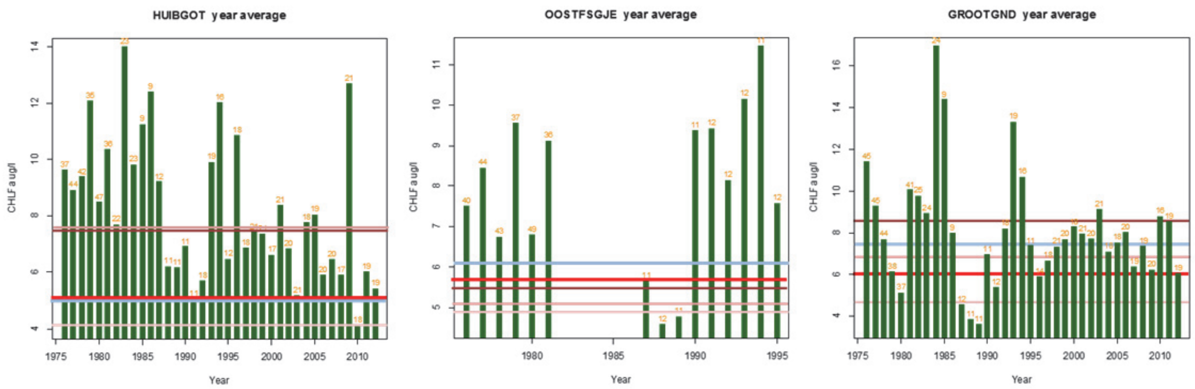


Figure 22 RWS results: year average chlorophyll-a concentrations (µg chla l^{-1}) for Huibertgat Oost (1975-2012), Oostfriese Gaatje (1975-1995) and Groote Gat Noord (1975-2012). Numbers give the number of observations. Thick lines: blue-grey line: average value found now for 2012, red line: average value found now for 2013. Thin lines: light brown-red: Colijn 1978, medium brown-red: Colijn 1979, dark brown-red: Colijn 1980. The RWS-monitoring data for Chlfa contained three extremely large values for 1996, which were considered as typo's and were removed from the data set.

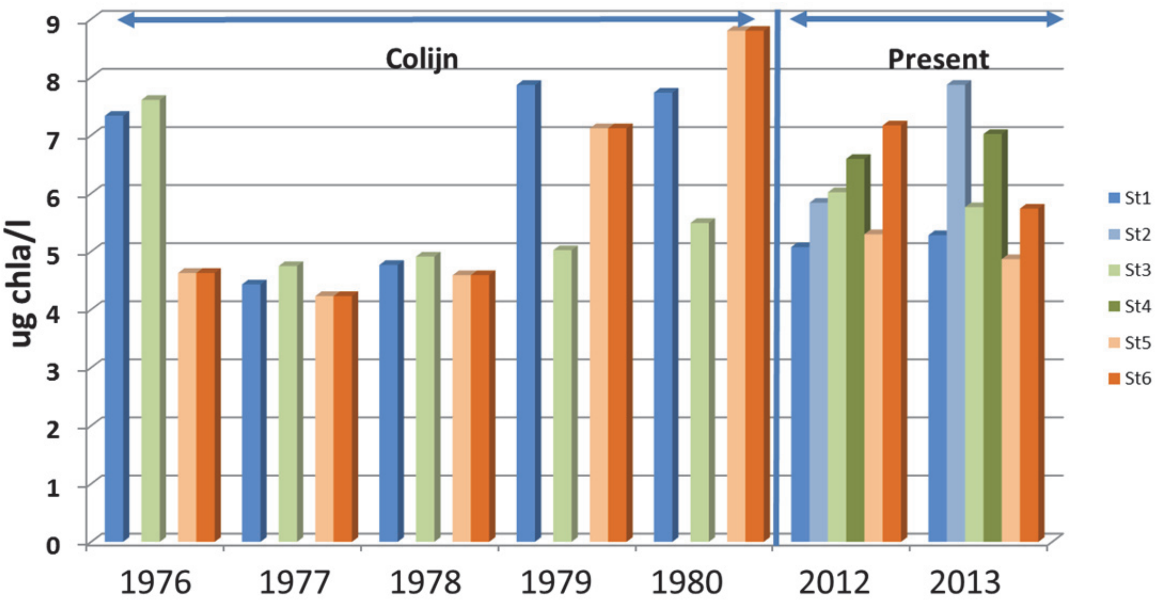


Figure 23 Chlorophyll-a in 2012 and 2013 (right part of the graph) and previous data from Colijn (1983), for each compartment. Note that for Colijns data, the same values were taken for compartments 5 and 6. In 1976 and 1977, Colijn only sampled during the second half of the year; stations 2 and 4 are missing in his data.

6.4.1.4 Comparison with 1976-1980

Finally, a comparison with results of Colijn (1983) can be made. In Figure 23 results for 1976-1980 and 2012-2013 are summarized as year-average values. In 1979 and 1980, Colijn found higher values than we found now for 2012 and 2013 for sites 1 and 6 (dark blue and red+orange bars respectively in Figure 23Figure 22), the opposite occurred for site 3 (light green bars in Figure 23Figure 22). Taking 1978 into account (and 1979-1980), it seems that the data found now fit into the rage found by Colijn. From the RWS-data (Figure 22) it can be concluded that in the outer area (Huibertgat Oost), chlorophyll-a concentrations show a negative trend from the late seventies onward, but this trend was not observed in the Dollard area (Groote Gat Noord).

Generally, we conclude that chlorophyll-a concentrations hardly changed in the Ems-Dollard area, with a possible exception for the outer area, where contents decrease slightly; this is according to the RWS-data trend.

6.4.2 Phytoplankton groups in 2013

Koeman and Bijkerk (Wanink et al, 2014) give a summary of the contribution of main algal groups to total biovolume, this is copied and shown in Figure 24. From this, it can be seen that diatoms are very dominant in the system. Next to diatoms, green algae appear and only now and then *phaeocystis* occurs. Blue-greens and dinoflagellates hardly appear in the Koeman & Bijkerk results.

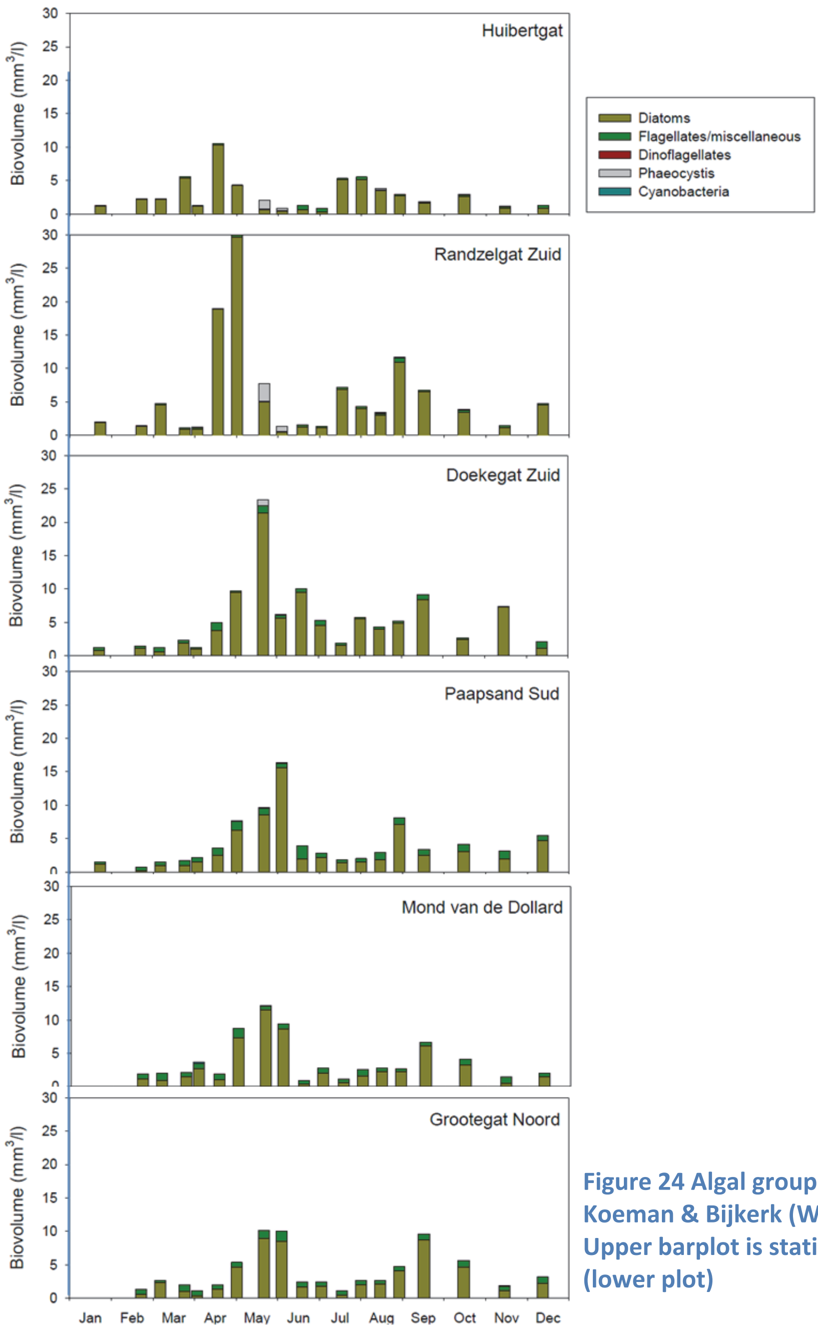


Figure 24 Algal groups identified in 2013 by Koeman & Bijkerk (Wanink et al, 2014, fig 3). Upper barplot is station 1, down to station 6 (lower plot)

Figure 3 Developments in bio-volume per functional group of autotrophic algae during 2013.

Colijn (1983) analysed species composition in 1980 at his sites 1 and 3 (close to present stations 1 and 2). He found diatoms as major phytoplankton species, and he also found considerable numbers of *Phaeocystis* at both sites in May and june 1980 (> 1000 cells ml^{-1}). *Phaeocystis* is an alga with a well-known high productivity per unit of biomass (Schoemann et al, 2005); in 2013 found to have some (but not a major) contribution to phytoplankton biomass in May at sites Huibertgat (site 1) and Randzelgat Zuid (site 2).

6.4.3 Pelagic primary productivity, or: chlorophyll-a specific maximum production

6.4.3.1 Results

The carbon uptake rate per unit of chlorophyll, depending on light intensity, was measured. As a results also the maximum productivity (at each sampling site) is known. This is the *potential* production: the algae can produce this under optimal conditions. It is not the *real* production since that is also determined by the chlorophyll-a content in the water column, the solar radiation and the water column light attenuation coefficient (thus: the water column light climate). The computed field primary production (the *real* production) is presented in section 6.10.

Maximum productivity values are presented as contour plots in Figure 25.

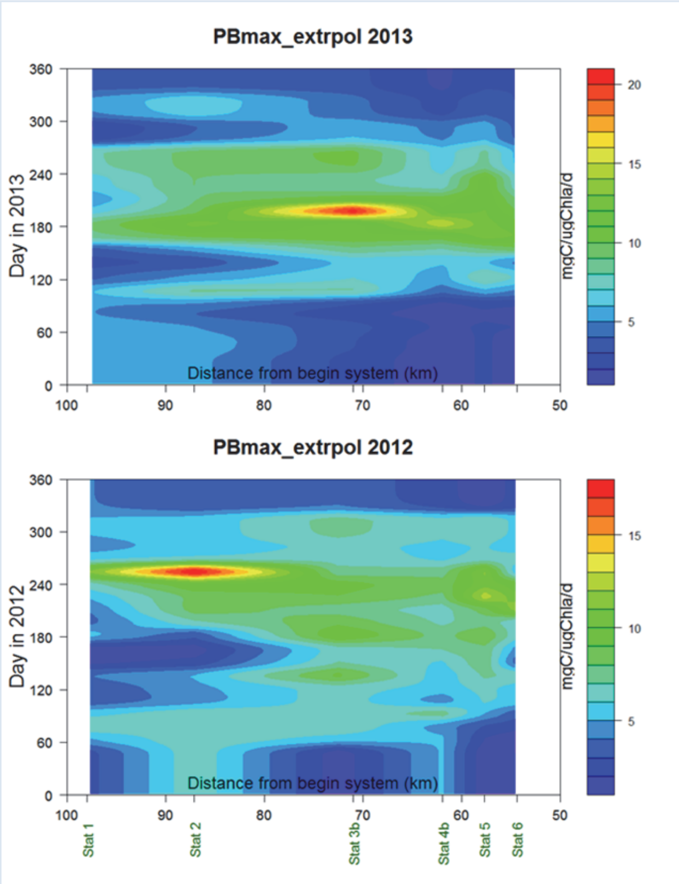


Figure 25 Contour plots for PBmax, the maximum productivity of the incubated samples. Unit: mg C (mg Chla $l^{-1})^{-1}$. Left: 2012, right: 2013. Mind the different scales for both figures.

6.4.3.2 Relationship with nutrients and temperature

We checked relationship between the temperature corrected maximum potential production (PB_{max}, mg C (mg Chla $l^{-1})^{-1}$) with nutrient concentrations. Temperature corrections are computed following Eppley's equation

$$PB_{max}(Tcorr) = PB_{max}/F(Temp) \quad \text{(mg C (mg Chla } l^{-1})^{-1}) \qquad (6.1)$$

where F(Temp) gives the temperature effect on the primary productivity (Eppley, 1972):

$$F(temp) = 0.59 * e^{(0.0633 \cdot Temp)} \quad (-) \qquad (6.2)$$

By doing this it is avoided that correlations between PB_{max} and nutrient contents are obscured by temperature effects. Relationship (6.2) comes close to a standard Q_{10}-factor of 2 (every 10 degrees temperature increase implies a doubling of the rate).

We checked possible relationships between $PB_{max}(Tcorr)$ and the observed silicate, phosphate, and nitrate concentrations, including Monod-like relationships like

$$PB_{max}(Tcorr) = BB * \frac{NUT}{K_N + NUT} \quad (\text{mg C (mg Chla l}^{-1})^{-1}) \qquad (6.3)$$

with BB as a maximum productivity, K_N is a Monod-coefficient and NUT the nutrient concentrations observed at the sampling site (see e.g. DiToro, 1971). We did not find a relationship with phosphate, silicate or nitrate. We also tested an alternative formula where all three nutrients are involved, taking the multiple of all three Monod-terms, and one where we took the minimum of the three Monod-terms. In neither case, a relationship with nutrient concentrations could be detected. This does not mean that there is no relationship between nutrient concentrations and primary production in the field, but just that the ^{14}C-uptake in the laboratory could not be related to the ambient nutrient concentrations.

6.4.3.3 Maximum productivity per unit of carbon biomass

Based on estimated C-content of phytoplankton (see the full data report for details, Brinkman, 2014), the observed carbon uptake rates can be related to the phytoplankton biomass (as mg C l^{-1}); the ratio (C uptake rate (mg C l^{-1} d^{-1})/ biomass (mg C l^{-1}) gives the first order uptake rate constant μ_{max} (d^{-1}) (or: specific maximum productivity; there are more terms possible). Results for 2012 and 2013 are shown in Figure 26 and Figure 27. Note that these are gross terms: respiratory losses are not part of the results.

Values reach up to over 5 d^{-1}, indicating that potentially a very rapid ^{14}C-uptake is possible; as a rough average, most values vary around 3 (d^{-1}).

Because of the natural loss processes (respiration, predation), net growth rates are considerably lower; but this is not a topic in this report.

6.4.3.4 Absorption ratios as an indication of nutrient or light growth limitation

An initial idea was, based on Riegman & Rowe (1994), that the ratio of spectrophotometric absorption at 480 nm and at 665 nm wavelength would give information on the importance of nutrient limitation of phytoplankton productivity. However, we had to conclude that now this method did not provide useful information; see section 8.13 in the full data report (Brinkman, 2014).

6.4.3.5 Conclusions

Potential gross productivity of the Ems-Dollard phytoplankton is high; the results provide the

Figure 26 Specific maximum productivity (or: first order gross ^{14}C uptake rate constant, P_{max_spec}) of Ems-Dollard phytoplankton in 2012; P_{max} from incubations divided by the concentration of phytoplankton carbon present in the water samples. Phytocarbon content was estimated by assuming a phytoplankton C : chlorophyll-a- ratio of 38 (mg C/mg chla). Mind the different Y-axis scales. Red results: corrected for temperature, blue: uncorrected.

parameters needed to compute field production from chlorophyll-a data, solar radiation and light attenuation data for the water column (section 6.11). Nutrient effects on ^{14}C-uptake could not be detected, but one must keep in mind that conclusions on nutrient effects are hard to draw from the incubations performed. Dynamic model computations, where mass budgets of nutrients are incorporated, are needed to further elucidate the role of nutrients in the primary production of the system.

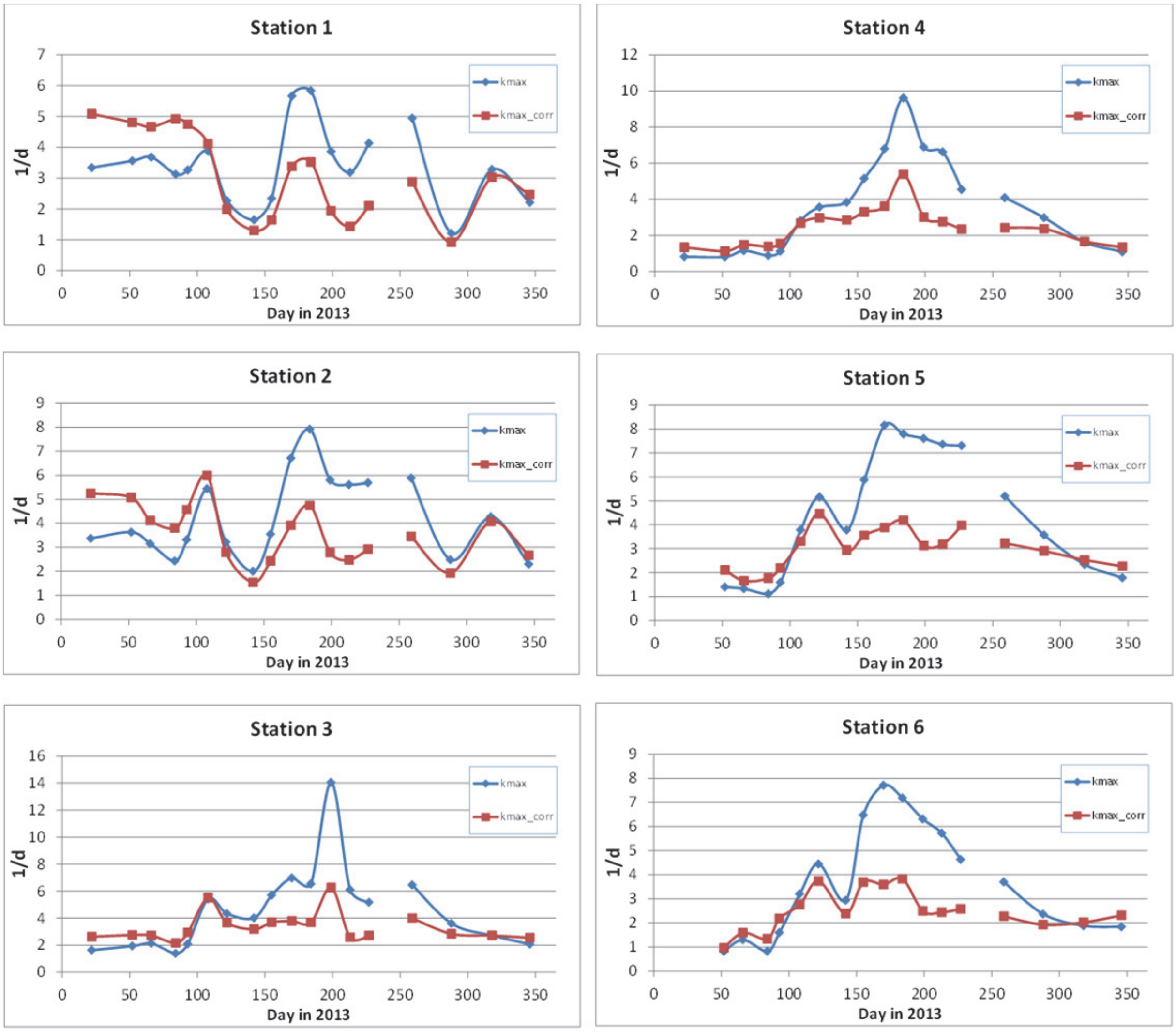


Figure 27 Specific maximum productivity (or: first order gross ^{14}C uptake rate constant, P_{max_spec}) of Ems-Dollard phytoplankton in 2013; P_{max} from incubations divided by the concentration of phytoplankton carbon present in the water samples. Phytocarbon content was estimated by assuming a phytoplankton C : chlorophyll-a- ratio of 38 (mg C/mg chla). Mind the different Y-axis scales. Red results: corrected for temperature, blue: uncorrected.

6.4.4 Gross pelagic primary production in the system

6.4.4.1 Results

The primary productivity (what can be produced per unit chlorophyll-a, depending on light availability, presented in the previous section) together with the known water column light climate and the chlorophyll-a content (sections 6.4 .. 6.6) gives the data needed to calculate the real primary production in the system. The water column light climate for each site was calculated for each day

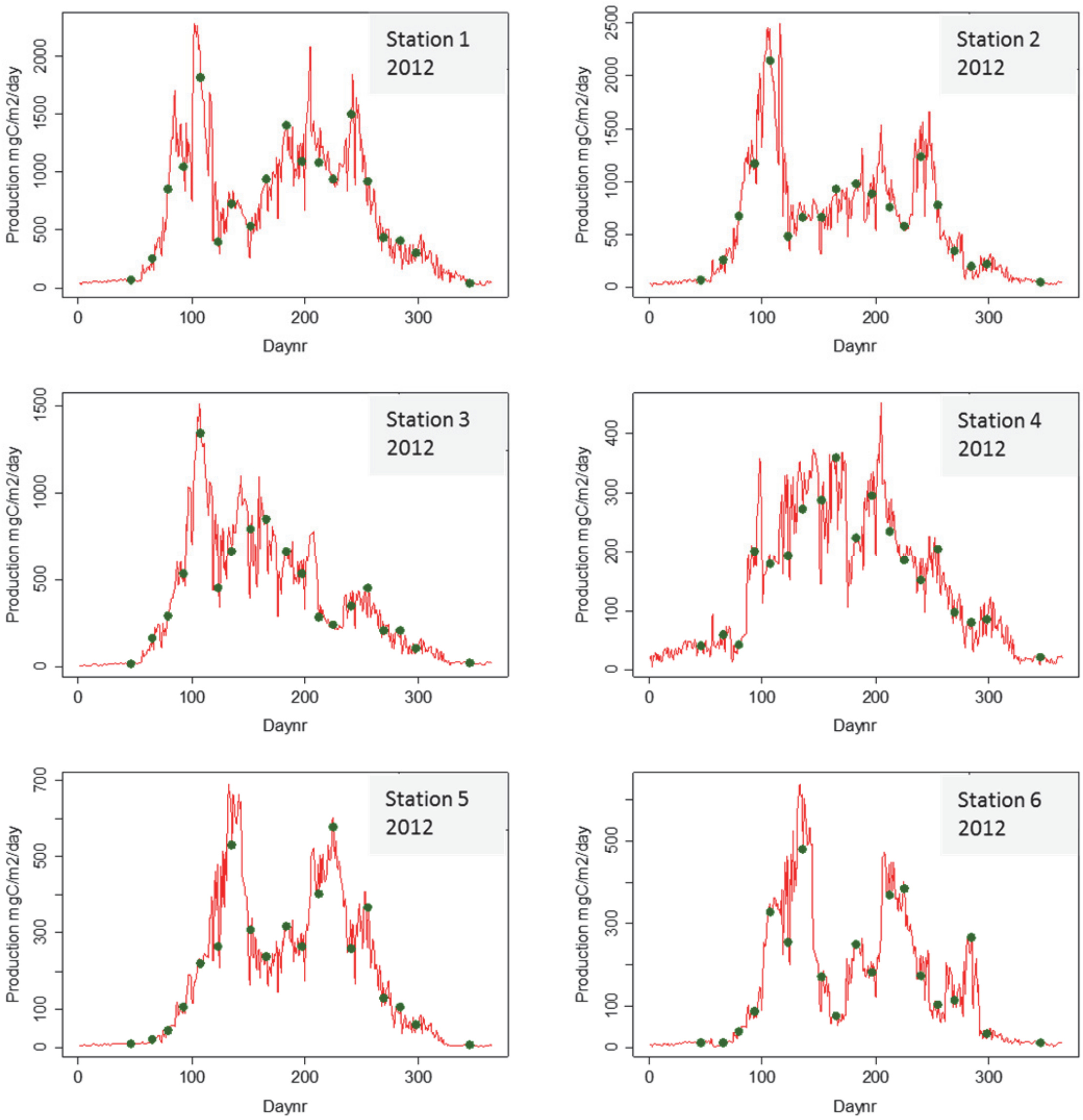


Figure 28 Computed gross primary production (mg C m^{-2} d^{-1}) for all stations in 2012, during high water in channels. Expressed as mgC m^{-2} day^{-1}. Chlorophyll-a, K_d- and Eilers-Peeters values all interpolated following a moving average method. K_d-values used are those from the IMARES-measurements. Dots mark the sampling days.

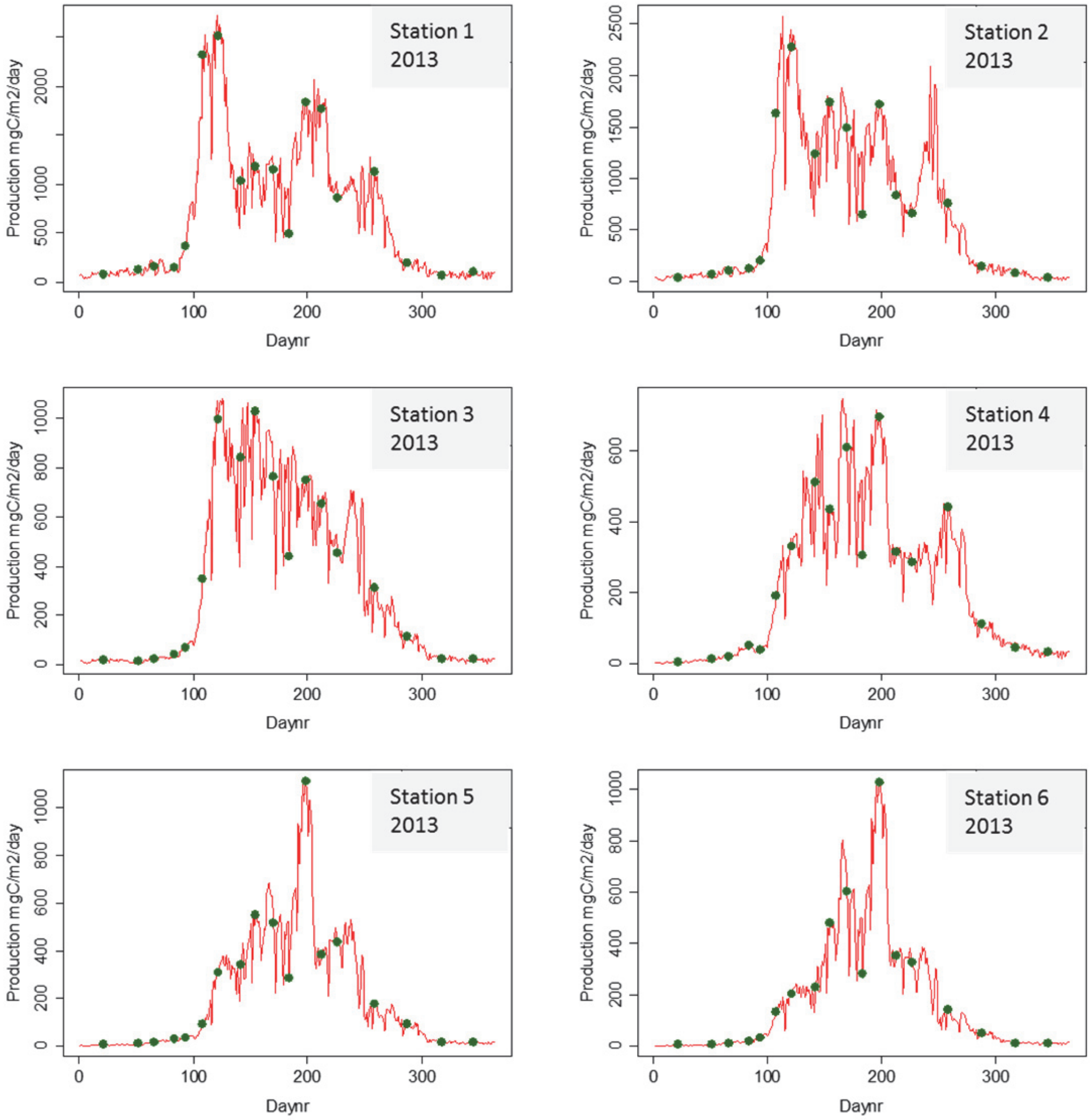


Figure 29 Computed gross primary production (mg C m^{-2} d^{-1}) for all stations in 2013, during high water in channels. Expressed as mgC m^{-2} day^{-1}. Chlorophyll-a, K_d- and Eilers-Peeters values all interpolated following a moving average method. K_d-values used are those from the IMARES-measurements. Dots mark the sampling days.

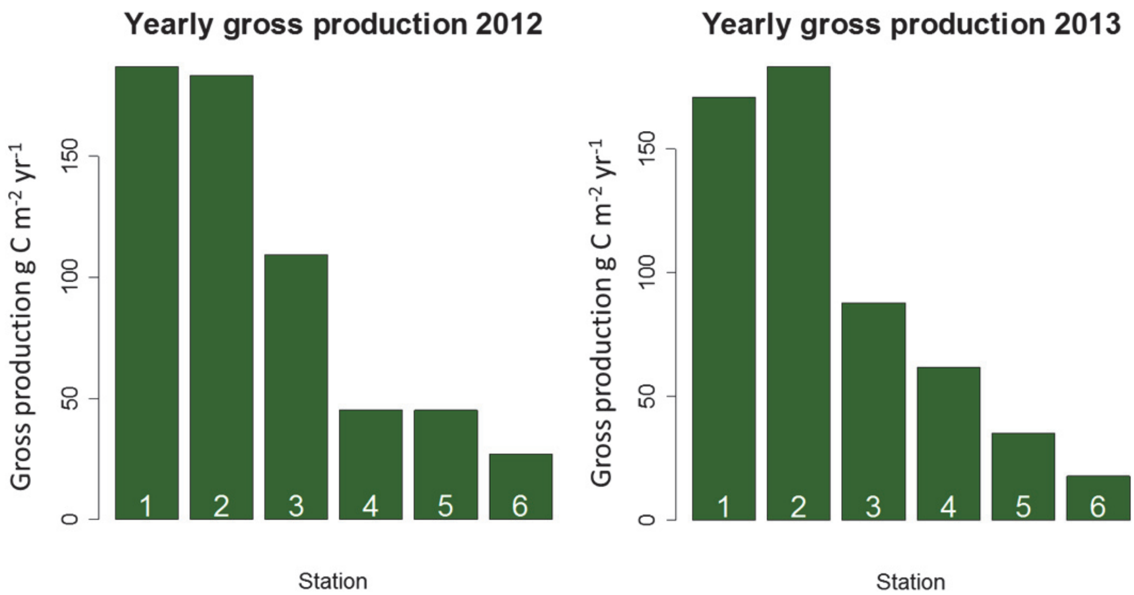


Figure 31 Computed yearly compartment integrated gross production in 2012 and 2013 in each of the six compartments (see Figure 16), expressed as g C m-2 y-1. Average water level assumed; radiation data used are those for 2012 and 213, respectively. For detals see the full data report (Brinkman et al, 2014), chapter 9.

of the years 2012 and 2013. This was also done for the chlorophyll-a content. With hourly irradiance data and known water column depth, primary production at each site was computed; results for 2012 and 2013 are plotted in Figure 28 and Figure 29. Lowest production per m^2 is found at station 4, and highest at both outer stations 1 and 2. The sum for each compartment, taking compartment area, depths and emersion times into account, is presented in Figure 31. Most primary production occurs in both outer compartments 1 and 2; the inner compartments 4-6 (the Dollard area and the transition part between Dollard and Eems) show a minor contribution to the overall system primary production. Gross primary production summed for the whole Ems-Dollard estuary is presented in Figure 30.

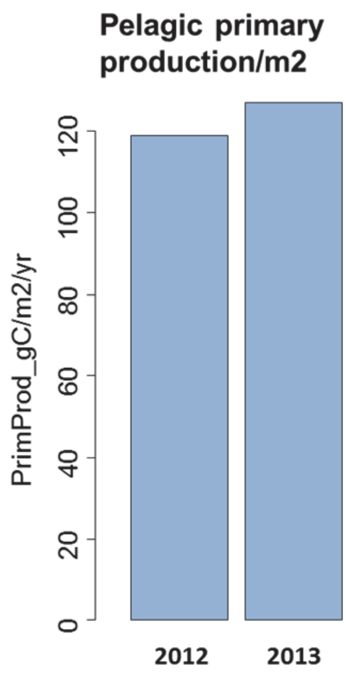


Figure 30 System primary production in 2012 and 2013, tidal flats and emersion period included

6.4.4.2 Primary production using 1978-1980 radiation data

When comparing present results with those by Colijn (1983), first different weather conditions (=solar radiation) have to be taken into account. With present production parameters, but radiation data for 1978-1980, primary production was computed as well. It was found that that different solar radiation conditions between 2012-2013 and 1976-1980 cannot explain for more than 5% the differences between the 1978-1980 period and the present results.

6.4.4.3 Contribution of each compartment to total system production

The data presented above are expressed as production per m^2. In Figure 32 absolute gross primary production is presented per compartment. It shows that the outer compartment 1 is most important for the system total, and the water column of the three inner compartments are hardly contributing to the overall system production. De Jonge (pers comm) says: the outer compartment is the part fuelling the whole estuary. This partly depends on the way hydrodynamics allow the produced phytoplankton to be transported into the deeper parts of the estuary, but the fact remains that in compartment 1 (and to a much lesser extend 2 and 3) the by far largest production occurs.

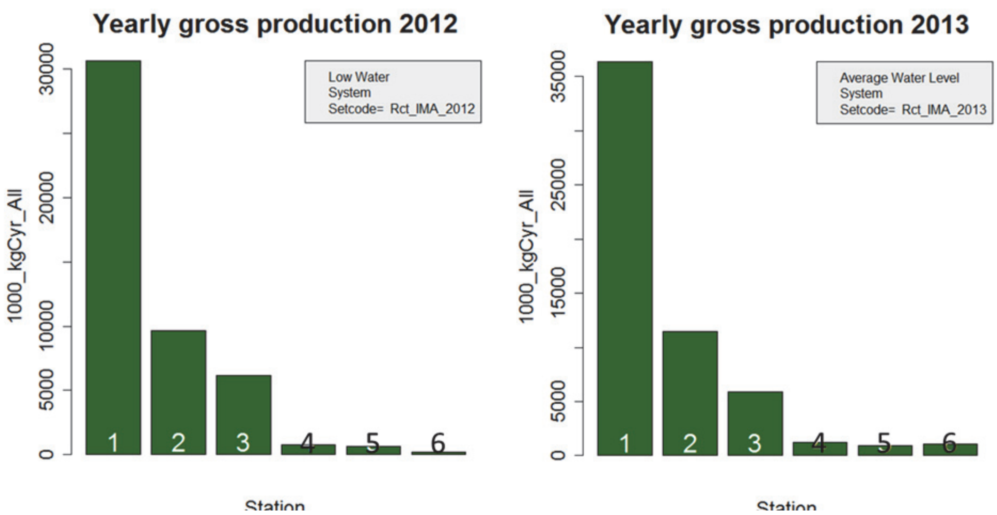


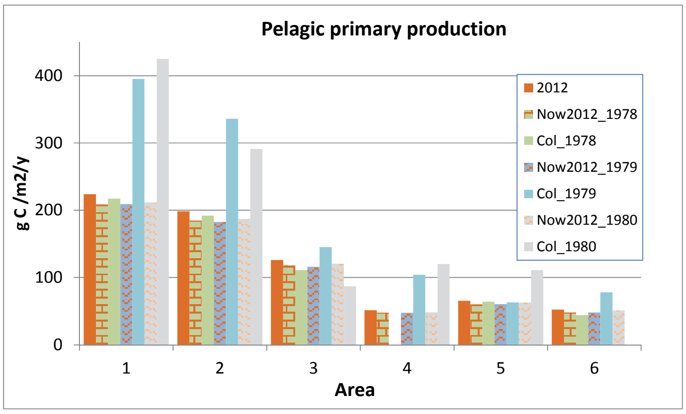
Figure 32 Absolute pelagic contribution of each of the six distinguished compartments to the whole Ems-Dollard estuary production.

6.4.4.4 Comparison with Colijn (1983)

Pelagic primary production data are mainly available from Colijn (1983). Other sources (Rijkswaterstaat, 1985; Essink & Esselink, 1998) refer to this source. Also for model tuning (Baretta & Ruardij, 1988) the same data were used.

In Figure 33, depth integrated channel primary production for 2012 and 2013 are plotted, together with results from Colijn (1983). Production data have also been computed based on the present parameters, and solar radiation for the Colijn-years 1978-1980.

From Figure 33 it follows that there is only a slight difference between the present results (for 2012 and 2013), and those for 1978. For 1979 and 1980, Colijn found much higher primary production values, especially in the outer areas 1 and 2. Colijn (1983) states that values for 1978 are low because of low chlorophyll-a data in that particular year. The conclusion is that primary production conditions



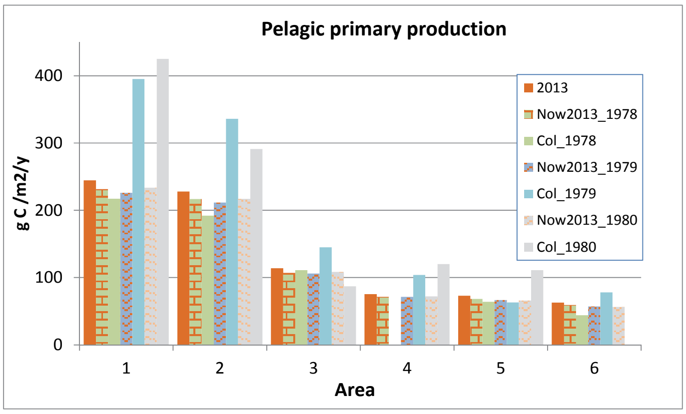


Figure 33 Summary of primary production values for each site: computed for the present situation (2012 (upper) and 2013 (lower), data by Colijn (1983) for the years 1978-1980, and values computed based on the present parameter values, and solar radiation data for 1978-1980. Values are depth integrated productions at each site, thus in the channels only.

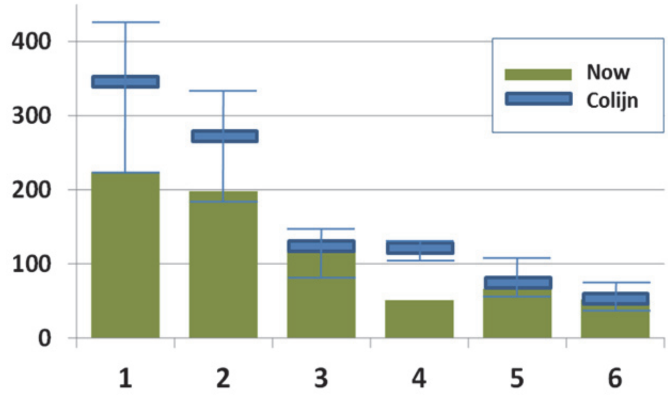
in 1979-1980 (the combination of production parameters and chlorophyll-a content) are better (to much better) than nowadays. In 1978 conditions were more or less similar.

Average primary production (at each site, thus channels only) found for the years 1978-1980 by Colijn, and the one found now, for each station, is presented in Figure 34. Differences are largest at station 1, 2 and 4.

It is obvious that the highest production (in terms of gross production) sites can be found in the outer Ems area, whereas the lowest production is found in the Dollard area. The differences in primary production found for the years 1979 and 1980 and nowadays are large, while the differences between 1978 and nowadays are minor. Results differ per station, but in all cases production at

2012 g C m^{-2} y^{-1}

Station	PP_now 2012	Colijn 78-'80	Colijn min	Colijn max
1	224	346	217	425
2	198	273	192	336
3	126	114	87	145
4	51	112	104	120
5	66	79	63	111
6	52	61	44	78



2013 g C m^{-2} y^{-1}

Station	PP_now 2013	Colijn 78-'80	Colijn min	Colijn max
1	245	346	217	425
2	228	273	192	336
3	114	114	87	145
4	75	112	104	120
5	73	79	63	111
6	63	61	44	78

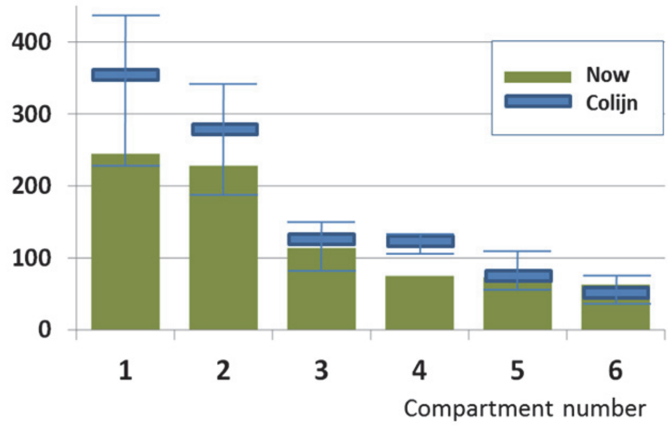


Figure 34 Average, minimum and maximum water column primary production values for Colijns 1978-1980 research (blue rectangles with min-max lines) and the present research (green bars), for each station (thus: channel values).

stations 1 and 2 nowadays is lower than it was in 1979 and 1980. This is also the case at station 4 and 6 (only 1979 data available), but varies between lower and the same for stations 3 and 5. Results for 1978 as reported by Colijn are much lower than the values found for 1979 and 1980, while being similar to our results.

6.4.4.5 Discussion

The question now is what may cause the differences found between 1978-1980 and present. One may suggest a number of possible causes: (i) different solar radiation conditions, (ii) changed water column light climate and suspended solid content, (iii) changed phytoplankton biomass (as chlorophyll-a content), (iv) different water temperatures, (v) different phytoplankton types, (vi) changing nutrient availability. The first one (solar radiation effects) was already eliminated above, which leaves the other five.

Changed water column light climate and suspended solid content

From section 6.4 plus Figure 15 (suspended solid content) and section 6.5 plus Figure 18 (light attenuation coefficients) it can be concluded that at site 4, the increased suspended solid content of the water column and light attenuation coefficient will have largely contributed to a lowered primary production. In the Dollard area, the observations that primary production hardly changed not did the light attenuation coefficient both agree. In the outer area, the lower primary production values nowadays do not agree with the observation that nowadays light attenuation is *less* than in 1978-1980 (light conditions are better nowadays). At site 3, primary production measured is the same as found by Colijn, although suspended matter concentrations and light attenuation coefficients are a bit larger.

Changed phytoplankton biomass (as chlorophyll-a content)

For 1979-1980, Colijn (1983) found higher chlorophyll-a values at site 1 than present values (not for 1978), these changes can at least partly explain the differences between his data and the present ones. Colijns chlorophyll-a data for the Dollard also were higher than those nowadays, but there's no higher production found.

Temperature effects

We checked a possible effect of temperature differences as well. In Figure 35 relevant temperature data for site 1 (Huibertgat Oost) are shown, making clear that temperature differences cannot explaining substantial differences between 1979 and 1980 P^B_{max} values and present results.

Different phytoplankton types

Most striking probably is the different occurrence of *Phaeocystis globosa*[1] in 2013 (present in May at sites 1 and 2) and 1980 (largest number ml^{-1} of all species in May and June). *Phaeocystis* is known as a fast producing species (Schoemann et al, 2005). If this occurrence of Phaeocystis indeed determines a difference between 1979/1980 and present, it should be reflected by the maximum of the chlorophyll-a specific ^{14}C-uptake rates (P^B_{max}). Colijn (1983, chapter IV, table VII) gives P^B_{max}-values of 5-12 mg C mg^{-1} chla h^{-1} (1979) and 12 -36 mg C mg^{-1} chla h^{-1} (1980) for months May and June, but unfortunately, he only gave averages for all experiments done then. Present values (see the full data report, chapter 9) all stay -with only two exceptions- below 12 mg C mg^{-1} chla h^{-1}. Colijn (1983) stated that his P^B_{max}-observations showed that *Phaeocystis* blooms showed 5-6 times higher P^B_{max}-values than during diatom blooms.

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[1] Colijn (1983) mentions *Phaeocystis pouchetii*, which was the identification then; nowadays it is split into two separate species *P. pouchetii* and *P. globosa*; the latter is common for Dutch waters. Wanink et al (2014) just mention *Phaeocystis spp.* as occurring species.

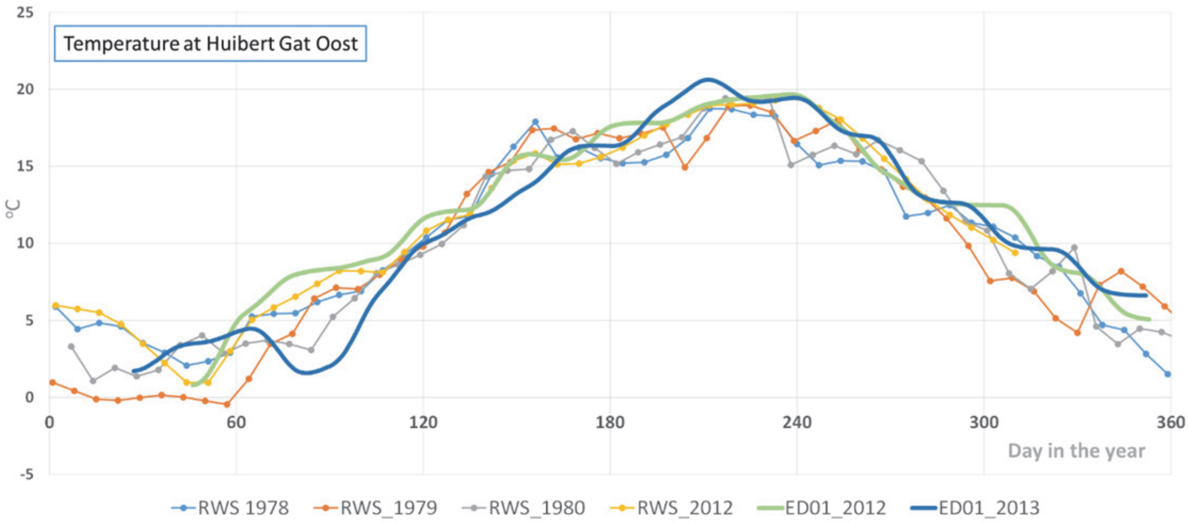

Figure 35 Temperature at Huibertgat Oost (site 1) in 1978-1980 and 2012 according to RWS-monitoring data (RWS 2014), and present data (ED01_2012 and ED01_2013); present data were interpolated.

Changed nutrient availability

Seen the changes observed in nutrient concentrations (section 6.3 and Figure 11), the decreasing eutrophication status of the system might be a good explanation for the lower primary production in the outer areas. In the Dollard area light limitation most likely will prevent nutrient depletion, as is the case at site 4. Nutrient concentrations also stay much higher than in the outer station (1 & 2) and never seem to reach real low values. The reason why present primary production data at site 3 are almost the same as those from 1978-1980 is not clear, since both light and nutrient availability decreased since the late ’70-s. De Jonge (2000) mentions a significant relationship between primary production in the outer reaches and river discharges. To elucidate the effect of discharges –and also of changed North Sea shore nutrient contents- better, ecosystem model simulations are to be carried out.

6.4.5 Conclusions

Primary production in the Ems-Dollard area as measured in 2012 and 2013 was considerably lower than in 1979 and 1980, and about the same as in 1978. It is also clear that in the outer area (stations 1 & 2) absolute differences are largest. In the inner areas, absolute differences are much smaller and it also differ per site. It also must be kept in mind that year-to-year differences may be large, a well-known phenomenon in ecosystems. There are three possible explanations left for the differences found in the outer areas:

i: lower chlorophyll-a content in the water column at site 1 compared to 1979-1980 ii: decreasing nutrient availability in the outer areas seems to be the most likely explanation for the lower primary production found there, since in 2012 and 2013 light attenuation was less than in the 1978-1980 period.

iii: major occurrence of *Phaeocystis pouchetii* (now: *P. globosa*) as highly productive alga in 1979-1980, opposite to 2013 when *Phaeocystis* did occur but not dominantly. This may also be an effect of a lower eutrophication status.

At station 4, lower present production can be explained by the increased turbidity.

6.5 Chlorophyll-a and primary production in the sediment

6.5.1 Chlorophyll-a and light attenuation in the sediment top layer

6.5.1.1 Present 2013 chlorophyll-a data

Benthic chlorophyll-a values are needed to translate primary production values from the ^{14}C-incubations to benthic primary production in the field situation. Our data in (Figure 36) show highest values for station 5, and lowest for station 3 and 4.

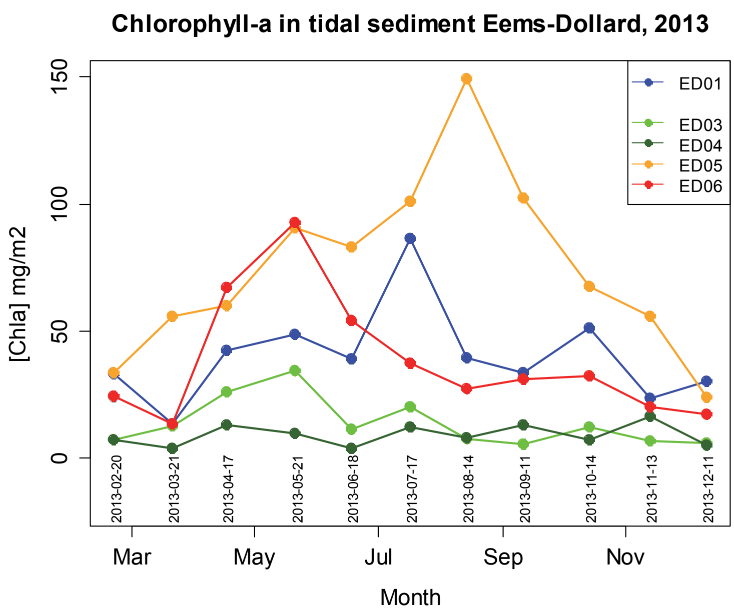

Figure 36 Benthic chlorophyll-a data for the five monitoring sites (see Figure 3). Station 2 (ED02) was only visited on one occasion and is omitted in the graph.

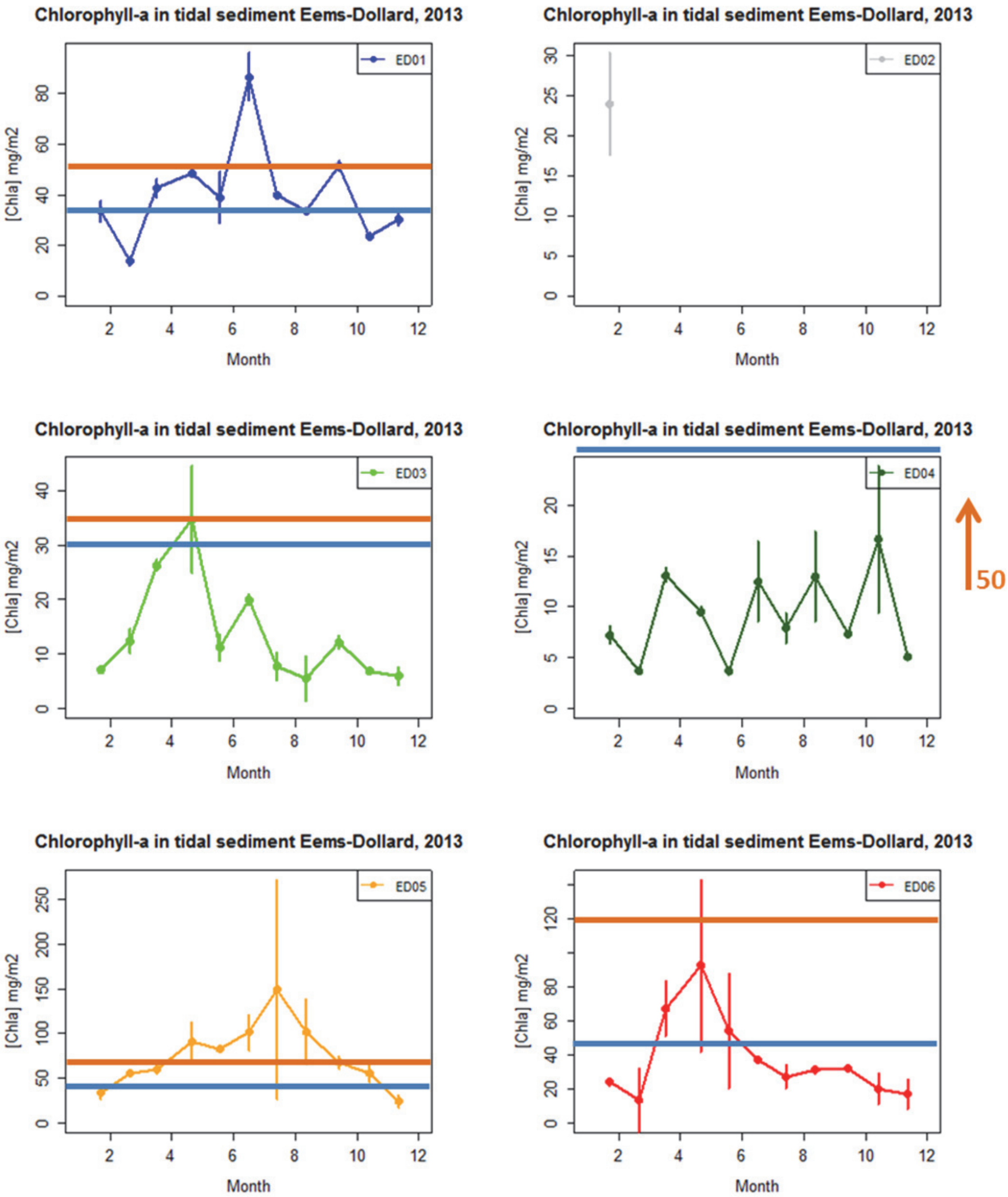

Figure 37 Chlorophyll-a densities in Eems-Dollard sediments, per station 1-6 (Figure 2), with year average results by Colijn & De Jonge (1984) (orange horizintal line) and minimum values of 1992-1999 results by De Jonge et al (2012); it concerns the year 1996. For all present data, n=2. Present sites 1, 3 and 5 are similar to Colijn & De Jonge (1984) and De Jonge et al (2012) sites 1, 4 and 5. Present sites 4 and 6 are closer to the low water line than Colijn & De Jonge (1984) and De Jonge et al (2012) sites 3 and 6. Note that maximum values for De Jonge et al (2012) sites are about 3.3 times the minimum values; their average values are about twice the minimum values.

6.5.1.2 Previous chlorophyll-a data

Our data (2013) can be compared with data found by Colijn & De Jonge (1984) and De Jonge et al (2012). Results are shown in Figure 37. It can be concluded that in 2013 values for stations 3 and 4 are well below previously recorded values, while chlorophyll concentrations for station 1 and 5 are almost similar. Values for station 6 are below the minimum De Jonge et al (2012)-values, but similar to the Colijn & De Jonge (1984) values.

One possible reason for the differences between studies is the position of the stations. Our stations 1 and 5 are close to the low water line, as were the Colijn & De Jonge (1984) and De Jonge et al (2012) stations. Our stations 4 and 6 also are close to the low water line, but in both previous studies these sites were much higher in the tidal zone. De Jonge et al (2012) explained that the higher in the tidal zone, the larger the chlorophyll-a values; it may differ up to a factor 2.5 from close to the water line up to high in the tidal zone. De Jonge et al (2012) also showed that low year average chlorophyll-a values are coupled to year average air temperature. In 2013, average air temperature at the KNMI Nieuw-Beerta station (KNMI, 2015) was 9.1 ^{o}C, and it belonged to the lowest ones in the 1992-1999 period (De Jonge et al, 2012).

6.5.1.3 Conclusions

Based on the previous we can conclude that the chlorophyll-a values found in 2013 are at the lower end of what was expected, based on earlier research; two stations (1, 5) have similar values, stations (3, 6) have lower values in 2013, and one station (4) has much lower values now. But, differences may be caused by sampling location (high or low in the tidal zone). Temperature effects may also be an additional explanation for the difference between the present values and the higher ones in the 1992-1999 period, since air temperature in 2013 was lower than almost all values in 1992-1999. Furthermore, present values were validated on a semi-quantitative way by BenthoTorch measurements confirming the lower values for stations 3, 4 and 6. If the analysis procedure would include a structural error, it would be reflected in our results, and apparently, this is not the case.

We must conclude that there is no precise validation of our data. But also, there is no falsification possible, since the largest differences with previous research can at least partially be explained by the positioning of the sampling sites in the tidal zone.

6.5.2 Benthic primary productivity, or: chlorophyll-a specific maximum production

As for the pelagic site, the carbon uptake rate per unit of chlorophyll, depending on light intensity, was measured for the five benthic sites (Figure 3). As a result also the maximum productivity (at each sampling site) is known, and presented in Figure 38Figure 27. Note that this is the *potential* production: what can the algae produce under optimal conditions? It is not the *real* production since that is also determined by the chlorophyll-a content in sediment top layer, plus the solar radiation and the

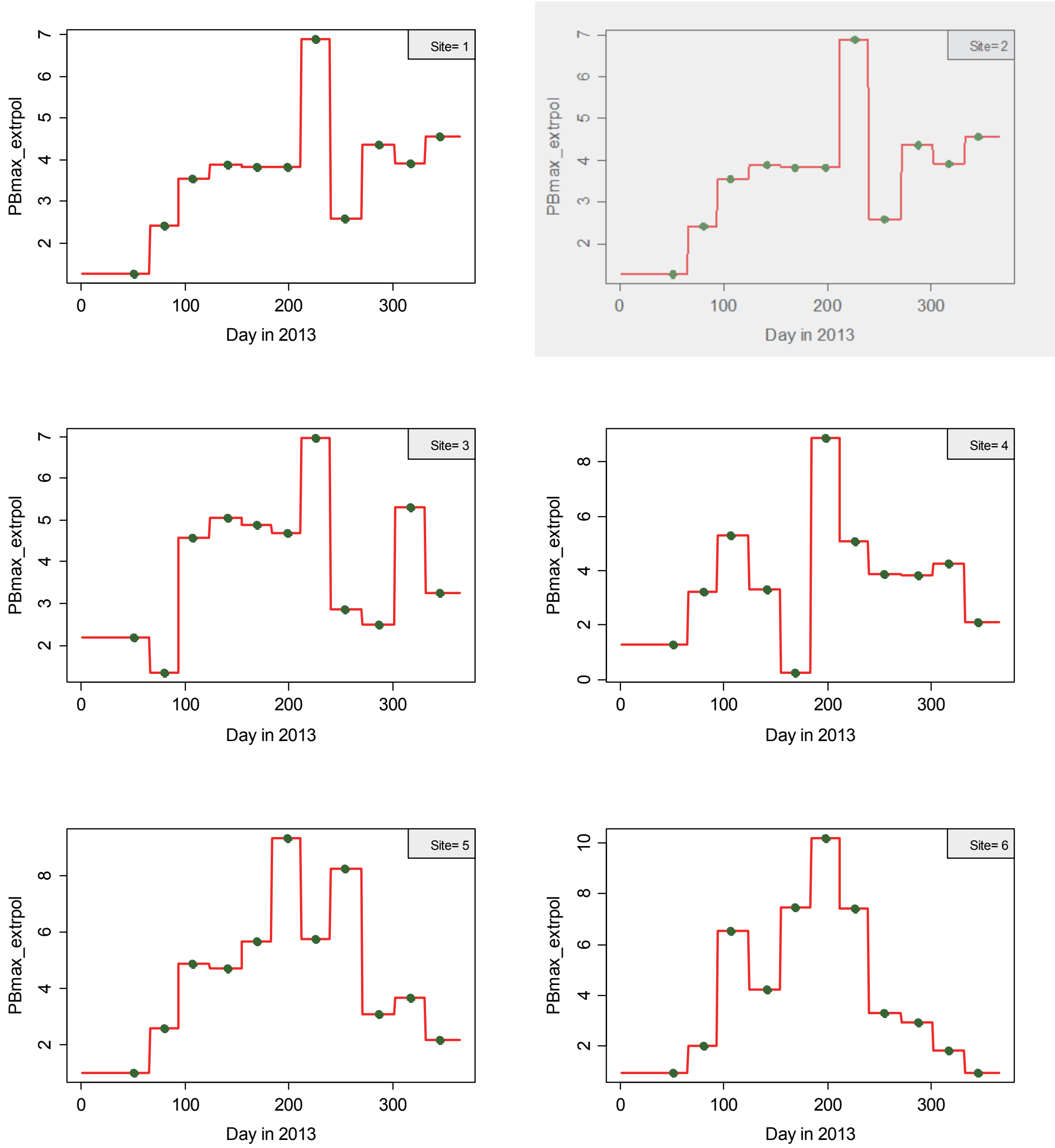

Figure 38 Maximum phytobenthos primary productivity, computed from the ^{14}C incubations, year 2013. Unit mg C mg^{-1} chla h^{-1}. Note that data for site 2 (shaded) are the same as those for site 1. The almost zero value at site 4 around day 170 probably must be considered as an outlier.

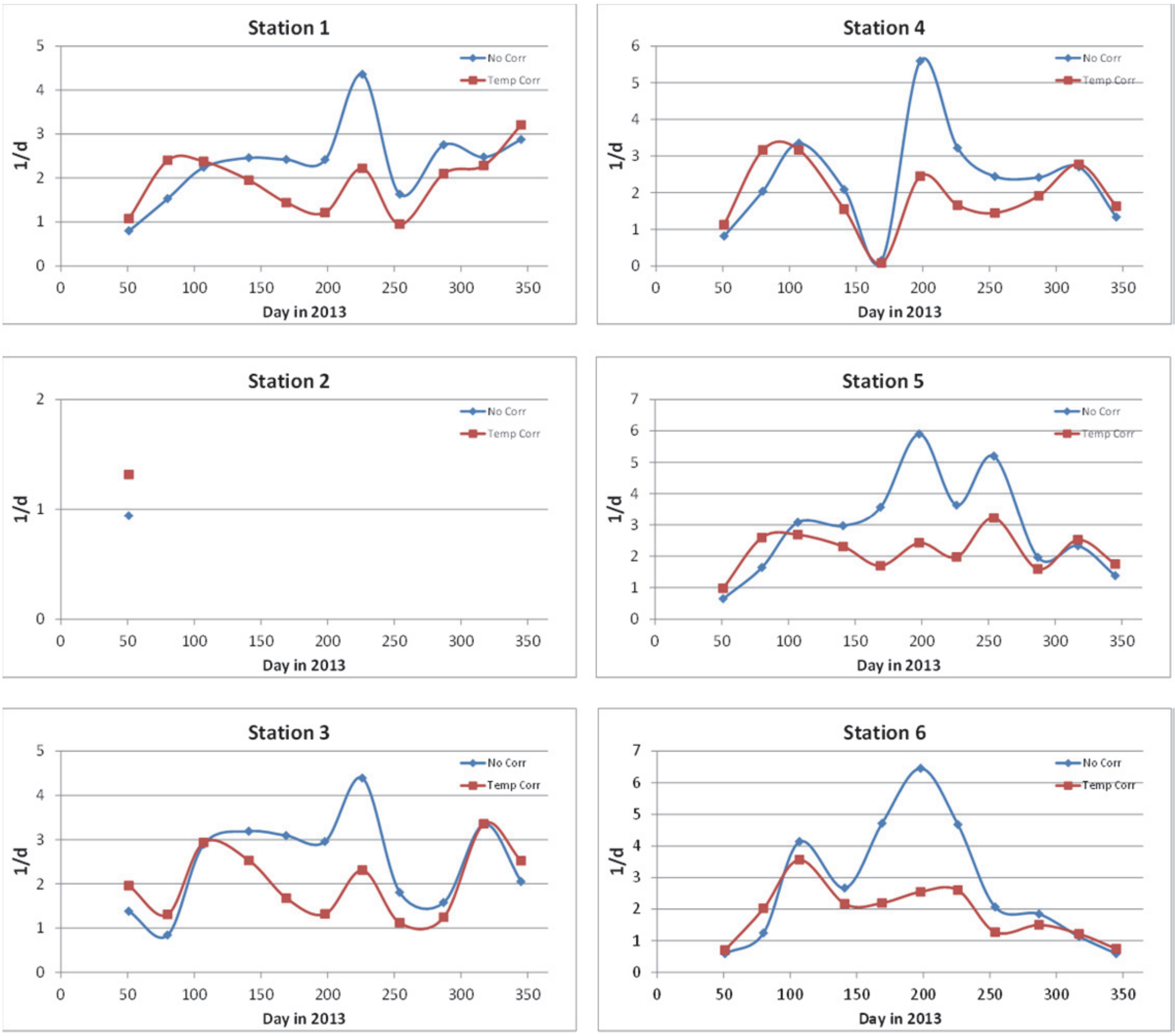

Figure 39 Specific maximum productivity (or: first order gross ^{14}C uptake rate constant, P_{max_spec}) of Ems-Dollard phytobenthos in 2013; P_{max} from incubations divided by the estimated concentration of phytobenthos carbon present in the incubated samples. Phytocarbon content was computed by assuming a phytobenthos C : chlorophyll-a- ratio of 38 (mg C/mg chla). Mind the different Y-axis scales. Red results: corrected for temperature after Eppley (1972), blue: uncorrected. The almost zero value at site 4 around day 170 probably must be considered as an outlier.

sediment top layer light attenuation. The computed field primary production is presented in section 6.13.

Mass related relative productivity values are obtained from the maximum chlorophyll-a specific productivity and the organic-C :chlorophyll-a ratio (which was taken as 38 (mg C mg^{-1} Chla)). Results are presented in Figure 39. These values roughly vary around 2 (d^{-1}), and thus are lower than those for phytoplankton (Figure 26). Also, maximum values (about 4 d^{-1}) are lower than maximum values for phytoplankton. Note that if the value for the C:Chla ration increases a lower mass related productivities will result. De Jonge (1980) mentions ratios between 10 and 154 for the years 1976-1978, and mean values of 40, 41 and 61 for 1976, 1977 and 1978 respectively. In the present research no new C/Chla-ratio data were collected.

6.5.3 Benthic chlorophyll distribution and diatom motility and implications for primary production calculation

During the elaboration of the benthic primary production data the difficulty was encountered that we

- had little information on the distribution of chlorophyll with depth in the sediment,
- had to estimate light attenuation in the sediment (based on section 6.3.1),
- had to estimate the effect of benthic diatom motility

Standard chlorophyll-a distribution with depth was assumed to be linear, but De Jonge and Colijn (1994) and Kromkamp et al (2006) showed that the sediment top layers contain largest chla-contents. Final calculation here were done with an even distribution, and with an exponential distribution with depth (see section 10.3 of the full data report)

Although light attenuation was computed based on sediment composition (section 6.3.1), we also calculated the (possible) situation that the attenuation values are 50% lower.

The real problem however was that benthic diatoms have the capability to move vertically and thus find a better position with respect to light conditions. Migration distances found in literature are about 0.6 to 1 mm h^{-1} (Consalvey et al, 2004). Du et al (2010) mention a study by Hopkins (1963) who observed that benthic diatoms were capable to migrate from 1 mm depth to the surface within 1.5 hour. Du et al (2010) found that this movement was triggered by light; e.g. such a migration was absent during night. They also found that in sandy areas migration could be faster than in silty areas.

As a result, we performed a couple of primary production computations, listed in Textbox 1.

Final calculation were done for four situations: i) no possibility for diatoms to move vertically, ii)- iv) diatoms have the capability to move to better light conditions over 0.1, 0.4 and 1.0 mm respectively. Such a movement can be downwards and upwards and implies that, when the optimum productivity is deeper in the sediment, algae from the sediment top layer will move downward, and algae from deeper in the sediment will move upward: effectively there's a (maximum) 2 mm region that will reach optimal light conditions if a 1 mm movement is assumed. Also, those algae that were further away from the optimum light conditions do not reach the optimum region, but still move to and reach conditions.

1 Light ext*1.0 Chla Linear	Normal light extinction, chla linear distribution
2 Light ext*1.0 Chlexp no mov	Normal light extinction, chla exponential distribution
3 Light ext*1.0 Chla exp mov 0.1 mm	Normal light extinction, chla exponential distribution, 0.1 mm diatom movement assumed
4 Light ext*1.0 Chla exp mov 0.4 mm	Normal light extinction, chla exponential distribution, 0.4 mm diatom movement assumed
5 Light ext*1.0 Chla exp mov 1.0 mm	Normal light extinction, chla exponential distribution, 1.0 mm diatom movement assumed
6 Light ext*1.0 Chla Linear	Light extinction *0,5, chla linear distribution
7 Light ext*1.0 Chlexp no mov	Light extinction *0,5, chla exponential distribution
8 Light ext*1.0 Chla exp mov 0.1 mm	Light extinction *0,5, chla exponential distribution, 0.1 mm diatom movement assumed
9 Light ext*1.0 Chla exp mov 0.4 mm	Light extinction *0,5, chla exponential distribution, 0.4 mm diatom movement assumed
10 Light ext*1.0 Chla exp mov 1.0 mm	Light extinction *0,5, chla exponential distribution, 1.0 mm diatom movement assumed

Textbox 1 Overview of benthic primary production options

6.5.4 Benthic primary production

Two extremes from the possible situations (from Textbox 1) are presented in Figure 40 and Figure 41, and summarised for the whole year in Figure 42. It is obvious that the results from both computations differ almost one order of magnitude.

Highest production is computed for station 5, lowest for stations 3 and 4. In all cases, differences between stations are mainly governed by the chlorophyll-a content of the sediment found (section 6.5.1).

The pattern is the same for all options mentioned in Textbox 1, the absolute values differ a lot: from 30 g C m^{-2} y^{-1} as highest value for option 1 (light attenuation coefficient as listed in Table 3, and microphytobenthos cannot move to better light conditions) to almost 300 g C m^{-2} y^{-1} for option 10 (light attenuation coefficient is half the one listed in Table 3, and microphytobenthos can effectively move to better light conditions over 1 mm distance.

The results from Figure 42 are integrated over the whole system, and presented in Figure 43, of course showing the same large difference between minimum and maximum computed values: 10 – 80 g C m^{-2} y^{-1}, when regarding the whole day including the period when tidal flats are submerged, and 18-130 g C m^{-2} y^{-1} if only the period when flats are dry is taken into account.

Such a large difference between lowest and highest values makes it hard to conclude what the benthic primary production has been in the system in 2013.

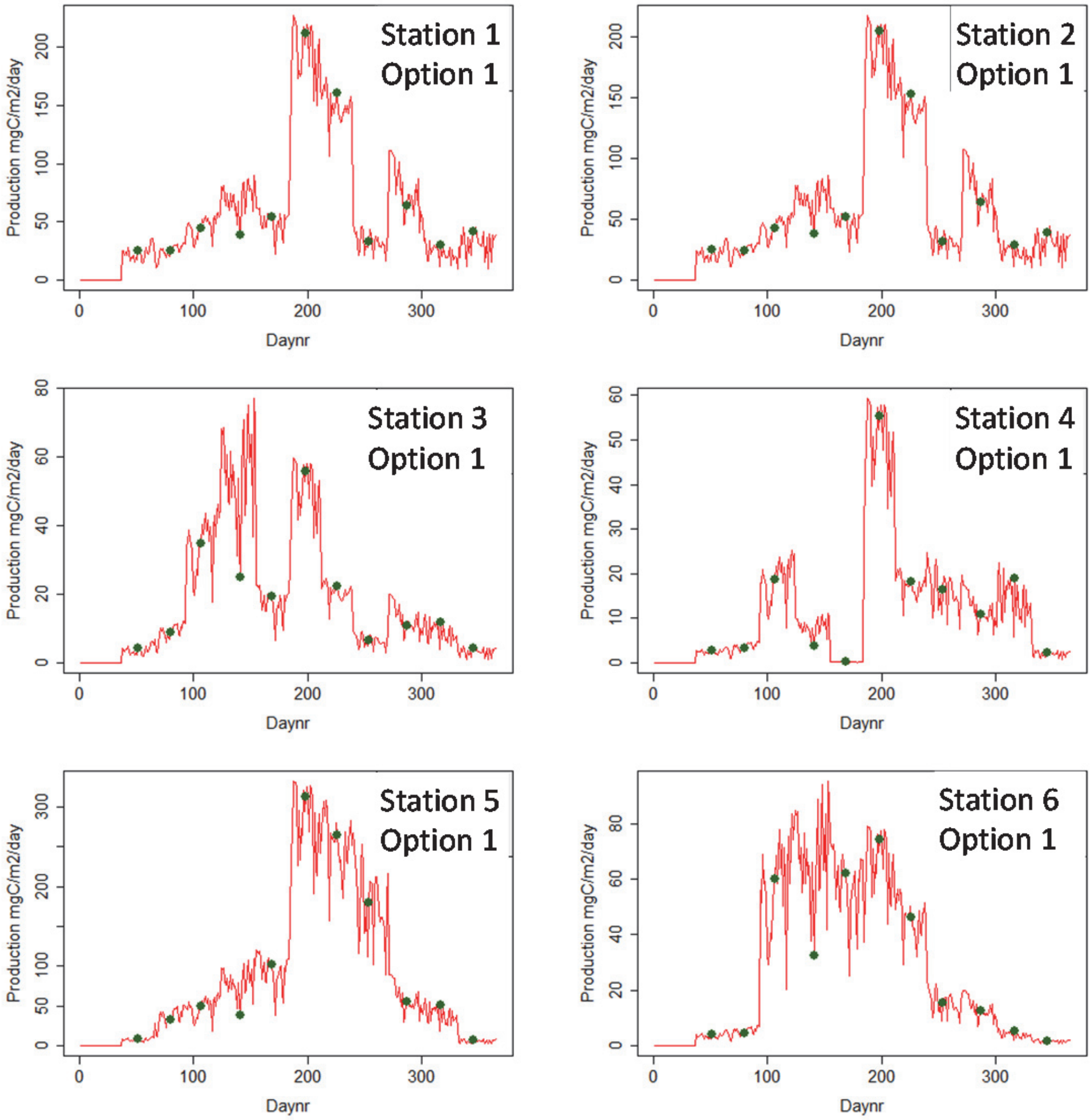

Figure 40 Benthic primary production as computed for all six field stations in 2013. Conditions: K_d as estimated from IMARES pelagic data and regression with suspended solids, Zwarts estimates for sediment composition and 2013 weather data. Parameters followed from a moving average interpolation with time. Note that station 2 parameters are the same as the ones for station 1; results are slightly different since the weather data interpolation is slightly different (other geographical position). Dots denote the sampling days

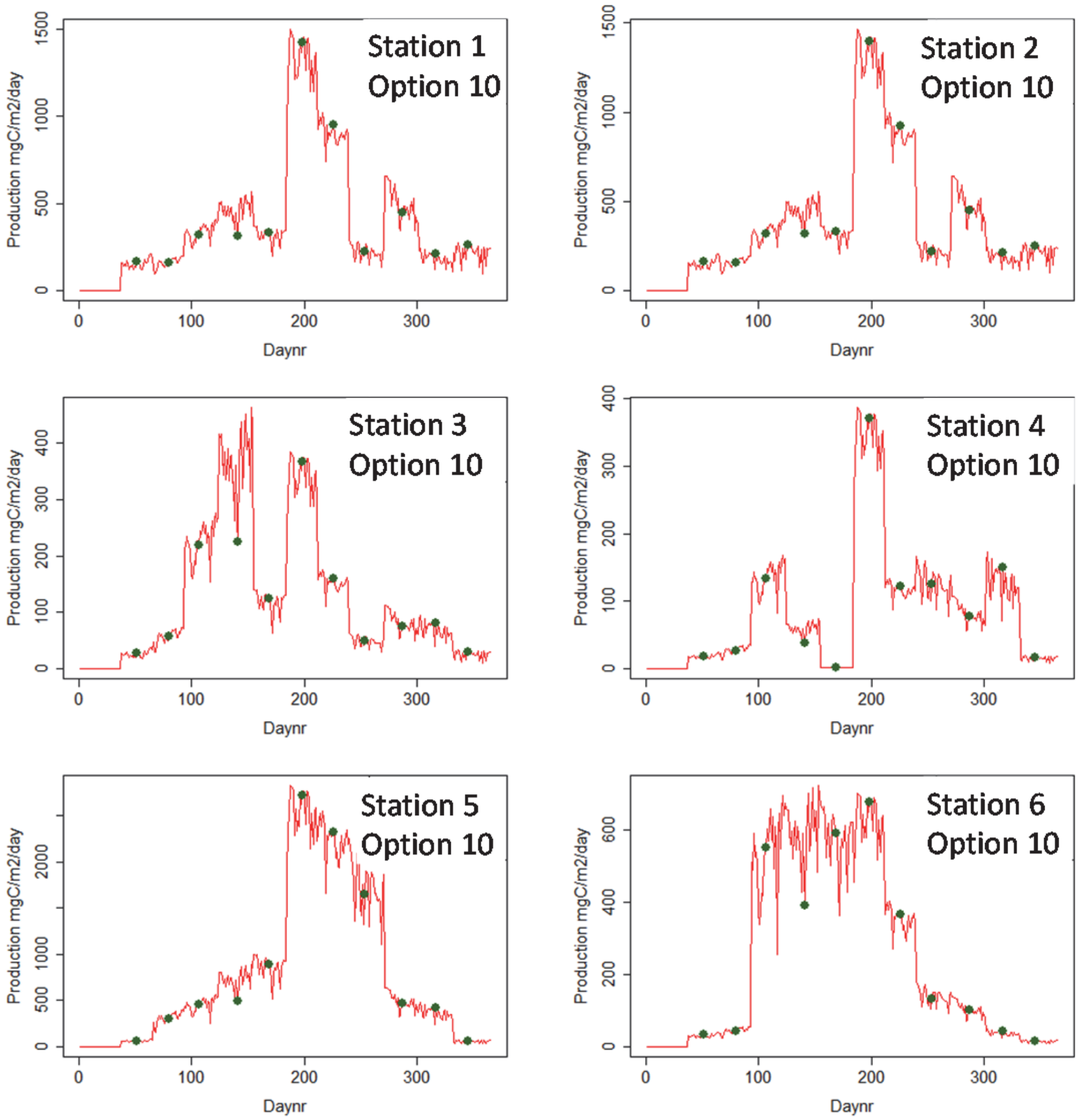

Figure 41 Benthic primary production computed with an exponential distribution of chlorophyll-a in the sediment (k_c = 0.7 cm^{-1}), light attenuation coefficients that are 50% of their standard values (see Table 3) and assumed that diatoms can move 1 mm towards the optimal light conditions (thus option 10 from Textbox 1 Error! Reference source not found.**). Radiation data for 2013.**

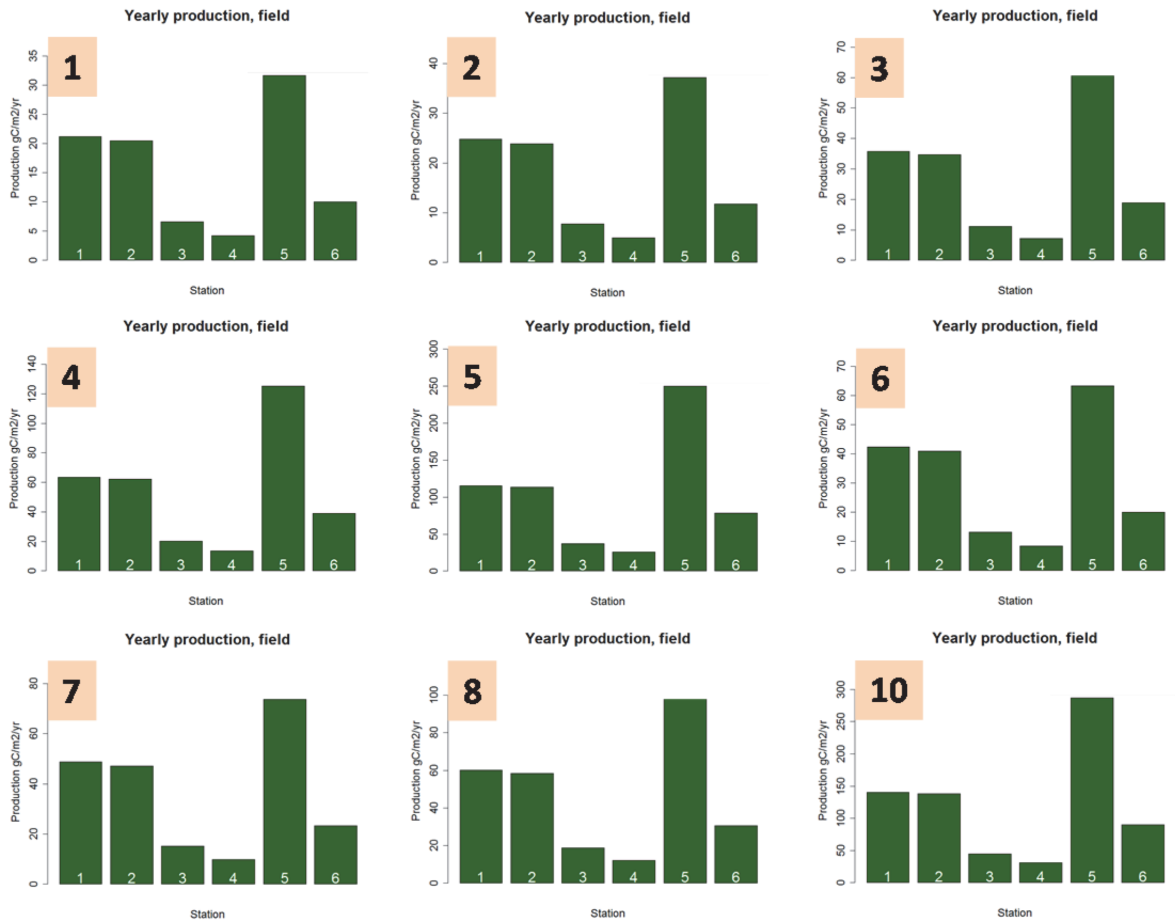

Figure 42 Benthic primary production at each station computed for the several possible light attenuation coefficients and phytobenthos movements as described inTextbox 1. Only option 9 is not shown. Radiation data for 2013. Note that the difference between station 1 and 2 is a result of slightly different solar radiation and different sediment characteristics; all production parameters have been copied from station 1.

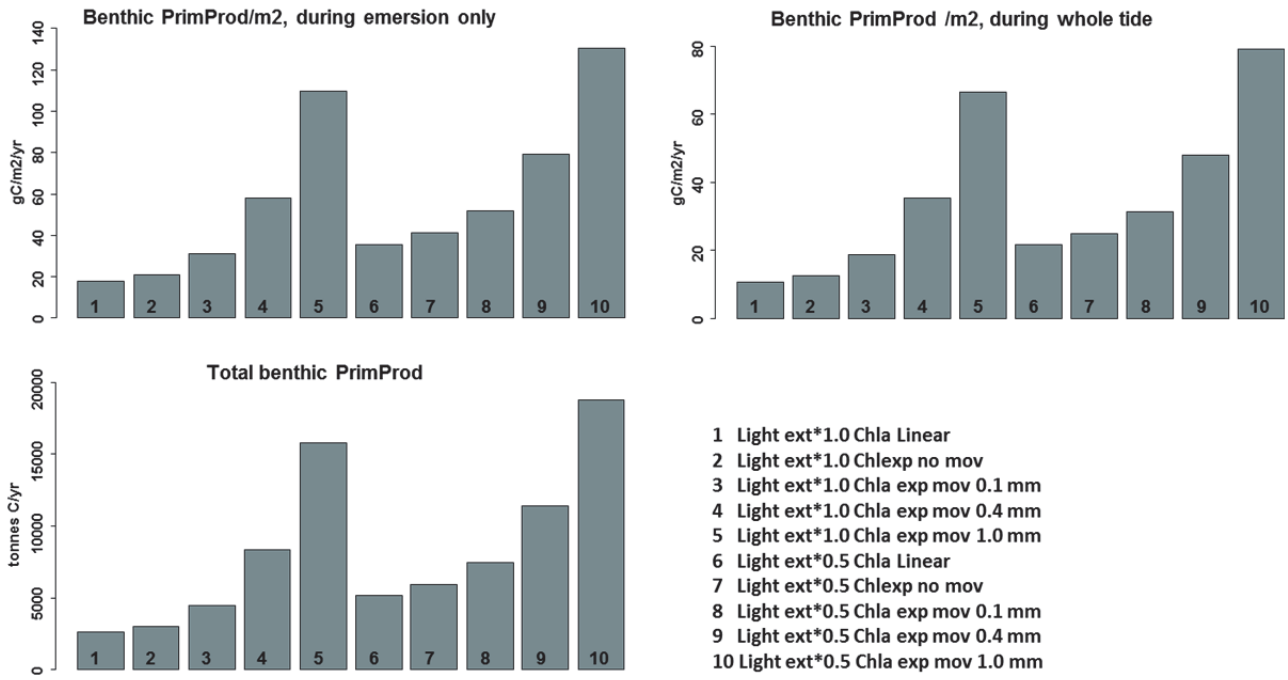

Figure 43 Benthic primary production in the Ems-Dollard estuary as computed for the possible light attenuation coefficients and phytobenthos movements (the 10 options mentioned here, same as Textbox 1). Radiation data for 2013. Upper left: production during emersion only, during the whole day (including night). Upper right: due to flooding, production is only possible during a part of the day, the real contribution of the tidal flats to system primary production is lower than that. Lower left: whole system benthic primary production.

6.5.5 How realistic are the values? Evaluation

The question now is what the value is of the above results. The range of calculated primary productions is almost one order of magnitude, and is based on different assumptions for the light attenuation coefficient in the sediment and the position of the benthic diatoms with respect to the light conditions in the sediment.

6.5.5.1 Light attenuation in the sediment top layer

The values for k_d we used here, and were listed in Table 3 (values used: k_{d_avg}), were based on our own estimate of effects of silt (measured in the water column) and an estimated contribution of sand (merely based on literature values), the sediment composition and a comparison with the estimates of Colijn & De Jonge (1983) plus other literature values. It was concluded that our estimates are within the ranges mentioned in literature, and possibly a bit on the high end of the ranges mentioned. The latter was a good reason to compute benthic primary production with a 50% light attenuation coefficient as well.

6.5.5.2 Chlorophyll-a content of the sediment

The results are linearly related to the amount of chlorophyll-a detected in the sediment (section 8.16); the values found here are, with one exception (station 5) at the lower end of normally reported ranges. The procedure followed here to analyse the chlorophyll-a content, including the qualitative validation with the BenthoTorch-data (see full data report, section 8.16.2) gave no reason to doubt these values. Nevertheless, De Jonge & Colijn (1994) argue that there are large differences with respect to the position in the tidal zone: the higher up in the tidal zone, the higher also phytobenthic biomass. They give average values of 4-12 gC m^{-2} from -50 to +100 cm NAP; with a C/Chla-ratio of 60 (as a rough average of the values mentioned in the same paper) it gives 60 – 200 mg chla m^{-2} (the range of individual chla-values is much larger: mean annual values range from 28.6 – 247 mg chla m^{-2}). Thus, it is to be expected that the primary production values computed here will be lower than those found by Colijn & De Jonge (1983).

6.5.5.3 Production rates per unit chlorophyll-a

PB_{max}-values found here range between 2 and almost 10 mg C (mg chla)$^{-1}$ h^{-1}, and are a bit lower than those found for the pelagic phytoplankton (section 6.4.4). Wolfstein & Hartig (1998) measured a maximum value of almost 2 mg C (mg chla)$^{-1}$ h^{-1} on the Keitum Watt (Sylt, Germany) with the ^{14}C-incubation method, and up to 4 mg C (mg chla)$^{-1}$ h^{-1} based on oxygen production during incubation. MacIntyre and Cullen (1996) found 8-10 mg C (mg chla)$^{-1}$ h^{-1} as maximum value in the Corpu Christi Bay (SE Texas, USA), with highest values at highest temperature. Such values are also presented by Dube (2012) in his master thesis on remote sensing methods, with values of 3 at 5 ^{o}C to 10 mg C (mg chla)$^{-1}$ h^{-1} at 25 ^{o}C.

6.5.5.4 Positioning of microphytobenthos in the sediment

A part of the benthic diatoms (the epipelic diatoms) can actively choose their position in the sediment, and thus find the optimal light conditions. De Jonge (1980) mentions that almost all benthic algae belong to this type. Migration distances found in literature are about 0.6 to 1 mm h^{-1} (see e.g. Consalvey et al, 2004). Thus we might conclude that from the computed options the ones with a 1 mm migration assumption are more likely than those with 0.1 mm or even without migration.

6.5.5.5 Effects of nutrients

Effects of nutrient limitation seems to be absent, since there no close-to-zero P_{max}-value in 2013 (Figure 38). This is also what may be expected, generally, since benthic algae have access to benthic nutrient resources and nutrient limitation is not very common. The absence of nutrient limitation is also confirmed by a benthic modelling exercise (unpublished results of the IMARES- EcoWasp ecosystem model), and is also documented by Rutgers van der Loeff et al. (1981).

6.5.6 Conclusions

We conclude that

i) Chlorophyll-a data found in the sediment are typical for the samples sites
ii) Lower or higher in the tidal zone chlorophyll-a values may be lower respectively higher
iii) Production rates per unit of chlorophyll-a is well in line with literature results
iv) The assumption that microphytobenthos can migrate over a 1 mm distance to the optimum light conditions probably is realistic
v) The computed light attenuation values are in line with those reported in literature. The case we also computed with a 50% lower attenuation coefficient probably is at the optimistic side.
vi) The final result is more sensitive to variations in migration distance than to variations in sediment light attenuation coefficients.

Since we did not measure primary production *in situ*, but computed it needing one estimate (on k_d) and one assumption (on the distribution of microphytobenthos with respect to light conditions), it is hard to draw strict conclusions on benthic primary production in 2013. Most likely, it ranges between 60 and 140 g C m^{-2} y^{-1} for the period only when flats are dry, and 40-80 g C m^{-2} y^{-1} as whole year contribution to overall primary production of the system.

Benthic primary production values computed for 2013 show a wide range, a result of the estimates for the light attenuation coefficient and assumptions for the microphytobenthos motility. The most likely values of 40-80 g C m^{-2} y^{-1} contribution to overall system production is a bit lower than the global range of 50-200 g C m^{-2} y^{-1}, mentioned by Colijn & De Jonge (1983) and their average of 93 g C m^{-2} y^{-1} which both is including the submersion period.

A comparison for each site between primary production found by Colijn & De Jonge (1983) and present values is presented In Figure 44 for five different possibilities from Textbox 1. It clearly shows that the whole range of what we now assume to be a most likely benthic primary production in compartment 5 is above the values Colijn & De Jonge presented, contrary to the other compartments. The results of Colijn & De Jonge for compartment 6 (part of the Dollard area) are dominant in their whole-system results, while in our estimates compartment 5 is dominant.

Most important, however, is that we unfortunately have to conclude that it is not possible based on present results to draw any conclusions on differences between phytobenthic primary production nowadays and in 1980.

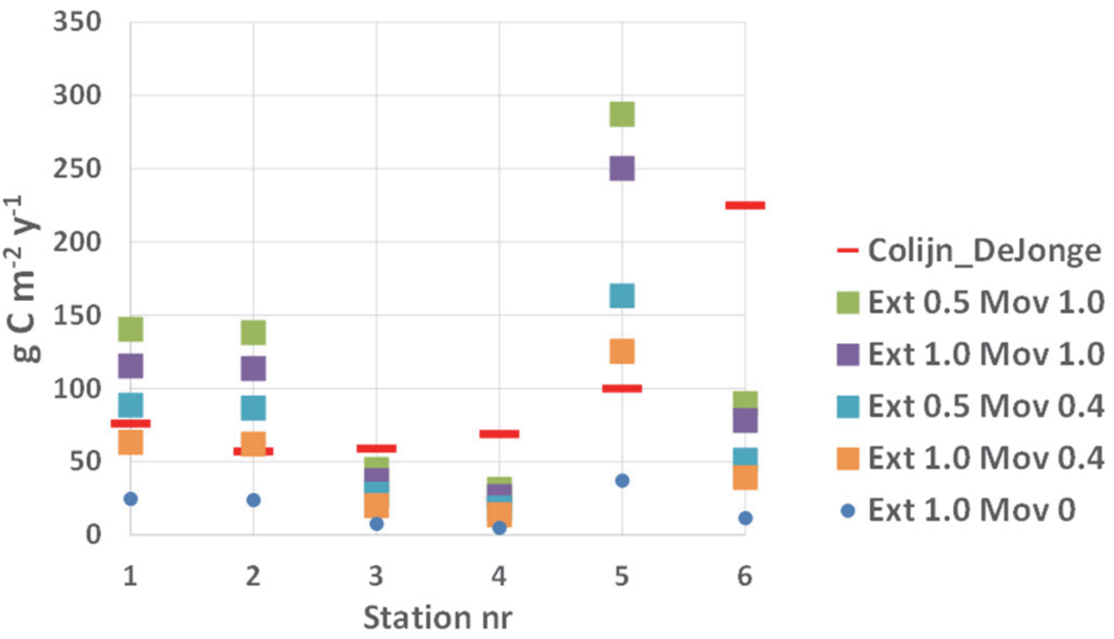

Figure 44 Benthic primary production at the several stations, during emersion, for 4 different options (from green to orange nrs 10, 5, 9, 4 and 1 from Textbox 1) and compared to results by Colijn & De Jonge (1983).

7 Final considerations and conclusions

7.1 General

Now we come to the final part: answering the main questions asked at the beginning of the research (see section 1.4). These questions will be answered in the next sections, including a short elucidation if appropriate. Furthermore, we made a shortlist of all topics mentioned in the full data report.

7.2 Question : What is the pelagic primary production (PP) at present and what are differences between now and the late seventies?

The first order gross ^{14}C uptake rate constant (or: mass specific ^{14}C uptake rate), corrected for temperature effects, reaches values up to 4 d^{-1} in 2012, and up to about 6 d^{-1} in 2013.

Primary production values computed for the channels in 2012 and 2013 are of the same order as for 1978, but much lower (almost half) than those measured in 1979 and 1980. Largest absolute differences are found at the two outer stations (1 and 2), where present results are 60% of the values in 1979-1980. Relative differences in the inner stations are of the same order. Maximum relative differences is about a factor 2.

System average primary production values found for in 2012 and 2013 are 120 and 125 g C m^{-2} y^{-1}, respectively; this is including the tidal area and taking into account the emersion time of the tidal flats. This value is about 70-75 % of the values found by Colijn (1983) (system wide average of 164 g C m^{-2} y^{-1}).

7.3 Question: What is the benthic PP at present, and what are differences between now and the late seventies?

Benthic production was determined at five stations and during 10 cruises in 2013. Most important results from the incubation measurements concern the maximum productivity per unit of chlorophyll-a (P_{max}) and the first order gross ^{14}C uptake rate constant (P_{max_spec}).

The estimated first order gross ^{14}C uptake rate constant, corrected for temperature effects, has values around 2 d^{-1}, with values up to 3-4 d^{-1} in 2013.

Yearly benthic primary production is computed at 11-14 g C m^{-2} y^{-1}; this value includes the submersion period of the tidal flats. For the emersion period only, primary production values of 16-23 g C m^{-2} y^{-1} are computed. The range is mainly determined by ranges of the benthic attenuation coefficient used. The result is rather sensitive to the choice of this attenuation coefficient.

Primary production values computed for 2013 are much lower than the value of about 93 g C m^{-2} y^{-2} on tidal flats (including the submersion period) found for 1976-1978 by Colijn & De Jonge (1984). Differences are found at all stations; the largest part of these differences can be attributed to lower benthic chlorophyll-a concentrations found in 2013 as compared to the late seventies. A part (but not all) of these difference can be attributed to the sites where the samples were taken: low or high in the tidal zone makes a considerable difference, and some of the present sample sites were in another tidal zone than the sample sites of Colijn & De Jonge.

7.4 Question: what is the impact of suspended matter (SPM) on pelagic and benthic PP?

For the most inner station, a 50 % change in light attenuation (which is near a 50% change of the suspended solid content of the water column) results in a 25% change in primary production. For the outermost station, a similar change results in a 35-40% change in primary production. These estimates did not take nutrient limitation effects into account. The two outer stations seem to suffer from nutrient deficiency in (late) spring; a drop in the light attenuation coefficient during that period in time does not necessarily imply an increase in primary production. Thus, the figures mentioned here for the outer stations are too optimistic: changes will probably be smaller. Better answers have to be provided after ecosystem modelling exercises.

It has not been investigated what the effect is of a change in light attenuation on the start of the phytoplankton growing season. However, it can be argued that, especially at the beginning of the phytoplankton growing season, light is the most important limiting component, more than temperature and nutrients. Especially then, changing light conditions will have their largest effect on algae biomass development. The more turbid, the lower the algal growth rates are, and thus, nutrient demands. Consequently, if nutrient limitation becomes relevant, this moment will be reached (a bit) later in the year with increasing turbidity.

7.5 Question: are there factors, other than SPM, that have affected the water column irradiances in the last decades?

Next to suspended solids, also coloured organic carbon (CDOM) cq Yellow Substances (mostly humic-like dissolved matter) contribute to the light attenuation. This is especially the case in the more inner stations, where high concentrations of suspended solids occur, and also (relatively) high concentrations of yellow substances and CDOM are found. Without CDOM/Yellow Substance taken into account, the proportionality coefficient between the light attenuation coefficient (m^{-1}) and suspended solids (mg l^{-1}) is 0.044; with CDOM it becomes 0.032 (plus the CDOM-contribution) with Yellow Substances it becomes 0.026 (plus the Yellow Substances –contribution).

Both CDOM and Yellow Substances are closely and inversely related to salinity, which raises the conclusion that both are mainly imported into the system; and thus, fresh water input (also) affects water column transparency through this CDOM/Yellow Substance import.

The relationship found here between K_d and suspended matter (K_d=(0.037 à 0.044)*[suspended solids]) is almost the same as found by Colijn (1982) (K_d=0.40+0.04*[suspended solids]). Colijn did not distinguish Yellow Substances or CDOM.

7.6 Question: to what extent is primary production by planktonic or benthic algae limited by nutrients or light?

Primary production in both outer stations found in this research was about 10-20% below the 1978-values, and almost half of the 1979-1980 values. This could not be attributed to weather conditions: applying 1978-1980 weather conditions to the present setting revealed roughly the same results. Since light attenuation presently was less (conditions improved) compared to 1979-1980, this could not be a reason. Nutrients limitation is a possible cause: concentrations, especially of ortho-phosphate, dropped a lot since the late seventies (down to about 50%) and this could be a major reason for lowering primary production in the outer areas. It can hardly be a reason for a changing primary production at the inner stations. A second possibility is the low contribution nowadays of highly productive *Phaeocystis*, which also is considered a result of declining eutrophication.

Although it seems likely that pelagic primary production in both outer stations (1 and 2) is limited by low phosphorus and silicate concentrations in spring, we could not prove this with the data from this research. Nitrate concentrations do not seem to have an impact nowadays. Based on the observed nutrient concentrations, the three most inner stations (4 - 6) very likely did not suffer from nutrient deficiency; the situation for station 3 is not clear.

There was no indication that nutrients play an important production limiting role for phytobenthos.

It must be noted that in any ecosystem there exist a lot of feedbacks; these have not been considered in this study. A most important one, also stressed in ecosystem modelling studies like the one by Brinkman (2013), is grazing by shellfish (and/or other organisms). Grazers on the one hand depend on food availability, but will also affect food concentration. Therefore, conclusions on increasing or decreasing primary production –and secondary production- are especially meaningful if such feedback mechanisms are fully accounted for.

7.7 Question: are there geographical variations and/or temporal variations in the limitation of the growth of algae within the estuary?

Nutrient limitations are most likely at both outer stations at the end of spring, begin summer. At the inner stations, nutrient limitation is not likely at all. Light limitation occurs in the whole estuary, but at the outer stations it mostly exists at the beginning of the phytoplankton growing season, and in late summer. At the inner stations, light limitation occurs throughout the year.

7.8 Question: is there a substantial contribution of phytobenthos to the water column algae?

Based on phytoplankton analyses on a species level a distinction between pelagic and benthic algae could be made (section 8.10 of the full data report). At the outer stations, benthic algae make of 15% (summer)-40% (winter) of the pelagic algae volumes; in the inner area these fractions are around 50%. Thus, it can be concluded that especially in the inner area phytobenthos substantially contributes to the algal biomass of the water column.

8 Recommendations

The most important recommendations are listed; for a complete list see section 11.9 of the full data report.

Sampling procedure water column

In this research, at each site one sample was taken. The water samples have been obtained from the pocketbox, and can be considered a mixed sampled for each location. However, even within one compartment the spatial variability is expected to be large. To include this variability it is advised for future sampling programmes to sample a track.

Sampling procedure sediment

From the sediment 2 mm slices are sampled for the ^{14}C-uptake incubations, and 5 mm slices are sampled for chlorophyll detection. The first is OK, for the chlorophyll detection it is recommended in future to sample a core, and take 1 mm slices and analyse these separately (down to a certain depth).

Assessing benthic chlorophyll-a content

Our suggestion is to sample along gradients from low to high tidal zones to gather more information on spatial distribution.

Assess phytobenthic organic C content.

Our suggestion is to also investigate the amount of phytobenthos bound organic C content. This gives, combined with the primary production measurements, extra and useful information on phytobenthic growth rates.

Handling and analyses of water samples for chlorophyll detection

It is needed to a) carefully test the procedure and b) to apply and mutually test more than one method for chlorophyll-a analyses.

The chlorophyll-analyses of chlorophyll-a and pheophytin is calibrated against chlorophyll-a standard solutions; it is recommended to use pheophytin standards as well.

The carotenoid:chlorophyll adsorption ratio that is supposed to give information whether phytoplankton growth was nutrient or light limited needs tests in order to improve the conclusions based on this ratio.

When measuring benthic primary production it would have been better to apply *and* the present method, *and* the one used by Colijn. Next to that, there are other methods to assess benthic primary production, and such methods need to be considered as well; not instead of, but additional to the present method.

For the continuous measurement of light attenuation the present sensor light pathway appeared to be too long (although the shortest one at time available); if available, additionally an even shorter sensor (2-3 cm) is needed next time.

Flow cytometer analyses appear promising, but to come to reliable results a combination with algae cell counts probably is needed.

Pelagic primary production

Despite the observation that the pelagic primary production incubations went OK, it is advised to include other methods as check, such as an oxygen optode detection and/or chlorophyll activity detection with a pulse-amplitude modulation method (PAM).

Sediment top layer light attenuation and phytobenthos motility

It would be interesting to study in more detail the sediment top layer light attenuation characteristics plus the motility of phytobenthos.

Nutrient limitations of phytoplankton growth

To find out whether light or nutrient are phytoplankton growth limiting, incubations with different nutrient additions could have been performed. A second possibility is after the bacteria activity tests following Kuipers & Van Noort (2008), being suitable to determine limiting nutrients in a water sample.

The research

The present research consisted of a two-years campaign. It must be concluded that at the end still questions remain that are related to the natural variability of such systems. To reduce such uncertainties, primary production measurements as part of a regular monitoring program are needed.

9 Personnel and acknowledgements

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A1. Quality Assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 124296-2012-AQ-NLD-RvA). This certificate is valid until 15 December 2015. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Fish Division has NEN-EN-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 1th of April 2017 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

A2. Justification

Report C163/14

Project Number: 4306119901

The scientific quality of this report has been peer reviewed by a colleague scientist and the head of the department of IMARES.

Approved: Dr Pauline Kamermans

Senior researcher aquaculture

Signature:

Date: 2015-07-02

Approved: Drs Jakob Asjes

Head Ecosystems Department

Signature:

Date: 2015-07-02