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Prepared for:

DG Rijkswaterstaat / RIKZ

# Analysis of the response of phytoplankton indicators in Dutch coastal waters to nutrient reduction scenarios

A model study with the Generic Ecological Model (GEM)

Report

December, 2004

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A. Blauw
F.J. Los

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# 1 Introduction

## 1.1 Background and problem definition

Concerns for the ecological status of the North Sea have made the bordering countries come together in the OSPAR commission to decide on measures to reduce the anthropogenic pollution of the sea. Within the OSPAR framework objectives for the ecological status of the North Sea have been agreed upon. These objectives included maximum concentrations of nutrients and phytoplankton that would not exceed the concentrations at "reference conditions" with more than 50%.

Recently the EU has adopted the Water Framework Directive (WFD) as a means to protect aquatic ecosystems from adverse human impacts. Contrary to OSPAR the WFD includes only marine waters within the first mile from the coastline for ecological objectives (12 miles for micro pollutants). Similar to OSPAR the ecological objectives in the WFD are related to the "reference conditions", if the ecosystems would not be affected by human impact.

As part of the implementation process of the WFD, the EU member states should describe and classify all aquatic ecosystems in their countries and draft ecological objectives for these ecosystems. For marine waters draft ecological objectives for phytoplankton, macrofauna and other organisms have been developed. The ecological objectives comprise indicators for ecological status, estimations of the values of these indicators at reference conditions and values corresponding with "good" ecological status.

For the definition of mitigating measures to obtain a good ecological status it is necessary to have insight in the relation between anthropogenic pressures and the indicators for ecological status. Furthermore, many objectives are defined relative to the reference conditions. Generally insufficient field data are available from the time before significant human impact on aquatic ecosystems took place. It is therefore difficult to assess what the reference conditions for most ecosystems are. Models can be used as a tool for estimating the reference conditions, provided that models are available that describe the response of the ecosystems to anthropogenic pressures adequately and sufficiently reliable information is available about the level of natural "pollution". For the effect of eutrophication on phytoplankton indicators a model study has been performed by de Vries et al. (1993) to assess reference conditions and the response to nutrient loading for Dutch coastal waters. Since their study both the water quality of the Rhine and our modelling capabilities have improved. Furthermore, some new indicators have been developed for the WFD. Therefore, RIKZ asked WL | Delft Hydraulics to perform a new model study to determine the phytoplankton response to the reduction of eutrophication and to reference conditions, focusing specifically on the areas and the indicators defined for the WFD.

## 1.2 Objectives of the study

The main objectives of this study are:

- to get quantitative insight in the relation between the nutrient loading to Dutch transitional and coastal waters and the response of a range of phytoplankton indicators; and
- to derive from this information the reduction of the nutrient loading required to meet ecological objectives, as defined within OSPAR and the WFD.

## 1.3 Structure of the report

After this introduction first the method used in this study is explained in more detail, including the models that are used. The model results for the base line simulations, without nutrient reduction, are validated with observations to get information about the reliability of the model. The validation results are described in chapter 3. The response of the phytoplankton indicators to different nutrient reduction scenarios is described in chapter 4. In this chapter also the nutrient reduction required to meet several ecological objectives is presented. Chapter 5 discusses different aspects with respect to reliability and usability of the results. Finally in chapter 6 the conclusions of this study are summarized.

## 1.4 Acknowledgements

RIKZ asked WL | Delft Hydraulics to perform the study in contract RKZ-1479. T. Prins and H. Baretta-Bekker guided the study on behalf of RIKZ. The study was performed at WL | Delft Hydraulics by A.N. Blauw (project leader) and F.J. Los, with assistance by J. Wijsman, and J. van Beek in the period September to November 2004. J.G.C. Smits did the internal review.

# 2 Material and methods

## 2.1 General approach

The main objective of this study is to get quantitative insight in the response of phytoplankton indicators, as defined for OSPAR and the Water Framework Directive, to nutrient reduction scenarios. In particular the following questions are addressed:

1. To what extent are phytoplankton indicators, as defined within OSPAR and WFD, affected by changes in nutrient loading?
2. What are the reference conditions of the water bodies in Dutch transitional and coastal waters? (These concern the values of the indicators in absence of any human impact).
3. To what level does the nutrient loading through Dutch rivers need to be reduced to meet ecological objectives as defined within OSPAR (<50% above reference conditions).
4. To what level does the nutrient loading through Dutch rivers need to be reduced to meet ecological objectives as drafted within the WFD?
5. What are the water quality objectives for the major Dutch rivers corresponding with the required nutrient reduction?
6. What would be the ecological status corresponding with the present water quality objectives, with respect to nitrogen and phosphorus in Dutch rivers?
7. What other phytoplankton indicators, that have not yet been included in OSPAR or the WFD, could be useful to demonstrate the response of the phytoplankton community to eutrophication?

Questions 2 to 6 can all be answered when the quantitative response of indicators to nutrient reduction (question 1) is clear. The quantitative response can be visualised as response curves for all relevant indicators in all water bodies defined for the WFD. If the response curve of phytoplankton indicators to nutrient reduction percentages is schematised as shown in Figure 2.1, the nutrient reductions percentages corresponding with the questions 2 – 6 can be represented as:

- % Ref: corresponding with reference conditions (question 2);
- % GES: the nutrient reduction required to achieve good ecological status (questions 3, 4 and 5), (The position of %GES relative to %Ref and %WQO is yet unknown and randomly chosen in this illustration).
- % WQO: corresponding with nutrient reduction in rivers according to present water quality objectives, (question 6).

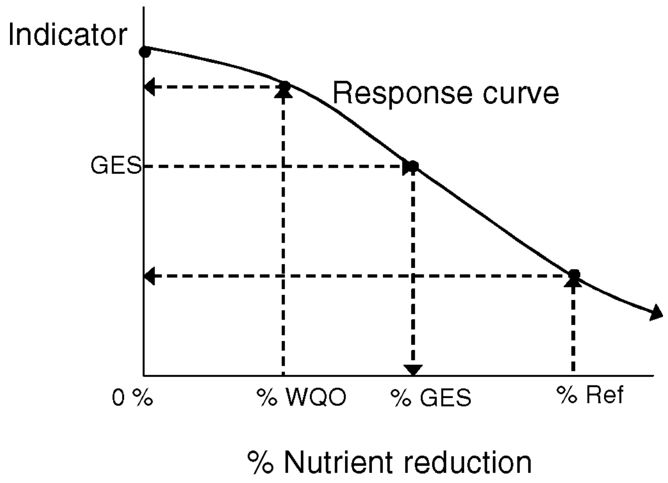



Figure 2.1: Schematic representation of a response curve of a phytoplankton indicator in relation to nutrient reduction in rivers.

The nutrient loading and transport from rivers into Dutch coastal and transitional waters show a large variation from year to year, due to variability in meteorologic conditions, especially rainfall. Meteorological conditions cause natural variability in the algal response to nutrient loading as well, for example due to solar irradiance and water temperature. These two phenomena lead to a different response of indicators to nutrient reduction scenario's in different years. In order to get insight in the range of natural variability in the response of indicators to nutrient reduction, the nutrient reduction scenarios are performed for three different years: an average year, a relatively wet year and a relatively dry year. As hydrodynamic and suspended matter simulations were available for the years 1989 and 1998 at the start of the project, we have chosen to use these years as examples of a relatively dry year (1989) and a relatively wet year (1998).

By simulating three different years, insight is gained in the uncertainty margin in the estimations of the values of indicators under the nutrient reduction scenarios %WQO and %Ref and in the estimations of the required nutrient reduction to comply with ecological objectives (%GES). Figure 2.2 illustrates how the response curves for three different years can be used to gain insight in uncertainty margins.

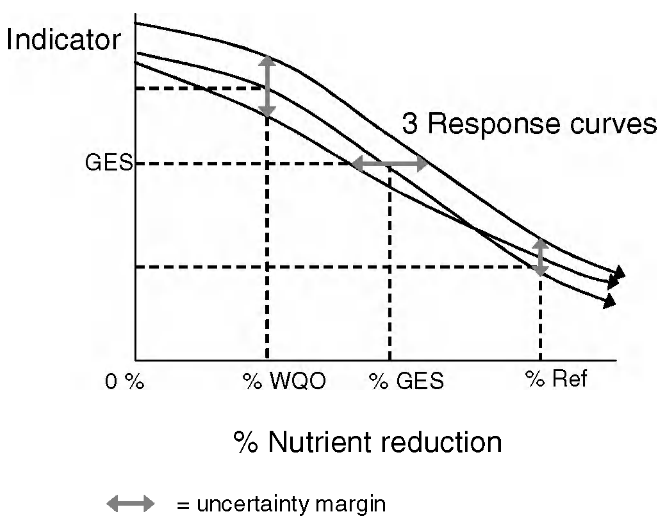



Figure 2.2: Schematic representation of a response curves for different years and uncertainty margins.

If mitigating measures are implemented to reduce the nutrient loading of Dutch coastal waters, the response of indicators in marine waters may be affected by other human impacts as well. For example land reclamations for the "Tweede Maasvlakte" may change the outflow of the Rhine and the suspended solids concentrations near the outflow. Also climate change may affect the phytoplankton community and the indicators under study. To avoid difficulties in the interpretation of results and debate on the assumed effects of these other impacts we have chosen to focus on the effects of nutrient reduction, assuming that all other conditions will remain unchanged ('ceteris paribus').

## 2.2 Definition of scenario's

As described in the general approach nutrient reduction scenarios will be simulated for three typical years: an average year, a wet year and a dry year. For pragmatic reasons the same reduction percentages are applied to all Dutch rivers and to all nutrient components (nitrate, ammonia, organic nitrogen, ortho-phosphate and organic phosphorus). We assume that the ratio between the different nutrient components is not affected by the nutrient reduction scenarios. As the turnover time of organic nutrients in the model is rather short, we expect that it will soon be available to phytoplankton, so the composition of the nutrients will not have a large impact on the modelling results. Since the present study focuses only on effects of nutrient reduction in Dutch rivers the loads from rivers debouching outside the Netherlands have been kept unchanged. For every typical year 12 combinations of N and P reduction have been simulated. These combinations are shown in Table 2.1.

Table 2.1: nutrient reduction scenarios in this study

| **Scenario** | **Nitrogen reduction (%)** | **Phosphorus reduction (%)** |
|---|---|---|
| Present situation / Base line (0%)<br>(representative of 1995 – 1998) | 0 | 0 |
| | 10 | 10 |
| Business As Usual * | 20 | 20 |
| Policy Target * | 30 | 30 |
| Deep Green * | 40 | 40 |
| | 50 | 50 |
| | 60 | 60 |
| | 70 | 70 |
| | 80 | 80 |
| Reference conditions A * (%Ref_A)** | 90 | 90 |
| Reference conditions B (%Ref_B)** | 86 | 80 |
| Present water quality objectives for rivers (%WQO) | 50 | 50 |

* The nutrient reduction percentages corresponding with the scenarios marked with * have been estimated within the EU-project EUROCAT.

**The nutrient reduction percentages marked with ** are both estimations of the reference conditions, A: according to EUROCAT project, B: according to de Vries et al. (1993).

Furthermore 9 reduction scenarios have been simulated for nitrogen reduction and phosphorus reduction separately, keeping the loading of the other nutrient at the present level (representative of 1995 – 1998). For these scenarios the same reduction percentages have been used as for the combined N and P reduction (at intervals of 10 % between 0 and 90%), except for the last two scenarios in table 2.1. These additional simulations with separate reduction of phosphorus and nitrogen have only been made for the average year. By comparing the results of these additional simulations with the results of the combined reduction scenarios, the effectiveness of nitrogen reduction can be compared with the effectiveness of phosphorus reduction.

Nutrient loading from rivers in 1989 (the dry year in this study) were much higher than at present. Therefore the baseline scenario for 1989 would not be comparable to 1998 and the average year. To account for this decreasing trend in nutrient concentrations between 1989 and 1995 the nutrient loads for 1989 have been multiplied by a correction factor of 40% for phosphorus and 15% for nitrogen (based on de Vries et al. (1998)) for the 0% reduction scenarios in the response curves. The year 1989 with thus corrected river nutrient loads can be regarded as representative of a dry year as it would occur in recent years.

The nutrient reduction percentages for nitrogen and phosphorus corresponding to the rivers meeting their water quality objectives (%WQO) have been calculated based on the report by van Liere and Jonkers (2002). According to this report the averaged concentrations in the Rhine river should be 1.8 mg N/l (annual average) and 0.08 mg P/l (summer average). At present (1995 – 1998) the annual nitrogen concentration and summer averaged phosphorus concentration in the Rhine (as observed at station 'Brienenoord' in Rotterdam) are 4.17 mg N/l (sum of nitrate, nitrite and Kjeldahl-N) and 0.18 mg P/l respectively. The reduction percentages required to meet water quality objectives in the river Rhine are therefore 55% for both nitrogen and phosphorus. Relative to river inputs over the period 1999 – 2003 the required reduction percentages would be 47% for nitrogen and 42% for phosphorus.

The estimates of reference conditions according to de Vries et al. (1993) (Reference conditions B in table 2.1) are based on Laane (1992) and Admiraal and Van der Vlught (1990). For the situation of 1987, which was used as "present situation" by de Vries et al. (1993), it was estimated that 88% of the nitrogen and phosphorus loads in the river Rhine were of anthropogenic origin. From 1987 until 1995 the average concentrations of nitrogen and phosphorus have decreased by circa 15% and 40% respectively (de Vries et al., 1998). The anthropogenic fraction of riverine nitrogen and phosphorus loads can thus be calculated as 86% and 80% respectively.

Since the concentrations of organic nitrogen and organic phosphorus in rivers are reduced in the scenario simulations, the concentrations of organic silicate should consequently decrease as well. After all, the organic fraction of the three macronutrients is mainly composed of live and dead phytoplankton. When less silicate is present in organic form, the dissolved inorganic fraction of silicate should increase. Although silicate is not the focus of this study, for consistency reasons we have reduced the concentrations of organic silicate in rivers at the same rate as the phosphorus reduction. In the model study by de Vries et al. (1993) the reduction of nitrogen and phosphorus of 88% was accompanied by an increase of dissolved inorganic silicate of 25%. In the present study we have adopted a similar estimate of the effect on dissolved inorganic silicate: for every 10% of phosphorus reduction we have increased the concentration of dissolved inorganic silicate in rivers with 2 or 3%. The adaptation of silicate loads with phosphorus reduction as described above has been applied in the simulations with separate reduction of phosphorus as well. In the simulations with nitrogen reduction only the loads of silicate have not been adapted, since we assume that phytoplankton growth in fresh waters is mainly controlled by phosphorus availability.

## 2.3 Interpretation of results

The response of phytoplankton indicators to the nutrient reduction scenarios is simulated for the water bodies defined in the WFD. The definition of the water bodies is shown in Figure 2.3.

The following water bodies are included in this study:
- Zeeland coast;
- Delta coast;
- Holland coast;
- Wadden coast;
- Westerschelde;
- Oosterschelde;
- Wadden Sea;
- Ems estuary;
- Ems coast.

As during the validation part of this study the results for the eastern part of the Wadden Sea, the Ems estuary and Ems coastal waters proved to be insufficiently adequate, response curves for these areas are not used in this study.

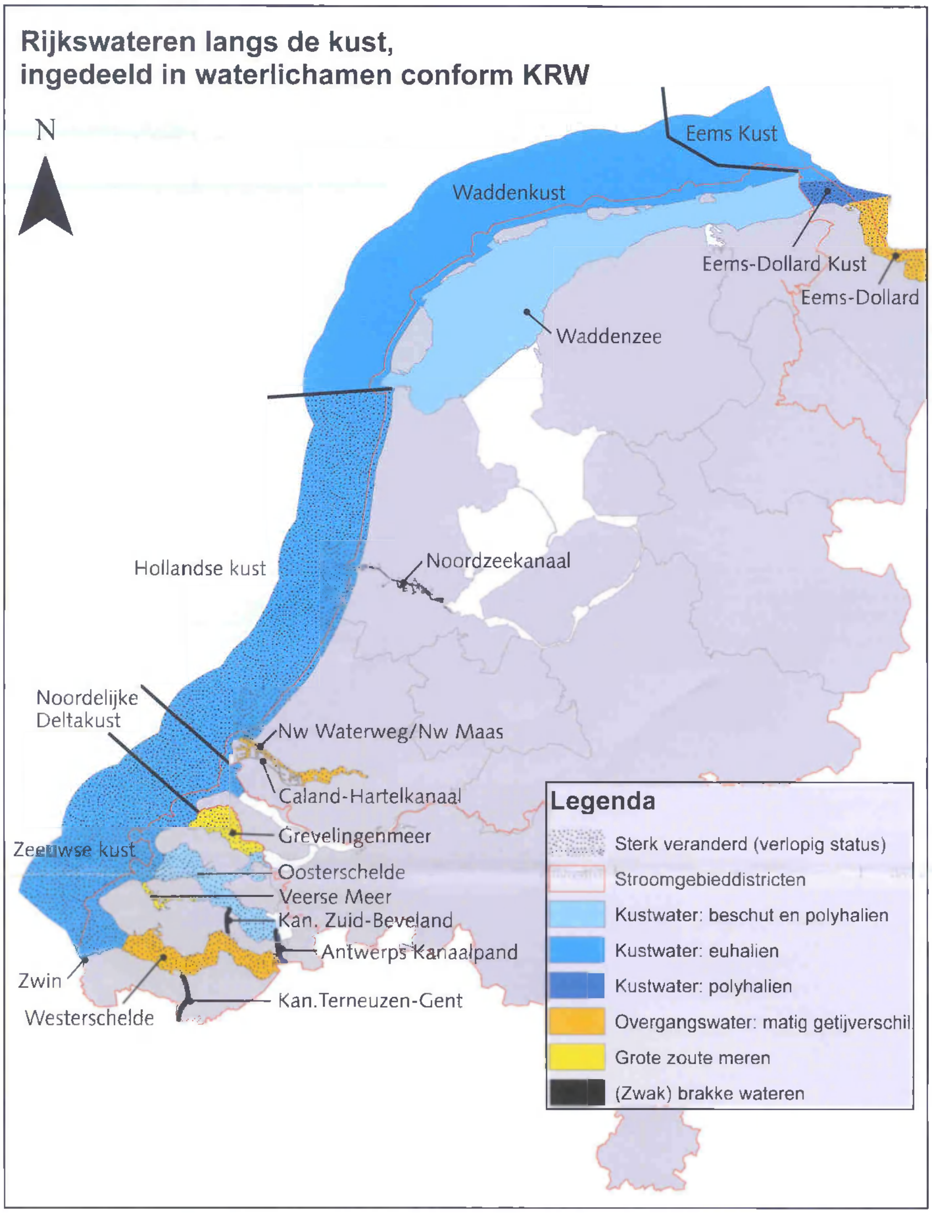



Figure 2.3: The Dutch water bodies as drafted within the WFD.

For each of these locations and areas the value of a number of indicators is calculated for each nutrient reduction scenario. The indicators include the indicators as defined for OSPAR and the preliminary set of indicators defined by the Dutch government for the Water Framework directive:

- Winter averaged concentrations of DIN and DIP. The winter period is defined as December, January and February;
- Winter averaged N/P ratio. The N/P ratio can be defined as DIN/DIP or as total N/total P. In marine waters it is more common to use the DIN/DIP definition. In fresh waters it is more common to use the total N / total P definition. We present the N/P ratio according to both definitions;
- The maximum and averaged chlorophyll-a concentration during the growing season. The growing season is defined as 1 April to 1 October;

- The maximum *Phaeocystis* bloom intensity per year. In the model all phytoplankton, including *Phaeocystis,* is simulated in the unit $gC/m^3$. Assuming that *Phaeocystis* cells contain circa 15 $10^{-12}$ gC/cell (Rousseau et al., 1990) the proposed threshold level of 10 million cells/L corresponds with 0.15 $gC/m^3$. Assuming that *Phaeocystis* cells contain circa 30 $10^{-12}$ gC/cell (Jahnke, 1989) 10 million cells/L corresponds with 0.3 $gC/m^3$.

Additionally some alternative indicators are evaluated:
- Ratio diatoms/ flagellates, expressed as the ratio of the yearly averaged biomasses of both groups;
- Daily nett primary production, averaged over the year ($gC.m^{-2}.d^{-1}$). (Please refer to appendix E for details about the definition and calculation of primary production in GEM).

In order to be able to relate the results for primary production (expressed in carbon units) with chlorophyll-a, we analyse results of phytoplankton biomass (in carbon units) as well. Since chlorophyll-a to carbon ratios in phytoplankton vary depending on growth conditions, chlorophyll-a and phytoplankton biomass may show a different decrease due to nutrient reduction.

The results for the baseline situation, without nutrient reduction, for all three years are compared with field observations to give insight in the reliability of the model results.

# 3 Model description

## 3.1 About GEM

The model used for this study is the Generic Ecological Model (GEM) for estuarine and coastal waters. GEM was developed by several Dutch marine research institutes in the period from 1995 till now. The first model documentation was written in 1997 (Smits et al., 1997). During different projects further model developments and calibration and validation of the model have taken place. An update of the model documentation took place in 2003 (Blauw et al., 2003). The model has been calibrated for the Dutch coastal zone in 1999 (Blauw et al., 1999) and was applied and validated, with (mostly) the same parameter settings, for the ecosystems listed below:

- Dutch coastal waters (Bokhorst and Los, 1997; Los and Bokhorst, 1997; Blauw et al., 1998; Blauw et al., 1999; Blauw, 1999; Blauw and Los, 2000; Wijsman, 2002);
- the Ems Estuary (Blauw and Smits, 2002; Smits et al., 2003);
- lake Veerse Meer (Nolte and Bijvelds, 2000; Smits et al., 1999, Nolte and Jansen, 1999);
- Wadden Sea and Westerschelde (Blauw and Boderie, 2001; Boon et al., 2003);
- the southern North Sea (MARE, 2002).

In this study we use the most recent application of GEM for the southern North Sea. This model application covers all areas listed above, except lake "Veerse Meer". The model grid in estuarine areas is rather course compared to the more detailed model applications for the Westerschelde, Ems estuary and Wadden Sea. Also the model input with respect to river discharge and concentrations of the Ems river is less detailed than in the detailed model (i.e. constant discharges and concentrations for an average year). Figure 3.1 shows a schematic representation of the processes included in GEM. In this study a simplified version has been used, without microphytobenthos, grazers and phosphate adsorption to suspended solids.

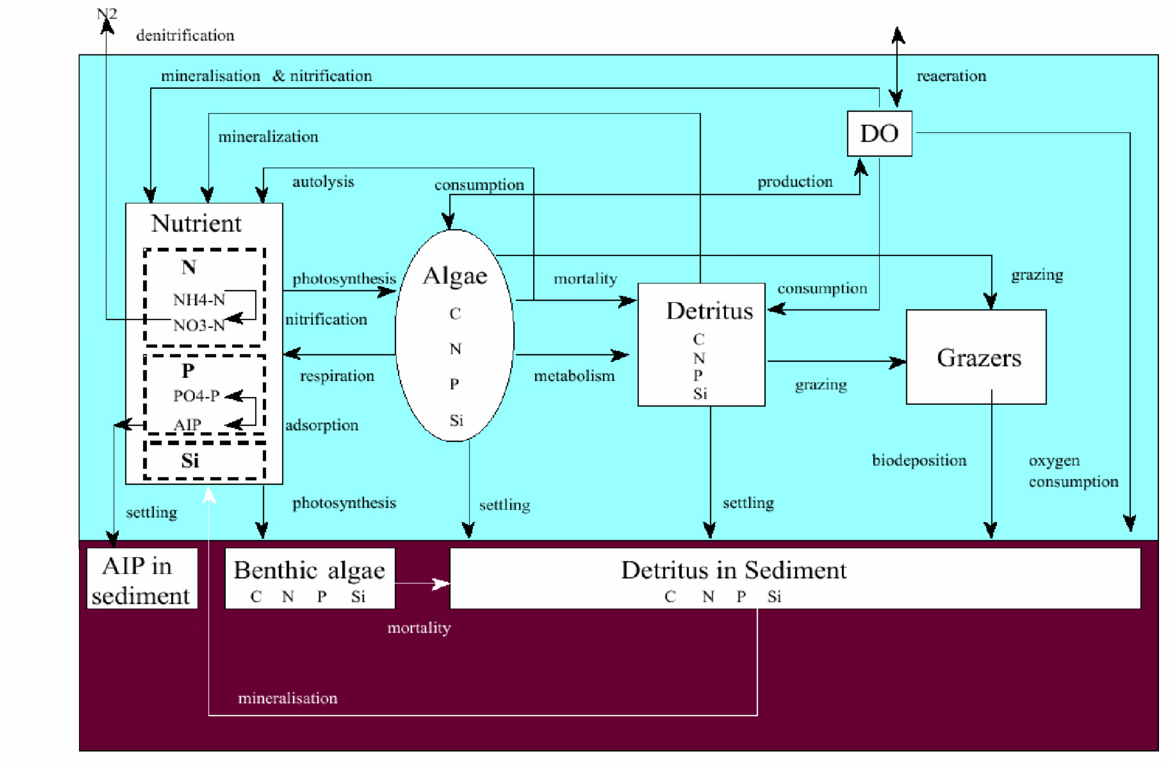



Figure 3.1: Schematic overview of the substances and processes incorporated in GEM. (In this study a simplified version has been used, without microphytobenthos, grazers and phosphate adsorption to suspended solids).

## 3.2 Set-up of the model applications in this study

### 3.2.1 Hydrodynamics

For all three year simulations used in this study the hydrodynamic model application uses the same grid (see Figure 3.2) in 3D, consisting of 10 vertical layers. The resulting flow fields of the 3D hydrodynamic models have been averaged over depth, to construct the hydrodynamic input to the 2D GEM simulations.

The hydrodynamic model application for the average year was set up for the "Flyland" study (MARE, 2003). The hydrodynamics of the average year are simulated with an average spring- neap cycle of 15 days. The wind forcing consists of a representative time series selected from KNMI data.

The hydrodynamic model application for the year 1989 (relatively dry year) was developed as part of the "Flyland" study as well (MARE, 2003). This model uses actual tidal information and wind and pressure fields for the whole year, resulting from the NOMADS project (Delhez et al., 2004). The model runs from November 1988 to November 1989.

The hydrodynamic model application for the year 1998 (relatively wet year) was developed during a research project at Delft Hydraulics, aiming at the integration of information on suspended solids concentrations from numerical modelling and remote sensing (Villars et al., 2003). The GEM application in this study is similar to the application for 1989, except that the hydrodynamic forcing, the suspended solids concentrations, the loadings and meteorologic forcings are specific for 1998.

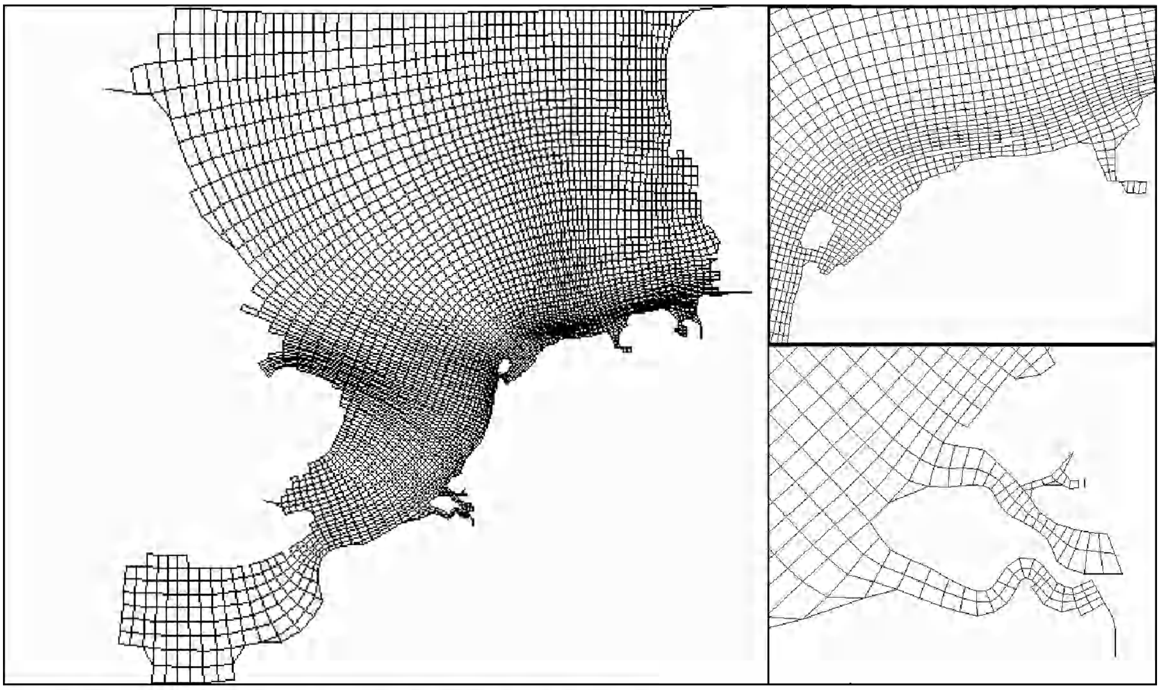


Figure 3.2: Model grid used in the hydrodynamic and GEM simulations

### 3.2.2 Initial conditions

For each model application (average year, 1989 and 1998) and each nutrient reduction scenario the initial conditions for the GEM simulations are determined by running the model two consecutive years. This is done to allow the model to adjust to the new loading conditions in particular with respect to winter nutrient concentrations and sediment-water interaction. The model results of the second year have been used for the analyses in this study.

### 3.2.3 Boundary conditions

The boundary conditions for the GEM simulations i.e. the concentrations of all substances at the boundaries in the Channel and the northern North Sea are the same in all simulations. The boundary conditions have been used as well during the "Flyland" project (MARE, 2002). Originally the boundary conditions were constructed and described in more detail during the MANS study (Los et al., 1994). At the Channel boundary the concentrations of GEM substances show a seasonal variation, based on measurements. At the Atlantic boundary the concentrations of GEM substances are constant throughout the year in the model.

### 3.2.4 Rivers and other nutrient sources

All three model applications (averaged year, 1989, 1998) contain the same point sources of nutrients and fresh water. Table 3.1 gives an overview of the rivers included in the GEM model for the southern North Sea.

Table 3.1: Rivers and other sources included in the GEM model for the southern North Sea (between brackets are the rivers that discharge through the different delta branches)

| Dutch rivers | Rivers outside Netherlands |
|---|---|
| Nieuwe Waterweg (Rhine and Meuse) | Thames |
| Westerschelde (Scheldt) | Wash |
| Ems (Ems) | Weser |
| Kornwerderzand (Rhine) | Humber |
| DenOever (Rhine) | Tyne |
| Oosterschelde (Meuse) | Seine |
| IJmuiden (Rhine) | Tees |
| Haringvliet (Rhine and Meuse) | Firth of Forth |
| | Solent |
| | Elbe |

For the years 1989 and 1998 the river discharges and concentrations of all Dutch sources except the Oosterschelde and Ems are based on actual observations at the river mouths, from the DONAR database (accessible through www.waterbase.nl). Discharge observations are generally available on a daily basis. Observations on concentrations of substances in waters are generally available one to two times per month, depending on the season. The discharges and concentrations were converted into 10 day averaged loads by RIKZ as part of another project (Blauw, 1999). Those loading files have been used again in the present study. The loads for other river sources, where frequent monitoring data are not available in the DONAR database, are based on long term averaged monthly concentrations and constant discharges.

For the average year the river loads for the Dutch rivers have been calculated by averaging the river loads per 10 day period for the years 1995 to 1998. The year 1995 has been chosen as breakpoint, as an estimation of the decreasing trend in nutrient concentrations in rivers has been estimated by de Vries et al. (1998) for the period 1989 - 1995. Furthermore, several nutrient reduction scenarios have been defined within the EUROCAT project with 1995 as reference year.

### 3.2.5 Forcings

Forcings to the model comprise the parameters: suspended solids concentrations (in order to calculate transparency), solar irradiance, wind speed (for reaeration) and water temperature. The forcing function for suspended solids is constructed from a steady state 3D suspended solids simulation, representing average conditions. The simulated suspended solids concentrations in the top layer are used as base line concentrations in the GEM simulations. A seasonal pattern of suspended solids concentrations is created by imposing a cosine function on the base line concentrations: with 150% of the base line concentration in winter and 50% of the base line concentration in summer. For the years 1989 and 1998 an additional wind effect has been superimposed in this seasonal pattern, to account for short term variations during strong wind events. The amplitude of this short term variation is a multiplication factor on the concentration at average wind speed (5.5 m/s). Therefore the amplitude is higher in areas with higher suspended solids concentrations than in other areas and the amplitude is higher in winter than in summer.

The solar irradiance for the years 1989 and 1998 consists of the daily observations by KNMI at station “de Kooy”. For the solar irradiance during the average year the observed irradiance in 1994 is used, as representative of a “normal” year. This is similar to the set-up of the average year model in the “Flyland” project.

The water temperature in the models for 1989, the average year and 1998 is based on linearly interpolated observations of water temperature at station Noordwijk 10 km in the years, 1989, 1994 and 1998 respectively.

### 3.2.6 Adaptation of the model for nutrient release from the sediment

In previous GEM studies it was concluded that GEM can simulate the dynamics of nutrients and phytoplankton accurately in most areas, except where anaerobic conditions in the sediment result in strong fluxes of ortho-phosphate and ammonia in summer. For this reason the eastern part of the Wadden Sea and the Ems estuary could not be simulated adequately. Due to the simple formulation of the sediment- water exchange (with linear decay of settled organic matter) the effect of fast release of ortho-phosphate and ammonium under anaerobic conditions in the sediment cannot be simulated accurately. This causes unrealistically low summer concentrations of these parameters, particularly in the eastern part of the Wadden Sea, which could result in a too large response to nutrient reduction scenarios. In order to keep as much as possible organic matter in the sediment available for remineralisation, the burial flux in the Wadden Sea has been reduced to zero.

# 4 Validation results

In this chapter the model results for the baseline simulations are compared with field observations at monitoring stations in all Dutch water bodies defined within the WFD. The simulation results for the average year, representing present conditions (averaged for 1995 – 1998) are compared with observations of 1995 –1998. The simulation results for the year 1989 are compared with observations of the year 1989 and with the ranges found in observations of 1988 to 1991. The simulation results for the year 1998 are compared with the observations of the year 1998 and with the ranges found in observations of 1995 to 1998. To allow for comparison with the model results the observations on *Phaeocystis* have been converted to the unit mgC/l by assuming that *Phaeocystis* cells contain circa 15 $10^{-12}$ gC/cell (Rousseau et al., 1990).

The accuracy of the model results is evaluated to assess whether reliable predictions can be made on the response to nutrient reduction scenarios. Not in all water bodies monitoring stations are located. In some cases the nearest station is more than one mile from the coast. In those cases the nearest station is used for the validation. The Figures showing the simulation results and the observations are presented in appendix A. The report of the "Flyland" study provides a more detailed description of validation results of the GEM application for the southern North Sea (MARE, 2002).

In (or near) each of the water bodies monitoring stations are located that can be used for the validation of model results in that water body. The following monitoring locations are used for the validation:

- Walcheren 2 km from the coast (Zeeland coastal waters);
- Goeree 6 km from the coast (Delta coastal waters);
- Noordwijk 2 km from the coast (Holland coastal waters);
- Terschelling 4 km from the coast (coastal waters outside Wadden Sea);
- Huibertgat oost, Rottum 3 km (Ems coastal waters);
- Vlissingen (Westerschelde);
- Wissenkerke (Oosterschelde);
- Marsdiep and Vliestroom (western Wadden Sea);
- Dantziggat (eastern Wadden Sea);
- Groote Gat Noord, Bocht van Watum (Ems estuary).

Observed data on primary production for the validation of the seasonal patterns simulated by the model are not available. Seasonal figures on simulated primary production are therefore just presented as an illustration of the results. They are not discussed in this chapter. Simulated primary production is shown averaged per WFD area because local primary production is very sensitive to local (inaccuracies in) suspended solids concentrations, salinity and water depth. Therefore we feel the results for primary production at specific monitoring stations are insufficiently reliable to be presented. Results on yearly primary production are validated and discussed in section 4.4.

## 4.1 Results for the average year

### 4.1.1 Zeeland coast

In the simulation for the averaged year at station Walcheren 2 km (Figure A.1) simulated salinity corresponds well to the range of values that is found in observations, suggesting that the transport of fresh water from the Rhine and Scheldt is simulated reasonably well. The chlorophyll-a spring peak is underestimated and delayed. The timing of the spring bloom is generally strongly affected by the underwater light climate, which is in turn strongly affected by suspended solids concentrations in this area. The imposed concentrations of suspended solids in the average year correspond with the lowest observations of the range of natural variability. Higher suspended solids concentrations would delay the spring bloom even more, suggesting that local suspended solids concentrations are not the cause of the delayed spring bloom. Probably the transport of chlorophyll-a from nearby waters is underestimated. Chlorophyll-a concentrations during summer are underestimated as well. In the model primary production at this station is limited by phosphorus in summer. Simulated concentrations of nitrate, ortho-phosphate and silicate correspond well to observations, despite a delay in the drop of phosphorus and silicate concentrations during the spring bloom and slightly underestimated winter concentrations of all three nutrients. The timing and height of the *Phaeocystis* bloom are simulated correctly. The results at station Schouwen 10 km (not shown) show similar patterns for all parameters to those at station Walcheren 2 km.

The fluctuations that are visible in the figures for nitrate, ortho-phosphate, dissolved silicate and salinity are due to tidal currents. The model output is written only every 7 days, which is not always at the same phase of the tide. As there is a cross-shore gradient of nutrients and salinity near station Walcheren 2 km, concentrations at this station fluctuate with the tide.

### 4.1.2 Delta coast

Simulated salinity at Goeree 6 km (Figure A.2) in winter and spring is circa 5 to 10 psu lower than the observations. In summer and autumn simulated salinities correspond with the observations. Suspended solids concentrations correspond well to the observations. The concentrations of the nutrients nitrate, ortho-phosphate and silicate are overestimated in winter and spring, due to too much import of nutrient rich fresh water. During the rest of the year nutrient concentrations are simulated correctly. The simulated chlorophyll-a concentrations are well within the range of natural variability indicated by the observations. The spring peak is predicted circa one month too late and somewhat too low. The *Phaeocystis* peak is predicted circa one month too late and a factor 2 too low. The rest of the *Phaeocystis* bloom is predicted correctly. The high fresh water import during winter and early spring decreases the transparency by its high content of humic substances. This may be the reason to the delay of the spring phytoplankton bloom.

### 4.1.3 Holland coast

Simulated salinities correspond well with observed salinities along the whole Noordwijk transect. The suspended solids concentrations in the model at Noordwijk 2 km (Figure A.3) are 2 to 3 times higher than the observations. At the stations Noordwijk 10 km, 20 km and 70 km (Figure A.4 – A.6) the suspended solids concentrations in the model correspond well to the observations. Simulated chlorophyll-a concentrations at station Noordwijk 2 km are underestimated by a factor of circa two. At the other stations along the Noordwijk transect simulated chlorophyll-a concentrations correspond well with the range found in observations. Simulated *Phaeocystis* concentrations are largely underestimated at station Noordwijk 2 km. At station Noordwijk 10 km, *Phaeocystis* bloom intensity is simulated correctly, but bloom timing is circa one month too late. At station Noordwijk 20 km *Phaeocystis* is simulated correctly. At station Noordwijk 70 km *Phaeocystis* bloom intensity is overestimated by the model. Simulated nitrate and silicate concentrations correspond well with the measurements at all 4 monitoring stations along the Noordwijk transect. Simulated ortho-phosphate concentrations in winter are circa 50 % higher than the observations. During the rest of the year the simulated ortho-phosphate concentrations correspond well with the observations. At the near-shore stations Noordwijk 2 km and 10 km silicate is depleted during summer. Further from the coast (Noordwijk 10 km and 20 km) also ortho-phosphate concentrations are depleted to limiting concentrations during late spring and summer. In the model the period of phosphorus limitation at these stations is longer than in the measurements. The duration of the period with limiting nitrate concentrations increases from circa 1 month at station Noordwijk 10 km to 6 months at station Noordwijk 70 km. This pattern of varying nutrient limitations along the Noordwijk transect corresponds to the findings of Peeters et al. (1993).

### 4.1.4 Wadden coast

Simulation results at the stations Terschelling 4 km and 10 km (Figures A.7 and A.8) for chlorophyll-a, *Phaeocystis,* salinity, suspended solids, nitrate and dissolved silicate correspond all very well with the observations. The simulated concentrations of ortho-phosphate are slightly overestimated in January and February and underestimated in summer. But in general also the concentrations ortho-phosphate corresponds reasonably well with the observations.

### 4.1.5 Ems coast

At station Huibertgat oost (Figure A.9) simulated salinity is higher than observed, so the input of fresh water into the coastal area is underestimated. Suspended solids concentrations in the model correspond well with the observations. Simulated ortho-phosphate concentrations are much too low in summer and autumn. Simulated nitrate concentrations are underestimated year round, which is probably due to too low fresh water input. Simulated silicate concentrations are too low in winter. The silicate depletion in summer is simulated correctly by the model. Despite all this, chlorophyll-a concentrations do not deviate too much from the observations. The peak of the *Phaeocystis* bloom is simulated circa two months too early, but the intensity of the peak is simulated correctly. Station

Rottum 3 km (not shown) near the Ems coast area shows similar patterns as station Huibertgat oost.

### 4.1.6 Westerschelde

Simulated salinity at Vlissingen (Figure A.10) corresponds fairly well to the observations. Suspended solids concentrations are too low in the model, especially during the winter months. All nutrient concentrations are too low in early winter. This is mostly due to too slow replenishment of nutrients in summer and autumn of the previous year. The nitrate concentrations agree well with observations in summer. The simulated ortho-phosphate concentrations drop too late in spring, due to the delayed spring bloom, and recover much slower than the observed concentrations in summer and autumn. Simulated chlorophyll-a concentrations at station Vlissingen are reasonably well in agreement with the observations, except for the spring bloom being simulated circa one month too late. Simulated *Phaeocystis* concentrations are well within the range of the observations.

### 4.1.7 Oosterschelde

Simulated salinity corresponds well to the observations at station Wissenkerke (Figure A.11). Suspended matter concentrations are at the upper end of the range found in observations. Similarly to the Westerschelde, nitrate and silicate concentrations are underestimated in winter. Simulated ortho-phosphate concentrations decrease later in spring than the observations and recover much slower than the observations. Simulated chlorophyll-a concentrations correspond with the range and seasonal dynamics found in the observations. Simulated *Phaeocystis* concentrations are well within the range of the observations.

### 4.1.8 Wadden Sea

The eastern and the western part of the Wadden Sea are separated by a tidal divide. The two regions have different characteristics with respect to tidal volume and relative importance of tidal flats. Furthermore the western part of the Wadden Sea is strongly influence by the discharge of fresh water from Lake IJssel.

At the stations Marsdiep (Figure A.12) and Vliestroom (not shown) in the western part of the Wadden Sea the modelling results are rather similar to the station Terschelling 4 km. Salinity, suspended solids and the winter concentrations of nitrate and silicate correspond all well with the observations. The simulated concentrations ortho-phosphate are slightly overestimated in January and February and underestimated in summer. But in general also the concentrations ortho-phosphate corresponds reasonably well with the observations. The concentrations of dissolved silicate are slightly overestimated in summer. This is probably caused by too low primary production due to too much phosphorus limitation, indicated by rather low chlorophyll-a concentrations compared to the observations. The *Phaeocystis* bloom has the correct magnitude but it is simulated too early in the year. At the stations Doove Balg (east and west) and Blauwe Slenk (not shown) the overestimation of ortho-phosphate in winter and underestimation in summer are much larger. At the latter three stations silicate concentrations are overestimated by the model in summer.

At monitoring station Dantziggat (Figure A.13) in the eastern part of the Wadden Sea simulated salinities are within the (large) range of the observations. Nitrate concentrations are simulated correctly. Ortho-phosphate concentrations are largely underestimated from April through October. The simulated seasonal pattern of dissolved silicate does not correspond to the observed pattern: winter concentrations are too low and decreases and increases of concentrations are a few months too late. Chlorophyll-a concentrations are underestimated by the model from March through September. The *Phaeocystis* bloom has the correct magnitude but it is simulated too early in the year.

### 4.1.9 Ems estuary.

Similarly to the results in the area Ems coast the concentrations of chlorophyll-a in the Ems estuary (Figure A.14) are simulated conform the observations, although all other parameters are simulated poorly. Silicate concentrations in the model are much lower than the observations, salinity is much higher and lacks seasonal variation. Simulated ortho-phosphate concentrations are much too high in winter and much too low in summer.

## 4.2 Results for 1989

During and after the Flyland project many simulations were conducted for the relatively dry year 1989. Some of these used 3D, others 2D vertically averaged hydrodynamic forcing. Because much effort has been put into optimizing the hydrodynamic forcing for 1989, the overall agreement between observations and GEM model for 1989 is good. This general conclusion is confirmed during the simulation performed within the framework of this project. Thus it is sufficient to present a limited number of representative results in this report. We have chosen stations Noordwijk 2, Noordwijk 10 and Terschelling 4. Results are compared to the measurements of 1989 (dots) and to the average, median and 90 percentile error bars for the years 1988 – 1991.

### 4.2.1 Holland Coast

At the station Noordwijk 2 (Figure A.15) salinity is simulated rather well, although concentrations tend to be low in summer compared with the measurements. Because we have used the same spatial suspended matter distribution for all simulations, concentrations are much too high also in this simulation. This means that the extinction due to suspended matter is overestimated in the model and as a result chlorophyll concentrations are too low during the production season. Because biomass levels are low relative to the available amounts of nutrients, their simulation results are hardly affected by the underprediction of chlorophyll. Thus simulated results of $NO_3$, $PO_4$ and dissolved Si agree rather well with the measurements, indicating that the hydrodynamic processes are simulated with sufficient accuracy.

At the station Noordwijk 10 (Figure A.16) both the simulated salinity and suspend matter agree well with the measurements. This means that the hydrodynamic and light forcing is sufficiently accurate. As a result simulated chlorophyll levels agree well with the measurements with respect to timing and average level, although in summer the observed level of variation is larger than simulated. Initial concentrations of all three nutrients are too high, which seems to be due to the hydrodynamic forcing since initial salinity levels are too low. During the production season computed levels of $NO_3$ and dissolved Si agree very well with the observations. The same holds for $PO_4$ with the exception of a two month period in summer which is probably due to an underestimation of the release from the sediment (See 3.6.2 for a more detailed explanation).

### 4.2.2 Wadden Coast

Similar to station Noordwijk 10, salinity and suspended matter agree sufficiently well with the measurements at Terschelling 4 (Figure A.17). The simulated pattern for chlorophyll is in accordance with the measurements, but absolute values are relatively low during the summer half year. Since both $NO_3$ and $PO_4$ are limiting in this part of the year, it seems that the availability of one or both nutrients is underestimated. Looking at the results and considering that the computed summer levels of $PO_4$ are generally too low, an underestimation of the release of $PO_4$ from the sediment is the most plausible explanation for the relatively low simulated chlorophyll levels in summer.

## 4.3 Results for 1998

The hydrodynamic modelling results for the relatively wet year 1998 were less rigorously validated than those for 1989. Simulated salinities at for example the Noordwijk transact indicate that the shape of the 'coastal river' is less accurately simulated than for 1989. This impairs the horizontal spreading of nutrients in the coastal zone has an impact on the simulated phytoplankton kinetics of GEM. As an additional complication nutrient loadings for the years 1995 through 1998 were determined independently from those for 1975 through 1994. This might cause some systematic differences in the model input (See also section 6.1 and appendix D for more details).

### 4.3.1 Zeeland Coast

The Southern part of the Dutch coastal zone is much less affected by changes in river discharges, density currents and loadings than Holland Coast. Therefore in 1998 observed and simulated levels for this area (Figure A.18) are similar to those for 1989.

### 4.3.2 Delta Coast

At the Goeree 6 station (Figure A.19) the simulated average level of salinity is in accordance with the measurements, but clearly the simulations show much more dynamic variations. With the exception of the size of the spring bloom, which is underestimated, there is sufficient agreement between model and observations with respect to the level and dynamics of chlorophyll. Simulations for all three dissolved nutrients: $NO_3$, $PO_4$, and dissolved Si show a good comparison to the measurements, with the exception of a peak at the end of the simulation, which coincides with a strong dip in the salinity simulation.

### 4.3.3 Holland Coast

At both stations Noordwijk 2 and Noordwijk 10 (Figures A.20 and A.21) the computed salinity levels are clearly below the measurements indicating that the horizontal transport perpendicular to the coast is too strong. The underprediction for chlorophyll at Noordwijk 2, which manifests itself in all simulations because of an overestimation of the amount of suspended matter, is even worse during the 1998 simulation because there is some $PO_4$ limitation in the model. Simulated levels of $NO_3$ and dissolved Si are below the measurements. Results for the dissolved nutrients clearly agree with the conclusion for salinity: there is too much horizontal mixing of the Rhine coastal river in the hydrodynamic simulation for 1998.

Unlike results for the average year and for 1989, simulated chlorophyll levels for 1998 at Noordwijk 10 (Figure A.21) are low compared with the measurements. This is due to an underestimation of the available amounts of both $PO_4$ as well as $NO_3$, which are limiting for four respectively two months during the summer half year. Again: this is most likely caused by too much dilution of the river Rhine plume with waters from marine sources with much lower nutrient contents. The period in which *Phaeocystis* occurs in the model agrees with the observations, but the amount is too small due to nutrient limitation.

It is interesting that simulated chlorophyll levels are also low at the Noordwijk 20 station (Figure A.22), where the simulated salinity levels agree fairly well with the measurements. In the model $PO_4$ is limiting for no less than 5 months so it must be concluded that these low chlorophyll levels are caused by an underestimation of the availability of phosphorus.

### 4.3.4 Wadden Coast

Results for station Terschelling 4 (Figure A.23) agree to those for Noordwijk 20: salinity agrees well with the measurements, indicating that transport nutrients is simulated correctly. The timing of the phytoplankton dynamics agrees with the measurements, but concentrations during the spring peak and during summer are on the very low side of the range of observations. $NO_3$ and $PO_4$ are both limiting. Simulated levels of $NO_3$ agree with the measurement, but summer $PO_4$ levels are too low. Dissolved Si is simulated very accurately. Simulated values for *Phaeocystis* are below the 1998 observations, but exceed the range of observations in 1995 - 1998.

### 4.3.5 Wadden Sea

At the station Marsdiep (Figure A.24) simulated levels of salinity are below the measurements during the first three months, but otherwise agree with the observations. Simulated levels of chlorophyll are consistently on the very low side of the range of observations. Although at this station light is the main limiting factor, it seems more likely that the low chlorophyll levels must be contributed to an underestimation of the $PO_4$ levels in the Wadden Sea. Simulations for $NO_3$ and $PO_4$ are similar to the observations, although $NO_3$ levels exceed the measurements periodically when the simulated salinity is too low. Unlike in other simulations or at other locations, the dynamics of the dissolved Si results do not agree with the observations: summer levels are too high. The most probable explanation is an underestimation of the dissolved Si uptake by diatoms, indicated by too low concentrations of chlorophyll-a. Model results for *Phaeocystis* are below the 1998 measurements, but not below the average of observations in 1995 - 1998.

## 4.4 Conclusions

Tables 4.1 to 4.5 summarize the comparison of the model with the observations, for the parameters that are used as indicators in this study. Winter nutrient concentrations have been averaged over the winter period (October – March); chlorophyll-a concentrations have been averaged over the summer period (April – September) and primary production has been cumulated over the year. All observations have been averaged per season without correcting for eventual bias due to irregular sampling effort in different months and years. For the ratio between diatoms and flagellates no data are available for comparison with the model. The tables show that nitrogen concentrations in winter are predicted rather well in most areas, except for overprediction at station Goeree 6 km. Also winter DIP concentrations do not deviate much from the observations. Summer averaged chlorophyll-a and maximum *Phaeocystis* bloom intensities are clearly underpredicted at the stations Noordwijk 2 km and Marsdiep. In the other areas there is no systematic underprediction or overprediction. The levels simulated in the different years correspond with the range of levels found in the observations.

Only few data are available for comparison on primary productivity in Dutch coastal waters. In table 4.5 field estimates of primary productivity by Peeters et al. (1991) at the stations Noordwijk 2 km and Terschelling 4 km are compared with simulated primary production, aggregated over the areas Holland coast and Wadden coast. In the model the primary production at station Noordwijk 2 km is strongly underpredicted and the primary production at station Terschelling 4 km is strongly overpredicted. The simulated primary production at the stations Noordwijk 10 km and Terschelling 10 km corresponds with the range estimated by Peeters et al. (1991). Local underprediction or overprediction of primary production is often compensated, when primary production is aggregated over larger areas. After all, when the uptake of nutrients by phytoplankton is too low in one location, this allows for extra uptake and primary production in other nearby locations. This effect shows for example along the Noordwijk transect and outside the Wadden Sea: primary production at Noordwijk 20 km is overestimated due to underestimation at Noordwijk 2 km. Similarly primary production at Terschelling 4 km is overestimated due to underestimation in the western Wadden Sea. Due to this compensation effect local chlorophyll-a concentrations often correspond better to local field observations than local simulated primary production corresponds to local field estimates of primary production. For the same reason primary production aggregated over larger areas often corresponds better to field estimates than local primary production. As in this study the primary production is averaged over the water bodies, the results are likely to be more reliable than results for specific monitoring stations.

In conclusion the simulation results correspond rather well to the observations except in the eastern part of the Wadden Sea and the Ems estuary and Ems coast. In shallow areas the return flux of ortho-phosphate from the sediment in summer and autumn is underpredicted, resulting in too low ortho-phosphate concentrations. In shallow areas with tidal flats this phenomenon is more pronounced than in open coastal waters. For the interpretation of the response to nutrient reduction this means that the effect of phosphorus limitation may be stronger in the model than in reality. Unfortunately the results for salinity and suspended solids in the simulations for 1989 and 1998 do not correspond better to observations for these years than the simulations for the average year, despite more detail in the forcings.

Table 4.1: Comparison of winter averaged DIN concentrations (mgN/l) in model simulations and field observations

| | model 1989 | observations 1988 – 1991 | model average | model 1998 | observations 1995 – 1998 |
|---|---|---|---|---|---|
| Delta coast (Goeree 6 km) | 1.2 | 0.6 | 1.3 | 1.1 | 0.6 |
| Holland coast (Noordwijk 2 km) | 0.8 | 0.9 | 0.7 | 0.6 | 0.7 |
| W. Wadden Sea (Marsdiep) | 0.8 | 0.6 | 0.8 | 0.8 | 0.6 |
| Oosterschelde (Wissenkerke) | 0.6 | 0.5 | 0.4 | 0.4 | 0.5 |
| Wadden coast (Terschelling 4 km) | 0.3 | 0.4 | 0.3 | 0.3 | 0.3 |
| Zeeland coast (Walcheren 2 km) | 0.5 | 0.5 | 0.3 | 0.3 | 0.5 |
| Westerschelde (Vlissingen) | 1.1 | 1.0 | 0.6 | 0.6 | 1.0 |

Table 4.2: Comparison of winter averaged DIP concentrations (mgP/l) in model simulations and field observations

| | model 1989 | observations 1988 - 1991 | model average | model 1998 | observations 1995 – 1998 |
|---|---|---|---|---|---|
| Delta coast (Goeree 6 km) | 0.08 | 0.06 | 0.07 | 0.05 | 0.04 |
| Holland coast (Noordwijk 2 km) | 0.08 | 0.09 | 0.05 | 0.04 | 0.05 |
| W. Wadden Sea (Marsdiep) | 0.06 | 0.05 | 0.05 | 0.04 | 0.03 |
| Oosterschelde (Wissenkerke) | 0.08 | 0.06 | 0.03 | 0.03 | 0.03 |
| Wadden coast (Terschelling 4 km) | 0.04 | 0.03 | 0.03 | 0.03 | 0.03 |
| Zeeland coast (Walcheren 2 km) | 0.07 | 0.05 | 0.03 | 0.03 | 0.04 |
| Westerschelde (Vlissingen) | 0.13 | 0.10 | 0.05 | 0.04 | 0.06 |

Table 4.3: Comparison of summer averaged chlorophyll-a concentrations (µg Chlfa/l) in model simulations and field observations

| | **model 1989** | **observations 1988 - 1991** | **model average** | **model 1998** | **observations 1995 – 1998** |
|---|---|---|---|---|---|
| Delta coast (Goeree 6 km) | 21 | 15 | 14 | 15 | 18 |
| Holland coast (Noordwijk 2 km) | 6 | 12 | 6 | 4 | 15 |
| W. Wadden Sea (Marsdiep) | 8 | 14 | 6 | 5 | 16 |
| Oosterschelde (Wissenkerke) | 11 | 6 | 5 | 6 | 8 |
| Wadden coast (Terschelling 4 km) | 6 | 8 | 8 | 4 | 10 |
| Zeeland coast (Walcheren 2 km) | 15 | 14 | 7 | 8 | 14 |
| Westerschelde (Vlissingen) | 8 | 10 | 10 | 9 | 12 |

Table 4.4: Comparison of maximum *Phaeocystis* bloom intensity (mgC/l) in model simulations and field observations

| | **model 1989** | **model average** | **model 1998** | **observations 1990- 2000 (15 $10^{-12}$ gC/cell)** | **observations 1990- 2000 (30 $10^{-12}$ gC/cell)** |
|---|---|---|---|---|---|
| Delta coast (Goeree 6 km) | 0.19 | 0.23 | 0.32 | 0.12 | 0.25 |
| Holland coast (Noordwijk 2 km) | 0.25 | 0.10 | 0.19 | 0.23 | 0.47 |
| W. Wadden Sea (Marsdiep) | 0.18 | 0.27 | 0.37 | 0.65 | 1.30 |
| Oosterschelde (Wissenkerke) | 0.24 | 0.24 | 0.17 | 0.16 | 0.31 |
| Wadden coast (Terschelling 4 km) | 0.26 | 0.37 | 0.31 | 0.13 | 0.26 |
| Zeeland coast (Walcheren 2 km) | 0.38 | 0.43 | 0.27 | 0.29 | 0.58 |
| Westerschelde (Vlissingen) | 0.30 | 0.27 | 0.10 | 0.06 | 0.11 |

Table 4.5: Comparison of yearly total primary production ($gC.m^{-2}.y^{-1}$) in model simulations and field estimates by Peeters et al. (1991)

| | **model 1989** | **model average** | **model 1998** | **observation 1988** | **observation 1989** | **observation 1990** |
|---|---|---|---|---|---|---|
| zone Holland coast | 256 | 147 | 227 | 108 | 258 | 291 |
| Noordwijk 10 km | 690 | 532 | 622 | | | 572 |
| zone Wadden coast | 471 | 501 | 345 | 272 | 294 | 337 |
| Terschelling 10 km | 314 | 295 | 334 | | 250 | 442 |

# 5 Responses to nutrient reduction

## 5.1 Introduction

In the next sections the response curves of the indicators included in this study are presented for the Dutch water bodies defined for the WFD. The model results for the indicators have been averaged over the areas covered by the water bodies (see Figure 2.3). As discussed under the validation (chapter 4) the model results for the eastern part of the Wadden Sea and the estuarine and coastal waters near the Ems outflow did not correspond well with the observations. Therefore we will not discuss the response to nutrient reduction for those water bodies in this study. The figures with response curves are shown in appendix B for combined reduction of both N and P en appendix C for separate reduction of N and P.

## 5.2 Phenomena determining the shape of response curves

To understand these curves it is essential to have some basic understanding of the limiting factors of the marine systems discussed here and how they vary in time and space. Due to the tidal motion the area of concern exceeds the borders of the zones distinguished for the water framework directive.

In the winter months phytoplankton in Dutch coastal waters is generally limited by the availability of light, in spite of the relatively small depth, because the turbidity is high. In the summer half year phytoplankton dynamics are more complicated because three different nutrients (DIN, DIP en dissolved Si) may get limiting locally in addition to light which remains an important limiting factor in several turbid areas.

Within the framework of the Flyland project Van Gils and Tatman (2002) demonstrated that the total light attenuation K in the North Sea can accurately be described by the following equation:

$$K_d = 0.067 + 0.081 \times \left(19.4 - \frac{\text{Salinity}}{1.8}\right) + 0.30 \times \text{POC} + 0.036 \times \text{Ashweight}_{<15\text{mg/l}} + 0.005 \times \text{Ashweight}_{>15\text{mg/l}}$$

in which POC is particular organic carbon and $\text{Ashweight}_{<15\text{mg/l}}$ and $\text{Ashweight}>_{15\text{mg/l}}$ are the small respectively large fraction of inorganic suspended matter.

In front of the coast of Zeeland light is the main limiting factor all year round due to the high turbidity by suspended matter. Light is also the main limiting factor in the North Delta coast. Nutrients have no significant impact here because ample nutrients enter this area through the Haringvliet. In fact the primary productivity in this area is negatively related to the outflow because with a decrease in salinity the extinction coefficient due to non-algal material increases hence less light is available for growth. Outflow of both Haringvliet and Nieuwe Waterweg strongly affect the Dutch coastal zone area. Roughly speaking south of IJmuiden light is the main limiting factor even in summer because suspended matter concentrations are high, salinity is low and nutrients are abundant. However, further north along Holland coast suspended matter concentrations are lower, and due to further mixing of the Rhine plume with marine waters the salinity is higher and the nutrient concentrations are lower. Hence limitations of all three macro nutrients occur in this area. In the Wadden Coastal zone nutrient limitations, particularly by phosphorus, occur frequently in summer. The western part of the Wadden Sea is similar to the Wadden Coast.

The pattern of limiting factors also affects the phytoplankton composition and internal stochiometry. Light limitation favours shade-adapted species with high chlorophyll content per unit of biomass and high internal nutrient levels. Nutrient limitations are advantageous to species with low nutrient requirements. These species contain relatively little chlorophyll per unit of biomass. As an implication nutrient reductions usually affect chlorophyll concentrations more strongly than biomass expressed in units of volume or mass.

An important question is what happens if we reduce the loading of one or two nutrients? If this nutrient is already limiting, an immediate response is expected, which may be fairly proportional if the phytoplankton community is already optimally adjusted to the limitation. In areas where light limitation prevails under present conditions, the initial response will be slower because the surplus in nutrients has to be removed first. A less than proportional response is also expected if there is variation in the limiting factors within a zone.

If we take a closer look at the model results, it may be observed that the responses for the different years are similar in shape, but not identical. The relative position of the response curves of the three years differs between the areas: in some areas the average year shows a relatively strong response to nutrient reduction, compared to other years, whereas in other areas the response of the average year may be similar to the wet year and the dry year is different. Several factors may be relevant for explaining the similarity and dissimilarity between years:

- Differences in discharges for instance between a dry and a wet year;
- The contribution of fresh water to the total extinction which also varies between wet and dry years;
- The hydrodynamic mixing between river water and sea water is different for all three years simulated.

Comparing a wet to a dry year, it is obvious that the nutrient loadings are relatively high under wet conditions, which results in a higher potential production. In contrast the salinity decreases locally which results in an enhanced light limitation. In the Dutch coastal area from Hook of Holland to IJmuiden, where light is already limiting, biomasses in wet years therefore tend to be relatively low. Since the loading of nutrients is enhanced and less nutrients are used for primary production in this area, more dissolved nutrients are transported to nutrient limited areas further north and to the west. Hence in these areas phytoplankton biomasses tend to be relatively high in wet years. This picture is further complicated by differences in hydrodynamics, which also vary between years.

## 5.3 Winter nutrients

As could be expected the concentrations of inorganic nutrients, DIN and DIP, decrease linearly with nutrient reduction. The N/P ratios decrease slightly with nutrient reduction, even though nitrogen and phosphorus are reduced at the same rate. As the input of nutrients from rivers becomes less with nutrient reduction, the fraction sea water from the central

North Sea water determines more and more the N/P ratio. Therefore the N/P ratio gets closer to the Redfield ratio (16).

Within the WFD no targets have been defined for winter nutrients. Within OSPAR the objectives for winter averaged DIN and DIP concentrations are defined at 50% above the reference concentrations. The reference concentrations have been simulated within this study for three years (wet, dry and average) and with two definitions of reference conditions: A (90% reduction of both N and P) and B (86% N and 80% P reduction) (see also section 2.2 of this report). Tables 5.1 and 5.2 show the required nutrient reduction percentage per area needed to comply with the OSPAR objectives for DIN and DIP. The nutrient reduction percentages are expressed as ranges, reflecting the uncertainty about the reference level (two estimations available) and the response curves (three years available).

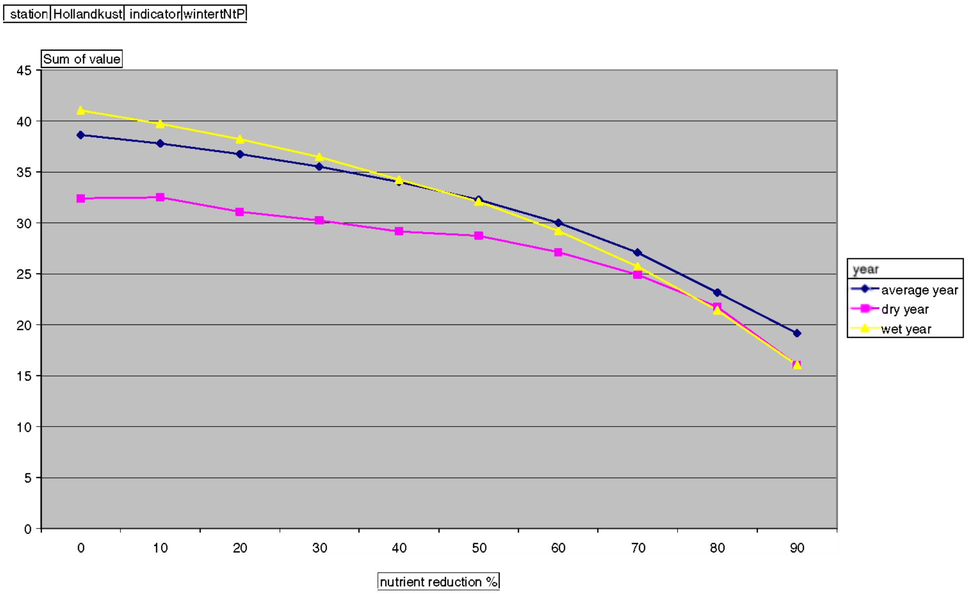
Table 5.1: Nutrient reduction % per WFD area, required to comply with the threshold winter averaged DIN concentrations (mg N/l) for non-problem areas, as defined within OSPAR.

| **Area** | **DIN reference** | | **DIN threshold (= 150% * reference)** | | **required nutrient reduction, (including uncertainty due to different references and different years) (%)** |
|---|---|---|---|---|---|
| **reference** | **A** | **B** | **A** | **B** | |
| Delta coast | 0.23 | 0.29 | 0.35 | 0.44 | 80 – 90 |
| Holland coast | 0.12 | 0.15 | 0.18 | 0.22 | 80 – 90 |
| W. Wadden Sea | 0.13 | 0.15 | 0.20 | 0.23 | 70 - 80 |
| Oosterschelde | 0.08 | 0.09 | 0.12 | 0.13 | 80 |
| Wadden coast | 0.06 | 0.06 | 0.09 | 0.09 | 70 – 80 |
| Zeeland coast | 0.09 | 0.10 | 0.14 | 0.15 | 70 - 80 |
| Westerschelde | 0.19 | 0.23 | 0.3 | 0.35 | 80 - 90 |

Table 5.2: Nutrient reduction % per WFD area, required to comply with the threshold winter averaged DIP concentrations (mg P/l) for non-problem areas, as defined within OSPAR.

| **Area** | **DIP reference** | | **DIP threshold (= 150% * reference)** | | **required nutrient reduction, (including uncertainty due to different references and different years) (%)** |
|---|---|---|---|---|---|
| **reference** | **A** | **B** | **A** | **B** | |
| Delta coast | 0.017 | 0.023 | 0.026 | 0.035 | 70 - 80 |
| Holland coast | 0.017 | 0.021 | 0.026 | 0.031 | 40 – 80 |
| W. Wadden Sea | 0.013 | 0.016 | 0.02 | 0.024 | 30 – 80 |
| Oosterschelde | 0.017 | 0.019 | 0.026 | 0.029 | 30 – 70 |
| Wadden coast | 0.013 | 0.014 | 0.02 | 0.021 | 30 - 50 |
| Zeeland coast | 0.018 | 0.020 | 0.027 | 0.030 | 20 – 30 |
| Westerschelde | 0.019 | 0.026 | 0.029 | 0.039 | 60 - 80 |

In this study we have determined the N/P ratio in two ways: as winter averaged DIN/DIP concentrations and as winter averaged totN/totP concentrations. Figure 5.1 demonstrates that both definitions gave very similar results.



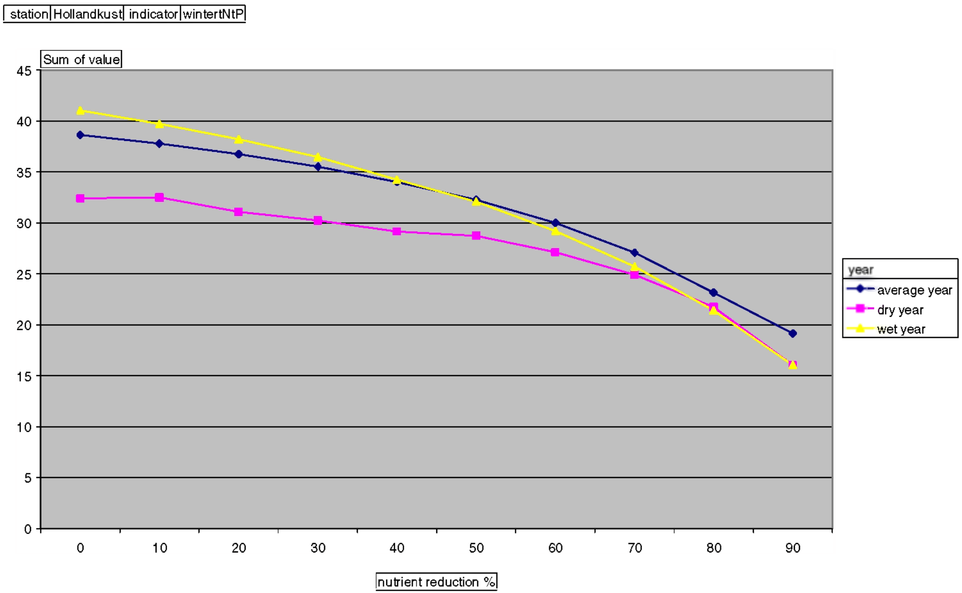




Figure 5.1: Comparison of response curves for the N/P ratio in the area Holland coast, defined as DIN/DIP (upper) and totN/totP (lower).

According to OSPAR the N/P ratio should remain below 25 in all areas. Table 5.3 shows the nutrient reduction percentages per area required to comply with the OSPAR objective for the N/P ratio.

Table 5.3: Nutrient reduction % per WFD area, required to comply with the threshold winter averaged N/P ratio for non problem area, as defined within OSPAR.

| **Area** | **Required nutrient reduction %** |
|---|---|
| Delta coast | > 90 % |
| Holland coast | 70 - 80 % |
| W. Wadden Sea | 90 % |
| Oosterschelde | 0 - 20 % |
| Wadden coast | 0 - 40 % |
| Zeeland coast | 0 % |
| Westerschelde | 90 % |

## 5.4 Summer chlorophyll-a and primary production

In GEM there are three possible indicators available related to phytoplankton abundance:

- Chlorophyll-a (µg Chla/l) (indicator for both OSPAR and WFD);
- Primary production rates ($gC.m^{-2}.d^{-1}$) (alternative indicator in this study);
- Algal biomass (mgC/l) (additional indicator for interpretation of differences between chlorophyll-a and primary production).

The concentration of chlorophyll-a is an approximation of the algal biomass, that can be easily measured. However, as the ratio between chlorophyll-a and carbon in phytoplankton can vary between circa 20 to 60 mgChla/gC, the estimation of algal biomass based on chlorophyll-a has a range of uncertainty of circa 50% to 150 %. When phytoplankton growth is limited by light availability the chlorophyll-a content of cells is usually relatively high. When phytoplankton growth is limited by nutrient availability the chlorophyll-a content of cells is generally lower.

The difference between the algal biomass approximations expressed in carbon and in chlorophyll-a shows when the response curves for both parameters are compared. In some areas, such as the Delta coast area and the Oosterschelde the decrease of algal biomass at 90% nutrient reduction is 75% for both approximations. However in other areas such as Holland coast or the western part of the Wadden Sea there is a difference between the decrease of chlorophyll-a and algal biomass expressed in carbon of 10 to 25%. The reason behind this difference is a change from light limitation to nutrient limitation, resulting in lower chlorophyll-a to carbon ratios in phytoplankton.

When looking at the resulting response curves when nitrogen and phosphorus river loads are reduced separately (Figure C.1), it becomes clear that in most areas the decrease of summer averaged chlorophyll-a is mainly due to phosphorus reduction. Only in the areas Oosterschelde, Wadden coast and Zeeland coast the decrease of summer averaged chlorophyll-a is due to a combination of phosphorus and nitrogen. Also for primary production (Figure C.3) phosphorus seems to be more important in controlling phytoplankton growth than nitrogen. In the areas Westerschelde and Holland coast there is hardly any effect visible of nutrient reduction on primary production. In the area Delta coast the decrease of primary production is mainly due to phosphorus limitation. In the other areas (Oosterschelde, Wadden coast, western Wadden Sea and Zeeland coast) the decrease of primary production is induced by a combination of phosphorus and nitrogen limitation.

The threshold values for good ecological status for summer averaged marine chlorophyll-a concentrations, that have been drafted for the WFD in the Netherlands, are:

- for open sea with fresh water influence (K1: Delta coast, Holland coast): 14 µg/l;
- for tidal areas (K2: Wadden Sea, Oosterschelde): 18 µg/l;
- for open sea (K3: Wadden coast, Zeeland coast): 14 µg/l;
- for transitional waters (O2: Ems estuary, Ems coast, Westerschelde): 12 µg/l.

The threshold concentrations for the WFD mentioned in Table 5.4 have been established as follows: The reference conditions are used as the middle of the class 'very good'. The upper boundary of the class 'very good' is defined as 133% of the reference. The boundary between the classes 'good' and 'moderate' is defined as 150% of the upper boundary of the class 'very good'. As a result the threshold value for good ecological status, which is equal to the boundary between the classes 'good' and 'moderate' is 200% of the reference. Table 5.4 presents the required nutrient reduction to reduce summer average chlorophyll-a concentrations to 200% of the reference level, for all three estimations of the reference level. Since the new estimations of the reference levels, in this study, are much lower than the previous estimations, the threshold levels, which are defined relative to the reference level, are lower. Therefore much higher reduction percentages are needed to achieve the objectives based on new estimations of reference levels.

Table 5.4: Required nutrient reduction % per WFD area required to comply with the threshold summer averaged chlorophyll-a concentration for good ecological status, as drafted for the WFD and the 3 different estimates for the chlorophyll-a reference per area (WFD threshold value of 2 x reference level between brackets).

| **Area** | **draft WFD reference (µg Chlfa/l)** | **reduction %** | **reference A (µg Chlfa/l)** | **reduction %** | **reference B (µg Chlfa/l)** | **reduction %** |
|---|---|---|---|---|---|---|
| Delta coast | 7 (14) | 30 | 4 (8) | 70 | 5.5 (11) | 50 |
| Holland coast | 7 (14) | 0 | 2.5 (5) | 50 - 70 | 3 (6) | 30 - 50 |
| Wadden Sea | 9 (18) | 0 | 4 (8) | 0 – 40 | 4 (8) | 0 – 40 |
| Oosterschelde | 9 (18) | 0 | 2.5 (5) | 40 – 60 | 2.5 (5) | 40 – 60 |
| Wadden coast | 7 (14) | 0 | 2 (4) | 20 - 60 | 2 (4) | 20 - 60 |
| Zeeland coast | 7 (14) | 0 | 2.5 (5) | 50 - 60 | 3 (6) | 40 – 50 |
| Westerschelde | 6 (12) | 10 – 20% | 3 (6) | 70 | 4 (8) | 50 - 60 |

For OSPAR the threshold values for maximum and summer averaged chlorophyll-a concentrations are defined as 150% of the reference level. Table 5.5 presents the required nutrient reduction to reduce summer average chlorophyll-a concentrations to 150% of the reference level, for all three estimations of the reference level.

Table 5.5: Required nutrient reduction % per WFD area, required to comply with the threshold summer averaged chlorophyll-a concentration for non-problem areas, as defined within OSPAR and the 3 different estimates for the chlorophyll-a reference per area (OSPAR threshold value of 1.5 x reference level between brackets).

| **Area** | **draft WFD reference (µg Chlfa/l)** | **reduction %** | **reference A (µg Chlfa/l)** | **reduction %** | **reference B (µg Chlfa/l)** | **reduction %** |
|---|---|---|---|---|---|---|
| Delta coast | 7 (10.5) | 60 | 4 (6) | 80 | 5.5 (8.5) | 70 – 80 |
| Holland coast | 7 (10.5) | 0 | 2.5 (4) | 70 – 80 | 3 (4.5) | 60 – 70 |
| Wadden Sea | 9 (13.5) | 0 | 4 (6) | 40 – 70 | 4 (6) | 40 – 70 |
| Oosterschelde | 9 (13.5) | 0 | 2.5 (4) | 70 – 80 | 2.5 (4) | 70 – 80 |
| Wadden coast | 7 (10.5) | 0 | 2 (3) | 60 – 80 | 2 (3) | 60 – 80 |
| Zeeland coast | 7 (10.5) | 0 | 2.5 (4) | 80 | 3 (4.5) | 70 |
| Westerschelde | 6 (9) | 40 – 50 | 3 (4.5) | 80 | 4 (6) | 70 |

## 5.5 *Phaeocystis*

In all areas except the Westerschelde the response curves show a clear response of the maximum *Phaeocystis* concentration to nutrient reduction. This response seems to be mainly controlled by phosphorus limitation, judging from the model results with separate reduction of nitrogen and phosphorus. Only in the area Zeeland coast the decrease of *Phaeocystis* abundance is controlled by a combination of phosphorus and nitrogen limitation.

The threshold value for good ecological status for maximum *Phaeocystis* concentrations that have been drafted for the WFD in the Netherlands, is $10 * 10^6$ cells/L in all coastal and transitional waters. Depending on the assumption on the carbon content per *Phaeocystis* cell this threshold corresponds to a *Phaeocystis* concentration of 0.15 to 0.3 mgC/L (based on (Rousseau et al., 1990) and (Jahnke, 1989) respectively, see also section 2.3). Table 5.6 shows for every area the present maximum *Phaeocystis* concentration (averaged over the area), according to the model and the required nutrient reduction to decrease the maximum *Phaeocystis* concentration below 0.15 and 0.3 mgC/L respectively.

Table 5.6: Nutrient reduction % per WFD area, required to comply with the threshold maximum *Phaeocystis* concentration for good ecological status, as drafted for the WFD.

| **Area** | **present maximum (mgC/L)** | **reduction for 0.15 mgC/L threshold (%)** | **reduction for 0.3 mgC/L threshold (%)** |
|---|---|---|---|
| Delta coast | 0.3 – 0.6 | 60 – 90 | 20 - 60 |
| Holland coast | 0.15 – 0.35 | 0 – 70 | 0 -20 |
| Wadden Sea | 0.3 – 0.7 | > 90 | 10 – 70 |
| Oosterschelde | 0.35 – 0.55 | > 90 | 30 – 70 |
| Wadden coast | 0.2 – 0.3 | 30 – 70 | 0 |
| Zeeland coast | 0.1 – 0.3 | 0* | 0 |
| Westerschelde | 0.3 – 0.5 | > 80 | 0 - 80 |

* Little effect of nutrient reduction, one year > 0.15 despite nutrient reduction, other years > 0.15 at 0 %.

## 5.6 Ratio diatoms / flagellates

In most areas the ratio diatoms / flagellates increases gradually with nutrient reduction. This is partly due to the slight increase of dissolved silicate loading, accompanying the decrease of nitrogen and phosphorus. Partly the relative availability of silicate compared to nitrogen and phosphorus increases by the decreasing nitrogen and phosphorus concentrations.

## 5.7 Expected results of present policies

Table 5.7 shows the values of the different indicators under study, averaged per area and averaged for the 3 different years, for the nutrient reduction scenario “Present water quality objectives for rivers” (%WQO in Figure 2.1, see also section 2.2). Dark shaded cells indicate that the indicators do not comply with the objectives for good ecological status for the indicator. Light shaded cells indicate that the nutrient reduction %WQO is within the range of uncertainty presented in the tables 5.1 to 5.6 and may or may not comply depending on the assumptions made with respect to the definition of reference conditions and carbon content of *Phaeocystis* cells. If the value of the indicator has the same value as the threshold the cell is also lightly shaded. Table 5.4 shows that all waters except the Delta coast and Westerschelde already comply with the objectives according to the draft WFD reference conditions. Therefore the table below is just based on the reference conditions based on the new model simulations (reference A and B in table 5.5).

Table 5.7: Overview of values of indicators (averaged for 3 simulated years: wet, dry and average) with the nutrient reduction scenario %WQO. Shading indicates whether the indicator would comply with objectives according to WFD and OSPAR (dark: indicator does not comply, light: indicator may comply, no shading: indicator complies)

| **Area** | **winter DIN** | **winter DIP** | **winter N/P** | **summer chlorophyll** | ***Phaeocystis* maximum** |
|---|---|---|---|---|---|
| Delta coast | 1.0 | 0.04 | 49 | 11 | 0.25 |
| Holland coast | 0.4 | 0.03 | 30 | 5 | 0.1 |
| Wadden Sea | 0.5 | 0.02 | 41 | 6 | 0.3 |
| Oosterschelde | 0.2 | 0.03 | 19 | 5 | 0.35 |
| Wadden coast | 0.2 | 0.02 | 20 | 4 | 0.15 |
| Zeeland coast | 0.2 | 0.03 | 19 | 5 | 0.35 |
| Westerschelde | 0.7 | 0.05 | 34 | 8 | 0.15 |

# 6 Discussion

## 6.1 Model applicability under various conditions

The GEM model is designed as a generic model for the Netherlands, meaning the processes involved are applicable in any (Dutch) aquatic ecosystem. Model coefficients have proven to be adequate for a wide range of ecosystems, including Veerse Meer, IJsselmeer, Grevelingen and Westerschelde. Despite the generic set-up of GEM, model results are not equally reliable in all areas where GEM is applied. Reasons for differences in reliability may be due to:

- the level of similarity to the ecosystems for which the model coefficients have been calibrated (especially if GEM is applied outside the Netherlands);
- the level of detail of the model forcing and inputs;
- the relative importance of different processes.

The calibration and validation of the GEM application for the southern North Sea, that is used in this study, has focused mainly on a proper representation of cross-shore gradients and seasonal patterns of nutrients and chlorophyll-a along the Noordwijk transect, the Terschelling transect and transects in between. Shallow near-shore areas such as the Westerschelde, Oosterschelde, Wadden Sea and Ems Estuary have received less attention during the calibration. The reasons for differences in model reliability in different areas listed above and their relevance for this study will be described in more detail below.

### Model coefficients

The model coefficients in GEM have been determined on the basis of literature survey and modification by model calibration. Calibration has taken place for Dutch coastal waters, the southern North Sea and other temperate waters such as Venice lagoon. Conditions that are similar to those for which the model has been calibrated can be expected to be simulated reasonably reliably. These conditions range from eutrophic conditions in near-shore waters in Dutch coastal waters around 1985 to oligotrophic conditions in the central North Sea. The response of the phytoplankton indicators to nutrient reduction scenarios in this study is therefore expected to be sufficiently reliable.

### Model forcings and inputs

The processes that take place in the water column depend to a large extent on the abiotic conditions defined in the model input, such as the solar irradiance, the concentrations of suspended solids in the water and the transport of fresh water and associated substances. The latter two are simulated in separate models, which are more successful in some areas than in others. In general one could say that in very near-shore waters, that are the focus of the WFD, gradients in salinity and suspended solids concentrations are more steep and therefore more difficult to simulate than in other waters, where gradients are more smoothed and stable. In the validation results for example it showed that in shallow areas such as Noordwijk 2 km and the eastern part of the Wadden Sea the suspended solids concentrations correspond less well to observations than elsewhere. Salinity was less well simulated at stations that are located very close to the discharges of fresh water, such as Goeree 6 km, near the Haringvliet and Harlingen near the discharge from the IJsselmeer. These stations are much more sensitive to (in)adequate model input such as the wind forcing, bathymetry and discharges and concentrations in river input.

One other aspect that affects the accuracy of the model, especially in near-shore areas with steep gradients is the size of the grid cells. As the GEM model for the southern North Sea covers such a large area, the grid cells have been made relatively large, to minimize the simulation runtime. For the same reason the original 3D model has been simplified to a 2D model. This can cause enhanced mixing and smoothing of gradients, because every grid cell is considered to be vertically homogeneous. For this reason model results in for example the Westerschelde or the Wadden Sea may not be as good in the model for the southern North Sea as in previous more detailed models for these areas.

In the 1998 simulations the concentrations of ortho-phosphate are underestimated by the model throughout the whole Dutch coastal area. The river inputs in 1994 to 1998 had been estimated with a different procedure than river inputs for other years. We have checked the possibility that this new procedure gives an underestimation of river inputs of nutrients compared to the old procedure. However, in a comparison for 1994, where we have loading files for both the new and the old procedure, the difference in the input of total phosphorus between the two procedures turned out to be negligible. For total nitrogen the difference was only 2%. Therefore it seems unlikely that that new procedure for estimating the river loads is the reason for the low prediction of ortho-phosphate in 1998. The difference between the two procedures per substance is shown in appendix D. Overestimation of horizontal mixing in the Rhine plume is a more likely cause for the underestimation of ortho-phosphate, as concentrations are overestimated at stations further from the coast (see also section 4.3.3).

### Processes

Some processes in GEM are simulated with relatively simple formulations. Examples include:

- storage and return flux of nutrients from the sediment;
- sedimentation and resuspension of particulate organic matter;
- adsorption of phosphate to suspended solids; and
- grazing on phytoplankton and food web interactions.

In the model used in this study grazing losses of phytoplankton are included in the mortality rate. The mortality rate (1/d) is constant, so the grazing flux (gC/m$^3$.d) increases linearly with phytoplankton biomass. Dead phytoplankton is subject to remineralisation in the water column and settling with a constant net settling velocity. Resuspension is not modelled explicitly in the model. The settling velocity is not influenced by differences in bottom shear stress, due to water depth in combination with tidal currents, wind or waves. Dead organic matter that has settled to the sediment is decaying with a decay rate that is only affected by temperature. The inorganic nutrients that are formed from the decaying organic matter are instantly released to the water column.

The simplified formulation of the fate of organic matter in the sediment as described above gives good results in coastal waters, where the water column and the aerobic top layer of the sediment are relatively deep. However, in estuaries and lagoons such as the Ems estuary the simple formulation does not suffice for an adequate simulation of nutrient dynamics. Sedimentation and resuspension play a much more important role in these shallow areas. Furthermore, the nutrient release from the sediment shows a strong response to oxygen profiles in the sediment, which vary substantially in time. The tidal flats are the home of high densities of filterfeeders and other biota, that result in a larger and more variable grazing pressure than in deeper waters.

## 6.2 Alternative indicators

Apart from the phytoplankton indicators defined for OSPAR and the WFD we have taken several alternative indicators into account in this study and evaluated their response to nutrient reduction. These alternative indicators are:

- ratio between diatoms and flagellates; and
- primary production.

The ratio between diatoms and flagellates showed a clear response to nutrient reduction. For this reason it could be a useful indicator for the level of eutrophication. On the other hand the ratio between diatoms and flagellates is not easy to derive from observations, as it is hard to convert the cell numbers of different species to uniform units such as mgC/L. Since the ratio between diatoms and flagellates is mainly an indicator for the relative availability of silicate compared to nitrogen and phosphorus, one could consider to use the ratio between these nutrients as an indicator. The ratio between nutrients can be determined easier and more reliable than the ratio between phytoplankton species groups. Another consideration with respect to the usability of the ratio between diatoms and flagellates as an indicator is its relevance for ecosystem functioning. There are no clear indications that diatoms are better "members" of the foodweb than flagellates, except that some (dino-) flagellates are considered to be harmful e.g. *Phaeocystis*. However, as *Phaeocystis* is already included as a separate indicator and harmful dinoflagellates often do not show a clear response to eutrophication the added value of the ratio between diatoms and flagellates as additional indicator remains uncertain.

The response of primary production to nutrient reduction is for most areas similar to chlorophyll-a. Only for the Westerschelde area the response curves for chlorophyll-a and primary production are very different. The main reason for differences between primary production and chlorophyll-a responses is that the primary production is just related to the local growth conditions for phytoplankton, whereas chlorophyll-a concentrations may also be affected by growth conditions elsewhere. For instance if the local background turbidity is high, the primary production is low but biomass and chlorophyll-a levels may still be high due to transport from sites with a lower turbidity. Similar to the ratio between diatoms and flagellates primary production is not easy to determine routinely in field monitoring. It is not included in the routine monitoring programme so far, which makes it difficult to determine long term trends of this indicator.

## 6.3 Comparison with results of other studies

### 6.3.1 Estimation of reference conditions

The draft reference conditions for chlorophyll-a for the WFD (reported in Baptist and Jagtman, 1997) have been established based on previous model studies (using the 'Noordzee BLOOM' model, which is very similar to GEM). In the present study two new estimates of reference conditions have been made, based on two estimations of river loads during reference conditions: A and B (see section 2.2). The large difference between the draft WFD reference and the reference conditions simulated in this study (a decrease of 20 to 70%, see Table 6.1) can be explained by a combination of the following differences in approaches:

1. Different model forcings (suspended solids concentrations, horizontal mixing etc.); and
2. Different definition of water bodies in coastal waters;
3. Different model coefficients for phytoplankton properties, such as nutrient requirements and carbon to chlorophyll-a ratio.

Table 6.1: Difference between chlorophyll-a concentrations under reference conditions according to the draft WFD reference and according to estimations in this study (reference A).

| Area | draft WFD reference (µg Chlfa/l) | reference A (µg Chlfa/l) | difference (%) |
|---|---|---|---|
| Delta coast | 7 | 4 | -43 |
| Holland coast | 7 | 3 | -57 |
| Wadden Sea | 9 | 4 | -56 |
| Oosterschelde | 9 | 2 | -78 |
| Wadden coast | 7 | 2 | -71 |
| Zeeland coast | 7 | 3 | -57 |
| Westerschelde | 6 | 3 | -50 |

#### Ad 1: model forcings

The model set-up in the present study is different from the model set-up used in the model study that estimated the draft WFD reference conditions. For example, the suspended solids concentrations at Noordwijk 2 km are overestimated in the present study, whereas de Vries et al. (1998) report an underestimation of suspended solids concentrations at this station. This difference in model forcing has a strong impact on the primary productivity in coastal waters. Other examples of differences that may affect the model results include the model grid and the underlying transport model, which determines the horizontal mixing between the Rhine plume and off-shore waters and therefore the cross-shore gradients.

## Ad 2: definition of water bodies

Furthermore the draft reference conditions for the WFD have been estimated for other areas than the reference conditions in this study. In the present study only the first mile along the coast has been included, whereas the draft WFD reference conditions have been estimated for a wider area of coastal waters (see Figure 6.1). Due to the different definition of the water bodies the results of the different studies cannot be compared well.

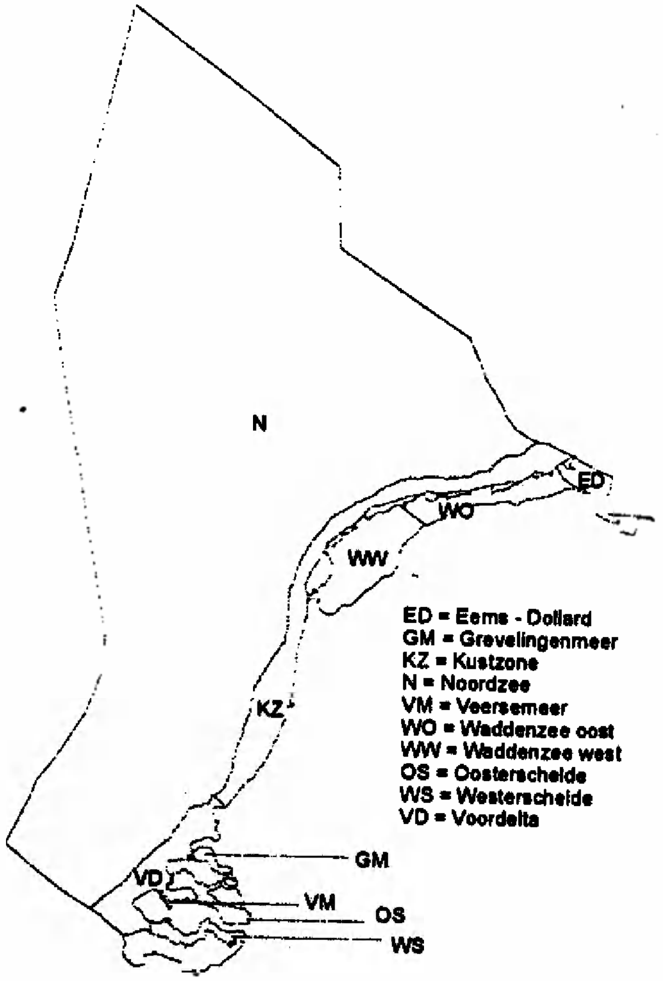



Figure 6.1: Definition of water bodies used for the estimation of draft WFD reference conditions (Baptist and Jagtman, 1997).

## Ad 3: model coefficients

Model coefficients such as the carbon to chlorophyll-a ratios, nitrogen to carbon ratios and phosphorus to carbon ratios in nutrient limited phytoplankton, have been recently updated following new scientific understanding within the Flyland project (MARE, 2002). The carbon to chlorophyll-a ratios for nutrient limited phytoplankton have been reduced by a factor of 2.5, compared to the 'Noordzee BLOOM' model. The adjustments have been based on laboratory experiments by R. Riegman (MARE, 2002b). This resulted in a much more accurate simulation of chlorophyll-a levels especially at the more offshore monitoring locations, such as Noordwijk 70 km. Table 6.2 compares the summer averaged chlorophyll-a concentrations under WFD draft reference conditions and 'reference conditions A' for an average year, simulated with old and new model coefficients in this study. It can be concluded that the difference in estimated chlorophyll-a levels under reference conditions according to the draft WFD and according to reference condition A in this study is for only circa 0 to 17 percent due to different model coefficients. The rest of the difference (total difference is shown in table 6.1) is due to different model set-up and different definitions of water bodies.

Table 6.2: Comparison of summer averaged chlorophyll-a concentrations under WFD draft reference conditions and 'reference conditions A' in this study, simulated with old and new model coefficients.

| **water body** | **summer averaged chlorophyll-a (µg/l)** | | | **% change, due to new model coefficients** |
|---|---|---|---|---|
| | draft WFD reference | present model set-up, old coefficients | present model set-up, new coefficients | |
| Delta coast | 7 | 5 | 4 | -14 |
| Holland coast | 7 | 3 | 3 | 0 |
| Wadden Sea | 9 | 5 | 4 | -11 |
| Oosterschelde | 9 | 3 | 2 | -11 |
| Wadden coast | 7 | 3 | 2 | -14 |
| Zeeland coast | 7 | 3 | 3 | 0 |
| Westerschelde | 6 | 4 | 3 | -17 |

Recently also new reference conditions for winter nutrient concentrations have been drafted for the WFD (Heinis et al., 2004). Table 6.3 shows the newly estimated ranges of reference conditions for winter nutrient concentrations with the estimations A and B in this study. For DIN concentrations the estimations of reference conditions in this study are similar to the results of Heinis et al., (2004) in the areas Holland coast, Oosterschelde, Zeeland coast and Westerschelde. In the areas Delta coast and Wadden Sea the estimations in this study are higher than the estimations by Heinis et al. (2004). The difference in the area Delta coast can be explained by the underestimation of salinity in this area, resulting in a too high content of nutrient rich fresh water. In the area Wadden Sea DIN concentrations are overestimated by 33% by the model (see table 4.1). If the reference conditions in this study are corrected for this overestimation they are within the same range as the estimations by Heinis et al. (2004). In the area Wadden coast the model estimations in this study are much lower than the estimations by Heinis et al. (2004). The reason for this is yet unclear. Simulated winter DIN concentrations correspond with the observations at station Terschelling 4 km. Averaged salinity is circa 32 at this station. According to Heinis et al. (2004) this corresponds to winter DIN concentrations of 0.09 to 0.17. However observations over the period 1995 – 1998 show that at monitoring station Vrouwezand in Lake IJssel winter DIN concentrations are circa 70% of winter DIN concentrations at the stations Brienenoord and Bovensluis, near the mouth of the river Rhine near Rotterdam. The estimation of natural background concentrations of DIN in winter used in their study may be an overestimation of natural background concentrations in discharges from Lake IJssel.

For winter DIP concentrations the reference conditions estimated by Heinis et al. (2004) are similar to those estimated in this study. Only for the area Wadden coast the model estimations are slightly lower than the estimations by Heinis et al. (2004). This may be explained by 80 to 90% lower winter DIP concentrations in discharges from Lake IJssel, compared to Rhine discharges near Rotterdam.

Table 6.3: Comparison between reference conditions for DIN and DIP in winter estimated by Heinis et al. (2004) and model estimations in this study.

| Area | DIN | | | DIP | | |
|---|---|---|---|---|---|---|
| | Heinis et al., 2004 | reference A | reference B | Heinis et al., 2004 | reference A | reference B |
| Delta coast | 0.10-0.22 | 0.23 | 0.29 | 0.015-0.025 | 0.017 | 0.023 |
| Holland coast | 0.10-0.22 | 0.12 | 0.15 | 0.015-0.025 | 0.017 | 0.021 |
| Wadden Sea | 0.06-0.13 | 0.13 | 0.15 | 0.008-0.020 | 0.013 | 0.016 |
| Oosterschelde | 0.06-0.13 | 0.08 | 0.09 | 0.008-0.020 | 0.017 | 0.019 |
| Wadden coast | 0.10-0.22 | 0.06 | 0.06 | 0.015-0.025 | 0.013 | 0.014 |
| Zeeland coast | 0.10-0.22 | 0.09 | 0.10 | 0.015-0.025 | 0.018 | 0.020 |
| Westerschelde | 0.16-0.47 | 0.19 | 0.23 | 0.020-0.043 | 0.019 | 0.026 |

### 6.3.2 Trend analysis

In this study we have used a simulation for 1989 as an example of a relatively dry year. To correct for the large decrease in nutrient loading since 1989 we have reduced the nutrient loading in the baseline simulation for the relatively dry year according to the percentages found by de Vries et al. (1998) (see section 2.2, page 2-4). De Vries et al. (1998) found a decreasing trend of winter averaged DIN and DIP concentrations along the Noordwijk transect of 15% and 40% respectively, over the period 1988 - 1995. A decreasing trend in summer chlorophyll-a concentrations was not found. Their study was supported by a model study with an application of the 'Noordzee BLOOM' model that corresponded well with the observed data used for the statistical analysis.

Blauw (1999) did a trend analysis for the period 1975 – 1998 with the GEM model (very similar to the Noordzee BLOOM model). In this study a decreasing trend of yearly averaged chlorophyll-a concentrations in the Dutch coastal zone (up to 10 to 15 km from the coastline) was found of circa 10% in 1998, compared to the period 1975 – 1985.

In the present study the relatively dry year has been simulated with the original nutrient loadings of 1989 (used in the validation, chapter 4) and with reduced nutrient loadings, corresponding with 1995 (used for the response curves). One would expect to see similar trends between these two simulations as found by de Vries et al. (1998). Table 6.4 shows the percentage difference in winter averaged concentrations of DIN and DIP and summer averaged chlorophyll-a concentrations between the two simulations for the relatively dry year. The simulated decrease in winter DIP concentrations of 40% corresponds with the findings of statistical trend analysis by de Vries et al. (1998). The simulated decrease in winter DIN concentrations of 20% is somewhat larger than the 15% found in the statistical trend analysis. The simulated decrease of 10 to 15% of summer averaged chlorophyll-a concentrations does not correspond with the absence of a trend in the statistical analysis. There may be two explanations for this, that both may tell part of the story:

- Masking of a trend in the statistical analysis by large natural variability and a short time series;
- Underestimation of ortho-phosphate concentrations in the model, resulting in an overestimation of the effect of phosphorus reduction.

Chlorophyll-a concentrations in the summer half year (especially during the spring bloom) show much more variability, both in space and time than nutrient concentrations during winter. Therefore it takes much more measurements before a significant trend in chlorophyll-a concentrations can be determined. In the GEM model and the Noordzee BLOOM model there is much less natural variability. Therefore even small trends can be easily detected.

As shown in chapter 4 ortho-phosphate concentrations in late summer are underpredicted in several areas of the model. This is also the case at the stations along the Noordwijk transect in the present study for the years 1989 and 1998, but not for the average year. Therefore the effect of reduced phosphorus loadings limiting phytoplankton growth may be overestimated by the model.

Table 6.4: Difference between simulated concentrations of chlorophyll-a, DIN and DIP between the simulation for 1989 with original nutrient loadings and reduced nutrient loadings, corresponding with the base line scenario for the relatively dry year, as it would occur in 1995 - 1998.

| **Monitoring station** | **summer chlorophyll-a** | **winter DIN** | **winter DIP** |
|---|---|---|---|
| Noordwijk 2 km | -10 % | -20 % | -39 % |
| Noordwijk 10 km | -17 % | -20 % | -39 % |
| Noordwijk 20 km | -14 % | -24 % | -41 % |
| Noordwijk 70 km | 0 % | -7 % | -22 % |

# 7 Conclusions

## Reference conditions

Reference conditions that have been determined with the present model study differ considerably from the draft WFD reference conditions (see table 7.1). The two estimations made within the present study (reference conditions A and B) are rather similar. The reason for the large deviation from the draft WFD reference may be due to a combination of three differences in approaches between the two model studies:

- Different definition of water bodies;
- Different model forcings such as suspended solids concentrations; and
- Different model coefficients for phytoplankton properties.

Table 7.1: Reference conditions for summer averaged chlorophyll-a concentrations, following three different methods.

| **Area** | **draft WFD reference (µg Chlfa/l)** | **reference A (µg Chlfa/l)** | **reference B (µg Chlfa/l)** |
|---|---|---|---|
| Delta coast | 7 | 4 | 5 |
| Holland coast | 7 | 3 | 3 |
| Wadden Sea | 9 | 4 | 5 |
| Oosterschelde | 9 | 3 | 3 |
| Wadden coast | 7 | 2 | 3 |
| Zeeland coast | 7 | 3 | 3 |
| Westerschelde | 6 | 3 | 4 |

New estimations of reference conditions for winter DIN and winter DIP concentrations are presented in Tables 5.1 and 5.2.

## Required nutrient reduction to meet OSPAR objectives

The required nutrient reduction to meet OSPAR objectives varies per indicator. To meet the objectives for winter DIN concentrations 70 to 90 % nutrient reduction would be required in all areas, compared to the level of nutrient loading in 1995. To meet objectives for winter DIP concentrations the required nutrient reduction ranges from 20 – 30% in the area Zeeland coast to 70 – 80% in the area Delta coast. To meet objectives for N/P ratios the required nutrient reduction ranges between 0 – 40% in the areas Zeeland coast, Oosterschelde and Wadden coast to 90 % or more in the areas Delta coast, western part of the Wadden Sea and the Westerschelde. For summer averaged chlorophyll-a the OSPAR threshold is set at 150% of the concentrations under reference conditions. In the present situation most areas would already comply with these objectives if the draft WFD reference is used as reference condition. Only in the areas Delta coast and Westerschelde a further nutrient reduction of 40 to 60% would be required. However, if the new estimations of reference conditions are used a nutrient reduction of circa 60 to 80% would be required to meet the objectives.

### Required nutrient reduction to meet WFD objectives

According to the WFD objectives summer averaged chlorophyll-a concentrations should not exceed a threshold level of 200% of the concentrations under reference conditions. Based on the draft WFD threshold values for chlorophyll-a corresponding to good ecological status the present situation in most water bodies already complies with the ecological objectives. Only for the water bodies Delta coast and Westerschelde a further nutrient reduction would be necessary of 30% and 10 – 20% respectively, compared to the level of nutrient loading in 1995. However, if the ecological objectives are defined based on the estimations of reference conditions resulting from this study, further nutrient reduction of 20 to 70% would be necessary.

To comply with the ecological objectives for *Phaeocystis* as defined in the WFD the required nutrient reduction. percentages vary largely per area and depending on the conversion factor used to convert cell numbers (unit in WFD) to carbon (model unit). If the more conservative conversion factor is used a reduction of nutrient loads of over 90% would not be sufficient to achieve the objectives for *Phaeocystis* in the Oosterschelde and Wadden Sea.

### Water quality objectives for compliance with good ecological status

Due to the large uncertainties and variability in required nutrient reduction percentages per indicator and per area it seems not feasible to determine one final reduction percentage that will be sufficient to achieve all objectives. Therefore we have not adjusted the water quality objectives as defined in van Liere and Jonkers (2002).

### Ecological status resulting from present water quality objectives

If the water quality objectives for the Rhine as described in van Liere and Jonkers (2002) were achieved, then the objective for chlorophyll-a would be complied with in 5 out of 7 areas, according to the draft WFD estimation of reference conditions and in one of the areas, according to the new estimations of reference conditions. The draft WFD ecological objectives for *Phaeocystis* would be complied with in all areas. If a more conservative estimation on the carbon content of *Phaeocystis* cells is assumed 3 out of 7 areas would not comply. With respect to nutrients the OSPAR objective for winter DIN concentrations would not be complied with in any of the areas. The objectives for winter DIP would not be met in the areas Delta coast and Westerschelde. In the other areas compliance with winter DIP objectives is uncertain and depends on the meteorology per year and the approach used for the estimation of nutrient loading under reference conditions. The OSPAR objectives for winter N/P ratio would be complied with in the areas Oosterschelde, Wadden coast and Zeeland coast. In the other areas the winter N/P ratio would be above the target of 25.

## Alternative phytoplankton indicators

Two alternative indicators have been evaluated in this study: the ratio between diatoms and flagellates and the primary production. Both indicators seem to have limited added value compared to the existing indicators chlorophyll-a and *Phaeocystis* abundance.

## Limitations and reliability of the approach taken in this study

There are several assumptions in the model, in the definition of scenarios and the translation of model results to indicator values that affect the shape of the response curves and their translation to ecological objectives. In this study we have quantified the level of uncertainty in the results by comparing the results based on different assumptions. Several years (average year, wet year and dry year) have been simulated, three estimations of reference conditions and two estimations of the carbon content of *Phaeocystis* cells have been used. This approach reveals the sensitivity of the results to the assumptions made. This sensitivity shows in for example the required nutrient reduction to comply with objectives for summer averaged chlorophyll-a. This is 40 to 70% in the western part of the Wadden Sea (much uncertainty) and 70 to 80% in the Zeeland coast area.

The conclusions above are based on the results of combined reduction of nitrogen and phosphorus. In many areas the effect of combined reduction of these two nutrients is mainly caused by the phosphorus reduction. This can be concluded from the comparison of the effect of combined reduction and separate reduction of nitrogen and phosphorus loads. However, the validation results showed that ortho-phosphate concentrations in summer are often underpredicted by the model. Therefore in the model the effect of phosphorus reduction is probably overestimated. The simulation of the nitrogen cycle appears more reliable than the simulation of the phosphorus cycle. Therefore the results of the combined reduction scenario can be regarded as the maximum effect of nutrient reduction. The results of the reduction of nitrogen loads only can be regarded as the minimum effect that can be expected from nutrient reduction.

In this study model applications have been used that were readily available at the start of the project and require a relatively short simulation time. These model applications have been calibrated for the entire southern North Sea area. The WFD and this study focus just on the very near-shore waters. In these areas large fluctuations and steep gradients occur in fresh water content and suspended solids concentrations that strongly affect the model results. If the models were optimised for reliable simulation of these fluctuations and gradients especially in near-shore waters, the reliability of the results would improve.

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# A Validation figures

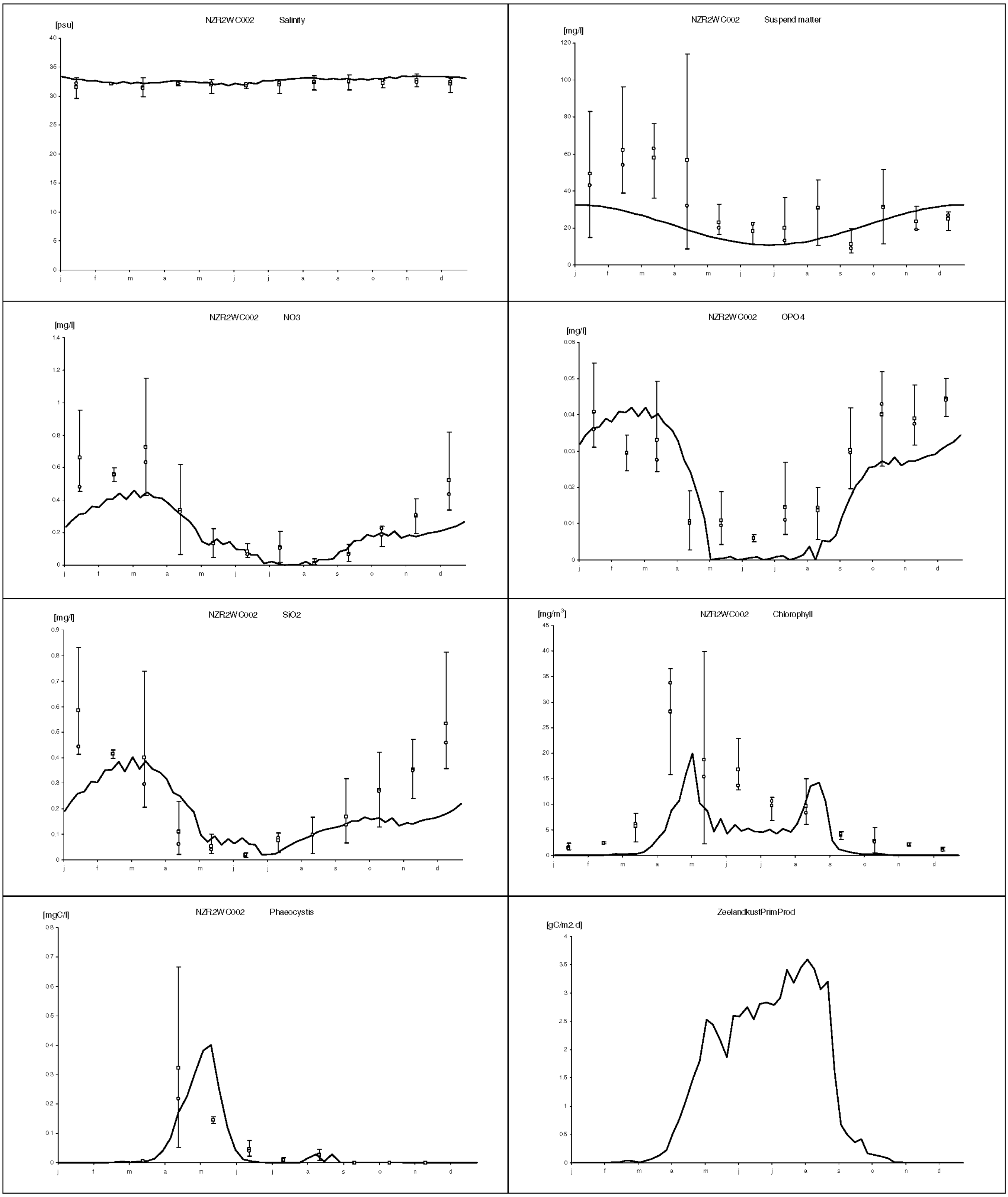


Figure A.1 Model results for the average year and average (square), median (circle) and 90 percentile of field observations of 1995 – 1998 at station Walcheren 2.

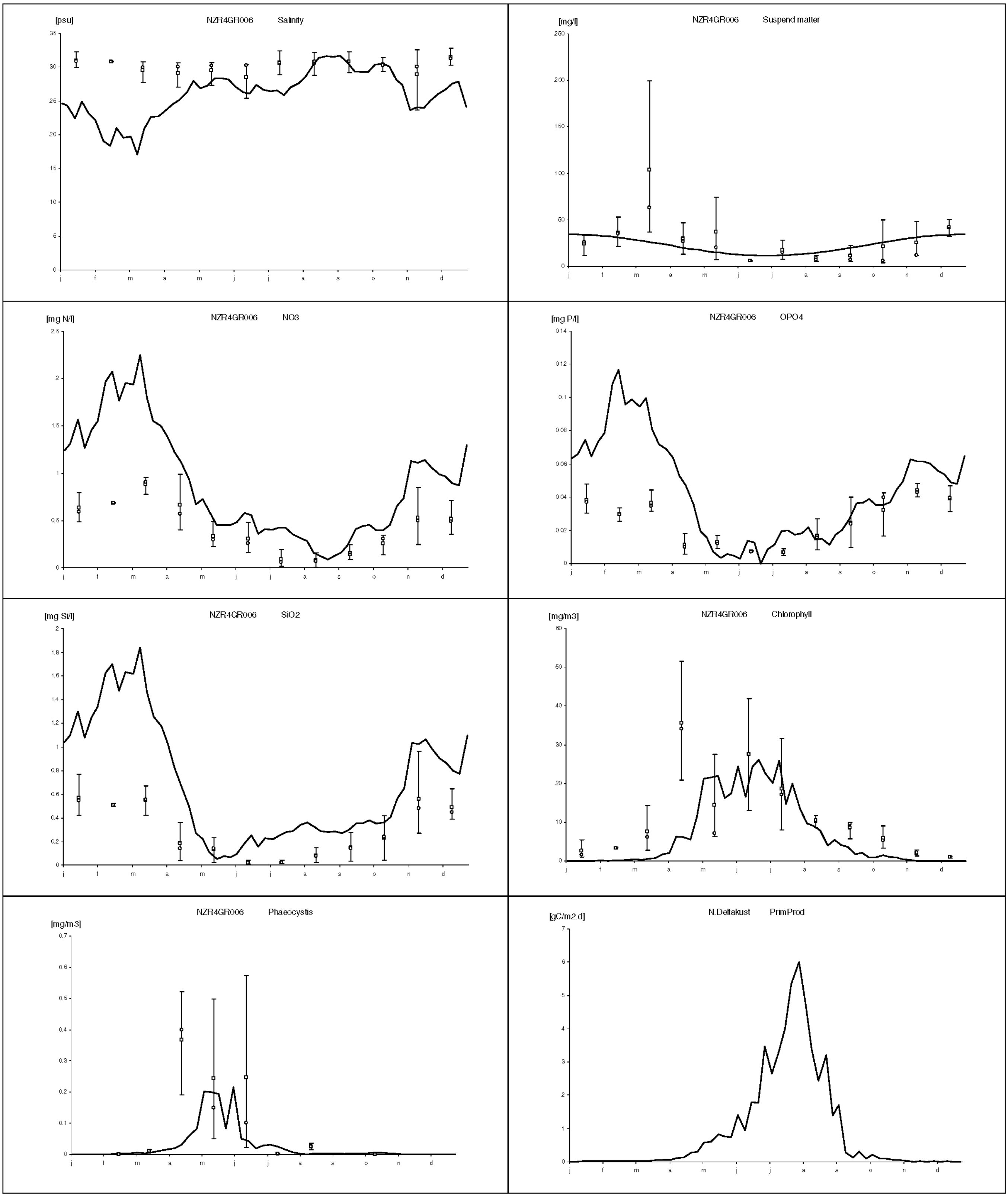


Figure A.2 Model results for the average year and average (square), median (circle) and 90 percentile of field observations of 1995 – 1998 at station Goeree 6.

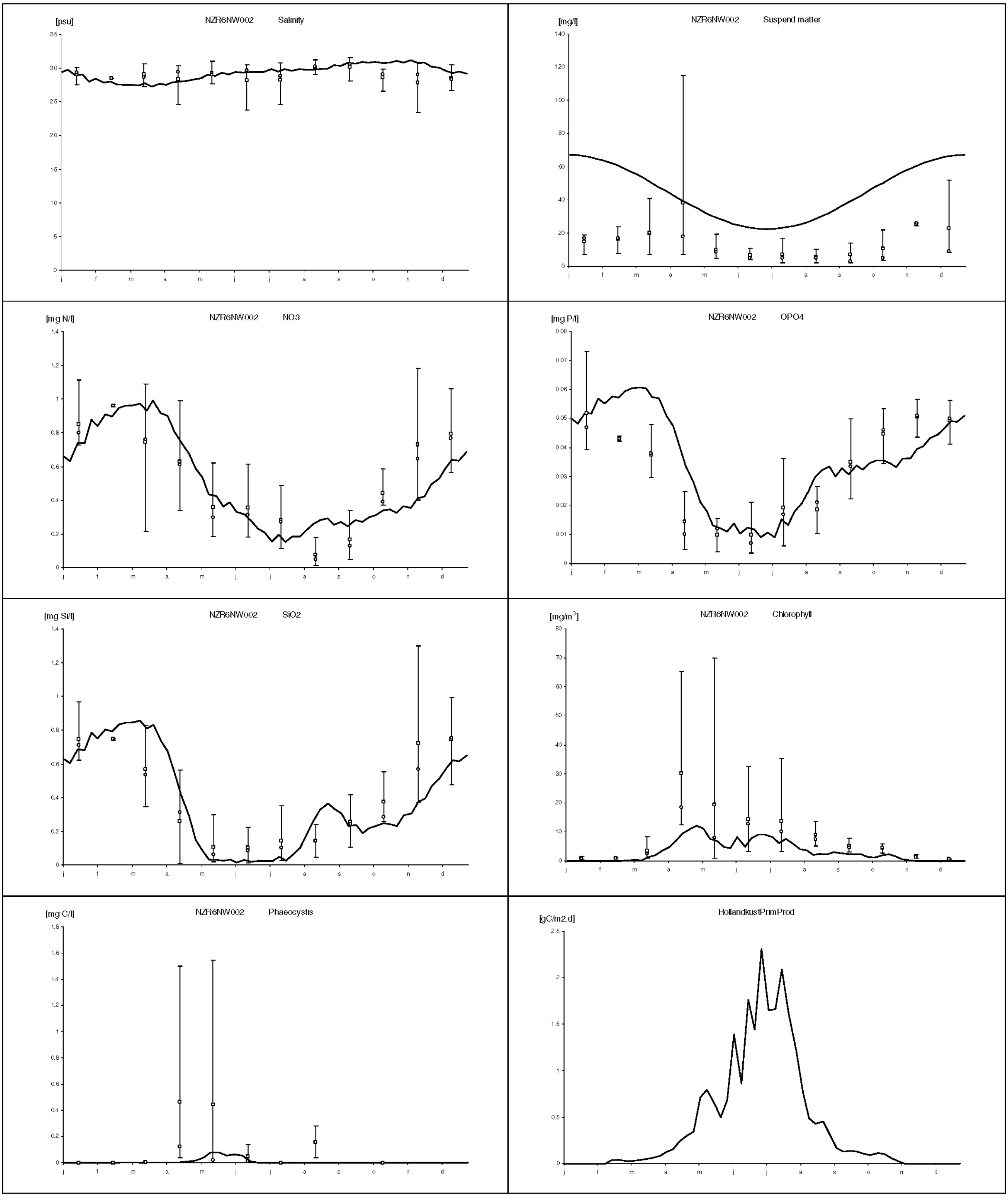


Figure A.3 Model results for the average year and average (square), median (circle) and 90 percentile of field observations of 1995 – 1998 at station Noordwijk 2.

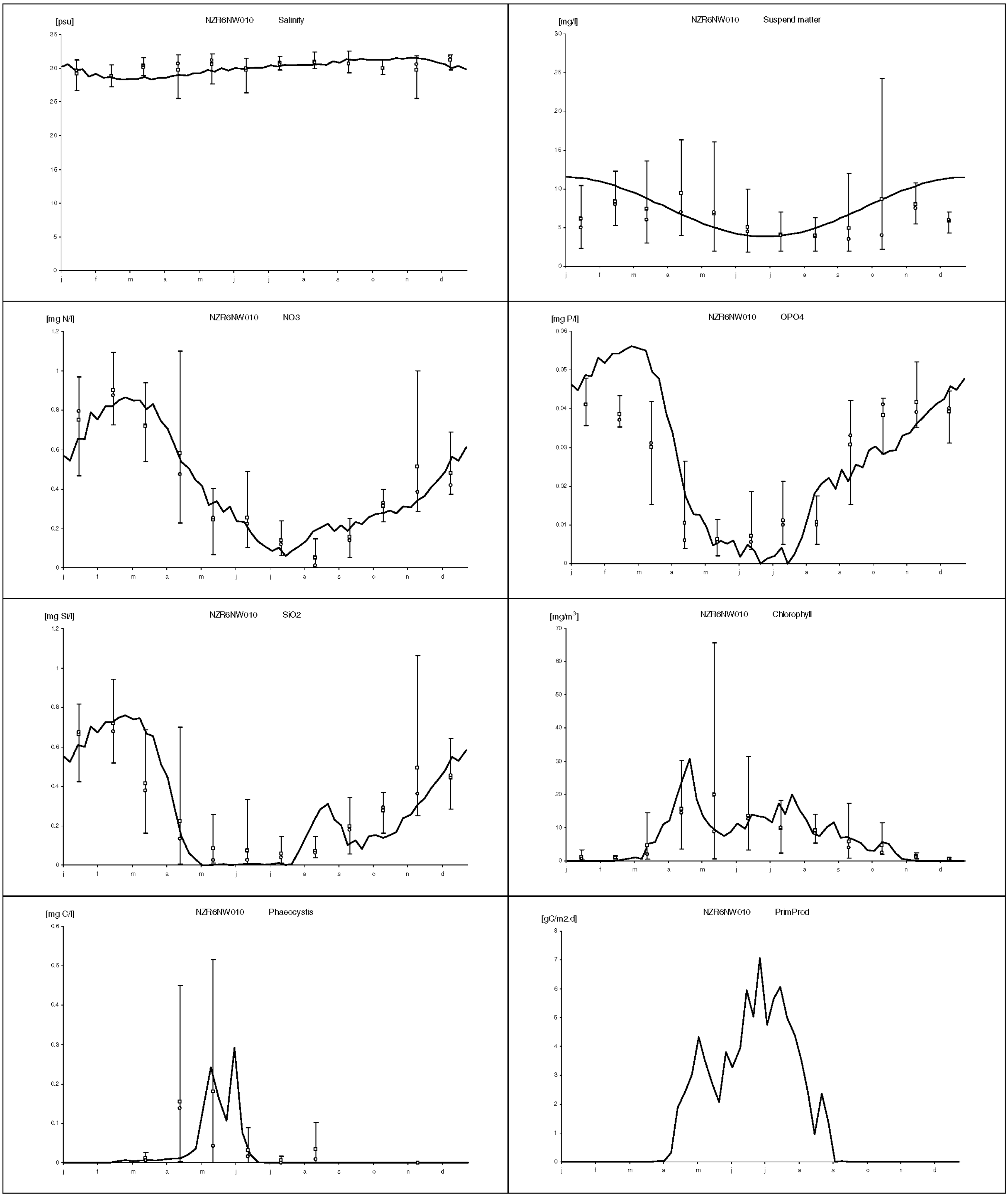


Figure A.4 Model results for the average year and average (square), median (circle) and 90 percentile of field observations of 1995 – 1998 at station Noordwijk 10.

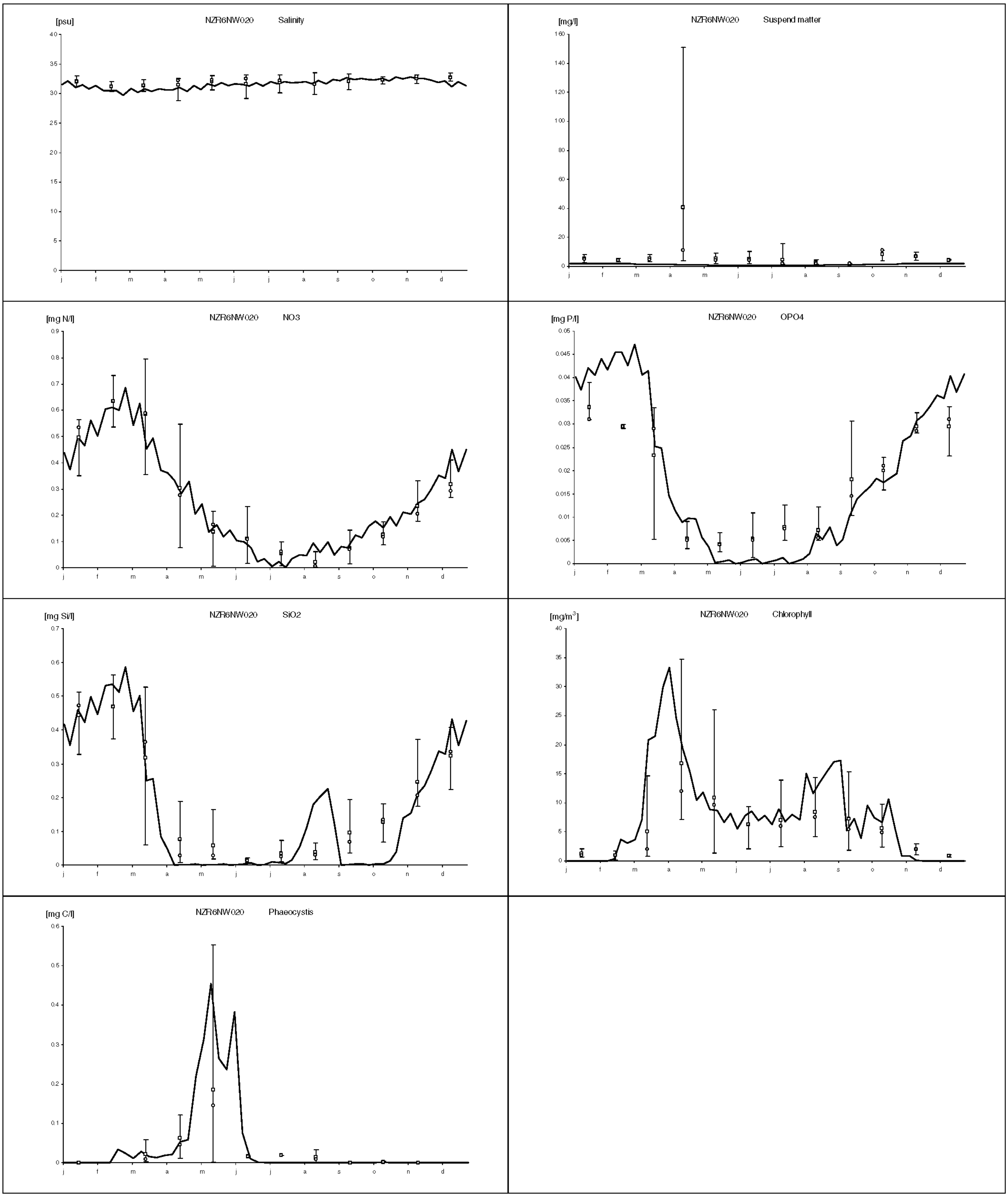


Figure A.5 Model results for the average year and average (square), median (circle) and 90 percentile of field observations of 1995 – 1998 at station Noordwijk 20 km.

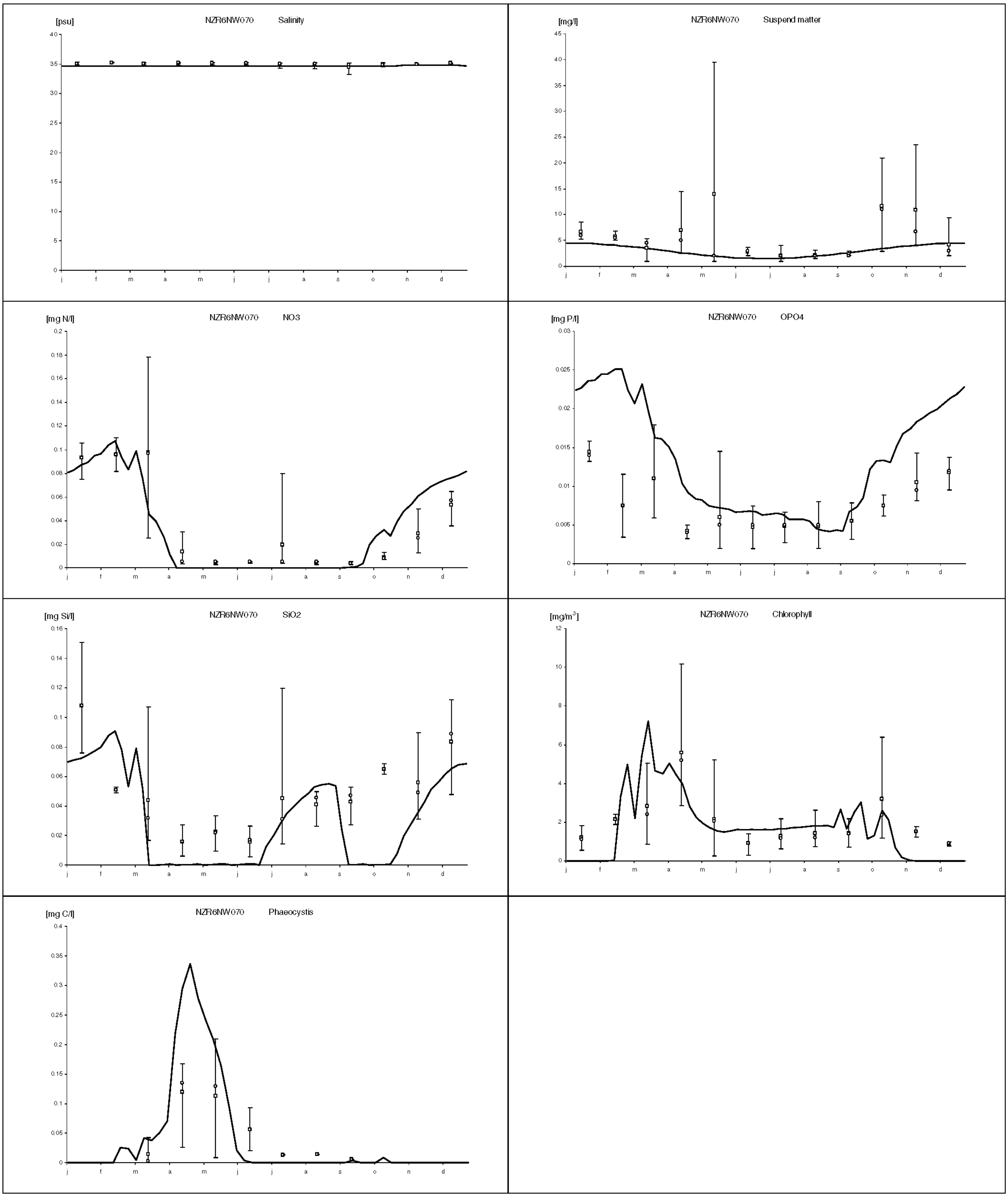


Figure A.6 Model results for the average year and average (square), median (circle) and 90 percentile of field observations of 1995 – 1998 at station Noordwijk 70 km

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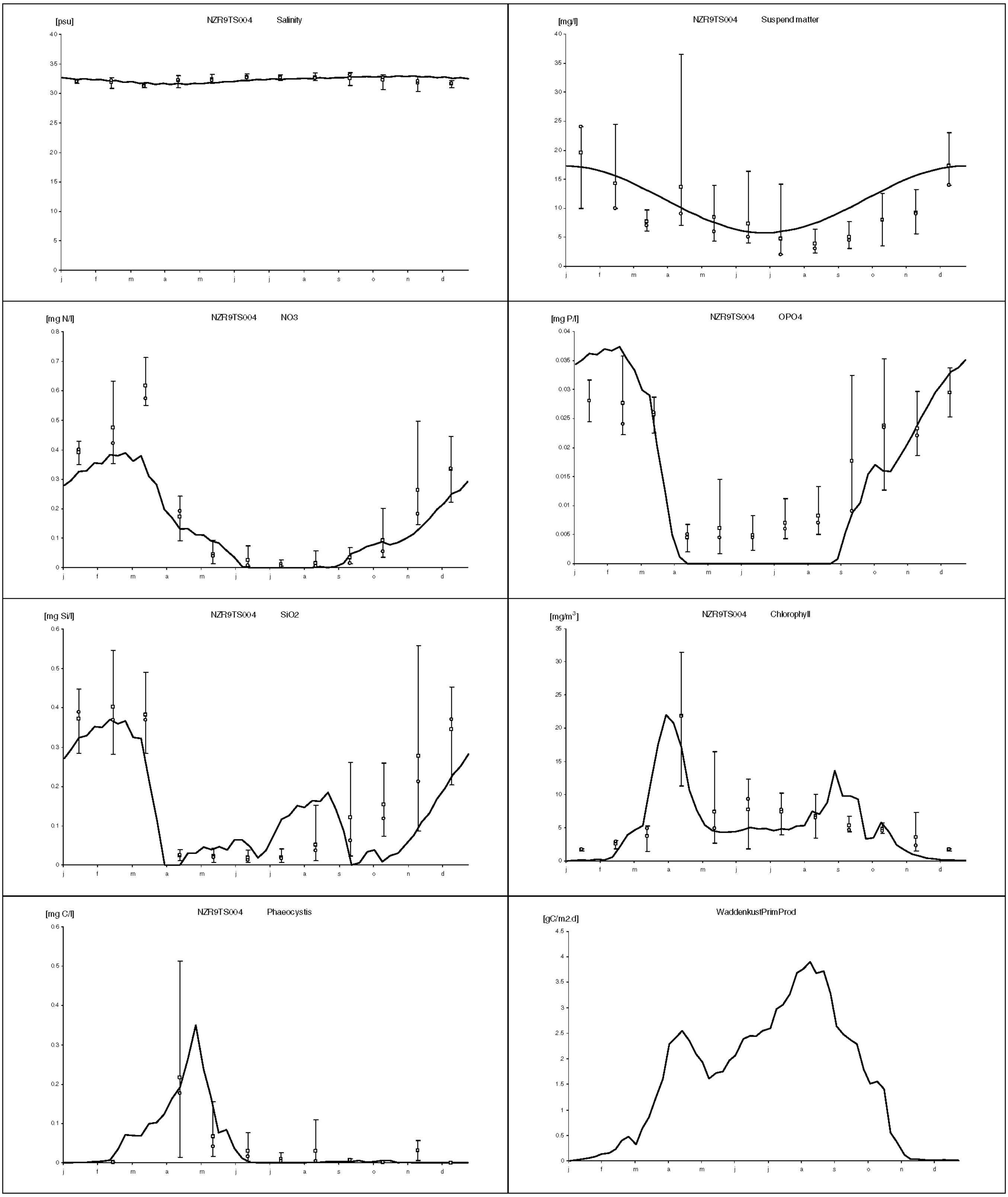



Figure A.7: Model results for the average year and average (square), median (circle) and 90 percentile of field observations of 1995 – 1998 at station Terschelling 4 km.

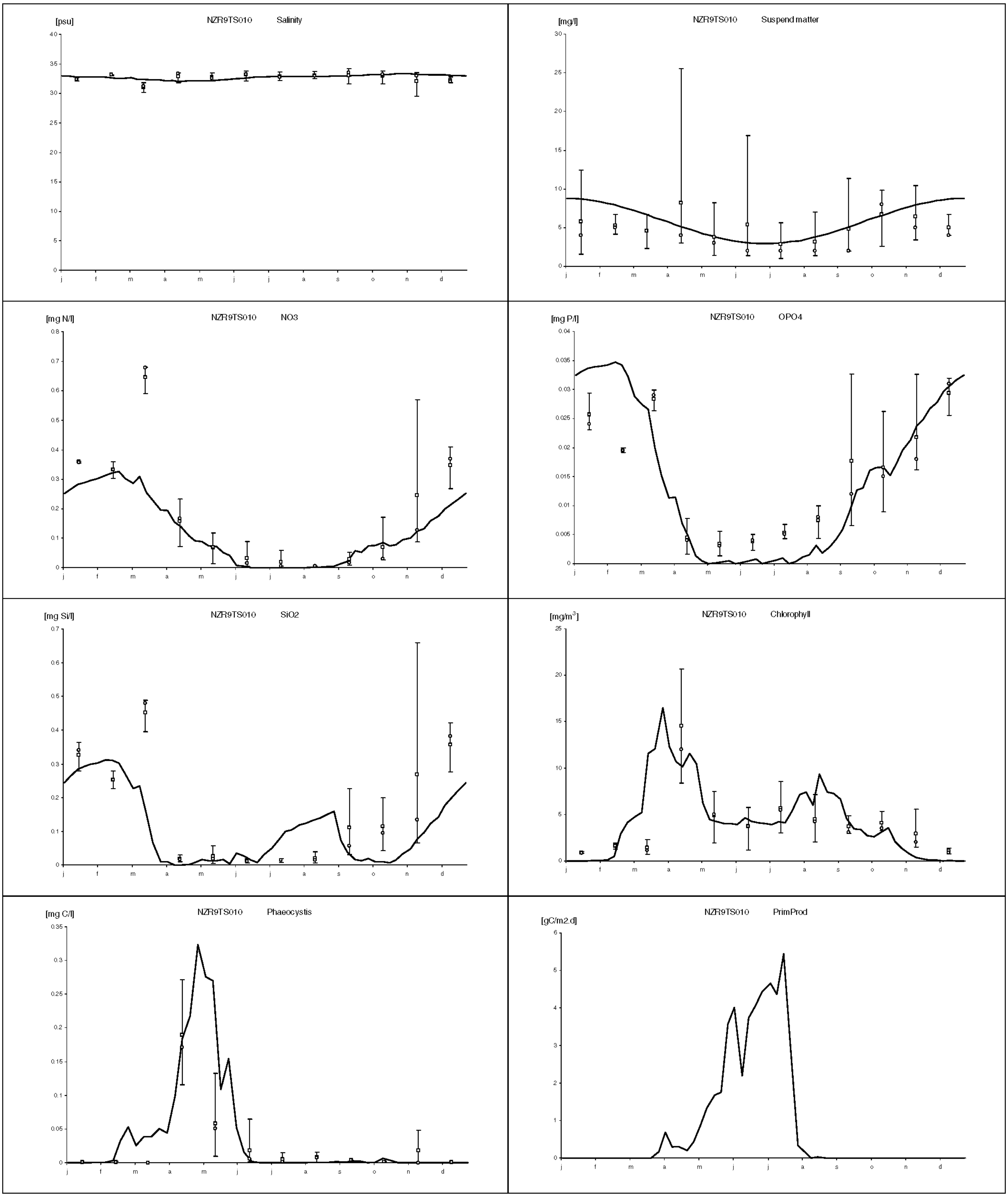



Figure A.8: Model results for the average year and average (square), median (circle) and 90 percentile of field observations of 1995 – 1998 at station Terschelling 10 km.

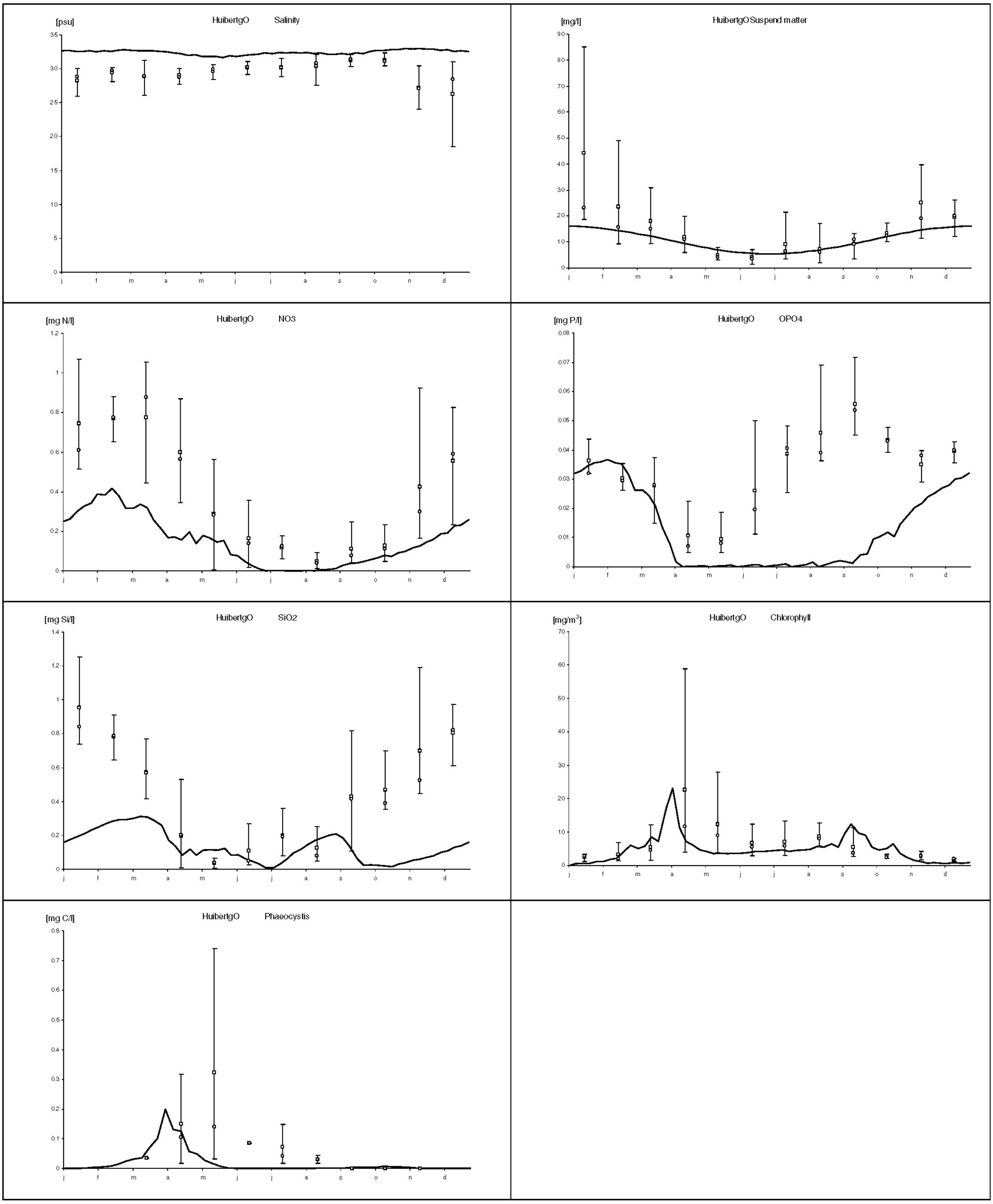



Figure A.9: Model results for the average year and average (square), median (circle) and 90 percentile of field observations of 1995 – 1998 at station Huibertgat Oost.

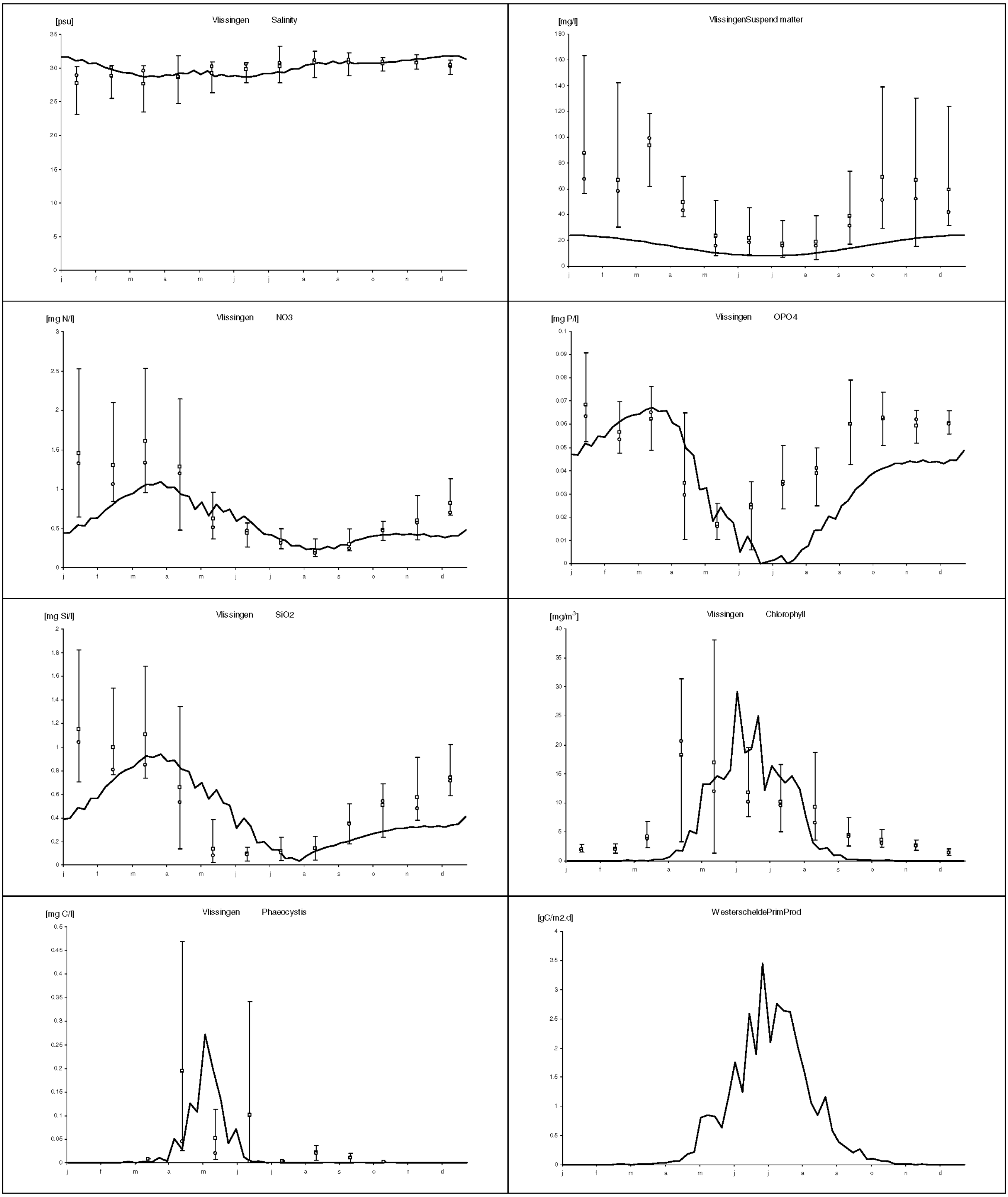



Figure A.10: Model results for the average year and average (square), median (circle) and 90 percentile of field observations of 1995 – 1998 at station Vlissingen.

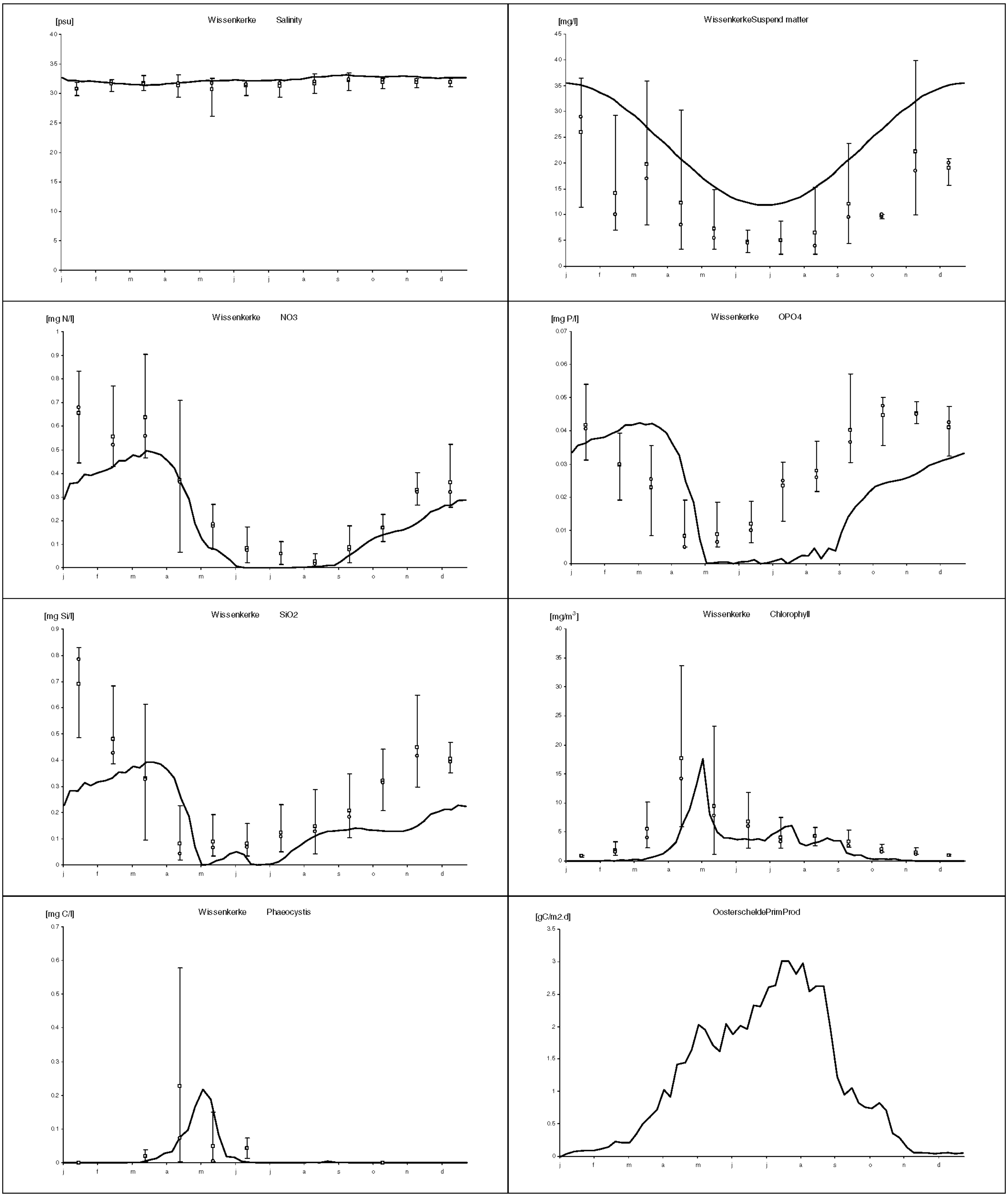



Figure A.11: Model results for the average year and average (square), median (circle) and 90 percentile of field observations of 1995 – 1998 at station Wissenkerke.

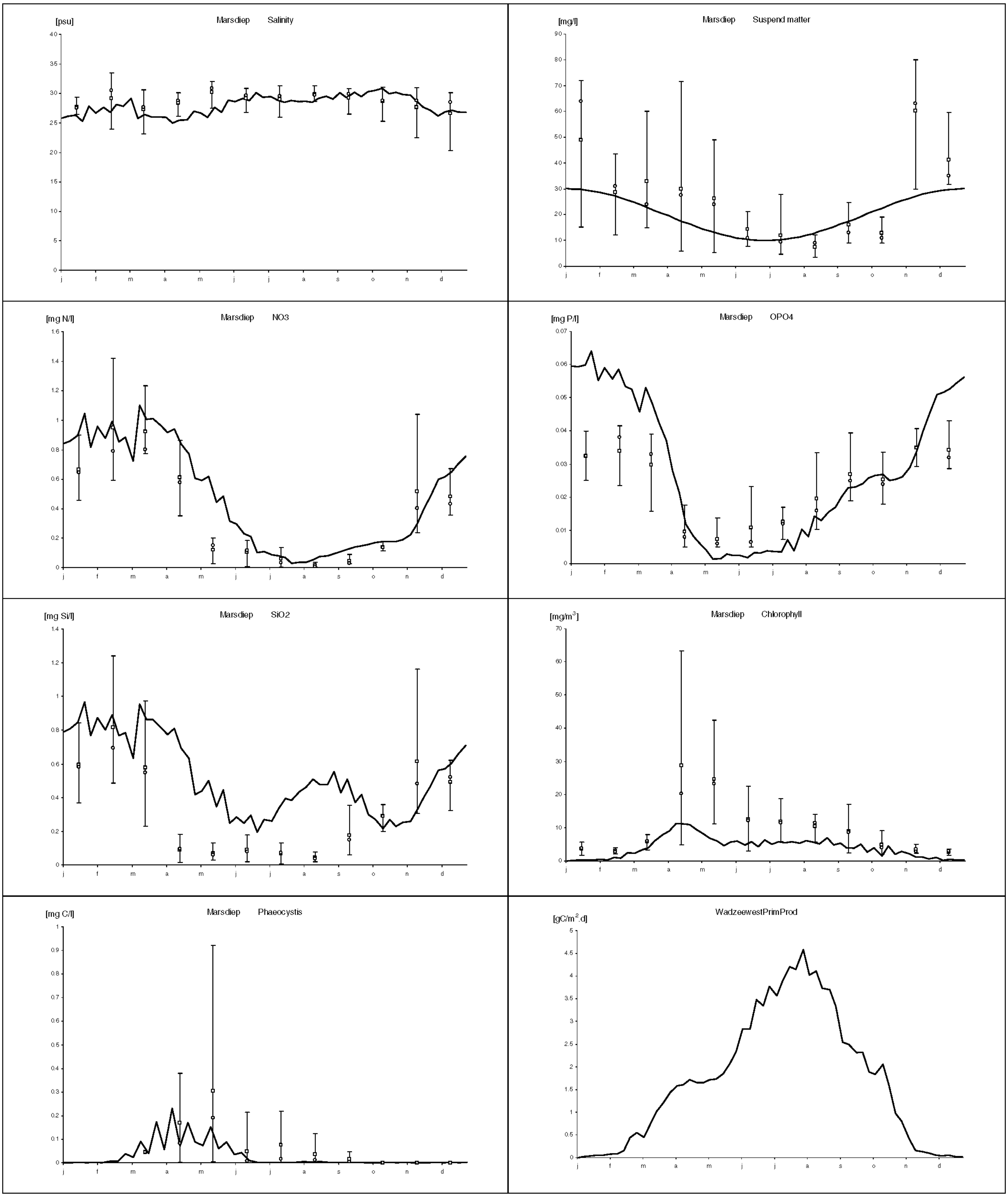



Figure A.12: Model results for the average year and average (square), median (circle) and 90 percentile of field observations of 1995 – 1998 at station Marsdiep.

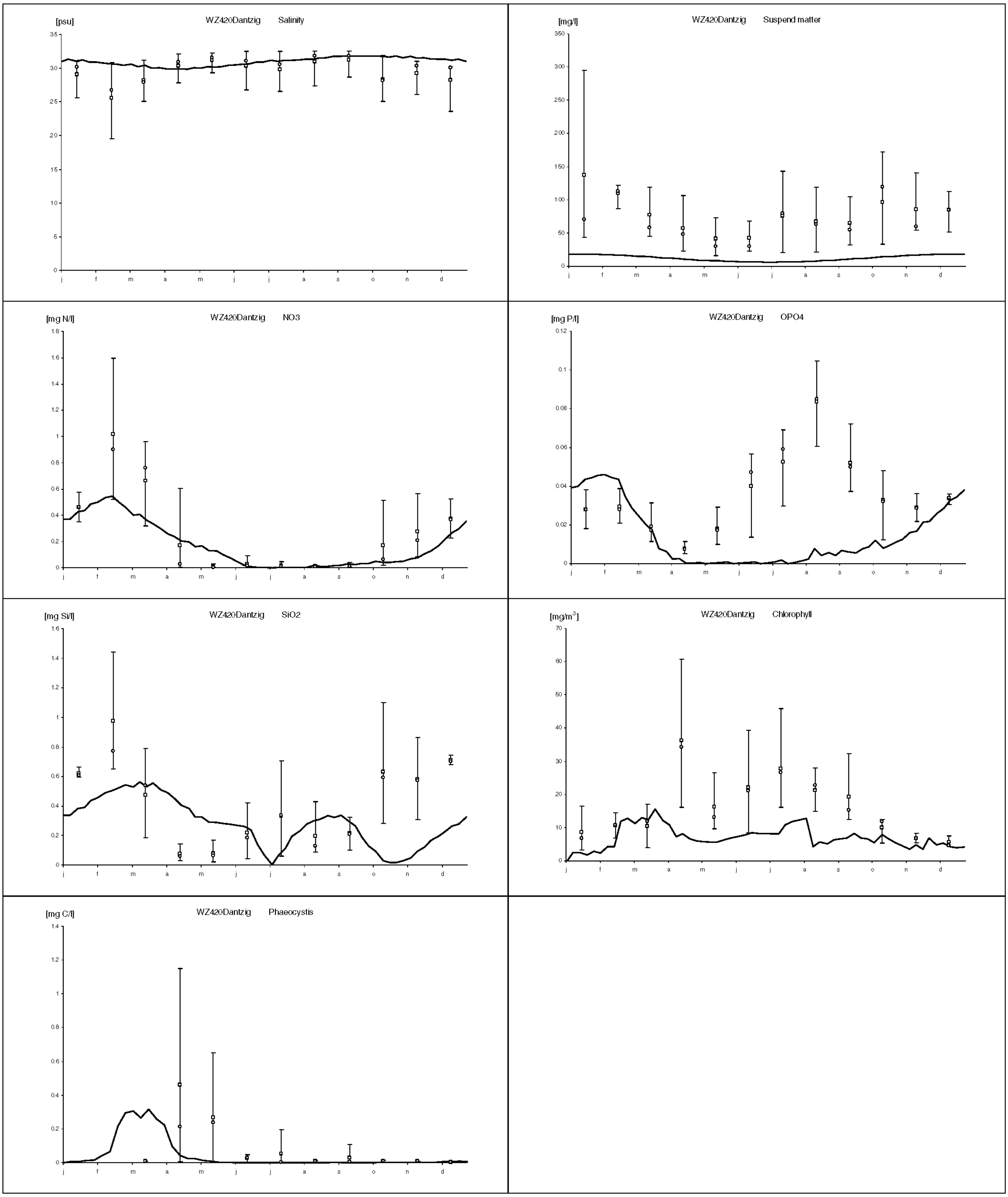



Figure A.13: Model results for the average year and average (square), median (circle) and 90 percentile of field observations of 1995 – 1998 at station Dantziggat.

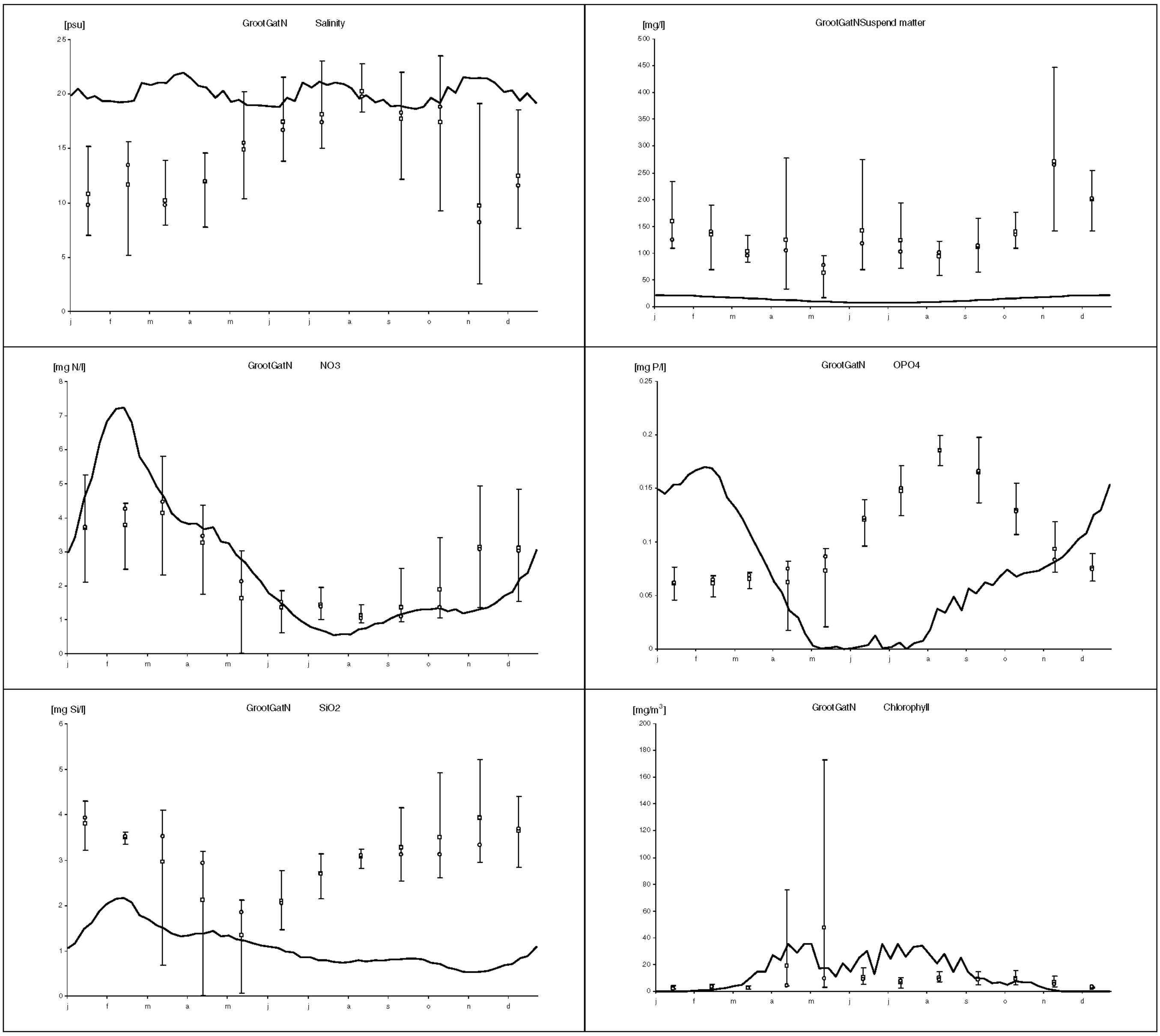



Figure A.14: Model results for the average year and average (square), median (circle) and 90 percentile of field observations of 1995 – 1998 at station Groote Gat Noord.

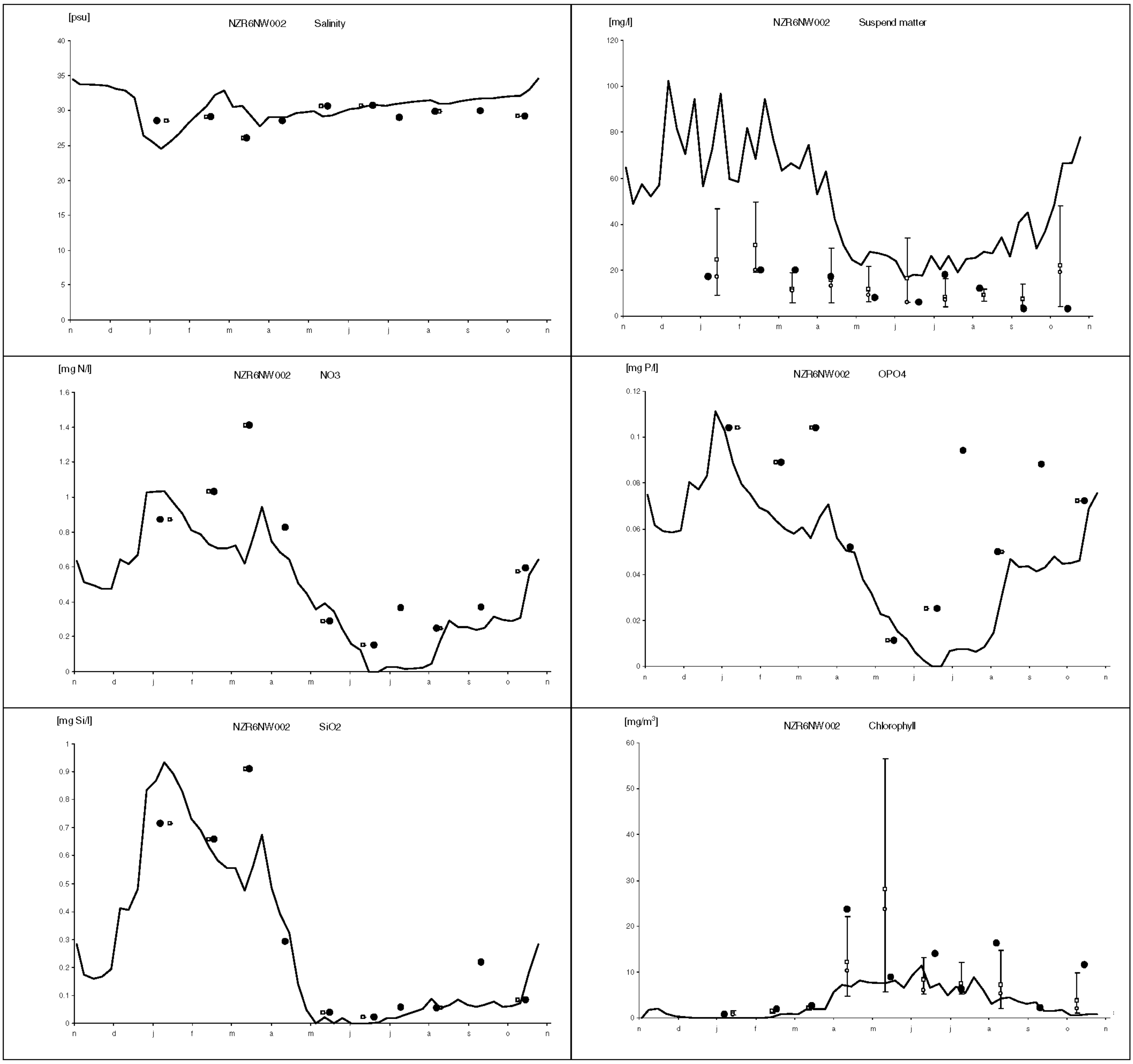



Figure A.15: Model results for the year 1989 and observations for 1989 (black circle) and average (square), median (white circle) and 90 percentile of field observations of 1988 – 1991 at station Noordwijk 2 km.

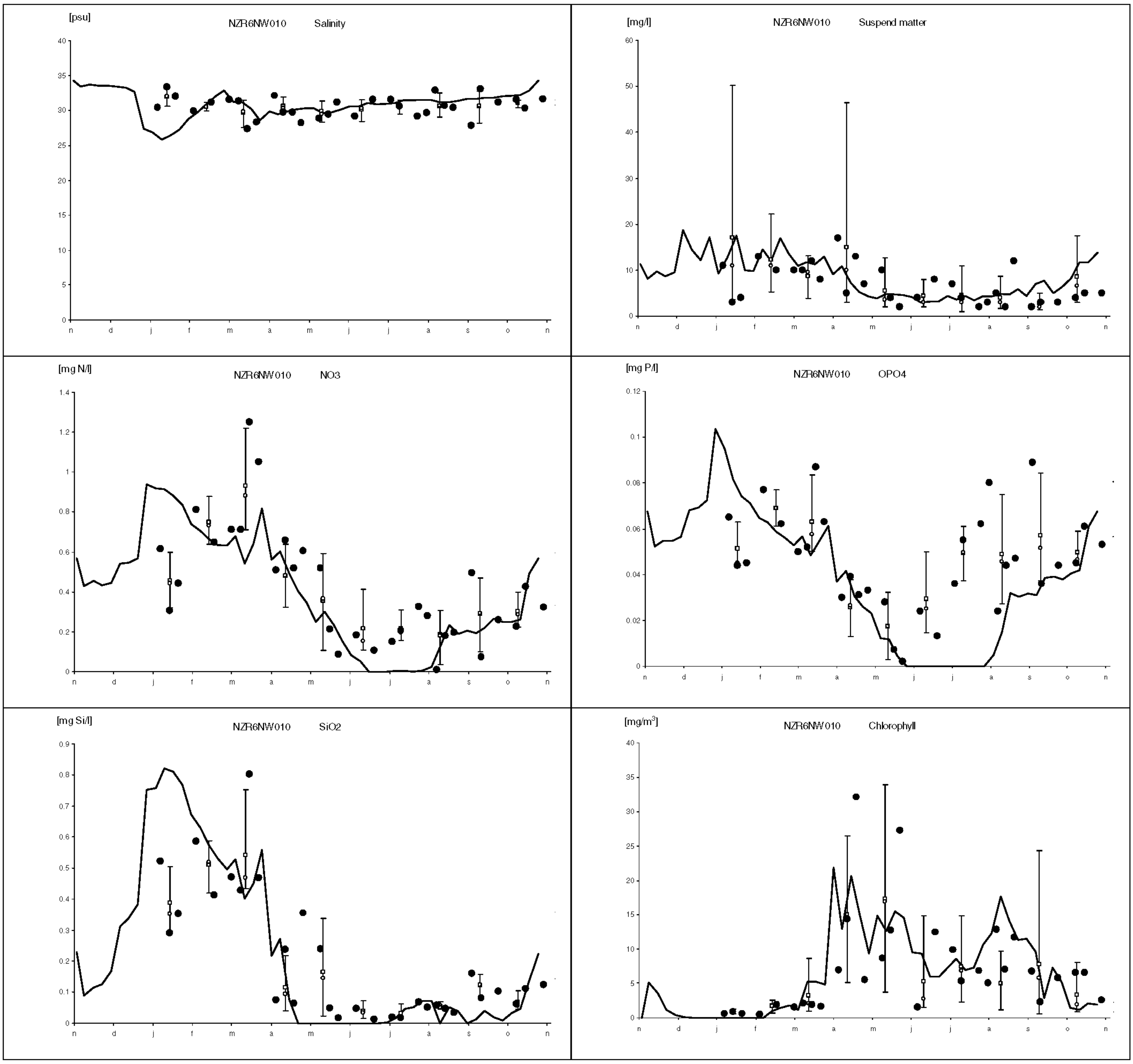



Figure A.16: Model results for the year 1989 and observations for 1989 (black circle) and average (square), median (white circle) and 90 percentile of field observations of 1988 – 1991 at station Noordwijk 10 km.

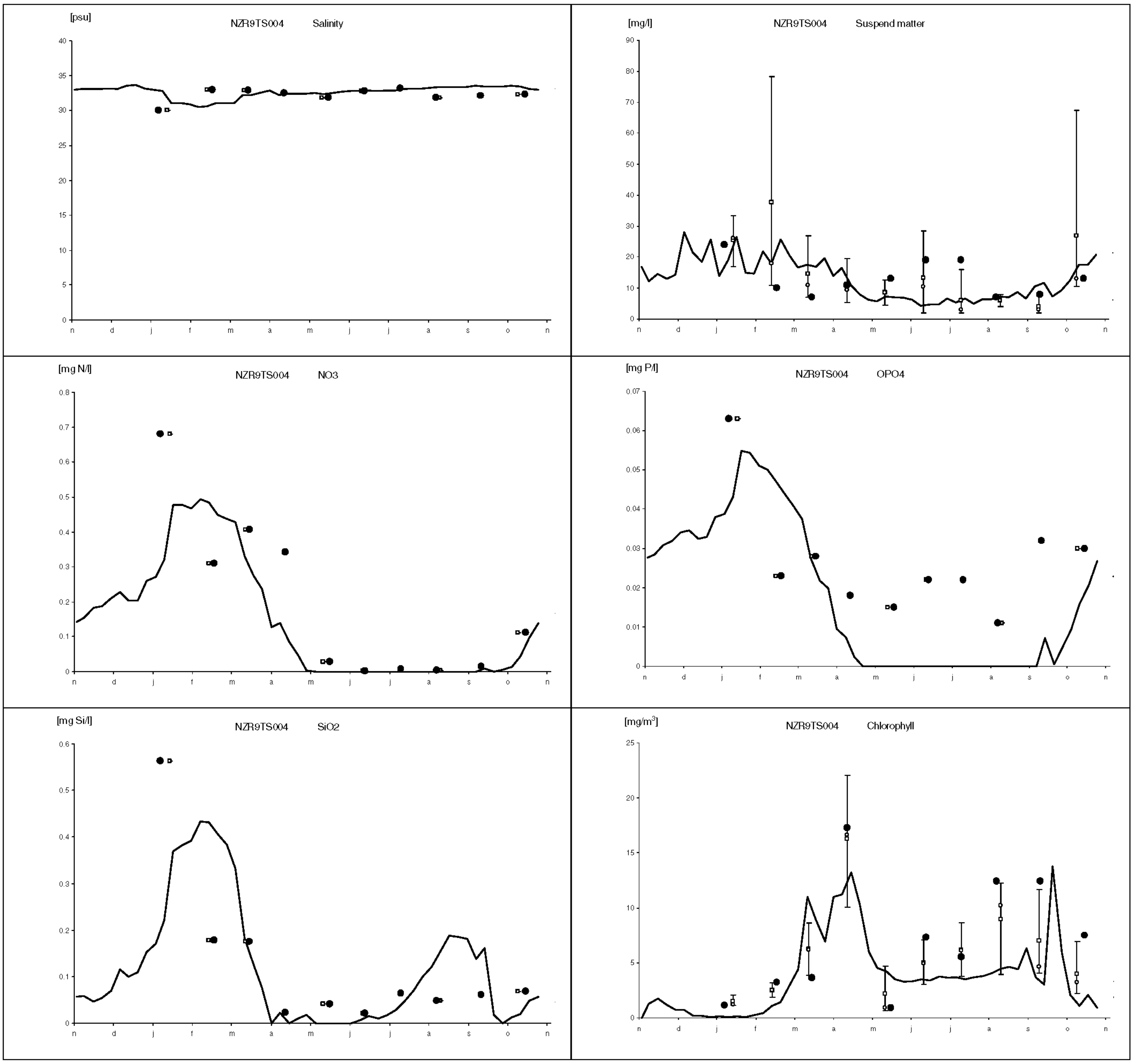



Figure A.17: Model results for the year 1989 and observations for 1989 (black circle) and average (square), median (white circle) and 90 percentile of field observations of 1988 – 1991 at station Terschelling 4 km.

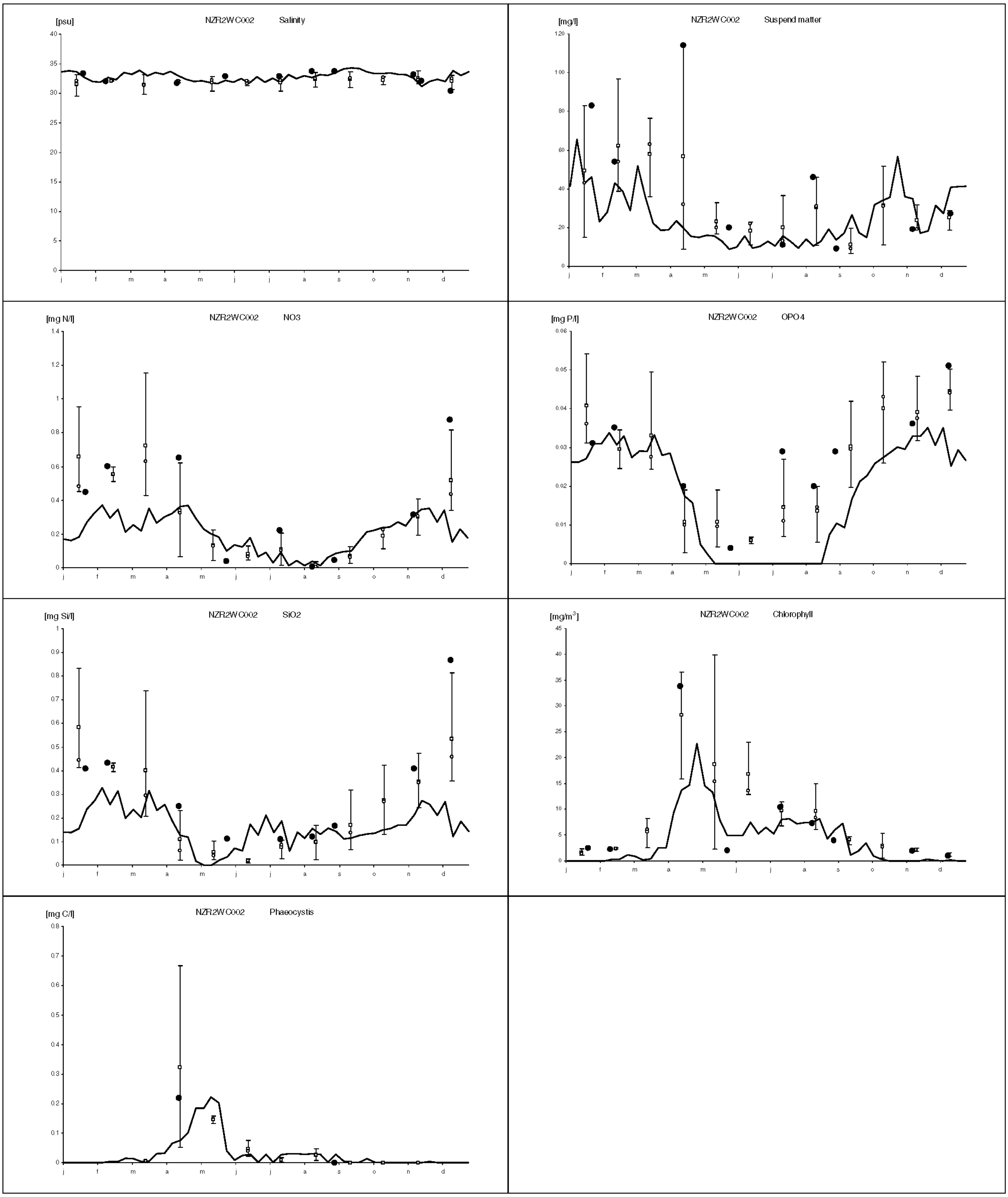



Figure A.18: Model results for the year 1998 and observations for 1998 (black circle) and average (square), median (white circle) and 90 percentile of field observations of 1995 – 1998 at station Walcheren 2 km.

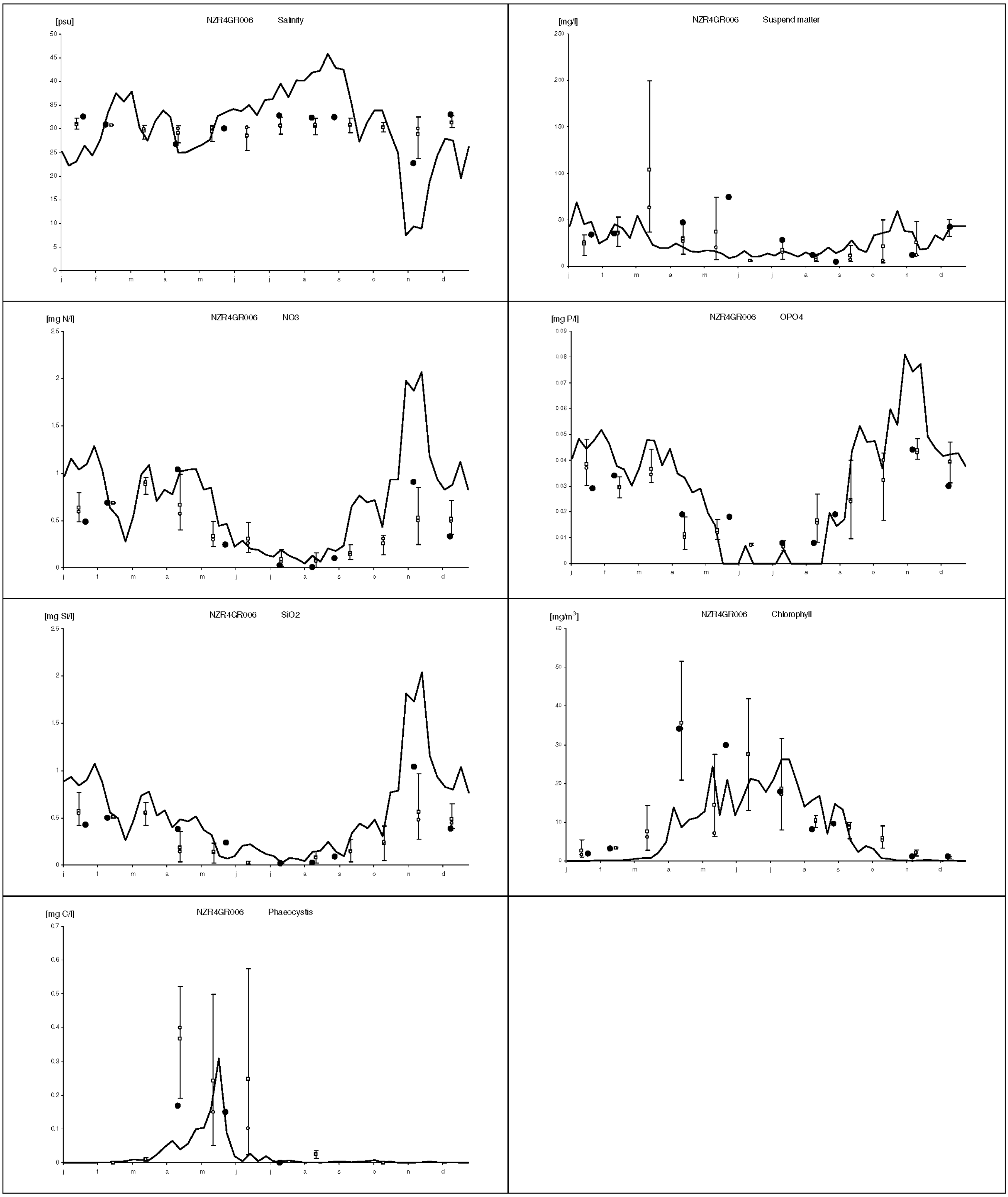



Figure A.19: Model results for the year 1998 and observations for 1998 (black circle) and average (square), median (white circle) and 90 percentile of field observations of 1995 – 1998 at station Goeree 6 km.

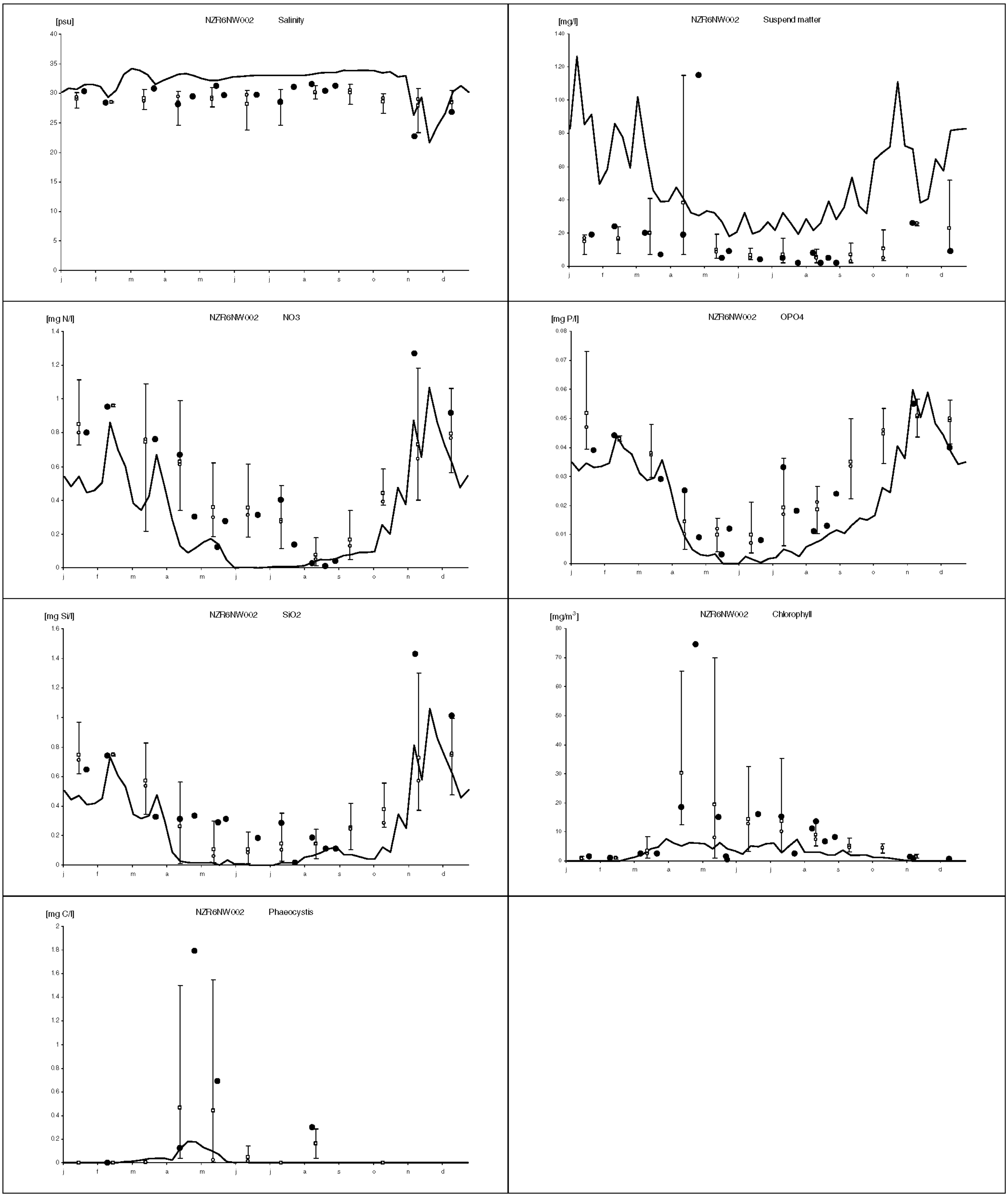



Figure A.20: Model results for the year 1998 and observations for 1998 (black circle) and average (square), median (white circle) and 90 percentile of field observations of 1995 – 1998 at station Noordwijk 2 km.

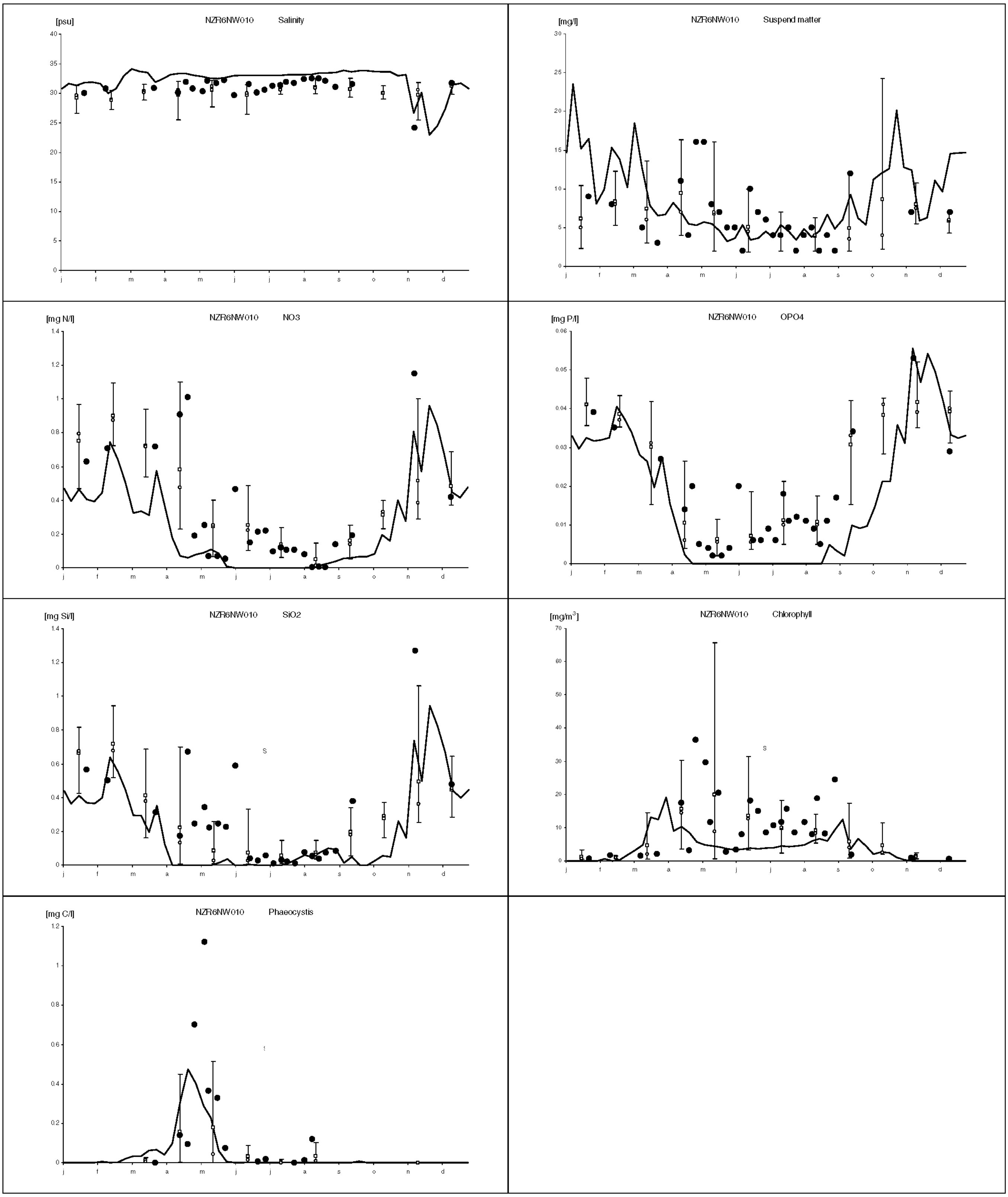



Figure A.21: Model results for the year 1998 and observations for 1998 (black circle) and average (square), median (white circle) and 90 percentile of field observations of 1995 – 1998 at station Noordwijk 10 km.

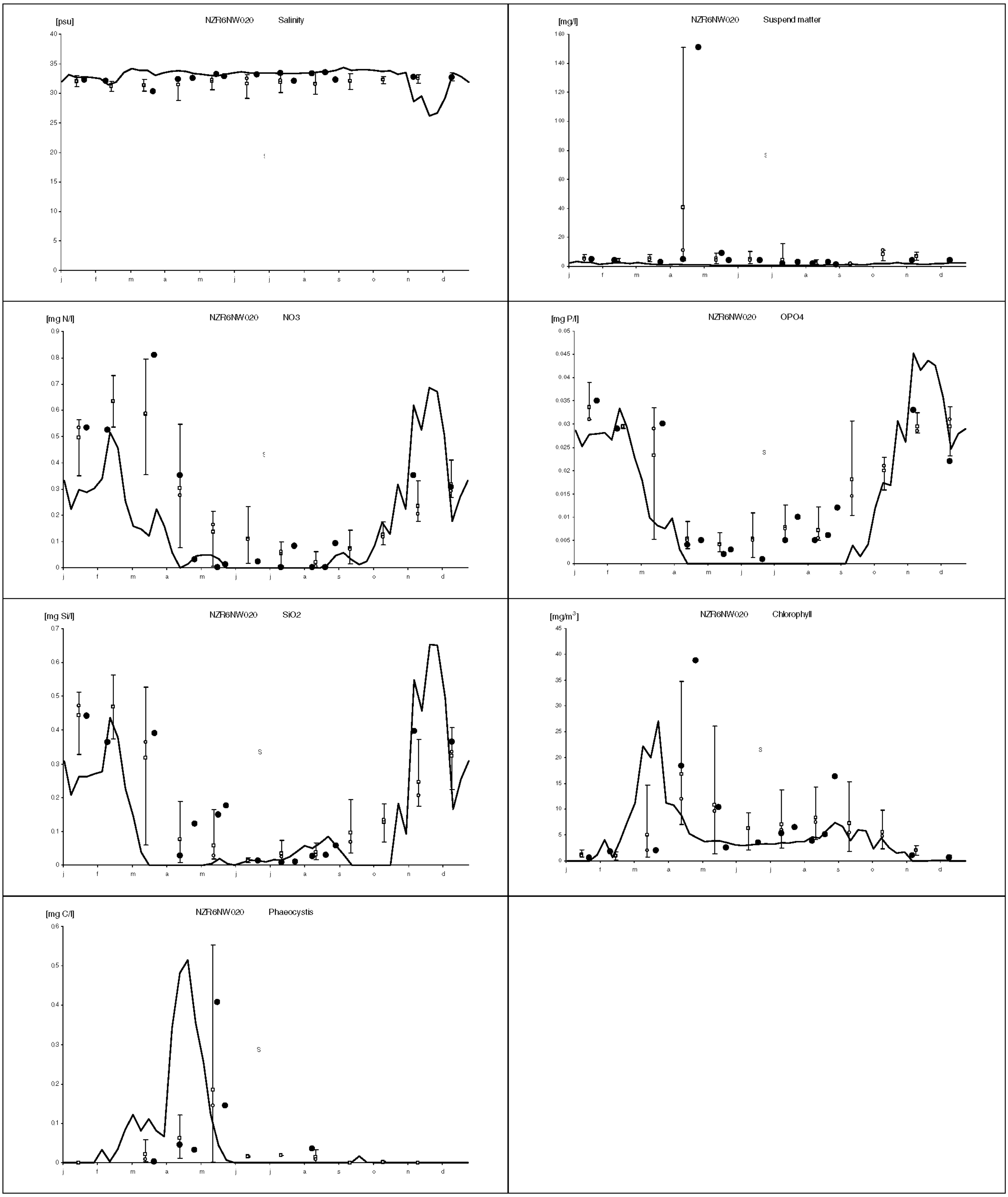



Figure A.22: Model results for the year 1998 and observations for 1998 (black circle) and average (square), median (white circle) and 90 percentile of field observations of 1995 – 1998 at station Noordwijk 20 km.

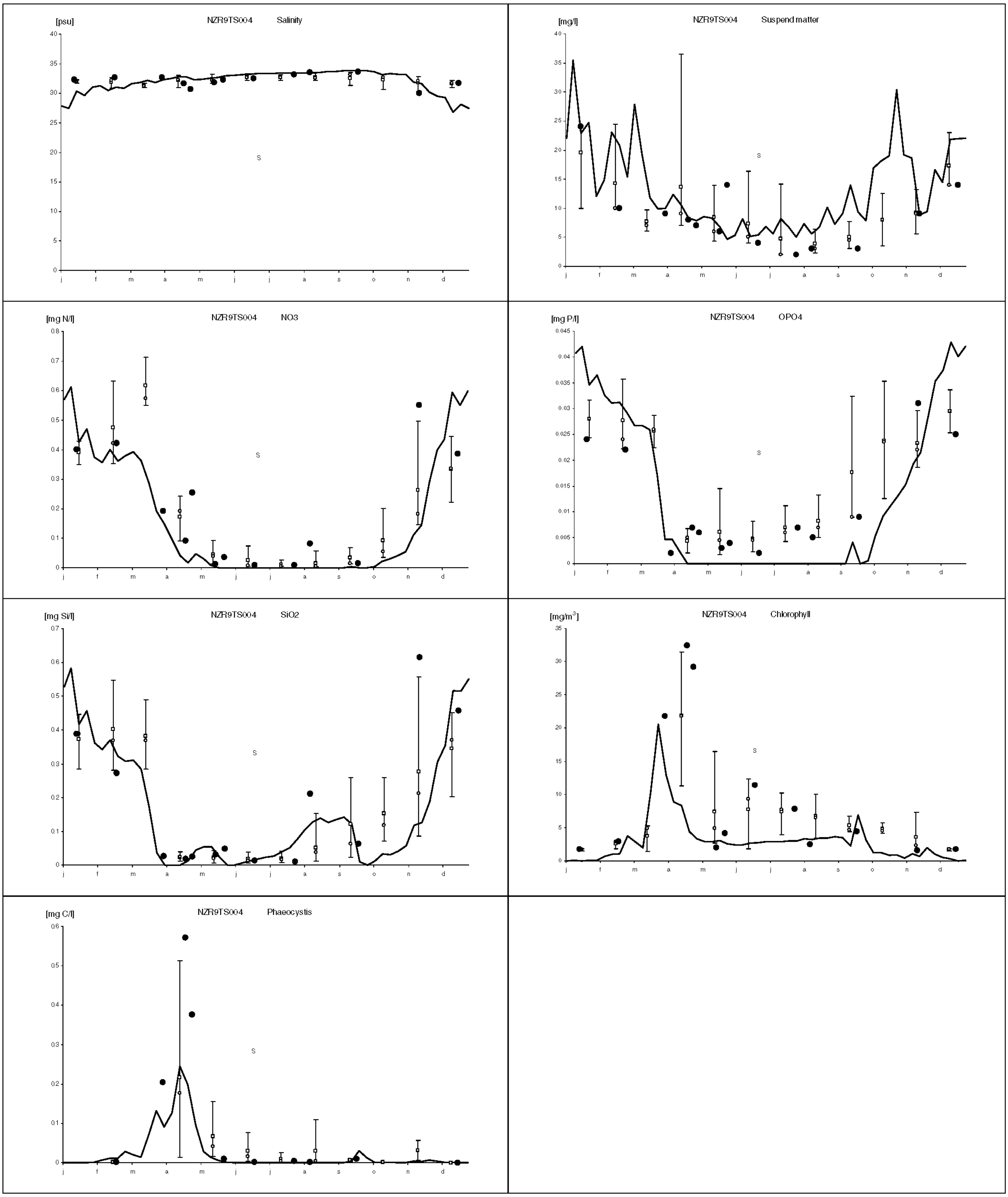



Figure A.23: Model results for the year 1998 and observations for 1998 (black circle) and average (square), median (white circle) and 90 percentile of field observations of 1995 – 1998 at station Terschelling 4 km.

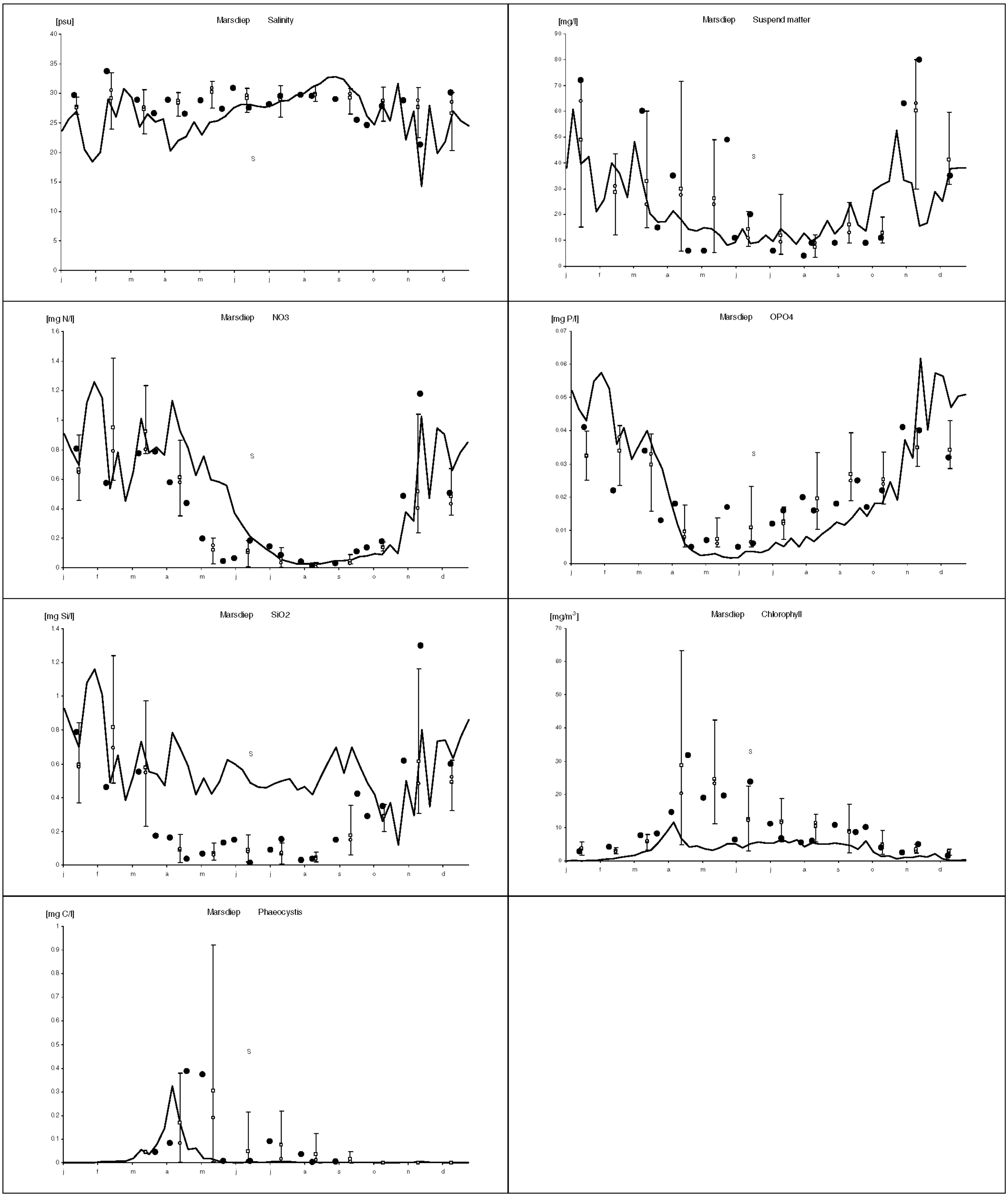
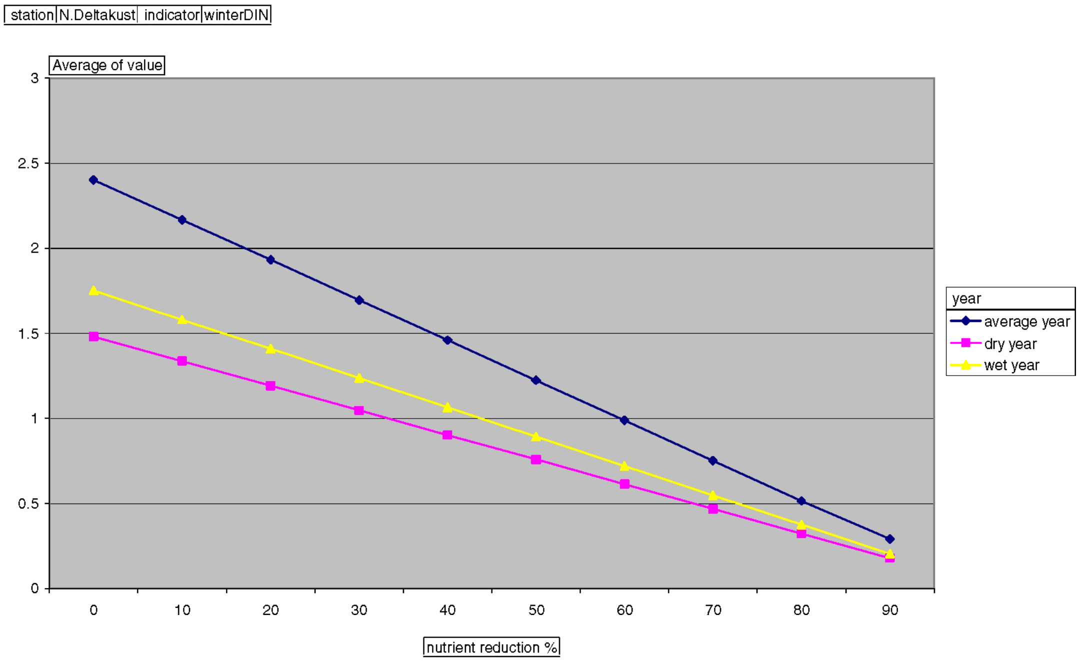



Figure A.24: Model results for the year 1998 and observations for 1998 (black circle) and average (square), median (white circle) and 90 percentile of field observations of 1995 – 1998 at station Marsdiep.

# B Response curves for combined N and P reduction



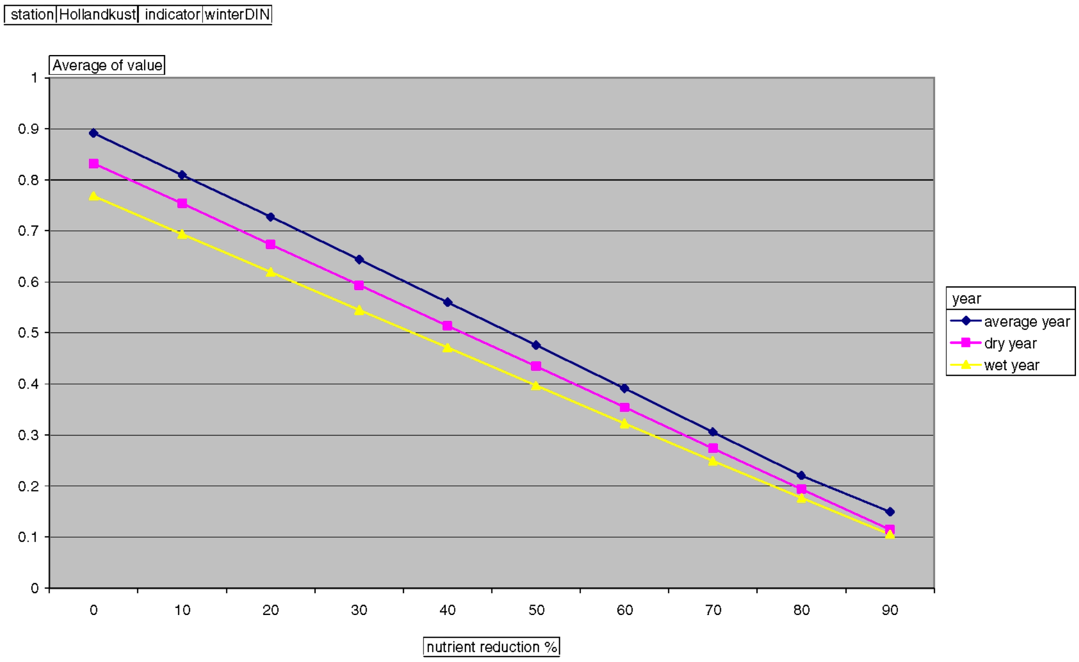
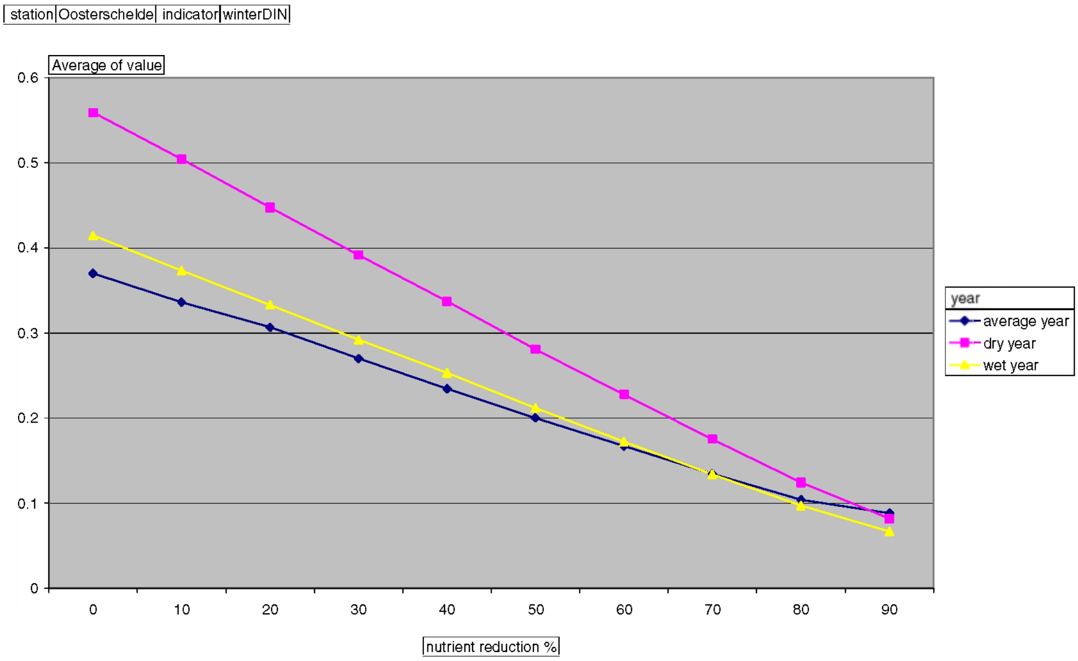




Figure B.1a: Response curves for winter averaged DIN concentrations (mgN/l) concentrations in the areas Delta coast and Holland coast



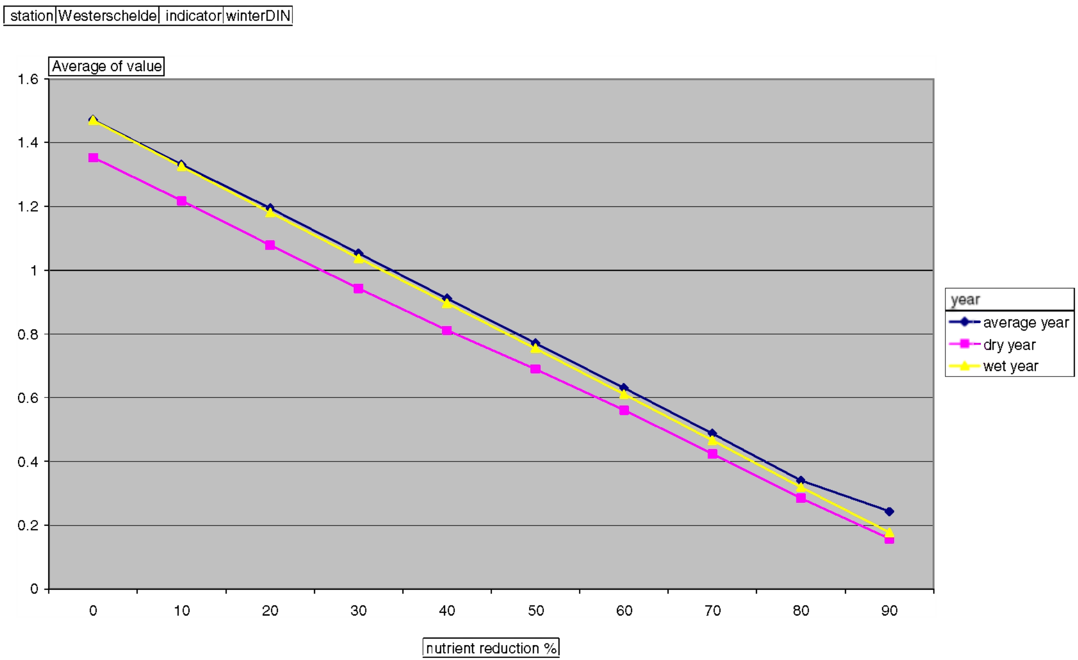
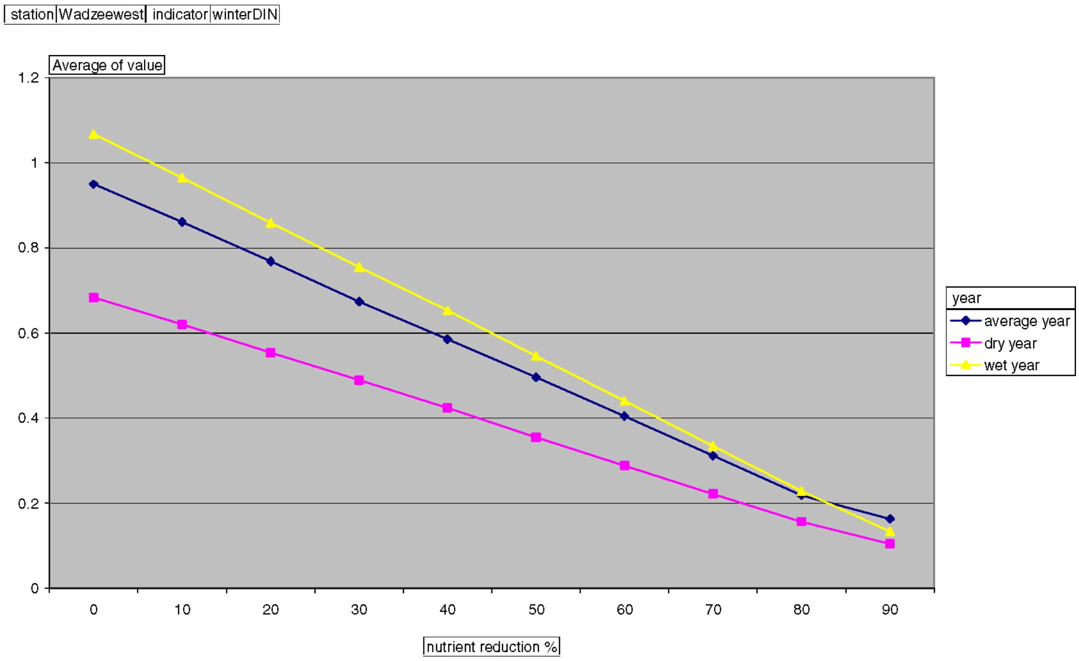




Figure B.1b: Response curves for winter averaged DIN concentrations (mgN/l)concentrations in the areas Oosterschelde and Westerschelde



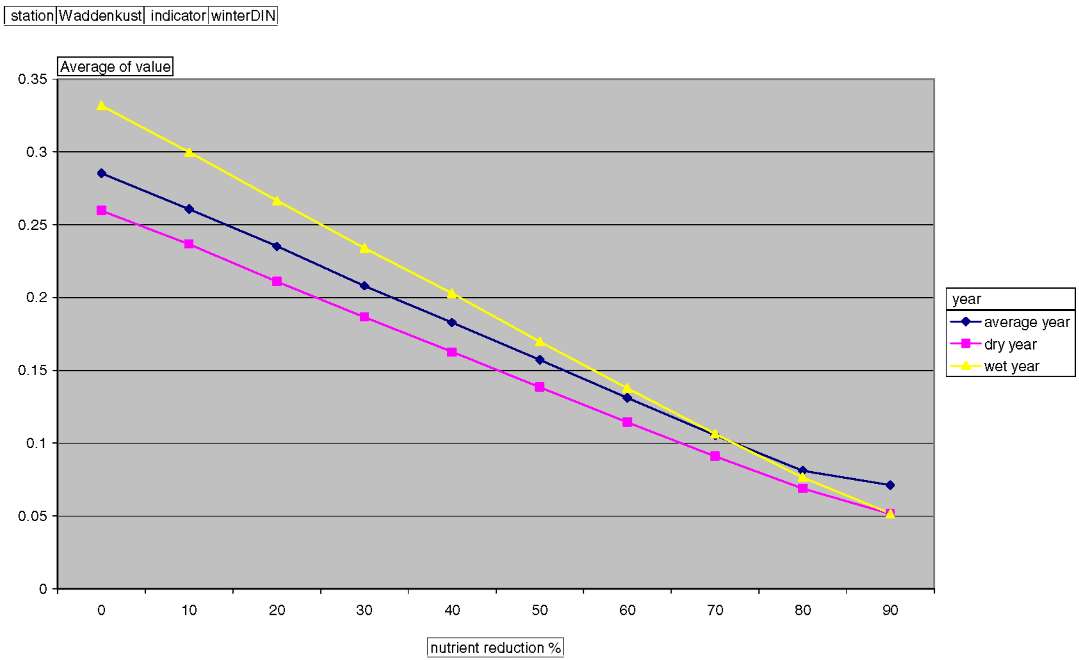




Figure B.1c: Response curves for winter averaged DIN concentrations (mgN/l)concentrations in the areas western Wadden Sea and Wadden coast.

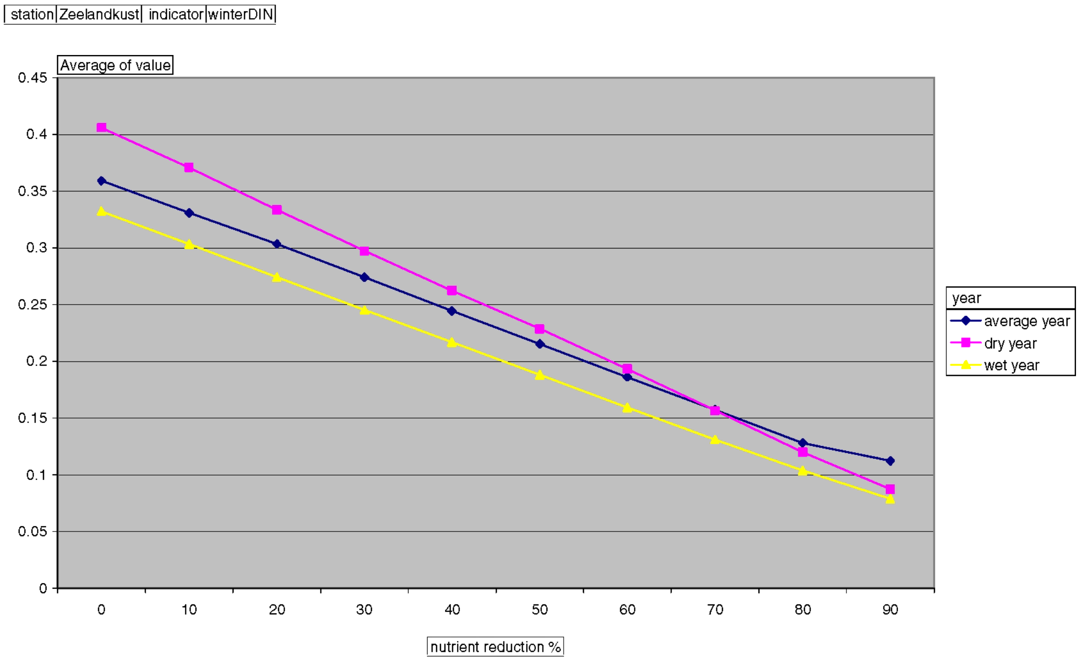
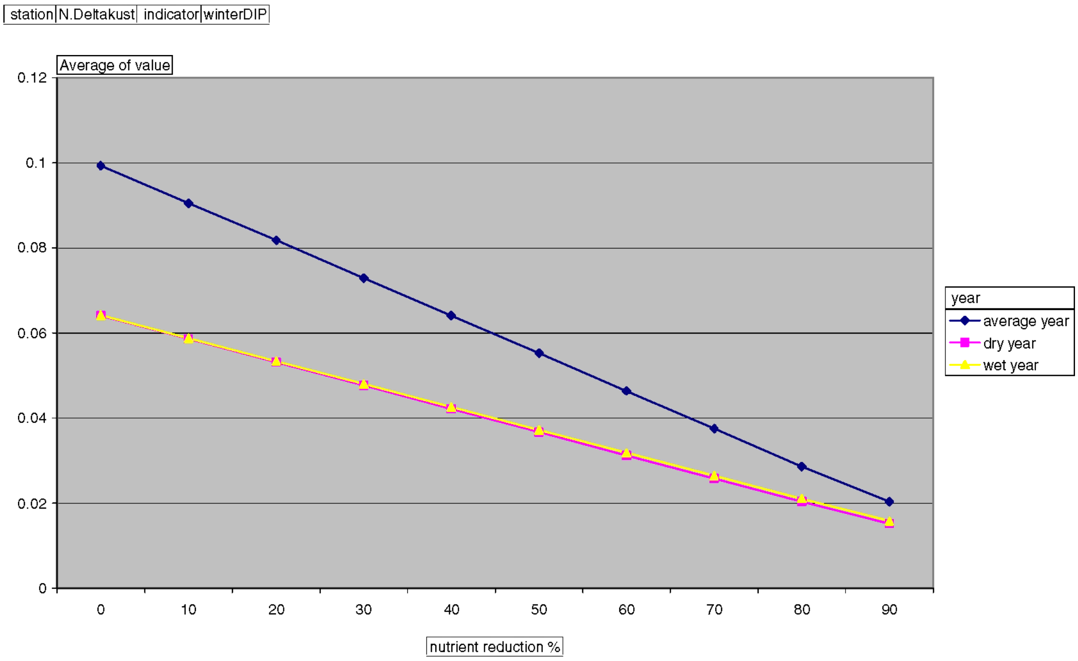



Figure B.1d: Response curves for winter averaged DIN concentrations (mgN/l)concentrations in the Zeeland coast area.



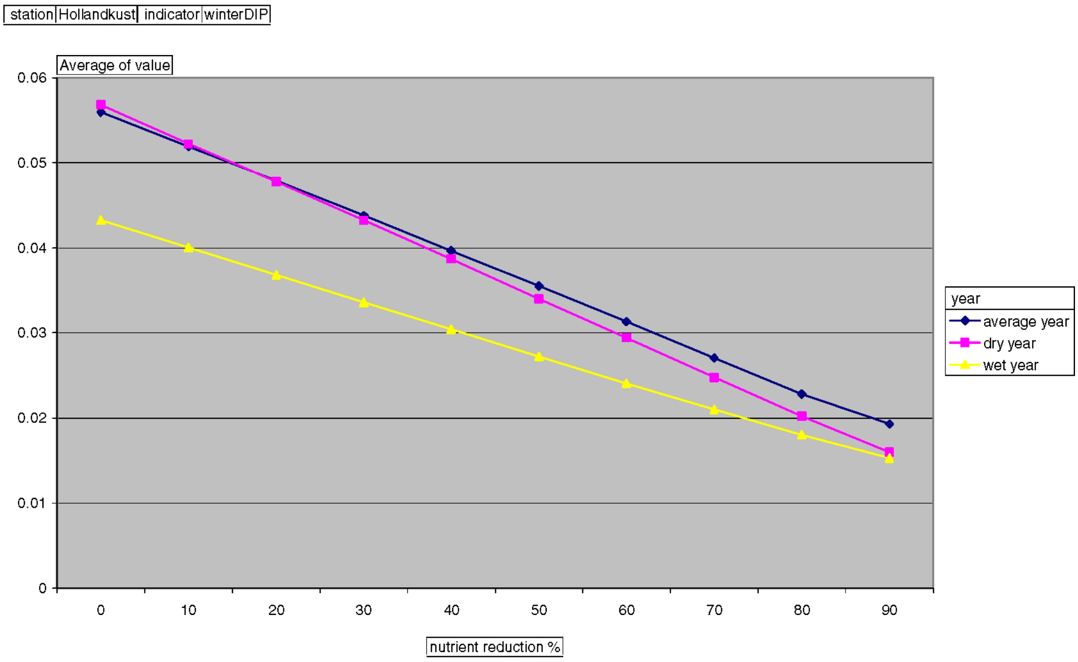
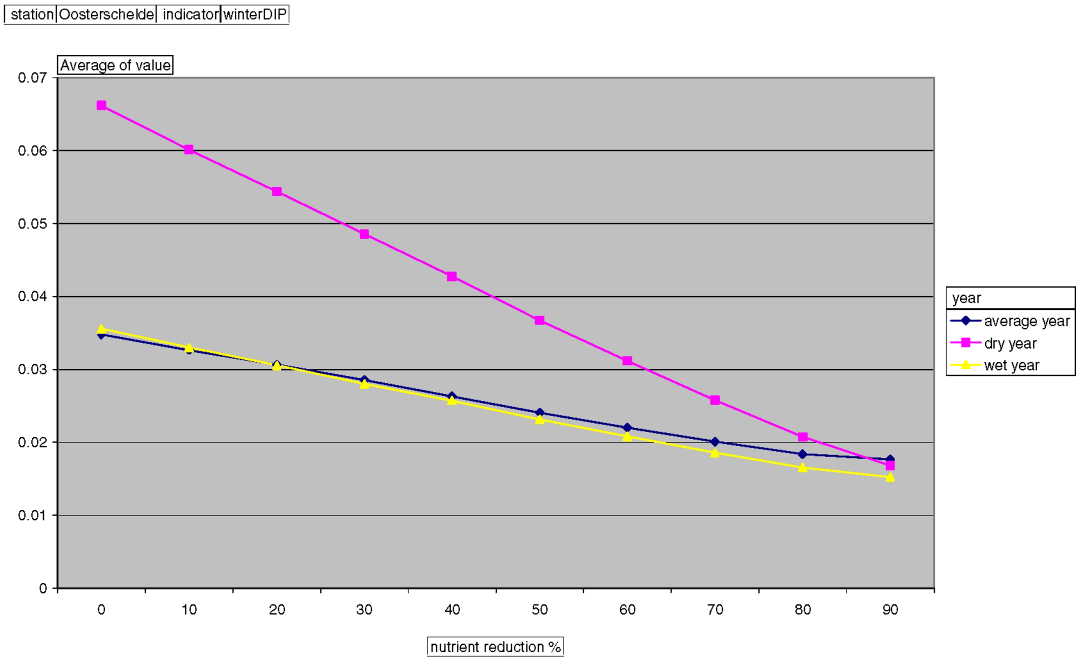




Figure B.2a: Response curves for winter averaged DIP concentrations (mgP/l)concentrations in the areas Delta coast and Holland coast



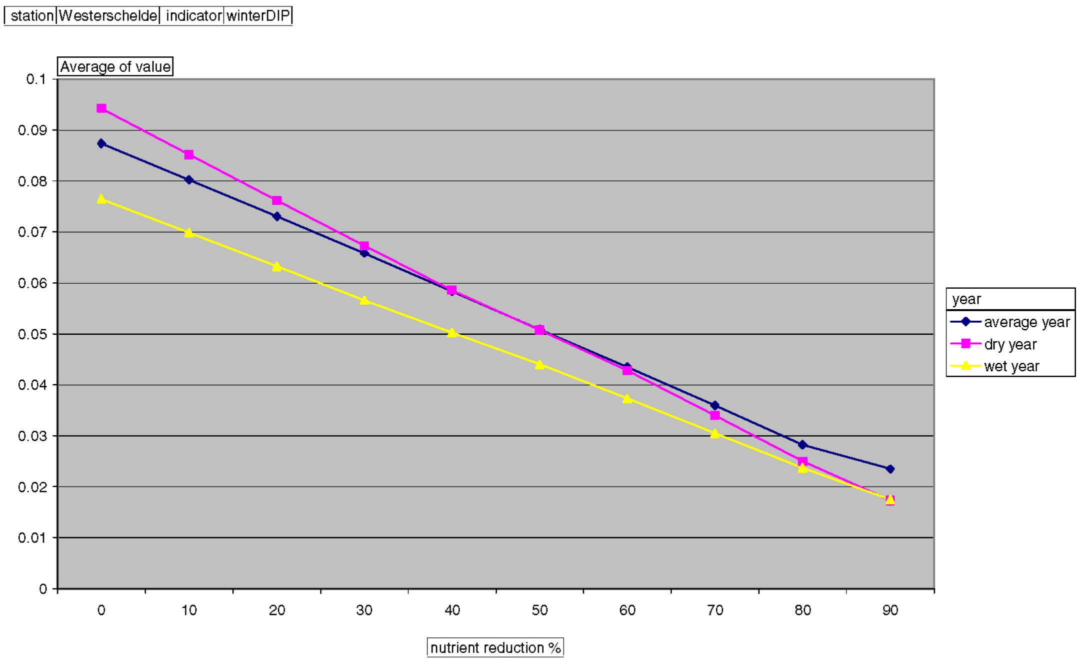
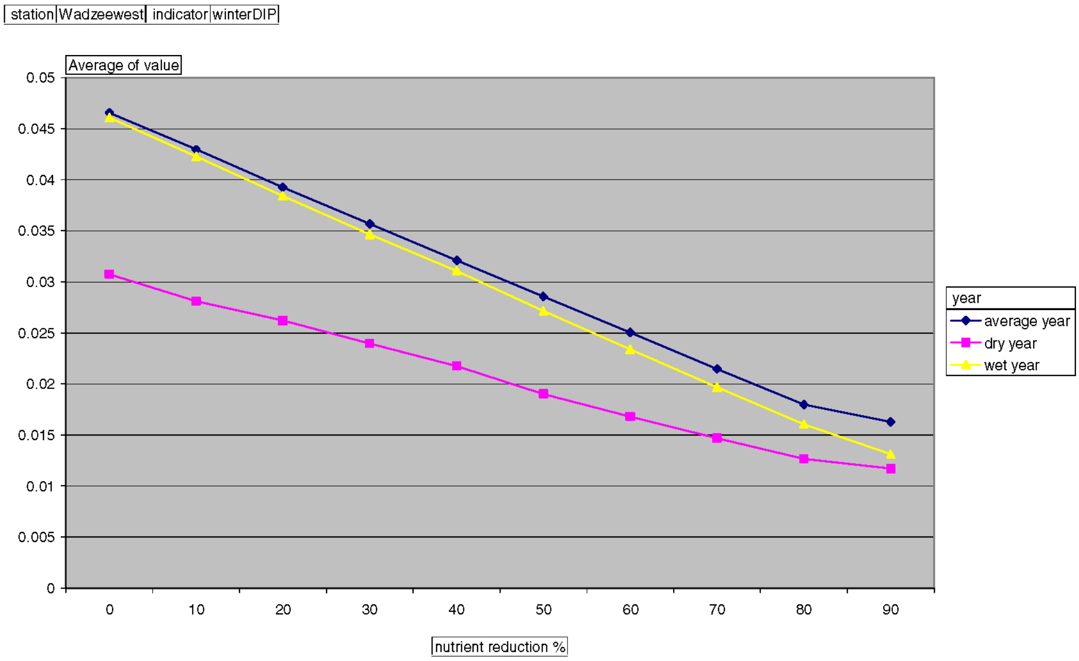




Figure B.2b: Response curves for winter averaged DIP concentrations (mgP/l)concentrations in the areas Oosterschelde and Westerschelde



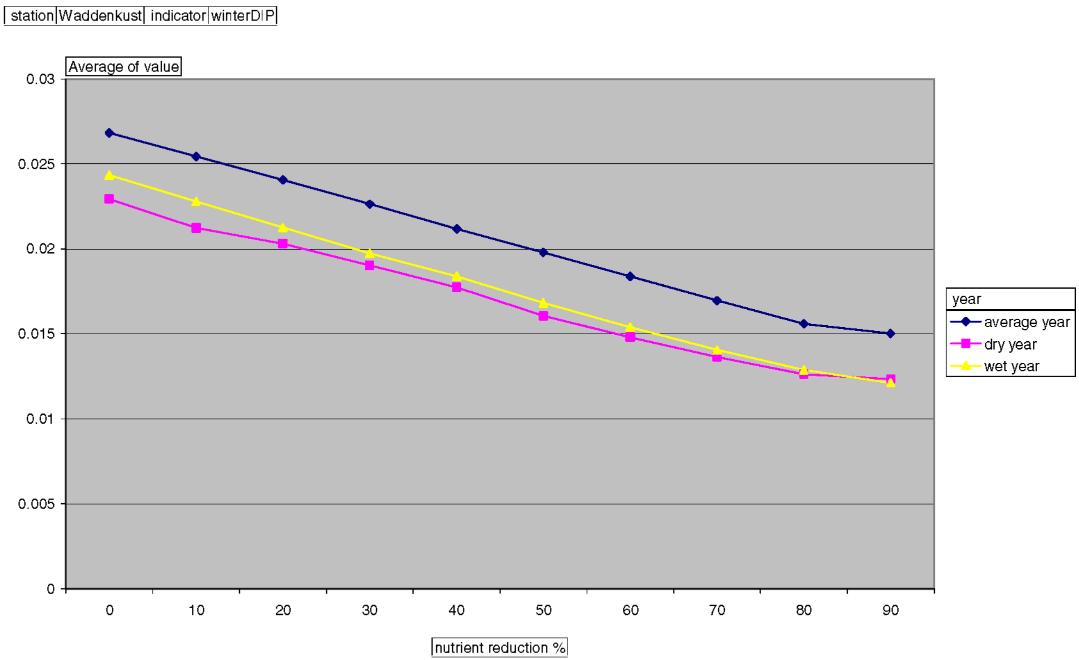




Figure B.2c: Response curves for winter averaged DIP concentrations (mgP/l)concentrations in the areas western Wadden Sea and Wadden coast.

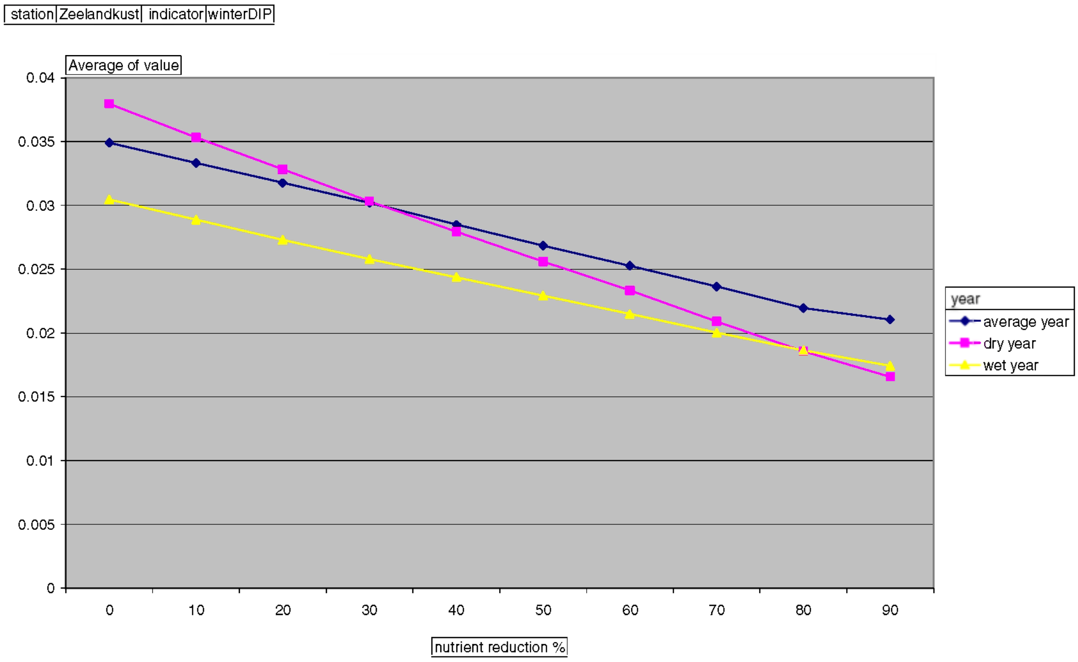
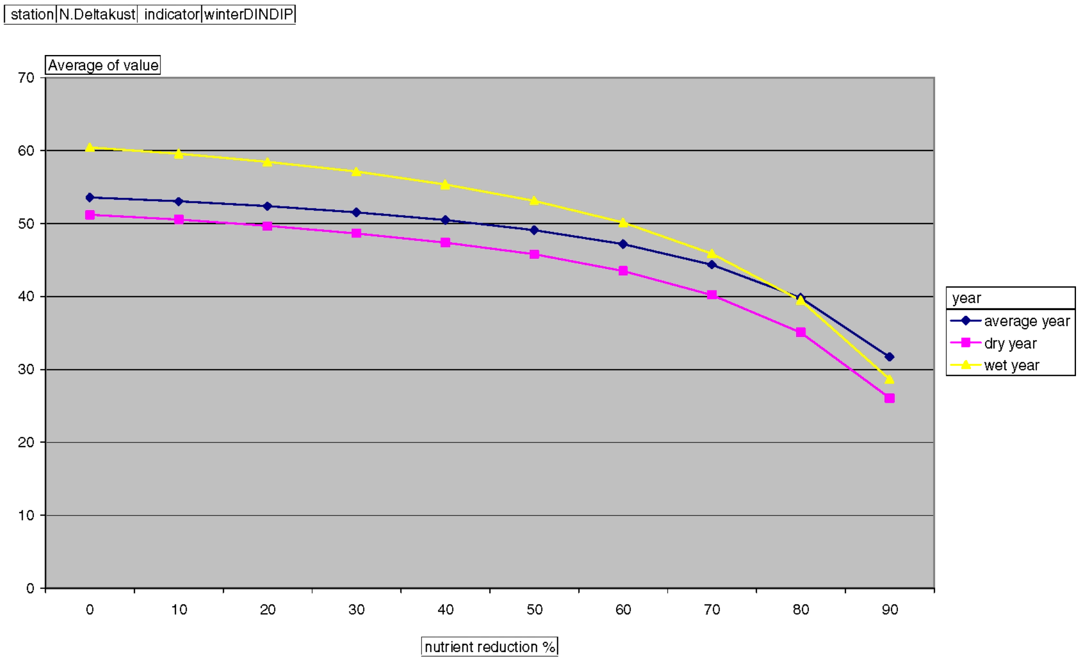



Figure B.2d: Response curves for winter averaged DIP concentrations (mgP/l)concentrations in the Zeeland coast area.



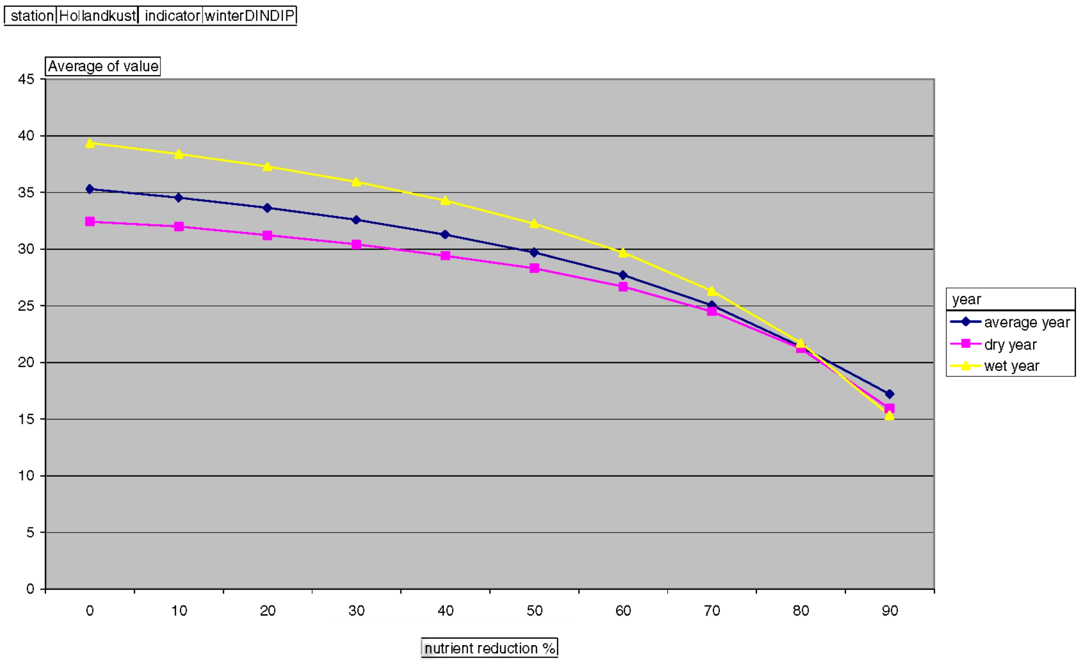
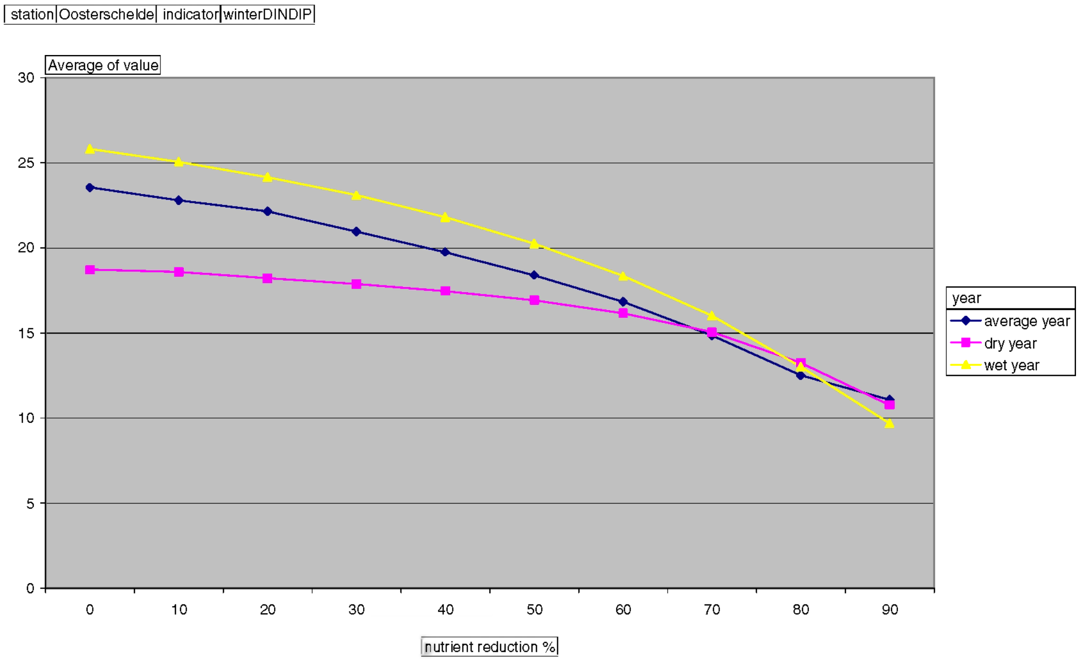




Figure B.3a: Response curves for winter averaged DIN/DIP ratios concentrations in the areas Delta coast and Holland coast



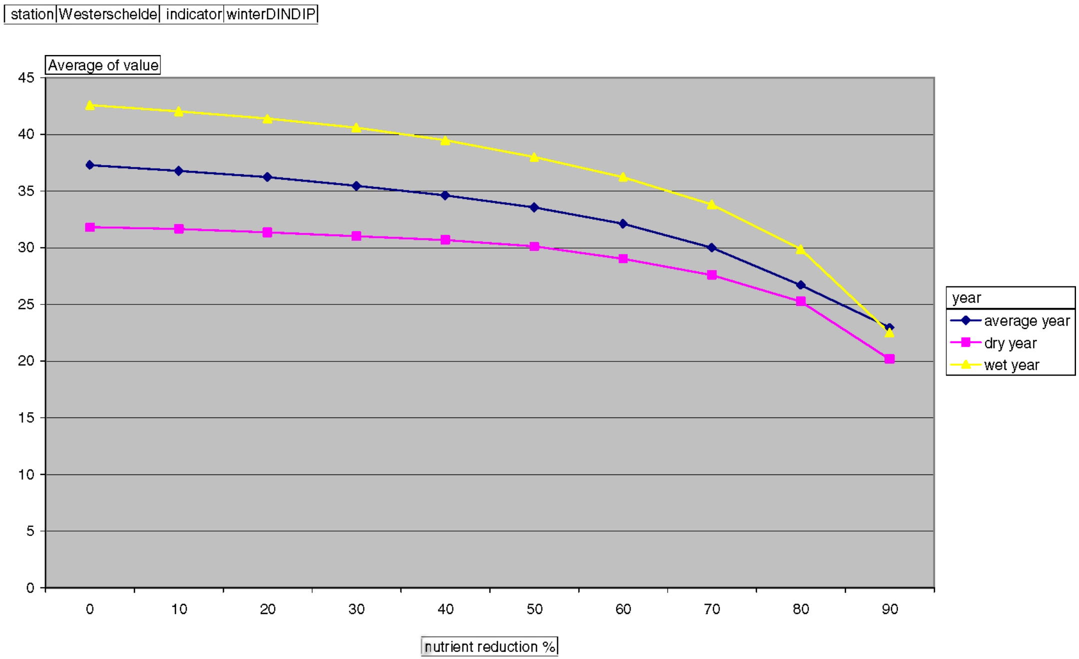
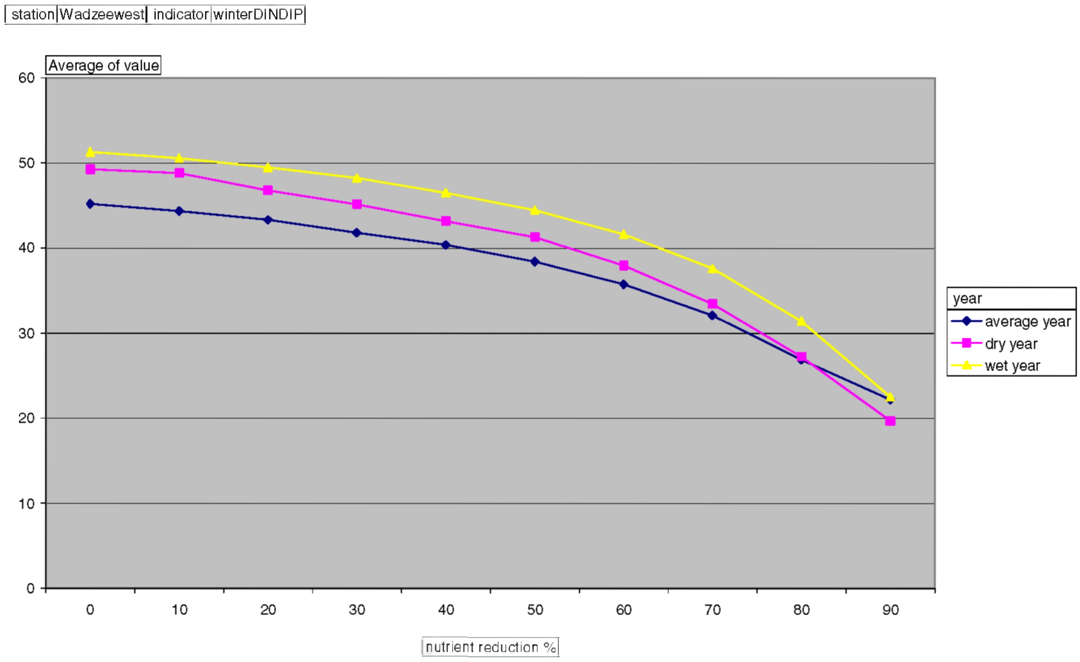




Figure B.3b: Response curves for winter averaged DIN/DIP ratios concentrations in the areas Oosterschelde and Westerschelde



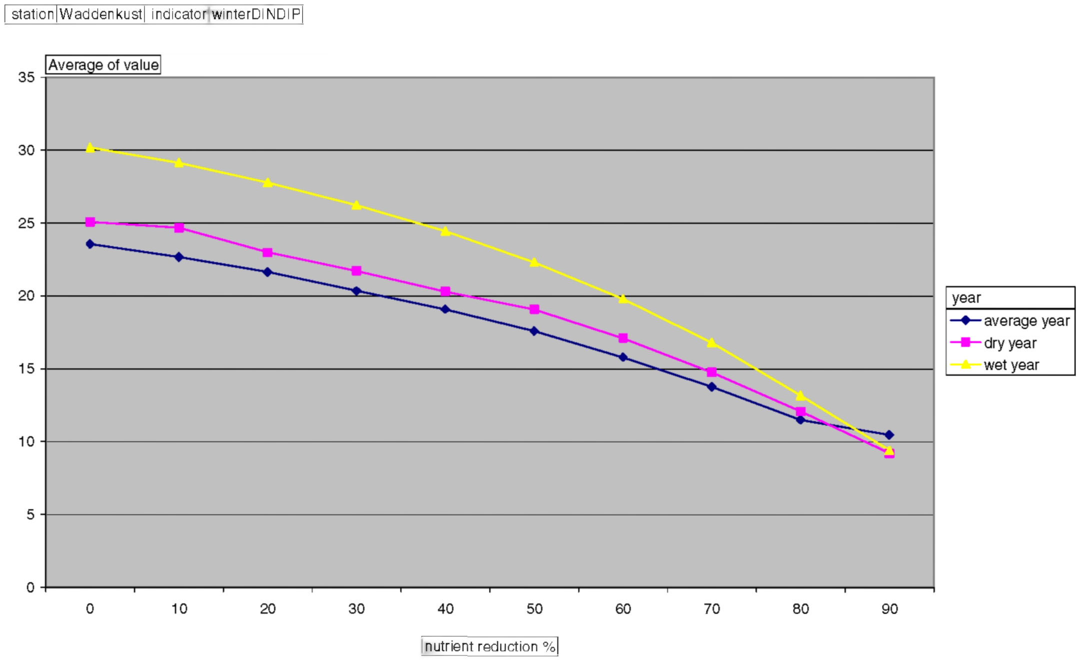




Figure B.3c: Response curves for winter averaged DIN/DIP ratios concentrations in the areas western Wadden Sea and Wadden coast.

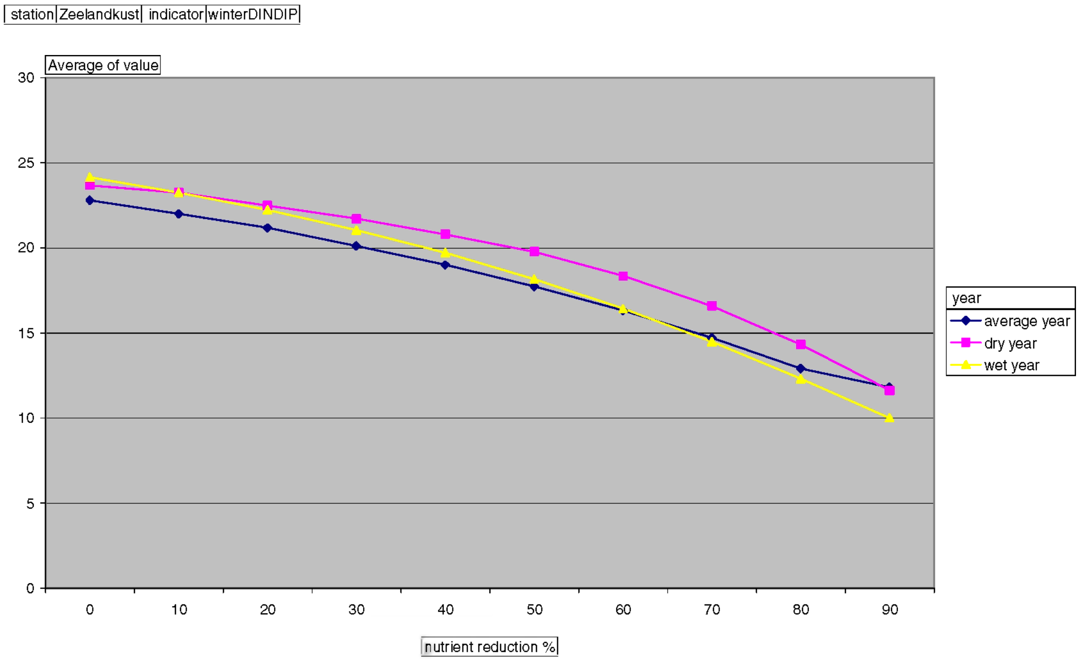
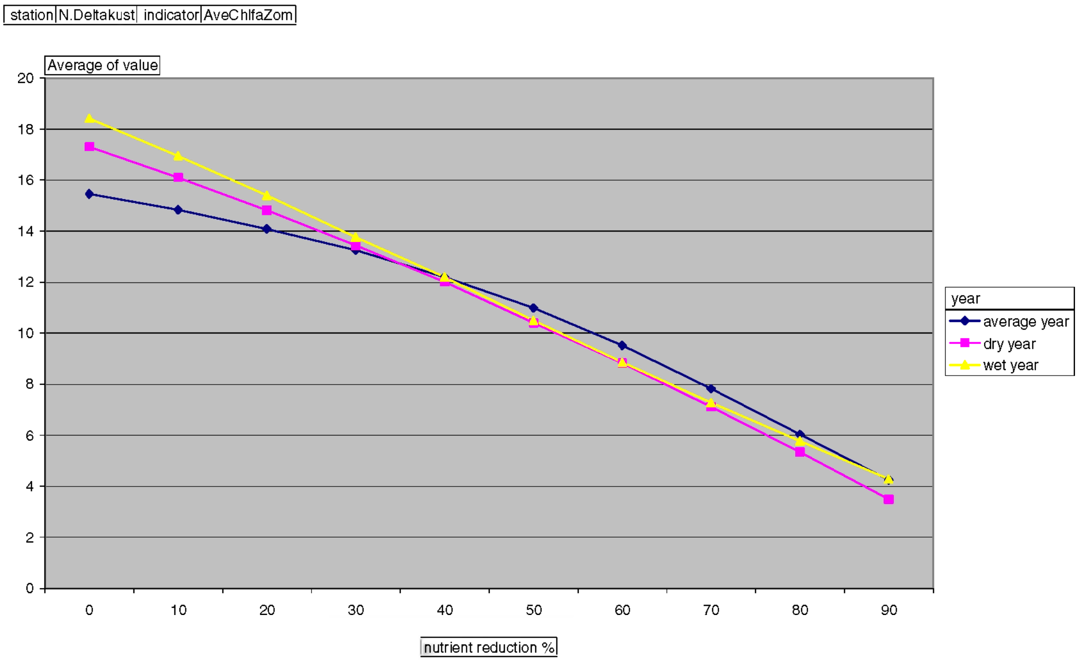



Figure B.3d: Response curves for winter averaged DIN/DIP ratios concentrations in the Zeeland coast area.



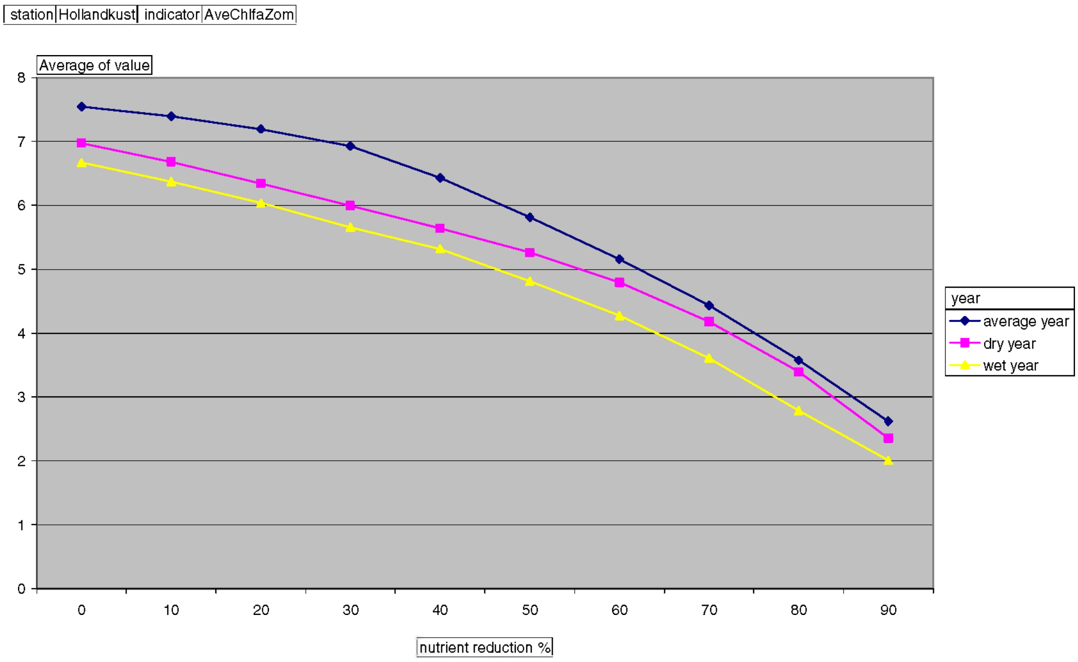




Figure B.4a: Response curves for summer averaged chlorophyll-a concentrations (µg/l) in the areas Delta coast and Holland coast

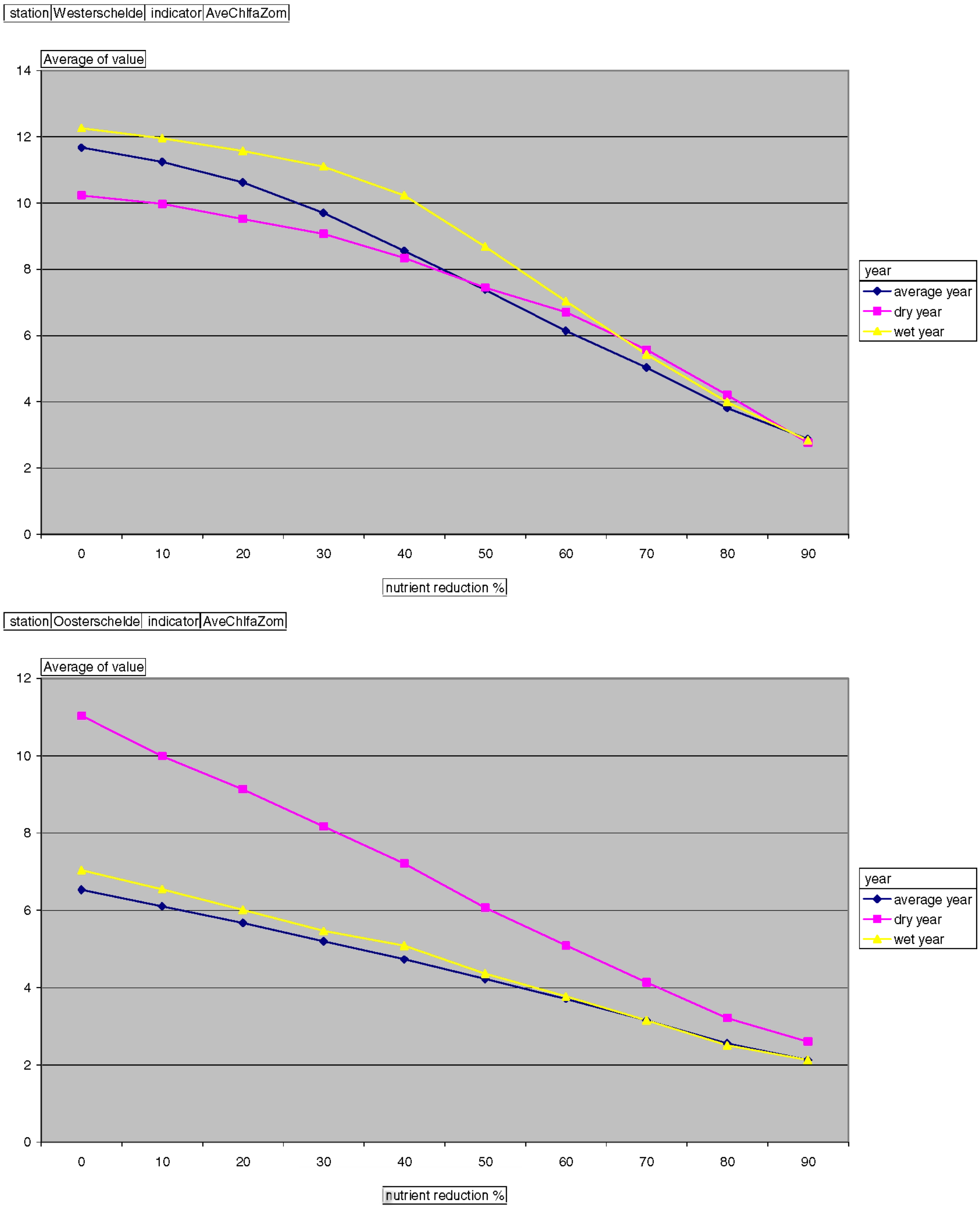
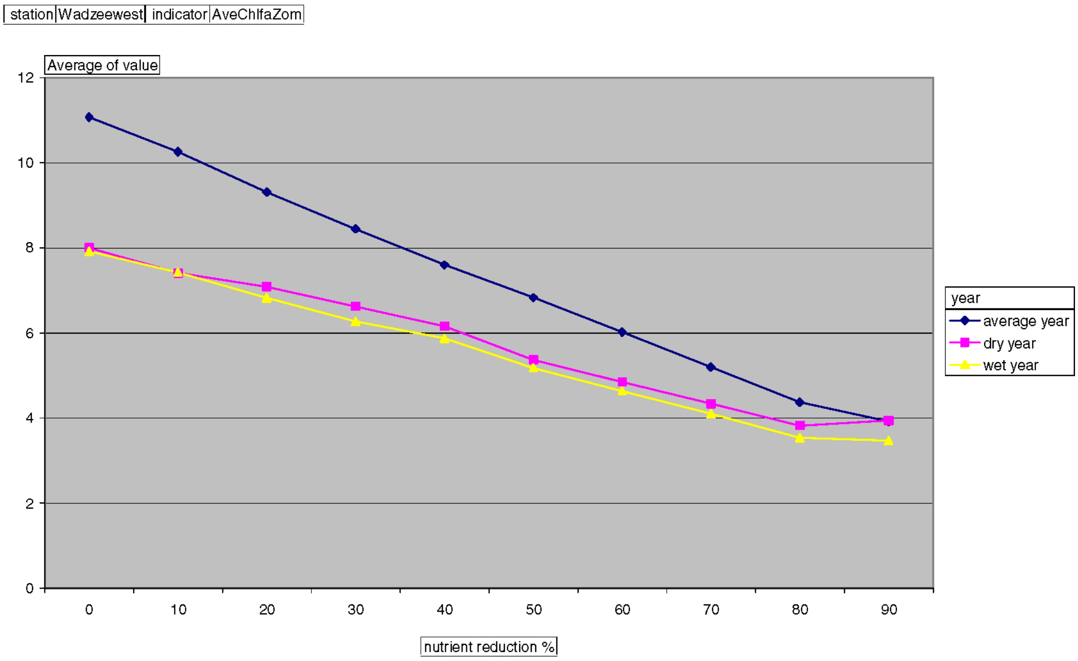



Figure B.4b: Response curves for summer averaged chlorophyll-a concentrations (µg/l)in the areas Oosterschelde and Westerschelde



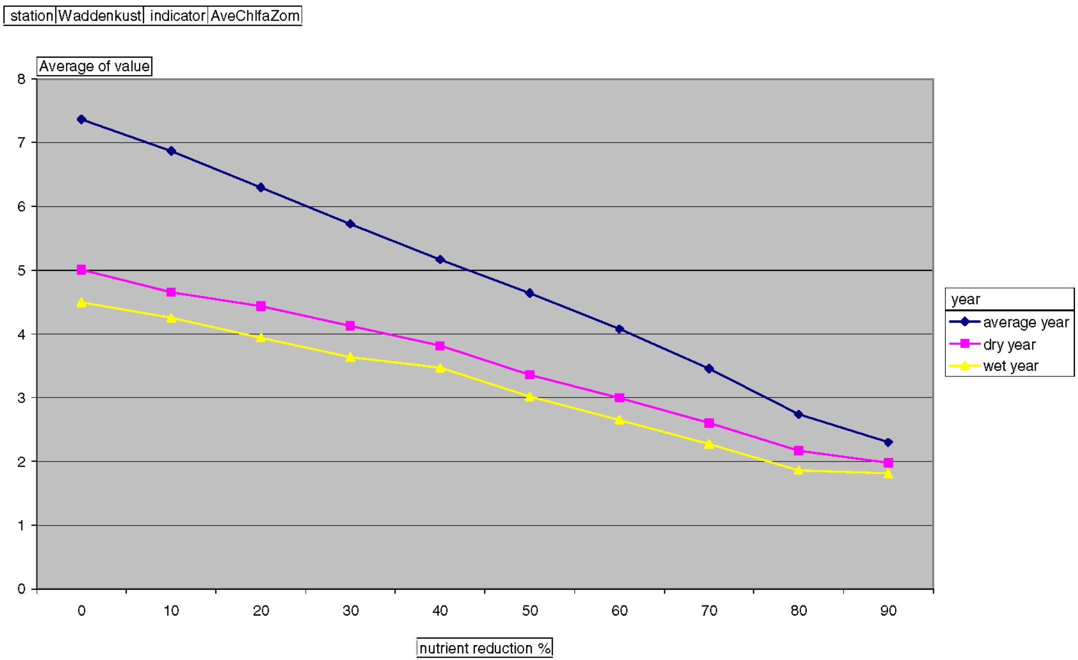




Figure B.4c: Response curves for summer averaged chlorophyll-a concentrations (μg/l)in the areas western Wadden Sea and Wadden coast.

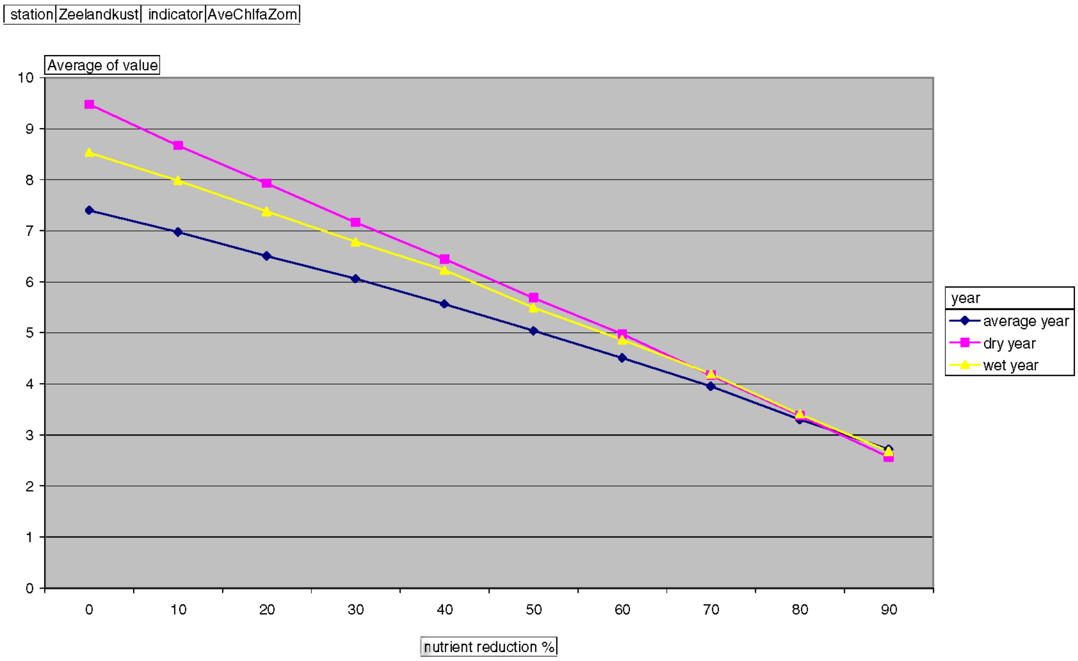
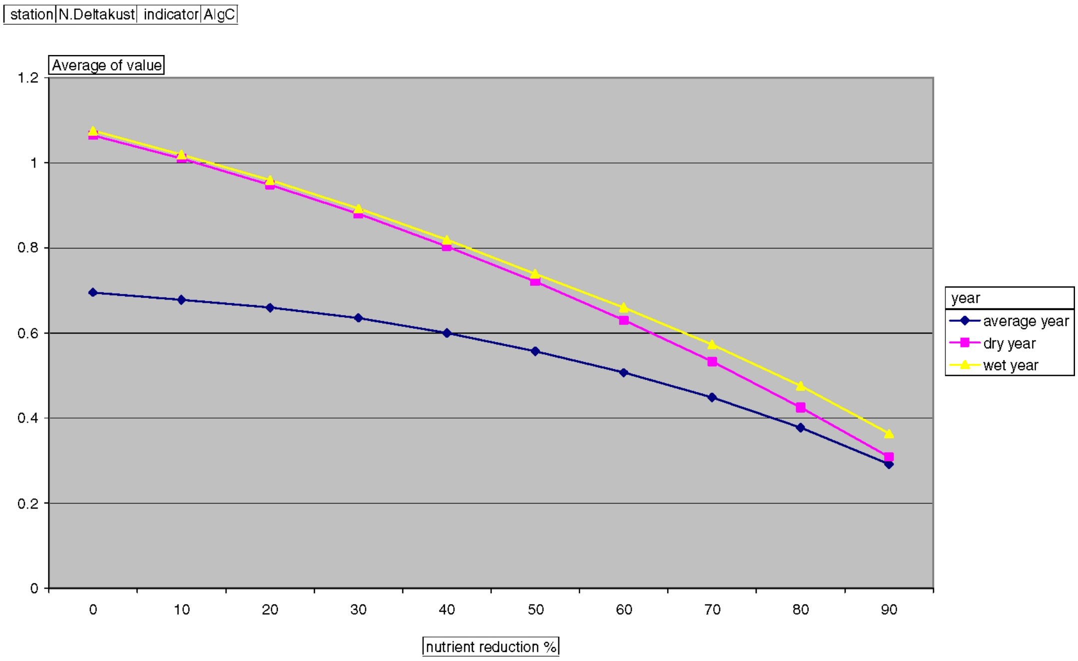



Figure B.4d: Response curves for summer averaged chlorophyll-a concentrations (µg/l)in the Zeeland coast area.



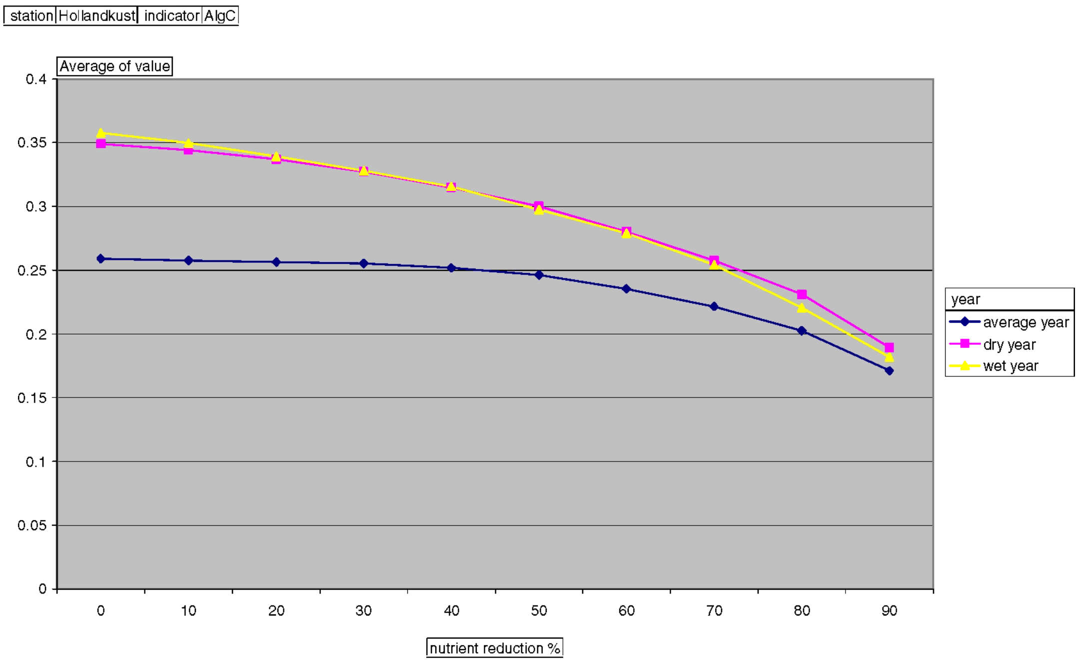
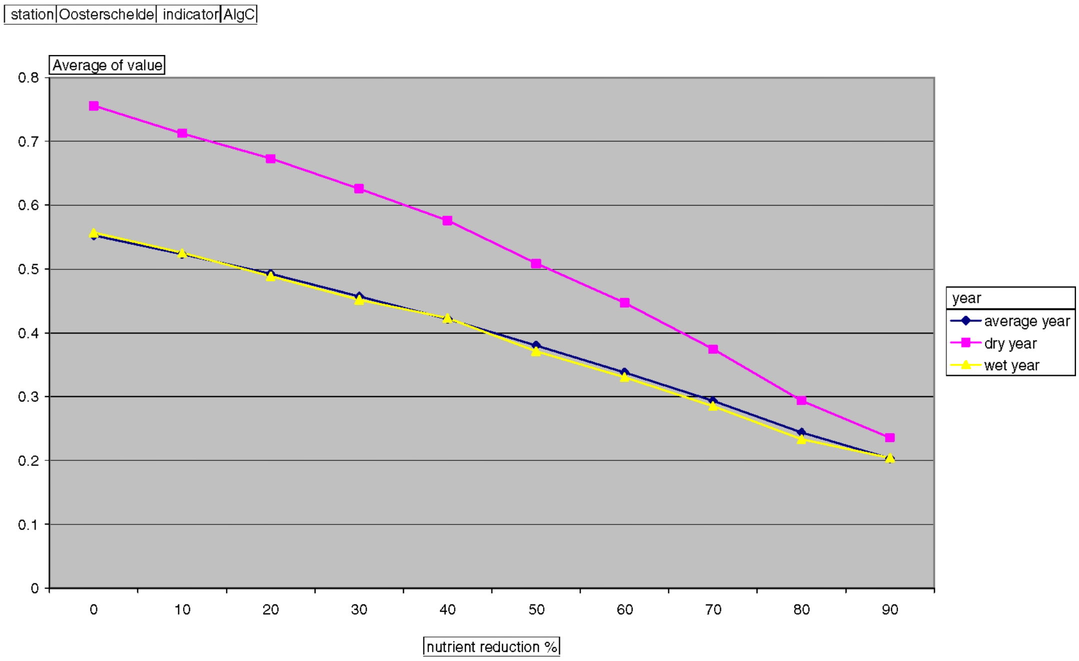




Figure B.5a: Response curves for summer averaged algal biomass (gC/m$^3$) concentrations in the areas Delta coast and Holland coast



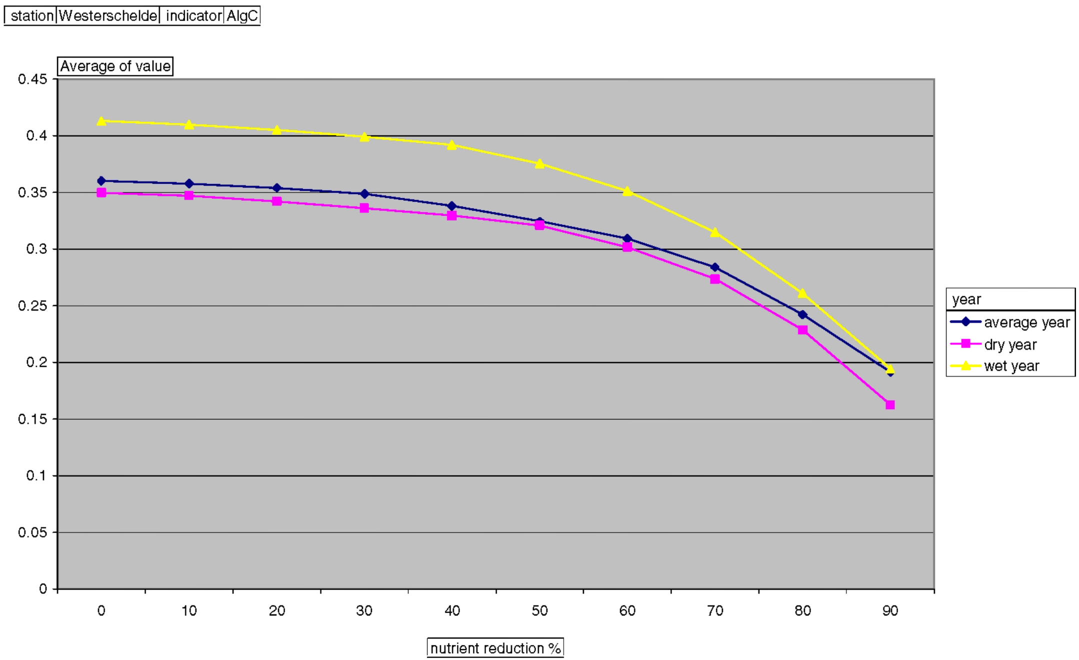
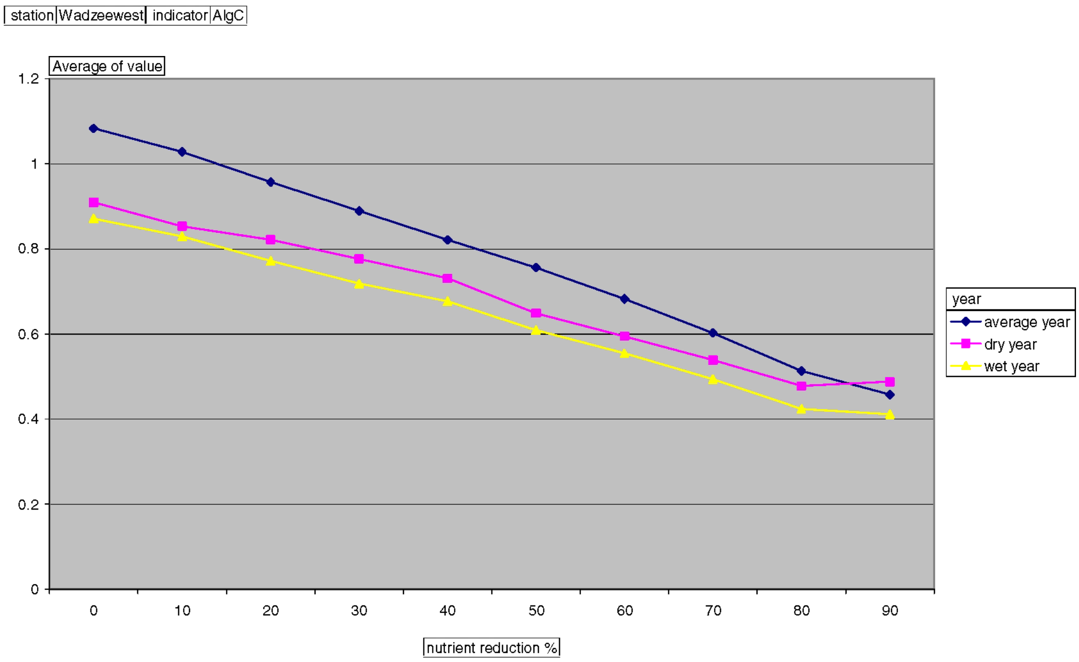




Figure B.5b: Response curves for summer averaged algal biomass ($gC/m^3$) concentrations in the areas Oosterschelde and Westerschelde



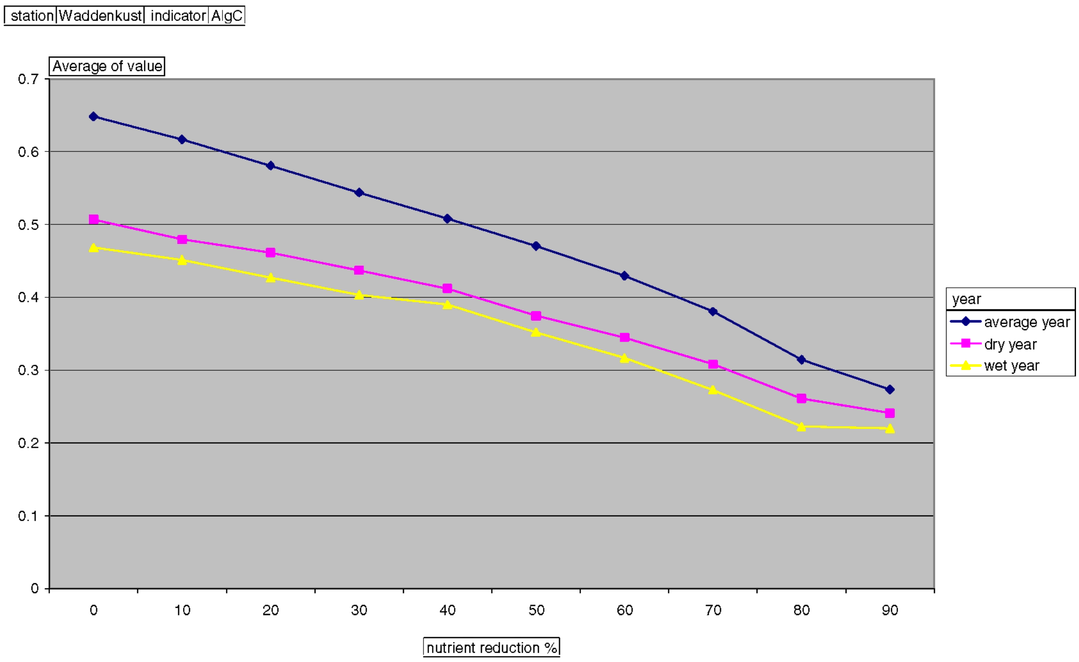




Figure B.5c: Response curves for summer averaged algal biomass (gC/m$^3$) concentrations in the areas western Wadden Sea and Wadden coast.

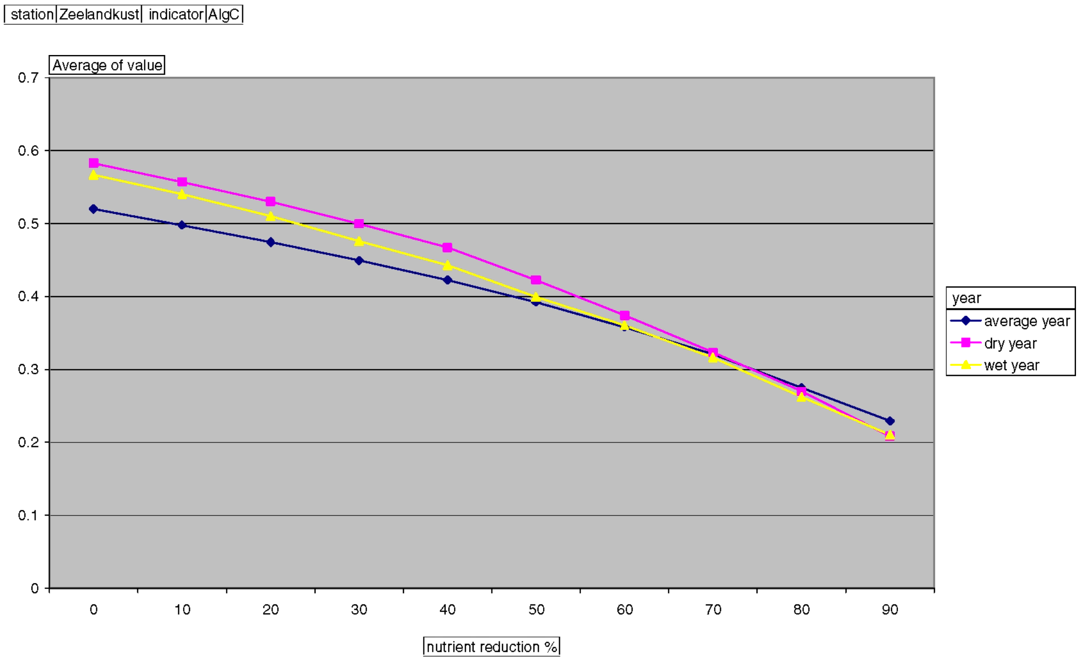



Figure B.5d: Response curves for summer averaged algal biomass (gC/m$^3$) concentrations in the Zeeland coast area.

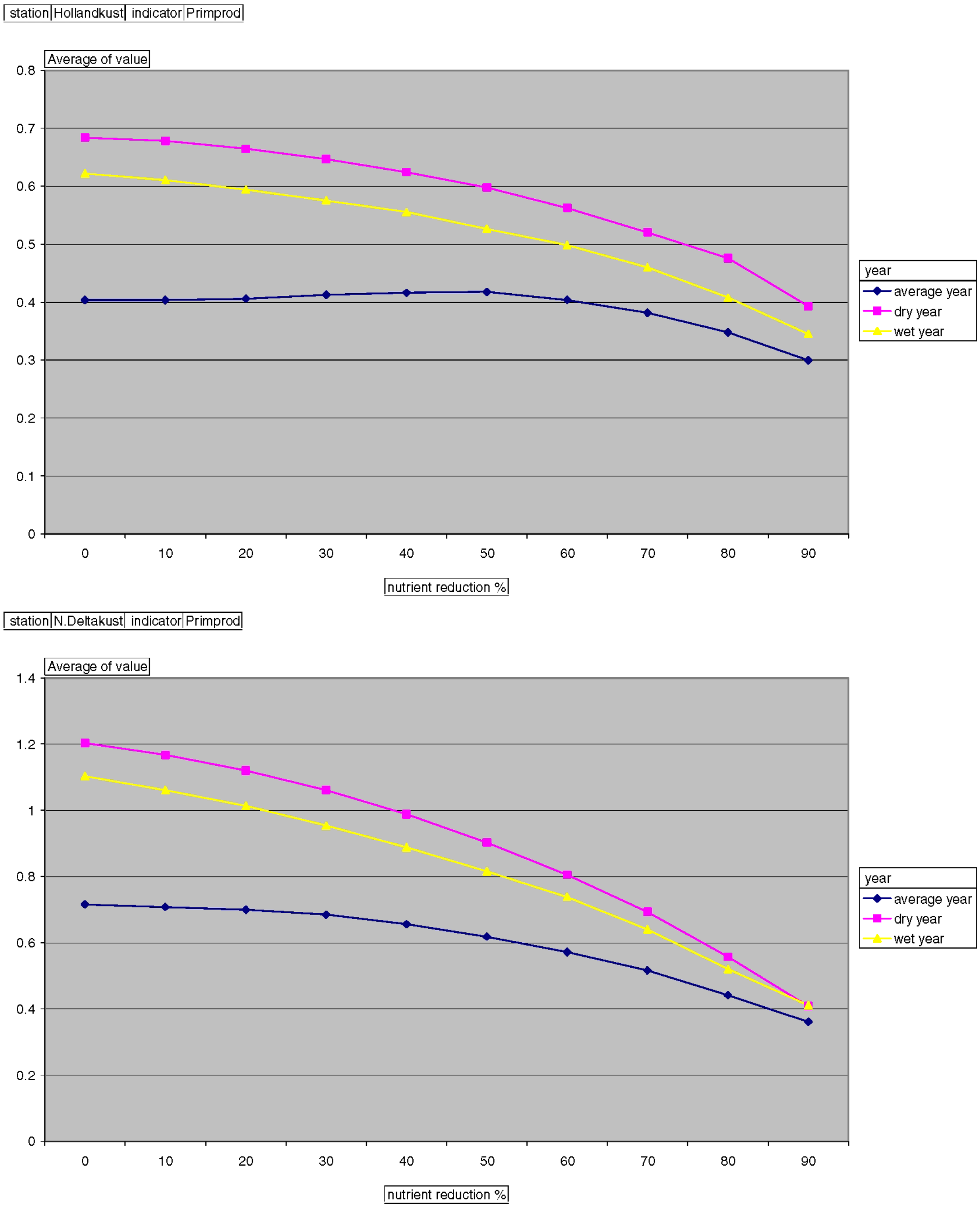
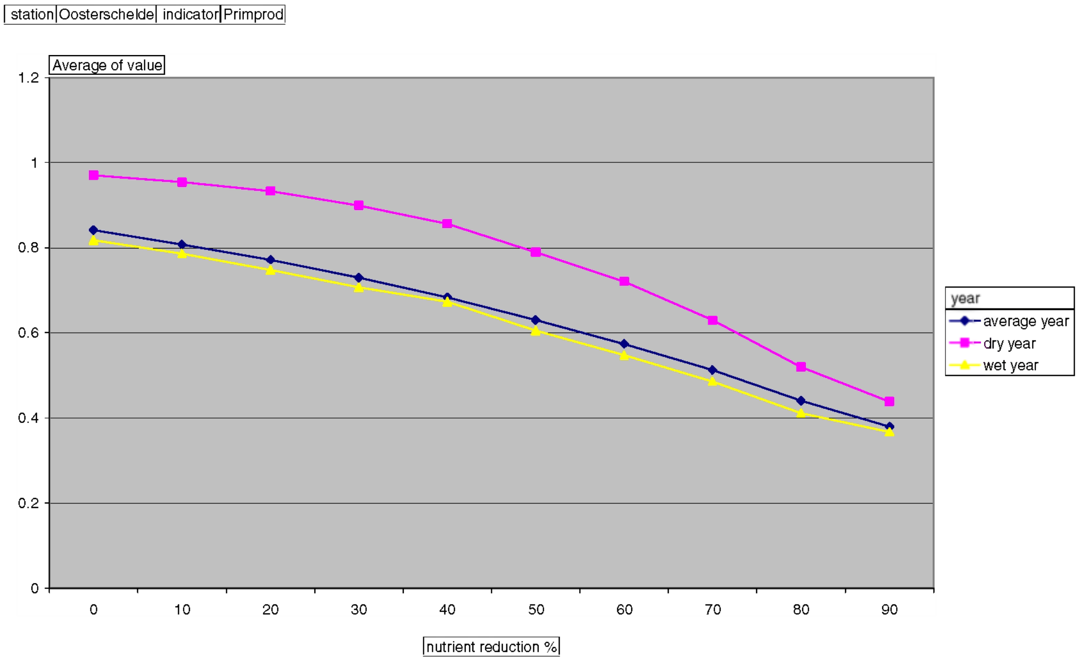



Figure B.6a: Response curves for yearly averaged primary production ($gC/m^3.d$) concentrations in the areas Delta coast and Holland coast



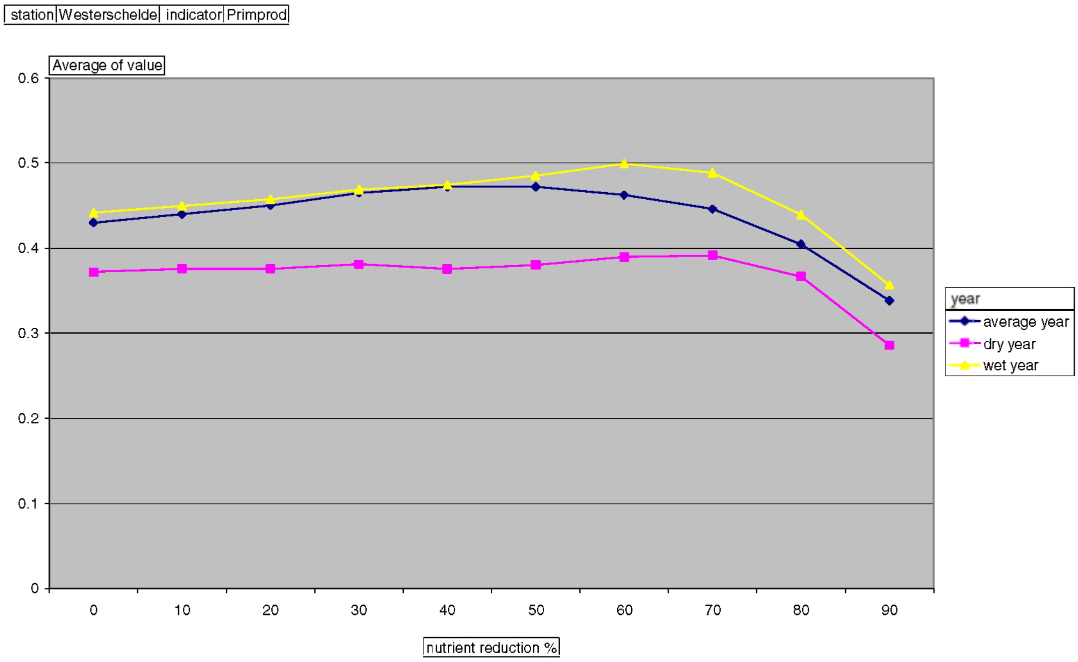
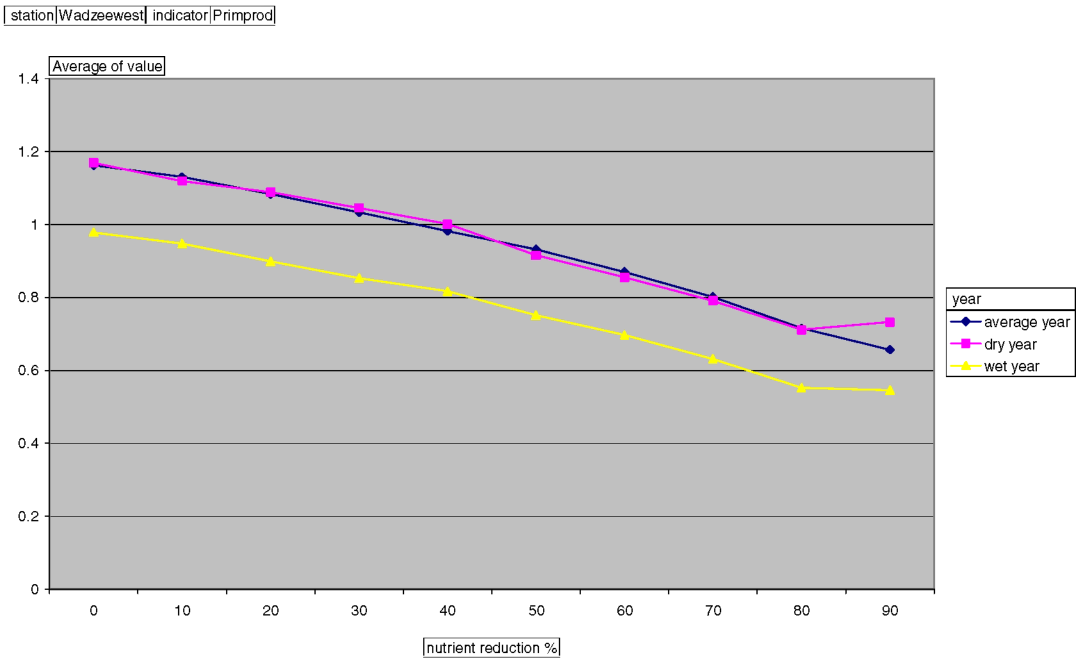




Figure B.6b: Response curves for yearly averaged primary production ($gC/m^3.d$) concentrations in the areas Oosterschelde and Westerschelde



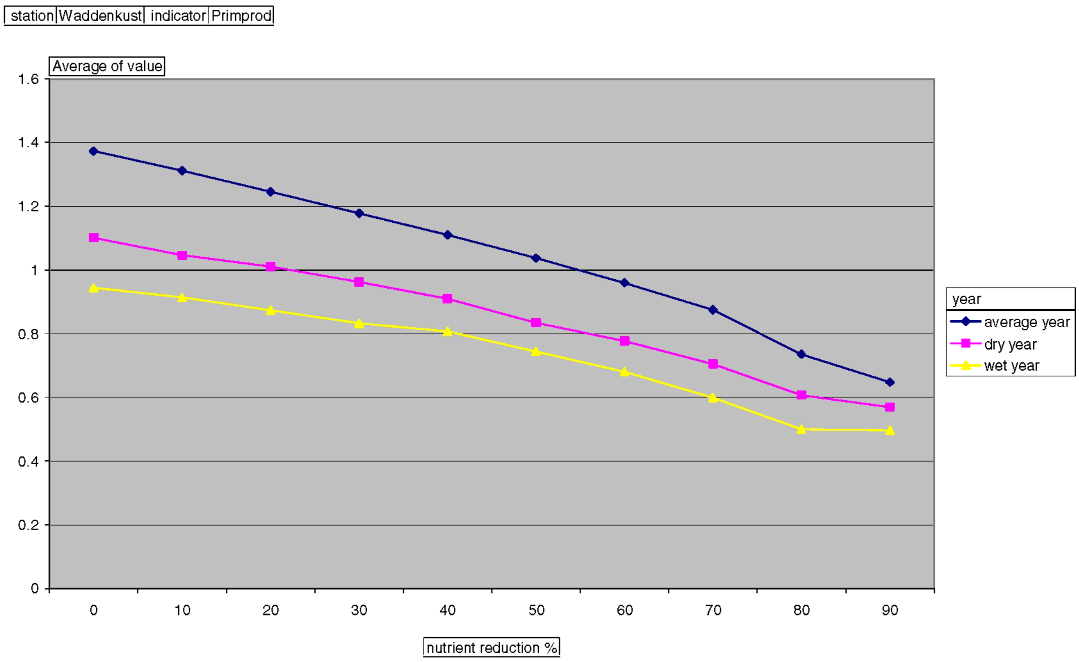




Figure B.6c: Response curves for yearly averaged primary production (gC/m$^3$.d) concentrations in the areas western Wadden Sea and Wadden coast.

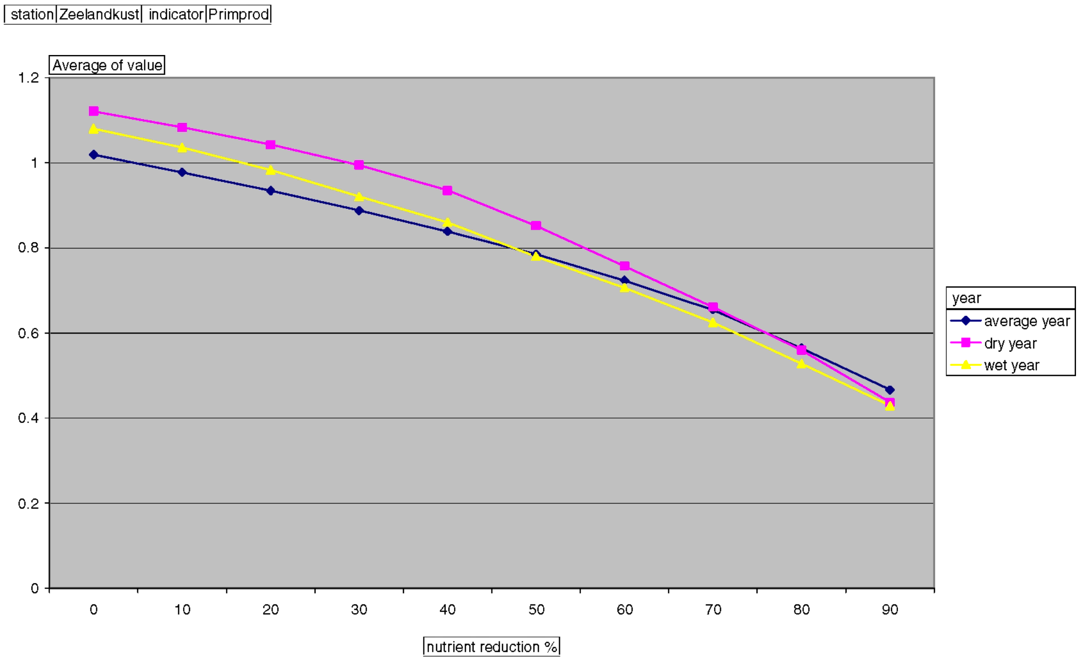
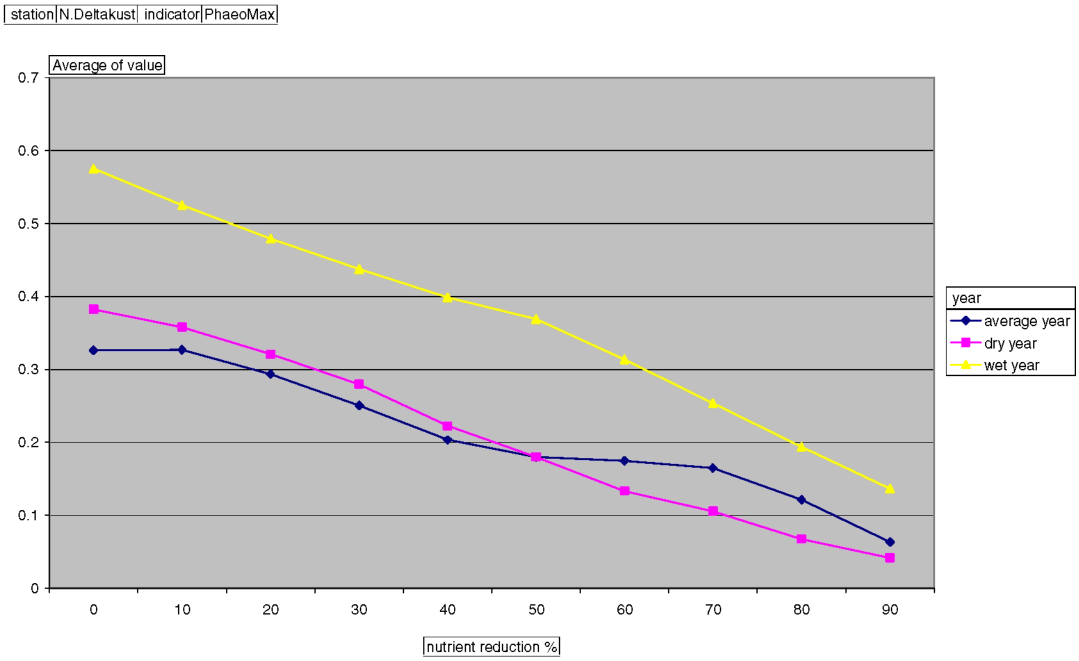



Figure B.6d: Response curves for yearly averaged primary production (gC/m$^3$.d) concentrations in the Zeeland coast area.



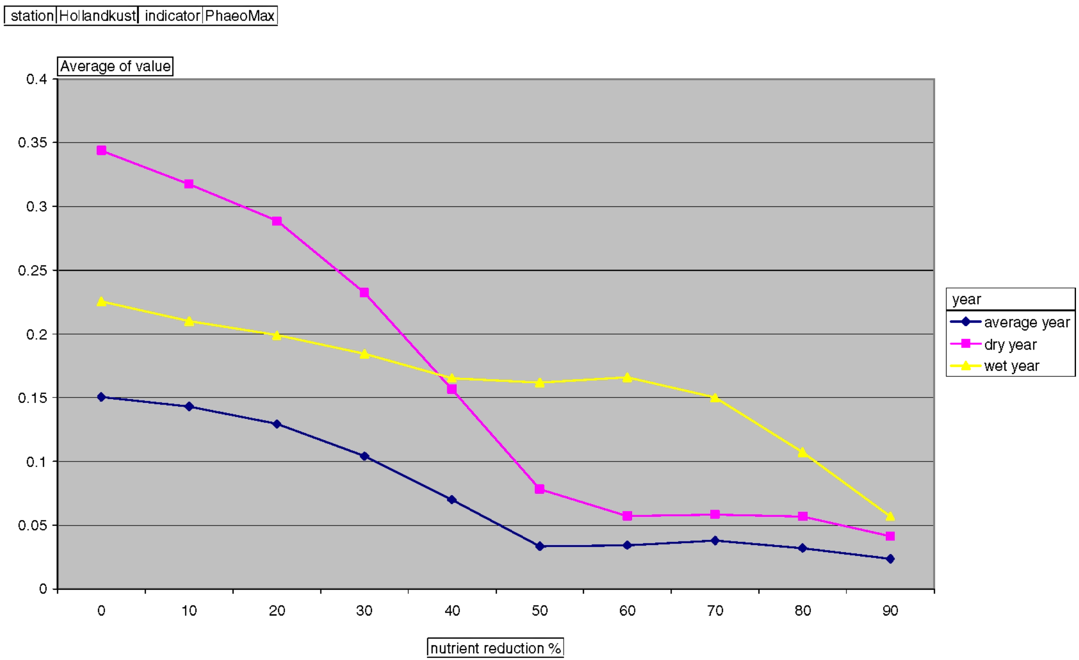
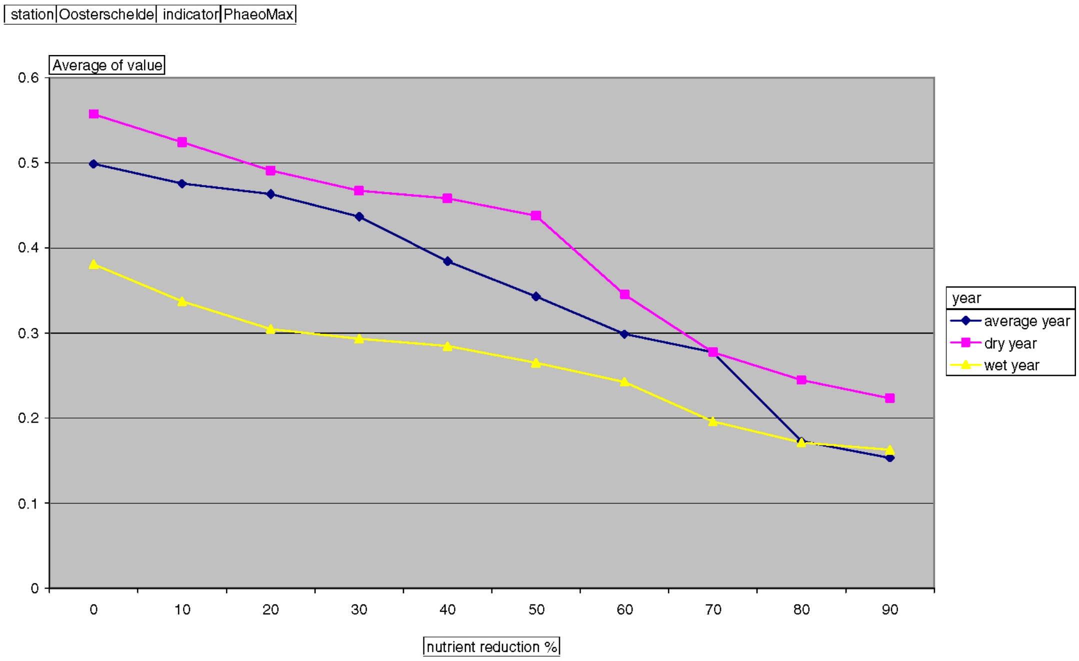




Figure B.7a: Response curves for maximum Phaeocystis concentrations (mgC/l)in the areas Delta coast and Holland coast



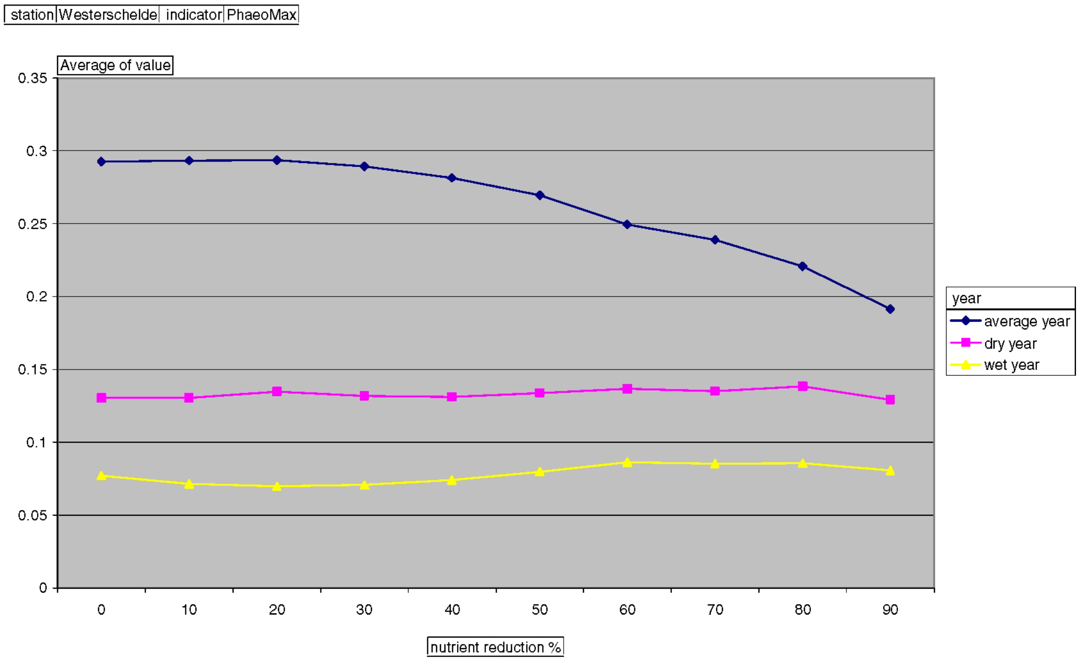
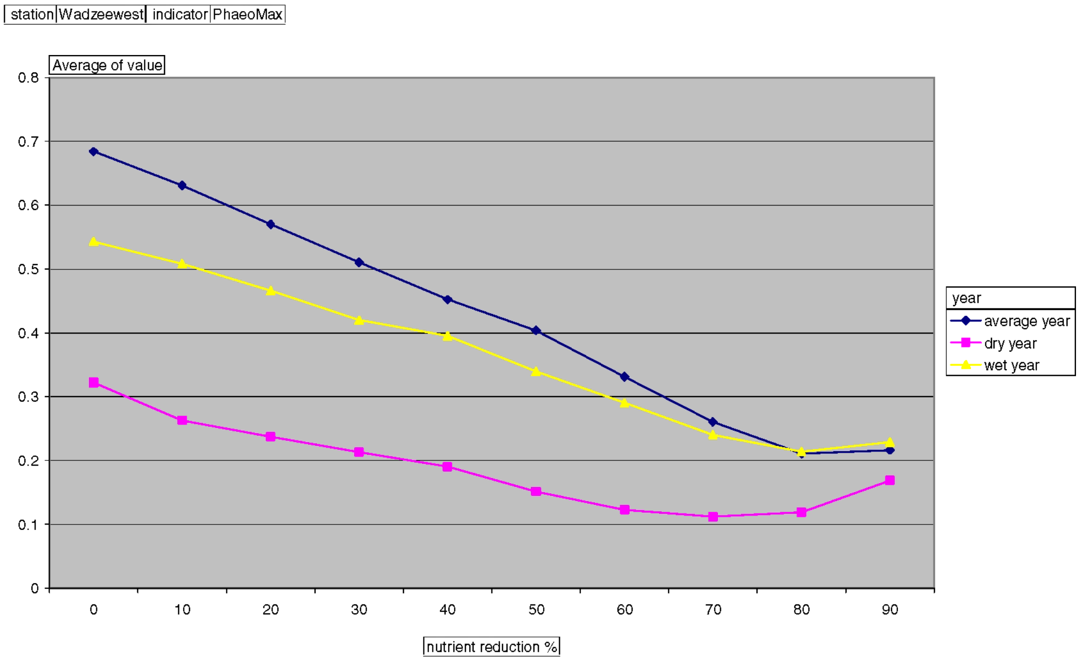




Figure B.7b: Response curves for maximum Phaeocystis concentrations (mgC/l)in the areas Oosterschelde and Westerschelde



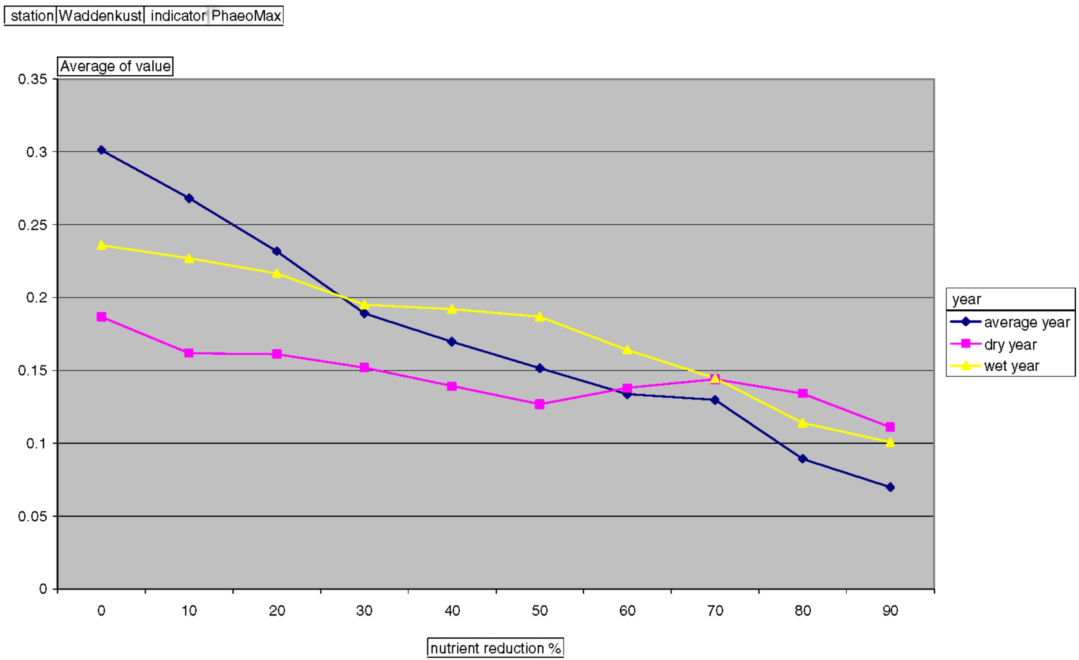




Figure B.7c: Response curves for maximum Phaeocystis concentrations (mgC/l)in the areas western Wadden Sea and Wadden coast.

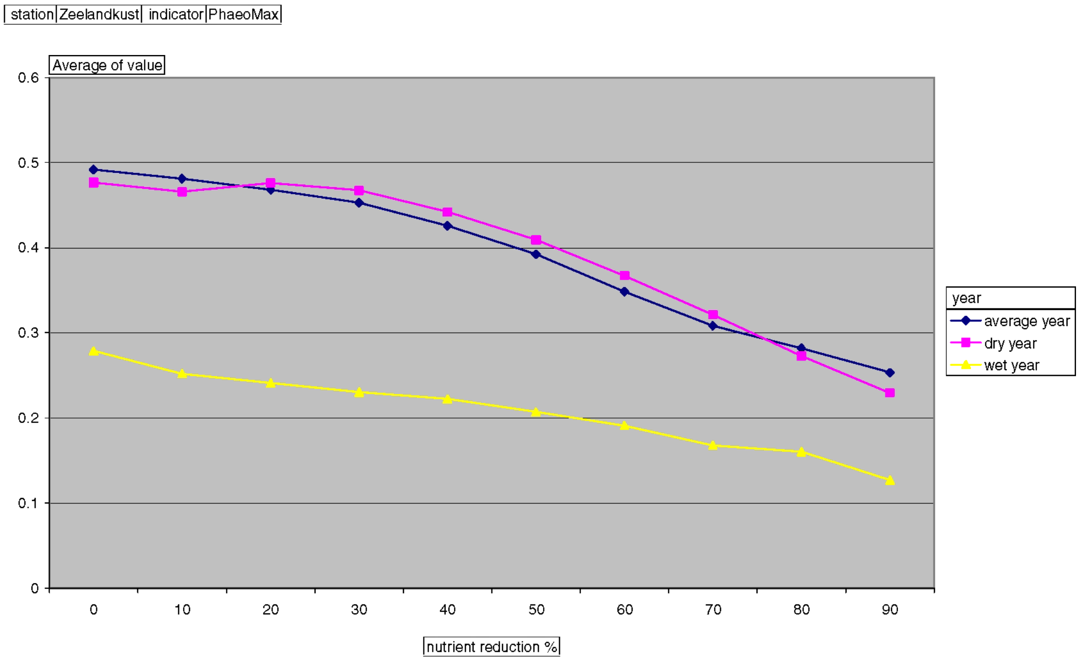
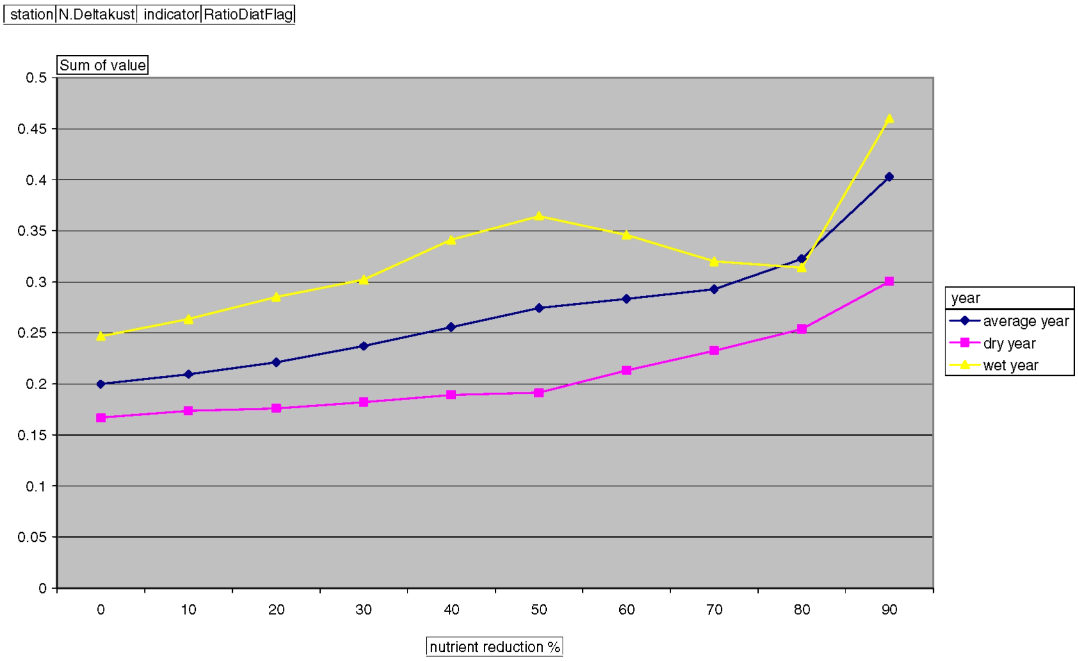



Figure B.7d: Response curves for maximum Phaeocystis concentrations (mgC/l)in the Zeeland coast area.



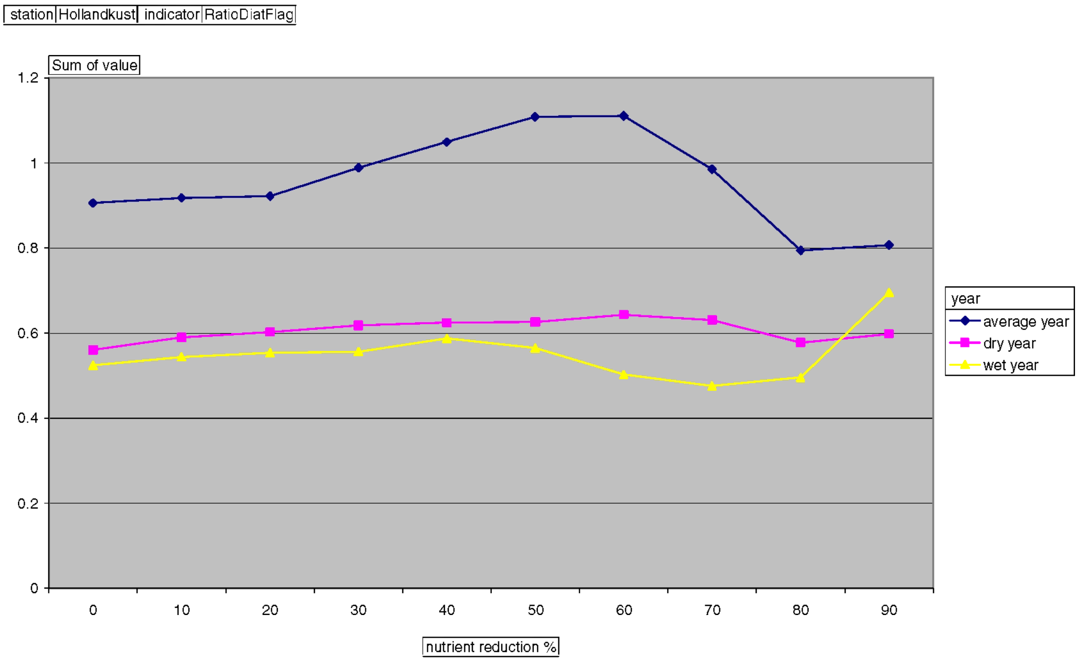
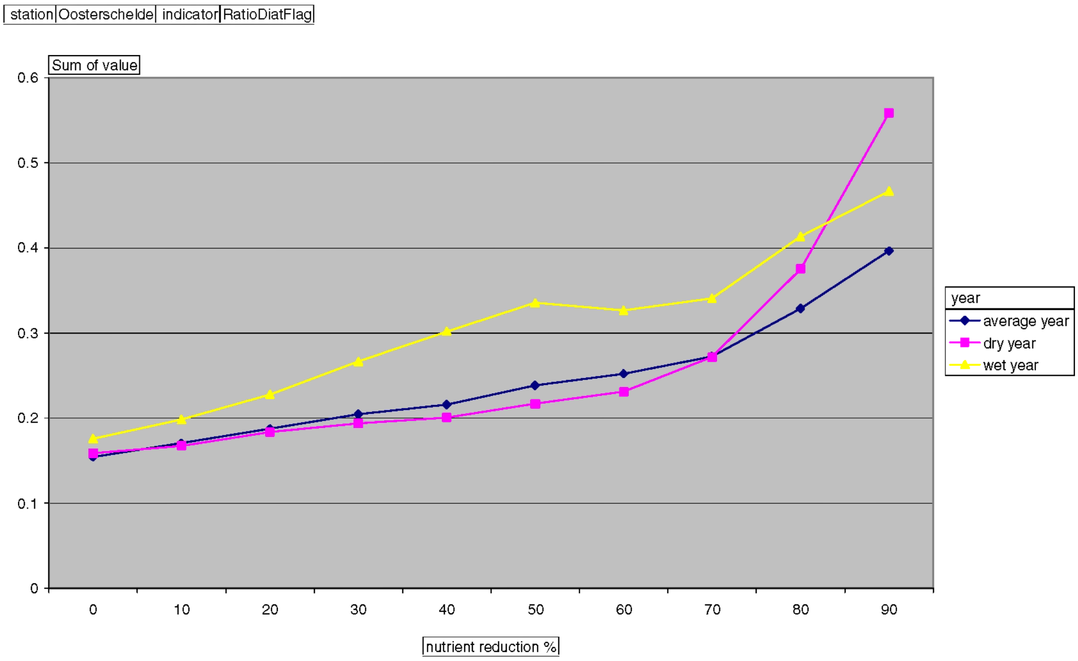




Figure B.8a: Response curves for ratio diatoms / flagellates (averaged biomasses per year) concentrations in the areas Delta coast and Holland coast



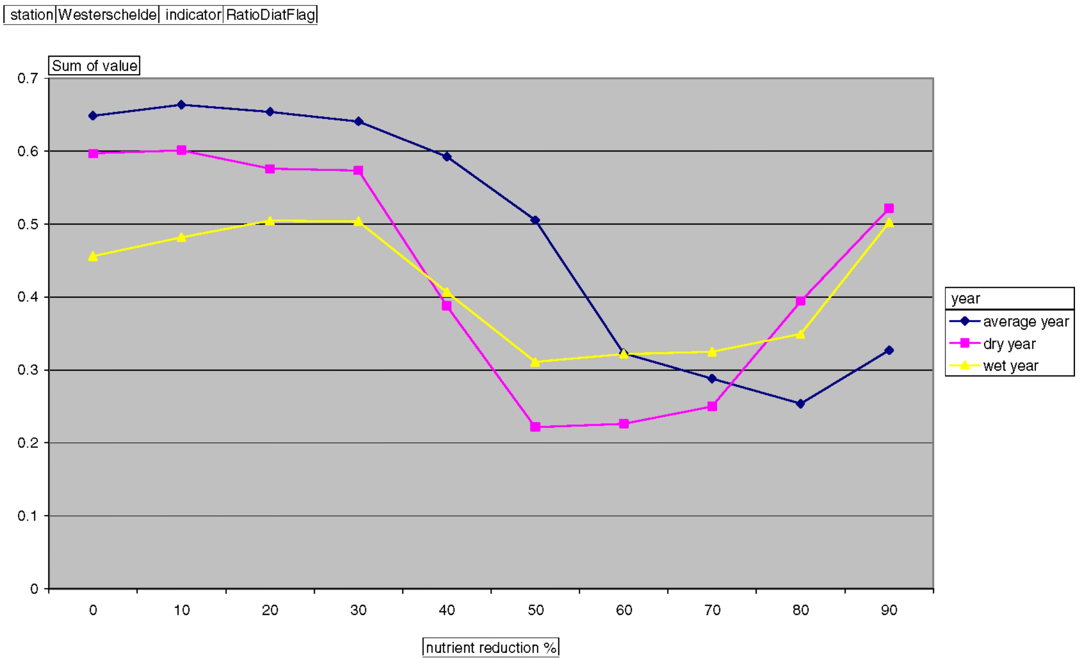
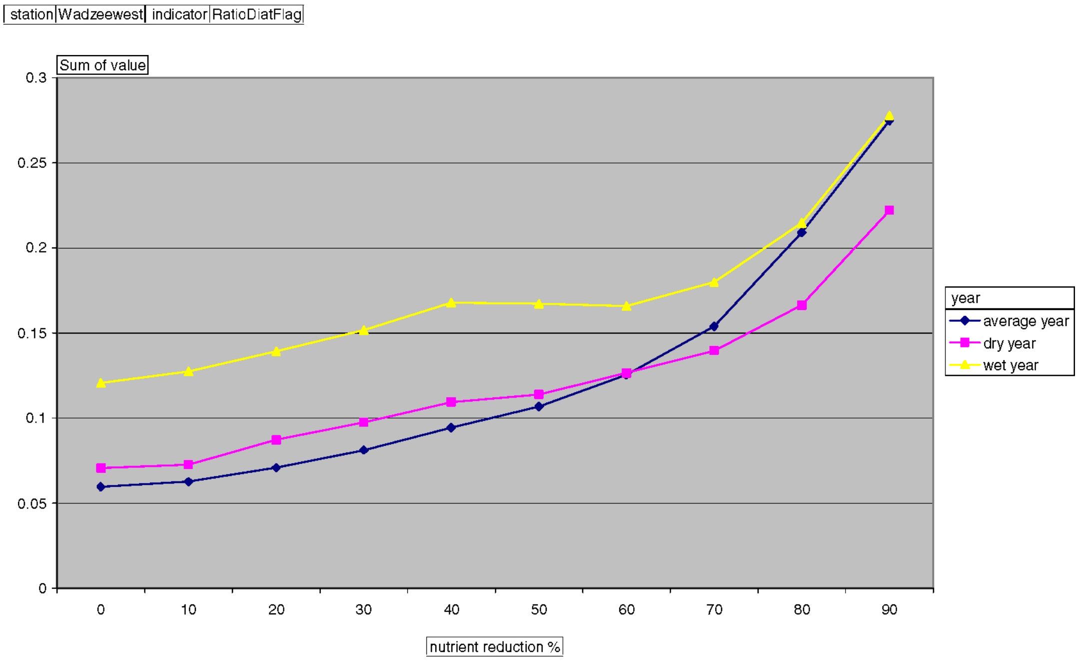




Figure B.8b: Response curves for ratio diatoms / flagellates (averaged biomasses per year) concentrations in the areas Oosterschelde and Westerschelde



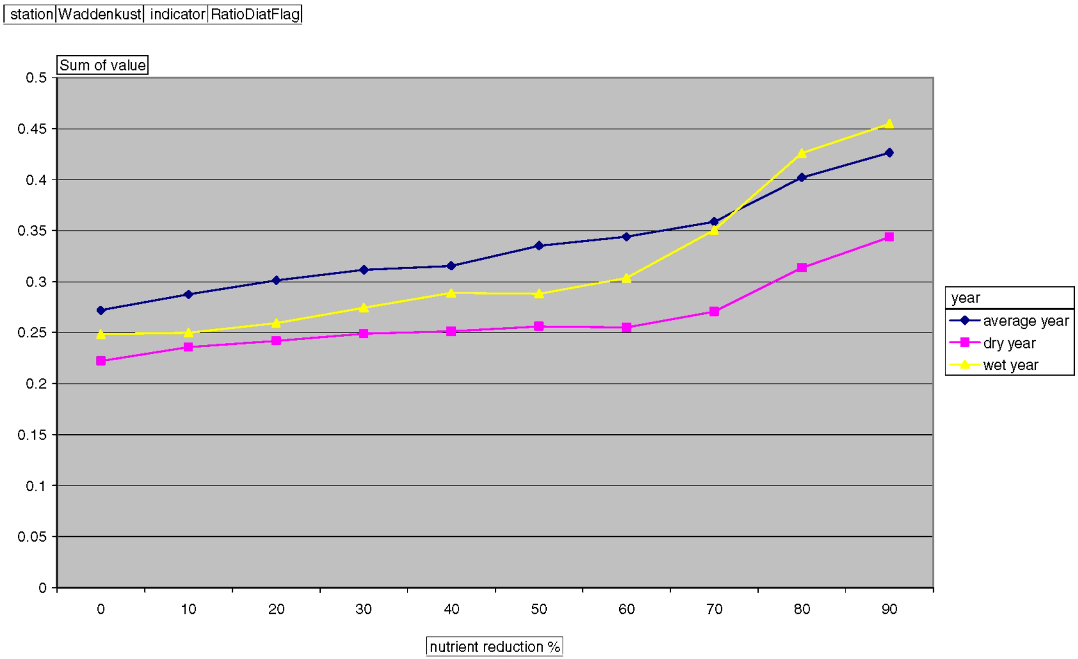




Figure B.8c: Response curves for ratio diatoms / flagellates (averaged biomasses per year) concentrations in the areas western Wadden Sea and Wadden coast.

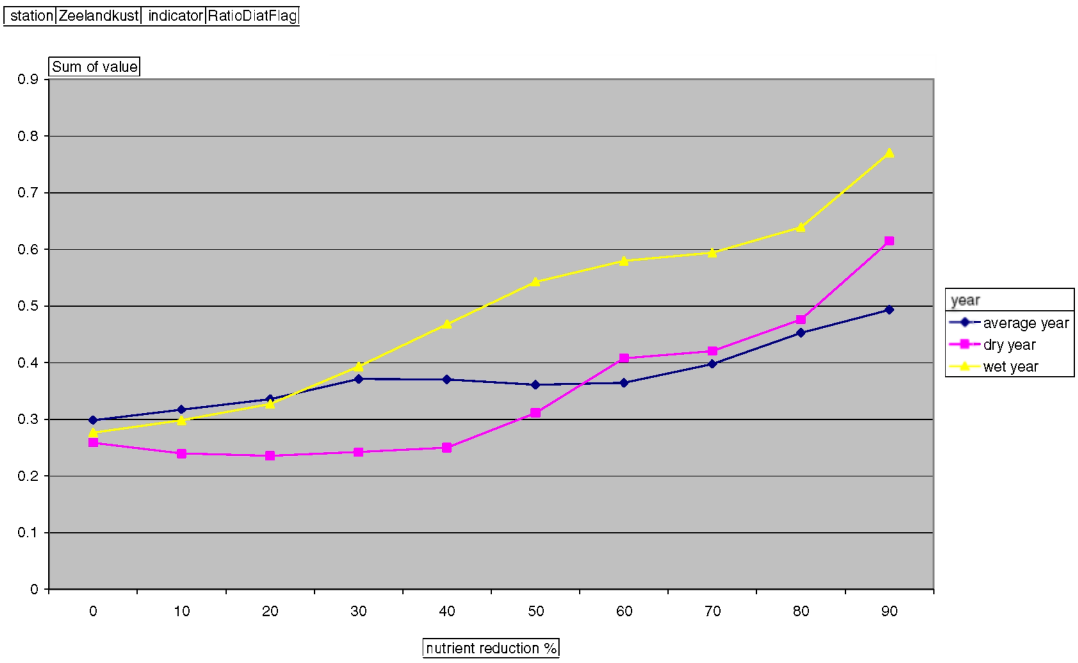
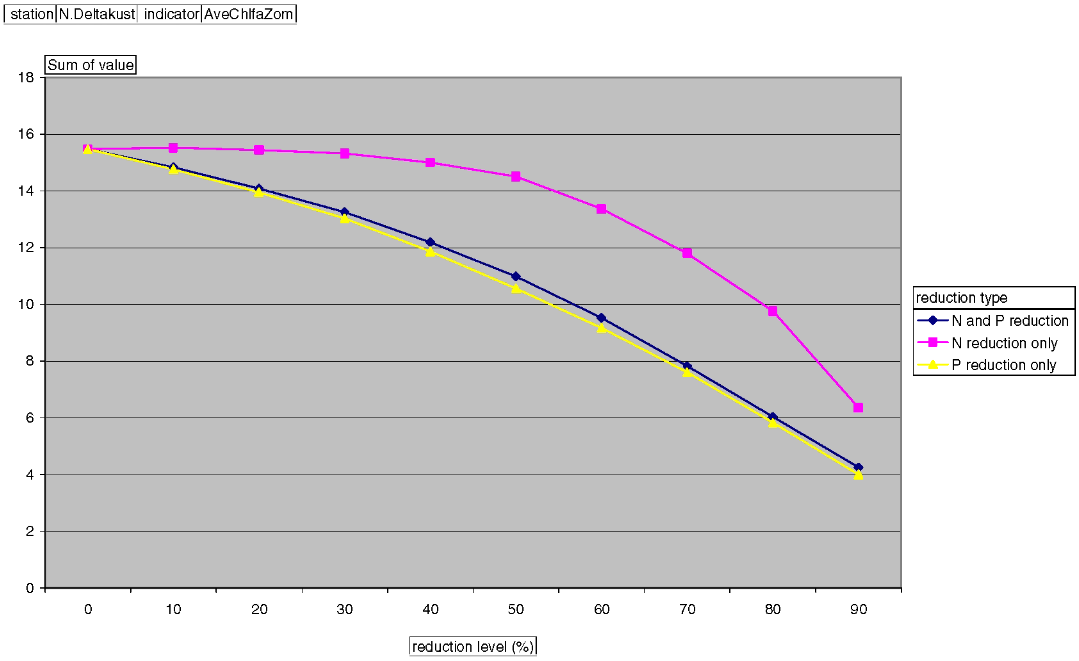



Figure B.8d: Response curves for ratio diatoms / flagellates (averaged biomasses per year) concentrations in the Zeeland coast area.

# C Response curves for separate N and P reduction for an average year



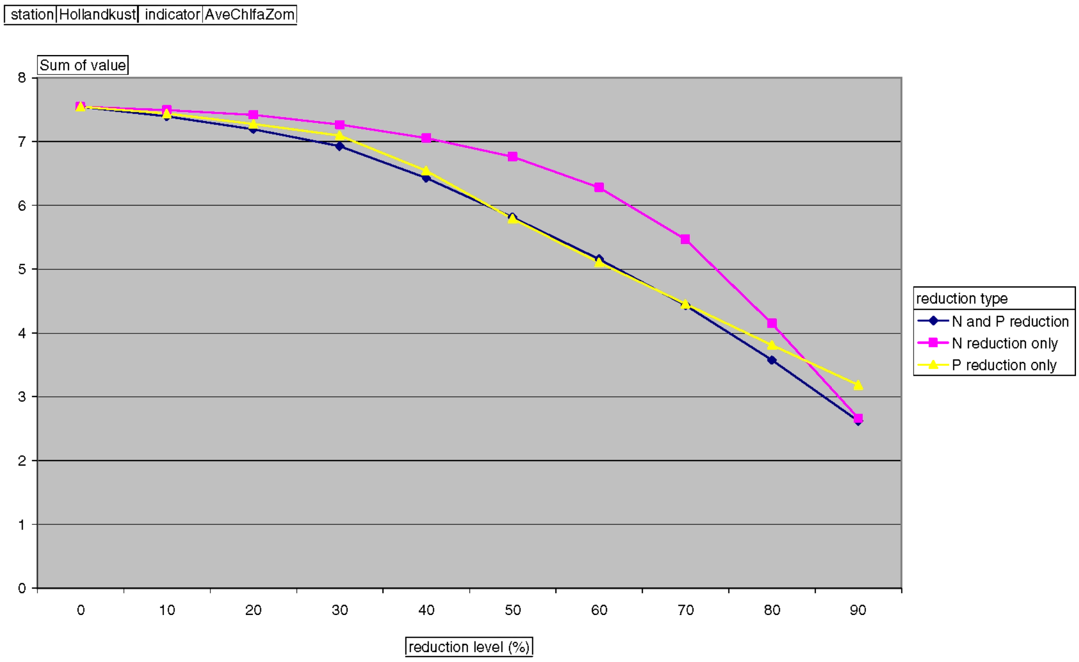
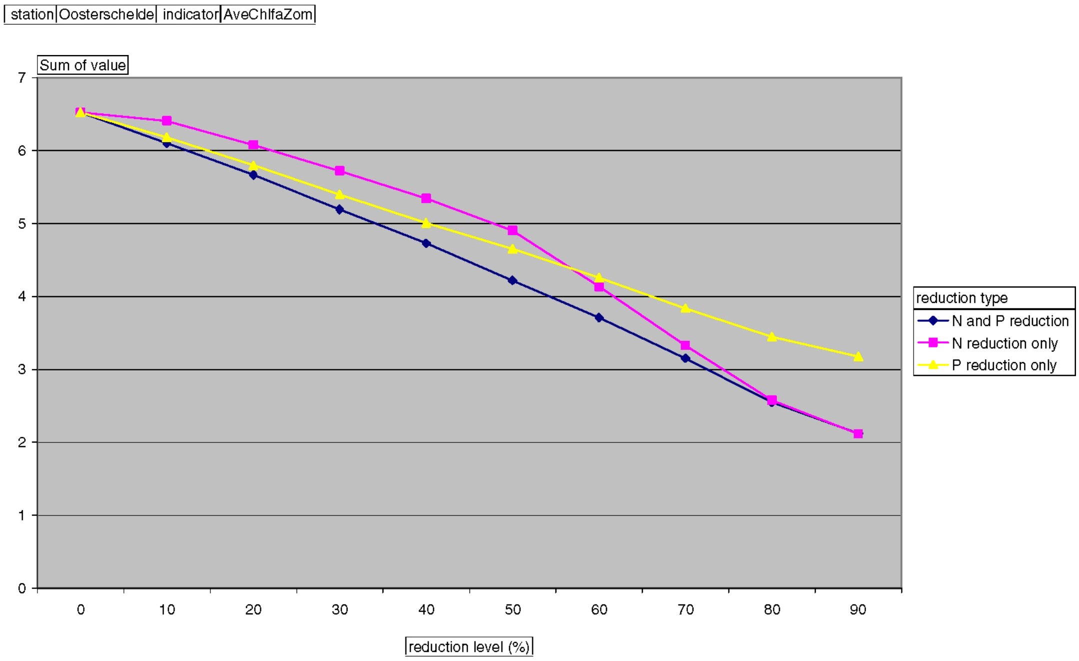




Figure C.1a: Response curves for summer averaged chlorophyll-a concentrations (µg/l)in the areas Delta coast and Holland coast



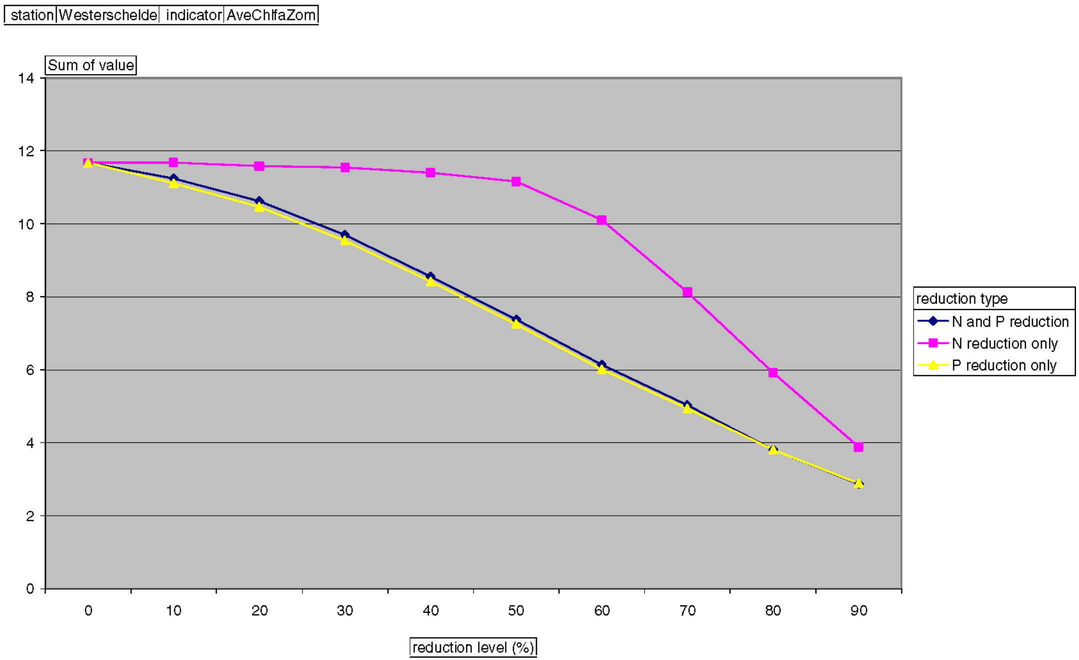
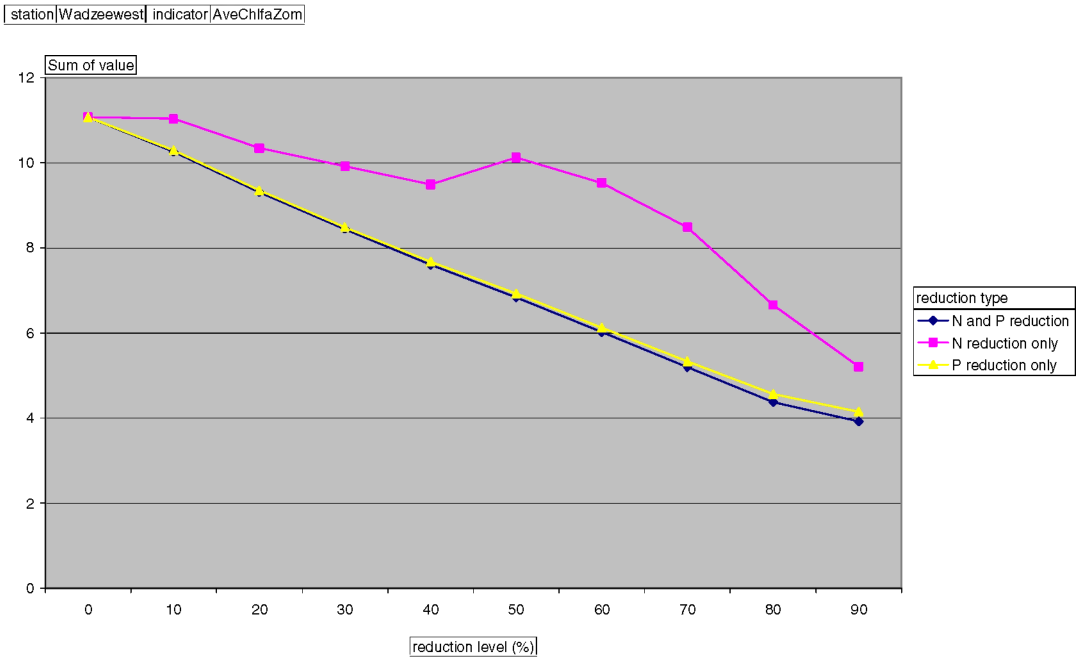




Figure C.1b: Response curves for summer averaged chlorophyll-a concentrations (µg/l)in the areas Oosterschelde and Westerschelde



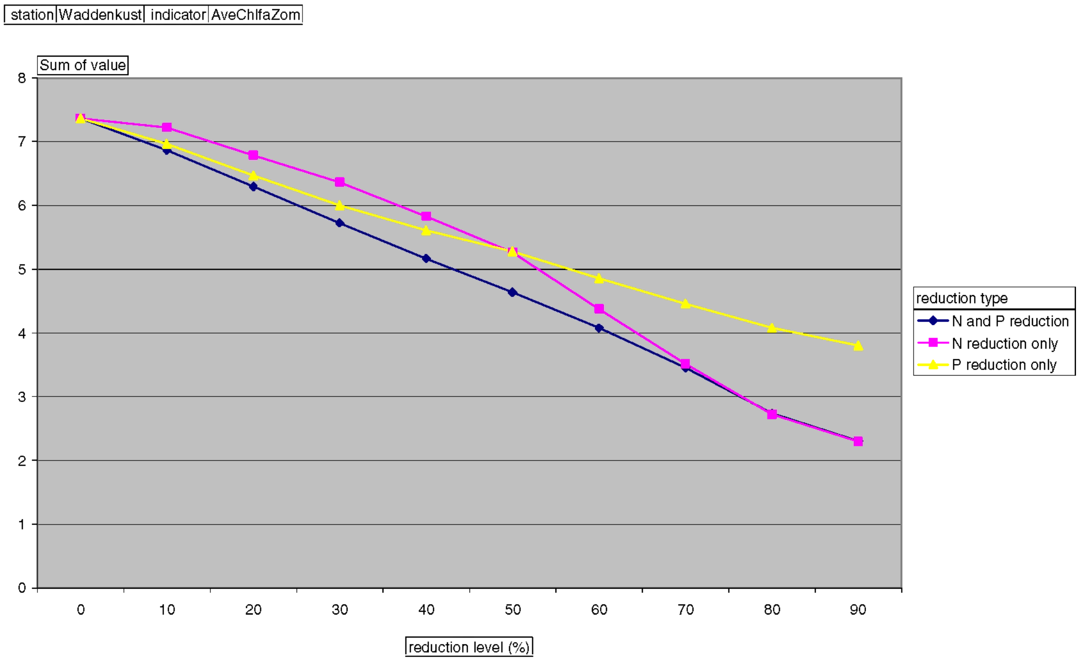




Figure C.1c: Response curves for summer averaged chlorophyll-a concentrations (µg/l)in the areas western Wadden Sea and Wadden coast.

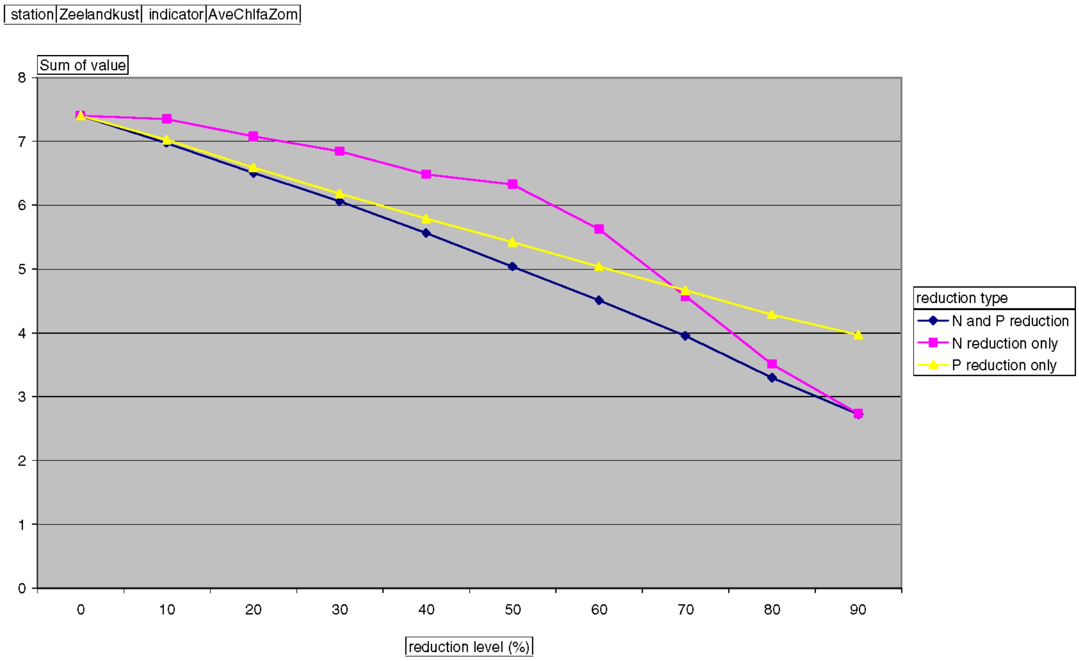
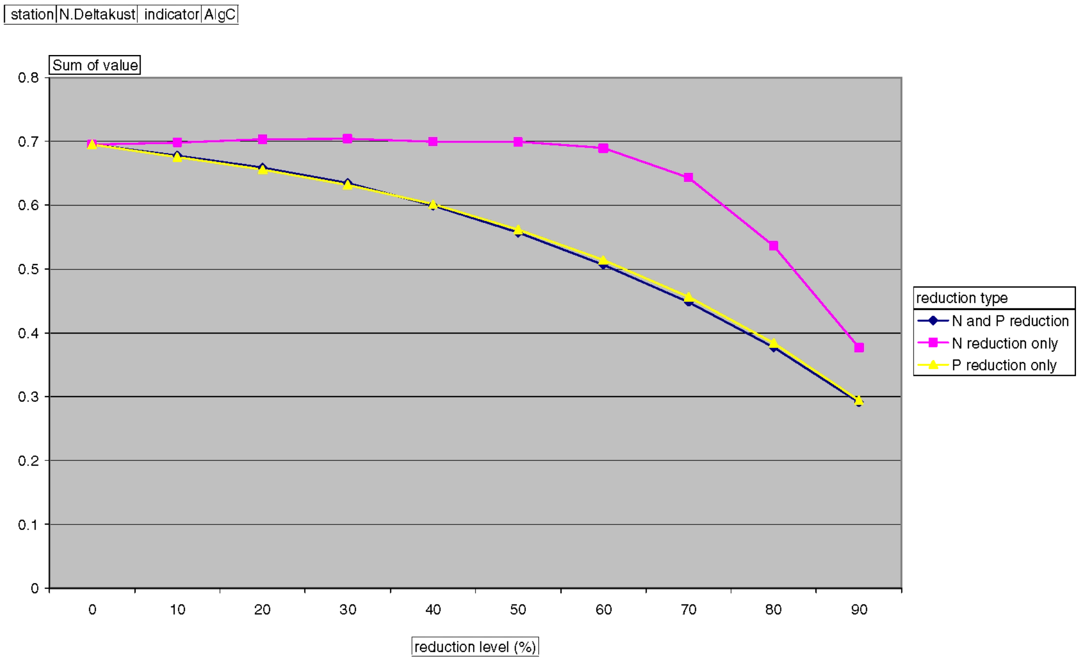



Figure C.1d: Response curves for summer averaged chlorophyll-a concentrations (µg/l)in the Zeeland coast area.



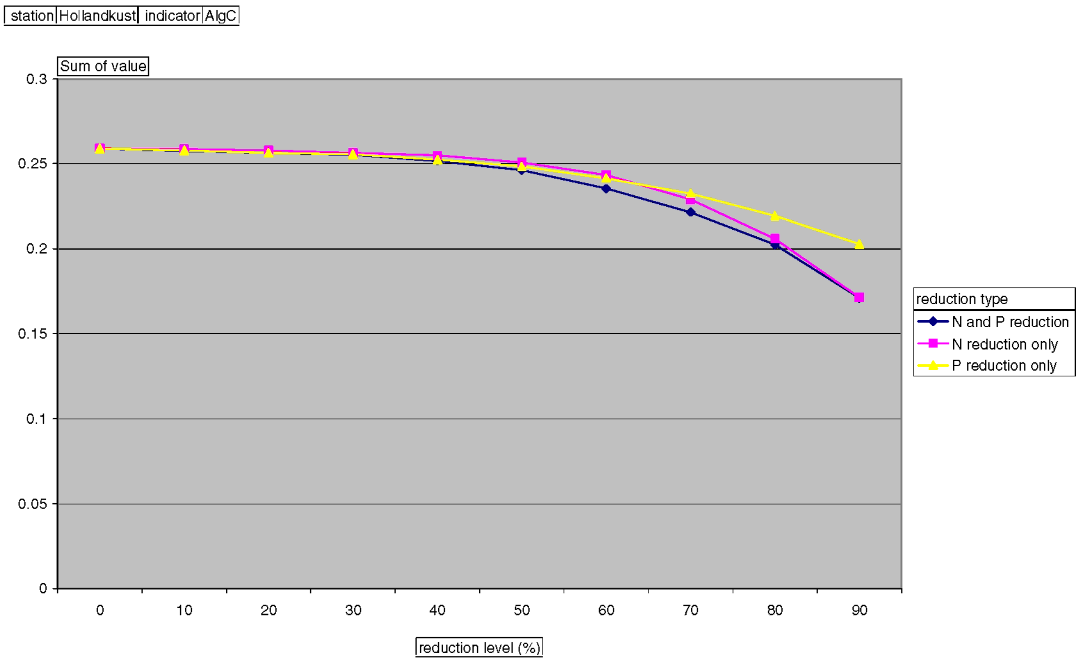
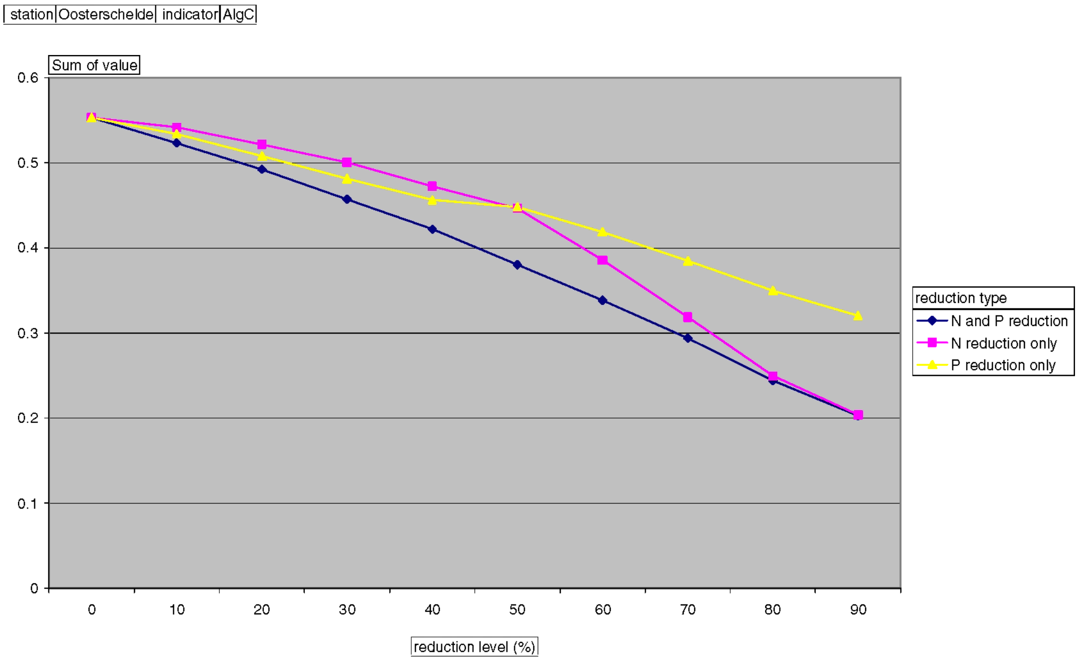




Figure C.2a: Response curves for summer averaged algal biomass (gC/m3) concentrations in the areas Delta coast and Holland coast



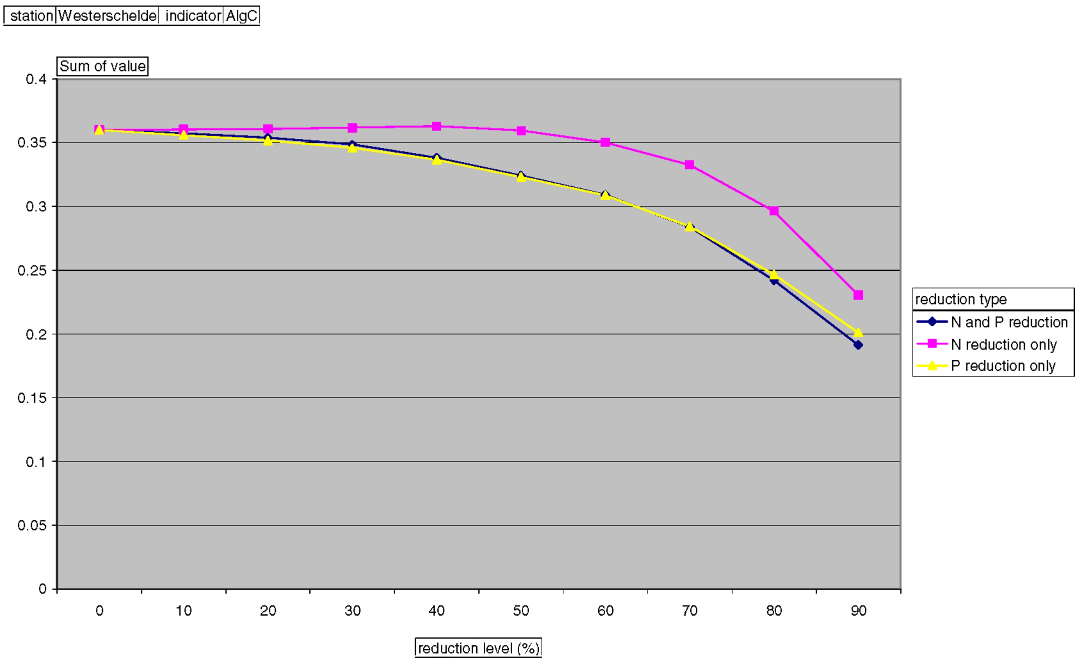
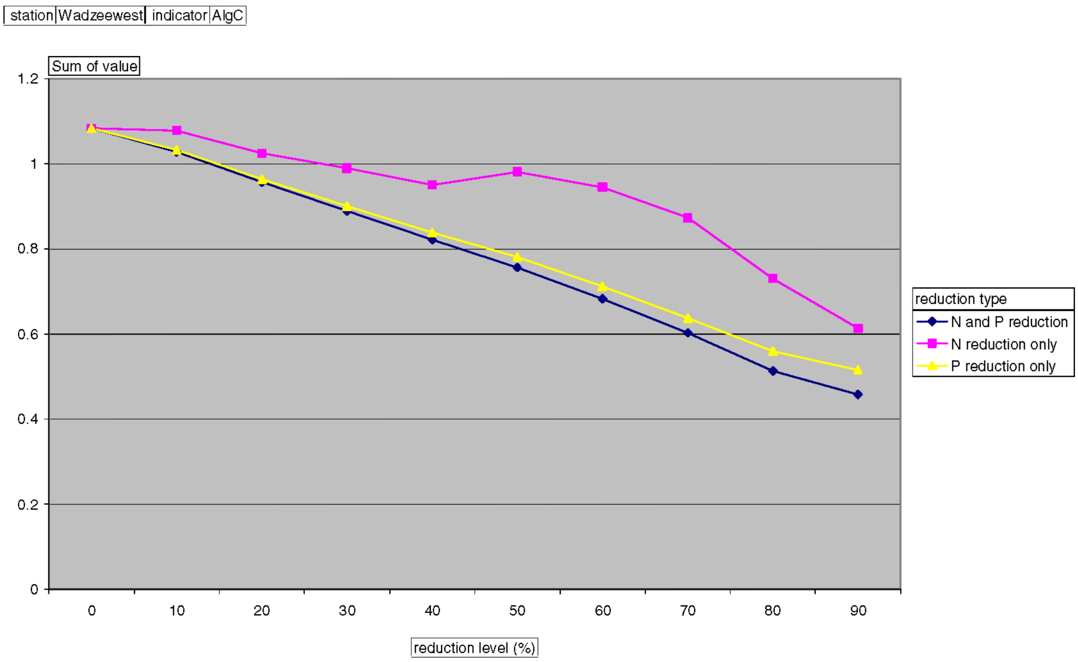




Figure C.2b: Response curves for summer averaged algal biomass (gC/m3) concentrations in the areas Oosterschelde and Westerschelde



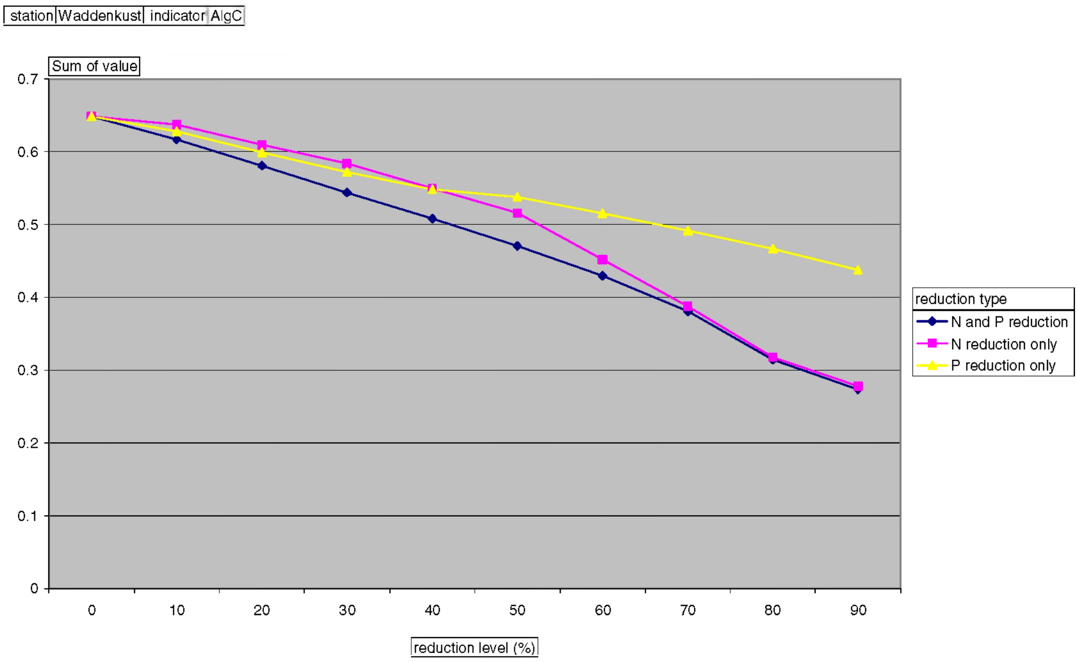




Figure C.2c: Response curves for summer averaged algal biomass (gC/m3) concentrations in the areas western Wadden Sea and Wadden coast.

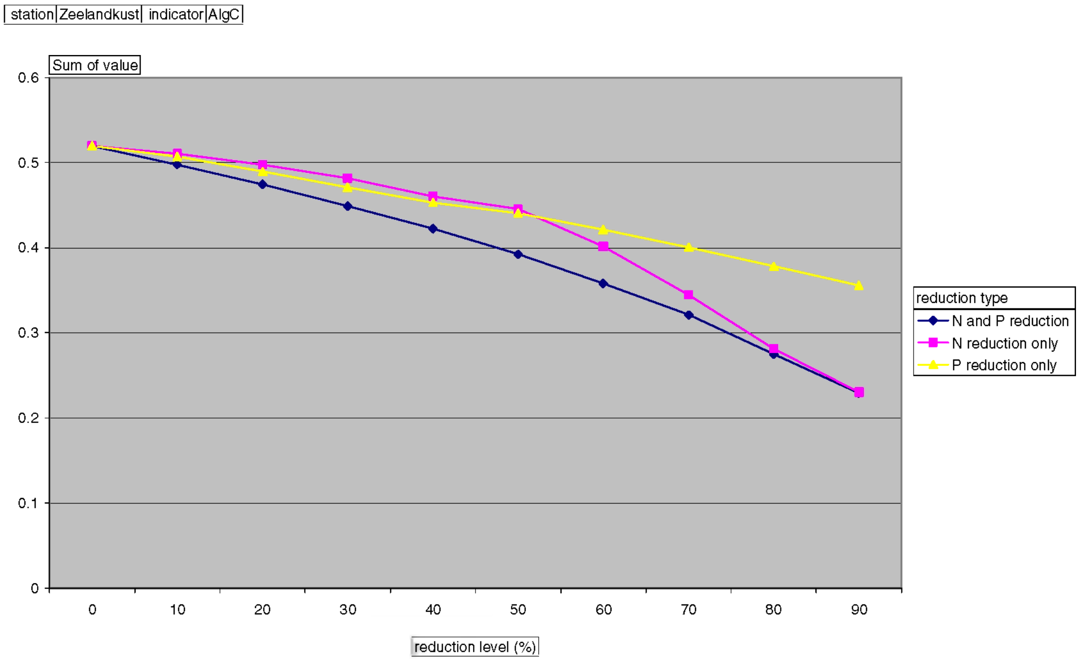
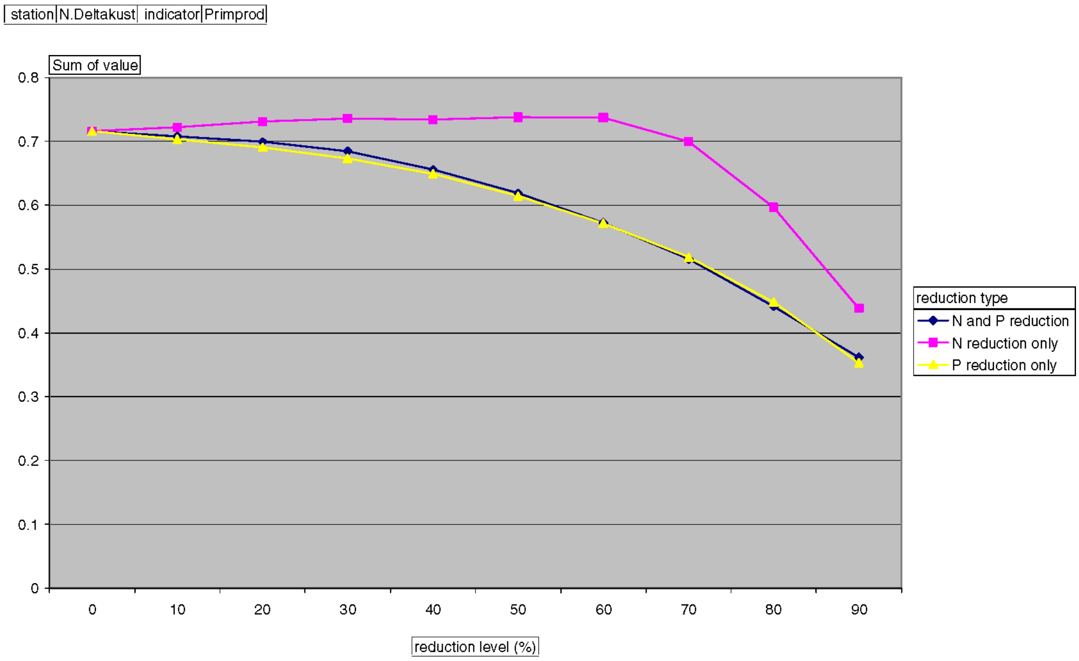



Figure C.2d: Response curves for summer averaged algal biomass (gC/m3) concentrations in the Zeeland coast area.



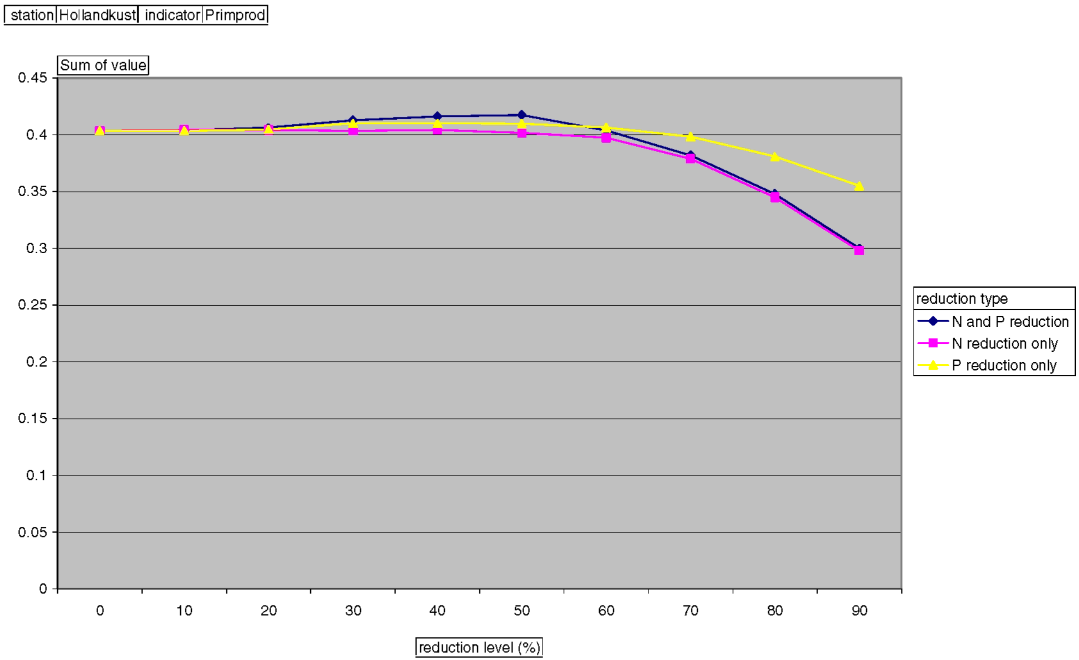
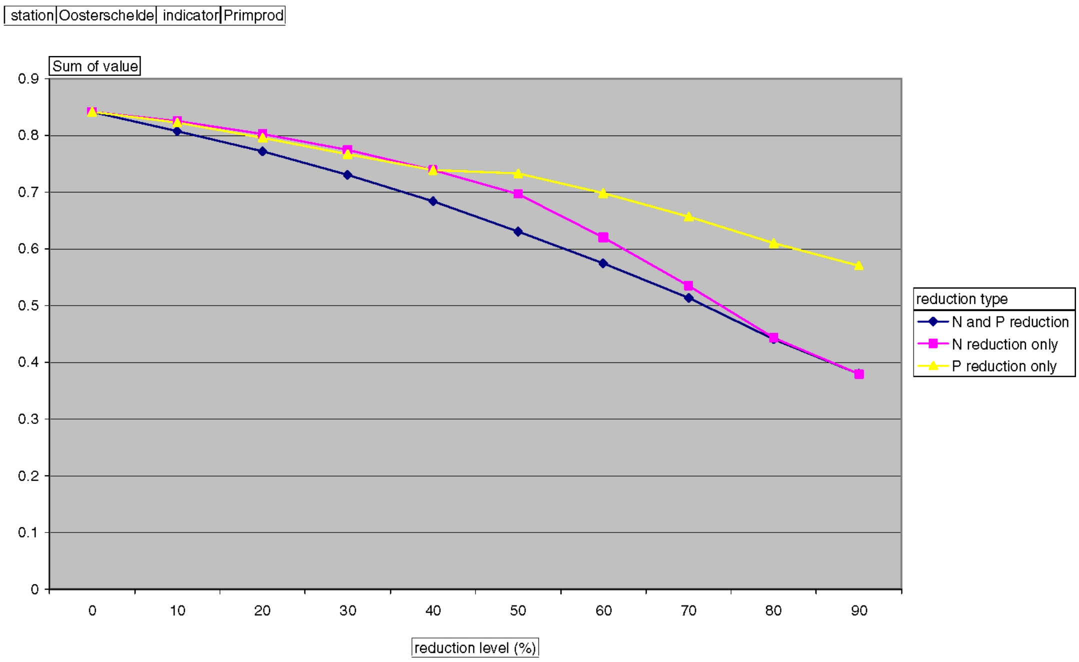




Figure C.3a: Response curves for yearly averaged primary production ($gC/m^3.d$) concentrations in the areas Delta coast and Holland coast



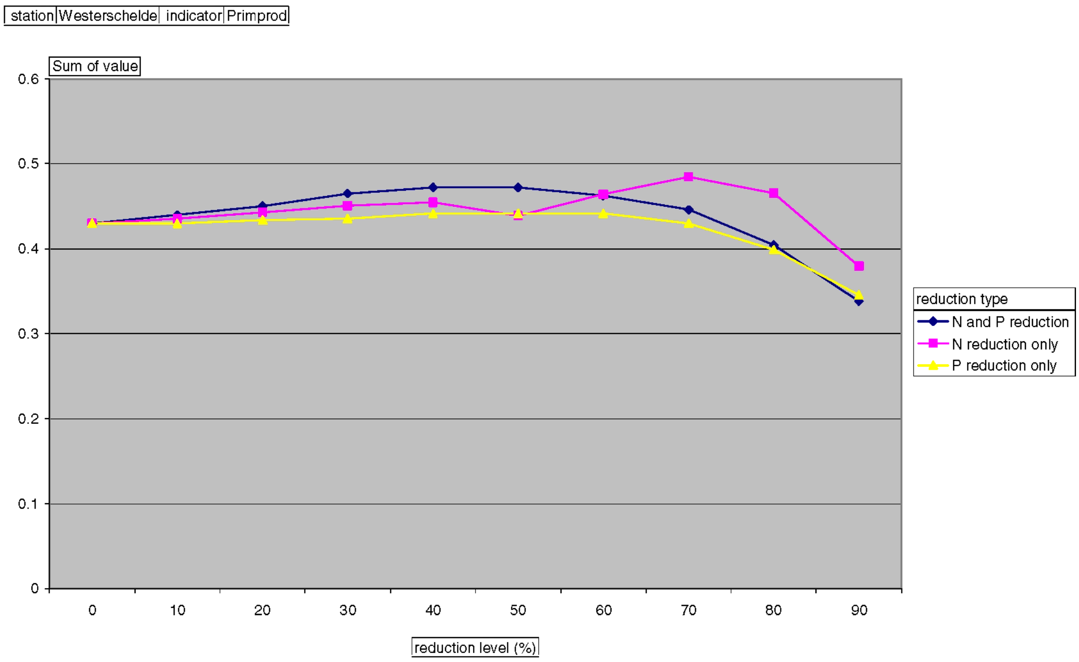
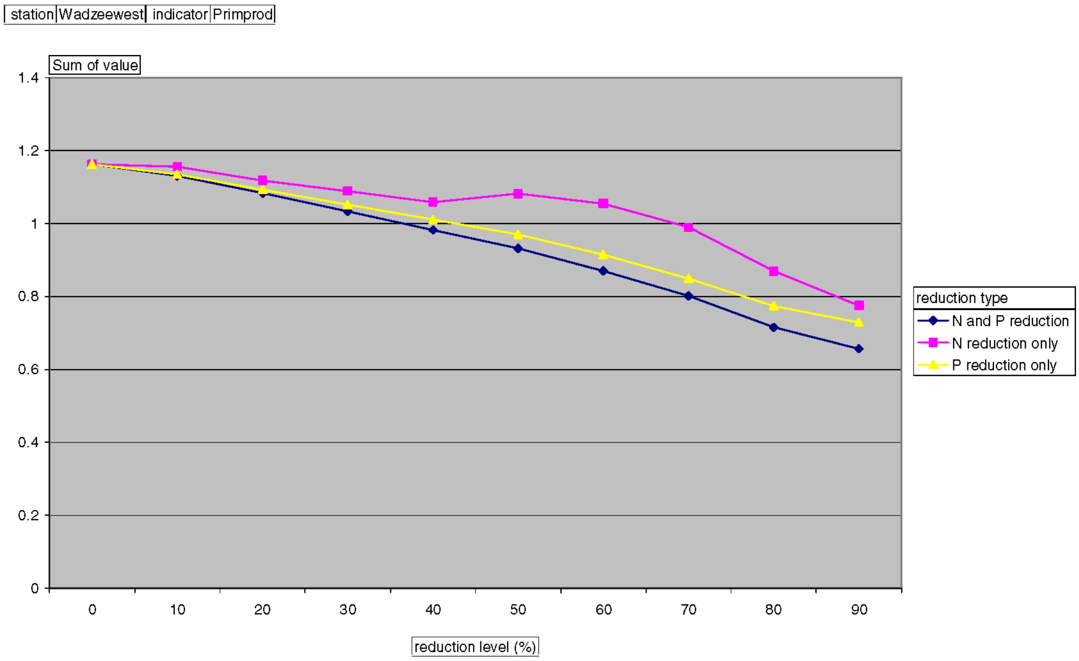




Figure C.3b: Response curves for yearly averaged primary production ($gC/m^3.d$) concentrations in the areas Oosterschelde and Westerschelde



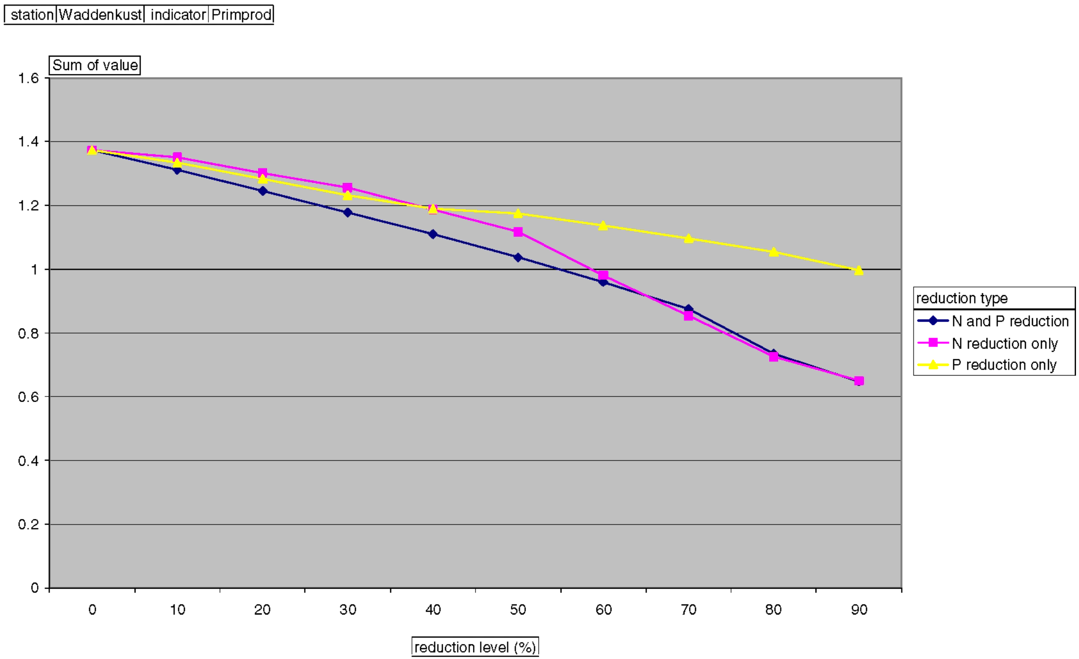




Figure C.3c: Response curves for yearly averaged primary production ($gC/m^3.d$) concentrations in the areas western Wadden Sea and Wadden coast.

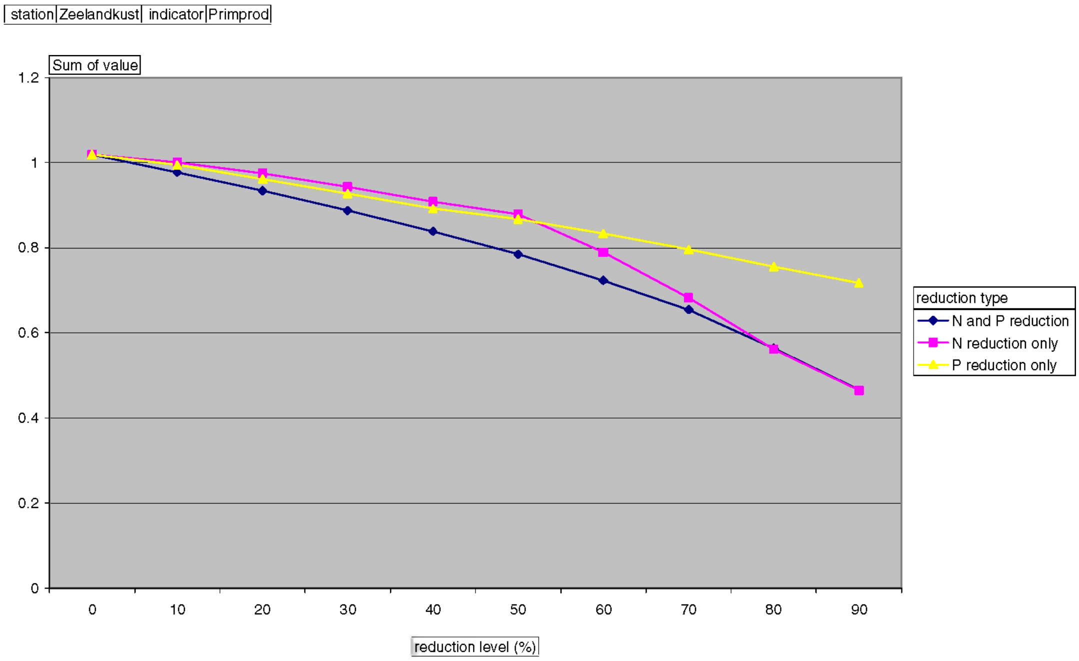
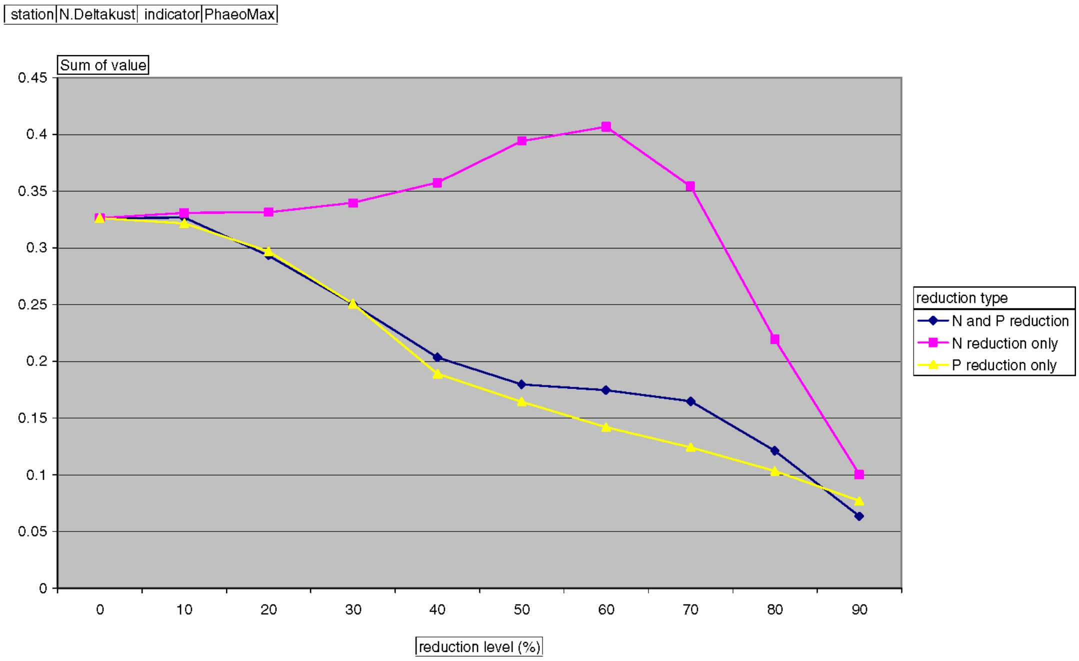



Figure C.3d: Response curves for yearly averaged primary production (gC/m$^3$.d) concentrations in the Zeeland coast area.



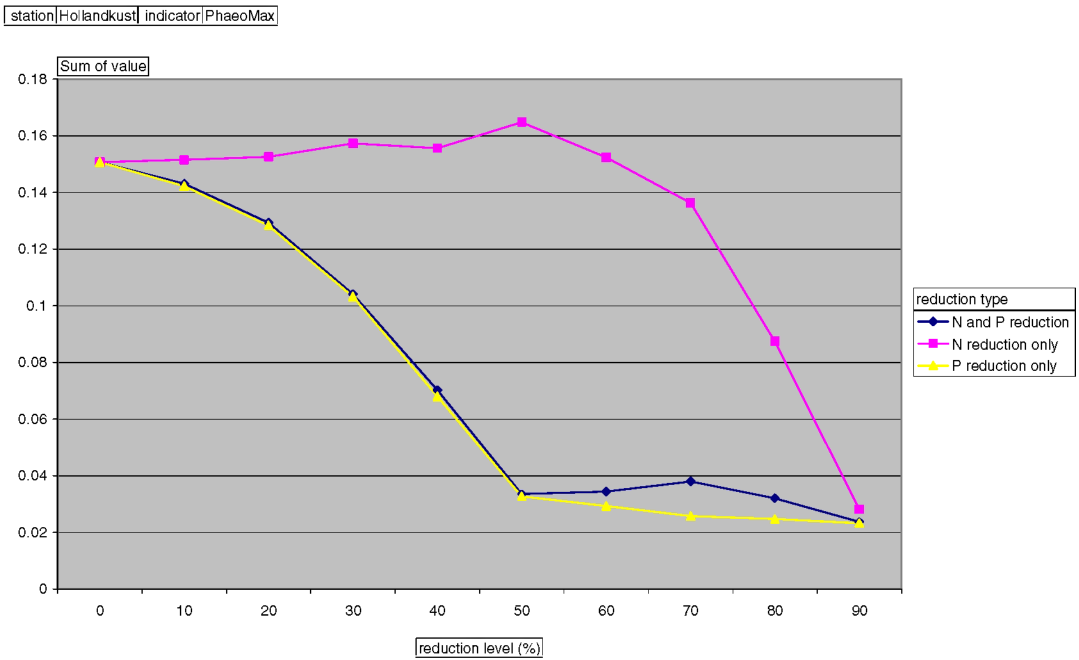
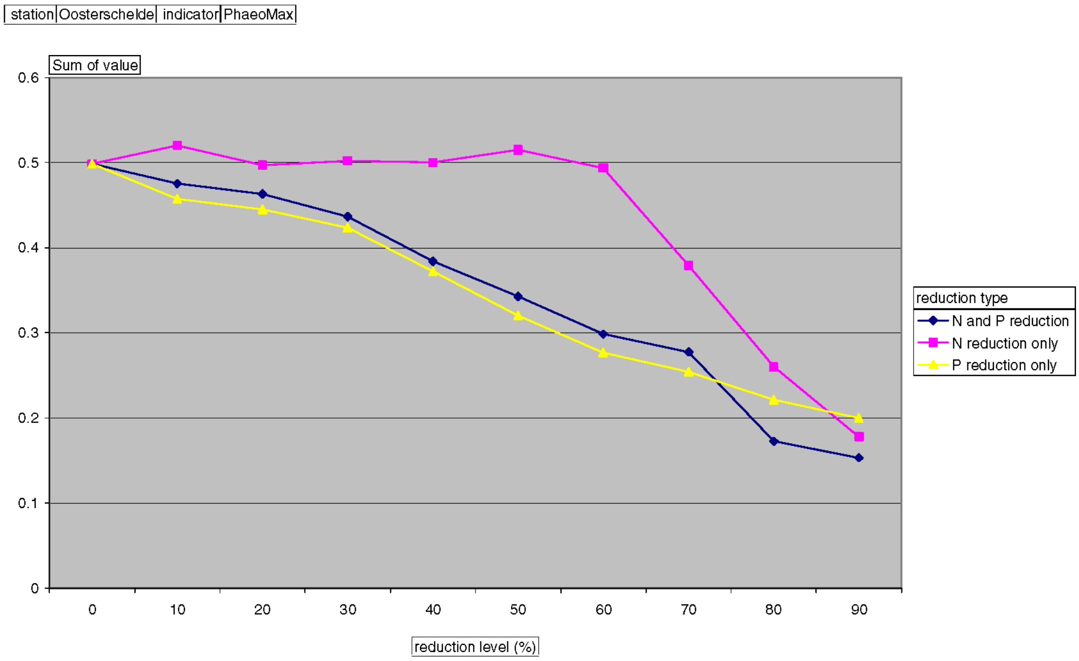




Figure C.4a: Response curves for maximum Phaeocystis concentrations (mgC/l)in the areas Delta coast and Holland coast



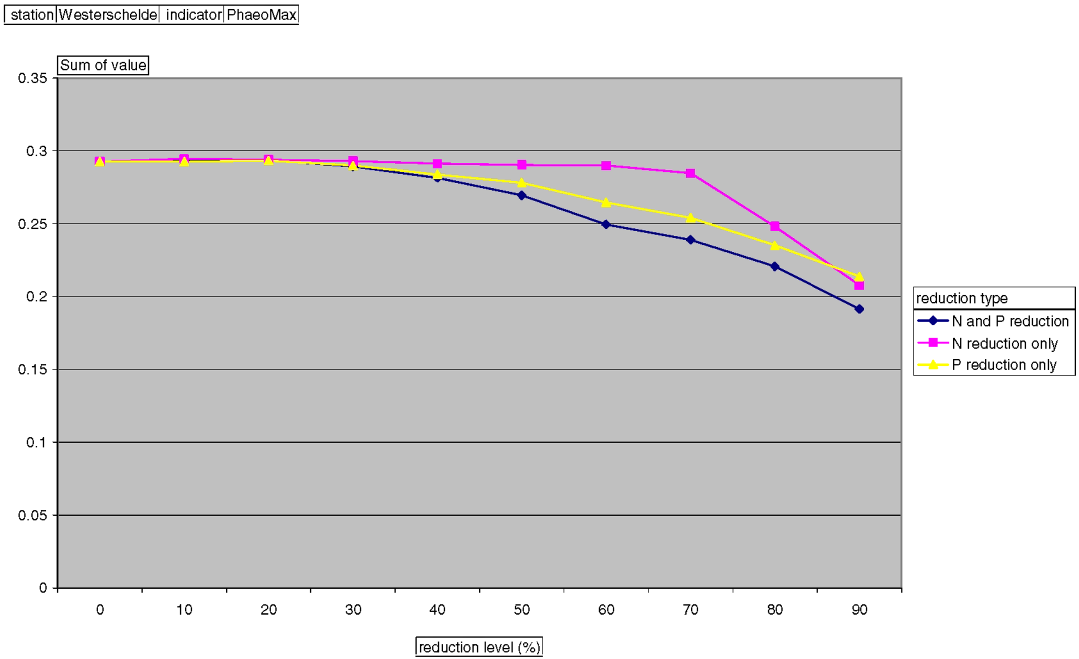
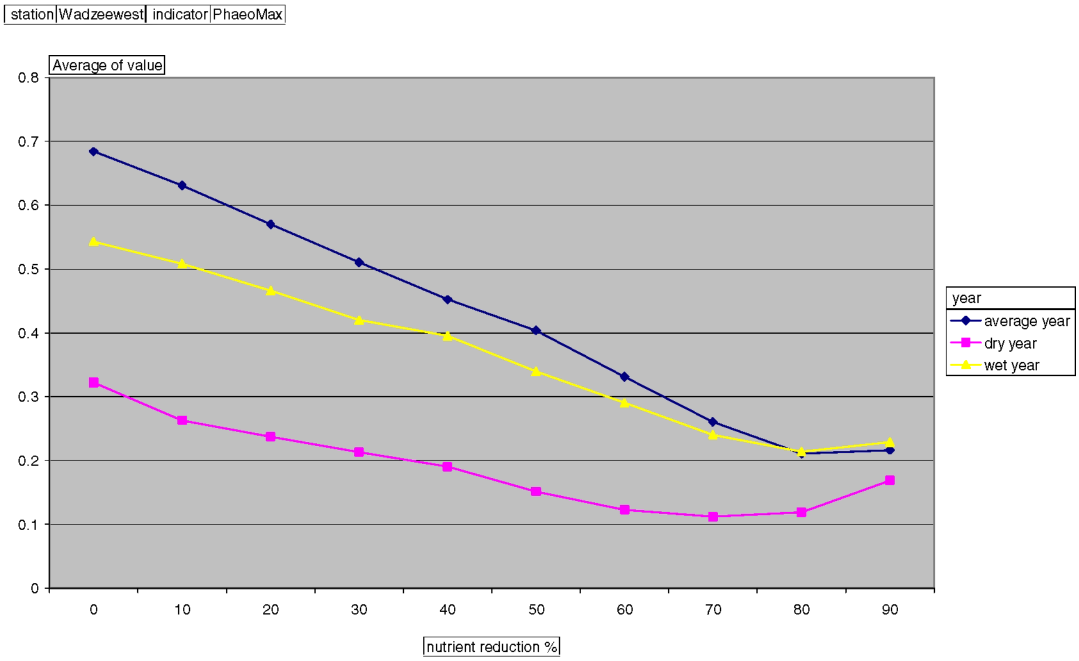




Figure C.4b: Response curves for maximum Phaeocystis concentrations (mgC/l)in the areas Oosterschelde and Westerschelde



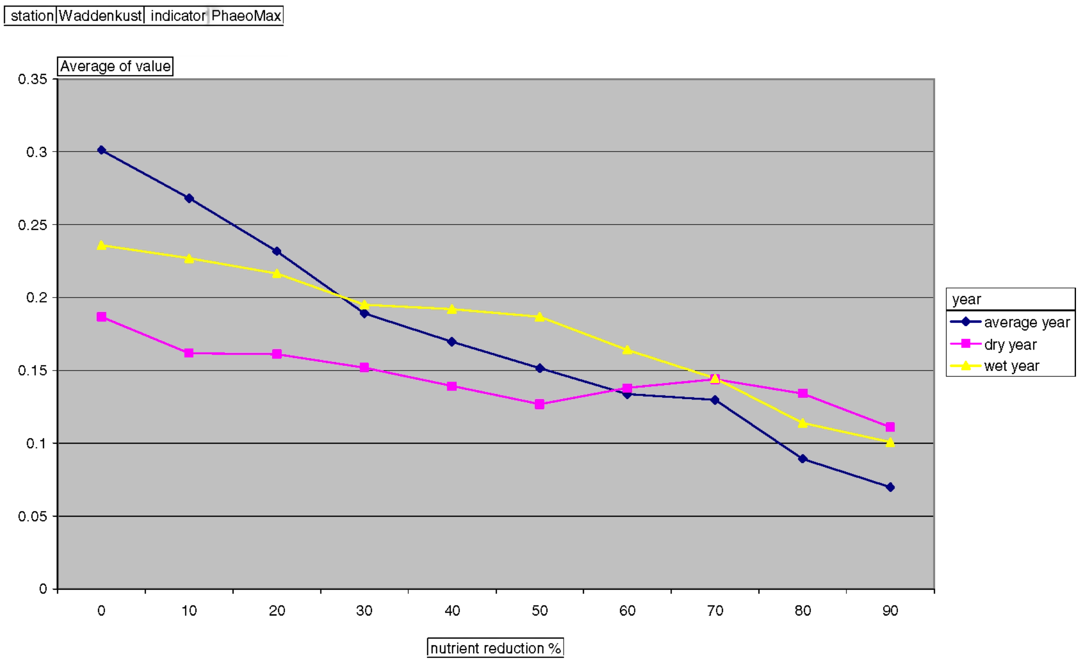




Figure C.4c: Response curves for maximum Phaeocystis concentrations (mgC/l)in the areas western Wadden Sea and Wadden coast.

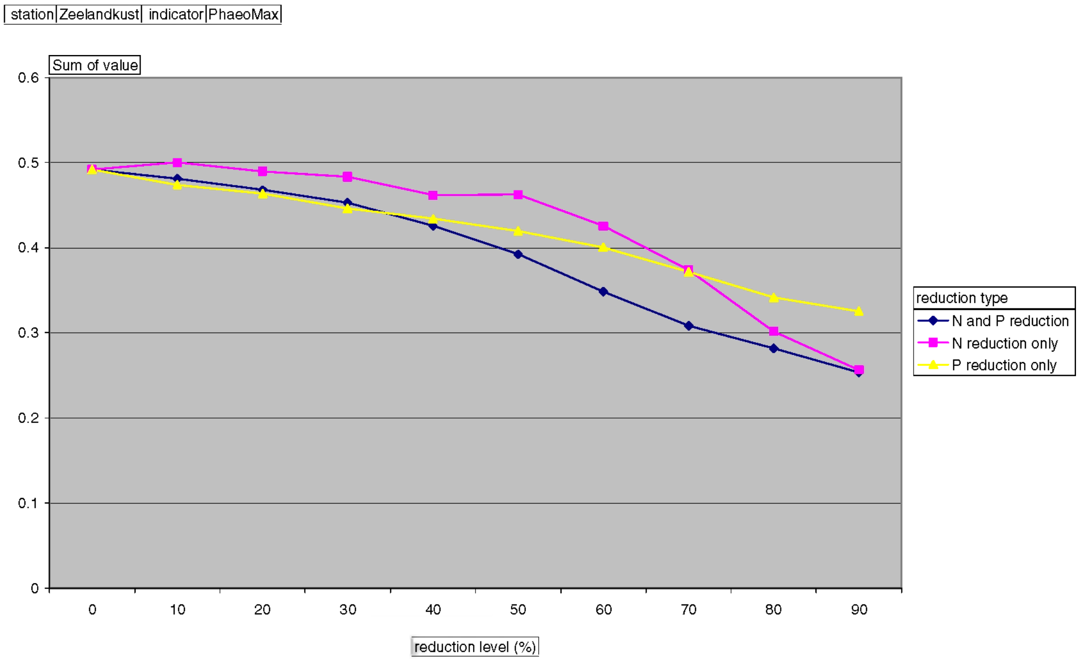
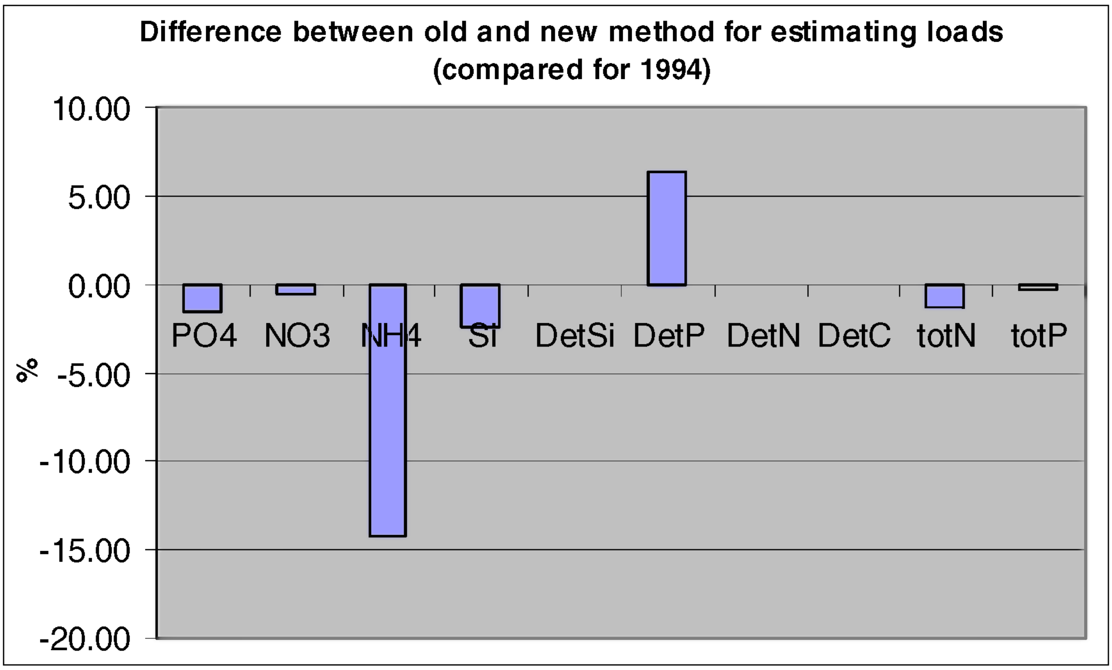



Figure C.4d: Response curves for maximum Phaeocystis concentrations (mgC/l)in the Zeeland coast area.

# D Comparison of methods for estimation of loads




Explanation of substances:

| | |
|---|---|
| $PO_4$ | ortho-phophate |
| $NO_3$ | nitrate |
| $NH_4$ | ammonia |
| Si | dissolved silicate |
| DetSi | particulate organic silicate |
| DetP | particulate organic phosphorus |
| DetN | particulate organic nitrogen |
| totN | total nitrogen |
| totP | total phosphorus |

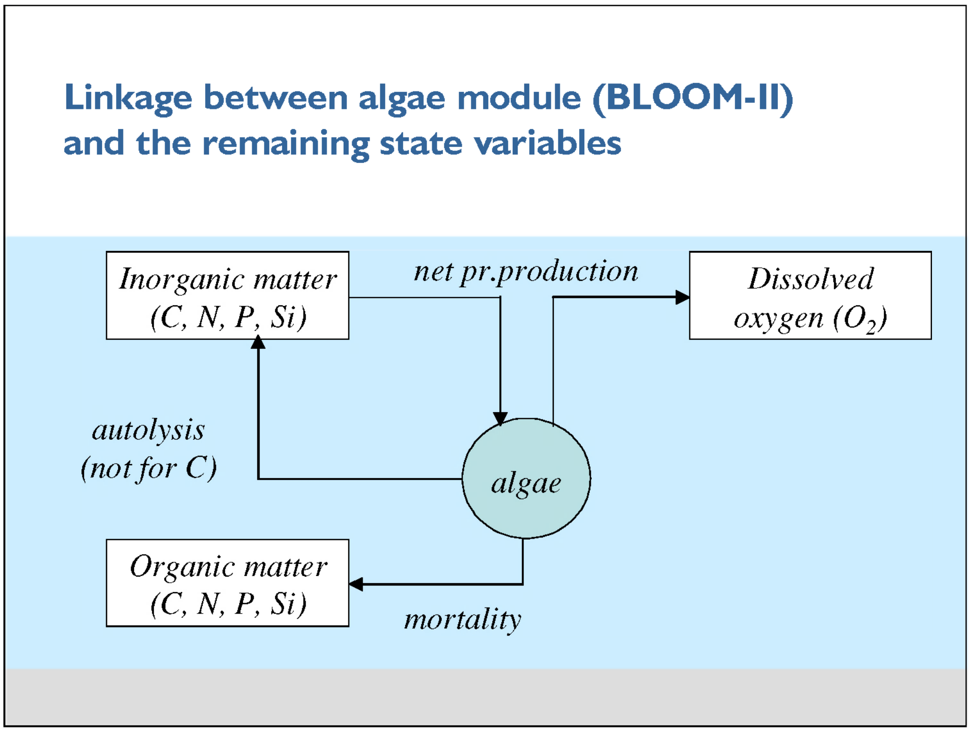
# E Calculation of nett primary production

In this appendix the calculation of primary production in the phytoplankton module BLOOM in GEM is described and compared with methods used for determination of primary production based on field observations.

## E.1 Calculation of primary production in GEM

Primary production within GEM is calculated by the phytoplankton module BLOOM.
In this description, the optimisation procedure of the BLOOM module is considered as a black box. For the moment, advanced features in BLOOM such as rooted macro-algae, mixotrophy and nitrogen fixation are neglected.

The diagram below provides an overview of the coupling between the BLOOM-module and the other state variables in GEM.




The diagram shows "net pr.production", which represents the (gross) primary production minus the respiration.

Apart from the fluxes shown in the diagram (which are internally defined in g/m$^3$/d and automatically incorporated in the mass balance equation for the relevant state variables), some additional output items with a flux character are calculated:

- Total net primary production (gC/m$^2$/d)
- Total respiration (gC/m$^2$/d)

### Calculation of fluxes and related output items

The interface quantities are calculated on the basis of a limited number of items:

| | |
|---|---|
| $B_i^t$ | Initial biomass per algae type i at the beginning of the BLOOM time step[1] (gC/m$^3$). |
| $X^t$ | Initial concentration of inorganic nutrients (N, P, Si) at the beginning of the BLOOM time step (gX/m$^3$). |
| $\mu_i$ | Mortality flux per algae type i during the BLOOM time step (calculated by BLOOM) (gC/m$^3$/d). |
| $B_i^{t+\Delta t}$ | New biomass per algae type i at the end of the BLOOM time step (calculated by BLOOM) (gC/m$^3$). |
| $X^{t+\Delta t}$ | Remaining concentration of inorganic nutrients (N, P, Si) at the end of the BLOOM time step (calculated by BLOOM) (gX/m$^3$). |

***Calculation of production fluxes of biomass (up to 15 types)***

The production flux per alga type is calculated as follows. First, the hypothetical new biomass without any production is calculated:

New biomass without production (gC/m$^3$) = $B_i^t - \mu_i \times \Delta t$

Then, the primary production is calculated as the new biomass including production minus the hypothetical biomass without production:

Production of biomass per algae type (gC/m$^3$/d) = $\dfrac{B_i^{t+\Delta t} - \left(B_i^t - \mu_i \times \Delta t\right)}{\Delta t}$

This clearly results in a flux which is positive even if the biomass is constant over time, because the mortality needs to be compensated by production.

***Calculation of output item: total net primary production***

Is equal to the sum of primary production fluxes of all algae types, multiplied with local water depth (to convert from g/m$^3$/d to g/m$^2$/d.

***Calculation of output item: Total respiration***

Th respiration is not taken from BLOOM, but "recalculated" from the new biomass $B^{t+\Delta t}$, the respiration parameters and the temperature.

Respiration flux (gC/m$^2$/d) = $RC\mathrm{Re}sp \times TC\mathrm{Re}sp^{Temperature\text{-}20} \times B^{t+\Delta t} \times Depth$

[1] *Numerically, BLOOM is called in a "fractional time step", which means that it makes its own time step, independent of the other processes and the advection/dispersion of algae. If necessary, BLOOM can use its own time step size, which deviates from the remaing processes.*

## E.2 Comparison with field methods

The behaviour of mechanistic models such as GEM is determined by the rates or fluxes between state variables. From observations we have information on the concentrations of a number of state variables at a number of stations at some regular time-interval. We know very little about fluxes, however, since these are much more difficult to obtain from the natural system. Thus computed state variables might correspond well with the observations for different values of the fluxes. If both the in- and outgoing fluxes of a particular state variable are off by the same factor, we might not notice that the simulated fluxes are actually wrong. Only one flux is estimated although infrequently within the North Sea: the rate of primary production. Comparing these estimates with model results enables us to validate the model's fluxes to some extend.

It is common to refer to these estimates from the natural system as 'primary production measurements', but actualy the term 'estimate' gives a better description of the nature of these numbers. There is no simple method to measure primary production directly. In stead estimates from the natural system are based upon observations of several variables followed by a series of computations. So one might say that primary production 'measurements' are the result of a model, which is forced by regularly updated observations. Numbers for some locations in the Dutch coastal zone (and at the Terschelling transact) have been obtained by Peeters et al. (1991). Basically they adopt the following approach. Water samples are collected bi-weekly during the summer half year. From these the amount of chlorophyll and the carbon the chlorophyll ratio are determined. Furthermore the light attenuation factor and the mixing depth are estimated. The sample is then exposed to a series of light intensities in a special incubator device to obtain the photosynthetic light response curve and the maximum photosynthetic rate constant Pmax. The primary production per unit of biomass for a bi-weekly time period is now computed using this production curve and Pmax in combination with daily surface irradiances and temperatures. It is assumed that the total extinction coefficient and mixing depth remain constant. Multiplication with the average amount of biomass estimated from the amount of chlorophyll gives the total primary production in mg C per $m^2$.

In GEM the rate of primary production for this same two-weekly period is determined in the following way. The model computes the maximum growth and respiration rates for the prevailing temperature on the bases of the simulation time-step of the model (usually one day, sometimes several hours) for each of the phytoplankton species considered by the model. The light response curve of each individual species is integrated over the mixing depth and diurnal variations in light intensity to obtain the light efficiency per day. This number is multiplied with the maximum growth rate to obtain the gross production rate for each species on a particular day. Multiplying with the biomass and subtracting the respiration gives the net rate of primary production in mgC per $m^2$ for each species and finally the summation over all species gives the total rate of primary production.
This procedure is repeated for each day with updated values for the temperature, biomass, surface light intensity, extinction coefficient and mixing depth.

A comparison of the two estimation methods reveals the following differences:

1. The field estimates use a single photosynthetic respose curve for the whole community. A different curve is determined for each location. In GEM each major group has its own curve which is the same at each location.
2. For the field estimates new curves are obtained bi-weekly. The curves in the model are fixed for the entire simulation period (usually one year).
3. In the field Pmax is estimated per location so again for the whole community for each measurement time. Respiration is not explicitly taken into account. In GEM Pmax varies per species (not location) and is affected by temperature only. Respiration is explicitly considered.
4. The forcing functions in GEM such as temperature, mixing depth and exinction coefficient are updated for each time step (so in the order of hours). Field estimates are based on the assumption that these factors remain constant for a 14 day period or they are updated using a linear interpolation approximation.
5. In the field the light attenuation coefficient is estimated locally. The extinction coefficient in GEM is computed using terms for the background extinction, humic substances (fresh water amount), total inorganic suspended solids (SPM), detritus and phytoplankton. Although this extinction model is extensively validated against field data (Van Gils and Tatman., 2002), there is uncertainty in some of its state variables. In particular the contribution of suspended solids is based upon model simulations. At some coastal stations such as Noordwijk 2 where (1) these simulated SPM results are not correct and (2) this term is considerable, the extinction coefficients used by GEM differ consiederably from the direct field estimates.
6. In general differences in mixing depth might also be significant. In this case they are not, however, since we have used in GEM in 2D not in 3D mode.
7. The phytoplankton biomass in the field is estimated from the amount of chlorophyll and the total amount of organic carbon to obtain the carbon to chlorophyll ratio. Errors in this estimate affect the primary production estimate. In the model biomass is the actual state variable, chlorophyll is computed using a type (so not species) dependent stochiometric factor. Here the computed rate of primary production does not independ on the carbon to chlorophyll ratios.

Since these differences can be both positive and negative, a much more detailed analysis is necessary to determined if there is a systematic difference between them for the Dutch coastal zone and/or for the North Sea. Such analysis is beyond the scope of this report. Occasionally, for instance at Noordwijk 2, local differences are so obvious that the do result in systematically different primary production estimates between GEM and the field.