Deltares

Development of sixth generation model schematisation 3D D-Water Quality Veerse Meer

Model set-up and calibration

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Summary

Recent water quality problems in the Veerse Meer have renewed efforts to develop modelling tools for the lake. In the context of setting up the new sixth-generation models for Rijkswaterstaat, a 3D D-Water Quality model of the Veerse Meer including eutrophication parameters, dissolved oxygen, and related water quality processes has been developed.

During this first phase of model development an initial water quality model was set up with the purposes of contributing to understanding of the system dynamics and biochemical processes which underly system functioning in the Veerse Meer. The model schematisation uses the latest advances in online coupling to the D-HYDRO hydrodynamic model and shares the same geometry. Two full years (2011-2012) of observations were used for initial calibration of the model parameters.

After calibration, the model reproduced spatial and seasonal dynamics in algae growth, spring bloom behaviour, nutrient depletion and low oxygen in deep water resulting from stratification during summer months in agreement with the current understanding and observation data. The model simulated winter concentrations well, however, summer concentrations of chlorophyll-a are generally overestimated and nutrient and dissolved oxygen concentrations underestimated.

During calibration of the eutrophication parameters it became apparent that grazing of algae by higher trophic organisms likely plays an important role in Veerse Meer. Observed chlorophyll-a concentrations are lower than predicted without grazing using typical algae growth and mortality processes, suggesting that algae populations are limited by predation. During winter primary production is limited by light, so adjustment of the specific coefficient for light extinction, and especially background extinction, were most effective in calibration of winter concentrations.

Analysis of the model results for 2011 and 2012 shows that transport in deeper sections of the Veerse Meer is highly dynamic and oxygen processes in the summer are dominated by sediment oxygen demand and mixing with inflow from the Eastern Scheldt via the Katse Heule. Inflow from Katse Heule is effective in consistently bringing oxygenated water to the eastern half of the lake but is less effective in the western half where dissolved oxygen concentrations decrease quickly during periods of low inflow which can last up to several days.

After initial calibration, the model was shown to accurately reflect the general system dynamics of the Veerse Meer related to eutrophication and dissolved oxygen. It can be used for qualitative assessments to investigate the research questions into system functioning of the system analysis including the effect of potential measures, i.e. to predict the direction and order of magnitude of change. A model validation should be carried out, before a judgement on the application for quantitative assessments, i.e. prediction of concentrations and effect of potential measures with an accuracy still to be defined, can be given. Validation of the model on more recent years is foreseen, to be executed in the first quarter of 2022, in parallel with and contributing to a system analysis including analysis of the additional monitoring data collected in 2021. The validation result and an extended assessment of model performance and model applicability will be added to an updated version of this report.

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1 Introduction

1.1 Background

Rijkswaterstaat Sea and Delta (RWS-ZD) is responsible for the water management (i.e. water level, water quality, nature management) of the Veerse Meer. The aim of water level management is to improve ecological functioning, to improve nature and recreational values, to optimize water management in extreme situations and to meet agricultural interests (Projectgroep EIA Peilbesluit Veerse Meer 2007). In order to gain insight into the system functioning of the Veerse Meer, regular monitoring is carried out.

The models previously set up for this area of interest are the result of studies and analyses in the run-up to the design and realisation of the Katse Heule permeation device (Kernkamp, et al. 2002). In 2004 and 2006 a study was carried out with Delft3D models for water movement, water quality and primary production to improve the water quality and ecology of the lake by adjusting the (winter) water level management (Nolte et al. 2006). This research was conducted with area models that were developed in the period 2000-2003. These area models are now outdated and not included in model management and maintenance.

In the context of setting up the new sixth-generation models for Rijkswaterstaat, a 3D D-Water Quality model of the Veerse Meer including eutrophication parameters, dissolved oxygen, and related water quality processes has been developed. This water quality model is coupled to the 3D D-HYDRO model (version *dflowfm3d-veerse_meer-j19_6-w4)* developed earlier in the year (Kaaij and Kerkhoven, 2021) for water movement including salinity and temperature and uses the same geometric schematisation.

This report provides an overview of the steps taken in the realization of the above 3D water quality schematization: the model set-up and the testing of the model for prediction of eutrophication and dissolved oxygen processes. This model development was performed under the sub-project KPP MA05 BOO Waterkwaliteitsmodelschematisaties - Ontwikkeling 6de generatie WQ schematisaties (Deltares reference 11206811-002).

1.2 Wider program context of this study

Recent problems with water quality and ecological system health have been observed in the Veerse Meer. The observed problems occur about 15 years after the changes to improve exchange with the Eastern Scheldt via the opening of the Katse Heule in 2004. While water quality and ecology in the lake have substantially improved, periods of low dissolved oxygen in the western and deeper parts of the lake are still observed during the summer season. Also, several fish kill events were observed in recent years. A concise and qualitative system analysis was performed of the available literature and measurement data and reported in "*Systeemanalyse en werkplan waterkwaliteitsmodel Veerse Meer*" (Prins et al., 2021) outlines a number of hypotheses and research questions to identify potential causes.

Following the observation of recent problems, Rijkswaterstaat Zee en Delta has started an investigative program which will continue in 2022 and potentially 2023. The objective of the program is to identify potential and feasible measures based on a sound understanding of the (root) cause or causes of the observed problems. To get to this sound understanding, a number of activities are carried out including 1) collection and compilation of available data and information in the Veerse Meer System Report, 2) additional monitoring, 3) model development, and 4) expert meetings. Ultimately, all activities contribute to a system analysis to identify and confirm the cause(s) of the chain of events. The system analysis is planned in 2022.

The model development, which is also part of the transition to the 6th generation model schematisations, consists of two phases. Phase 1 is the model set-up and calibration and is described in this report. Phase 2 is the model validation, which is planned in January-March 2022. The model validation will be added to this report to complete a full model set-up, calibration and validation report. A third phase may be to investigate effectiveness of measures with model scenarios, but no planning is known at this moment.

1.3 Purpose of this study

The aim of this study is to develop a 3D D-Water Quality sixth-generation model to aid in understanding the transport and biochemical process dynamics of the Veerse Meer to test the hypotheses and research questions put forth by the system analysis and to provide a tool with which possible management scenarios can be evaluated.

This Phase 1 report includes the model set-up and calibration. An initial assessment on model performance – how well does it represent and reproduce essential system processes and system behaviour? – is based on the calibration result. In Phase 2, the report will be extended with the model validation. After validation and most likely in combination with insights from the system analysis, a final and complete assessment of the model performance will be done and included to the Phase 2 report.

2 System understanding

As indicated in paragraph 1.2, understanding the physical, chemical and ecological state and trend of the Veerse Meer in general and the cause or causes of the observed problems in particular, are the basis for identifying possible and feasible measures or solutions. This chapter contains a summary of the current system understanding as gathered from expert sessions and other activities organised by Rijkswaterstaat Zee en Delta. An initial system analysis was carried out prior to this report with also the objective to identify the essential features to be represented and reproduced by the 3D water quality model (Prins et al., 2021). For convenience, the relevant information is summarized here.

2.1 System analysis Veerse Meer

This assessment builds upon the system analysis performed earlier this year, "*Systeemanalyse en werkplan waterkwaliteitsmodel Veerse Meer*" (Prins et al., 2021), which documented the main research questions and hypotheses on system functioning in the Veerse Meer. The report prioritises actions to be taken into three groups. The first of these was development of a hydrodynamic model to simulate water transport dynamics including salinity and temperature, and quantification of freshwater discharges and nutrient loads to Veerse Meer from the surrounding polders. Both actions were previously undertaken in prior projects. As the second priority, the development of a water quality model for the purpose of better understanding causes and possible solutions to oxygen depletion is needed and is the objective of this work. Finally, as third priority and not included in this study, aims to describe higher trophic processes such as the effect of water quality on shellfish, bird and fish species, and are better done in the first instance through the analysis of monitoring data.

2.2 Enriched effect chain for Veerse Meer

As part of the system analysis a conceptual model was developed to describe the complex interaction of processes important for water quality and ecology in the Veerse Meer (see Figure 2.1). Using an enriched effect chain methodology, each link in the conceptual model was evaluated in terms of the current level of understanding, either based on data analysis, expert process knowledge, or both, using a colour code as described in the legend. A first draft of the enriched effect chain was discussed during the project kick-off meeting on 16 February 2021 with participants from RWS WVL, RWS ZD and Deltares.

The conceptual model contains the processes and parts of the ecosystem that are considered most relevant to arrive at a better understanding of the system and ultimately insight into possible solutions. The conceptual model indicates which processes are included in the water quality model (orange arrows) and which cannot at this time (black arrows) either due to lack of data or lack of process knowledge.

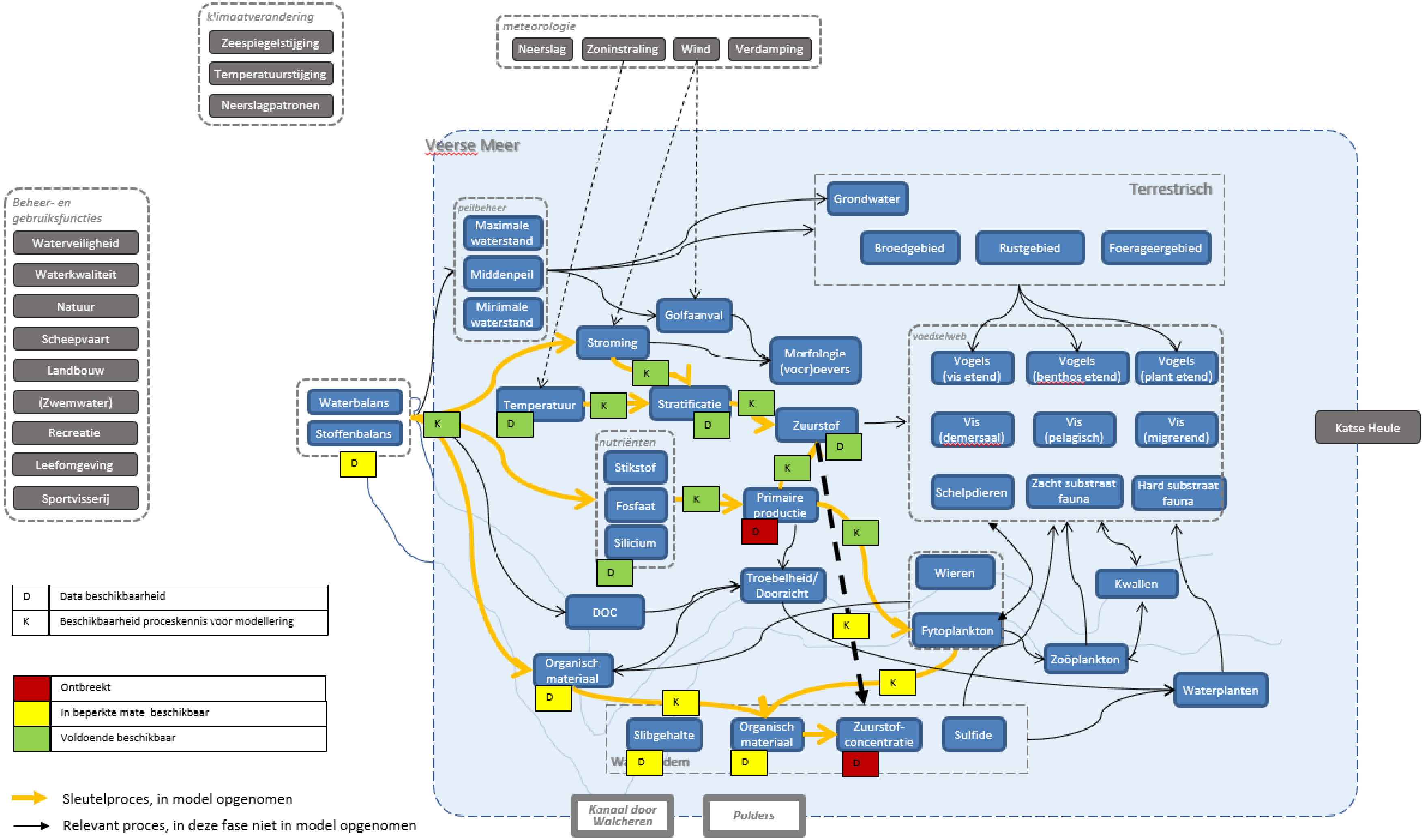


Figure 2.1 Conceptual model and enriched effect chain for Veerse Meer. Orange arrows indicate process links included in the current model; those in black indicate process which cannot yet be included in the model.

2.3 Modelling objectives for system understanding

From the conceptual model one can see that the numerical model cannot answer all questions with regards to the whole system understanding. There are simply limitations to what can be adequately parameterised in a numeric model, for which data and/or process knowledge is lacking. Therefore, in order to aid in the system understanding the modelling objectives for this project have been defined as follows. The model should::

- describe the horizontal and vertical transport and whether or not salt and/or temperature stratification occurs;
- contribute to understanding of the processes that determine the oxygen concentrations (transport and exchange with the atmosphere, primary production and oxygen consumption in soil and water column)
- describe the effect of temperature on oxygen dynamics, including increased oxygen consumption in the soil and water column at higher water temperatures
- describe the nutrient balance, which concerns not only the load with inorganic nutrients but also the load with organic material;
- describe the phytoplankton production and derive realistic values for sedimentation of organic material including (dead) phytoplankton.

The system analysis sets out several other objectives for continuing research, which cannot be addressed with the current state of the numerical modelling. These include improved understanding of grazing behaviour by zooplankton and benthic animals, and quantification of higher-order ecological effects on fish, birds, and other aquatic flora and fauna.

2.4 Assessment criteria for model performance

The modelling objectives set forth in the previous section are elaborated here to into detailed assessment criteria on which to base the model calibration. Based on the current understanding of system dynamics in the Veerse Meer, the model should:

- reproduce the limiting factors for primary production (algae growth); demonstrate nitrogen limitation in summer months and light limitation in winter months and the timing of nutrient depletion following the spring bloom;
- reproduce average summer and winter nutrient concentrations; reproduce typical seasonal patterns of high winter and low summer concentrations;
- reproduce the seasonal pattern in chlorophyll-a concentration including spring bloom behaviour;
- reproduce the maximum level of individual peaks in chlorophyll-a concentration (if any) but not necessarily the timing of individual peaks due to limitations in both the model and available observation data;
- reproduce low oxygen level and oxygen depletion in deep areas during summer months observed from TSO depth profiles.

In Phase 1, evaluation of the model performance will be based on subjective assessment of these criteria. In Phase 2 in the first quarter of 2022, a validation of the model is foreseen including an objective, goodness-of-fit assessment of the model performance.

2.5 Available datasets in Veerse Meer

2.5.1 Digital System Report Veerse Meer

A comprehensive overview of water quality data in the Veerse Meer has been compiled into the digital System Report Veerse Meer based on publicly available data from RWS's waterinfo.nl and other information. The report includes measurements from the start of recording in 1965 until 2020 and analysis of long-term trends. A work-in-progress version of the digital report can be accessed at http://testsysteemrapportage.nl/veersemeer/waterkwaliteit-en-bodemkwaliteit.html.

2.5.2 Nutrients and eutrophication parameters

Nutrient concentrations are measured at a number of locations in the Veerse Meer since recording started. An example for dissolved ortho-phosphate is shown in Figure 2.2. The only location where records are continuous and current (since 2010) is Soelekerkepolder Oost, indicated by the largest circle in Figure 2.2.

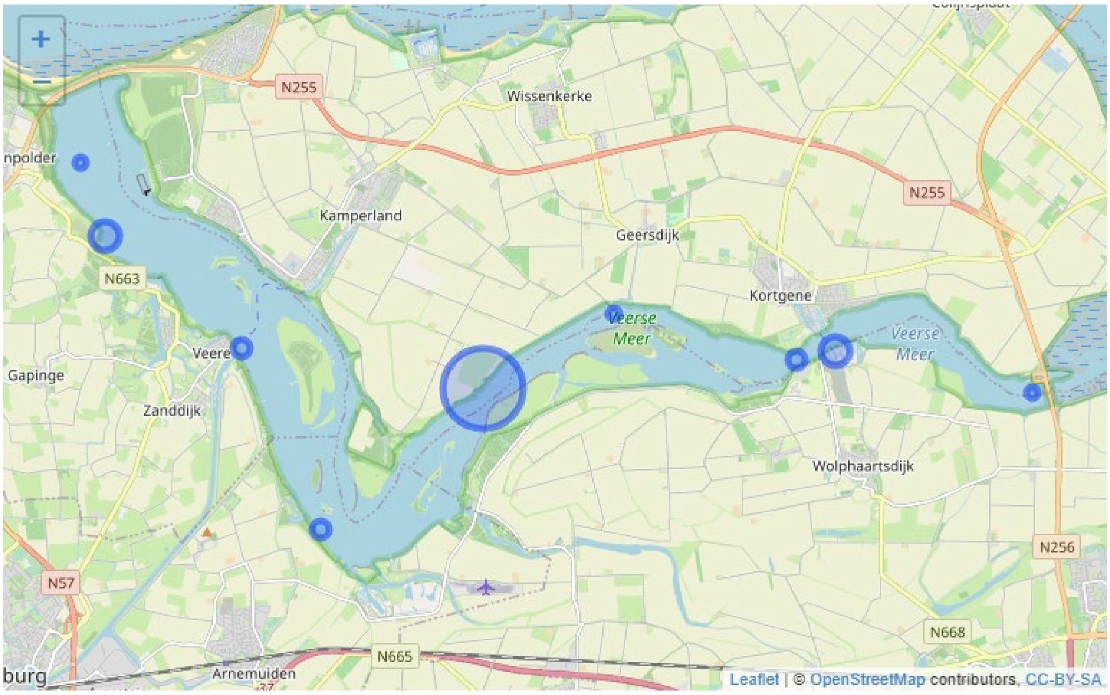


Figure 2.2 Map displaying locations at which phosphate is measured in Veerse Meer. The size of the circle indicates the number of total measurements since recording started in 1965. (Taken from testsysteemrapportage.nl/veersemeer)

2.5.3 TSO depth profiles (Temperature, Salinity, and dissolved Oxygen)

About 15 times per year depth profiles are measured in the Veerse Meer for temperature, salinity, dissolved oxygen concentration, and a few other parameters. The measurements are taken by lowering a probe from a boat during cruises along the deepest part of the lake. Thus, the exact sampling locations vary between individual campaigns but can be clustered as shown in Figure 2.3. A transect is available up to and including 2011 and from 2019 onwards. From 2012 until 2018, a TSO profile was monitored at one central location only (no. 7 in Figure 2.3) corresponding with the MWTL location Soelekerkepolder Oost.

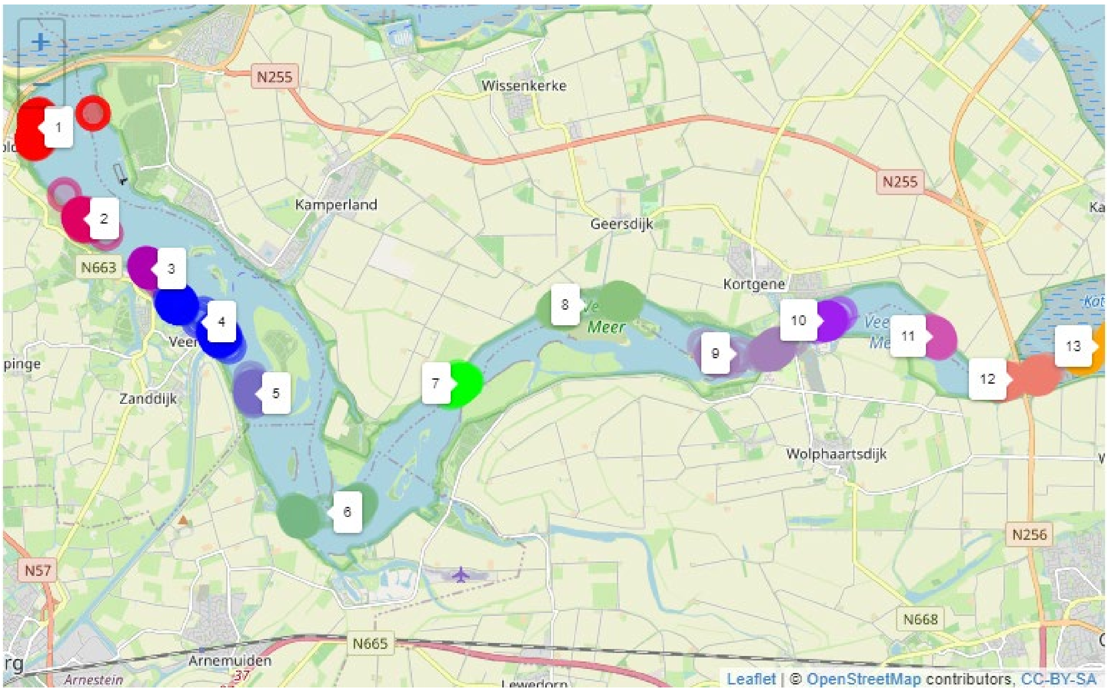


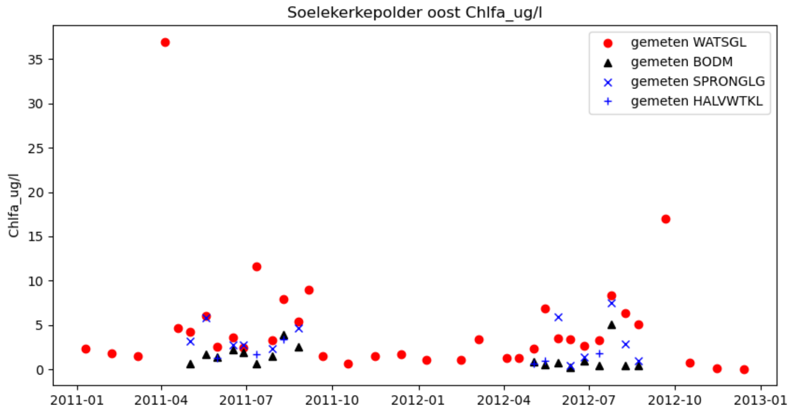
Figure 2.3 Map displaying clustered locations of TSO measurements from 2010 - 2019. (Taken from testsysteemrapportage.nl/veersemeer)

2.6 Nutrients and primary production (phytoplankton)

Observations of chlorophyll-a and nutrient concentrations were analysed over the study period for years 2011 and 2012 (Figure 2.4 and Figure 2.5). Measurements were taken at the water surface (WATSGL) throughout the year, and at lower depths during the summer months. The acronyms HALVWTKL, SPRONGLG, and BODM correspond to half the water depth, the approximate location of stratification, and at the bottom, respectively.

Chlorophyll-a concentrations in winter tend to be low, between 0 and 2 ug/l, and higher with more variability during spring and summer months. The inverse is found in nutrient concentrations. Nitrate and ammonium are highest in winter, around 1.2 and 0.25 mg/l, respectively, with a rapid decrease in spring followed by very low concentrations throughout the summer. Phosphate shows the same pattern of rapid decrease in the spring, but slowly increases through the summer months to reach an average winter concentration around 0.16 mg/l. Winter silica dioxide concentrations are around 3.0 mg/l in the winter, dipping to between 0.01 and 1.0 mg/l in the summer.

From chlorophyll-a observations there is some evidence of a spring bloom in April 2011 derived from only one measurement, and no instances in 2012. When observed over multiple years between 2005 and 2020 a consistent spring bloom pattern is more apparent, though blooms are not present in every year. The observations are not high enough in frequency to conclude whether blooms are not present or whether these events are simply not captured in the measurements. There is strong evidence, however, that spring blooms do occur regularly when looking at nutrient concentrations. Macronutrients appear to deplete rather quickly, in a period of only a few weeks in late March and April. Such rapid nutrient depletion can only result from an algae bloom, though the exact magnitude and timing cannot be derived directly from observations.



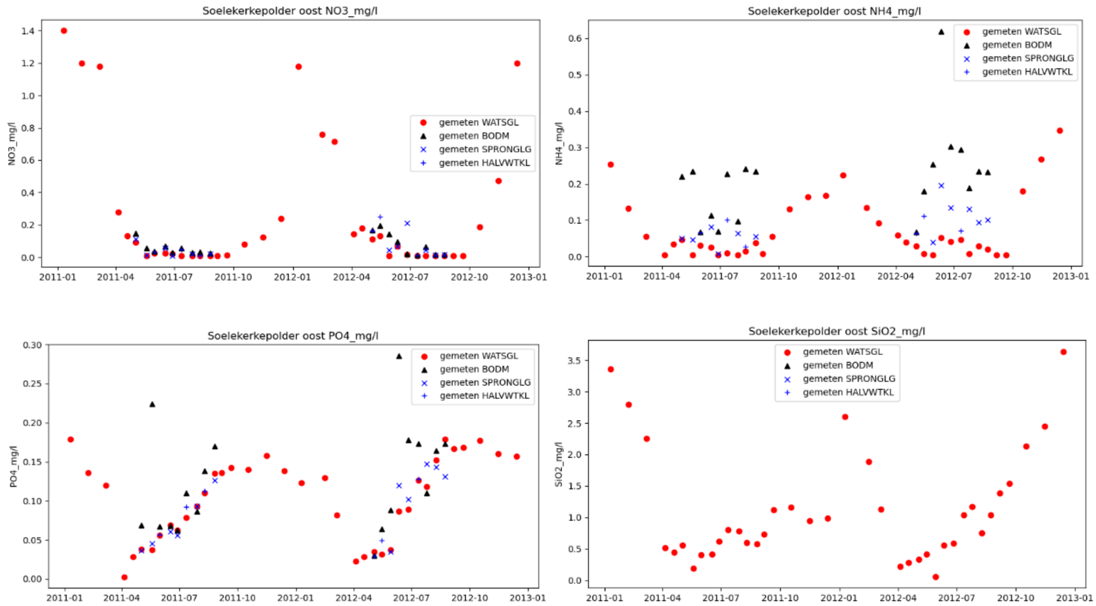
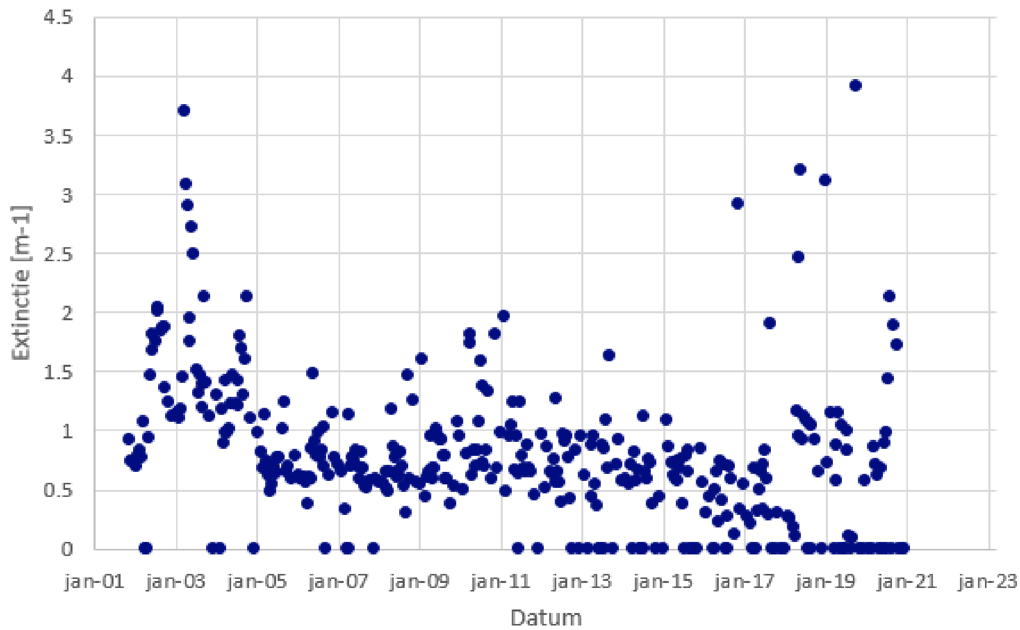


Figure 2.5 Time series of observations of (from upper left, clockwise) nitrate (NO3), ammonium (NH4), silica dioxide (SiO2), and phosphate (PO4) at Soelekerkepolder Oost

2.7 Light penetration and visibility

A key component of the quantification of primary production is the amount of light energy that algae can use for photosynthesis. Measurements of light extinction and Secchi depth at Soelekerkepolder where analysed from the year 2001 to present (all data available up to 8-10-2020). Figure 2.6 shows a time series plot of the available data. Values for light extinction vary greatly, between 0 and 3.9 m^{-1}, with an average value of 0.92 m^{-1} and standard deviation of 0.57 m^{-1}. It is difficult to derive any real trends from the data in terms of increasing or decreasing over years, nor seasonal patterns.



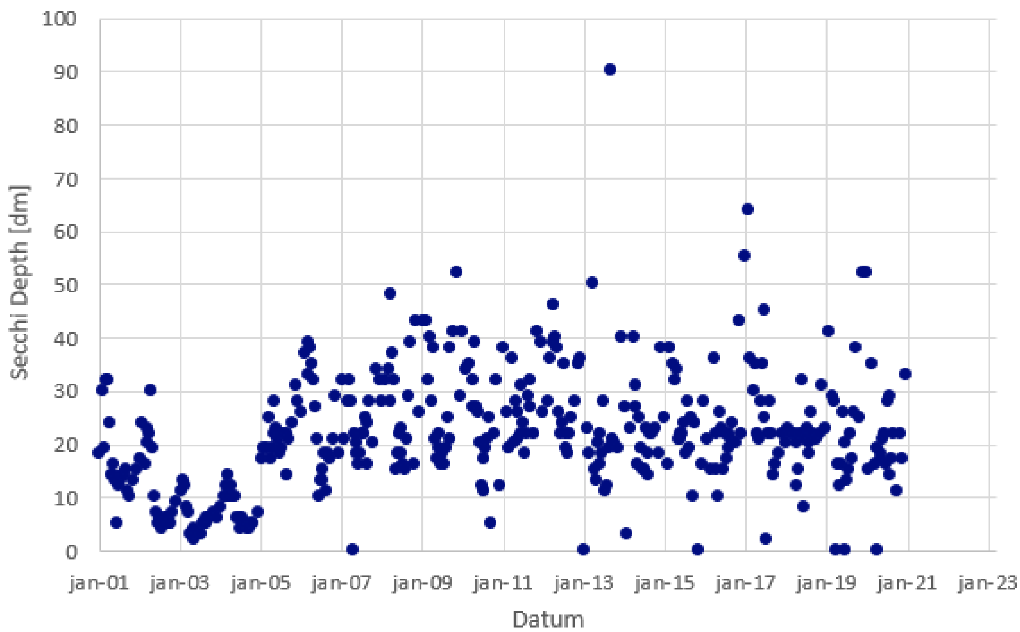


Figure 2.6 Time series of observed light extinction [m-1] and Secchi Depth at Soelekerkepolder Oost

The same holds true for Secchi depth. Values range from 0 to 9 m with an average value of 21.8 dm and standard deviation of 11.1 dm. Other than a clear dip in Secchi depth over years 2001-2004 during commissioning of the Katse Heule, year on year trends from 2005 onwards are hard to detect, as are seasonal patterns.

Further, correlation between measured extinction and measured Secchi depth is weak (r^2 = -0.40), meaning a direct relationship between the two cannot be derived from measurements alone. Measurement of both extinction and Secchi depth can be greatly influenced on any given day by factors such as weather conditions, the presence of wind-induced waves, local activities which can stir up sediment from the bed, and reflection of the water surface which can affect the vision of the observer.

Total light extinction is made up of the cumulative effect of several factors and varies greatly from one location to another. To better understand which factors are most important in Veerse Meer, a regression analysis was performed against concentrations of chlorophyll-a, dissolved organic carbon (DOC), particulate organic carbon (POC), and total suspended solids (SS). Additionally, salinity was evaluated. Though salinity has no actual effect on extinction, it can be used as a fractional quantification of the amount of freshwater present in saltwater systems. This is relevant as humic acids resulting from the decay of organic matter are often present in freshwater at a higher concentration than in seawater and give it a brownish colour. These acids are dissolved in the water and a persistent component of light extinction. Since humic acids are not explicitly modelled, a relationship with salinity can be derived instead.

Table 2-1 shows correlation of each measured quantity with the measured extinction. Chlorophyll-a, POC and, to a lesser extent, DOC and salinity were shown to have relevant correlation. Similar correlation found from chlorophyll-a and POC is not surprising, since chlorophyll-a is a component of phytoplankton which make up a large proportion of the POC. The concentration of suspended solids was not shown to have high correlation with light extinction, meaning measured extinction values at this location are likely not heavily influenced by local events which stir up the bed. This is logical since Soelekerkepolder is located within a deep gully and likely not affected by the bed at all. We cannot say though that suspended matter concentration does not have a stronger effect in shallower areas where measurements are lacking.

Table 2-1Correlation factors between measured concentrations and measured light extinction

	Chlorophyll-a	DOC	POC	Salinity	SS
Correlation factor (light extinction)	0.75	0.48	0.83	-0.50	0.18

The brief analysis shows that our understanding of the factors which cause light extinction in the Veerse Meer is not complete and should be expanded in the upcoming system analysis. A more extensive statistical analysis of the available measurements may provide enough information from which to derive the relationships between water quality states (concentrations) and light extinction, although more measurements may be needed.

Therefore, the model will make use of known relationships derived from experiments and 30+ years of experience. However, we cannot expect that the model will reproduce the measured light extinction from measured states given that the method cannot be validated using data obtained from Veerse Meer. Still, some tuning of the light extinction model using the measurement data was done. This is elaborated in Appendix B.3.

2.8 Stratification and oxygen depletion

The Veerse Meer is shallow over much of the area with a deep gully cutting through from east to west. In the shallow areas, oxygen depletion is not expected in the water column (there are no measurements in shallow areas to confirm this), since the normal action of wind and waves brings oxygen into the water from the free air surface. In the deep channel, stratification is known to occur in the summer months (April – September) with occasionally relatively strong gradients in both water temperature and salinity over the vertical. Depth profiles for years 1996 – 2020 are provided in Appendix A.

Figure 2.7 shows observed oxygen concentrations at Soelekerkepolder Oost at the water surface, at mid depth and near the bed. Measurements at the surface are taken throughout the whole year, whereas at deeper levels only during the summer months measurements are taken, as this is when issues with low dissolved oxygen are observed. During the summer months oxygen concentrations near the surface are high, always around full saturation, adequate to support biologic life (i.e. fish, mussels, etc.) and always above 6 mg/l. At mid-depth and near the level at which stratification occurs concentrations fluctuate often between 5 and 8 mg/l, suggesting that the measurements are highly sensitive to changes in the position of the stratification layer as it rises and falls. Near the bed, low oxygen is observed at several moments over the summer periods in both years. While never completely depleted, concentrations between 2 and 4 mg /l indicate a severe risk of stress to organisms which could result in permanent damage or death. There is some fluctuation in time observed, which indicates that the deeper channels receive periodic mixing of water higher in oxygen concentration from the mid and surface layers, so prolonged stagnation is not likely at this location. However, since summer concentrations generally remain below 6 mg/l there is some cause for concern for bottom-dwelling organisms within deep channels.

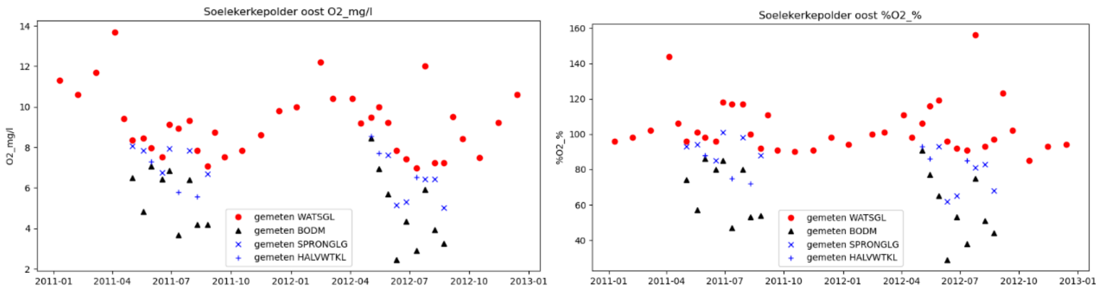


Figure 2.7 Observed dissolve oxygen as concentration (left) and % of saturation (right) at Soelekerkepolder Oost; measured near water surface (WATSGL), near the bed (BODM), and near mid-depth (SPRONGLG & HALVWTKL)

Soelekerkepolder Oost is located about halfway from east to west in Veerse Meer so measurements at this station may not be representative in the western part of the Veerse Meer, where recent problems with low oxygen and fish kills have been observed. The TSO measurements include several locations in the west of the lake. These are presented along with the model results in section 3.3.2.

3 Modelling

3.1 Model setup

3.1.1 Model software and hardware

The model is built using the D-HYDRO flexible mesh suite for hydrodynamics and D-Water Quality module. The D-Water Quality module, as the successor of Delft3D-WAQ, simulates the far- and mid-field water and sediment quality due to a variety of transport and water quality processes. To accommodate these, it includes several advection diffusion solvers and an extensive library of standardized process formulations with the user-selected substances.

The hydrodynamic and water quality components are built from the Baseline version 6.1.1 model schematisation and D-HYDRO Suite 2020.05. Simulations are calculated on the h6 (CentOS 7) Linux cluster at Deltares. Using this hardware the online-coupled simulations ran about 6 days per simulation year, or 12 days for the entire 2-year run period.

3.1.2 Coupling to hydrodynamics

The water quality model uses the same geometric schematisation as the hydrodynamic model described in the report “Ontwikkeling zesde-generatie modelschematisatie 3D D-HYDRO Veerse meer” (Kaaij and Kerkhoven, 2021). The model domain (see Figure 3.1) includes the Veerse Meer and is enclosed by the surrounding dikes, whose geometry comes from Baseline (DTB). The grid is aligned with the Zandkreekdam and the Veersegatdam. The inner area is filled with completely regular triangular calculation cells with a resolution of 50 meters, near a number of ports these triangular cells are refined to a resolution of 20 meters. Over the vertical the model is composed of z-layers chosen to run (more or less) parallel to the pycnoclines with a layer thickness of 1.25 m.

Figure 3.1 Computational model domain of online-coupled D-HYDRO and D-Water Quality model for Veerse Meer

This model makes use of the online coupling method with D-HYDRO hydrodynamics, meaning that the hydrodynamic and water quality models run together in a single simulation and the boundary forcing time series are prepared together in the same file format (*.tim files). It is not possible to decouple the two with this version.

3.1.3 State variables and processes

Substances (state variables) and processes were chosen according to the standard used by Deltares for saltwater systems as applied in the latest North Sea model (Zijl et al., 2021). However, one change to the standard was made, consisting of the removal of the state variable and processes for grazers (Ensis in the North Sea model). Inclusion of a grazing module requires analysis of the available data on species composition, spatial distribution and seasonal variation. Such analysis was not available and could not be included as part of this study. A different, simpler approach to include grazers was adopted instead equivalent to the approach in the Grevelingen water quality model (see paragraph 3.2).

A list of the modelled substances used are given in Table 3-1.

Table 3-1 State variables included in the water quality model for Veerse Meer

State Variables	Names
OXY	Dissolved oxygen [mg/l]
NH4, NO3, PO4, Si, Opal	Ammonium, nitrate, ortho-phosphate, dissolved silica, and opal silica [mg N/l]
POC1, PON1, POP1	Particulate organic carbon, nitrogen, and phosphorus in the substrate [mg P/l]
DINOFLAG_N, DINOFLAG_E, DINOFLAG_P	Dinoflagellates of the nitrogen, energy, and phosphorus limited types [mg C/l]
MDIATOMS_N, MDIATOMS_E, MDIATOMS_P	Marine diatoms of the nitrogen, energy, and phosphorus limited types [mg C/l]
MFLAGELA_N, MFLAGELA_E, MFLAGELA_P	Marine flagellates of the nitrogen, energy, and phosphorus limited types [mg C/l]
PHAEOCYS_N, PHAEOCYS_E, PHAEOCYS_P	Phaeocystis of the nitrogen, energy, and phosphorus limited types [mg C/l]
DetCS1, DetNS1, DetPS1, DetSiS1	Detritus carbon, nitrogen, phosphorus and silica in the substrate [g CNPSi/m2]

3.1.4 Boundary conditions and loads

The Veerse Meer is a closed system with free water exchange only through an opening in the Zandkreekdam via the Katse Heule (see Figure 3.2). Exchange of saline water through the sluice at Zandkreekdam results in a net outflow of approximately 303,000 m^3/day (3.5 m^3/sec) as calculated from the water balance. Freshwater enters from the polder drainage canals at pumping stations, as well as a small amount which falls as rainwater directly into the lake or enters as runoff from the shores. Brackish water is exchanged through sluis Veerse to the south.

A water balance and nutrient balance were constructed to quantify the net exchange of water and nutrients between the Veerse Meer, Eastern Scheldt, Sluis Veere and the polders as reported in *"Water- en stoffenbalans Veerse Meer 2011-2020"* (Heijden, 2021). Boundary conditions for the 3D water quality modelling were derived directly from the water and nutrient balances.

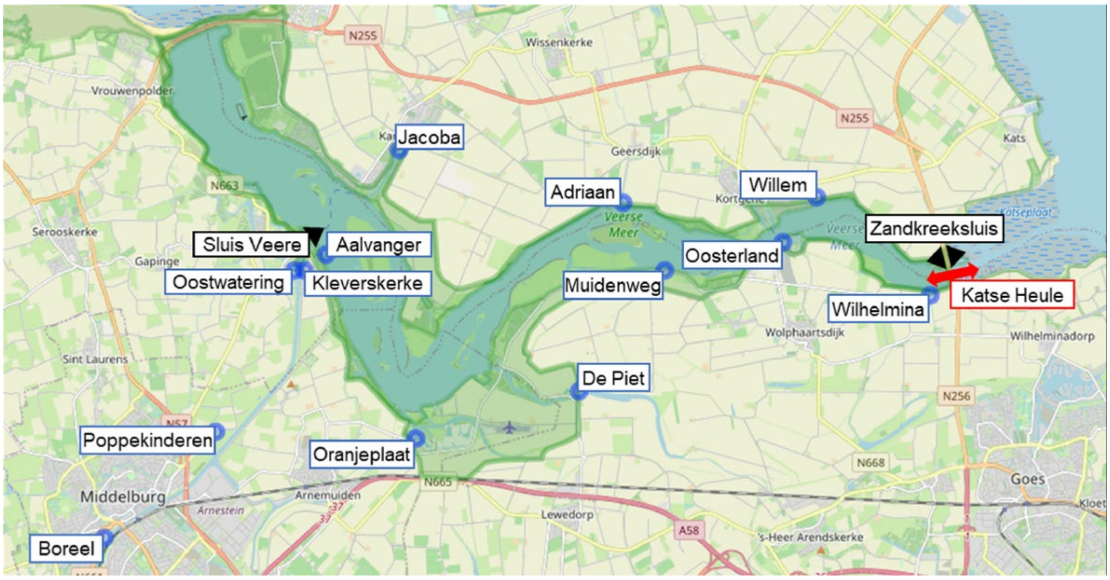


Figure 3.2 Map of the Veerse Meer with poldergemalen (blue circles), sluices (black triangles), and the Katse Heule exchange device (red arrow)

3.1.4.1 Exchange with Eastern Scheldt through Katse Heule

<u>Discharge rate</u>

A time series of discharge rate for the exchange with the Eastern Scheldt were extracted directly from the water balance.

<u>Measured concentrations</u>

Concentrations of ammonium (NH_4), nitrate (NO_3), phosphate (PO_4), Silica (Si), oxygen (OXY), particulate organic carbon (POC), particulate organic nitrogen (PON) and particulate organic phosphorus (POP) were derived from measurements in the Eastern Scheldt (stations Lodijkse Gat and Wissenkerke) for the inlet at the Katse Heule. Silica concentrations were derived from measured silicon dioxide (SiO_2) concentrations with a conversion factor ($Si = SiO_2 * 0.4674$). The measurement data were obtained from https://waterinfo.rws.nl/.

<u>Closure error</u>

Flow though the Katse Heule and the exact rate of evaporation cannot be measured directly. Taken together with the inflowing water from the polders and rain the estimated result in a net loss of water from the Veerse Meer. In the model this balance error results in a decreasing water level which does not occur in reality. Therefore, an additional (non-existent) closure error boundary is applied to keep water levels constant. The hydrodynamic model setup report describes the methodology for calculations of the closure error (Kaaij, 2021). For the closure error boundary concentrations of NH_4, NO_3, PO_4 and OXY were also derived from measurements in the Eastern Scheldt (stations Lodijkse Gat and Wissenkerke).

3.1.4.2 Polder discharges

<u>Discharge rate</u>

A time series of discharge rate from each of the polder pumping stations (Gemalen Oosterland, Muidenweg, Kleverskerke, Jacoba, Adriaan, De Piet, Willem, Wilhelmina, Oranjeplaat, Oostwatering, and Aalvanger), Sluis Veere, and Sluis Jacoba were extracted directly from the water balance.

Nitrogen and phosphorus
Concentrations of NH_4, NO_3 and PO_4 were derived from measurements at each location. Measurements are not always available at each location for the entire years of 2011 and 2012. The nutrient balance report provides a detailed description of how data gaps were filled to generate the boundary time series.

Silica
No measurements are available for dissolved silica in polder discharges. Therefore, the dissolved silica concentration is estimated by inverse calculation from the measured concentration in the Eastern Scheldt and in the Veerse Meer. In winter, when processes affecting the dissolved silica concentrations such as primary production by diatoms are low, dissolved silica can be considered as a conservative, non-reacting substance. Therefore, an average factor can be derived for the contribution of polder discharges, assuming a well-mixed lake. This is calculated as

$$f_{Polder} \cdot C_{Polder} + f_{Eastern\ Scheldt} \cdot C_{Eastern\ Scheldt} = C_{Veerse\ Meer}$$

Where C is the concentration of any conservative substance and f is the volumetric fraction of the source water to the Veerse Meer, assuming both fractions sum to 1.

For salinity, concentrations are known in the polder discharges, Eastern Scheldt and Veerse Meer. As salinity is also a conservative, non-reactive substances it can be substituted as a proxy for silica to derive the following:

$$f_{Polder} \cdot 3\ ppt + f_{Eastern\ Scheldt} \cdot 30\ ppt = 25\ ppt\ ;$$
$$f_{Polder} = 0.18\ ;\ f_{Eastern\ Scheldt} = 0.82\ ;$$

Measured concentrations of dissolved silica in the Eastern Scheldt and Veerse Meer are 0.8 and 2.5 mg/l, respectively, leading to an approximate concentration of 10 mg/l of dissolved silica in the polder water. This value was applied as a constant for all freshwater input (pumping stations and Sluis Jacoba).

Algae
Since Veerse Meer is mostly saline and the discharge of water from the polders relative to exchange through the Katse Heule is small, freshwater algae are not expected to make up a significant portion of the algae present in the lake. Therefore, no algae are added at the polder discharge boundaries.

Dissolved oxygen
Dissolved oxygen concentration in the polders were derived from measurements at each location. Measurements are not always available at each location for the entire years of 2011 and 2012. For these cases data from other nearby locations was chosen to be the best fit for oxygen concentrations of that gemaal/sluice. Table 3-2 provides the cases (gemalen) where data was derived from other locations. Gemaal Willem and Sluis Veere (measurement station Middelburg) had complete datasets for the years 2011 and 2012 considering oxygen concentrations. Data for station Middelburg was obtained from https://waterinfo.rws.nl/.

Table 3-2 Origin of oxygen concentrations for different gemalen/sluice with missing data for the years 2011 and/or 2012.

Gemaal	Aalvanger	Adriaan	Jacoba	Sluis Jacoba	Klevers-kerke	Muiden-weg	Ooster-land	Oostwate-ring	Piet	Wilhelmina
2011				Jacoba		De Piet	Wilhelmina	Boreel		
2012	Willem	Willem	Willem	Willem	Boreel	Willem	Willem	Boreel	Willem	Willem

3.1.4.3 Atmospheric deposition

Values for atmospheric deposition were derived from estimates provided by the national emission registry (Rijksoverheid, 2021). Only estimates for nitrogen deposition were available so deposition of other nutrients is not included in the model. A constant rate of deposition over the Veerse Meer was calculated as the given rate of 28,751 kg/year for the year 2010 divided by the average surface area of the lake (23,420,000 m^2) to provide a rate constant of 3.4 mg-NO_3/(m^2-day) to the model.

3.1.5 Run period and initialization

The hydrodynamic model calculates with a dynamic time step not exceeding 30 seconds for all transport-related variables including the water quality state variables in the water column (state variables in the sediment are not subject to transport). The water quality processes are calculated using a constant hourly time step, with the exception of the algae-related processes of the BLOOM module, which calculates at a daily time step. 3D spatial water quality variables are written to file on a daily frequency and as time series on an hourly frequency.

The chosen time step settings are the default settings. However, experience from the Grevelingenmeer model has revealed that the time step settings may influence certain model results, in particular the dissolved oxygen concentration in the lower water column in stratified conditions. These conditions occur in Veerse Meer and are therefore relevant for the Veerse Meer model. The investigation of time step settings has not been carried out yet in the model calibration, but will be addressed and included in the validation step (Phase 2).

The model was initialized from a set of spatially homogeneous concentrations given in Table Table 3-3. The model was then run for two years using the boundary and loads data for 2011 and 2012 to produce a spatially heterogeneous initial condition file with realistic concentrations of substances both in the water column and in the sediment. This initial condition file was then used as the starting point for all simulations.

Table 3-3 Initial values used for spin-up of water quality state variables

Substance/parameter	State variable name	Initial value
Salinity	Salinity	28.0 ppt
Water temperature	Temperature	15 deg. C
Dissolved oxygen	OXY	8.0 mg/l
Ammonium	NH4	0.0454 mg/l
Nitrate	NO3	0.0273 mg/l
Phosphate	PO4	0.02 mg/l
Silica	Si	0.2 mg/l
Opal silica	Opal	0.0 mg/l
Particulate organic carbon	POC1	0.0 mg-C/l

Particulate organic nitrogen	PON1	0.3105 mg-N/l
Particulate organic phosphorus	POP1	0.0 mg-P/l
Dinoflagellates	DINOFLAG_E, DINOFLAG_N, DINOFLAG_P	0.0 mg-C/l
Marine Diatoms	MDIATOM_E, MDIATOM_N, MDIATOM_P	0.0 mg-C/l
Marine Flagellates	MFLAGELA_E, MFLAGELA_N, MFLAGELA_P	0.0 mg-C/l
Phaeocystis	PHAEOCYS_E, PHAEOCYS_N, PHAEOCYS_P	0.0 mg-C/l
Detritus nitrogen in the sediment	DetNS1	0.0 g/m^2
Detritus phosphorus in the sediment	DetPS1	0.0 g/m^2
Detritus silica in the sediment	DetSiS1	0.0 g/m^2

3.2 Model calibration

A full calibration and validation exercise was not part of the scope of this project; still, an initial calibration was performed to analyse the model performance and come as close as possible to a fully calibrated model within the project constraints.

The calibration was performed following a two-step approach:

- Step 1:
    - Use the North Sea parameter settings to run years 2011 and 2012 for Veerse Meer and examine results at Soelekerkepolder Oost
    - Assess whether seasonal patterns in primary production and nutrient concentrations seen in measurements are reproduced by the model, including patterns in spring bloom and nutrient/light limiting factors
    - Assess whether magnitude of primary production and nutrient concentrations seen in measurements are reproduced by the model
- Step 2:
    - Assess whether spatial and temporal patterns in dissolved oxygen concentrations seen in TSO depth profiles and Soelekerkepolder Oost are reproduced by the model
    - Assess whether the magnitude of dissolved oxygen concentrations seen in TSO depth profiles and at Soelekerkepolder Oost are reproduced by the model

Several model process parameters were evaluated during this process, including:

- Light extinction (magnitude and timing)
- Mineralisation rates of organic matter in the water column
- Grazing behaviour (modelled as increased settling velocity)
- Temperature dependence of algal growth
- Dissolved silica concentration as a limiting factor for the growth of diatoms

A detailed discussion of the calibration procedure is included in Appendix B. Here we summarise the main findings:

- The Veerse Meer model is nitrogen limited in summer and light limited in winter. This is in line with analysis of measurements and with the current system understanding. Therefore, adjustment of light parameters in the summer will have no significant effect on the model results for primary production, nor will adjustment of nutrient parameters in the winter.
- The default values for specific coefficients for light extinction generally result in an overall extinction that is too low. Analysis of this model, combined with experience

from similar studies, suggests that specific extinction of particulate organic matter is an important factor in marine systems and should be increased. There is discussion now whether this default should be doubled from 0.1 to 0.2 m^{-1} for future modelling projects. Increasing the specific extinction coefficient from 0.2 to 0.3 had no significant effect so we expect limitation on algae growth due to extinction is sufficiently represented in the model.

- Adjusting the background extinction to follow a seasonal pattern (0.4 m^{-1} in winter, 0.08 m^{-1} in summer), similar to the approach in the Grevelingen water quality model, did not have the desired effect of supressing and/or changing the onset of the spring bloom. Rather, we found it results in squeezing the spring bloom into a shorter period and resulting in higher amplitude and is therefore not recommended.
- Grazing by macrozoobenthos is likely a highly important factor in the system dynamics based on experimentation with the model. Though not modelled explicitly, we approximated the uptake of organic matter and algae by grazer feeding and eventual fixation in sediments by increasing settling velocity of particulate organic matter. Observed summer concentrations of chlorophyll-a are relatively low when compared to the light and nutrient availability, suggesting that there must be another process or processes which remove algae from the water. Predation by organisms logically and functionally fills this gap. Increasing settling velocities of organic matter proved to be an effective tool in calibrating chlorophyll-a and nutrient concentrations. Increased settling mimics grazing by benthic organisms. Grazing by zooplankton in the water column is likely to occur as well but is not included as such in the model. Data on zooplankton is scarce.
- The presence of silica is needed for the growth of diatoms in the model, though as long as it is not limiting the growth of diatoms the concentration of the dissolved silica does not have any effect on algae species composition and chlorophyll-a concentration. Modelled concentrations are low compared to observed values, but no adjustments were made since further improvement would not have any effect on the overall system functioning. For later work on scenarios, improving the silica concentrations may be needed.

3.3 Model performance assessment

3.3.1 Nutrients and chlorophyll-a

To assess the model performance time series of modelled state variables were compared against observations at Soelekerkepolder Oost. In general, the model shows good reproduction of winter chlorophyll-a concentrations but overpredicts concentrations during the summer months (Figure 3.3). This is most pronounced near the water surface, where chlorophyll-a is generally higher due to higher light availability, and less so deeper in the water column. The model shows a distinct pattern of spring blooms appearing in late March of 2011 and 2012. The observations are not frequent enough during the calculated spring bloom to quantitatively assess whether the magnitude of the chlorophyll-a concentration is accurate. The timing of a peak in observed concentration and rapid decrease in ammonium and nitrate concentrations (Figure 3.4) in early April suggest the likely occurrence of a bloom, so it is not unreasonable to assume it is simply missed in the observed record and the modelled results are feasible.

Winter concentrations of nitrate and ammonium are in agreement with observed values and the general pattern of high concentrations in winter and low to zero concentrations summer are well predicted. The model displays sharper temporal gradients linked to algae growth than the observations. This is known behaviour of the BLOOM model and is therefore not surprising. However, it makes prediction of the exact start and end of a bloom cycle difficult.

Similarly, this pattern is observed in modelled and measured dissolved phosphate and silica concentrations (Figure 3.5). The modelled results show depletion of both phosphate and silica resulting from a spring bloom, which is not supported by the observations, and underpredicts in both summer and winter. Since both are impacted by release from the sediment, it's possible that the sediment model used is not yet suitable, or that the sediment layer in the model is simply not spun up enough so that the release flux has not reached equilibrium with processes in the water column. The similarity in slope between the observed and modelled values suggests the sediment processes work well, but that a longer spin-up period is needed. While overall concentrations of silica are too low in the model, this is not expected to have an effect on algae growth rates, since doubling of the incoming silica load entering from the Eastern Scheldt had little effect during calibration.

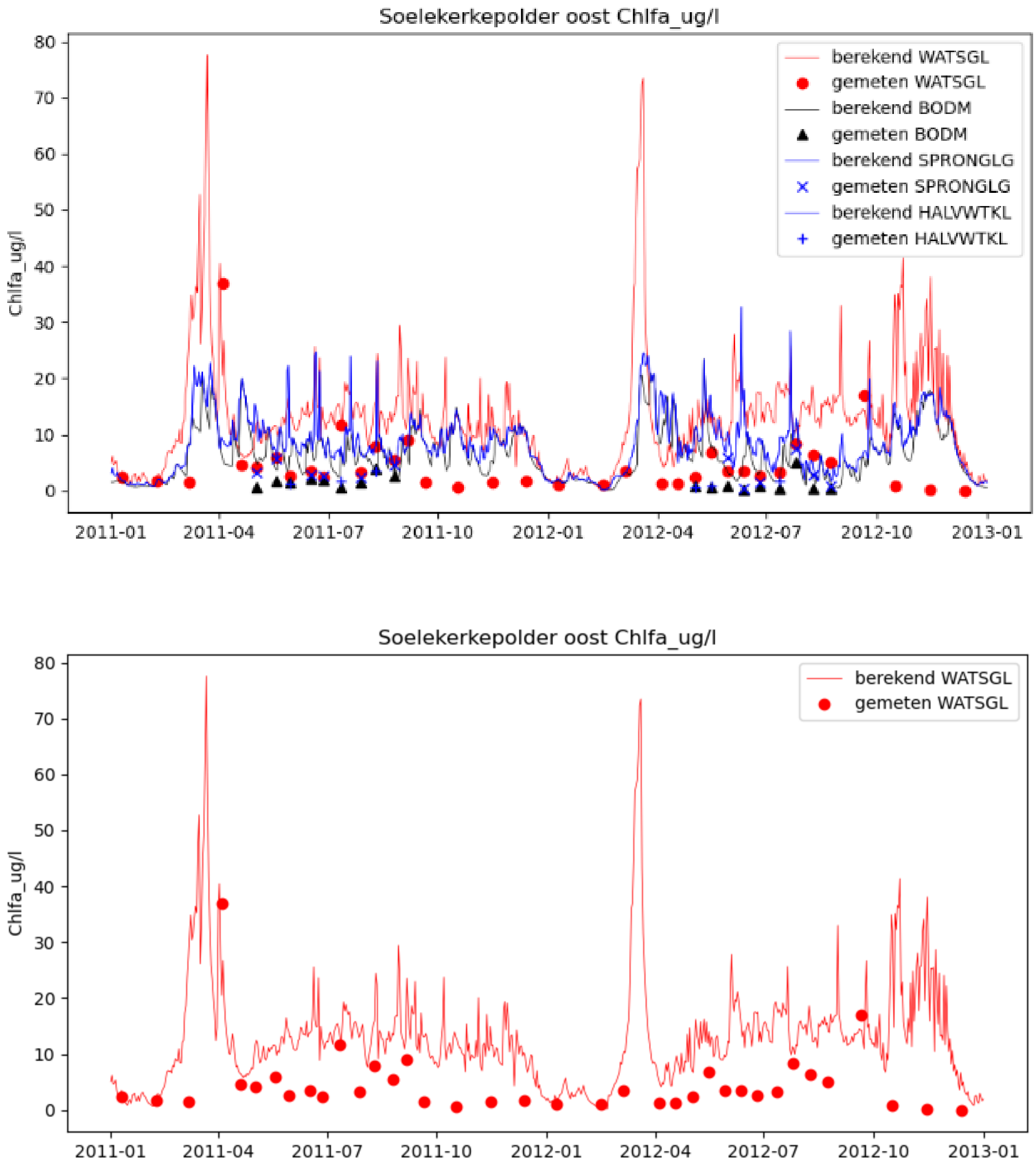
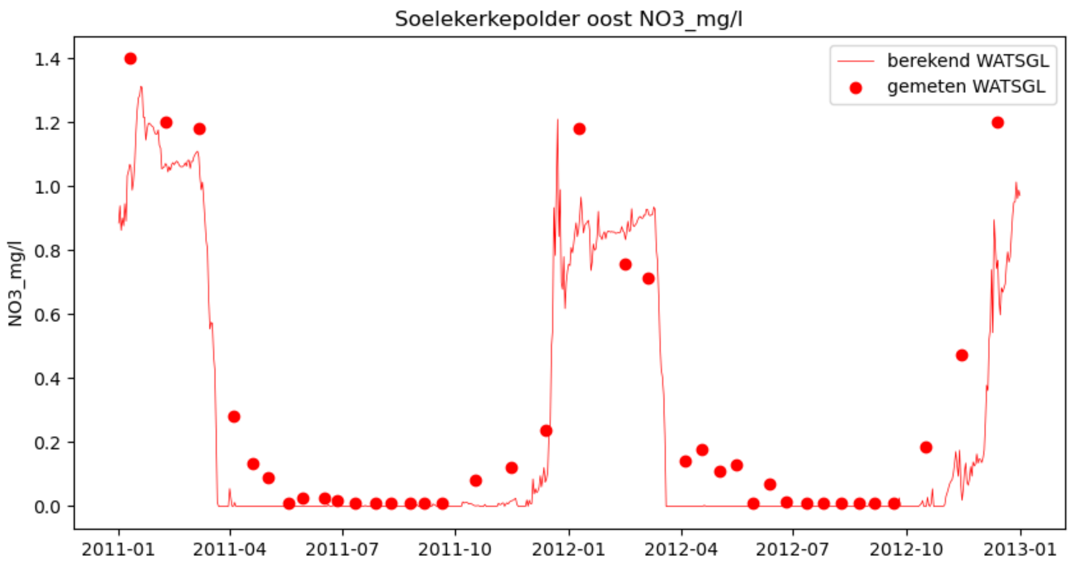


Figure 3.3 Modelled chlorophyll-a concentration near the water surface (WATSGL), near the bed (BODM), and near mid-depth (SPRONGLG & HALVWKTL) (top), and detail near the water surface (bottom), compared against observations



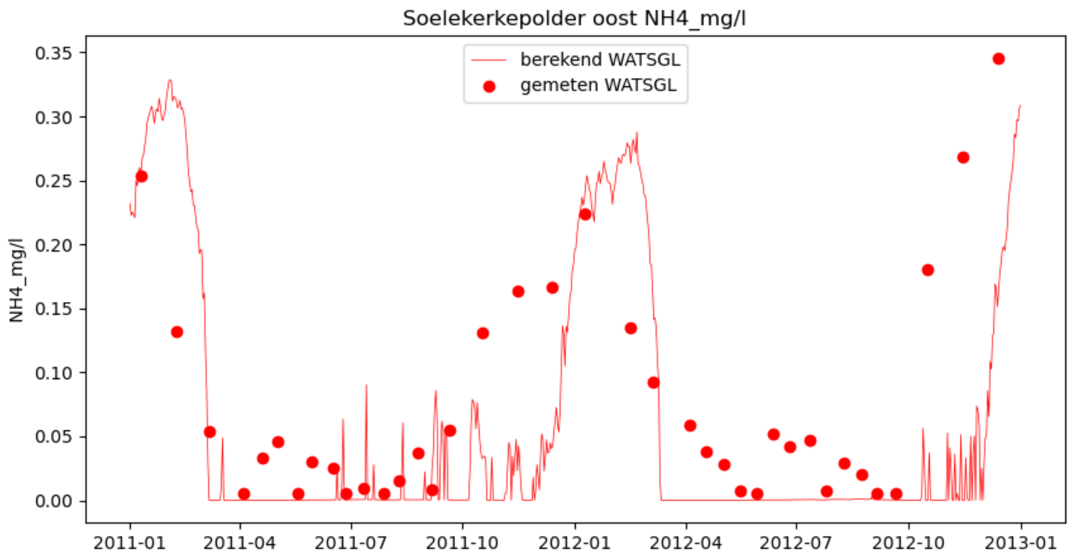


Figure 3.4 Modelled nitrate (top) and ammonium (bottom) concentrations near the water surface (WATSGL) compared against observations

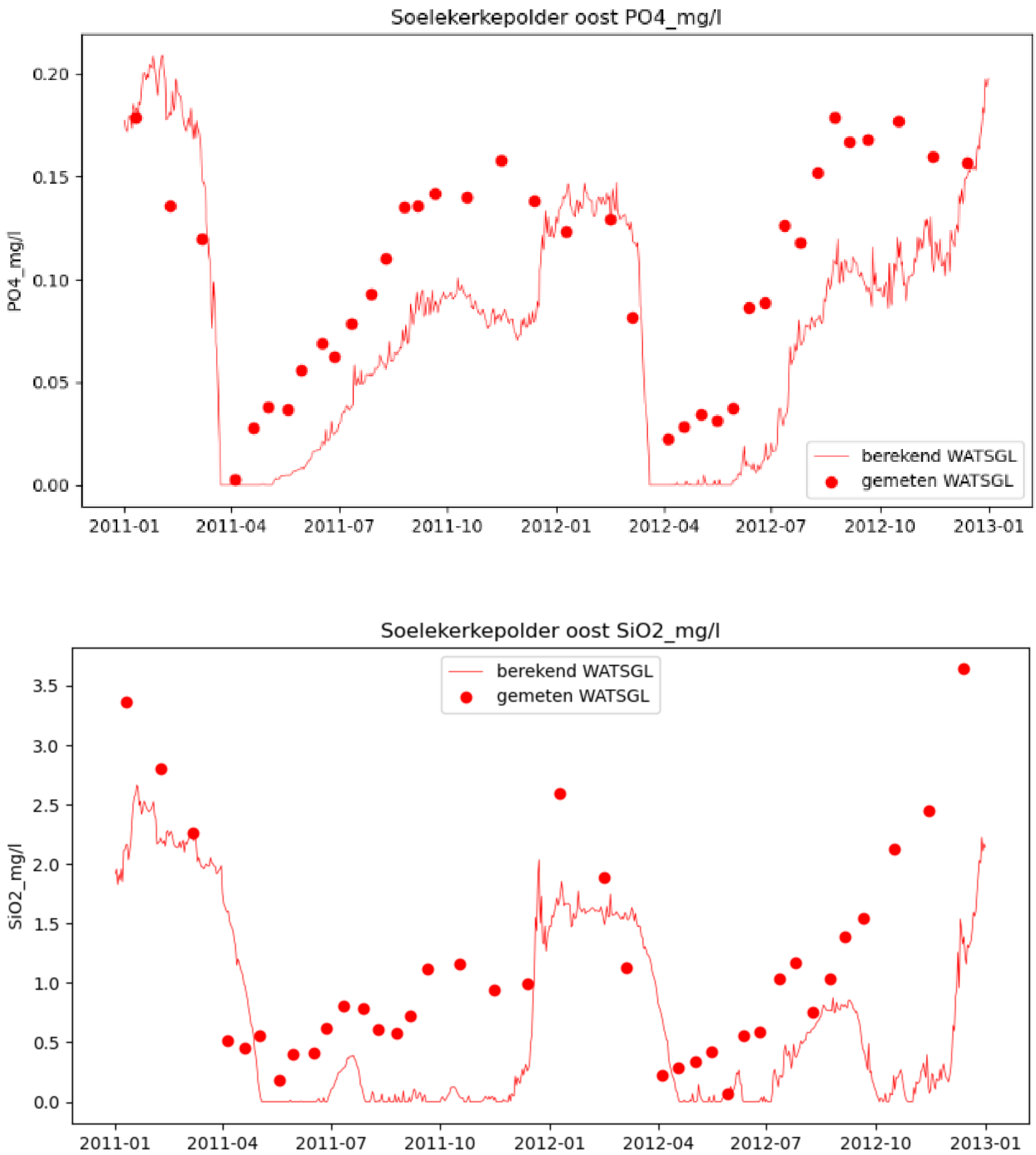


Figure 3.5 Modelled dissolved phosphate (top) and silica (bottom) concentrations near the water surface (WATSGL) compared against observations

3.3.2 Dissolved oxygen

Figure 3.6 shows dissolved oxygen as % of saturation value over the years 2011 and 2012. Modelled dissolved oxygen concentrations at the water surface are almost always at or above saturation. In the winter months this aligns well with observed values consistently near 100% saturation. During the summer months the model predicts generally supersaturated conditions but with more variation likely corresponding to cycles in photosynthesis and respiration of algae. Supersaturated values also appear in the measurements, so these concentrations are realistic, though maybe not sustained over the whole summer period as predicted by the model. Supersaturation of oxygen at the surface and overestimation of chlorophyll-a could be explained by a lack of pelagic grazers in the model, which would consume oxygen while feeding on algae and reduce the concentrations of both near to the water surface.

The gradient over the vertical seen in the observations is produced by the model, as well as the seasonal pattern of low oxygen concentration during the summer months. Near the bed (Figure 3.7) there is a great deal of variability in concentrations during the summer, with average values around 4 mg/l in 2011 and 0 mg/l in 2012. Large negative concentrations are produced by the model, which while physically impossible, can be interpreted as an oxygen deficit caused by high sediment oxygen demand. Such negative concentrations skew the concentration over the whole of the water column downwards, resulting in underprediction of the model at Soelekerkepolder Oost at mid-depth and near the bed.

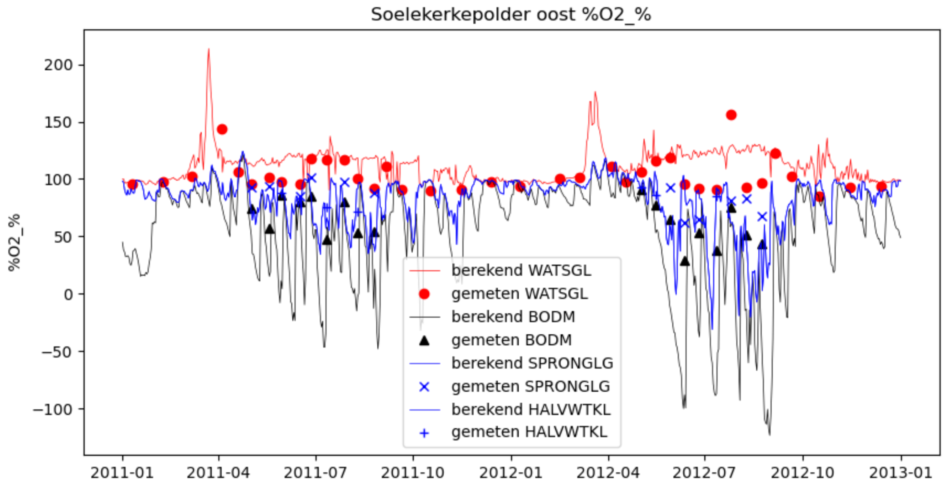


Figure 3.6 Modelled dissolved oxygen as % of saturation near the water surface (WATSGL), near the bed (BODM), and near mid-depth (SPRONGLG & HALVWKTL), compared against observations

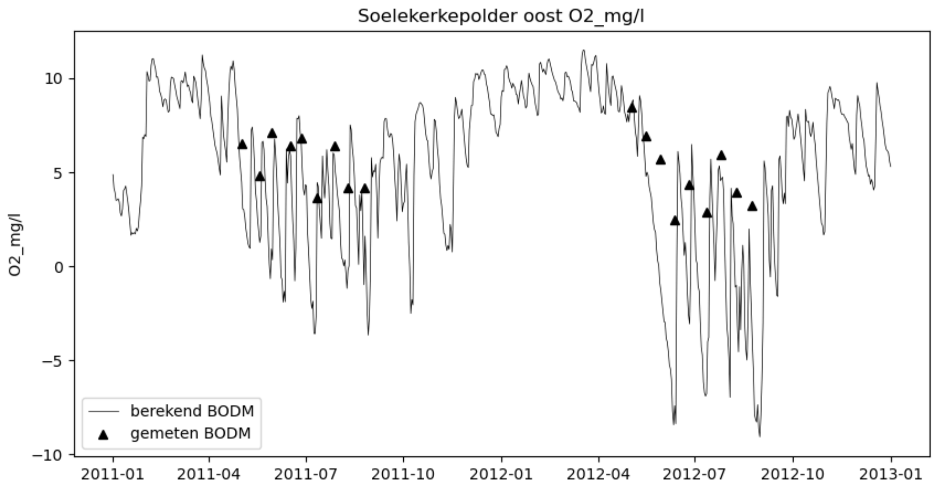


Figure 3.7 Modelled dissolved oxygen concentration near the bed (BODM) compared against observations

When evaluated over a larger spatial domain, the model performs well in reproducing patterns of stratification and mixing in Veerse Meer. Figure 3.8 shows vertical profiles of the dissolved oxygen concentration compared against the TSO measurements taken at multiple depths during a period of observed low oxygen (11 and 12 July 2011). The figures display a clear stratification layer, with higher oxygen concentrations near the surface (>8 mg/l) and low to severely low oxygen concentrations within the gullies at a depth of 8 m and greater (<6 mg/l). Near the bed and within the gullies oxygen can be completely depleted, as also observed from the TSO profiles. Complete oxygen depletion occurs several times during the summers of 2011 and 2012 but generally doesn't last for more than a day or two.

Horizontal gradients are evident within individual gullies and appear to follow the slope of the bed at various moments in time. Though not persistent, these gradients occur many times throughout the summer periods. The TSO measurements are more or less spread evenly across a horizontal distance of 25 km, which results in generally one sampling profile per gully. This method gives a good representation of vertical patterns in dissolved oxygen, but not adequate horizontal resolution to confirm or deny the existence of horizontal gradients within individual gullies as predicted by the model.

The time resolution of the water quality model 3D output (for a full 2-year simulation) is only 1 day, whereas TSO measurements are taken at distinct moments in time. This makes direct comparison difficult, as transport is highly dynamic and leads to varying dissolved concentrations throughout a single day. Therefore, the model is evaluated on its ability to reproduce general trends and not exact concentration values.

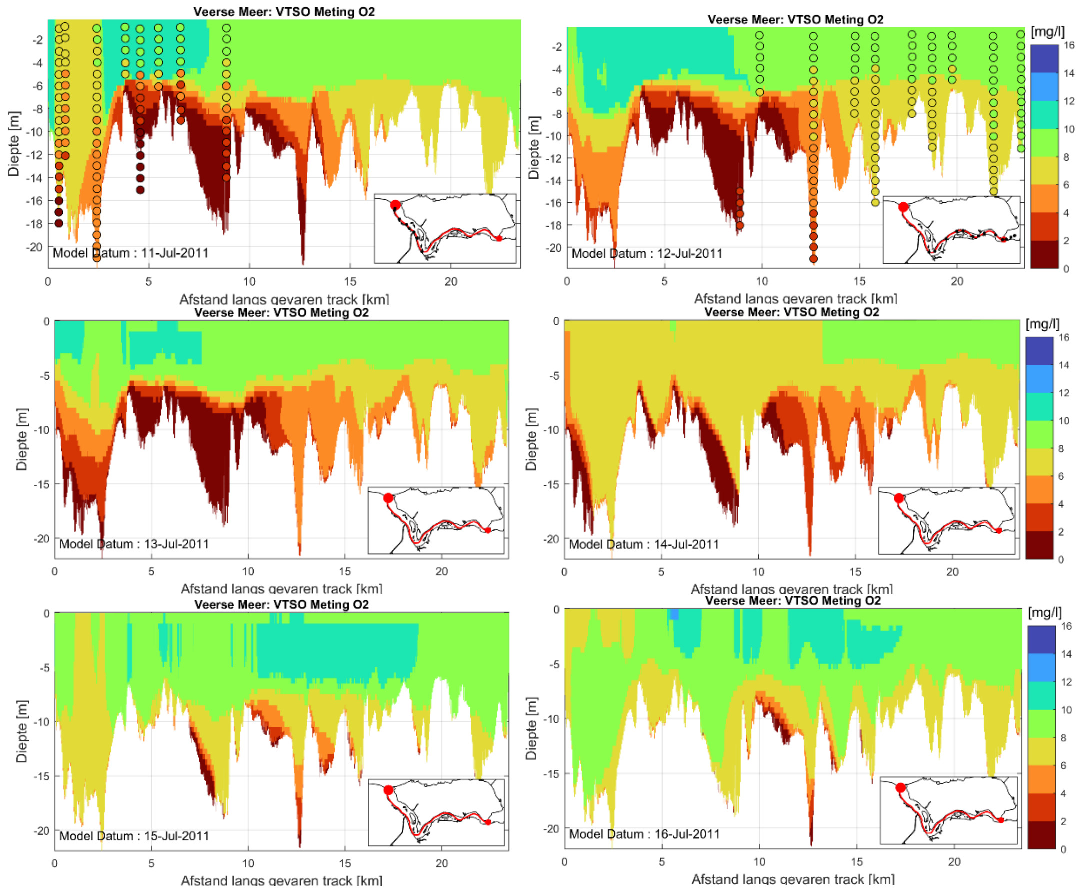


Figure 3.8 Time lapse of cross-sectional profiles of dissolved oxygen concentration along TSO measurement track from west to east (visualised in lower right-hand side) from 11 to 16 July 2011

3.3.3 Transport and mixing

Transport through Veerse Meer is highly dynamic, with mixing dominated by exchange with the Eastern Scheldt through the Katse Heule. Figure 3.9 presents a time lapse of the age of a tracer entering from the Katse Heule boundary (from the east, or right in the figure) over 6 days from 11 to 16 July 2011. From the figures we can see that during the same period as shown in Figure 3.8, water enters Veerse Meer from the Katse Heule through the bottom layer and passes gradually from east to west over each peak and valley in the bedform. When there is little inflow through the Katse Heule,(11-12 July) the age of tracer in the western half of the TSO measurement track exceeds 20 days, indicating high risk of oxygen depletion. When inflow is higher (13-16 July) the age of tracer reduces to between 6 and 10 days. Similar to dissolved oxygen, horizontal gradients in tracer age can be observed within individual gullies. Above the stratification line, water does not penetrate as far as below and with very little mixing. This leads to strong horizontal gradients in age.

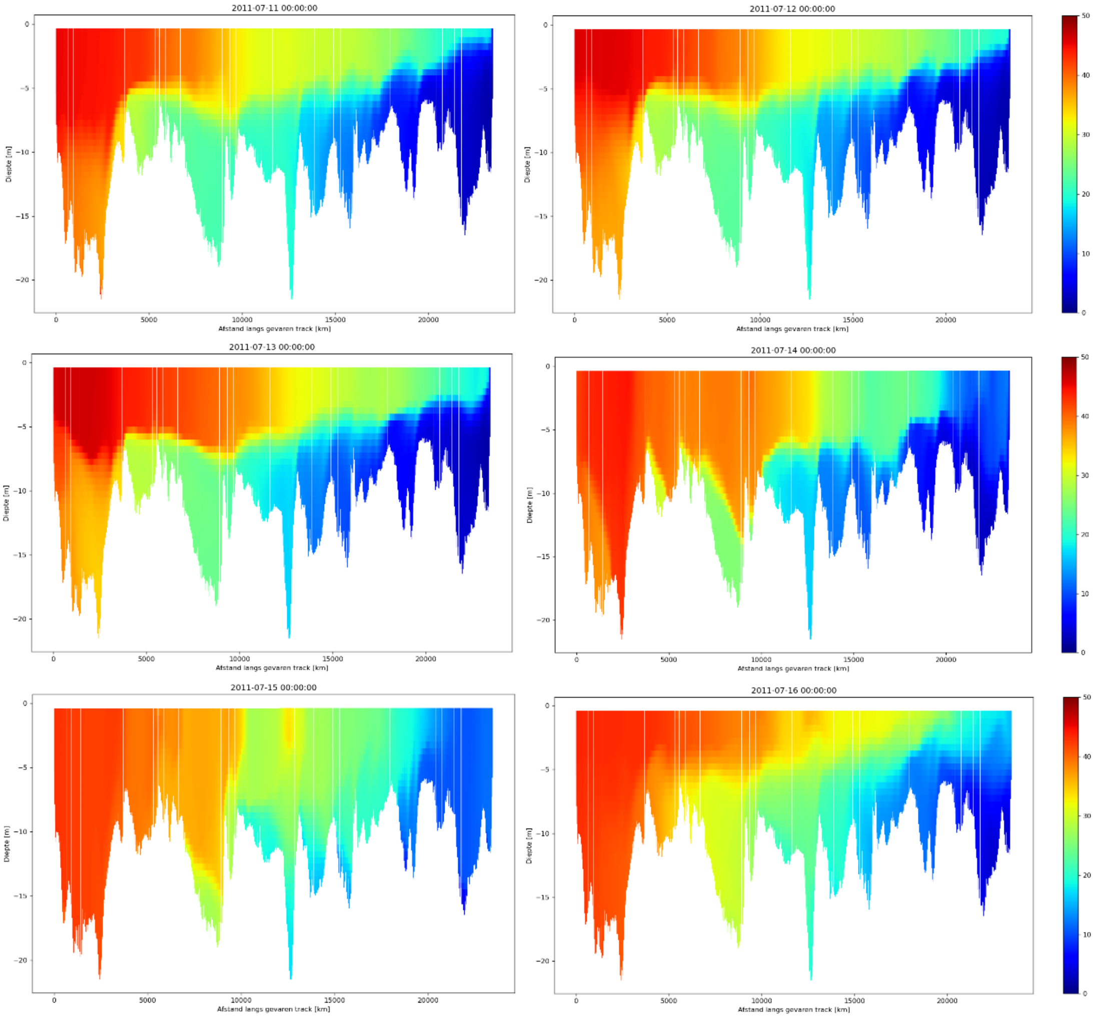


Figure 3.9 Time lapse of the age of tracer entering from Katse Heule boundary (right of figures) in days from 11 to 16 July 2011

3.3.4 Discussion

In evaluating the model we look at the aggregated effects of processes in a wholistic manner with respect to system functioning. In general, the model responds as we would expect based on our knowledge of the system and relevant dynamics. We distinguish between the surface layer and deeper layers, where concentrations are much more sensitive to the parameter settings describing the extent of mixing, settling rates, and interaction with the bed.

The strong seasonal pattern of high winter and low summer nutrient concentrations is well reproduced by the model. The model accurately predicts summer nitrogen limitation preceded by a spring bloom of algae in early spring. Winter concentrations for nutrients are consistent with measured values, so estimation of loads entering the model from the polders and through the Katse Heule boundary is accurate enough for the intended purpose of this model. Summer concentrations of chlorophyll-a are generally overestimated and concentrations of nutrients underestimated. This, combined with oversaturation of oxygen near the water surface, suggest a missing process in the system functioning, possibly a lack of grazing by pelagic organisms.

The calculated magnitude of the bloom peak cannot be verified by the available measurement data and the timing of the bloom does not match exactly with what can be derived from measurements. Therefore, the model should not be used specifically to simulate individual bloom events.

The model was shown to reproduce horizontal and vertical gradients in dissolved oxygen resulting from strong stratification during summers and period of low oxygen or depleted oxygen as observed from measurements. There is still some discrepancy between the model and individual observations both in time and space. This is expected to some extent though, as dissolved oxygen concentrations result from many processes, each of which carry uncertainty in parameterisation. As noted above, further refinement of the nutrient and algae processes are needed for further calibration, and this should be performed first as dissolved oxygen processes result from primary production processes. Still, the model can be used to identify areas and environmental conditions which lead to increased risk of low oxygen and quantify the extent in time and space.

Simulated transport below the pycnocline as shown in Figure 3.8 is highly dynamic in the model, behaving more like a tidal estuary than what would be expected for a closed lake system such as Veerse Meer. Concentration gradients in the tracer simulations match similar patterns in the dissolved oxygen, indicating the dissolved oxygen concentrations in deeper areas are dependent on the extent of mixing with inflow from the Eastern Scheldt. Thus, a lack of mixing of water from the Eastern Scheldt in the western half of Veerse Meer is a leading cause of low oxygen concentrations in the gullies and near the bed. Although TSO profiles are measured every 2 weeks in summer, this is not enough to capture short term processes such as mixing of salt Eastern Scheldt water and resulting oxygen dynamics. It is recommended to perform higher frequency measurements over a period of a few days in the summer. This would help in better defining the frequency, duration and severity of low oxygen events which lead to fish kills and understand under what conditions this is likely to occur and when these conditions might be expected.

While periods of low oxygen occur in the deeper parts of Veerse Meer, the model results show no risk of low oxygen during the simulated years in shallower parts of the lake, which make up the vast majority of the horizontal domain. Observations of dissolved oxygen are limited to a single transect in the lake, so the possibility of low oxygen in other shallow areas cannot be confirmed. Also with a vertical layer thickness of 0.5 m, steep oxygen gradients near that sediment-water interface cannot be captured by the model. Recent insights indicate that such steep gradients could possibly occur and if so, probably under certain conditions (calm, hot weather?) only. Results of ongoing research need to feedback into the model or at least into the model applicability assessment.

The ability of the model to replicate the general spatial and temporal (seasonal) patterns in relevant parameters for primary production, nutrient cycling and oxygen demand means that this model can already be used for the desired purpose of contributing to system understanding of water quality in the Veerse Meer and the relative effect of measures. Further conclusions on model applicability and suitability will be drawn after and based on the model validation in interaction with the system analysis and data and knowledge gap identification.

4 Conclusions and recommendations

During this first phase of model development an initial water quality model was set up to better understand system dynamics and biochemical processes which underly system functioning in the Veerse Meer. The first phase of the model development focused on the set-up of the model geometry, boundaries and loads and an initial calibration of the water quality process parameters. Here we summarise the current status of the model with respect to each of the objectives set forth in the system analysis and project work plan. The status will be updated and extended in more detail following the finalisation of the model validation in the next phase.

1) Describe the horizontal and vertical transport and whether or not salt and/or temperature stratification occurs
This has been achieved to the extent that is currently needed for modelling water quality processes. Seasonal patterns in horizontal and vertical transport, including the "conveyor belt" flushing of the lake by inflow from the Katse Heule and stratification in the summer months are reflected in years 2011 and 2012. We refer to Deltares reference 11206811-002-001 for more detail regarding hydrodynamic transport.

2) Contribute to understanding of the processes that determine the oxygen concentrations (transport and exchange with the atmosphere, primary production and oxygen consumption in soil and water column)
The model has been setup to include the relevant processes related to oxygen concentrations in the water. These include hydrodynamic transport, exchange with the atmosphere, primary production and oxygen consumption in both the water column and sediment using the standard BLOOM phytoplankton primary production model for saltwater systems. Quantifying the magnitude of influence of each of these processes relies on a combination of system knowledge and observations. Therefore, default parameter settings are applied unless strong evidence suggested adjustment is needed. Measurements of (sediment) oxygen demand are not available; therefore, we depend on the TSO vertical oxygen profiles to look instead at the implications of variations in the settling and mineralisation rates in the water column and sediment. The model was used in this way to test the relative influence of processes and thus, provide qualitative information about system functioning in the Veerse Meer.

Analysis of the model results for 2011 and 2012 shows that transport in deeper sections of the Veerse Meer is highly dynamic and oxygen processes in the summer are dominated by mixing with inflow from the Eastern Scheldt via the Katse Heule and "conveyor belt" flow pattern. Inflow from Katse Heule is effective in consistently bringing oxygenated water to the eastern half of the lake but not to the western half where dissolved oxygen concentrations decrease quickly during periods of low inflow which can last up to several days. Within the deep sections dissolved oxygen concentrations are highly dependent on the distribution of inflowing water from Katse Heule over the bed which results in a concentration gradient parallel to the bed. Without higher resolution observations it is not possible to confirm nor deny this behaviour, therefore we recommend some additional TSO measurements at multiple locations within one or two of the larger longitudinal depressions.

The model was shown to respond as expected in simulating spatial and temporal changes in oxygen concentration based physical and biochemical processes. In the second phase of model development more effort will be put into further quantifying these processes, if possible, using newly available continuous oxygen monitoring.

3) Describe the effect of temperature on oxygen dynamics, including increased oxygen consumption in the soil and water column at higher water temperatures
Temperature increases mineralisation rates in the water and sediment and thus has a definite effect. Increased surface water temperature can also increase the strength of stratification. Both effects are included in the model using the standard parameterisation. Without measurement of the (sediment) oxygen demand (i.e. mineralisation rates) it is impossible to quantify this effect directly. Using the model to approximate these quantities based on known process relationships contributes to the system analysis. The model adequately describes these processes and can therefore be used to investigate the impacts of temperature on dissolved oxygen concentrations. This will be further investigated in the second phase of the project.

4) Describe the nutrient balance, which concerns not only the load with inorganic nutrients but also the load with organic material
Modelled mass balances and simulated winter concentrations of inorganic nutrients and chlorophyll-a (as a proxy for phytoplankton biomass) are consistent with the water and nutrient balance calculations and measured concentrations, indicating that the total water and nutrient balance of the model is correctly described. Details of the water and nutrient balance are included in a separate report, Deltares reference 11206834-002-ZKS-002.

5) Describe the phytoplankton production and derive realistic values for sedimentation of organic material including (dead) phytoplankton.
The algae growth (and mortality) model and sedimentation processes were applied using the default settings for Dutch salt-water systems (i.e. North Sea, Grevelingen) and responds in line with our current understanding and observation data. The model accurately predicts winter concentrations of nutrients, chlorophyll-a, and dissolved oxygen and the appearance of a spring bloom in late March-early April in both 2011 and 2012, though the exact timing and magnitude of the bloom is not possible to validate with measurements.

Summer concentrations of chlorophyll-a are generally overestimated and nutrient concentrations underestimated, which may suggest that grazing of algae by benthic organisms and/or zooplankton plays an important role in Veerse Meer. The model was insufficiently capable of reproducing the consistently low summer concentrations of chlorophyll-a observed from measurements with nutrient limitation alone. Low concentrations were only achieved by the model when increased settling rates of algae were applied as a representation of removal by benthic grazing, suggesting there must be removal of algae by other process(es) or an even higher grazing pressure. Further, overprediction of chlorophyll-a and supersaturation of dissolved oxygen near the water surface strengthen the idea that grazing by pelagic organisms is relevant higher in the water column, though not yet included in the model. This will be taken up in the future work for validation of the model with respect to if and how this process can be quantified and any implications for interpreting the model results.

Summarizing assessment
After initial calibration, the model was shown to accurately reflect the general system dynamics of the Veerse Meer. It can be used for qualitative assessments of concentrations including the effect of potential measures, i.e. to predict the direction and order of magnitude of change. A model validation should be carried out, before a judgement on the application for quantitative assessments, i.e. prediction of concentrations and effect of potential measures can be given. The decision was made not to calibrate further on the years 2011 and 2012 to avoid potential curve-fitting which could result in a less representative model parameterisation for other simulation years. Validation of the model on more recent years will continue based on objective assessment criteria, to be executed in the first quarter of 2022, in parallel with and contributing to a system analysis including analysis of the additional monitoring data collected in 2021.

5 Further steps (Phase 2)

This report concludes the first phase of model building for system understanding in the Veerse Meer. A follow-up project (Phase 2) is already underway to update the model forcing files for a full 10 years (2010 – 2020) and to simulate recent years during which water quality issues (i.e. fish kills) were observed. The exact simulation years are still to be defined. During this work we will continue the model calibration and validation using insights gained during the initial model set up and address some of the issues identified in this report, including:

- Assessment of time step settings, i.e. the sensitivity for short time steps for transport (maximum 30 seconds) and longer time steps for water quality processes (per hour, except for per day for primary production by BLOOM).
- Further calibration of processes related to primary production;
- A deeper look into the role of grazing by macrozoobenthos and the implications for uptake of oxygen near the bed, whether this can be quantified by data and/or expert judgement;
- Investigating the model sensitivity to grazing by organisms in the water, and whether this leads to better estimation of algae and dissolved oxygen concentrations by the model near the water surface;
- Quantitative assessment of model performance based on criteria to be developed;
- Development of a method for objective comparison for dissolved oxygen concentrations that account for the high variability shown in the model results, for example by looking at model data within a 10-day bracket and over full spring/neap tide period;
- Development of metrics for quantifying risks with respect to low oxygen, for example not just by concentrations but also in terms of frequency and duration.

This work will run through the first quarter of 2022, the results of which will be combined with this Phase 1 report.

6 References

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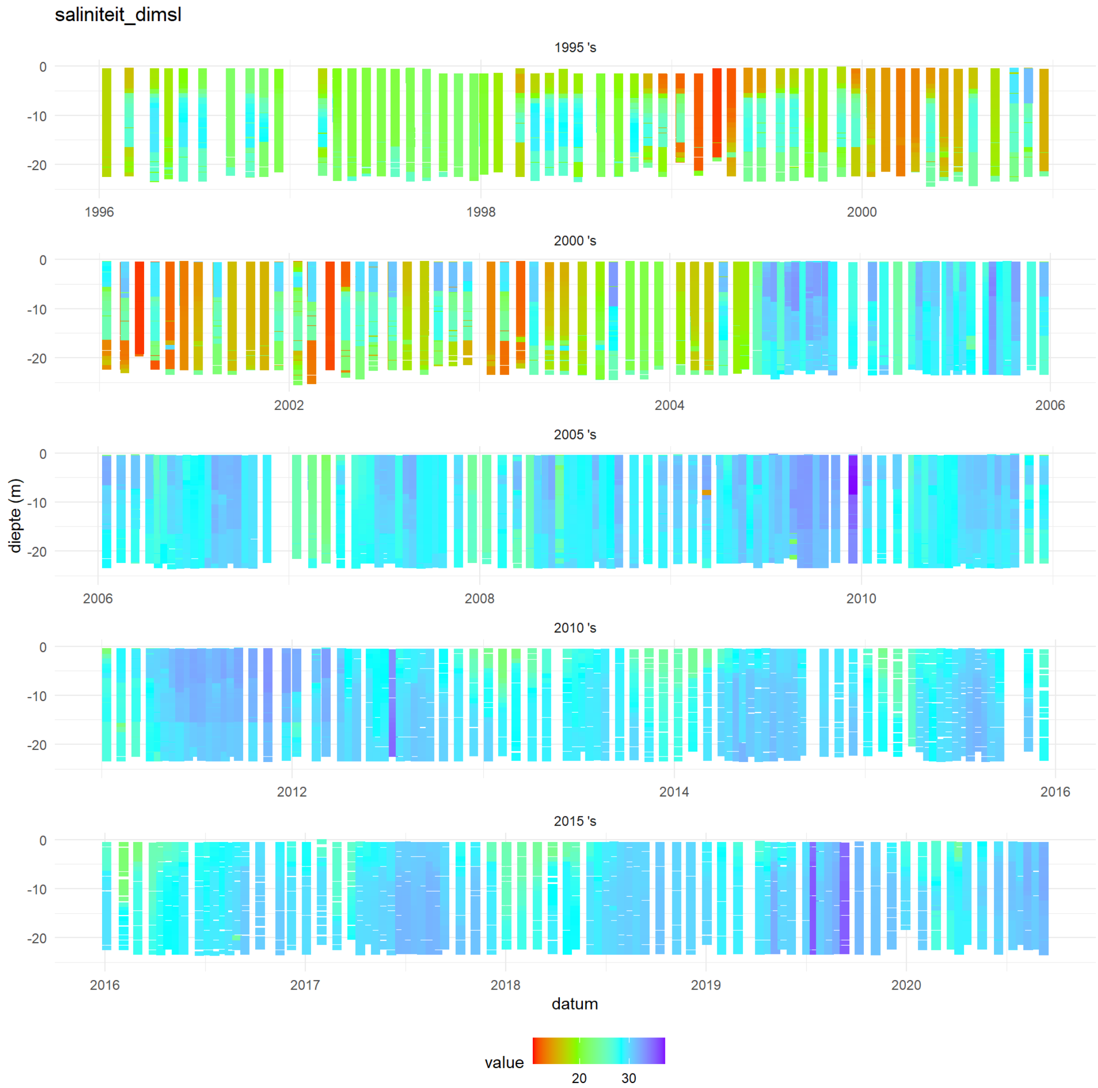
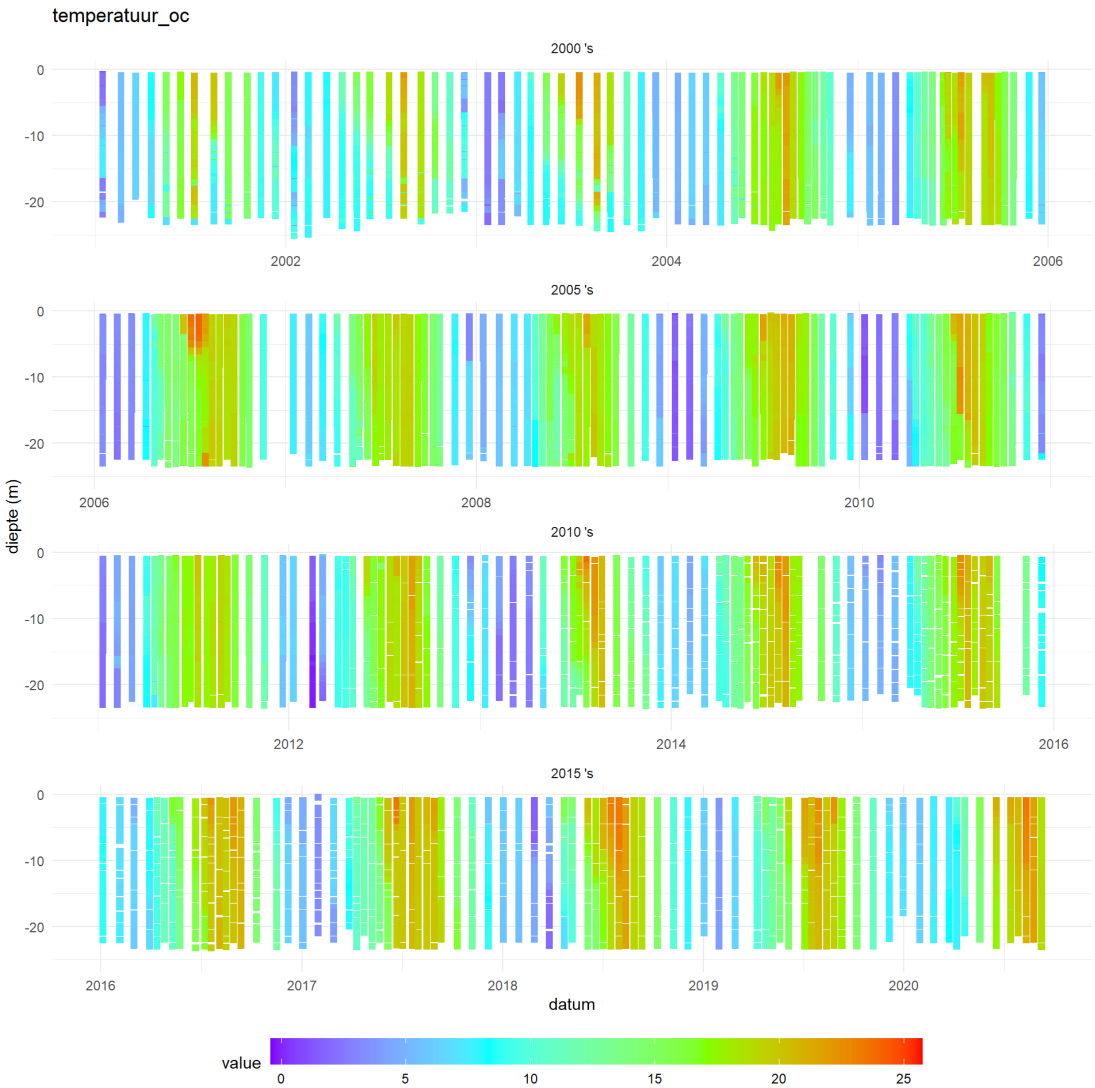
A Depth profiles of observed salinity, temperature, and dissolved oxygen

These figures are taken from the preliminary Digital Systeemrapportage Veerse Meer (http://testsysteemrapportage.nl/veersemeer/waterkwaliteit-en-bodemkwaliteit.html). These figures may be adapted in the future.





temperatuur_oc
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-20
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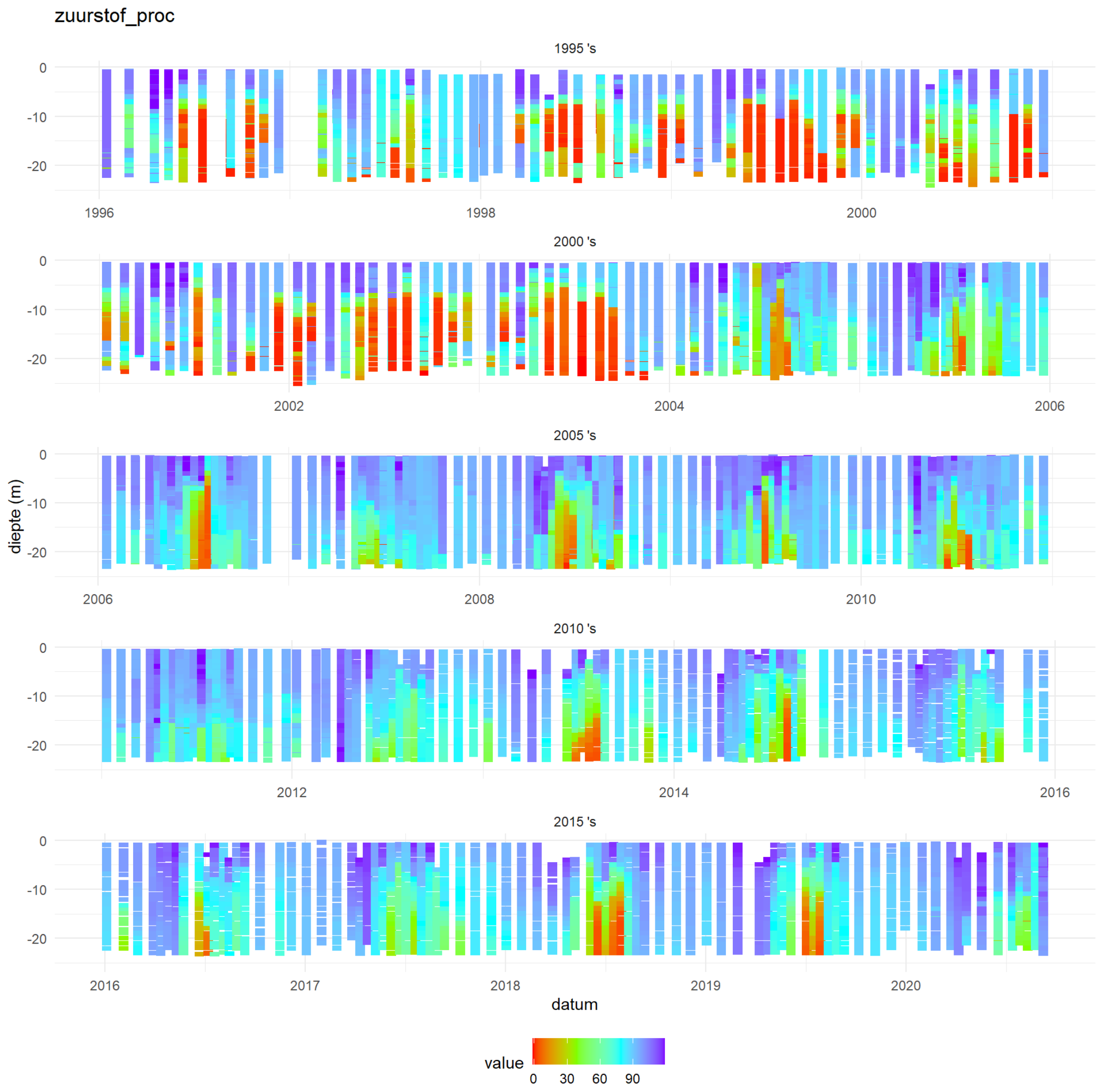

zuurstof_proc
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diepte (m)
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90

B Discussion on calibration and model sensitivity

B.1 Procedure

This section describes the methodology for calibration of the model, including how and why decisions were made to adjust model parameters throughout the process. It is not intended to be a full documentation of all results but instead to highlight specific results which underly the reasoning for subsequent steps. This section also serves as a record for future work with the model to explain what analysis steps have already been undertaken to understand the model behaviour and sensitivity to various parameters.

The calibration procedure generally went as follows:

1. Use the North Sea parameter settings to run years 2011 and 2012 for Veerse Meer and examine results at Soelekerkepolder Oost
2. Assess whether seasonal patterns in primary production and nutrient concentrations seen in measurements are reproduced by the model
3. Assess whether magnitude of primary production and nutrient concentrations seen in measurements are reproduced by the model
4. Assess whether spatial and temporal patterns in dissolved oxygen concentrations seen in TSO depth profiles and Soelekerkepolder Oost are reproduced by the model
5. Assess whether the magnitude of dissolved oxygen concentrations seen in TSO depth profiles and at Soelekerkepolder Oost are reproduced by the model

B.2 Simulation based on North Sea model parameters

The starting point for the water quality modelling in this study is the current (Zijl, 2021) North Sea model developed by Deltares. All model parameters describing biochemical processes were taken from this model. This, together with boundary conditions data resulting from the water balance and nutrient balance were used to run a first simulation from which to calibrate.

Figure B.1 and Figure B.2 show simulated concentrations of chlorophyll-a and nutrients against measurements near the water surface. Simulated chlorophyll-a concentrations were generally too high compared to measurements, both in summer and winter months. The simulated results show a spring bloom pattern not well represented in the measured concentrations. There is evidence that a spring bloom does occur in both years, however, when observing measured nutrient concentrations. The sudden reduction in concentration observed for all nutrients can only be explained by the presence of a spring bloom where the growth of algae explodes until nutrient limitation sets in around May of each year.

This seasonal pattern in nutrient concentrations for NO3, NH4 and PO4 were reproduced by the model, though the magnitude and timing still require refinement. The simulated growth of algae tends to peak too early in the spring, resulting in depletion of NO3 and NH4 4-5 weeks before this is shown in the measurements. Overall winter concentrations were too low, which could be an effect of there simply being too much primary production. For this reason we decided to first look at factors leading to high primary production in the winter months before adjusting any nutrient cycling parameters.

Dissolved silica concentrations produced by the model were far too low when compared to measurements. This is because dissolved silica was not included from the polders since it is not a measured quantity. In further simulations a constant silica concentration of 10 mg/l was added to all polder discharges (see section 3.1.4.2).

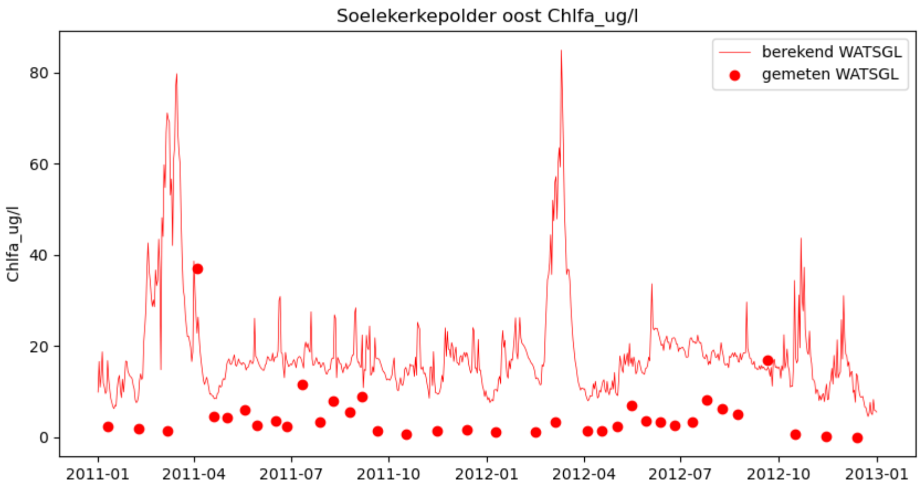

Figure B.1 Chlorophyll-a concentration at the water surface at station Soelekerkpolder Oost

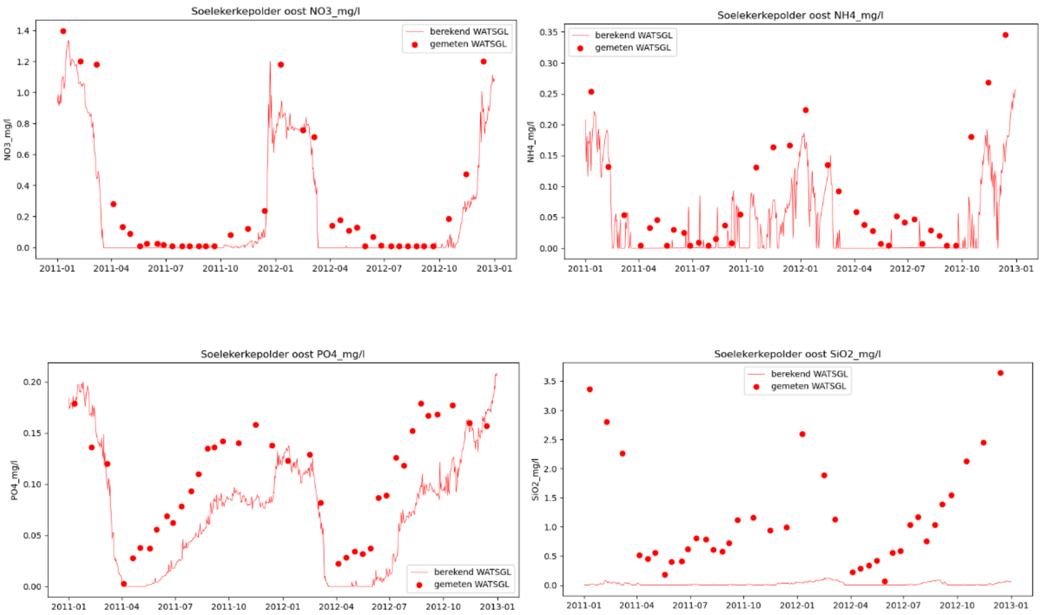

Figure B.2 (from upper left, clockwise) Concentration of NO3, NH4, Si, and PO4 at the water surface at station Soelekerkepolder Oost

B.3 Effect of light extinction parameters

As a result of the data analysis described in section 2.7 a further regression analysis was performed in an attempt align with the correlations derived from measurements of light extinction. Since chlorophyll-a is a derived parameter and captured already in POC it was excluded. DOC was also excluded as it is not a state variable in the model and SS was excluded as it was shown to have poor correlation with light extinction.

A multi-parameter linear regression was calculated for POC and salinity, the result of which is shown in Table B-1.

Table B-1 Results of a multi-parameter linear regression of observed POC and salinity (SAL) against observed light extinction for the years 2001 through October 2020

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.8356	0.1305	6.4008	2E-09	0.5775	1.0936	0.5775	1.0936
POC [mg/l]	0.3165	0.0185	17.11	2E-36	0.28	0.3531	0.28	0.3531
SAL [ppt]	-0.009	0.0047	-1.826	0.0699	-0.018	0.0007	-0.018	0.0007

From the data analysis we conclude that the influence of POC on light extinction is higher in the Veerse Meer than the default settings present in the model. Similarly, salinity was shown to have a lesser effect than current settings. The light extinction equation is non-linear, such that the specific extinction coefficients required by the model must be back-calculated from the relationships derived above. Doing this results in a specific extinction coefficient of 0.5 for salinity and 0.21 for POC.

Two scenarios were calculated. For both, the specific extinction coefficient for salinity (ExtVlSal0) was decreased from 0.97 to 0.5 m^{-1}. The first scenario used a specific extinction coefficient for POC (ExtVlPOC1) was increased from 0.1 to 0.2 m^{-1}. In the second scenario the rate was increased to 0.3 m^{-1}.

Adjusting the specific extinction coefficients in both cases resulted in reducing the magnitude of the spring bloom peaks in chlorophyll-a concentrations. Average chlorophyll-a concentration however remained high around 20 ug/l. Comparing the two scenarios hardly any difference can be observed (see Figure B.3). Therefore, we conclude that while adjustment of the extinction parameters does have some positive effects in reducing peak chlorophyll-a concentrations during spring bloom events, the magnitude of the coefficients has little to no effect. This is supported by further evidence that the system is hardly ever light limited, even during winter months. We expect then that further refinement of the extinction parameters will have no added benefit, therefore the settings for the first scenario (ExtVlSal0 = 0.5 m^{-1} and ExtVlPOC1 = 0.2 m^{-1}) were used for further calibration.

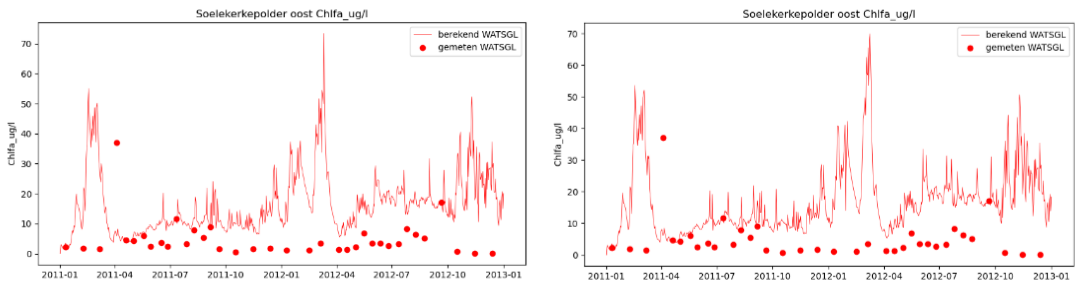

Figure B.3 Chlorophyll-a concentration resulting from ExtVlPOC1 = 0.2 m-1 (left) and 0.3 m-1 (right)

B.4 Effect of mineralization rates

The other limiting factor on algae growth besides light extinction is the availability of dissolved nutrients. We hypothesized that one possible reason for high algae concentrations could be to an overabundance of freely available nutrients produced from mineralization of detritus. To test this hypothesis, mineralization rates for NO3, NH4, and PO4 were reduced by 25%.
The reduction in mineralization rates had no significant effect of chlorophyll-a or nutrient concentrations (see Figure B.4). Since the model did not show sensitivity to these parameters the original values were maintained for further calibration.

Table B-1 Modified mineralization rates to test model sensitivity

Parameter	Original value	Modified value
Upper limit mineralization rate for detritus-C (ku_dFdcC20)	0.18	0.135
Lower limit mineralization rate for detritus-C (kl_dFdcC20)	0.12	0.09
Upper limit mineralization rate for detritus-N (ku_dFdcN20)	0.18	0.135
Lower limit mineralization rate for detritus-N (kl_dFdcN20)	0.12	0.09
Upper limit mineralization rate for detritus-P (ku_dFdcP20)	0.18	0.135
Lower limit mineralization rate for detritus-P (kl_dFdcP20)	0.08	0.06

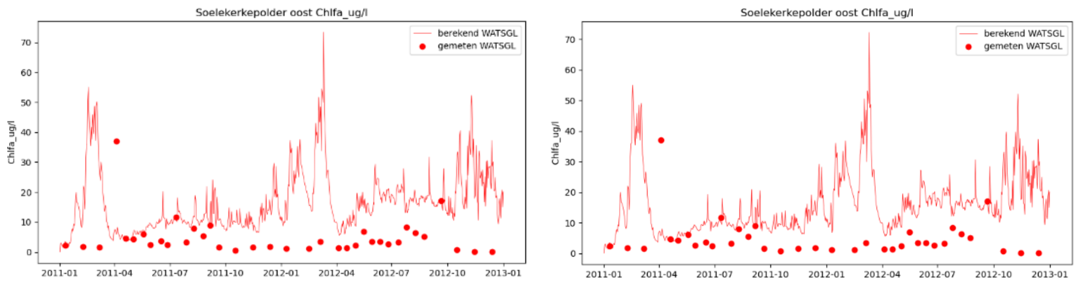

Figure B.4 Chlorophyll-a concentration with North Sea settings (left) and with mineralization rates decreased by 25% (right)

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