Development of Mechanistic Models

Mechanistic Model for Odense Fjord

Technical documentation on biogeochemical model

Miljø- og Fødevareministeriet
Miljøstyrelsen

Technical Note
August 2020

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Eelgrass in Kertinge Nor
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Project number	11822245
Approval date	3. August 2020
Classification	Open

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1 Executive Summary

The model development presented in this technical note represents the biogeochemical model development for Odense Fjord. The Odense Fjord model is part of a larger model complex comprising several mechanistic models developed by DHI and a number of statistical models developed by Aarhus University (AU), Bioscience.

The model complex is developed with the overall aim to support the Water Framework Directive (WFD) by introducing mechanistic models in as many Danish water bodies as possible and to integrate with Bayesian statistical modelling, and cross-system modelling carried out by AU, Bioscience.

Here we present the overall biogeochemical model set-up covering Odense Fjord, together with a quality assessment of the model performance. This specific model includes two Danish water bodies:

Water Body*)	ID Number
Odense Fjord, ydre	92
Odense Fjord, Seden Strand	93

*) Water bodies defined for the River Basin Management Plans 2015-2021

The Odense Fjord biogeochemical model builds on the developed hydrodynamic model of Odense Fjord and is developed to describe the biogeochemistry within the model domain with a focus on parameters relevant for WFD, including dynamics in nutrients, phytoplankton, primary production, dissolved oxygen, organic matter and benthic vegetation.

The model quality is evaluated from three model performance measures: Percent Bias (P-Bias), Spearman Rank Correlation and Cost Function (CF). According to DHI (2019b), Model Efficiency Factor (MEF) was suggested initially, but during the model development, it was concluded that MEF is not suitable to evaluate this kind of estuarine biogeochemical models, why Cost Function (CF) is introduced. The quality measure CF was used in Erichsen and Timmermann (2017) as part of an international evaluation (Hermann et al. 2017). As described in DHI (2019b), the MEF evaluates the Root Mean Square Error (RMSE) to the standard deviation (based on measurements). As model results are compared against measurements at the exact point in time in dynamic estuarine systems with strong gradients, the MEF has proven not to be suited (due to its dependency on entirely right timing). The CF assesses the fit/misfit between measurements and observations also normalized to the standard deviation (based on measurements) why it is decided to use this measure in the overall assessment of the model performance.

Concerning the performance measures, the ambition is to have 75% of all measures (Percent Bias, Spearman Rank Correlation and Cost Function to meet ‘excellent’, ‘very good’, or ‘good’ for all parameters and stations (lumped).

As can be seen from the present technical note, 92% of all annual data sets meet the success criteria when evaluated against the three performance measures, and 88% when assessing both annual performance and only summer/winter performance of all data. The average model performance, evaluated at four stations within the model domain, for the biogeochemical model of Odense Fjord is summarized in chapter 5 and briefly below:

- Model performance measures for dissolved oxygen (DO) are on average 6.9% (P-Bias), 0.9 (Spearman Rank Correlation), and 0.4 (CF). The average model performance for DO is categorized to be ‘excellent’ (P-Bias and Spearman Rank Correlation) and ‘very good’ (CF).

- Model performance measures for chlorophyll-a (CH) are on average 48.5% (P-Bias), 0.2 (Spearman Rank Correlation) and 1.1 (CF). The average model performance for CH is categorized to be 'good' (CF) and 'poor' (P-Bias and Spearman Rank Correlation).
- Model performance measures for light attenuation coefficient (K_d) are on average 21.4% (P-Bias), 0.1 (Spearman Rank Correlation) and 1.0 (CF). The average model performance for K_d is categorized to be 'very good' (CF), 'good' (P-Bias) and 'poor' (Spearman Rank Correlation).
- Model performance measures for dissolved inorganic nitrogen (DIN) are on average 12.6% (P-Bias), 0.9 (Spearman Rank Correlation) and 0.3 (CF). The average model performance for DIN is categorized to be 'excellent' (CF) and 'very good' (P-Bias and Spearman Rank Correlation).
- Model performance measures for dissolved inorganic phosphorus (DIP) are on average 35.2% (P-Bias), 0.6 (Spearman Rank Correlation) and 0.9 (CF). The average model performance for DIP is categorized to be 'very good' (Spearman Rank Correlation and CF) and 'good' (P-Bias).
- Model performance measures for total nitrogen (TN) are on average 19.1% (P-Bias), 0.8 (Spearman Rank Correlation) and 0.4 (CF). The average model performance is categorized to be 'very good' (P-Bias, Spearman Rank Correlation and CF).
- Model performance measures for total phosphorous (TP) are on average 12.7% (P-Bias), 0.5 (Spearman Rank Correlation) and 0.8 (CF). The average model performance is categorized to be 'very good' (P-Bias and CF) and 'good' (Spearman Rank Correlation).

The details behind the above performances are available in Table 5-1 to Table 5-3. Time-series comparisons are available here: rbmp2021-2027.dhigroup.com (Google Chrome only).

The ambition to meet 'excellent, very good', or 'good' for 75% for all parameters and stations (lumped) has been well reached. Hence, in this technical note, we conclude that the Odense Fjord biogeochemical model has been developed successfully for the Odense Fjord waterbodies and will be applied for modelling nutrient scenarios in these waterbodies in the assessment of maximum allowable inputs (MAI).

2 Introduction

The model development presented in this technical note represents the biogeochemical model development for Odense Fjord and builds on top of the Odense Fjord hydrodynamic model (DHI 2019d). Documentation for the model application will be presented in the following reports. The biogeochemical model is part of the mechanistic model complex development, which includes two regional models, three local-domain models, and six estuary specific models. The model complex is developed with the overall aim to support the Water Framework Directive (WFD) by introducing mechanistic models in as many Danish water bodies as possible and integrating with Bayesian statistical modelling, and cross-system modelling carried out by AU, Bioscience.

Here we present the overall biogeochemical model set-up covering Odense Fjord, together with a quality assessment of the model performance. The Odense Fjord model includes two Danish water bodies listed in Table 2-1 below. The location of the Danish water bodies is documented in Erichsen *et al.* (2019).

Table 2-1 Water bodies included in the Odense Fjord model.

Water Body*)	ID Number
Odense Fjord, ydre	92
Odense Fjord, Seden Strand	93

*) Water bodies defined for the River Basin Management Plans 2015-2021

The biogeochemical model computes the development during the modelling period in ecological parameters, including concentrations of nutrients, dissolved oxygen, and organic matter and the Secchi depth, due to, e.g. primary production. The results represent short term changes due to specific weather events, seasonal variations and interannual trends. This project will focus on summer chlorophyll-a and parameters influencing distribution and growth of eelgrass. A detailed description of the specific state variables included in the Odense Fjord biogeochemical model can be found in DHI (2019c).

According to DHI (2019b), the quality measure Model Efficiency Factor (MEF) was suggested as a quality measure initially, but during the biogeochemical model development, it was concluded that MEF is not suitable to evaluate this kind of estuarine biogeochemical models. As described in DHI (2019b), the MEF evaluates the RMSE to the standard deviation (based on measurements). As we compare model results to the measurements at the exact point in time in a number of estuary system with strong gradients and variable dynamics, the MEF has proven not to be suited (due to its dependency on entirely right timing). For the validation of the biogeochemical models, we have included the quality measure Cost Function (CF) in replacement of MEF (Table 5-3). The CF measure was also used in Erichsen & Timmermann (2017) and describes how the difference between measured and modelled values is related to the inherent variation in field observations.

3 Modelling Concept

3.1 Mechanistic Modelling

The present technical note represents the biogeochemical part of the model complex covering Odense Fjord. The Odense Fjord model is one model out of eleven mechanistic models developed to increase the knowledge of pressures and status in Danish marine waters and to provide tools for the Danish EPA as part of the implementation of the WFD. Mechanistic models enable dynamic descriptions of ecosystems and interactions between natural forcing and anthropogenic pressures. Hence, mechanistic models can be applied for predictions of changes in specific components, like chlorophyll-a concentrations, due to changes in, e.g. anthropogenic pressures.

The Odense Fjord model is defined as an estuary specific model. The mechanistic model complex development as part of the present projects includes two regional models, three local-domain models, and six estuary specific models:

- The regional models cover both specific Danish water bodies and regional waters, such as the North Sea and a small part of the North Atlantic, which is included in the North Sea-model, and the Baltic Sea, which is covered by the IDW-model (Inner Danish Waters). These models provide model results for specific water bodies but, equally important, give boundaries to local-domain models and estuary specific models.
- Local-domain models are developed to allow for resolving most small and medium-sized water bodies in the north-western Belt Sea, the south-western Belt Sea and the water bodies in and around Smålandsfarvandet.
- Estuary specific models: Six specific estuary (fjord) models are developed to allow for detailed modelling of specific estuaries.

The ecological conditions in marine waters are determined by several different natural factors like water exchange, stratification, water temperature, nutrient availability, sediment characteristics, the structure of the food web etc. On top of that, several anthropogenic factors like nutrient loadings, fishery, etc., also impact the ecosystem and potentially the ecological status.

The model developed in this specific project aims at supporting the Danish EPA's implementation of the WFD. During this project, the models are developed to represent the period (2002-2016) evaluated against NOVANA measurements. Here we use current data on solar radiation, current nutrient loadings, etc.

After the models are developed, they will be applied for scenario modelling with changed nutrient loading to assess the Maximum Allowable nutrient Inputs (MAIs).

3.2 Model Development

The model development consists of a 3D hydrodynamic model describing the physical system (water levels, current, salinity and water temperatures), and a 3D biogeochemical (ecosystem) model describing the governing biogeochemical pelagic and benthic parameters and processes like phytoplankton, dissolved oxygen, primary production, etc. The model structure is modular, meaning that a hydrodynamic model is developed independently of the biogeochemical model (for further information about the hydrodynamic model see DHI (2019a)). A more detailed description of the biogeochemical model is available in DHI (2019c), and the underlying Odense Fjord hydrodynamic model is described in DHI (2019d).

All mechanistic models have been set up and calibrated/validated for the period 2002-2016 and reported according to the performance measures P-Bias, Spearman rank Correlation and CF (DHI 2019b). Results from the entire modelling period are furthermore presented as time series in a WEB-tool (rbmp2021-2027.dhigroup.com, Google Chrome only) with a few examples included in section 5.3. Most data used for calibration and validation originate from the national monitoring programme NOVANA (see http://odaforalle.au.dk for more details). For some models and some parameters, other data are included, and the specific origin of those data will be referenced when used.

3.3 Modelling System

The biogeochemical model is based on the 3D modelling software MIKE 3 HD FM (version 2017) developed by DHI together with the numerical 3D equation solver MIKE ECO Lab to describe the relevant biogeochemical processes in the modelling system. The MIKE 3 FM modelling system is based on a flexible mesh approach with horizontal mesh elements of varying sizes within the modelling domain. The water column is resolved by multiple layers. The modelling system has been developed for applications within oceanographic, coastal, and estuarine environments.

The scientific documentation of MIKE 3 HD FM is given in DHI (2019a).

The main components and processes determining the status of the water quality and the response in the ecosystem (e.g. changes in eelgrass biomass) are included in the biogeochemical model. They are based on external factors (meteorology and nutrient supply). The model describes the turnover of organic material and nutrients, both in the pelagic (water column) and the benthic phase (seabed or sediment). The pelagic phase includes phytoplankton and nutrients, and the benthic department covers sediment pools of nutrients and the exchange of nutrients between the sediment and water phase. Furthermore, the benthic part of the model describes the biomass and growth of benthic vegetation at the sea bed. The mechanisms behind the biogeochemical model and the ECO Lab templates used are described in DHI (2019c).

4 Model Set-up

The biogeochemical model for Odense Fjord builds on top of the hydrodynamic model (HD) and an integrated transport model (AD). The set-up and calibration/validation of the physical Odense Fjord model (HD and AD) are documented in DHI (2019d).

For the present project, the model is set up for the period 2002-2016, which means that all model input data need to cover this period.

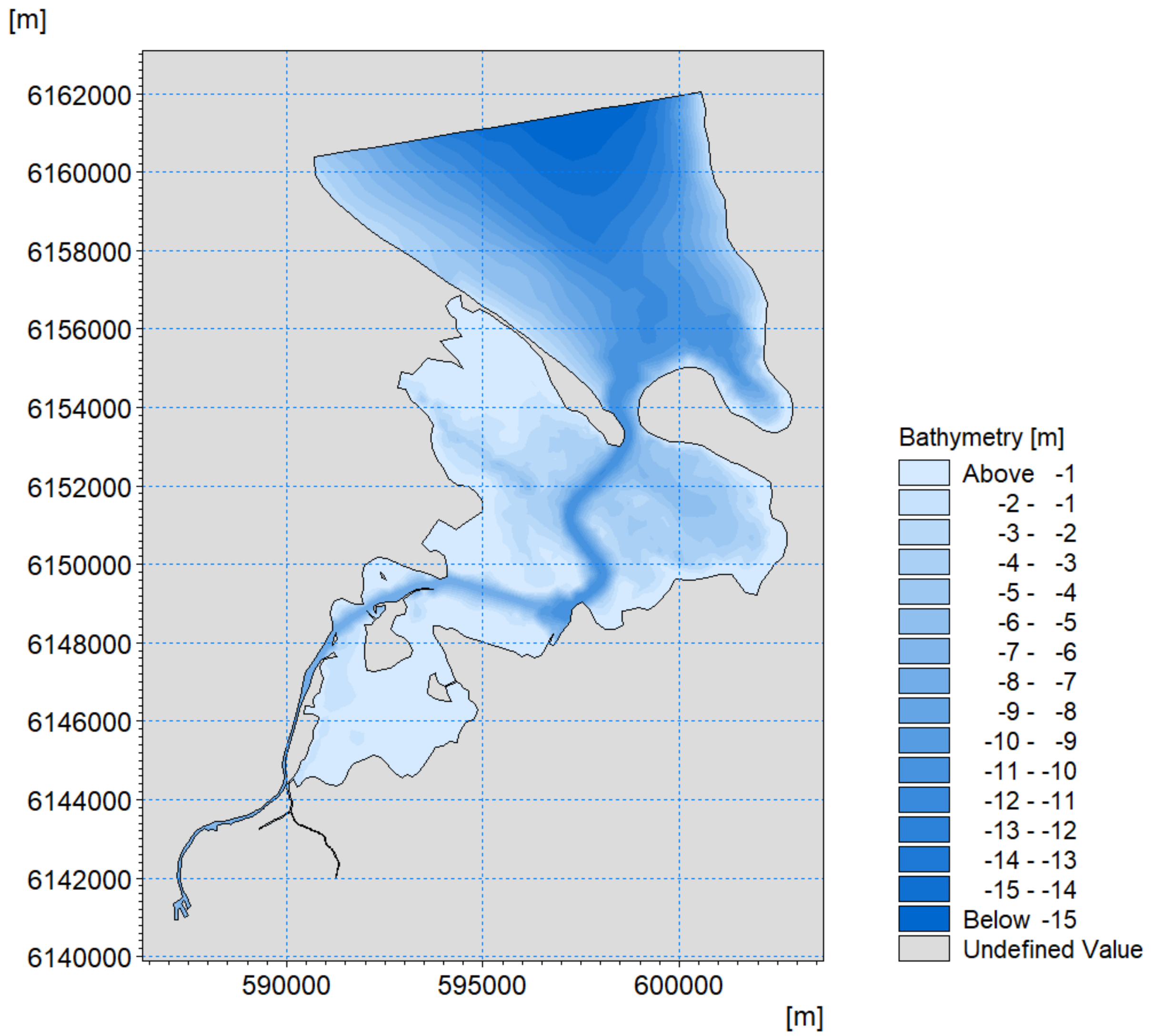

Figure 4-1 Model bathymetry of the Odense Fjord model. Water depths refer to MSL. The model has one open boundary towards the Danish straits.

4.1 Model Domain

The model domain is determined in accordance with the area of interest of the modelling study. Also, considerations of the area of influence, being the surrounding areas that affect the area of interest, and suitable open boundary locations, affect the choice of the model domain.

The model mesh is the representation of the model domain. More specifically the model mesh defines the model area, the location of the open boundaries, the land-water boundaries, the horizontal and vertical model resolution (discretization), and the water depths (bathymetry) of the area. The bathymetry of the Odense Fjord model is shown in Figure 4-1, whereas Figure 4-2 shows the resolution of the horizontal mesh. Vertically, the water column is resolved by three sigma layers (same local thickness) from the surface to -3m below mean sea level (or local depth if less than 3m), and the water column below is resolved by up to 18 z-layers (depending on the local water depth), with a layer thickness of 1m. Further documentation on the model mesh and horizontal and vertical resolution of the Odense Fjord HD model can be found in DHI (2019d).

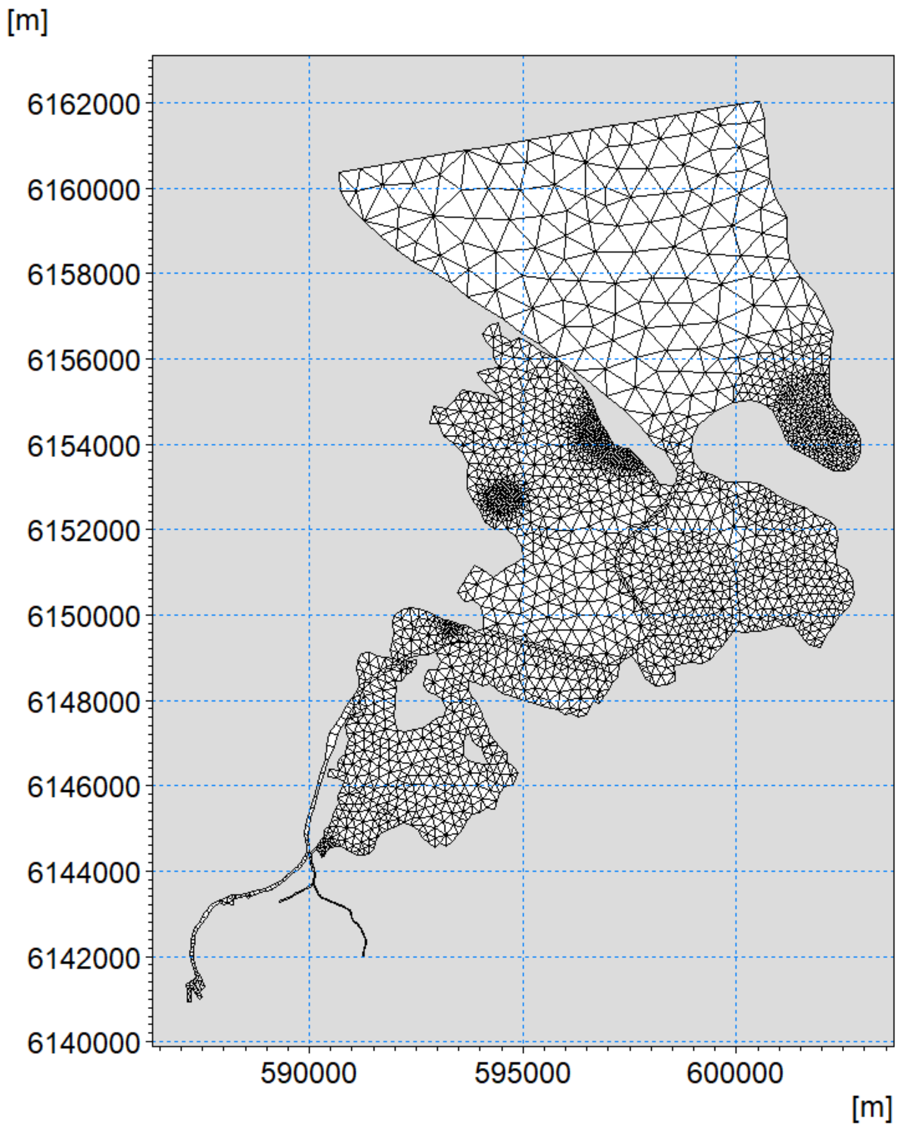

Figure 4-2 Resolution of the horizontal model mesh of the Odense Fjord model. Map projection: ETRS-1989-UTM-32.

4.2 Open Boundary Conditions

The Odense Fjord model has one open boundary towards the Danish straits located to the northeast of the model. Documentation on boundary conditions for the biogeochemical model development is given in DHI (2020).

4.3 Forcings

Data on solar radiation are calculated from clearness percentages and applied as a temporally varying forcing.

Area distributed atmospheric deposition of nitrogen (N) is provided by AU, Department of Environmental Science, and aligned with HELCOM depositions (see DHI 2020).

To estimate suspended sediment concentrations, a dynamic bottom shear stress information is needed. Wave parameters from a Spectral Wave model are included as model forcing, including significant wave height, wave period and mean wave direction, together with current conditions from the hydrodynamic model results.

Documentation on model forcing is given in technical report DHI (2020).

4.4 Sources

The Odense Fjord model includes sources with land-based nutrient loadings via streams together with intake and discharge of cooling water from Fynsværket. In Figure 4-3, the location of the sources is shown. Freshwater run-off from land is included in the hydrodynamic module.

The model sources are specified as time series with daily loadings of inorganic and organic nutrients, including also total nitrogen (TN) and total phosphorus (TP). The land-based nutrient loadings are based on data from DCE/AU, Department of Bioscience on a 4^{th} order water body level. Fynsværket's cooling water intake and discharge are not contributing to any nutrients to the fjord system.

More details are included in DHI (2020).

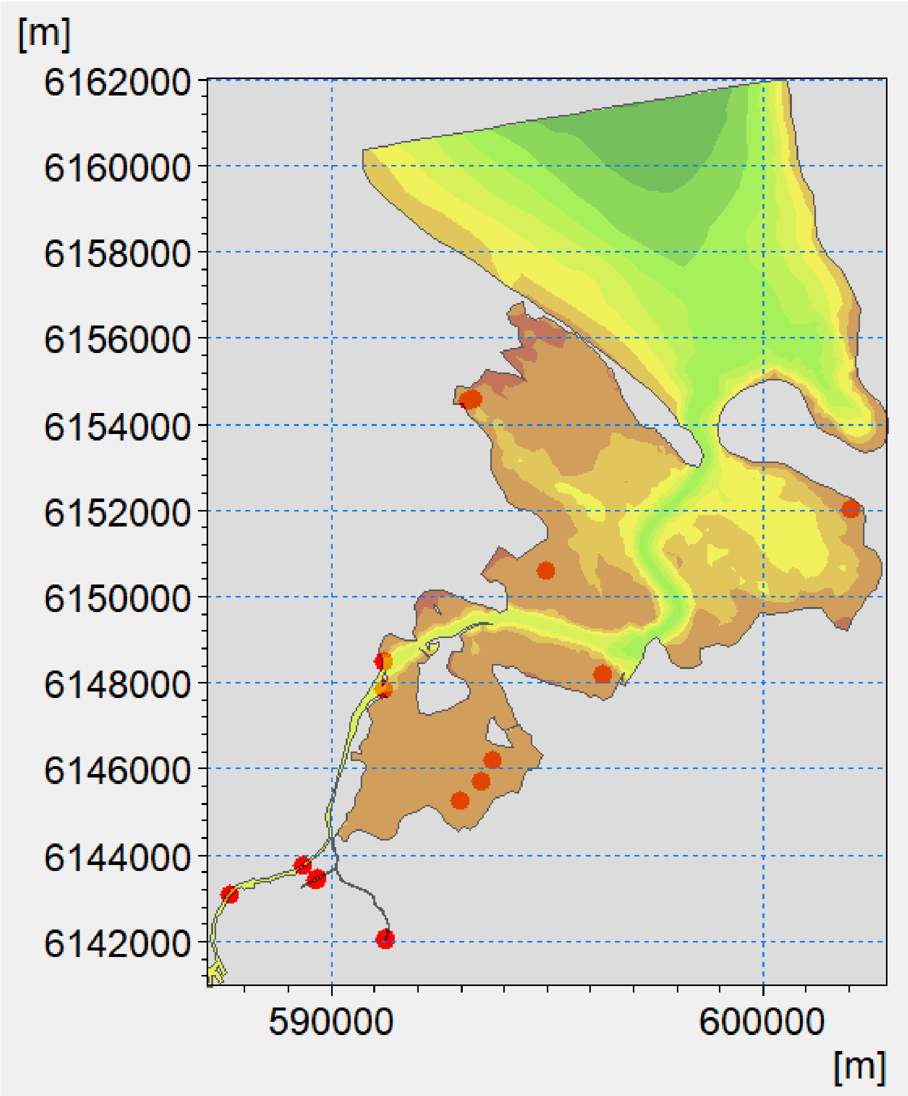

Figure 4-3 Location of sources in the Odense Fjord model. The source positions represent the main streams, but loadings are scaled to include local run-off and point sources from land to the fjord.

4.5 Initial Conditions

To properly initiate a model simulation, the model requires initial conditions for the various state variables. Initial values in the pelagic phase applied in the Odense Fjord model were estimated based on measurements within the Odense Fjord area. The available measurements from around 2002 were applied as uniform values in the entire model domain, and the model was spun-up by four times run for the year 2002 before being used for calibration/validation.

Initial fields of seabed substrates are based on mud-data from EMODnet (2016). Initial values of benthic vegetation (e.g. eelgrass) were estimated by running a MIKE ECO Lab model with defined initial biomass for the entire model domain for a three-year simulation period.

In DHI (2020) further details on initial model values are given.

5 Model Calibration and Validation

After set-up of the model, calibration and validation of the model are undertaken. The model **calibration** is the process of adjusting model process settings and model constants within the literature range to obtain satisfactory agreement between monitoring data and model results in the local modelling domain. In practice, the model set-up and the model calibration are often performed iteratively, since a good comparison between observations and model results requires a well-proportioned model domain as well as adequate model forcings.

The model **validation** is the process of comparing observations and model results qualitatively and quantitatively for a different period from the calibration period, to demonstrate the suitability of the calibrated model more generally. The qualitative comparison is typically made graphically, and the quantitative comparison is usually made using certain performance (goodness of fit) measures (DHI 2019b; Erichsen & Timmermann 2017). As such, the model validation constitutes the final documentation of the model performance.

The Odense Fjord model was run for the period 2002-2016, and the entire period is used for a combined calibration and validation effort, due to lack of enough observation data for separate calibration and validation tasks. Consequently, model performance measures are presented for this period. The model results compared with observations of the different biogeochemical parameters are presented for the entire period using a WEB-tool (rbmp2021-2027.dhigroup.com) (Google Chrome only).

5.1 Model Calibration Procedure

Calibration of the biogeochemical Odense Fjord model is achieved by tuning model constants to optimize model results on calibration parameters compared to measured data. The constants adjusted in the calibration procedure are numerous. They include, e.g. phytoplankton growth rates, grazing rates, mortality rates (phytoplankton and zooplankton), light attenuation constants, sedimentation rates, re-suspension rates, mineralization rates (pelagic and sediment), denitrification rates (pelagic and sediment).

The key parameters to optimize in the calibration procedure include dissolved oxygen, chlorophyll-a, light attenuation, inorganic nutrients, total nitrogen and total phosphorus. After each adjustment of calibration constants, the model is run, and time-series are compared to measured data at selected stations. The procedure is iterated until model results, and measured data compare in both time and space.

5.2 Presentation of Key Model Results

During the model calibration procedure, an extensive amount of data on state variables and processes is produced. To allow for a smooth and homogeneous quality assurance, few standard plots and time series are generated automatically and evaluated during the baseline and scenario execution.

Examples of modelled key validation parameters are presented as 2D fields in Figure 5-1 to Figure 5-4, and illustrate the spatial variation of the validation parameters. In the following sections, a brief assessment of the spatial distribution of key parameters, within the water bodies covered by the model domain, will be given.

Annual average concentrations of dissolved oxygen in bottom waters during 2016 are presented in Figure 5-1 and ranges from 8.5-12 mg/l in the water bodies within Odense Fjord (Figure 5-1).

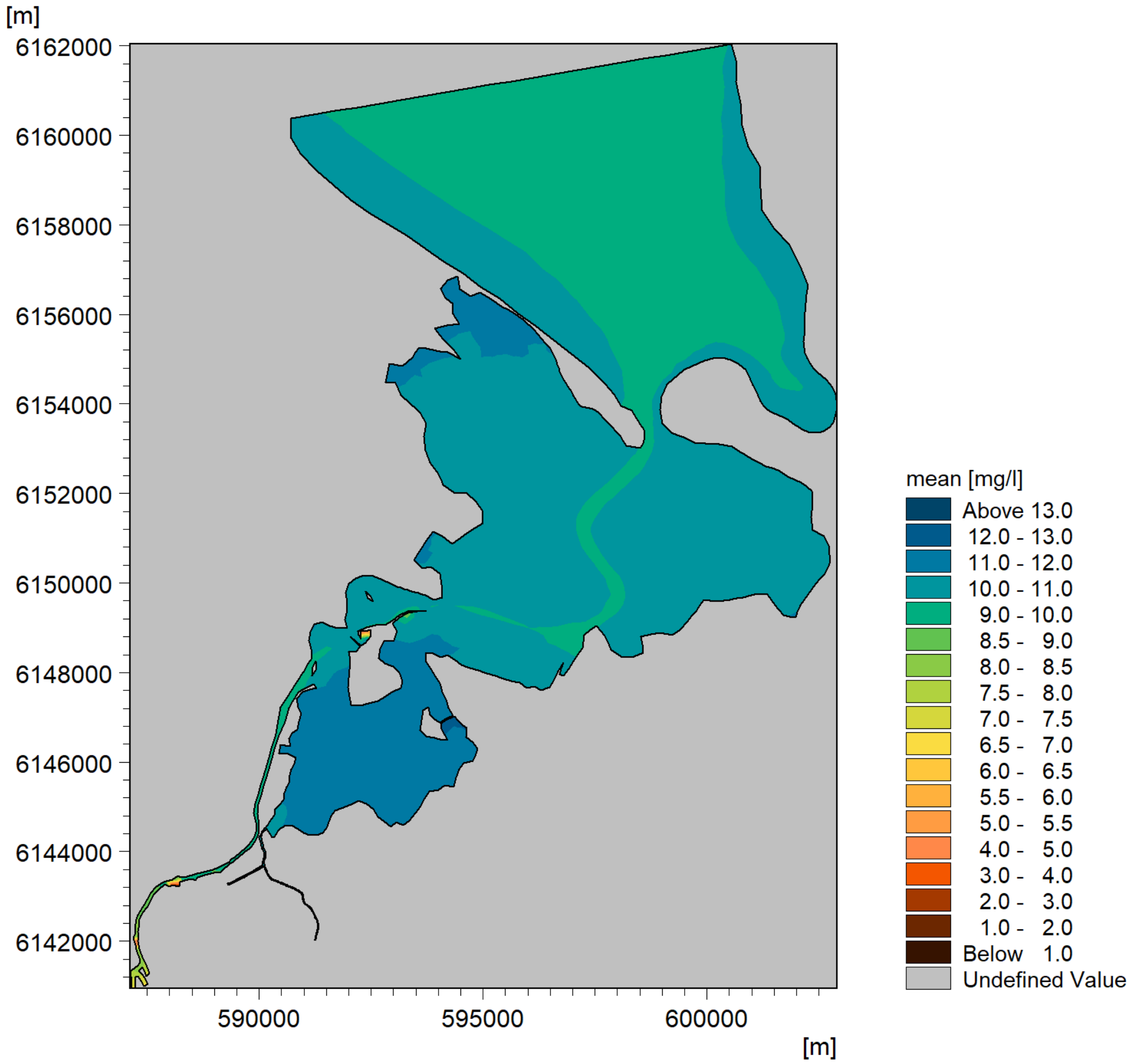

Figure 5-1 Modelled yearly average bottom water concentrations of dissolved oxygen (DO, mg/l) for 2016.

Annual average concentrations of surface chlorophyll-a for 2016 ranges from 0.001-0.006 mg/l in the outer part of Odense Fjord and above 0.016 mg/l in the inner part of Odense Fjord (Figure 5-2).

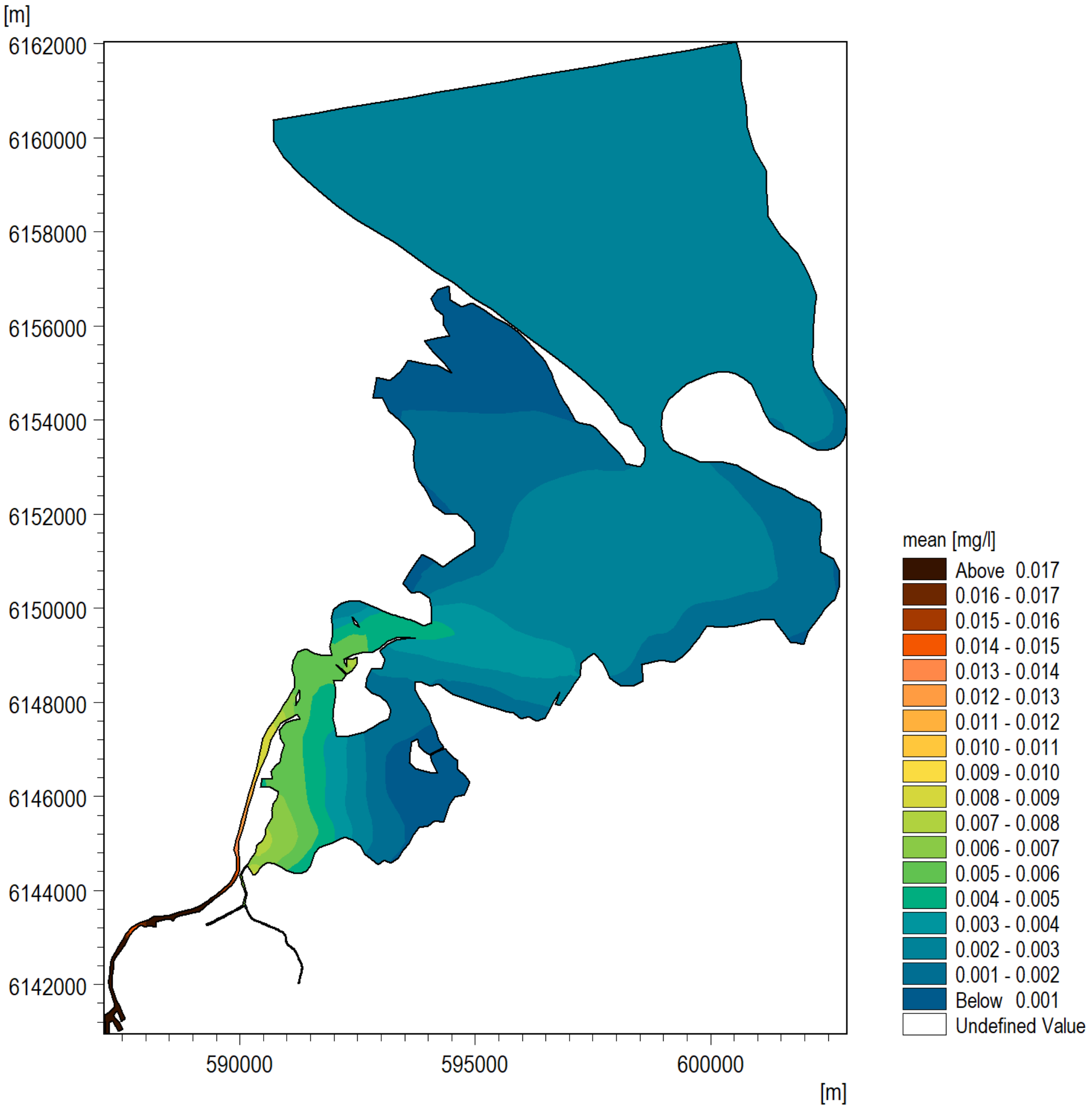

Figure 5-2 Modelled yearly average surface water concentrations of chlorophyll-a (CH, mg/l) for 2016.

Annual average concentrations of surface total nitrogen for 2016 ranges between 0.5 – 1.5 mg/l (Figure 5-3) throughout the fjord. The highest values are predicted in the inner part of Odense Fjord.

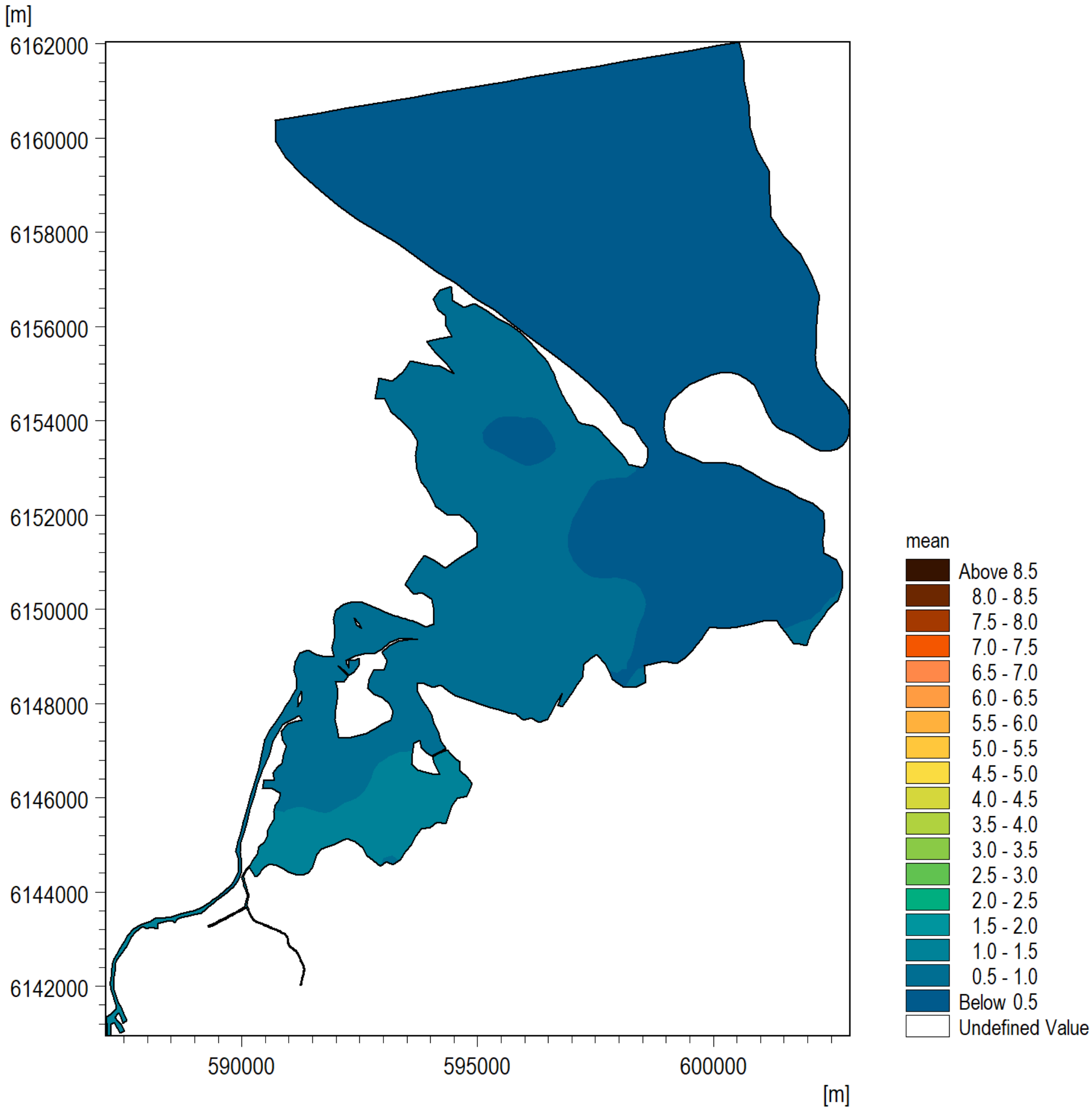

Figure 5-3 Modelled yearly average surface water concentrations of total nitrogen TN, (mg/l) for 2016.

Annual average concentrations of surface total phosphorus during 2016 are between 0.25 mg/l to 2.5 mg/l (Figure 5-4). The highest values are observed in the inner part.

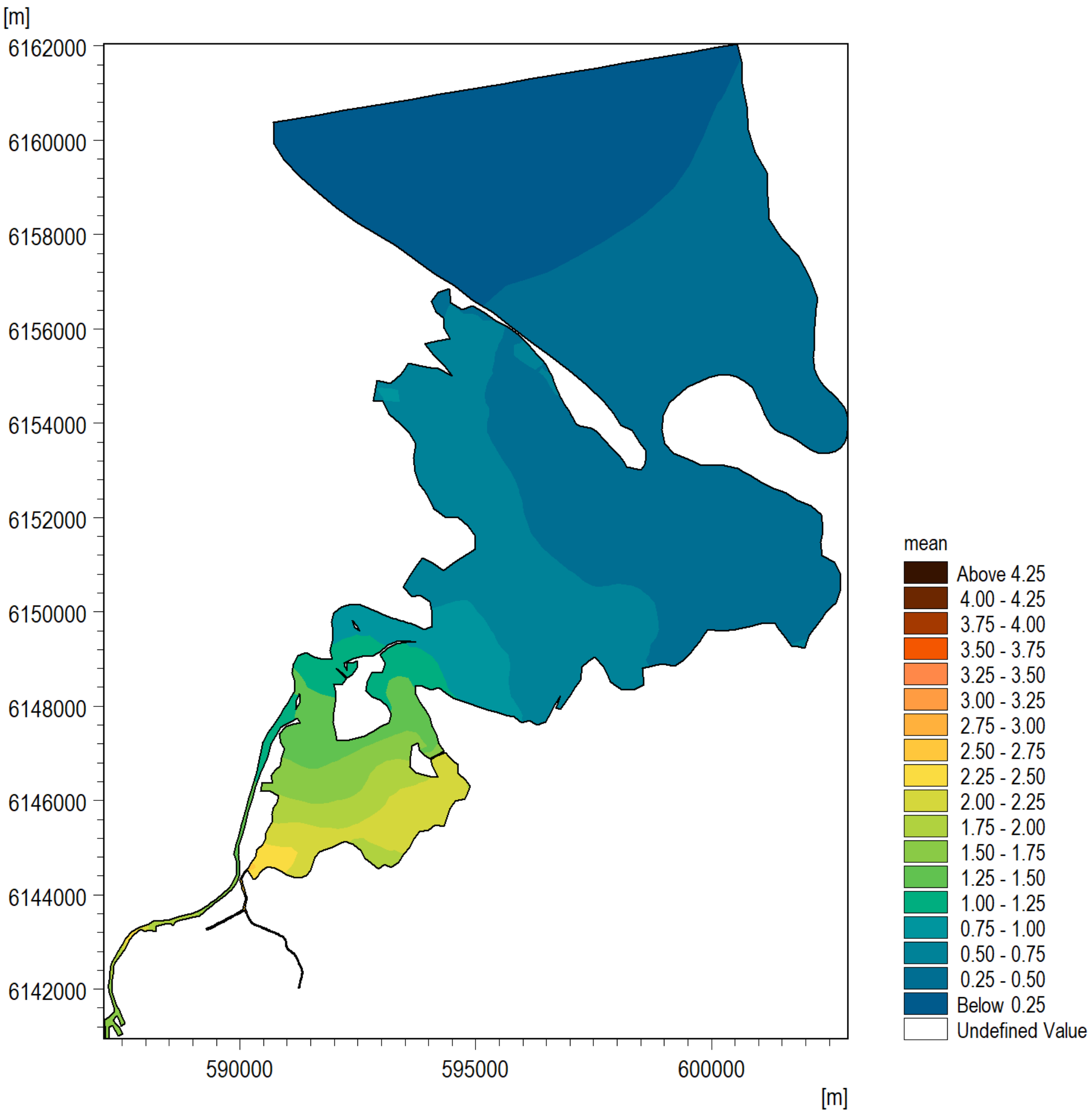

Figure 5-4 Modelled yearly average surface water concentrations of total phosphorous (TP, mg/l) for 2016.

5.3 Model Performance

The Odense Fjord biogeochemical model was calibrated and validated against measured data (observations) on modelled ecosystem parameters at selected stations within the model domain. Figure 5-1 shows the location of four stations within the model domain. All stations within the model domain had enough measurement data in the period 2002-2016 to be included in the model calibration and validation (at least one year of weekly or bi-weekly data). The biogeochemical calibration/validation parameters include dissolved oxygen (DO), chlorophyll-a (CH), light attenuation (K_d), dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), total nitrogen (TN) and total phosphorus (TP). Generally, the Odense Fjord model compares well to the measurements in terms of model parameters (see Figure 5-3 to Figure 5-9), and the overall performance measure (summarized in Table 5-1 to Table 5-3) confirms a statistically good agreement between measurements and model results.

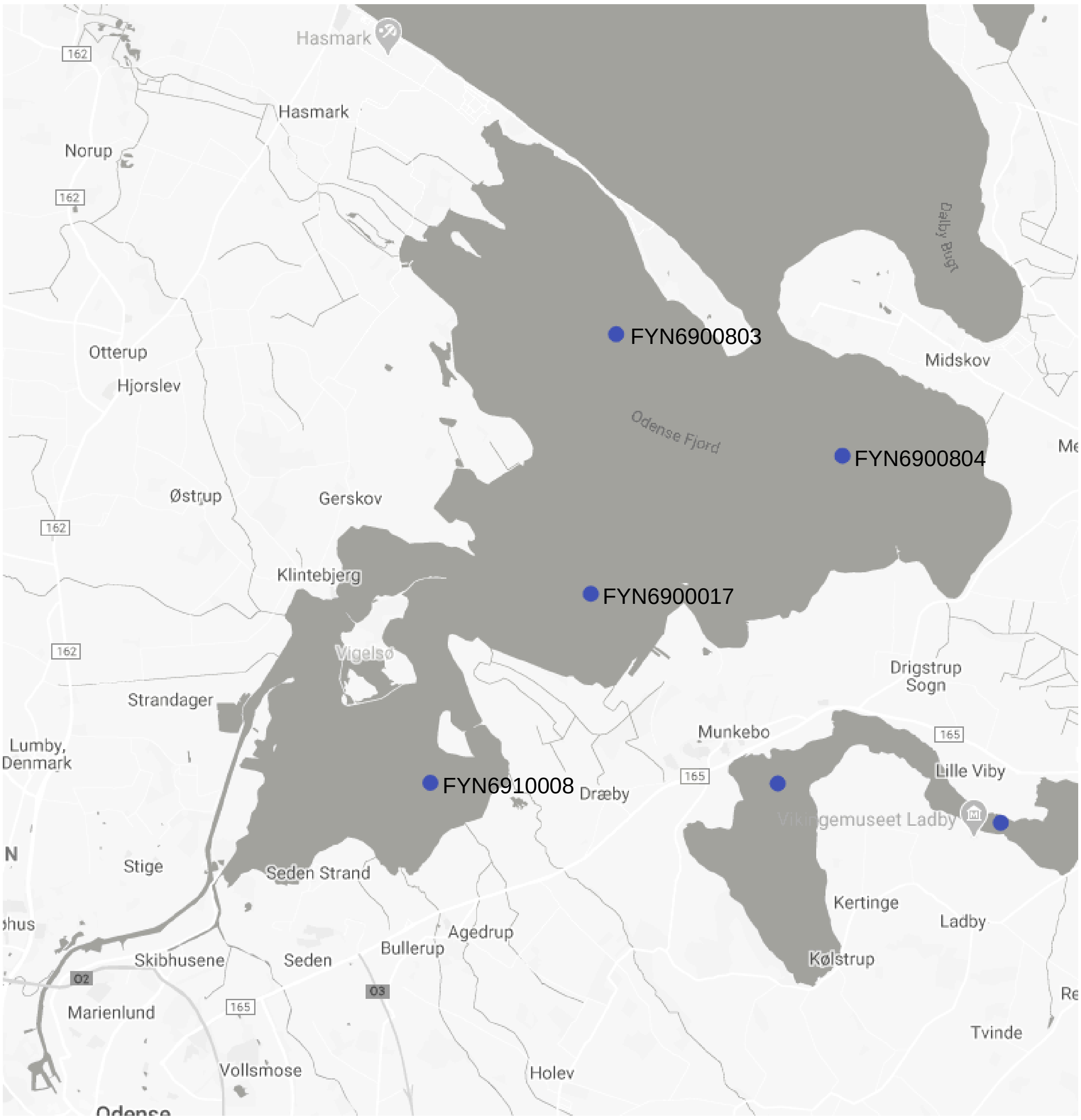

Figure 5-5 Location of stations used for performance analyses in Odense Fjord.

5.3.1 Calibration/Validation at Station FYN6900017

In the following, we present an example of the calibration/validation from Odense Fjord station FYN6900017 and refer to rbmp2021-2027.dhigroup.com (Google Chrome only) for more details on the Danish measurement stations. The location of station FYN6900017 is shown in Figure 5-5.

The comparison at station FYN6900017 shows a good agreement between the measurements and Odense Fjord model for 87.9% of the parameters according to the three performance measures P-Bias, Spearman Rank Correlation and CF (see Table 5-1 to Table 5-3 together with DHI (2019b) and Erichsen *et al.* (2017) regarding the applied measures).

In Figure 5-6, measured and modelled concentrations of dissolved oxygen (DO) at station FYN6900017 in the surface and at bottom waters (here 4 m) are shown. From the figure, it is seen that for DO the variability and seasonality of the surface and bottom (4 m) waters are well represented by the model. During late summer/autumn months, the model tends to overestimate the predicted DO concentrations in bottom waters. Modelled bottom layer depth (4 m) is different from the measured DO bottom depth (8 m). According to the statistical performance measures (see Table 5-1 to Table 5-3), measured and modelled DO compare 'excellent' (P-bias and Spearman Rank Correlation) and 'very good' (CF) at station FYN6900017.

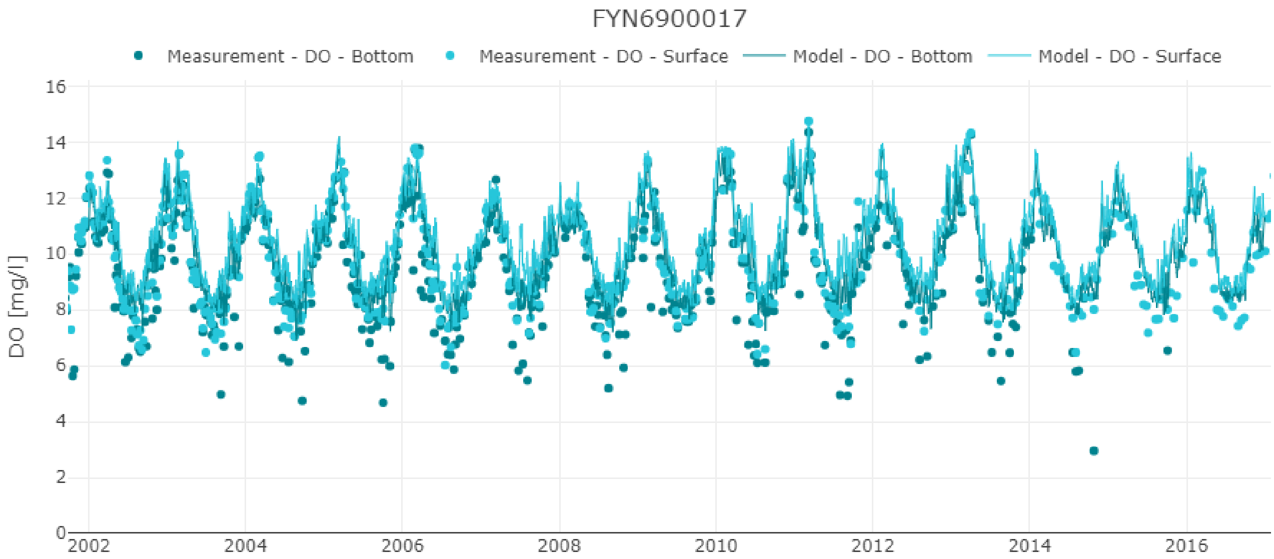

Figure 5-6 Comparison of measured and modelled concentrations of dissolved oxygen (DO, mg/l) at station FYN6900017 in the surface and bottom waters (4 m bottom depth for modelled DO and 8 m bottom depth for measured DO). Dots represent measurements, and the solid line shows modelled data for the entire period.

For chlorophyll-a (CH), the dynamics in seasonality are well represented by the model (see Figure 5-7). From the statistical performance measures, annual CH compares 'very good' (P-Bias and CF) and 'good' (Spearman Rank Correlation) (see Table 5-1 to Table 5-3). For summer CH, the model performance for this station is 'excellent' based on P-Bias, 'good' according to CF and 'poor' when evaluated from Spearman Rank Correlation.

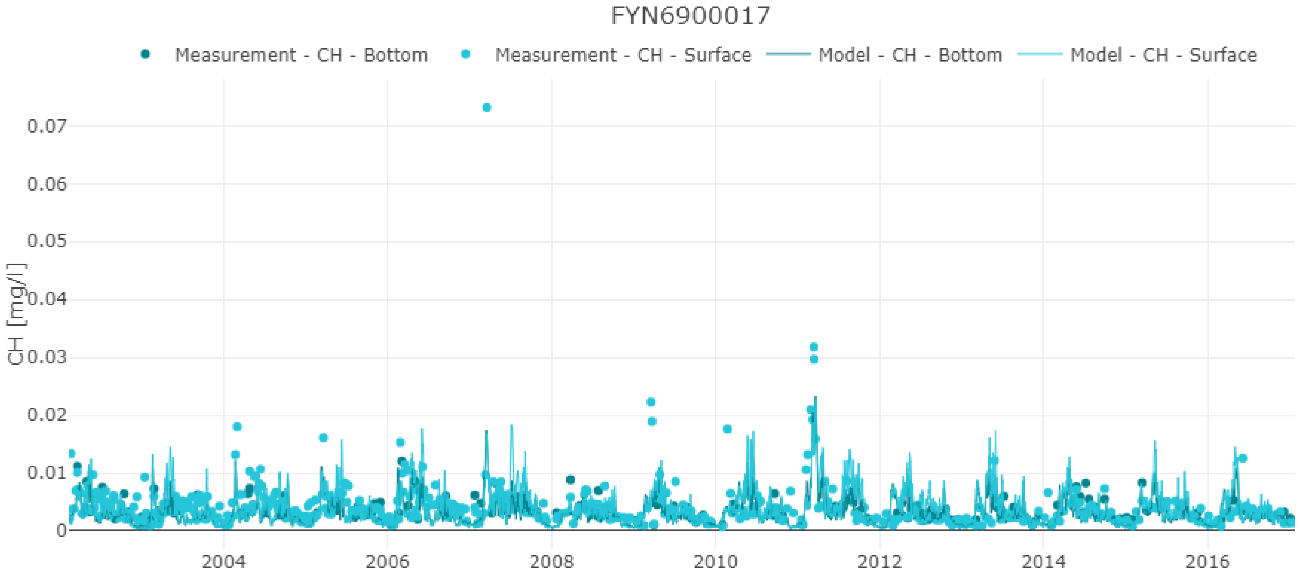

Figure 5-7 Comparison of measured and modelled concentrations of chlorophyll-a (CH, µg/l) at station FYN6900017 in surface and bottom (4 m) waters. Dots represent measurements, and solid lines show modelled data for the entire period.

For light attenuation coefficient (K_d), the majority of the seasonality is well represented by the Odense Fjord model (see Figure 5-8). From the statistical performance measures, annual K_d compares 'very good' according to P-Bias and CF and 'poor' according to Spearman Rank Correlation (Table 5-1 to Table 5-3).

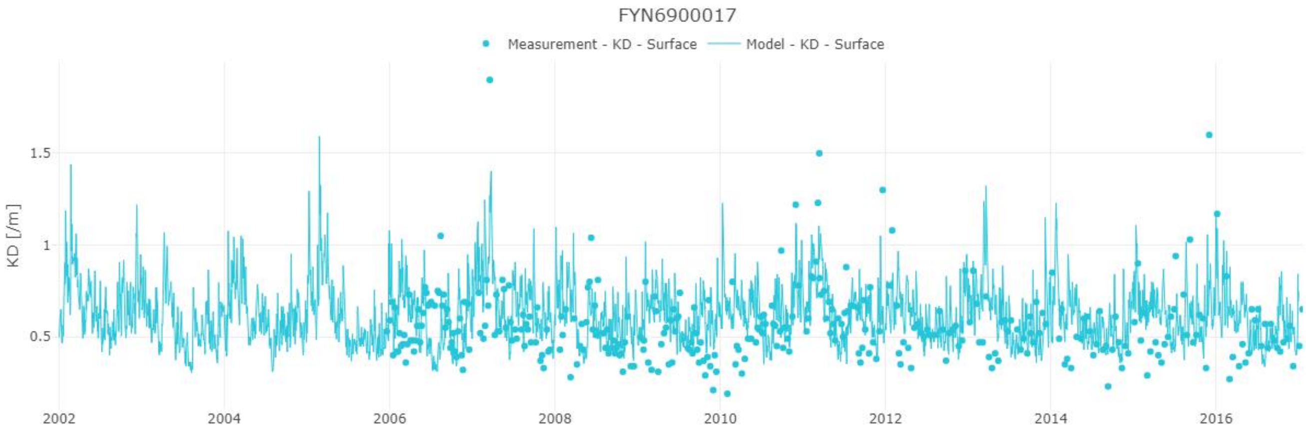

Figure 5-8 Comparison of measured and modelled concentrations of light attenuation (K_d, m^{-1}) at station FYN6900017 in surface water. Dots represent measurements, and solid lines show modelled data for the entire period.

For dissolved inorganic nitrogen (DIN), the structure in the seasonality is well represented by the Odense Fjord model (see Figure 5-9). The modelled bottom layer depth (4 m) is different from the measured DIN bottom depth (8 m). The statistical performance measures for annual DIN compare 'excellent' according to P-Bias and CF and 'very good' according to Spearman Rank Correlation (Table 5-1 to Table 5-3).

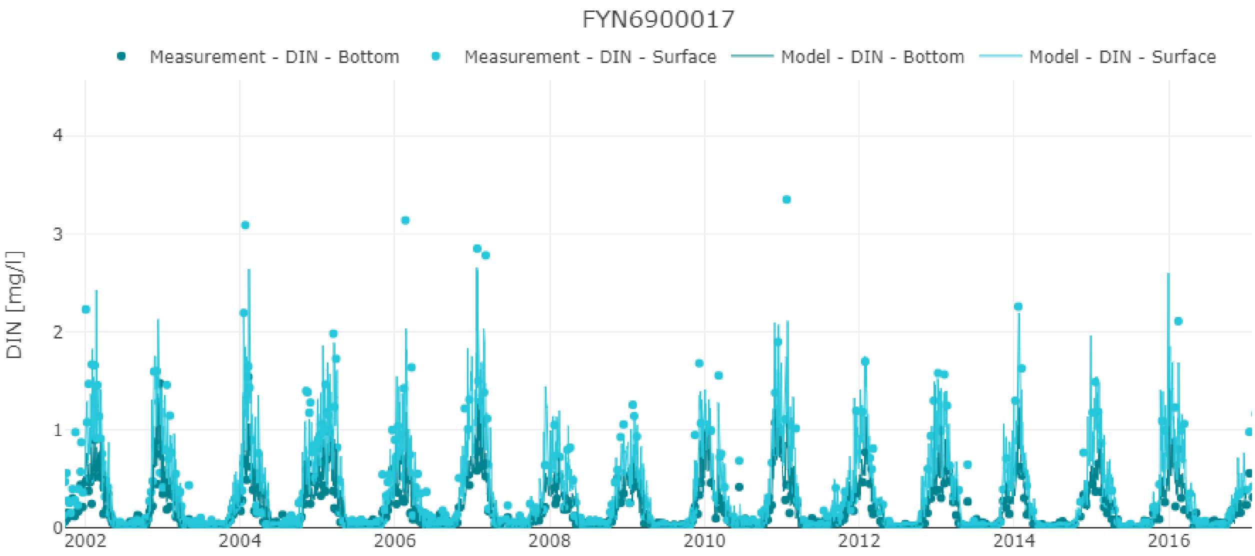

Figure 5-9 Measured and modelled concentrations of dissolved inorganic nitrogen (DIN, mg/l) at station FYN6900017 in the surface and bottom waters (4 m bottom depth for modelled DIN and 8 m bottom depth for measured DIN). Dots represent measurements, and solid lines show modelled data for the entire period.

When comparing measured and modelled concentrations of DIP (see Figure 5-10), we see relatively similar winter concentrations and a definite drop in modelled DIP during spring. The modelled bottom layer depth (4 m) is different from the measured DIP bottom depth (8 m). When considering the quality measure CF for DIP, it is noted that the model error is 87% of the standard deviation of the measurements, and based on this measure, the model meets the 'very good' model performance. According to the statistical performance measures, the model performance for annual DIP is 'very good' for two of the three quality measures (Spearman Rank Correlation and CF) and 'good' according to P-Bias (see Table 5-1 to Table 5-3).

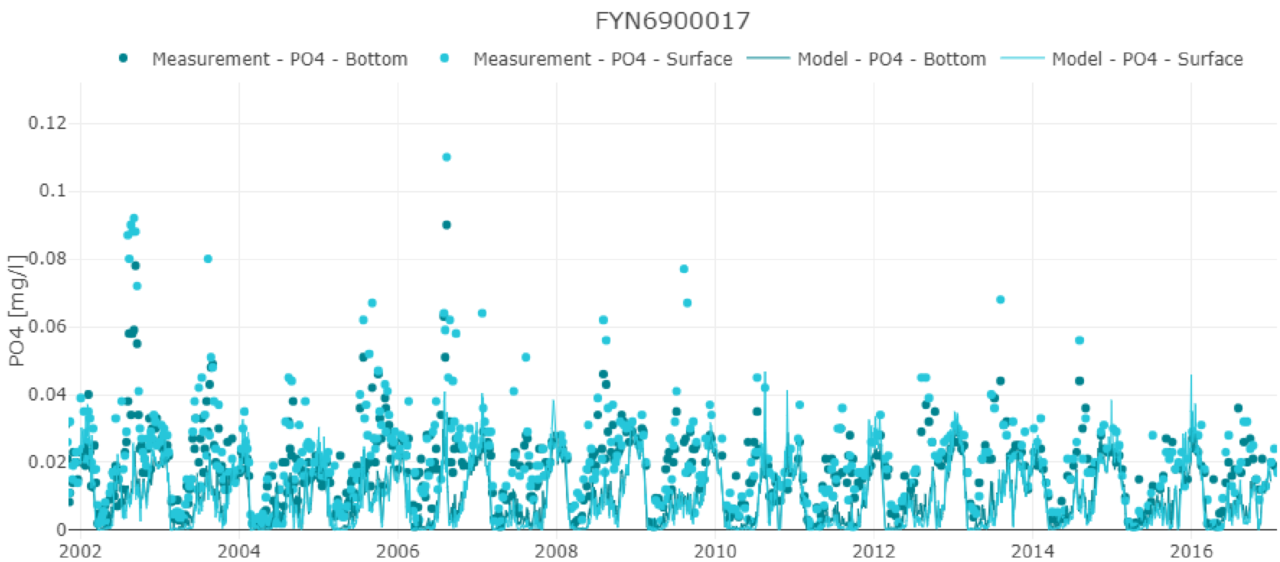

Figure 5-10 Measured and modelled concentrations of dissolved inorganic phosphorus (DIP, mg/l) at station FYN6900017 in the surface and bottom waters (4 m bottom depth for modelled DIP and 8 m bottom depth for measured DIP). Dots represent measurements, and solid lines show modelled data for the entire period.

In Figure 5-11, comparisons of measured and modelled total nitrogen (TN) at station FYN6900017 in surface water and bottom water are shown. It should be noted that the modelled bottom layer depth (4 m) is different from the measured TN bottom depth (8 m). For TN, the variability in time and through the water column is well represented by the model. The statistical performance measures support this (see Table 5-1 to Table 5-3), where measured and modelled annual TN compares ‘excellent’ (P-Bias and CF) and ‘very good’ (Spearman Rank Correlation) at station FYN6900017.

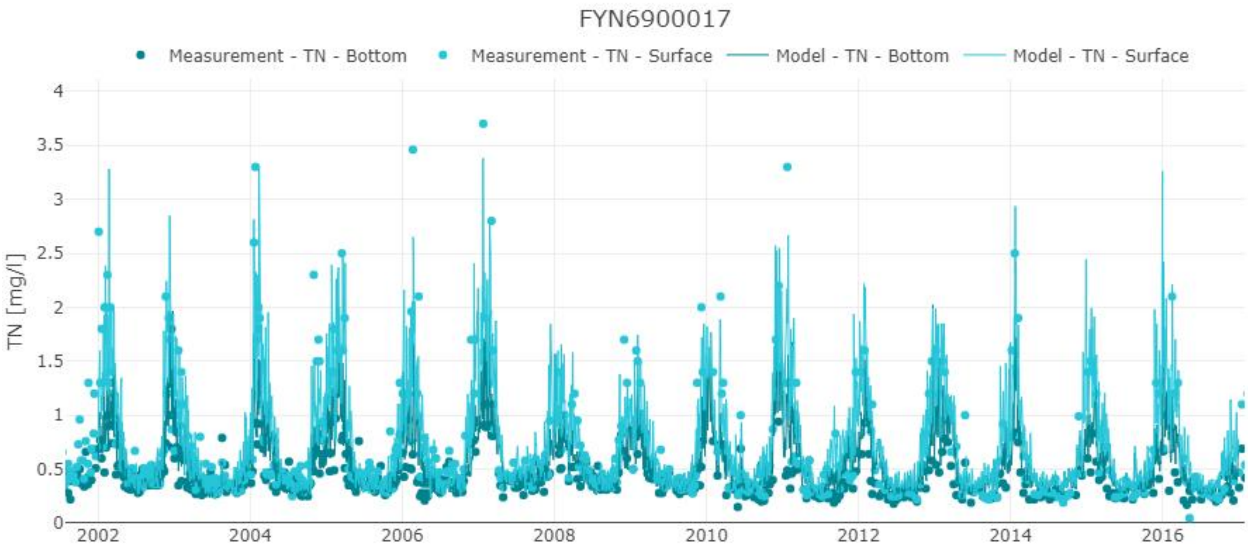

Figure 5-11 Comparison of measured and modelled concentrations of total nitrogen (TN, mg/l) at station FYN6900017 in surface and bottom waters (4 m bottom depth for modelled TN and 8 m bottom depth for measured TN). Scatter data represent measurements, and solid lines show modelled data for the entire period.

The seasonal dynamics in TP predicted by the model are presented in Figure 5-12. It should be noted that the modelled bottom layer depth (4 m) is different from the measured TP bottom depth (8 m). The model performance for annual TP at station FYN6900017 is ‘very good’ (CF) and ‘good’ (P-Bias and Spearman Rank Correlation) (see Table 5-1 to Table 5-3).

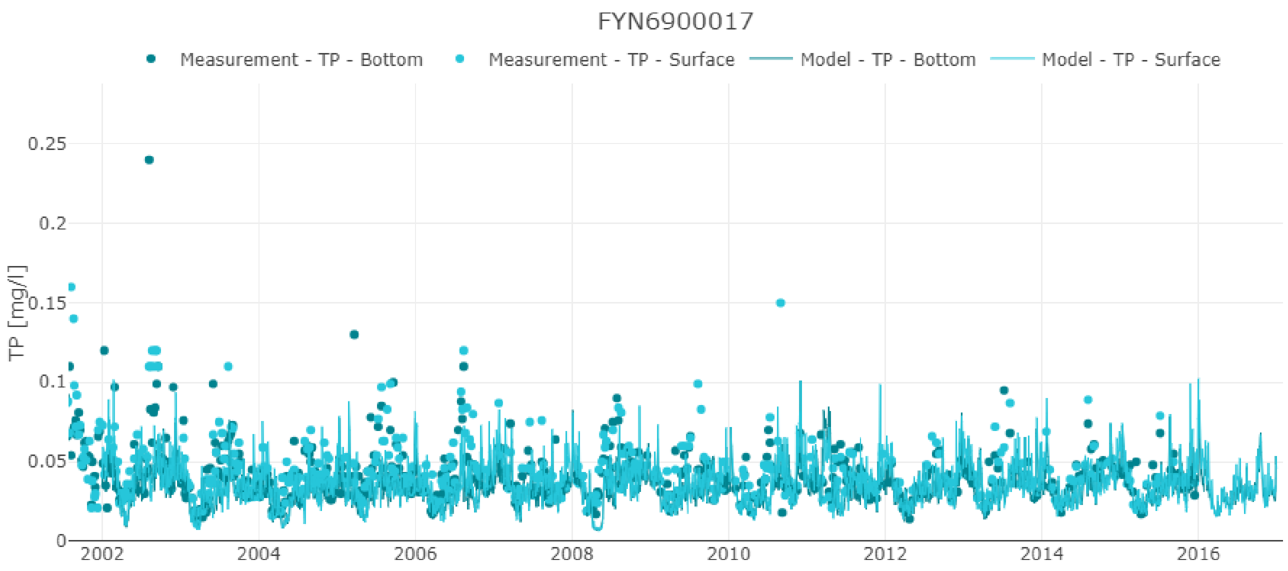

Figure 5-12 Comparison of measured and modelled concentrations of total P (TP, mg/l) at station FYN6900017 in surface and bottom waters (4 m bottom depth for modelled TP and 8 m bottom depth for measured TP). Scatter data represent measurements, and solid lines show modelled data for the entire period.

5.3.2 General Calibration/Validation

For the calibration/validation period (2002-2016) all stations had a sufficient amount of measurement data (at least one year of weekly or bi-weekly data) to be included in the model performance analysis. Figure 5-5 shows the four locations with measurements on ecosystem parameters (chlorophyll-a (CH), light attenuation (K_d), dissolved oxygen (DO), dissolved inorganic phosphorous (DIP), dissolved inorganic nitrogen (DIN), total nitrogen (TN), and total phosphorus (TP)) during the period 2002-2016. Time series data are presented using the WEB-tool (http:// rbmp2021-2027.dhigroup.com).

In Table 5-1 to Table 5-3 the model performance is evaluated based on three performance measures: P-Bias, Spearman Rank Correlation and CF.

In the tables, colour codes are included to highlight the overall model performance as 'excellent, very good, good' or 'poor'. For the biogeochemical model covering Odense Fjord, we aim at 'excellent, very good' or 'good' model performance for 75% of the data sets on measures. All model performances (both annual and summer/winter) evaluated against the three different quality measures at four stations were found to be 'excellent, very good' or 'good' for 88% of the parameters (see Figure 5-13 and Table 5-1 to Table 5-3). The annual model performance was found to be 'excellent', 'very good' or 'good' for 92% of the measurements.

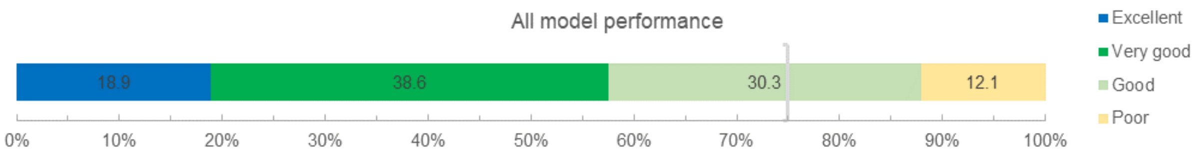

Figure 5-13 Bar chart illustrating Odense Fjord model performance evaluated against three different quality measures and all parameters. Vertical line indicates the aim of 75% being 'excellent', 'very good' or 'good'.

According to P-bias (Table 5-1), the model meets ‘excellent’, ‘very good’ or ‘good’ for 86% for all measurements (including specific winter and summer evaluations) and when evaluating the annual measurements only. A ‘good’ model performance measured by P-Bias for summer and winter measurements indicates that the predicted absolute values of summer chlorophyll-a, summer light attenuation, and winter inorganic nutrient concentrations correspond well with the observed values. In general, the P-Bias obtains negative values for most of the parameters, indicating that the model underestimates observed values. On average, P-Bias evaluates the model performance for dissolved oxygen as ‘excellent’; for DIN, TN and TP the model performance on average is ‘very good’; for K_d and DIP the average performance is ‘good’; The model performance for CH evaluated from P-bias is on average ‘poor’.

From the quality measure Spearman Rank Correlation (Table 5-2) the model performance meets ‘excellent’, ‘very good’ or ‘good’ in 77% of all measurements (including specific winter and summer evaluations) and 89% in the annual measurements. A good annual correlation obtained from the Spearman Rank Correlation measure indicates a good seasonal correlation, where the predicted dynamics correspond well with the observed seasonal variability. On average, the Spearman Rank Correlation evaluates the model performance for dissolved oxygen to be ‘excellent’; for DIN, DIP and TN the performance is assessed to be ‘very good’; for TP and K_d the average model performance is ‘good’. The average model performance for all CH evaluated from Spearman Rank Correlation is on average ‘poor’.

According to the performance measure CF (Table 5-3), the model meets ‘excellent, very good’ or ‘good’ in 100% of all measurements at the stations (Table 5-3). On average, the Cost Function evaluates DIN to be ‘excellent’; DO, K_d, DIP, TN, and TP to be ‘very good’ on average for all measures and ‘good’ for CH.

Table 5-1 Review of model performance at station P-Bias (%) based on measured and modelled data for the validation period 2002-2016. Blue colour indicates an ‘excellent’ model (|x|≤10%), dark green indicates a ‘very good’ model (10<|x|<20%), light green indicates a ‘good’ model (20<|x|<40%) and yellow indicates a ‘poor’ model (|x|>40%).

Station	TN	TP	DIP		DIN		CH		DO	K_d		Number of observations	
	Annual	Annual	Annual	Winter[a]	Annual	Winter[a]	Annual	Summer[b]	Annual	Annual	Summer[c]	Annual	Summ/Wint
FYN6900017	7.7	-21.4	-59.9	-21.0	-7	-5.5	-18.6	-9.8	7.9	10.1	7.7	[337-1052]	[212-397]
FYN6900803	10.0	-16.9	-36.6	-16.9	7.4	3.1	-51.3	-67.1	3.8	-20.1	-25.1	[36-122]	[21-52]
FYN6900804	20.0	-11.2	-31.9	-19.6	21.8	22.5	-34.4	-37.1	2.7	23.7	20.6	[48-282]	[35-52]
FYN6910008	38.5	-1.3	-73.8	-24.8	26.3	7.0	87.6	81.8	13.1	-33.0	-31.1	[155-359]	[69-163]

[a] Jan, Feb, Dec
[b] May-Sep
[c] Mar-Sep

Table 5-2 Review of model performance at station Spearman Rank Correlation (no unit) based on measured and modelled data for the validation period 2002-2016. Blue colour indicates an ‘excellent’ model (≥0.9), dark green indicates a ‘very good’ model (0.9-0.6), light green indicates a ‘good’ model (0.6-0.3) and yellow indicates a ‘poor’ model (<0.3).

Station	TN	TP	DIP		DIN		CH		DO	K_d		Number of observations	
	Annual	Annual	Annual	Winter[a]	Annual	Winter[a]	Annual	Summer[b]	Annual	Annual	Summer[c]	Annual	Summ/Wint
FYN6900017	0.77	0.44	0.64	0.70	0.84	0.87	0.39	-0.03	0.91	0.19	0.00	[337-1052]	[212-397]
FYN6900803	0.78	0.49	0.72	0.68	0.86	0.89	0.31	-0.10	0.95	-0.36	-0.46	[36-122]	[21-52]
FYN6900804	0.77	0.65	0.78	0.61	0.82	0.84	0.45	0.38	0.4	0.31	0.25	[48-282]	[35-52]
FYN6910008	0.81	0.34	0.43	0.30	0.89	0.80	0.10	0.09	0.84	0.34	0.31	[155-359]	[69-163]

[a] Jan, Feb, Dec
[b] May-Sep
[c] Mar-Sep

Table 5-3 Review of model performance at station Cost Function (CF, no unit) based on measured and modelled data for the validation period 2002-2016. Blue colour indicates an 'excellent' model (≤0.4), dark green indicates a 'very good' model (0.4-1), light green indicates a 'good' model (1-2) and yellow indicates a 'poor' model (≥3).

Station	TN	TP	DIP		DIN		CH		DO	K_d		Number of observations	
	Annual	Annual	Annual	Winter[a]	Annual	Winter[a]	Annual	Summer[b]	Annual	Annual	Summer[c]	Annual	Summ/Wint
FYN6900017	0.33	0.74	0.87	0.78	0.23	0.35	0.57	1.29	0.46	0.83	0.88	[337-1052]	[212-397]
FYN6900803	0.37	1.15	0.64	1.26	0.19	0.30	0.75	1.66	0.29	1.04	1.05	[36-122]	[21-52]
FYN6900804	0.46	0.67	0.49	0.97	0.27	0.47	0.60	1.22	0.28	1.33	1.26	[48-282]	[35-52]
FYN6910008	0.53	0.78	0.74	1.53	0.29	0.42	0.92	1.55	0.74	0.71	0.71	[155-359]	[69-163]

[a] Jan, Feb, Dec
[b] May-Sep
[c] Mar-Sep

6 Conclusion

This technical note shows that the model performance for the biogeochemical model covering Odense Fjord meets the performance measure ‘excellent’, ‘very good’ or ‘good’ for 92% of the annual measures and 88% for both annually and summer/winter measurements evaluated against three quality measures. The ambition is to meet the above criteria in 75% of all measures for all parameters and all stations (lumped).

Few local areas covered by the Odense Fjord model show a lower model performance and hence a higher uncertainty, which will be considered in further analysis. Thus, we conclude that the biogeochemical model covering Odense Fjord is well suited for modelling scenarios within the water bodies covered by the model domain, as part of the overall development of mechanistic models towards the RBMP 2021-2027.

7 References

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