Development of Mechanistic Models

Mechanistic Model for Limfjorden

Technical documentation on biogeochemical model

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Development of Mechanistic Models

Mechanistic Model for Limfjorden

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Eelgrass in Kertinge Nor
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1 Executive Summary

The model development presented in this technical note represents the biogeochemical model development for Limfjorden. The Limfjorden model is part of a large 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 integrating with Bayesian statistical modelling, and cross-system modelling carried out by AU, Bioscience.

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

Water Body*)	ID Number
Nissum Bredning, Thisted Bredning, Kås Bredning, Løgstør Bredning, Nibe Bredning and Langerak	156
Bjørnholms Bugt, Riisgårde Bredning, Skive Fjord and Lovns Bredning	157
Hjarbæk Fjord	158

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

The Limfjorden biogeochemical model builds on the developed hydrodynamic model of Limfjorden 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 based on 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 model performance.

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

As can be seen from the present technical note, 88% of all annual data sets meet the success criteria when evaluated against the three performance measures, and 85% when assessing both annual performance and summer/winter performance of all data. The average model performance for the biogeochemical model covering Limfjorden is summarized below:

- Model performance measures for dissolved oxygen (DO) are 3.4% (Percent Bias), 0.8 (Spearman Rank Correlation) and 0.5 (Cost Function). The average model performance for

DO is categorized to be 'excellent' (P-Bias), and 'very good' (Spearman Rank Correlation and CF).

- Model performance measures for chlorophyll-a (CH) are on average 37.1% (P-Bias), 0.3 (Spearman Rank Correlation) and 0.8 (CF). The average model performance for CH is categorized to be 'very good' (CF) and 'good' (P-Bias and Spearman Rank Correlation).
- Model performance measures for all light attenuation coefficient (K_d) are on average, 22.9% (P-Bias), 0.1 (Spearman Rank Correlation) and 1.1 (CF). The average model performance for K_d is categorized as 'good' (P-Bias and CF) and 'poor' (Spearman Rank Correlation).
- Model performance measures for all dissolved inorganic nitrogen (DIN) are on average, 10.4% (P-Bias), 0.8 (Spearman Rank Correlation) and 0.5 (CF). The average model performance for DIN is categorized to be 'very good' (P-Bias, Spearman Rank Correlation and CF).
- Model performance measures for dissolved inorganic phosphorous (DIP) are on average 30.5% (P-Bias), 0.3 (Spearman Rank Correlation) and 0.9 (CF). The average model performance for DIP is categorized as 'very good' (CF) and 'good' (P-Bias and Spearman Rank Correlation).
- Model performance measures for total nitrogen (TN) are, on average, 9.1% (P-Bias), 0.8 (Spearman Rank Correlation) and 0.7 (CF). The average model performance for TN is categorized as 'excellent' (P-Bias) and 'very good' (Spearman Rank Correlation and CF).
- Model performance measures for total phosphorus (TP) are 20.6% (P-Bias), 0.5 (Spearman Rank Correlation) and 0.8 (CF). The average model performance for TP is categorized as 'very good' (CF) and 'good' (P-Bias and Spearman Rank Correlation).

The details behind the above performance 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 of meeting 'excellent', 'very good', or 'good' for 75% of all parameters and stations (lumped) has been well reached. Hence, in this technical note, we conclude that the Limfjorden biogeochemical model has been developed successfully for Danish 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 Limfjorden and builds on top of the Limfjorden hydrodynamic model (DHI 2019d). Documentation on the model application will be presented in the following notes. 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 Limfjorden, together with a quality assessment of the model performance. The Limfjorden model includes three Danish water bodies listed in Table 2-1 below. The location of the Danish Waterbodies is documented in Erichsen *et al*. (2019).

Table 2-1 Water bodies included in the Limfjorden model.

Water Body[*)]	ID Number
Nissum Bredning, Thisted Bredning, Kås Bredning, Løgstør Bredning, Nibe Bredning and Langerak	156
Bjørnholms Bugt, Riisgårde Bredning, Skive Fjord and Lovns Bredning	157
Hjarbæk Fjord	158

[*)] 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 Limfjorden biogeochemical model can be found in DHI (2019c).

According to DHI (2019b), the quality measure Model Efficiency Factor (MEF) were 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 Limfjorden. The Limfjorden model is one 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 Limfjorden 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 are 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 present 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 Limfjorden 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 Limfjorden builds on top of the hydrodynamic model (HD) and an integrated transport model (AD). The set-up and calibration/validation of the physical Limfjorden 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.

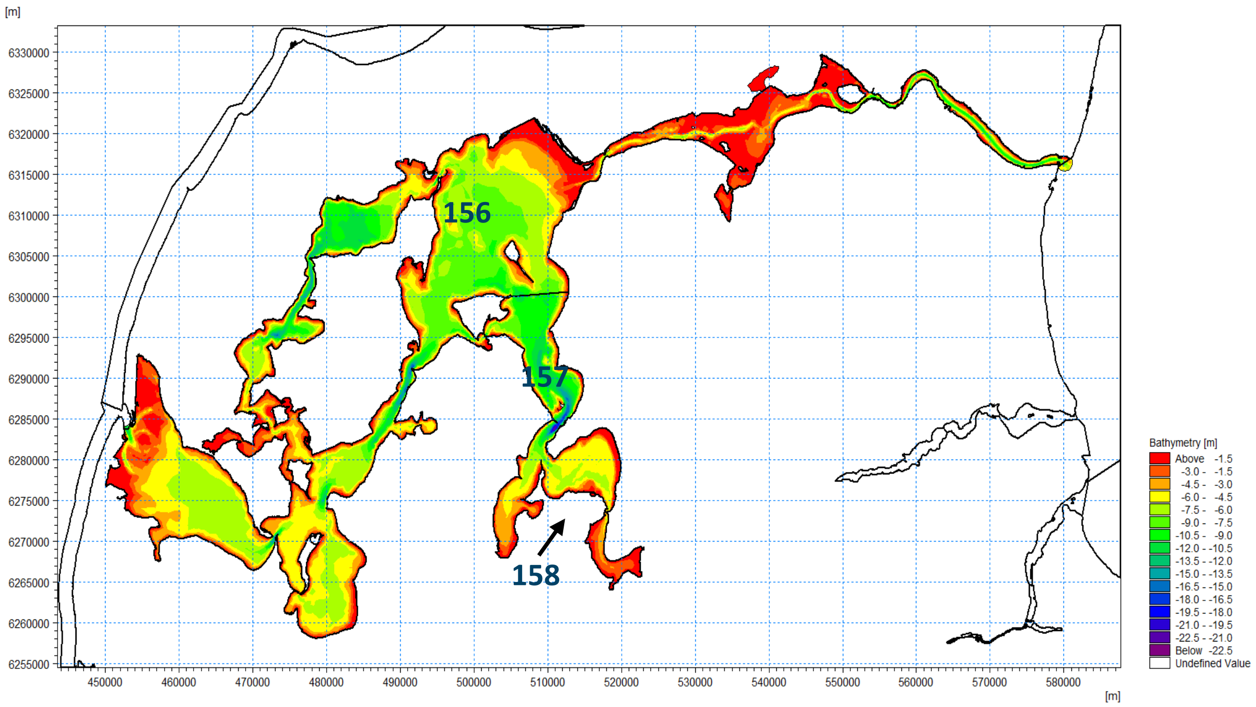

Figure 4-1 Model bathymetry of the Limfjorden model and indication of water bodies. Water depths refer to MSL. The model has two open boundaries. Map projection is ETRS-1989-UTM-32.

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 model. The bathymetry of the Limfjorden model is shown in Figure 4-1, whereas Figure 4-2 shows the resolution of the horizontal mesh. The vertical mesh of the Limfjorden model has a total of 20 model layers (5 sigma-layers for the upper 5 m of the water column and up to 15 z-layers with a thickness of 1m for the deeper positions). Further documentation on model mesh and horizontal/vertical resolution of the Limfjorden HD model can be found in DHI (2019d).

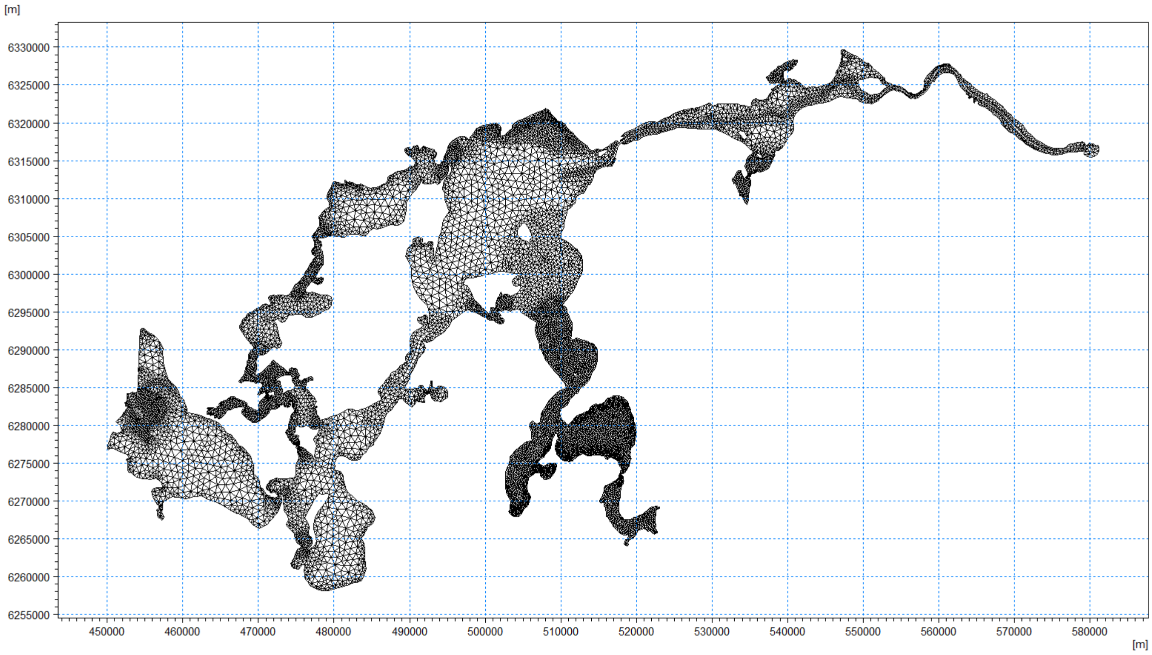

Figure 4-2 Resolution of the horizontal model mesh of the Limfjorden model. The map projection is ETRS-1989-UTM-32.

4.2 Open Boundary Conditions

The Limfjorden model has two open boundaries. The boundary to the west at Thyborøn is in the narrow opening connecting Limfjorden to the North Sea, and the eastern boundary (Hals) is in the narrow opening connecting Limfjorden to the Kattegat. Profiles of biogeochemical state variables at the boundaries are extracted from DHI's operational North Sea model (UKNS2). Documentation on boundary conditions for the biogeochemical model development is given in DHI (2020).

4.3 Forcings

Data on solar radiation is calculated from clearness percentages and applied as a temporally and spatially varying forcing covering the model domain.

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 DHI (2020).

4.4 Sources

The Limfjorden model includes sources with land-based nutrient loadings. 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 4th order water body level.

More details are included in DHI (2020).

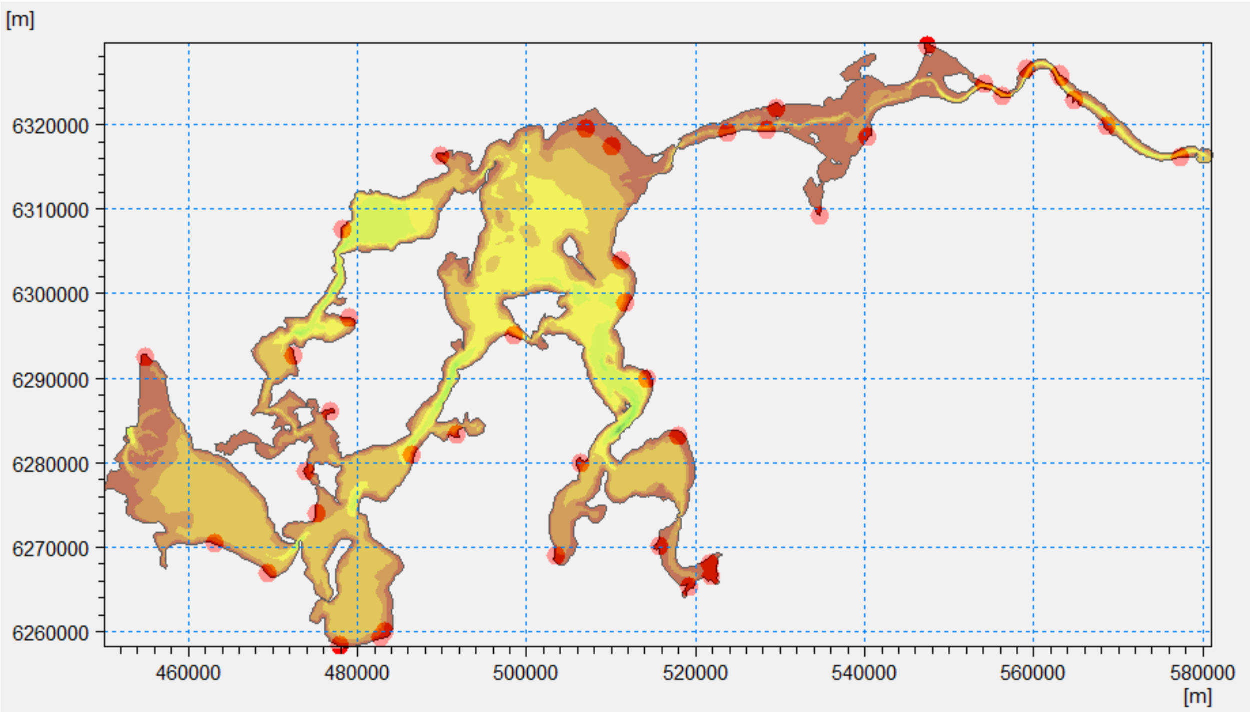

Figure 4-3 Location of sources in the Limfjorden model. The sources' positions represent the main rivers, but loadings are scaled to include all local run-off and point sources from land to the fjord.

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 Limfjorden model were estimated based on measurements within the Limfjorden 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 observations 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 specific performance (goodness of fit) measures (DHI 2019b; Erichsen & Timmermann 2017). As such, the model validation constitutes the final documentation of the model performance.

The Limfjorden 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 given for the entire period using a WEB-tool (rbmp2021-2027.dhigroup.com, Google Chrome only).

5.1 Model Calibration Procedure

Calibration of the biogeochemical Limfjorden 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), and 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.

Average concentrations of dissolved oxygen in bottom waters of the water bodies during 2016 range between 4 - 14 mg/l in Hjarbæk Fjord; between 5 - 12 mg/l in Bjørnholms Bugt, Riisgårde Bredning, Skive Fjord and Lovns Bredning, and between 7 - 13 mg/l in Nissum Bredning, Thisted Bredning, Kås Bredning, Løgstør Bredning, Nibe Bredning and Langerak (see Figure 5-1).

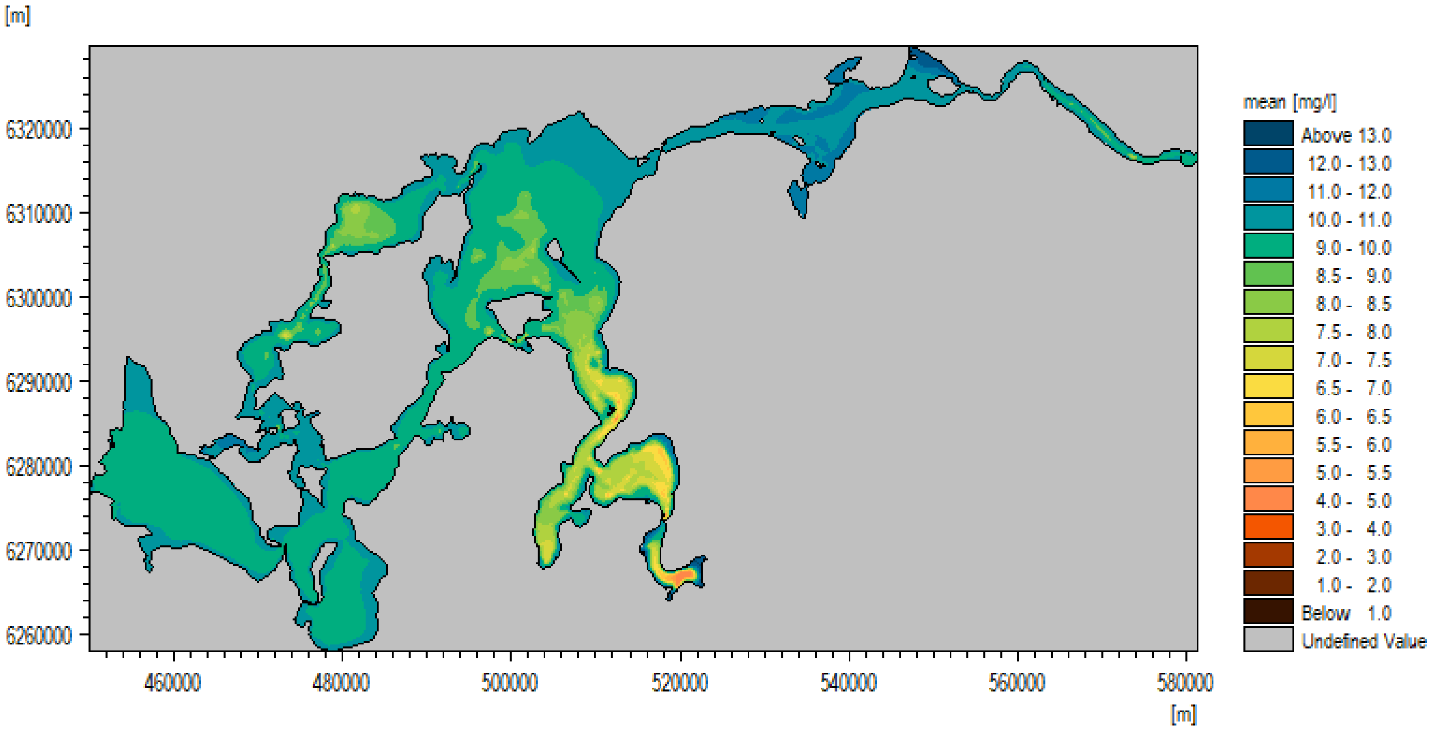

Figure 5-1 Modelled yearly average bottom water concentrations of dissolved oxygen (DO, mg/l) for 2016.

Yearly average concentrations of surface chlorophyll-a during 2016 range from 0.003 – 0.034 mg/l in Hjarbæk Fjord ; between 0.003 – 0.013 mg/l in Bjørnholms Bugt, Riisgårde Bredning, Skive Fjord and Lovns Bredning and between 0.002 - 0.013 mg/l in Nissum Bredning, Thisted Bredning, Kås Bredning, Løgstør Bredning, Nibe Bredning and Langerak (Figure 5-2). In the surface waters close to the two open boundaries (Thyboron and Hals), concentrations of chlorofyll-a are between 0.003 – 0.005 mg/l.

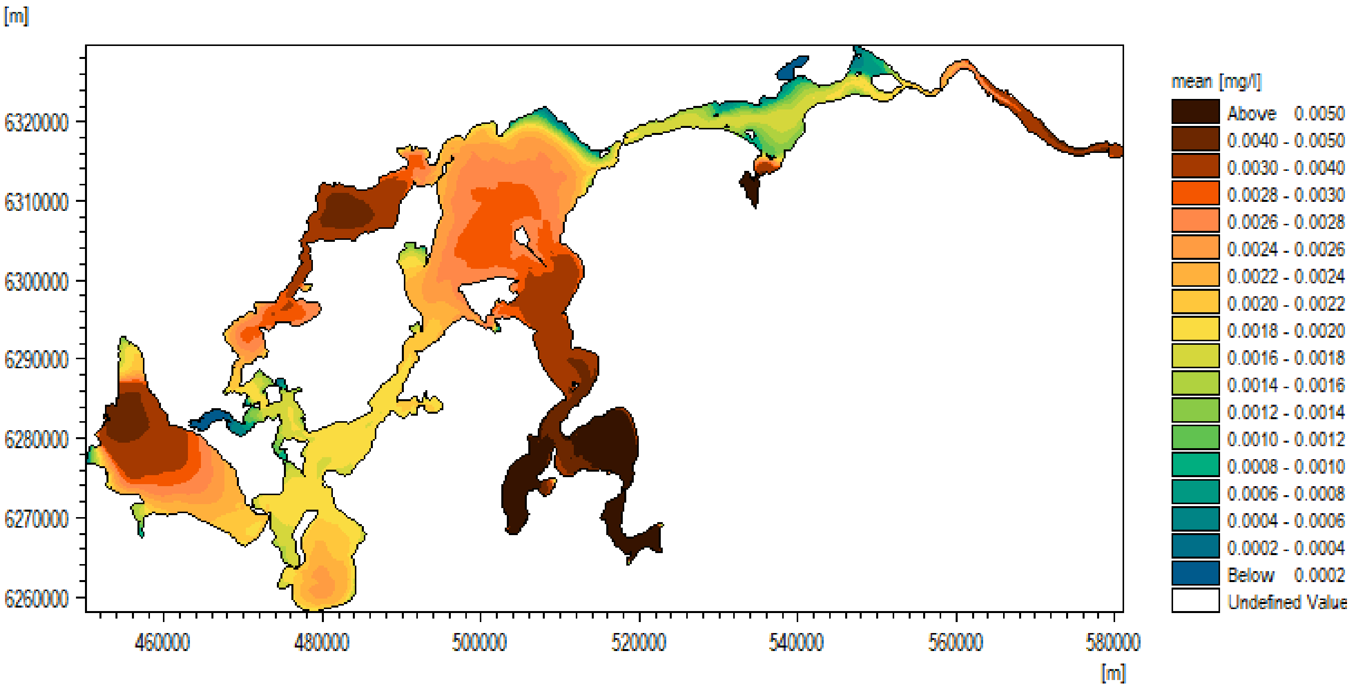

Figure 5-2 Modelled yearly average surface water concentrations of chlorophyll-a (CH, mg/l) for 2016.

Yearly average concentrations of surface total nitrogen during 2016 ranging between 1.8 – 3.6 mg/l in Hjarbæk Fjord; between 0.5 - 2 mg/l in Bjørnholms Bugt, Riisgårde Bredning, Skive Fjord and Lovns Bredning and between 0.4 – 3.2 mg/l in Nissum Bredning, Thisted Bredning, Kås Bredning, Løgstør Bredning, Nibe Bredning and Langerak (Figure 5-3).

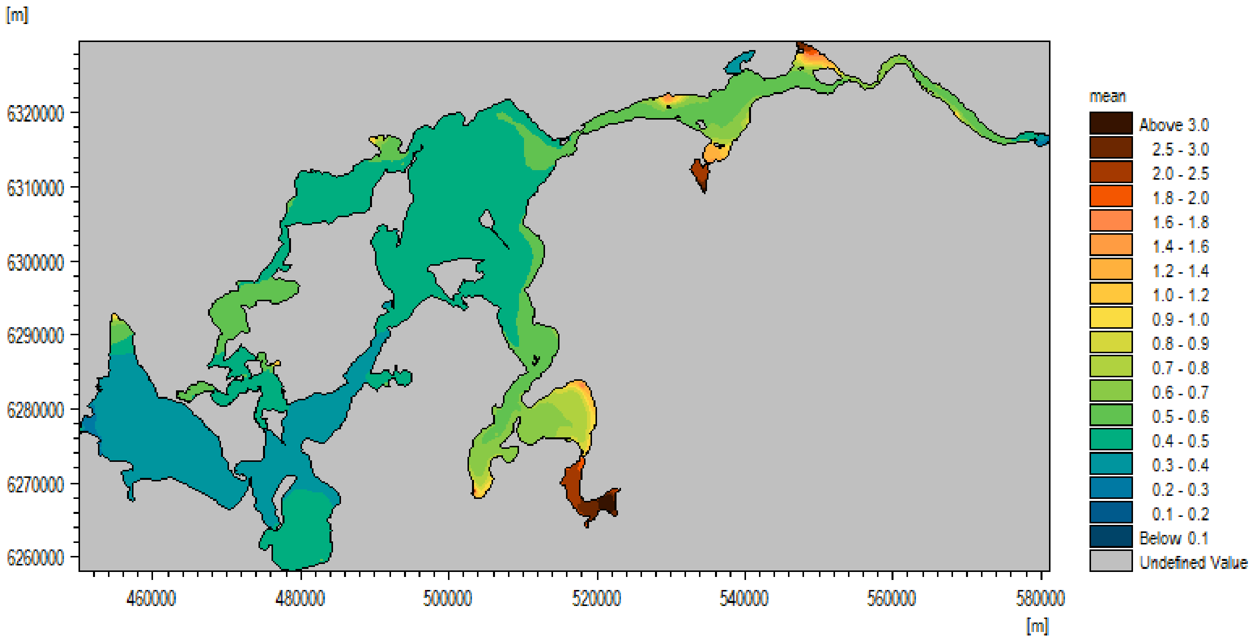

Figure 5-3 Modelled yearly average surface water concentrations of total nitrogen (TN, mg/l) for 2016.

Annual average concentrations of surface total phosphorus during 2016 are between 0.06 – 0.25 mg/l in Hjarbæk Fjord; between 0.02 – 0.10 mg/l in Bjørnholms Bugt, Riisgårde Bredning, Skive Fjord and Lovns Bredning and between 0.01 – 0.25 mg/l in Nissum Bredning, Thisted Bredning, Kås Bredning, Løgstør Bredning, Nibe Bredning and Langerak (Figure 5-4).

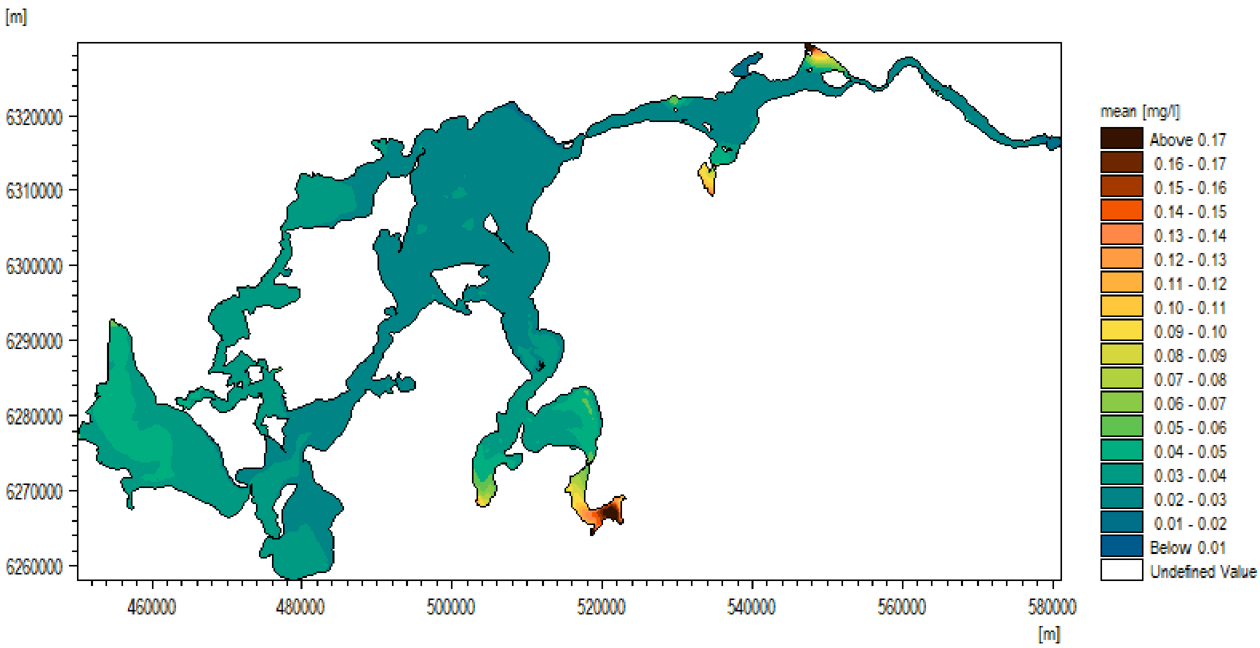

Figure 5-4 Modelled yearly average surface water concentrations of total phosphorus (TP, mg/l) for 2016.

5.3 Model Performance

The Limfjorden biogeochemical model was calibrated and validated against measured data (observations) on modelled ecosystem parameters at selected stations within the model domain. Figure 5-5 shows the location of 36 stations within the model domain. Out of the 36 stations, 12 stations had enough measurement data in the period 2002-2016 (at least one year of weekly or bi-weekly data) to be included in the model calibration and validation (stations NOR6602, RKB59, VIB3702-00001, VIB3705-00001, VIB3708-00001, VIB3711-00001, VIB3720-00001, VIB3723-00001, VIB3726-00001, VIB3727-00001, VIB3728-00001, and VIB3729-00001).

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 Limfjorden model compares well to the measurements in terms of model parameters (see Figure 5-6 to Figure 5-12), and the overall performance measure (summarized in Table 5-1 to Table 5-3) confirms a statistically good agreement between measurements and model results.

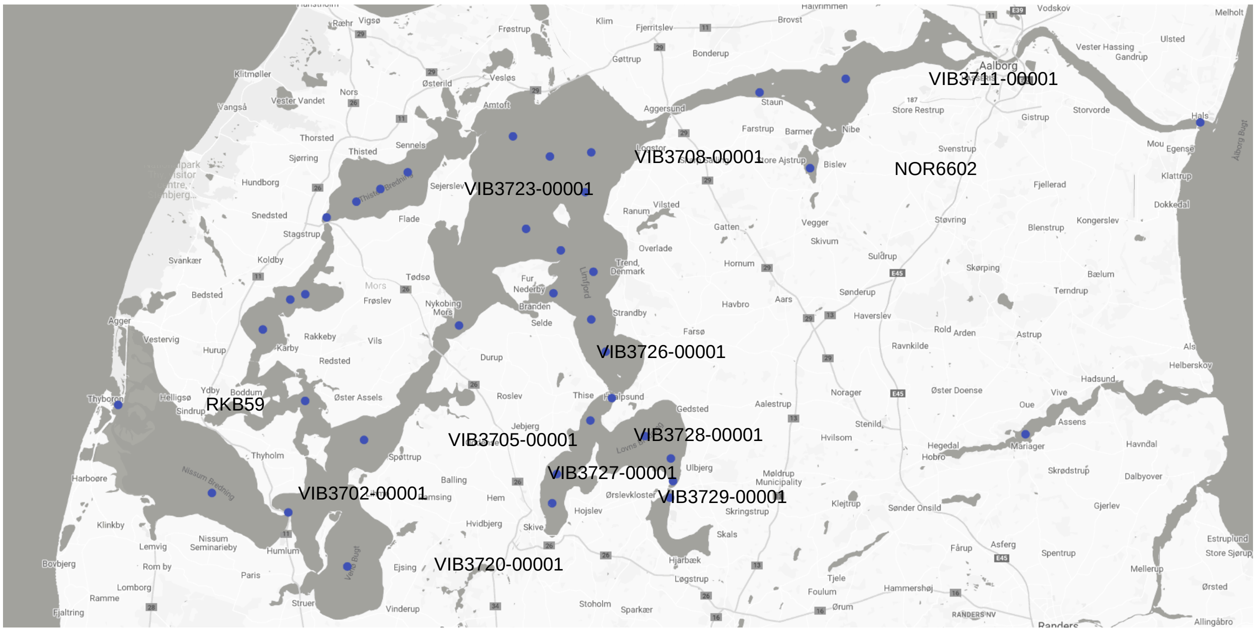

Figure 5-5 Location of stations used for performance measures in Limfjorden (only stations with an ID).

5.3.1 Calibration/Validation at Station VIB3727-00001

In the following sections, we present an example of the calibration/validation from Limfjorden at station VIB3727-00001 (Skive Fjord) and refer to rbmp2021-2027.dhigroup.com (Google Chrome only) for more details on the Danish measurement stations. The location of station VIB3727-00001 is shown in Figure 5-5.

The comparison at station VIB3727-00001 shows a good agreement between the measurements and the Limfjorden model for 95% of the parameters according to the three performance measure 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 VIB3727-00001 in the surface and bottom waters (here 5 m) are shown. From the figure, it is seen that for DO, the model represents well the variability and seasonality of the surface and bottom waters. This is in agreement with the statistical performance measures (see Table 5-1 to

Table 5-3), where measured and modelled DO compare ‘excellent’ (P-Bias) and ‘very good’ (Spearman Rank Correlation and CF) at station VIB3727-00001.

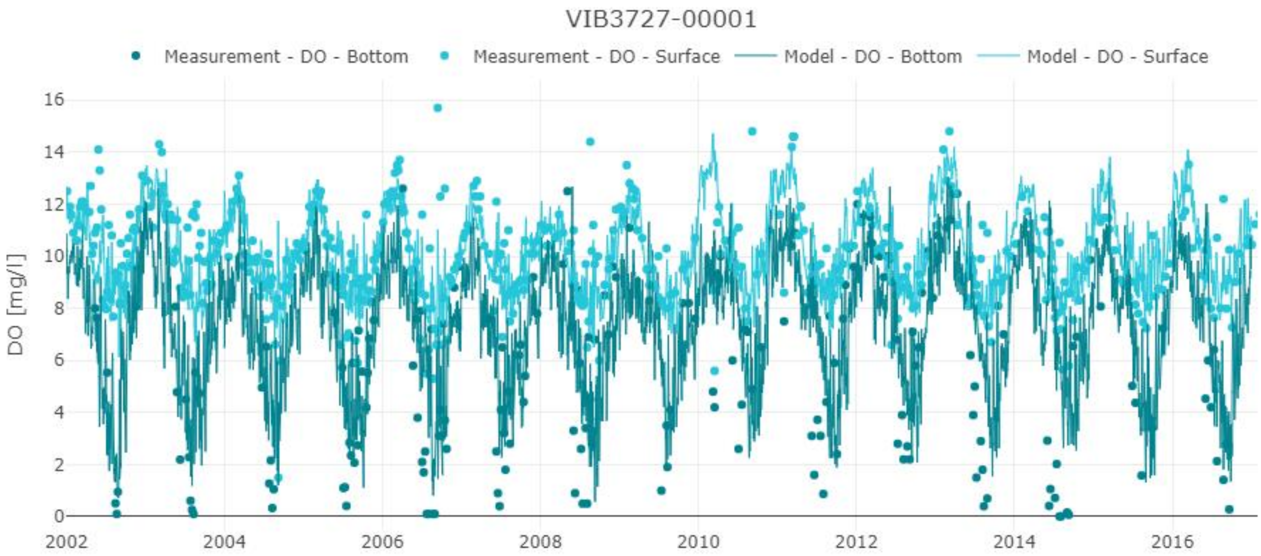

Figure 5-6 Comparison of measured and modelled concentrations of dissolved oxygen (DO, mg/l) at station VIB3727-00001 in the surface and bottom waters (5 m). Dots represent measurements, and the solid line shows modelled data for the entire period.

For chlorophyll-a (CH), the dynamics in seasonality is, in general, well represented by the model (see Figure 5-7). During September 2006, however, the observed bloom in measured surface CH (up to 1.1 mg/l) is not detected in the modelled surface waters. From the statistical performance measures, annual CH compares ‘very good’ (CF) and ‘good’ (P-Bias and Spearman Rank Correlation) (see Table 5-1 to Table 5-3).

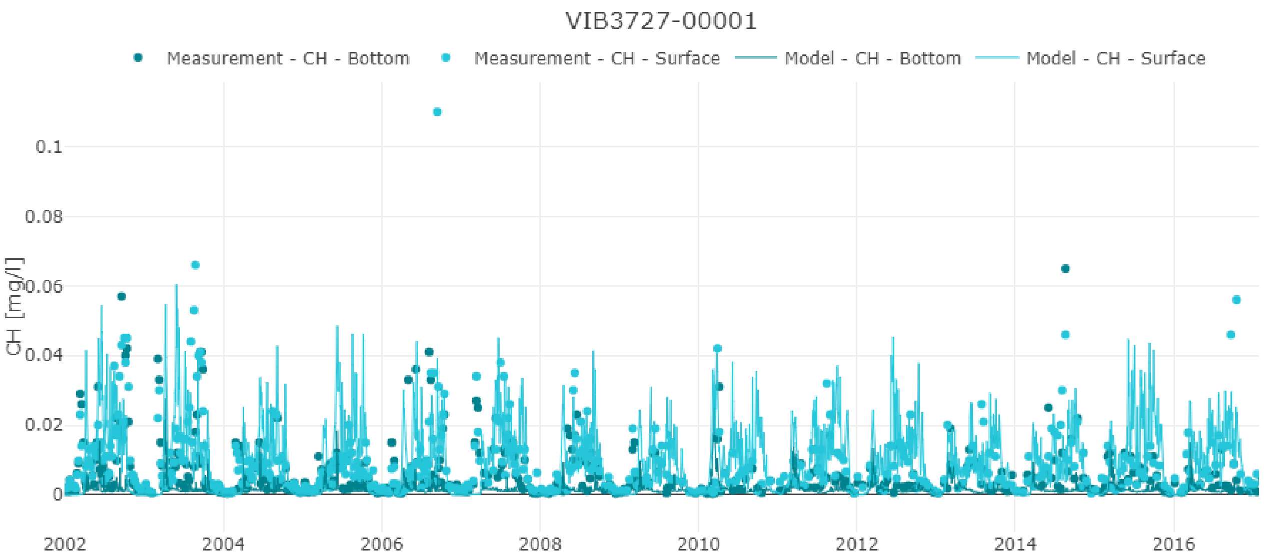

Figure 5-7 Comparison of measured and modelled concentrations of chlorophyll-a (CH, µg/l) at station VIB3727-00001 in surface and bottom waters (5 m). Dots represent measurements, and solid lines show modelled data for the entire period.

For light attenuation coefficient (K_d), the seasonality is in general well represented by the model (see **Error! Reference source not found.**). The model captures not all peaks in observed Kd; h owever, the model seems to reproduce the slight reduction within the period seen in the measurements. 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).

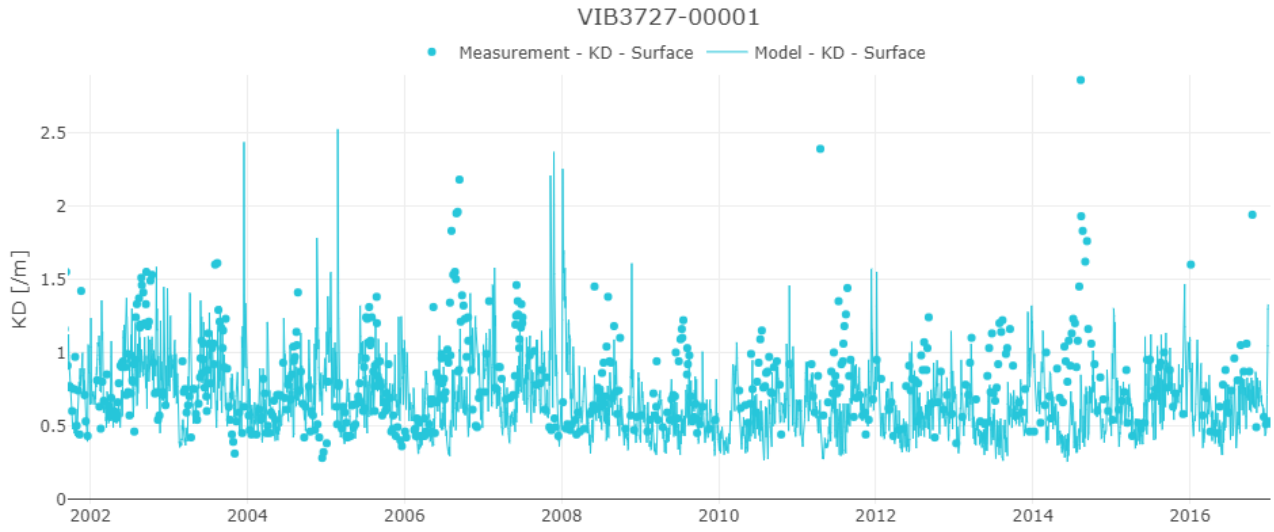

Figure 5-8 Comparison of measured and modelled concentrations of light attenuation (K_d, m^{-1}) at station VIB3727-00001 in surface water. Dots represent measurements, and solid lines show modelled data for the entire period.

For dissolved inorganic nitrogen (DIN), the structure in the seasonality is well represented by the Limfjorden model (see Figure 5-9). From the statistical performance measures, annual DIN compares 'excellent' (P-Bias) and 'very good' (Spearman Rank Correlation and CF) (Table 5-1 to Table 5-3).

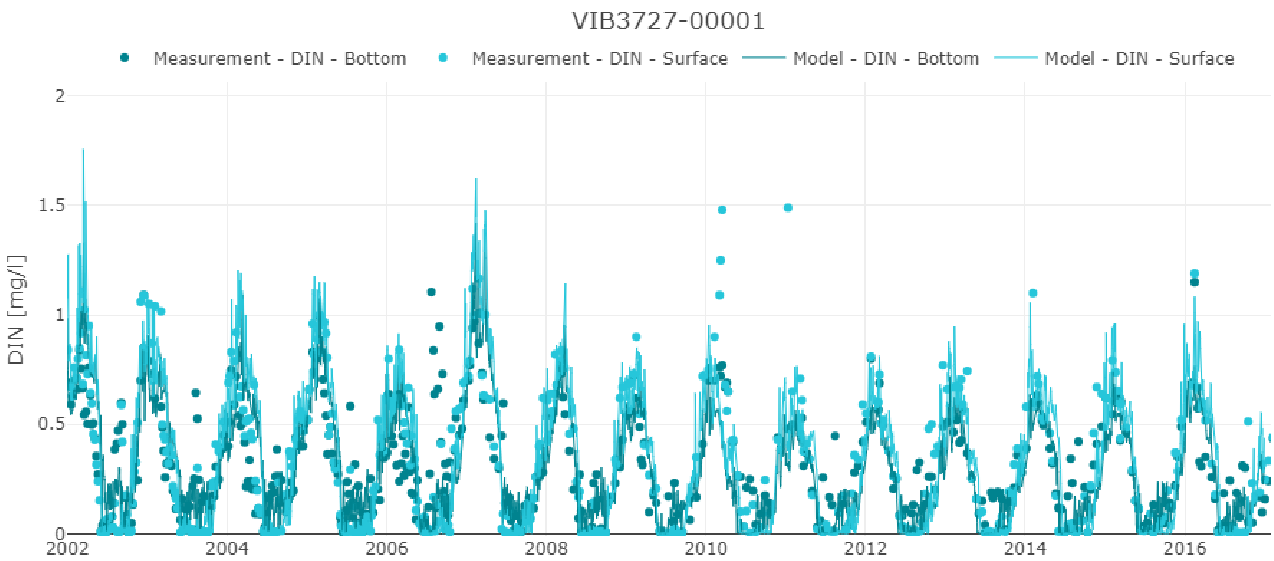

Figure 5-9 Measured and modelled concentrations of dissolved inorganic nitrogen (DIN, mg/l) at station VIB3727-00001 in the surface and bottom waters (5 m). Dots represent measurements, and solid lines show modelled data for the entire period.

When comparing measured and modelled concentrations of DIP (see Figure 5-10), we see similar winter concentrations and a definite drop in spring. The model tends to underestimate absolute values of winter DIP in bottom waters. However, the overall patterns are well represented by the model, which is further supported by the statistical performance measures, where the model performance for annual DIP is 'excellent' (P-Bias), 'very good' (CF) and 'good' (Spearman Rank Correlation) (see

Table 5-1 to

Table 5-3).

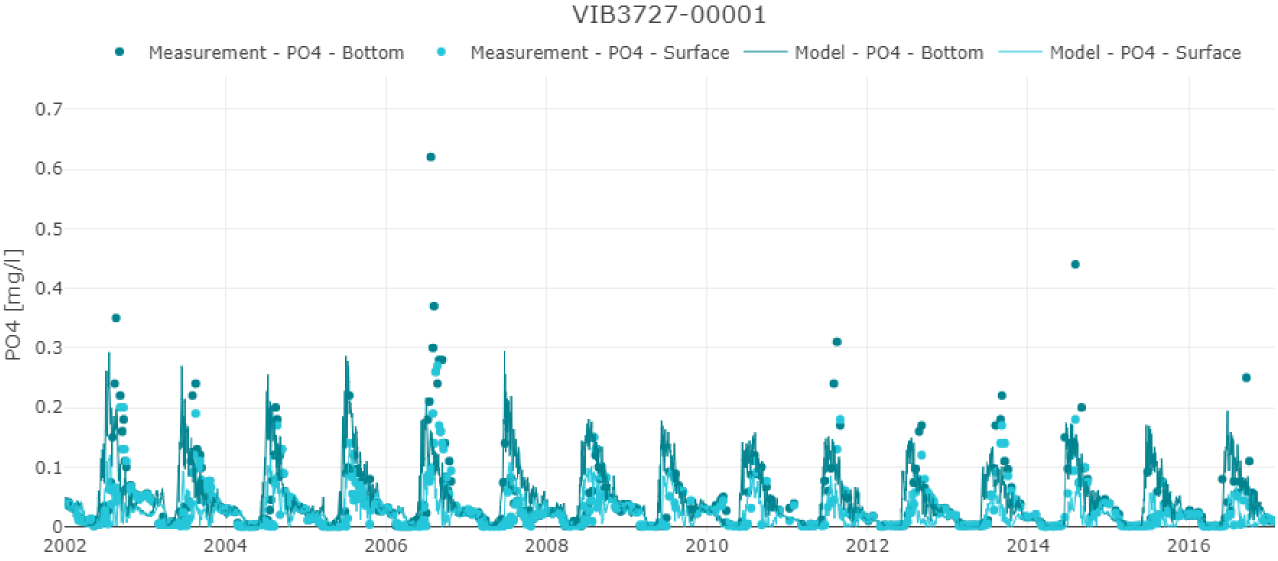

Figure 5-10 Measured and modelled concentrations of dissolved inorganic phosphorus (DIP, mg/l) at station VIB3727-00001 in the surface and bottom waters (5 m). Dots represent measurements, and solid lines show modelled data for the entire period.

In Figure 5-11, comparisons of measured and modelled total nitrogen (TN) at station VIB3727-00001 in surface water and bottom water are shown. 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), as measured and modelled TN compare 'excellent' (P-Bias) and 'very good' (Spearman Rank Correlation and CF) at station VIB3727-00001.

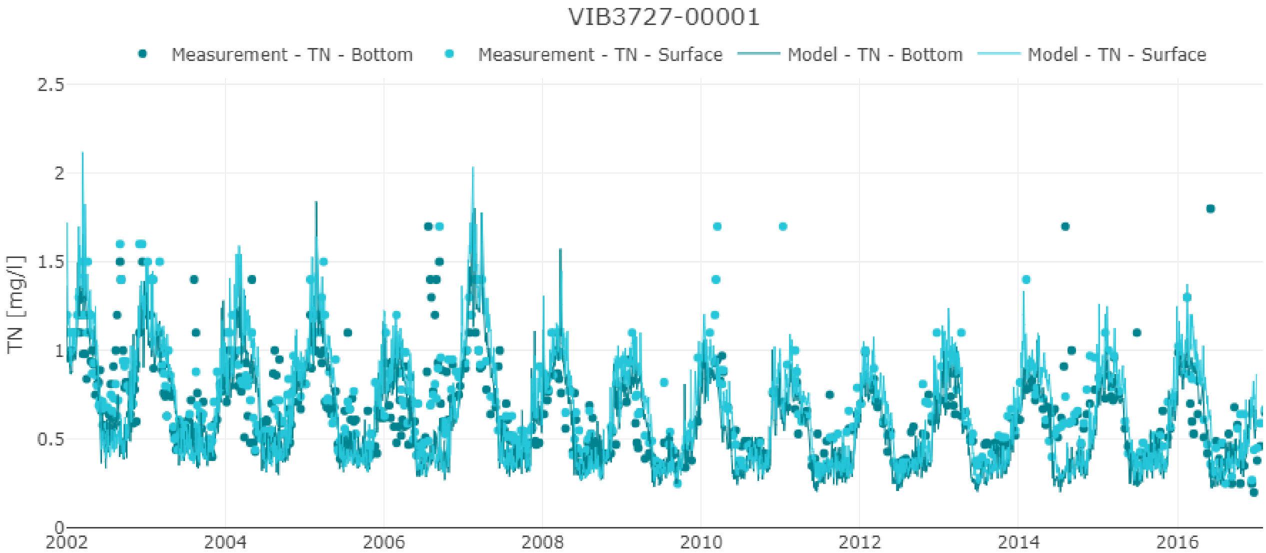

Figure 5-11 Comparison of measured and modelled concentrations of total nitrogen (TN, mg/l) at station VIB3727-00001 in surface and bottom waters (5 m). Scatter data represent measurements, and solid lines show modelled data for the entire period.

The seasonal dynamics in TP predicted by the model (see Figure 5-12) compare well with measured data on TP. The model tends to underestimate measured winter concentrations of TP. The model performance for TP at station VIB3727-00001 (Table 5-1 to Table 5-3) is 'very good' (Spearman Rank Correlation and CF) and 'good' (P-Bias).

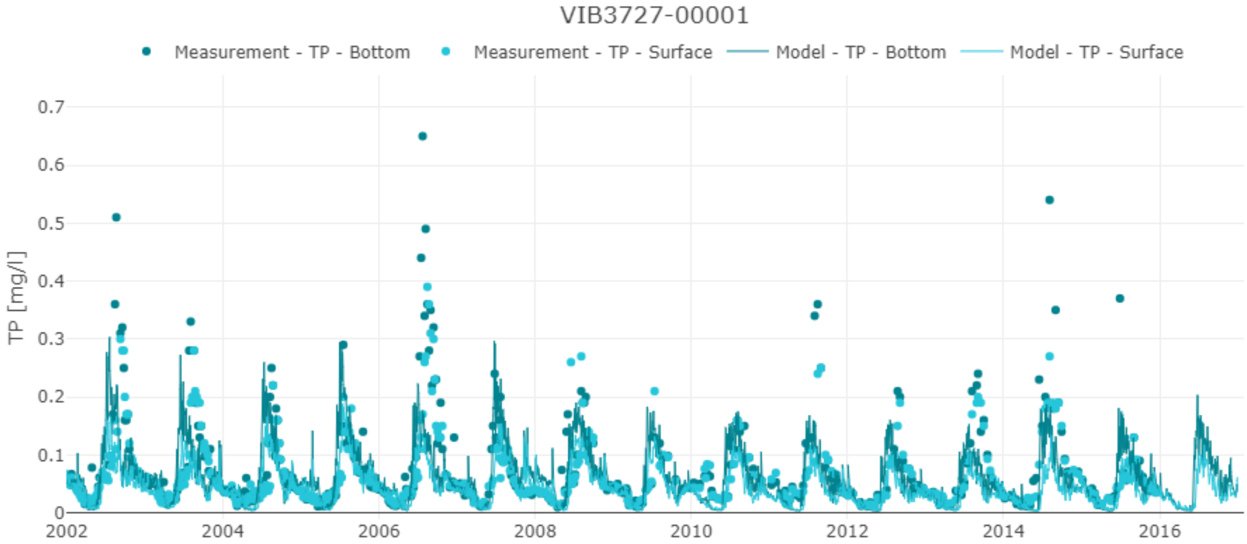

Figure 5-12 Comparison of measured and modelled concentrations of total P (TP) at station VIB3727-00001 in surface and bottom waters (5 m). Scatter data represent measurements, and solid lines show modelled data for the entire period.

5.3.2 General Calibration/Validation

For the calibration/validation period (2002-2016) 12 out of 36 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 (stations NOR6602, RKB59, VIB3702-00001, VIB3705-00001, VIB3708-00001, VIB3711-00001, VIB3720-00001, VIB3723-00001, VIB3726-00001, VIB3727-00001, VIB3728-00001 and VIB3729-00001). Figure 5-5 shows the locations with measurements on ecosystem parameters (chlorophyll-a (CH), light attenuation (K_d), dissolved oxygen (DO), dissolved inorganic phosphorus (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, Google Chrome only).

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 Limfjorden, 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 five different quality measures at 12 stations were found to be 'excellent', 'very good' or 'good' for 85% of the measurements (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 88% of the measurements.

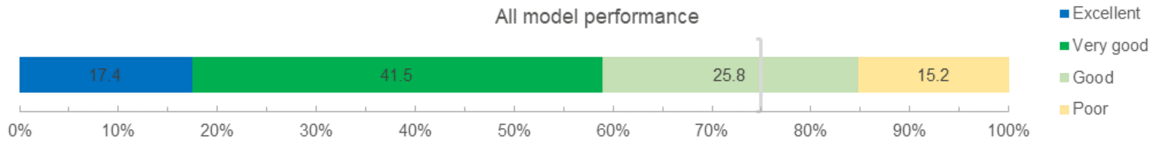

Figure 5-13 Bar chart illustrating all model performance evaluated against three different quality measures and all parameters. The vertical line indicates the aim of 75% being ‘excellent’, ‘very good’ or ‘good’.

According to P-Bias (Table 5-1), the model meets ‘excellent’, ‘very good’ or ‘good’ in 83% of all measurements (including specific winter and summer evaluations) and 84% 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 to the observed values. In general, the P-Bias obtains negative values for most of the parameters, indicating that the model tends to underestimate observed values. On average, P-Bias evaluates the model performance for dissolved oxygen and TN to be ‘excellent’; for DIN the model performance is on average ‘very good’, and for CH, K_d, DIP and TP the model performance is on average ‘good’ evaluated from P-Bias.

From the quality measure Spearman Rank Correlation (Table 5-2), the model performance meets ‘excellent’, ‘very good’ or ‘good’ in 71% of all measurements (including specific winter and summer evaluations) and 81% 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, DIN and TN to be ‘very good’. For CH, DIP and TP, the average model performance is ‘good’ and ‘poor’ for K_d when evaluated from Spearman Rank Correlation.

According to the performance measure CF (Table 5-3), the model meets ‘excellent’, ‘very good’ or ‘good’ in 98% of all measurements and 100% of annual measurements at the stations. On average, the Cost Function evaluates CH, DO, DIN, DIP, TN, and TP to be ‘very good’ and K_d to be ‘good’ on average.

Table 5-1 Review of model performance (P-Bias, in %) 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
NOR6602	20.2	-23.0	-58.9	-11.0	18.2	-2.2	-65.0	-49.3	4.9	6.8	-14.6 [d]	[97-158]	[37-70]
RKB59	-2.2	13.2	-6.8	-1.7	-5.7	-8.1	8.2	21.8	-2.2	-15.4	-7.2	[79-260]	[56-114]
VIB3702-00001	9.8	15.1	-39.1	4.8	9.2	-35.0	-43.6	-33.3	-0.2	50.8	27.2	[323-402]	[61-222]
VIB3705-00001	2.3	-3.8	-53.5	-12.6	11.8	-64.1	-47.1	-30.9	-0.8	49.7	13.0	[49-165]	[17-118]
VIB3708-00001	-5.1	-29.4	-24.6	-11.3	8.2	-49.8	-45.2	-31.2	0.4	6.3	-20.0	[414-577]	[84-330]
VIB3711-00001	-2.1	-24.9	-30.7	-12.0	10.0	-43.9	-65.3	-64.4	3.5	29.9	-6.0	[275-301]	[58-195]
VIB3720-00001	15.0	3.3	-25.2	-2.2	27.4	-62.7	-62.6	-47.6	-1.1	59.9	17.1	[34-60]	[9-30]
VIB3723-00001	-5.9	15.6	32.7	-5.4	8.4	6.6	-20.0	11.8	-2.9	27.7	1.9	[56-108]	[20-52]
VIB3726-00001	-4.7	-9.2	18.3	-4.8	21.0	-17.3	-60.7	-51.0	-2.8	-5.3	-21.8	[307-536]	[106-249]
VIB3727-00001	-6.0	-21.6	3.5	-3.3	2.6	-8.7	-30.7	-28.7	1.7	-18.1	-28.0	[563-956]	[169-455]
VIB3728-00001	-2.0	-26.2	-3.4	2.8	13.5	15.4	-41.1	-36.7	1.1	-15.2	-22.1	[215-454]	[83-215]
VIB3729-00001	13.9	-50.5	-30.1	9.0	13.2	-2.2	-44.9	-24.6	14.8	-29.8	-32.2	[142-314]	[50-154]

[a] Jan, Feb, Dec
[b] May-Sep
[c] Mar-Sep
[d] K_d calculated from Secchi Depth (SD)

Table 5-2 Review of model performance (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
NOR6602	0.61	0.11	0.40	0.52	0.77	0.38	0.38	0.06	0.43	0.10	-0.06 [d]	[97-158]	[37-70]
RKB59	0.84	0.85	0.94	0.90	0.93	0.85	0.80	0.79	0.74	0.45	0.34	[79-260]	[56-114]
VIB3702-00001	0.74	0.53	0.57	0.79	0.84	0.46	0.19	0.00	0.85	0.48	0.44	[323-402]	[61-222]
VIB3705-00001	0.72	0.48	0.37	0.94	0.87	-0.15	0.55	0.08	0.80	0.01	0.01	[49-165]	[17-118]
VIB3708-00001	0.74	0.53	0.56	0.68	0.79	0.31	0.10	0.12	0.82	-0.03	-0.05	[414-577]	[84-330]
VIB3711-00001	0.67	0.39	0.59	0.63	0.77	0.33	0.18	0.12	0.88	0.05	0.05	[275-301]	[58-195]
VIB3720-00001	0.84	0.15	0.36	0.87	0.83	0.28	0.24	0.15	0.87	0.42	0.41	[34-60]	[9-30]
VIB3723-00001	0.86	0.55	0.25	0.94	0.90	-0.02	0.27	-0.19	0.79	-0.43	-0.38	[56-108]	[20-52]
VIB3726-00001	0.74	0.66	0.57	0.81	0.87	0.15	0.39	0.43	0.88	-0.38	-0.22	[307-536]	[106-249]
VIB3727-00001	0.71	0.67	0.57	0.79	0.83	0.35	0.46	0.36	0.80	0.06	0.18	[563-956]	[169-455]
VIB3728-00001	0.69	0.65	0.45	0.80	0.87	-0.09	0.33	0.22	0.80	0.08	0.03	[215-454]	[83-215]
VIB3729-00001	0.77	0.38	0.50	0.73	0.89	0.39	0.47	0.46	0.80	0.12	0.08	[142-314]	[50-154]

[a] Jan, Feb, Dec
[b] May-Sep
[c] Mar-Sep
[d] K_d calculated from Secchi Depth (SD)

Table 5-3 Review of model performance (Cost Function, 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
NOR6602	0.70	0.74	0.42	0.66	0.51	0.74	0.63	0.73	0.69	0.94	0.94[d]	[97-158]	[37-70]
RKB59	0.34	0.38	0.17	0.16	0.12	0.43	0.28	0.43	0.57	0.57	0.68	[79-260]	[56-114]
VIB3702-00001	0.72	0.84	0.69	0.43	0.33	0.92	0.72	0.98	0.42	1.01	0.84	[323-402]	[61-222]
VIB3705-00001	0.89	0.92	0.92	0.55	0.42	2.14	0.95	0.99	0.38	1.63	0.97	[49-165]	[17-118]
VIB3708-00001	0.67	0.63	0.53	0.62	0.43	1.08	0.70	0.96	0.41	1.37	1.17	[414-577]	[84-330]
VIB3711-00001	0.75	1.06	0.81	0.79	0.50	1.11	0.66	0.94	0.41	2.21	1.50	[275-301]	[58-195]
VIB3720-00001	1.07	1.20	0.95	0.48	0.39	2.92	0.86	1.25	0.28	1.67	1.48	[34-60]	[9-30]
VIB3723-00001	0.54	0.83	0.96	0.36	0.33	1.03	0.84	1.34	0.41	1.70	1.24	[56-108]	[20-52]
VIB3726-00001	0.73	0.60	0.67	0.48	0.43	0.91	0.74	0.85	0.36	1.25	1.13	[307-536]	[106-249]
VIB3727-00001	0.62	0.54	0.57	0.52	0.44	0.81	0.71	0.79	0.42	0.96	0.98	[563-956]	[169-455]
VIB3728-00001	0.55	0.55	0.62	0.50	0.36	1.00	0.83	0.87	0.39	0.88	0.95	[215-454]	[83-215]
VIB3729-00001	0.53	0.71	0.43	0.57	0.39	0.77	0.74	0.77	0.53	1.10	1.14	[142-314]	[50-154]

[a] Jan, Feb, Dec

[b] May-Sep

[c] Mar-Sep

[d] K_d calculated from Secchi Depth (SD)

6 Conclusion

This technical note shows that the model performance for the biogeochemical model covering Limfjorden meets the performance measure ‘excellent’, ‘very good’ or ‘good’ in 88% of the annual measures and 85% in both yearly and summer/winter measurements evaluated against five quality measures. The ambition is to meet the above criteria in 75% of all measures for all parameters and all stations (lumped). Hence, we conclude that the biogeochemical model covering Limfjorden is well suited for modelling scenarios as part of the overall development of mechanistic models towards the RBMP 2021-2027.

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