Development of Mechanistic Models

Mechanistic Model for Roskilde Fjord

Hydrodynamic model documentation

Miljø- og Fødevareministeriet
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The expert in **WATER ENVIRONMENTS**

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Mechanistic Model for Roskilde Fjord

Hydrodynamic model documentation

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1 Executive Summary

The model development presented in this technical note represents the hydrodynamic model development for Roskilde Fjord. The Roskilde Fjord model is a part of a larger model complex comprising a number of 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 hydrodynamic (HD) model setup covering Roskilde Fjord. This specific model includes two Danish water bodies:

Water Body*)	Number
Roskilde Fjord, ydre	1
Roskilde Fjord, indre	2

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

The Roskilde Fjord hydrodynamic model is developed to describe the physical system (water levels, currents, turbulence, mixing, salinity and water temperature). The model is developed to ensure a quality that will support a robust ecosystem (biogeochemical) model, an ecosystem model that eventually can be used for modelling a number of scenarios in support of the WFD implementation in Denmark.

As can be seen from the present technical note, the Roskilde Fjord hydrodynamic model was developed successfully for the entire model period 2002-2016. Only one station exists for the validation period (2011-2016):

- For that specific station the P-Bias is -5.4% with respect to salinity and -10.1% with respect to water temperature. Hence, the model meets a model performance of ‘excellent’ for salinity and ‘very good’ for temperature.
- With respect to the Spearman Rank Correlation the numbers are 0.91 and 0.99 for salinity and water temperature, respectively, which corresponds to an ‘excellent’ model performance.
- The Modelling Efficient Factor (MEF) for salinity is 0.59 corresponding to a ‘very good’ model, whereas the MEF for water temperature is 0.92 corresponding to an ‘excellent’ model.

The details behind the above data are available in Table 6-1 and Table 6-2 and time series comparisons are available here: rbmp2021-2027.dhigroup.com (Google Chrome only).

Based on the two tables and the time series (the time series are available at rbmp2021-2027.dhigroup.com) we conclude that the model describes the overall physical features in Nissum Fjord and that the model is adequate for ecosystem model development.

2 Introduction

The model development presented in this technical note represents the hydrodynamic model development for Roskilde Fjord. The Roskilde Fjord model is part of a larger model complex comprising a number of mechanistic models developed by DHI and a number of statistical models developed by 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 hydrodynamic (HD) model setup covering Roskilde Fjord. This specific model includes two Danish water bodies (see Table 2-1) and the water bodies are shown in Figure 2-1.

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

Water Body*)	Number
	1
Roskilde Fjord, indre	2

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

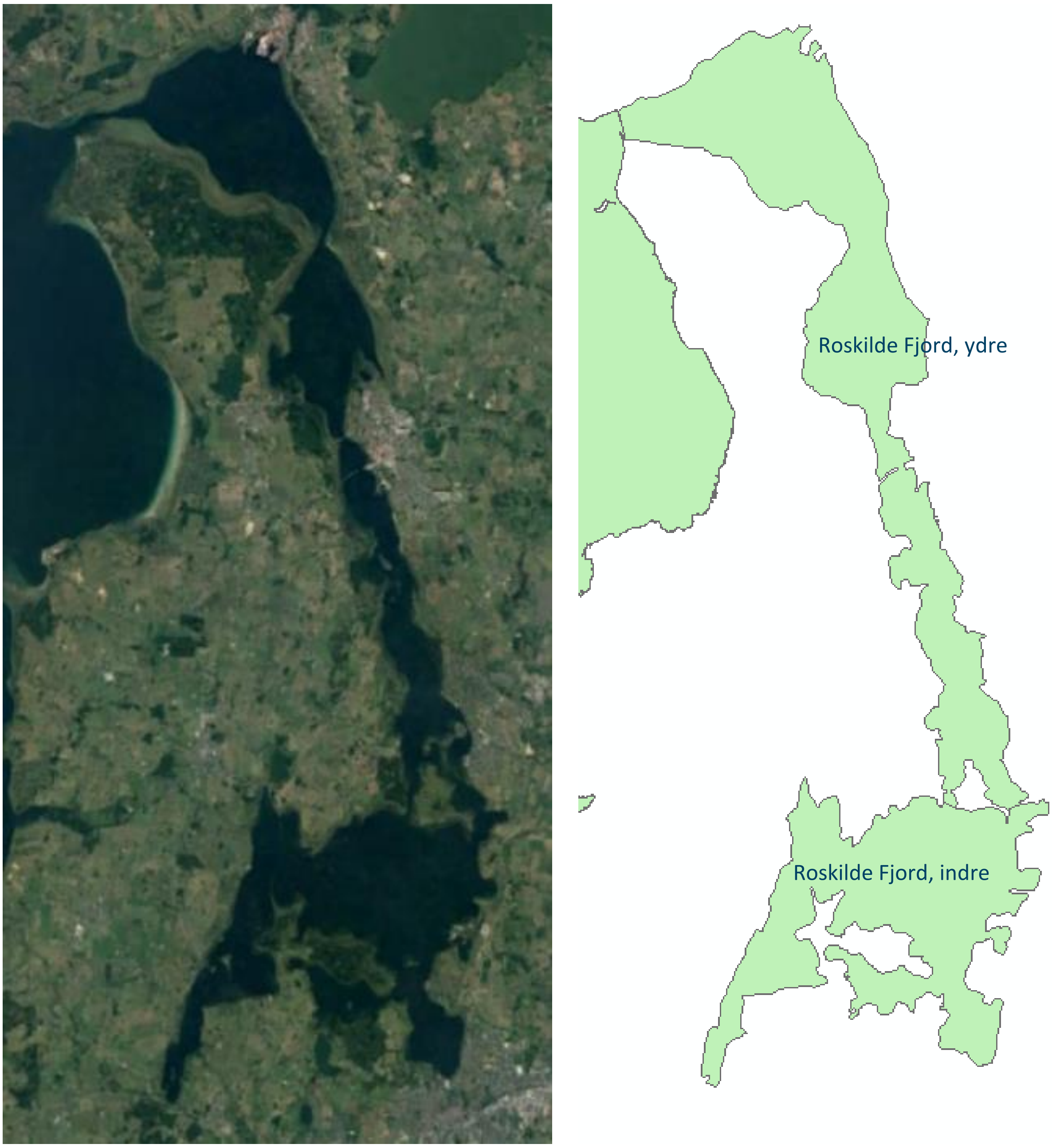


Figure 2-1 (Left) Roskilde Fjord (from Google Maps) and (right) the two water bodies included in the Roskilde Fjord model.

3 Modelling Concept

3.1 Mechanistic Modelling

The present technical note represents the hydrodynamic part of one model out of eleven mechanistic models. The eleven mechanistic models are developed to increase the knowledge of pressures and status in Danish marine waters and to provide tools for the Danish Environmental Protection Agency (EPA) as part of the implementation of the WFD.

Mechanistic models enable dynamic descriptions of ecosystems and interactions between natural forcings and anthropogenic pressures. Hence, mechanistic models can be applied for predictions of changes in specific components, like chlorophyll-a concentrations, due to climatic changes or changes in anthropogenic pressures.

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

The model development in this specific project aims at supporting the Danish EPA's implementation of the WFD. In this first phase of the model development the models are developed to represent the present period (2002-2016) evaluated against NOVANA measurements. Here we use present meteorological data, present nutrient loadings, etc.

After the models are finalized, they will be applied for scenario modelling, although the specific scenarios are not yet defined.

3.2 Model Development

The model development consists of a 3D hydrodynamic model describing the physical system; water levels, currents, salinities and water temperatures. Following the development of the hydrodynamic model is the development of the 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.

The Roskilde Fjord model is defined as an estuary specific model. The mechanistic model complex developed as part of the present project includes two regional models, three local-domain models and six estuary specific models.

- Regional models: 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, provide boundaries to local-domain models and estuary specific models.

- Local-domain models: These 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 waters bodies in and around Smålandsfarvandet.

- Estuary specific models: Six specific estuary (fjord) models are developed to allow for detailed modelling of the particular estuary.

All mechanistic model will be setup and calibrated for the period 2002-2010 and validated for the period 2011-2016. In this note the validation will be reported according to specific indices (DHI 2019a), whereas the entire period is included as time series in a WEB-tool (rbmp2021-2027.dhigroup.com) with one example included in section 6.1.1. Most data used for calibration and validation originate from the national monitoring programme NOVANA, see http://odaforalle.au.dk for 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 hydrodynamic model is based on the modelling software MIKE 3 HD FM (version 2017 SP2) developed by DHI. MIKE 3 HD FM is based on a flexible mesh approach and has been developed for applications within oceanographic, coastal and estuarine environments.

The system is based on the numerical solution of the three-dimensional (3D) incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and of hydrostatic pressure. Thus, the model consists of continuity, momentum, temperature, salinity and density equations and it is closed by a turbulent closure scheme. The free surface is taken into account using a sigma-coordinate transformation approach. The scientific documentation of MIKE 3 HD FM is given in DHI (2017a).

4 Model Setup

4.1 Introduction

The model setup comprises defining the model domain, establishing the model bathymetry and calculation mesh, preparing the model forcings in terms of open boundary conditions, atmospheric forcing and freshwater inflows, preparing the initial model conditions and setting up the model.

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

4.2 Model Domain

4.2.1 Introduction

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 of suitable open boundary locations, affect the choice of model domain.

For the Roskilde Fjord model, the selection of model domain is rather straight forward since Roskilde Fjord is an estuary with only one opening towards Isefjorden. The model covers the entire Roskilde Fjord and consists of two water bodies: The outer fjord and the inner fjord.

Generally, Roskilde Fjord is shallow (< 5m), but in the northern parts and in the central channel the depths are larger than 5m. The water is usually mixed, but periodical stratification in the deeper parts of the fjord can be observed.

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. In the following sections the details of the horizontal and vertical model mesh are described.

4.2.2 Horizontal Mesh

The horizontal mesh is unstructured and generally composed of triangular elements but may also include quadrangular elements. The mesh for the Roskilde Fjord model is shown in Figure 4-1 and the model bathymetry is shown in Figure 4-2.

The applied projection is ETRS_1989_Kp2000_Zealand and the horizontal calculation resolution varies from approximately 40m and up to approximately 500m using both triangular and quadrangular mesh elements. The vertical datum of the bathymetry is DVR90.

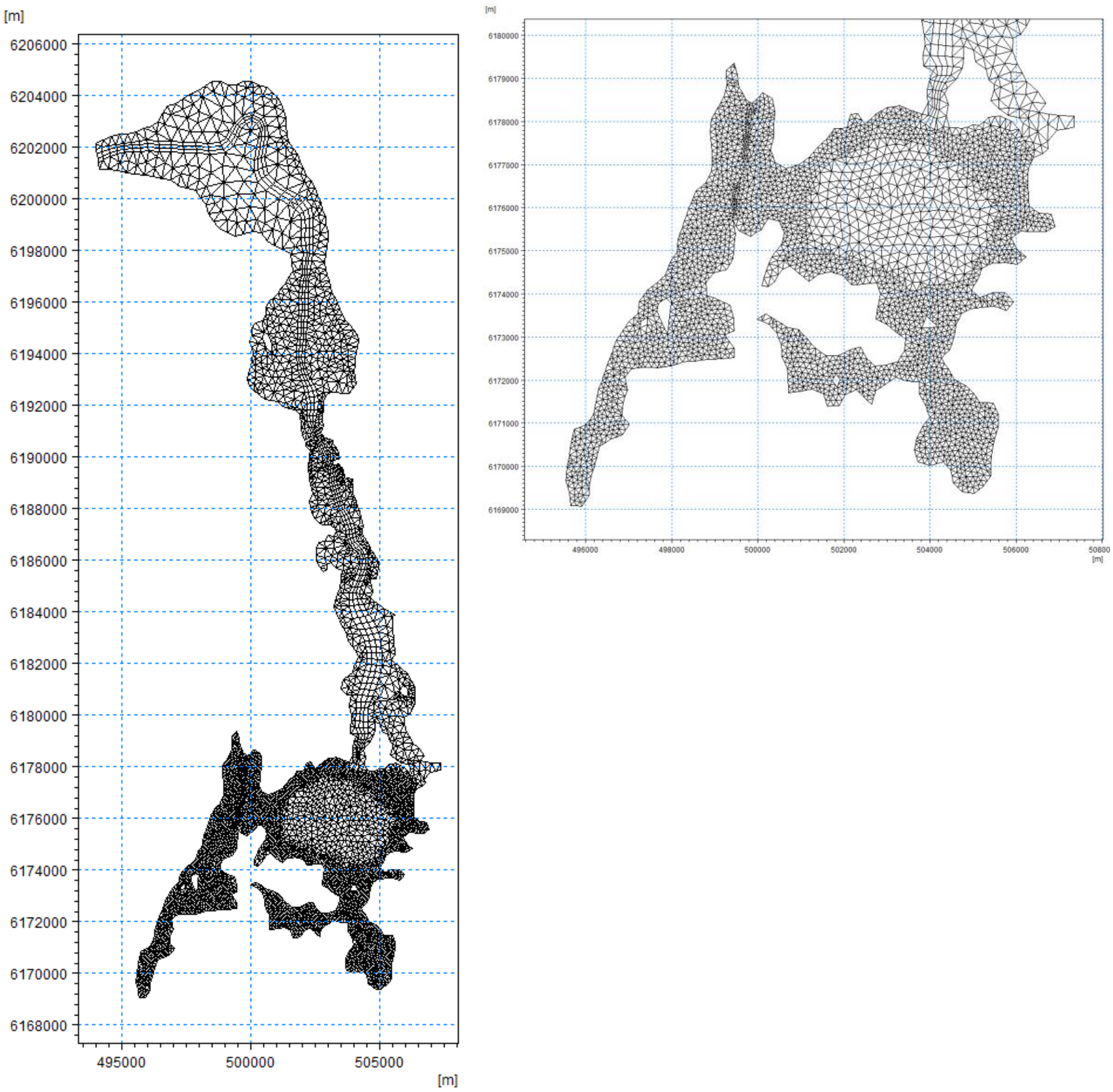


Figure 4-1 Roskilde Fjord horizontal model mesh (left: full model area, right: zoom to the southern inner fjord).

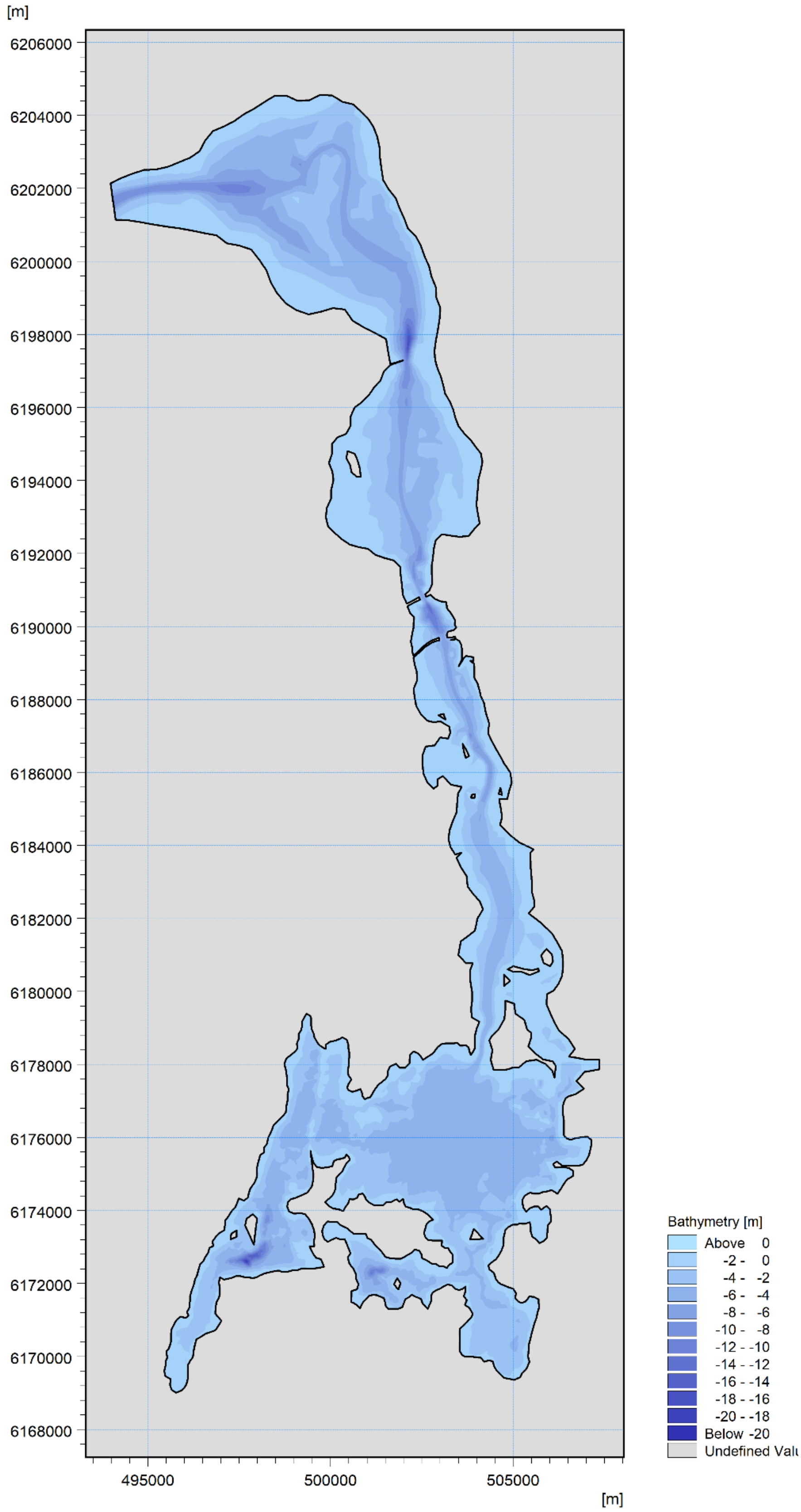


Figure 4-2 Roskilde Fjord model bathymetry with an open boundary towards Isefjorden to the northwest.

4.2.3 Vertical Mesh

The vertical mesh is structured and consists of either sigma-layers or a combination of sigma- and z-layers. In the Roskilde Fjord model, a total of 22 model layers are applied. The water column from the surface to -2m below MSL is resolved by two sigma-layers and the water column below is resolved by up to 20 z-layers. The z-layers consist of 14 layers with a layer thickness of 0.5m between -2m and -9m and 6 layers of 3m depth down to –27m.

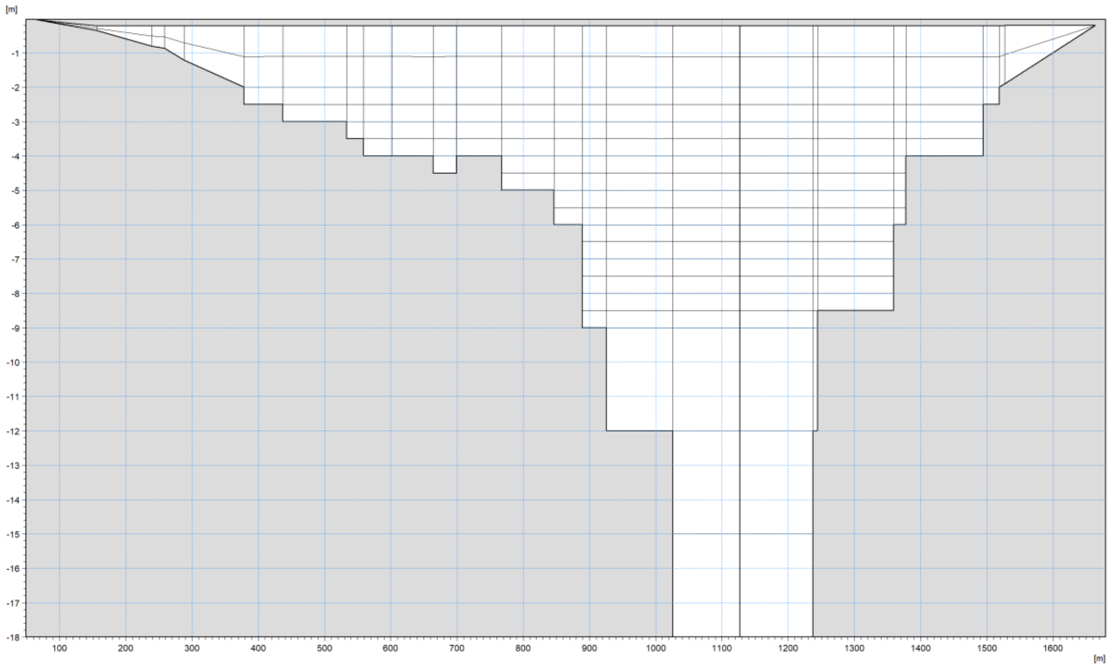


Figure 4-3 Example of cross section in Roskilde fjord showing the vertical model mesh consisting of two sigma layers down to -2m, z-layers of 0.5m resolution down to -9m and z-layers of 3m resolution below -9m (here down to the local depth of -18m).

4.3 Model Forcings

4.3.1 Open Boundary Conditions

The model has an open boundary towards Isefjorden, which is located to the northwest of the model. At this boundary the time variation of water levels, water temperature and salinity is specified.

The water levels were extracted from DHI's existing regional model, whereas measured water temperature and salinity profiles from Station VSJ10003 were used for specification of the time varying water temperature and salinity profiles at the boundary.

4.3.2 Atmospheric Forcing

The applied atmospheric forcing consists of:

- Wind speed/direction
- Air temperature
- Relative humidity
- Precipitation
- Clearness

Three-hourly time series of measured wind speed/direction, air temperature and relative humidity from station Roskilde Airport (Station 6170) were used for the full simulation period.

Measured time series of daily precipitation from Kollekolle (Station 29020) and Roskilde Airport (Station 0617) together with measured hourly data of clearness (cloud cover) from Roskilde Airport (Station 0617) were used for the period 1-1-2002 to 1-2-2009. For the period 1-2-2009 to 1-1-2017 hourly time series of model data extracted from meteorological fields provided by StormGeo were used.

4.3.3 Freshwater Sources

The Roskilde Fjord model includes a number of model sources representing the freshwater run-off from land to fjord. The freshwater data are available based on data from DCE (Aarhus University) – Denmark on a 4th order water body level and these data were distributed based on catchment area and knowledge of specific point sources and included in the model according to Figure 4-4.

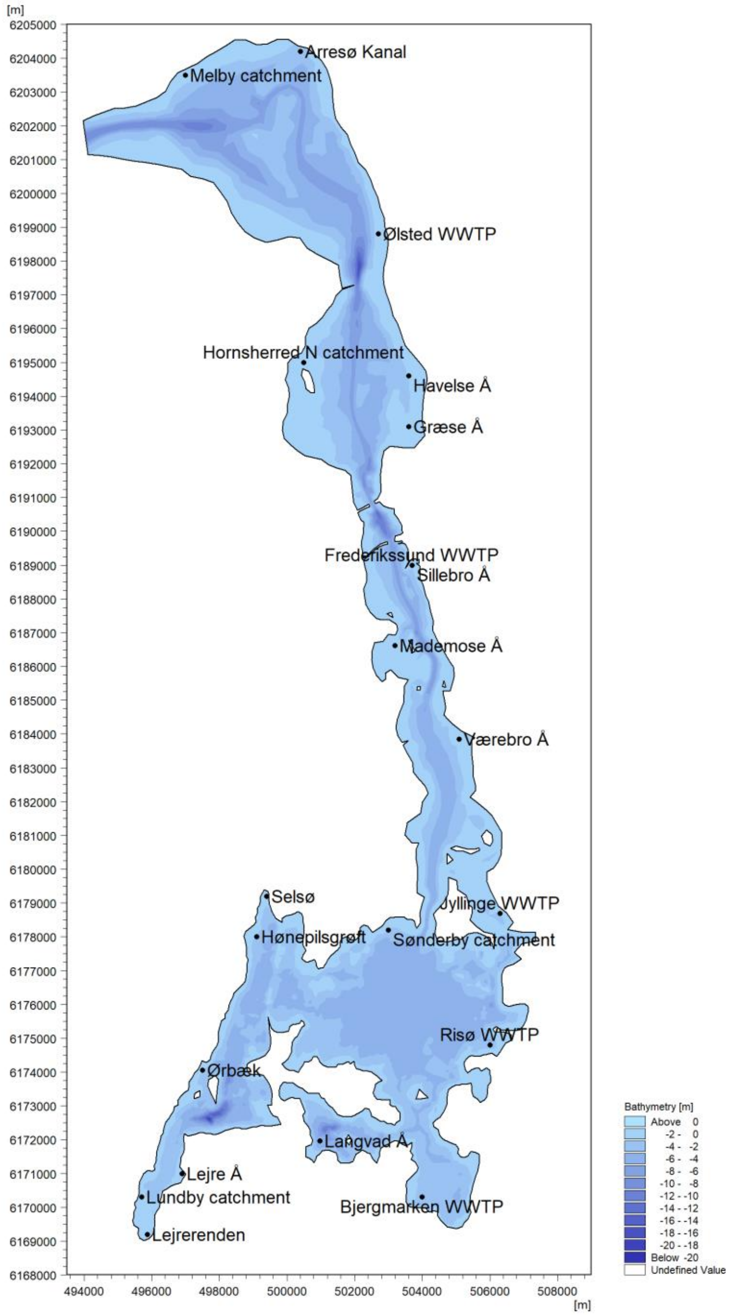


Figure 4-4 Distribution of fresh water sources applied in the Roskilde Fjord model.

4.4 Initial Conditions

The 3D model requires initial conditions of all prognostic parameters including water level, currents, salinity and sea temperature, etc. Water level and currents are specified as MSL and zero velocity, respectively, ('cold start') as the model quickly 'warms up' the currents and adjusts the water levels to the forcing.

For the 3D initial salinity and sea temperature fields, however, the warm-up takes longer time and accordingly initial fields of these two parameters are provided as input to the model. Monitoring data from stations within Roskilde Fjord are used to create the initial temperature and salinity fields.

5 Model Calibration

5.1 Introduction

Having set up the model, the model calibration is undertaken. The model calibration is the process of adjusting model settings and model parameters in order to obtain satisfactory agreement between observations and model results. In practice the model setup 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 and model parameters, and this is not always obtained in the first attempt.

5.2 Model Settings

In Table 5.1 a summary of applied model settings and constants is given.

Table 5.1 Summary of applied hydrodynamic model settings in the Roskilde Fjord model.

Feature/Parameter	Setting/Value
Flooding and drying	Included with parameters: 0.005m (drying) and 0.1m (wetting)
Wind friction coefficient	Constant equals 0.001255
Bed roughness	Constant equals 0.05m
Eddy viscosity	Horizontally: Smagorinsky formulation, C_s=0.28 Vertically: k-ε model with standard parameters and no damping
Solution technique	Shallow water equations: Low order Transport equations: Low order
Overall time-step	300s
Heat exchange	Constant in Dalton's law: 0.675, Wind coefficient Dalton's law :1.35 Otherwise standard parameters
Dispersion (S/T)	Scaled to Eddy viscosity. Horizontal/vertical scaling factors = 1.0/0.1

6 Model Validation

6.1 Introduction

The model validation is the process of comparing observations and model results qualitatively and quantitatively to demonstrate the suitability of the model. The qualitative comparison is typically done graphically, and the quantitative comparison is typically done by means of certain performance (goodness of fit) measures. As such the model validation constitutes the documentation of the model performance.

The Roskilde Fjord model has been run for the period 2002-2016, but the validation period was defined as the 6-year period 2011-2016. Model comparison plots and performance measures are consequently presented for this period, whereas model results and measurements of salinity and water temperature are presented for the entire period using a WEB-tool (rbmp2021-2027.dhigroup.com).

Figure 6-1 shows the different locations with salinity and temperature (ST) measurements during the period 2002-2016. These data are presented using the WEB-tool. For the validation period (2011-2016) the station ROS60 had sufficient data to be included in the model validation.

Figure 6-1 Location of monitoring stations for salinity and water temperature used in the model validation.

6.1.1 Salinity and Water Temperature

Figure 6-2 and Figure 6-3 show examples of comparisons of modelled and measured water temperature and salinity at the one station having measured data during the entire model period (2002-2016). The model reproduces well the variability and seasonality observed in the water temperature.

Similarly, the model reproduces well the variability and seasonality of salinities at station ROS60.

Further the figures illustrate that also interannual variations in the two parameters are represented by the model.

More comparisons are available at rbmp2021-2027.dhigroup.com.

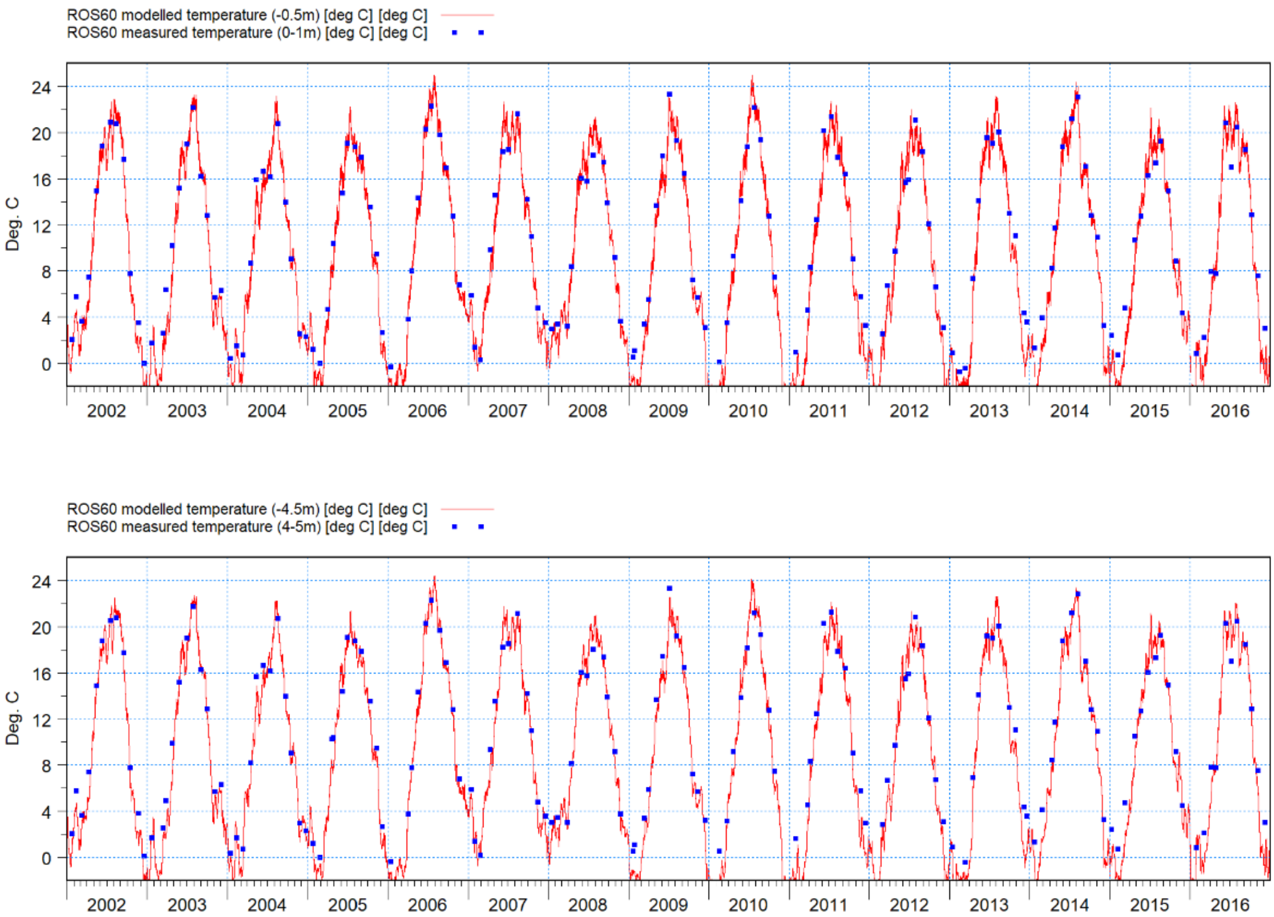
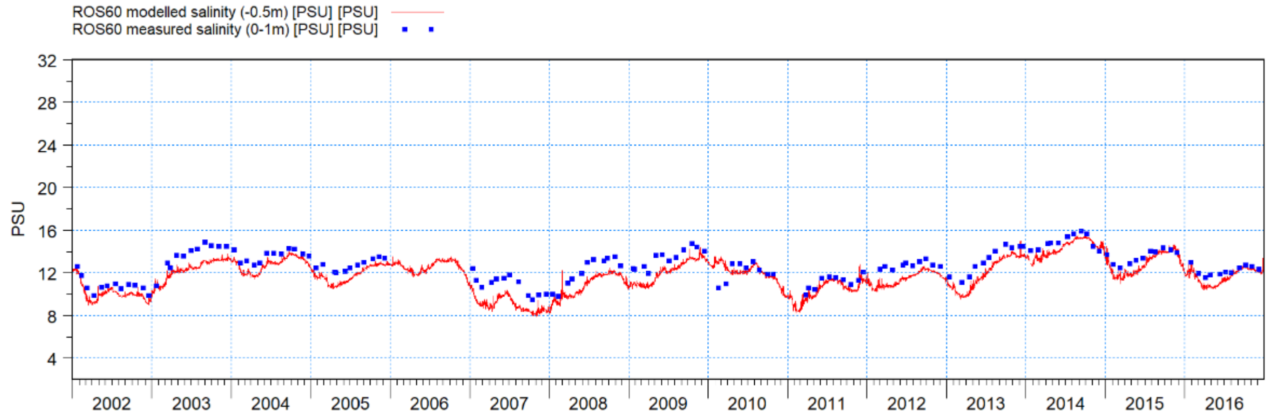


Figure 6-2 Comparison of measured and calculated water temperature at station ROS60 for the model period 2002-2016. Top panel show surface values and bottom panel shows bottom values.



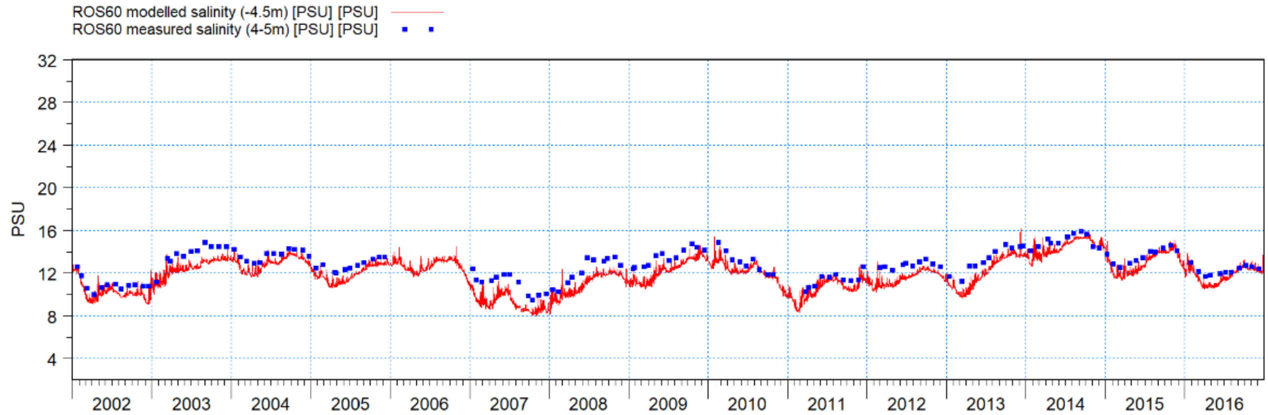


Figure 6-3 Comparison of measured and calculated salinity at station ROS60 for the model period 2002-2016. Top panel show surface values and bottom panel show bottom values.

In Table 6-1 and Table 6-2 the model performance is evaluated according to DHI (2019a) based on three performance measures: P-Bias, Spearman Rank Correlation and Modelling Efficiency Factor. Representative stations with good coverage available for the period 2011-2016 (here only ROS60) are included and the entire station network in the Roskilde Fjord model domain is shown in Figure 6-1. In the tables color codes are included to highlight the overall model performance as ‘excellent’, ‘very good’, ‘good’ or ‘poor’.

Generally, we aim at ‘excellent’ or ‘very good’ model performance at more than 3 out of 4 measurement stations in the different hydrodynamic models. However, in Roskilde Fjord only one station is available for validation. For salinity the model performance was evaluated against the three different quality measures at ROS60, and according to Table 6-1 the model meets ‘excellent’ at ROS60 for P-Bias and the Spearman Rank Correlation and ‘very good’ for the Modelling Efficiency Factor. For water temperature (see Table 6-2) the model meets ‘very good’ for P-Bias and ‘excellent’ for Spearman Rank Correlation and MEF.

Hence, we conclude that the hydrodynamic model covering Roskilde Fjord is well suited for continued biogeochemical model development as part of the overall development of mechanistic models towards the RBMP 2021-2027.

Table 6-1 Review of model performance based on measured and modelled salinities for the validation period 2011-2016. The performance is evaluated according to DHI (2019a) and blue colour indicates an ‘excellent’ model, dark green indicates a ‘very good’ model, light green indicates a ‘good’ model and yellow indicates a ‘poor’ model.

Station	P-Bias (%)	Spearman Rank Correlation	Modelling Efficiency Factor	Number of observations
ROS60	-5.4	0.91	0.59	296

Table 6-2 Review of model performance based on measured and modelled water temperatures for the validation period 2011-2016. The performance is evaluated according to DHI (2019a) and blue colour indicates an ‘excellent’ model, dark green indicates a ‘very good’ model, light green indicates a ‘good’ model and yellow indicates a ‘poor’ model.

Station	P-Bias (%)	Spearman Rank Correlation	Modelling Efficiency Factor	Number of observations
ROS60	-10.1	0.99	0.92	299

7 References

DHI (2017a). MIKE 21 & MIKE 3 Flow Model FM. Hydrodynamic and Transport Module. Scientific Documentation (http://manuals.mikepoweredbydhi.help/2017/Coast_and_Sea/MIKE_321_FM_Scientific_Doc.pdf)

DHI (2019a). Development of Mechanistic Models. Assessment of Model Performance. DHI technical report (project no. 11822245)