Development of Mechanistic Models

Mechanistic Model for Mariager Fjord

Hydrodynamic model documentation

Miljø- og Fødevareministeriet
Miljøstyrelsen

Technical Note

December 2019

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Eelgrass in Kertinge Nor
Photo: Peter Bondo Christensen

Prepared for	Danish EPA (Miljøstyrelsen, Fyn)
Represented by	Mr. Harley Bundgaard Madsen, Head of Section

Project manager	Anders Chr. Erichsen & Mads Birkeland
Quality supervisor	Anne Lise Middelboe

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DHI • Agern Allé 5 • • DK-2970 Hørsholm • Denmark
Telephone: +45 4516 9200 • Telefax: +45 4516 9292 • dhi@dhigroup.com • www.dhigroup.com

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The model development presented in this technical note represents the hydrodynamic model development for Mariager Fjord. The Mariager 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 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 Mariager Fjord: This specific model includes two Danish water bodies:

Table 1-1 Mariager Fjord water bodies.

Water Body*)	Number
Mariager Fjord, indre	159
Mariager Fjord, ydre	160

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

The Mariager 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 Mariager Fjord hydrodynamic model has been 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 0.8% with respect to salinity and -1.7% with respect to water temperature. Hence, the model meets a model performance of 'excellent' for salinity and temperature.
- With respect to the Spearman Rank Correlation the numbers are 0.97 and 0.96 for salinity and water temperature, respectively, which corresponds to an 'excellent' model performance.
- The Modelling Efficient Factor (MEF) for salinity are 0.95 and 0.97 for salinity and water temperature, respectively, 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 of the Mariager model and conclude that the model is sufficient for ecosystem model development.

2 Introduction

The model development presented in this technical note represents the hydrodynamic model development for Mariager Fjord. The Mariager 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 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.

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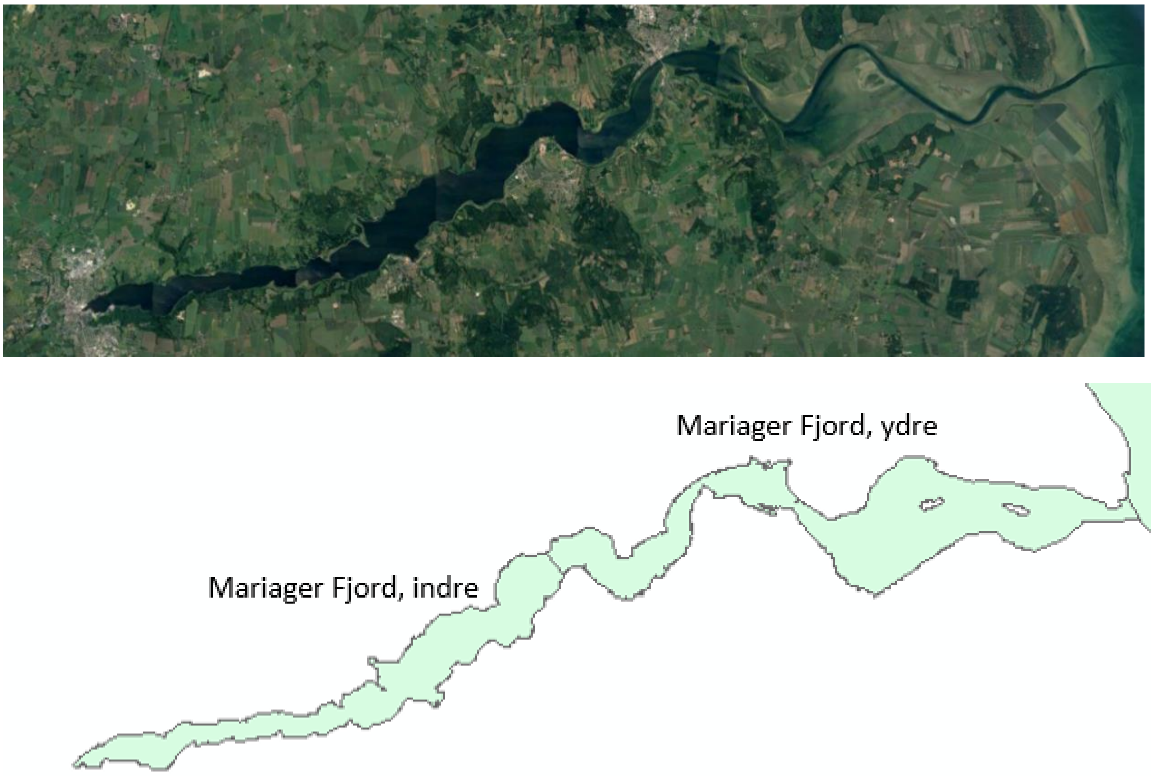

Figure 2-1 (Top) Mariager Fjord (from Google Maps) and (bottom) the two water bodies included in the Mariager Fjord model.

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 forcing's and anthropogenic pressures. Hence, mechanistic models can by 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 is determined by a number of different natural factors like water exchange, stratification, water temperature, nutrient availability, sediment characteristics, structure of the food web etc. On top of that a number of anthropogenic factors, like nutrient loadings, fishery, etc., also impacts the ecosystem and potentially the ecological status.

The model development in this specific project aims at supporting the Danish EPAs 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 developed they will be applied for scenario modelling, although the specific scenarios are not yet defined.

As mentioned in the introduction (section 2) the model documented in this specific technical note covers Mariager Fjord and includes two specific water bodies.

3.2 Model development

The model development consists of a 3D hydrodynamic model describing the physical system; water levels, current, salinity 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 Mariager Fjord model is defined as an estuary-specific model. The mechanistic model complex develop as part of the present projects 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, as the North Sea and a small part of the North Atlantic Ocean which is included in the North Sea-model and the Baltic Sea which is covered by the IDF (Inner Danish Waters). These types of 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 types of models are developed to allow for a resolution of the majority of small and medium sized water bodies in the North-western Belt Sea, the South-western Belt Sea and the waters bodies in and around Smaalandsfarvandet.

- Estuary specific models: For six specific estuaries local models are developed to allow for as detailed modelling as possible.

All mechanistic models will be set up 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 (http://rbmp2021-2027.dhigroup.com) with a few examples included in section 6.2. Data used for calibration and validation originate from the national monitoring programme NOVANA, see http://odaforalle.au.dk for more details.

3.3 Modelling System

The hydrodynamic model is based on the modelling software MIKE 3 HD FM (version 2017) 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 considered 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 mesh, preparing the model forcing’s in terms of open boundary conditions, atmospheric forcing and freshwater inflows, preparing the initial 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 forcing’s 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 Mariager Fjord model, the selection of model domain is rather straight forward since Mariager Fjord is an estuary with only one opening towards Kattegat. The model covers the entire Mariager Fjord and consists of two water bodies: The outer fjord and the inner fjord.

Mariager Fjord is a silt fjord, characterized by a deep inner fjord (<30m) and a shallower outer Fjord, with a silt at the opening towards Kattegat.

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 do also include quadrangular elements. The mesh resolution is in the range 150 m – 250 m between element centres. The model mesh and bathymetry for Mariager Fjord model is shown in Figure 4.1. The map projection given by ETRS-1989-UTM-32.

The model bathymetry shown in Figure 4.1(below) is based on satellite derived bathymetry data by GRAS (in the shallow areas up to approximately 0.75m depth) (DHI 2019b) and a combination of C-Map navigation chart data and the Danish Coastal Authority survey data for the rest. The vertical datum of the bathymetry is DVR90.

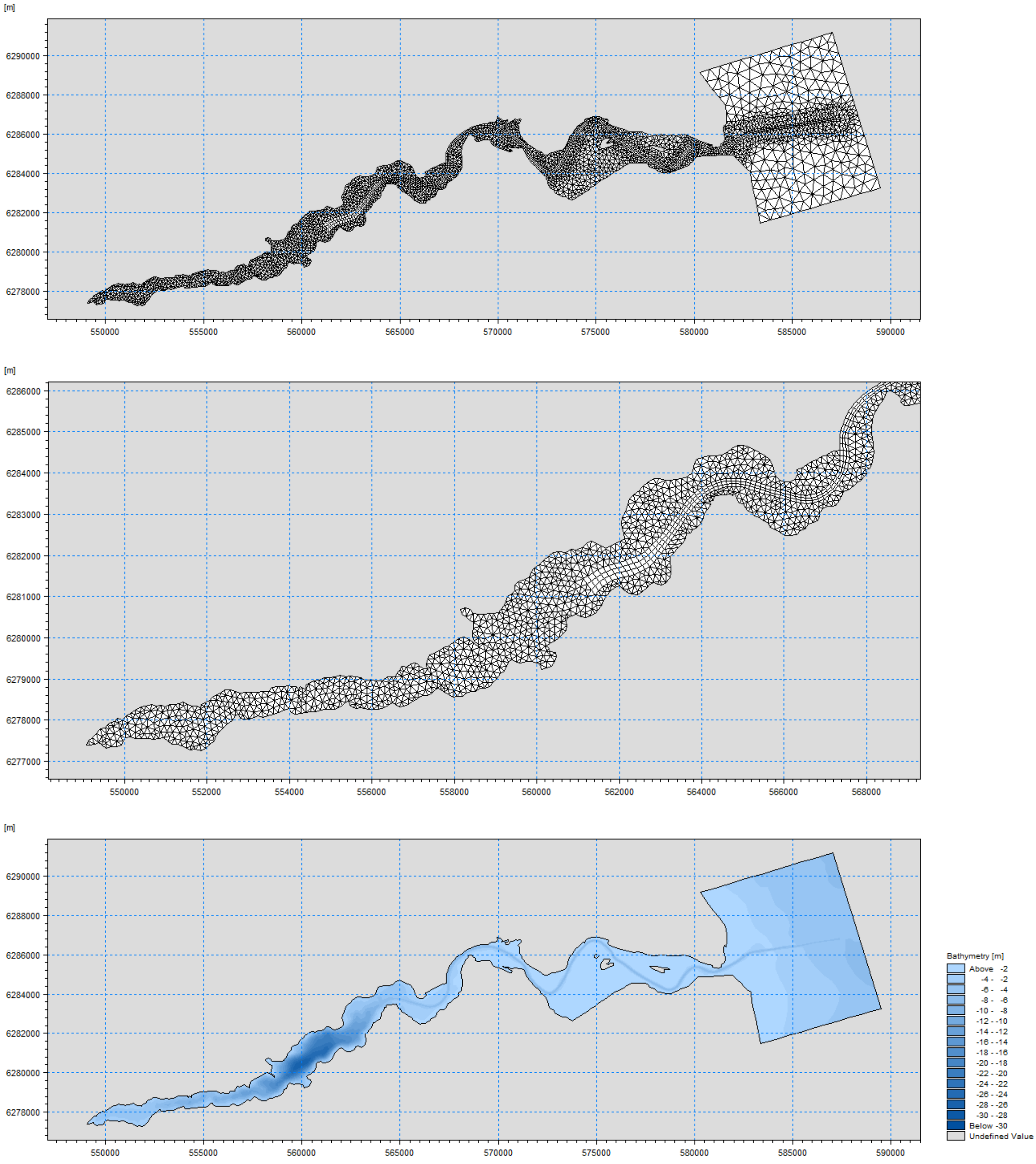

Figure 4.1 (top) Horizontal mesh, (mid) zoom to the inner fjord and (bottom) bathymetry of the Mariager Fjord model. Map projection ETRS-1989-UTM-32 and vertical datum DVR90.

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 Mariager Fjord model, a total of 94 model layers are applied. The water column from the surface to -10m below mean sea level (MSL) is resolved by ten sigma-layers and the water column below is resolved by up to 84 z-layers. The z-layers consist of 4 layers of 0.5m (from -10-12m) and 80 layers with a layer thickness of 0.2m (from -12m to seabed).

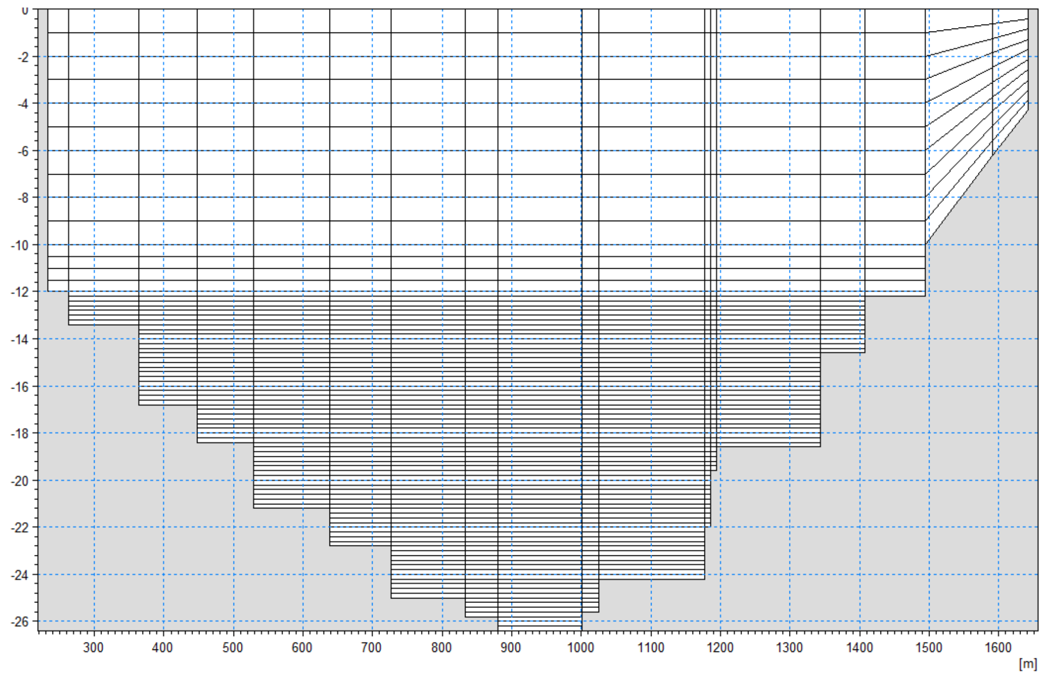

Figure 4-2 Example of cross section in Mariager Fjord showing the vertical model mesh consisting of ten sigma layers down to --10m, z-layers of 0.5m resolution from -10m to -12m and z-layers of 0.2m resolution below -12m (here down to the local depth of > -26m).

4.3 Model Forcing's

4.3.1 Open Boundary Conditions

The model has three open boundaries towards Kattegat, which is located to the east of the model. At those boundaries the time variation of water levels, water temperature and salinity are specified. Data were extracted from DHI's existing regional model.

4.3.2 Atmospheric Forcing

The atmospheric forcing of the Mariager Fjord model is provided by StormGeo in terms of temporally and spatially varying fields of:

- Wind (10 m)
- Atmospheric pressure
- Precipitation
- Air temperature (2 m)
- Relative humidity
- Cloud cover

The applied atmospheric data are from StormGeo's WRF meteorological model covering the North Atlantic. The data are provided in a resolution of 0.1° x 0.1° in hourly time-steps.

The StormGeo data are only available from 2009 and onwards. Therefore, meteorological fields from Vejr2 of Denmark (0.15°, hourly) were applied for the period 2005-2009, and meteorological fields from Climate Forecast System Reanalysis (CFSR) (0.3-0.5°, hourly) were applied for the period 2002-2005. Since these wind fields do not resolve the topography around Mariager Fjord, a reduction of 60% in the inner fjord and 80% in the outer fjord were applied.

4.3.3 Freshwater Sources

The Mariager Fjord model includes a number of model sources representing the freshwater run-off from land to the estuary. The freshwater data are available based on data from DCE (Aarhus University) – Denmark on a 4th order water body level. These data were distributed based on catchment area and knowledge of specific point sources and included in the model according to Figure 4-3. In order to compensate for a significant inflow of groundwater to Mariager Fjord, all sources are increased with 20%.

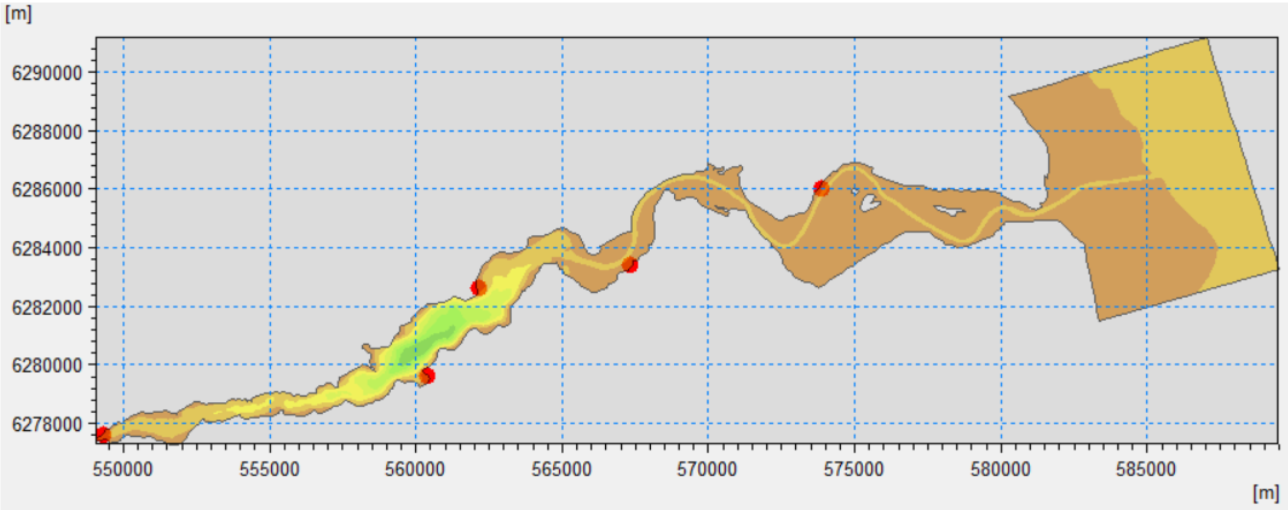

Figure 4-3 Distribution of fresh water sources applied in the Mariager Fjord model.

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 (‘cold start’), respectively, as the model quickly ‘warms up’ the currents and adjusts the water levels to the forcing.

For the 3D initial salinity and water temperature fields, however, the warm-up takes longer time and accordingly initial fields of these two parameters are provided as input to the model. NOVANA data from stations within Mariager 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 constants 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 require a well-proportioned model domain as well as adequate model forcing's, 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 and constants in the Mariager model.

Feature/Parameter	Setting/Value
Flooding and drying	Included with parameters: 0.005m (drying) and 0.1m (wetting)
Wind friction coefficient	Linearly varying between 0.001255 and 0.002425 for wind speeds between 7 and 25m/s
Bed roughness	Varying from 0.00001-0.01m
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	Light extinction coefficient 0.3, otherwise standard parameters Humidity: Constant = 88%
Dispersion (S/T)	Scaled to Eddy viscosity. Horizontal/vertical scaling factors = 1.0/0.8-1.0

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.

For the present model, the model has been run for the period 2002-2016, but the validation period has been 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 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 NOR5503 had sufficient data to be included in the model validation.

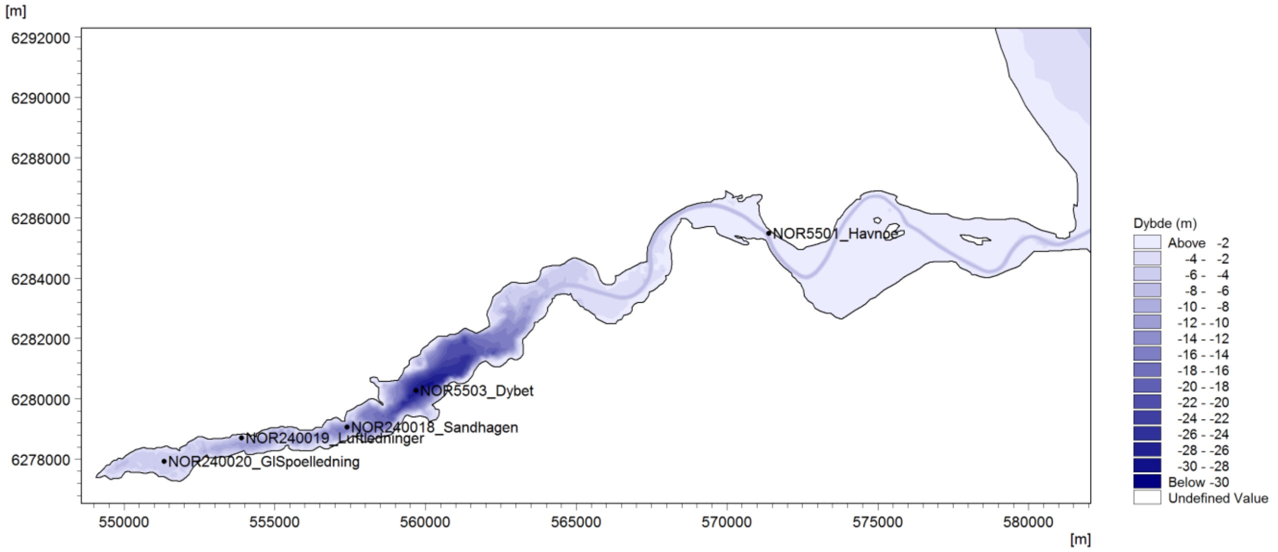

Figure 6-1 Location of monitoring stations for salinity and water temperature used in the model validation.

6.2 Model Performance

6.3 Salinity and Water Temperature

Figure 6-2 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 NOR5503.

Furthermore, 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 (top panel) and salinity (bottom panel) at station NOR5503 for the model period 2002-2016. Data are also displayed at rbmp2021-2027.dhigroup.com.

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 NOR5503) are included. The entire station network in the Mariager 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 Mariager Fjord only one station is available for validation. For salinity the model performance was evaluated against the three different quality measures at NOR5503, and according to Table 6-1 the model meets ‘excellent’ at NOR5503 for P-Bias, the Spearman Rank Correlation and the Modelling Efficiency Factor. For water temperature (see Table 6-2) the model also meets ‘excellent’ for all three measures.

Hence, we conclude that the hydrodynamic model covering Mariager 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
NOR5503	0.8	0.97	0.95	297

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
NOR5503	-1.7	0.96	0.97	285

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)

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