DHI

# Development of Mechanistic Models

## Mechanistic Model for Odense Fjord

### Hydrodynamic model documentation

Miljø- og Fødevareministeriet
Miljøstyrelsen

Technical Report
May 2020

The expert in **WATER ENVIRONMENTS**

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## Mechanistic Model for Odense Fjord

### Hydrodynamic model documentation

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*Eelgrass in Kertinge Nor*
*Photo: Peter Bondo Christensen*

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| Project number | 11822245 |
| Approval date | 11-05-2020 |
| Classification | Open |

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# 1 Executive Summary

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

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

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

The Odense 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 Odense Fjord hydrodynamic model has been developed successfully for the entire model period 2002-2016, and from the validation, we conclude

- On average the P-Bias is 12.4% concerning salinity and 21.4% concerning water temperature. Hence, in average the model meets a model performance of 'very good' for salinity (one station being 'excellent' and one 'very good') and 'good' for temperature (one station being 'good' and one 'very good').
- For the Spearman Rank Correlation, the average numbers are 0.59 and 0.95 for salinity and water temperature, respectively. That means that the average model performance at the two stations used for validation meets 'good/poor' and 'excellent' for salinity and temperature, respectively. The salinity performance, however, covers a station meeting 'very good' and a station meeting 'good/poor' quality.
- The average Modelling Efficient Factor (MEF) for salinity is -0.01 corresponding to a 'poor' model. For both stations, the modelled salinity levels are correct and overall variability seems correct, which is also highlighted by the two other measures P-Bias and Spearman Rank Correlation. However, the timing is not entirely correct, which is why the MEF is not evaluated as 'excellent' or 'very good'. The average Modelling Efficient Factor (MEF) for temperature is 0.77, corresponding to a 'very good' 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 Odense Fjord and 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 Odense Fjord. The Odense 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 by integrating with Bayesian statistical modelling, and cross-system modelling carried out by AU, Bioscience.

Here we present the hydrodynamic (HD) model setup covering Odense 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 Odense Fjord model.

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

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


Figure 2-1 (Top) Odense Fjord (from Google Maps) and (bottom) the different water bodies included in the Odense 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 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 is determined by a number of different natural factors like water exchange, stratification, water temperature, nutrient availability, sediment characteristics, the structure of the food web, etc. On top of that, numerous 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 EPAs implementation of the WFD. In this first phase of the model development, the models are designed to represent the present period (2002-2016) evaluated against NOVANA measurements. Here we use current meteorological data, current nutrient loadings, etc.

After the model developments 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, 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 Odense Fjord model is defined as an estuary specific model. The mechanistic model complex developed as part of the existing 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 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 Smålandsfarvandet.
- Estuary specific models: Six specific estuary (fjord) models are developed to allow for detailed modelling of the particular estuary.

All mechanistic models will be set up and calibrated for the period 2002-2011 and validated for the period 2012-2016. In this note, the validation will be reported according to specific indices

(DHI 2019a). In contrast, the entire period is included as time series in a WEB-tool (rbmp2021-2027.dhigroup.com) with a few examples included in section 6.1.1. The majority of data used for calibration and validation originates 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 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 designed 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 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

The model setup comprises defining the model domain, establishing the model mesh, preparing the model forcings 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 forcings need to cover this period.

## 4.1 Model Domain

### 4.1.1 Introduction

The model domain is determined following 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 the model domain.

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

Generally, Odense Fjord is shallow (< 2m), but in and around the central channel the depths are up to 10m. 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.

### 4.1.2 Horizontal Mesh

The horizontal mesh is unstructured and generally composed of triangular elements but may also include quadrangular elements. For the Odense Fjord model, the majority of the area is covered by a triangular mesh. In the innermost part of the fjord and Odense River, quadrangular elements were used to direct the water flow. ETRS-1989-UTM-32 gives the map projection.

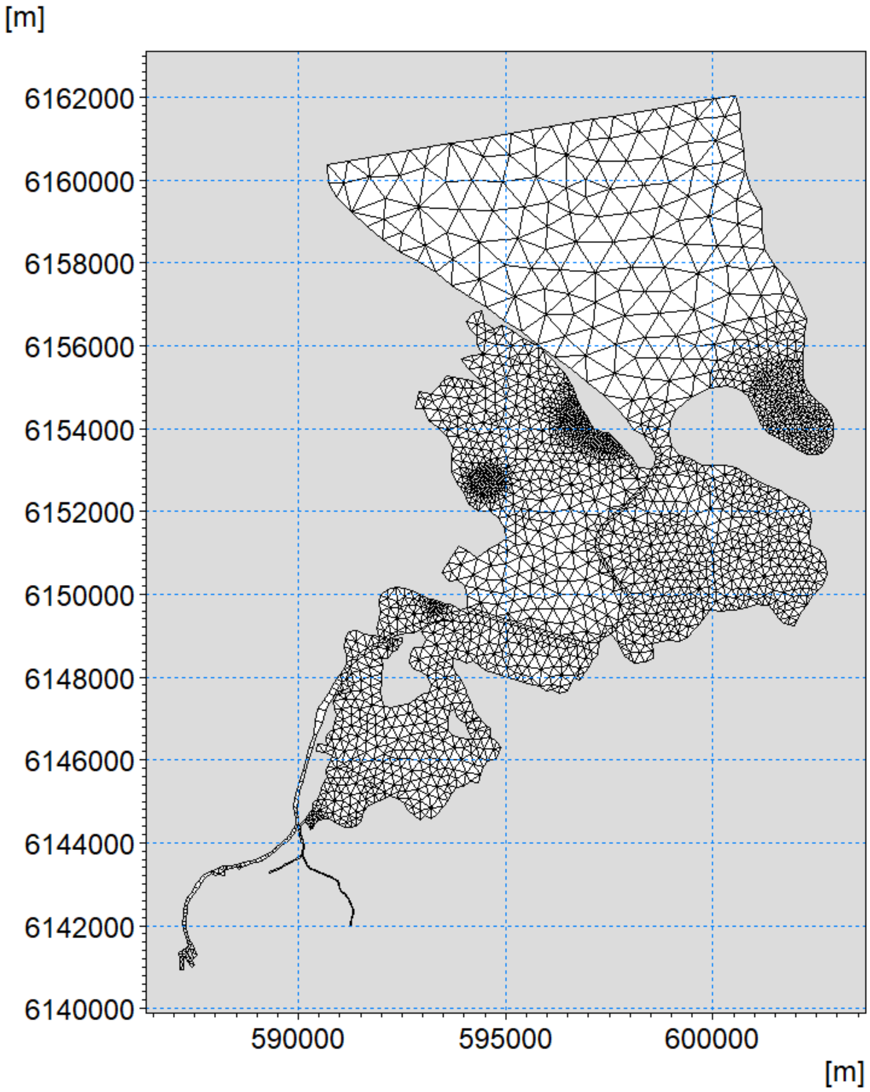


Figure 4-1 Odense Fjord mesh.

The horizontal resolution varies gradually from 150-200m to 1000m. Areas important for eelgrass growth/restoration have higher resolution (e.g. Engsø Dybet) or in areas with complicated flows (e.g. innermost fjord and Odense River)

The model bathymetry shown in Figure 4-2 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.

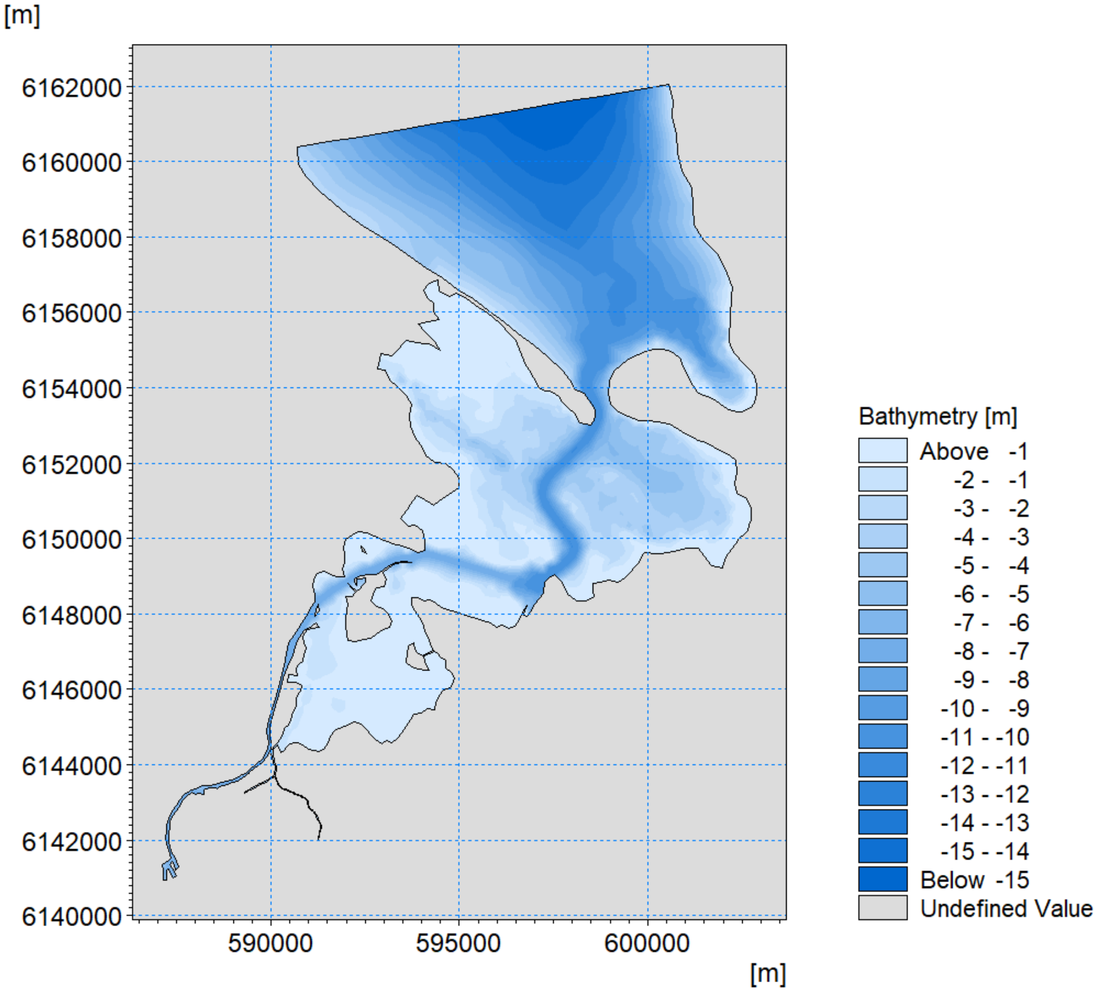


Figure 4-2 Odense Fjord Bathymetry.

### 4.1.3 Vertical Mesh

The vertical mesh is structured and consists of either sigma-layers or a combination of sigma- and z-layers. In the Odense Fjord model, a total of 21 model layers are applied. The water column from the surface to -3m below mean sea level (MSL) is resolved by three sigma-layers, and the water column below is resolved by up to 18 z-layers, with a layer thickness of 1m.

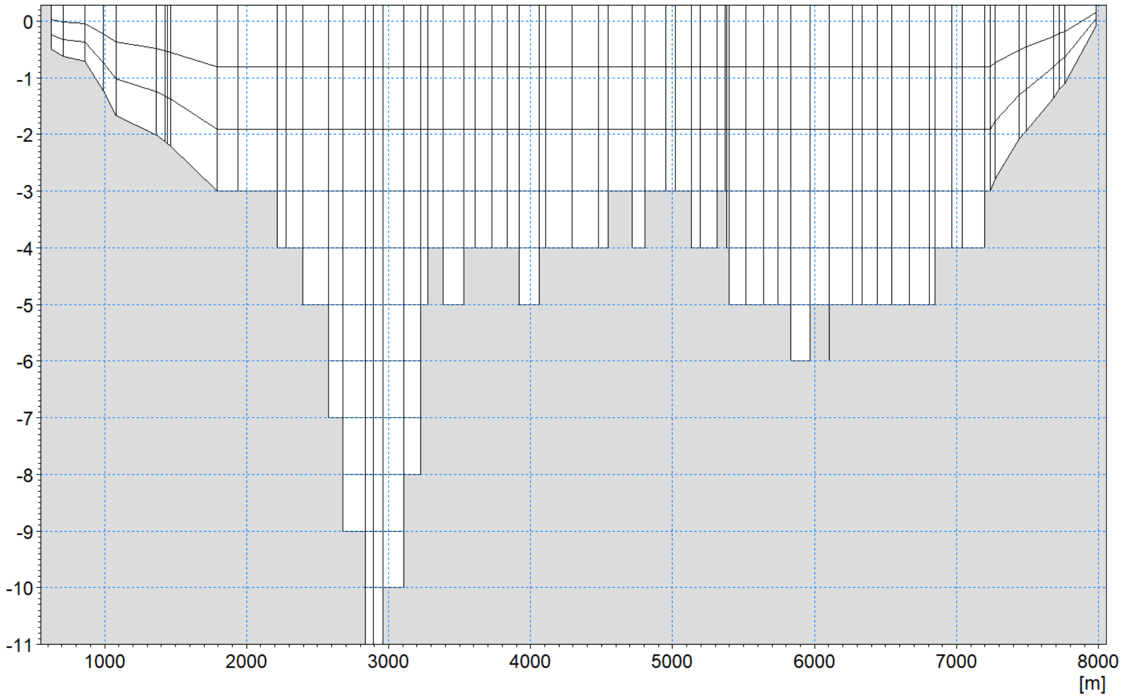


Figure 4-3 Example of a cross section in Odense fjord showing the vertical model mesh consisting of three sigma layers down to -3m, z-layers of -1m resolution down to local depth (here down to the local depth of -11m).

## 4.2 Model Forcings

### 4.2.1 Open Boundary Conditions

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

The water levels were extracted from DHI's existing regional model, whereas measured water temperature and salinity profiles from Station FYN6940622 were used for specification of the time-varying water temperature and salinity profiles at the boundary.

### 4.2.2 Atmospheric Forcing

The applied atmospheric forcing consists of:

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

Hourly time series of measured wind speed/direction, air temperature and relative humidity from station Odense Airport (Station 612000) were used for the full simulation period, while air temperature and relative humidity used data from Odense Airport station from 2002 to 2012 and StormGeo from 2013 to 2017.

Measured time series of daily precipitation from Agernæs (period 2002 to 2011) and Odense Airport (from 2011 to 2013) together with measured hourly data of clearness (cloud cover) from Odense Airport were used. For the period 2013 to 2016 hourly time series of model data extracted from meteorological fields provided by StormGeo were used.

### 4.2.3 Freshwater Sources

The Odense Fjord model includes a number of model sources representing the freshwater run-off from land to the 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.

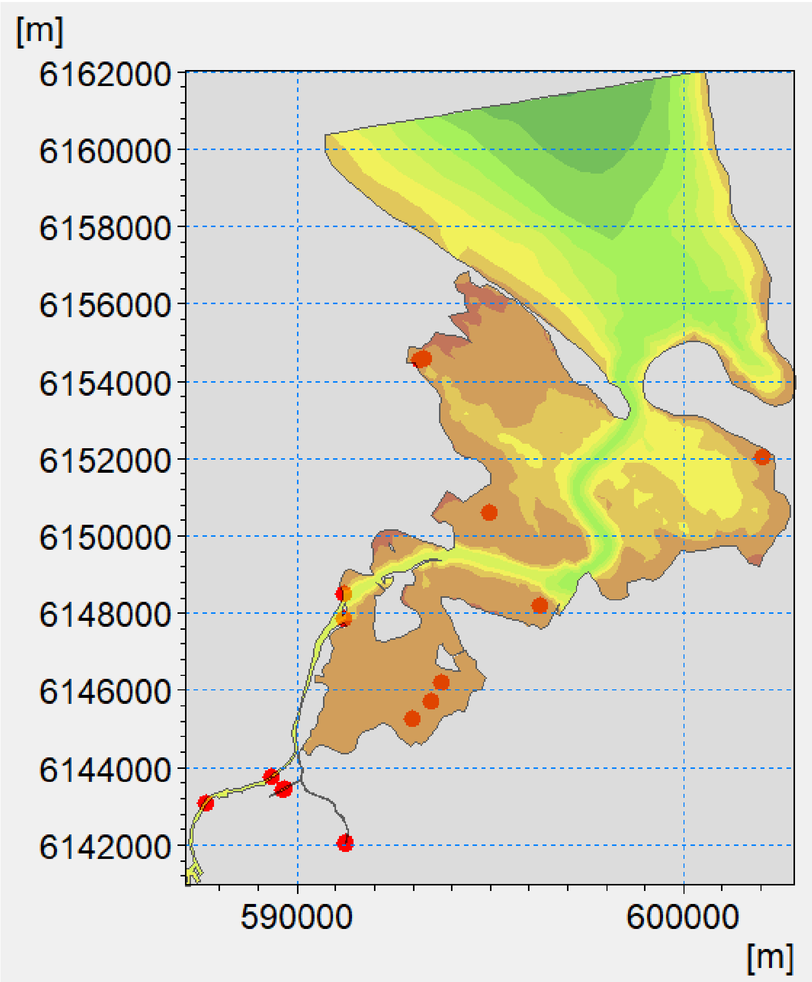


Figure 4-4 Distribution of freshwater sources applied in the Odense Fjord model.

### 4.2.4 Fynsværket

The Odense Fjord model includes the discharge of cooling water from Fynsværket. Information about volume ($m^3$ $s^{-1}$) and water temperature is based on data from Fynsværket covering the period from 2002-2016.

## 4.3 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 Odense Fjord are used to create the initial temperature and salinity fields.

# 5 Model Calibration

## 5.1 Introduction

After the model setup, the model calibration is undertaken. The model calibration is the process of adjusting model settings and model constants 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 forcings, 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 Odense 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<br>Vertically: k-ε model with standard parameters and no damping |
| Solution technique | Shallow water equations: Low order<br>Transport equations: Low order |
| Overall time-step | 300s |
| Heat exchange | Constant in Dalton's law: 0.675,<br>Wind coefficient Dalton's law :1.35<br>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 made graphically, and the quantitative comparison is generally made using specific performance (goodness of fit) measures. As such, the model validation constitutes the documentation of the model performance.

The Odense Fjord model has been run for the period 2002-2016, but the validation period was defined as the 6 years 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 given 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 stations FYN6900017 and FYN6910008 had sufficient data to be included in the model validation.

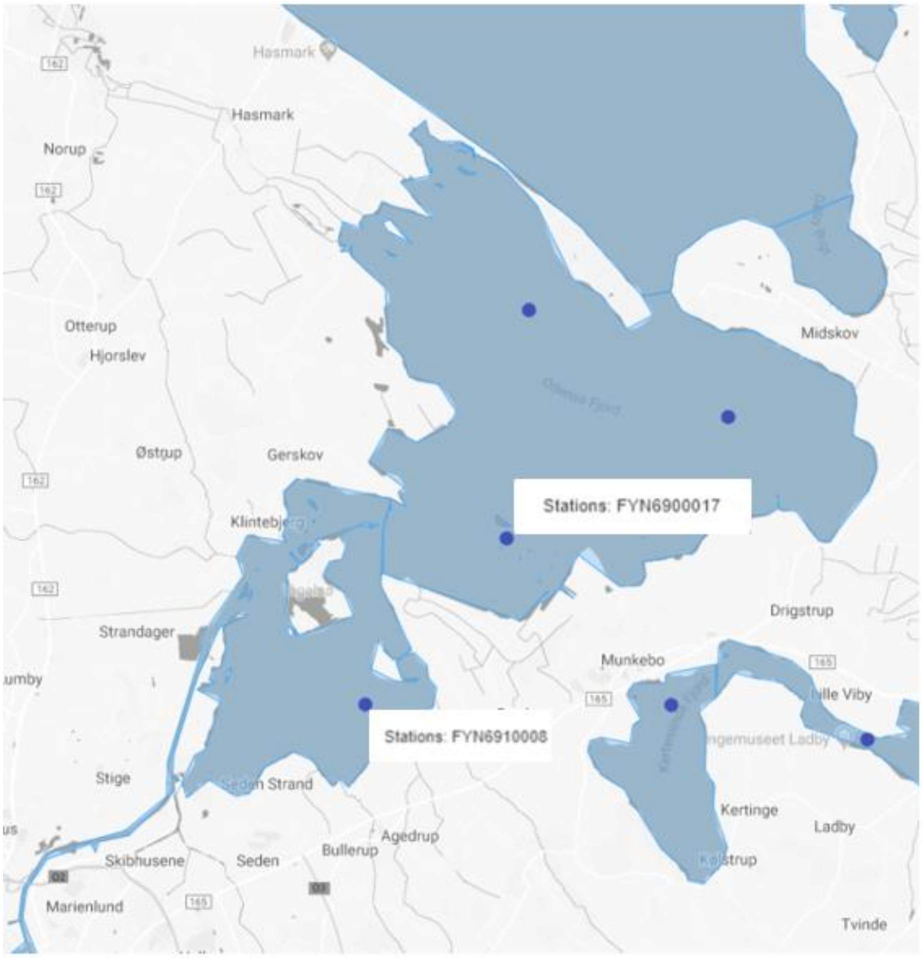


Figure 6-1 Location of monitoring stations for salinity and water temperature used in the model validation.

### 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 FYN6900017 and FYN6910008.

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.

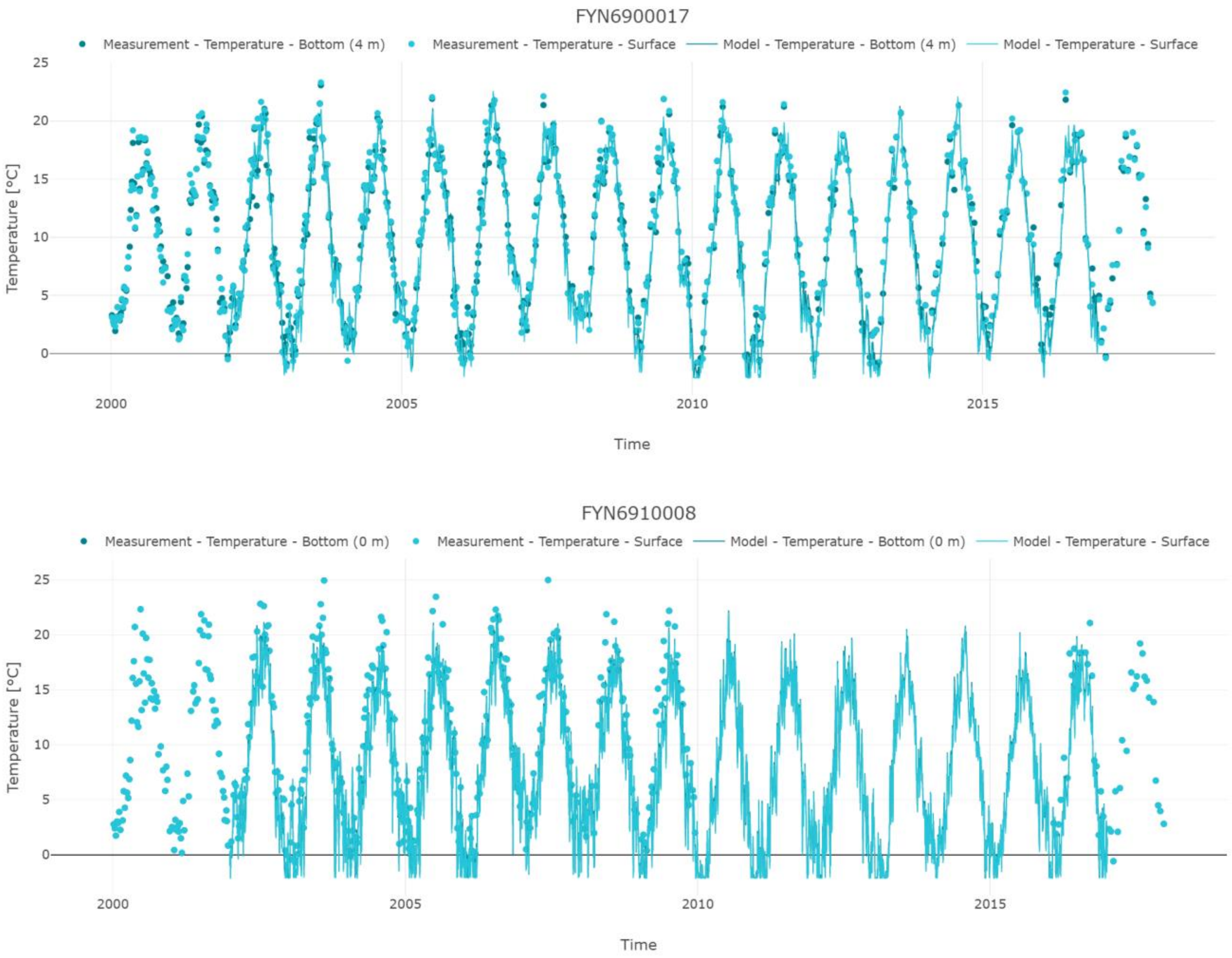


Figure 6-2 Comparison of measured and modelled water temperature at stations FYN6900017 and FYN6910008 for the model period 2002-2016.

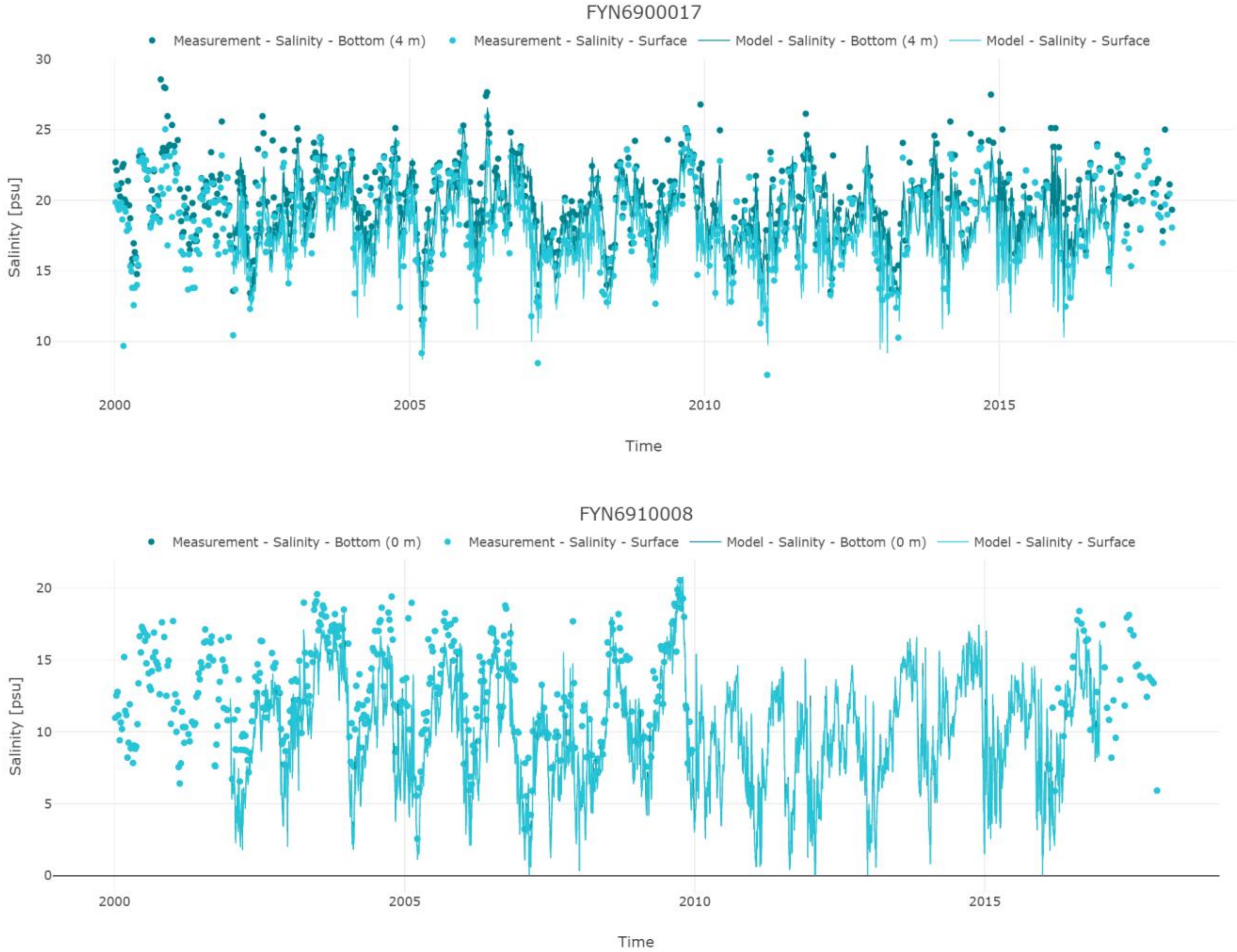


Figure 6-3 Comparison of measured and modelled salinity at stations FYN6900017 and FYN6910008 for the model period 2002-2016.

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 are included, and the selected stations in the Odense Fjord model domain are shown in Figure 6-1 (FYN6900017 and FYN6910008). In the tables, colour 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. For salinity, the model performance was evaluated against the three different quality measures at FYN6900017 and FYN6910008. According to Table 6-1, the model meets 'excellent' at FYN690008 for P-Bias and 'poor' for the Spearman Rank Correlation and Modelling Efficiency Factor, while meeting 'very good' at FYN6900017 for all the three different quality measures. For water temperature (see Table 6-2) the model meets 'very good' for P-Bias and 'excellent' for Spearman Rank Correlation and MEF at FYN6900017 and 'good' for P-Bias, 'excellent' for Spearman Rank Correlation and 'very good' for MEF at FYN6910008.

For both stations, the modelled salinity levels are correct and overall variability seems correct, which is also highlighted by the two other measures P-Bias and Spearman Rank Correlation. However, the timing is not entirely right, which is why the MEF is not evaluated as 'excellent' or 'very good'.

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 Odense Fjord and that the model is sufficient for ecosystem model development.

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 shows a 'poor' model.

| Station | P-Bias (%) | Spearman Rank Correlation | Modelling Efficiency Factor | Number of observations |
|---|---|---|---|---|
| FYN6910008 | -17.9 | 0.71 | 0.59 | 44 |
| FYN6900017 | -6.8 | 0.46 | -0.13 | 314 |

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 shows a 'poor' model.

| Station | P-Bias (%) | Spearman Rank Correlation | Modelling Efficiency Factor | Number of observations |
|---|---|---|---|---|
| FYN6910008 | -31.1 | 0.92 | 0.64 | 44 |
| FYN6900017 | -11.6 | 0.97 | 0.9 | 314 |

# 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)

DHI (2019b). Udvikling af Mekanistiske Modeller. Satellitbaseret bathymetri i Danmark. DHI Gras technical report (project no. 11822245)