DHI

Development of Mechanistic Models

Mechanistic Model for Limfjorden

Hydrodynamic model documentation

Miljø- og Fødevareministeriet
Miljøstyrelsen

Technical Note

December 2019

The expert in **WATER ENVIRONMENTS**

Development of Mechanistic Models

Mechanistic Model for Limfjorden

Hydrodynamic model documentation

Prepared for Danish EPA (Miljøstyrelsen, Fyn)

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Project number	11822245
Approval date	20-12-2019
Classification	Open

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

Table 1 Limfjord water bodies.

Water body*)	ID number
Nissum Bredning, Thisted Bredning, Kås Bredning, Løgstør Bredning, Nibe Bredning og Langerak	156
Bjørnholms Bugt, Riisgårde Bredning, Skive Fjord og Lovns Bredning	157
Hjarbæk Fjord	158

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

The Limfjord 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 Limfjord hydrodynamic model was developed successfully for the entire model period 2002-2016, and from the validation we conclude:

- On average the P-Bias is 2.2% with respect to salinity. This covers 32 stations with a difference between model and measurement of less than 10% (corresponding to an ‘excellent’ model) and 1 station with a difference of less than 20% (corresponding to a ‘very good’ model).

  For water temperature the average P-Bias is 2.2% covering 27 stations with a difference of less than 10% (‘excellent’ model), four stations with an absolute difference of less than 20% (‘very good’ model) and one stations with differences larger than 20% (‘good’ model).

- With respect to the Spearman Rank Correlation the average numbers are 0.70 and 0.90 for salinity and water temperature, respectively. This covers two stations evaluated as ‘excellent’ and 26 stations as ‘very good’ and five stations as good/poor with respect to salinity. For water temperature, 22 stations were evaluated as ‘excellent’ and 11 stations as ‘very good’.

- The average Modelling Efficient Factor (MEF) for salinity is -0.10 corresponding to a ‘poor’ model. This covers three station evaluated as ‘very good’ and eight stations evaluated as ‘good’. 22 stations are evaluated as ‘poor’.

The average Modelling Efficient Factor (MEF) for temperature is 0.70 corresponding to a ‘very good’ model. This covers nine stations evaluated as ‘excellent’ and twenty stations evaluated as ‘very good’, three stations as ‘good’ and one station evaluated as ‘poor’.

The details behind the above data are available in **Error! Reference source not found.** 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 the Limfjord 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 the Limfjord The Limfjord 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 the Limfjord. This specific model includes 3 Danish water bodies:

Table 2 Water bodies included in the Limfjord model

Water body*)	ID number
Nissum Bredning, Thisted Bredning, Kås Bredning, Løgstør Bredning, Nibe Bredning og Langerak	156
Bjørnholms Bugt, Riisgårde Bredning, Skive Fjord og Lovns Bredning	157
Hjarbæk Fjord	158

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

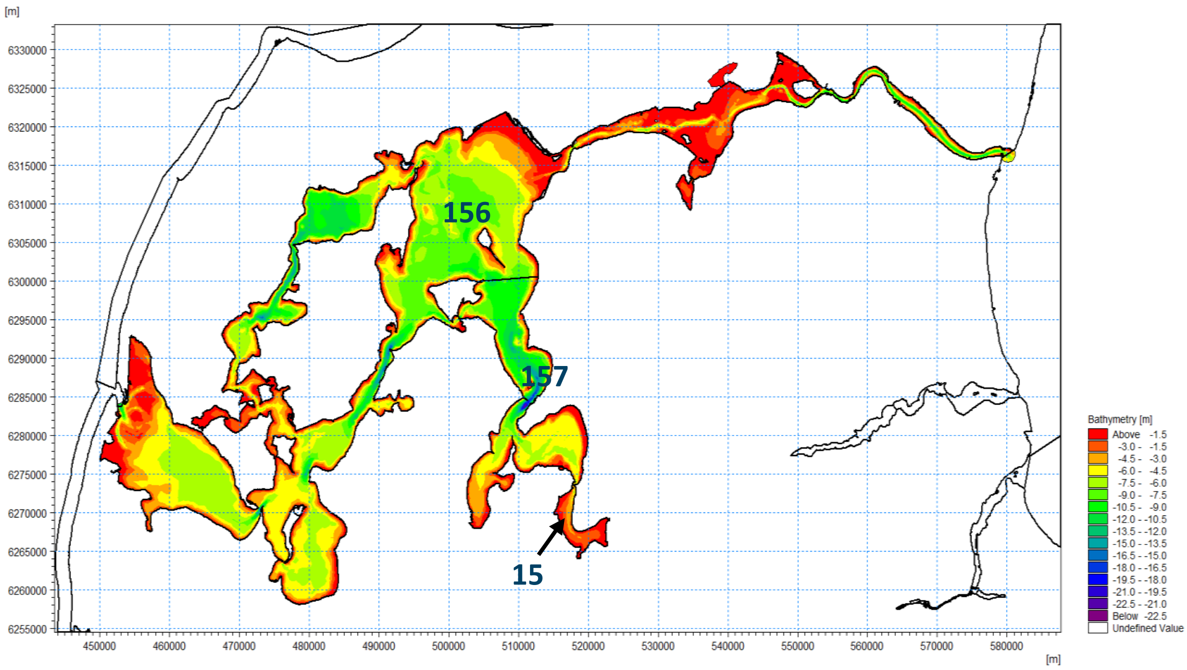


Figure 2-1 Limfjord bathymetry and waterbodies.

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, 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 Limfjord model is defined as an estuary specific model. The mechanistic model complex developed 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 model (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 Smålandsfarvandet.

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

All mechanistic models 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 few examples 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) 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 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.

4.2 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 Limfjord model, the setup is straight forward since the Limfjord is an estuary with two openings: one towards the North Sea and the other towards Kattegat. Thus, the Limfjord model has two open boundaries: the boundary to the west at Thyborøn, is located in the narrow opening connecting the Limfjord to the North Sea, and the eastern boundary (Hals) is located in the narrow opening connecting the Limfjord to the Kattegat (Figure 4-1).

Generally, the Limford is a shallow fjord with a mean depth around 5m and a maximum depth of 24m.

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. For the Limfjord model the majority of the area is covered by a triangular mesh. In four areas quadrangular elements were used to direct the water flow (from Kattegat boundary to Løgstør broad, in Salling sound, Oddesund and Vildsund). The map projection is given by ETRS-1989-UTM-32.

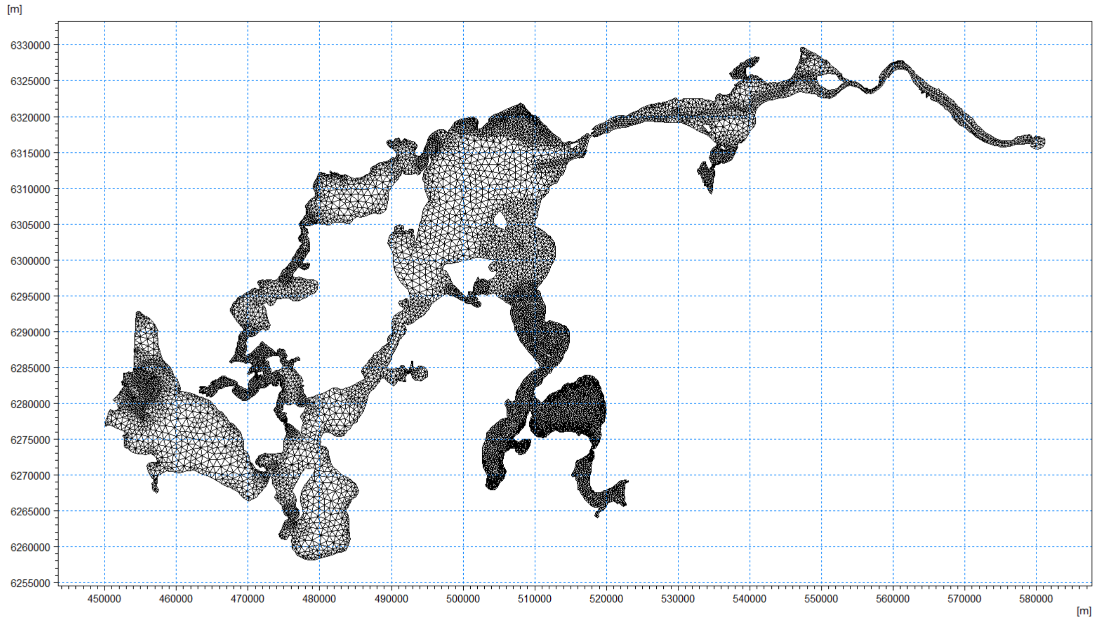


Figure 4-1 Limfjorden mesh.

The horizontal resolution varies gradually from 150-200m to approximately 1.000m. Areas important for eelgrass growth/restoration have higher resolution e.g. Skive and the northern Løngstør) and narrow areas or in areas with complicated flows (e.g. North of Mors) and bathymetry (e.g. Western part of Nissum broad) (Figure 4-1).

The model bathymetry shown in Figure 4-2 (below) is based on a combination of C-Map navigation chart data and the Danish Coastal Authority survey data. The vertical datum of the bathymetry is DVR90.

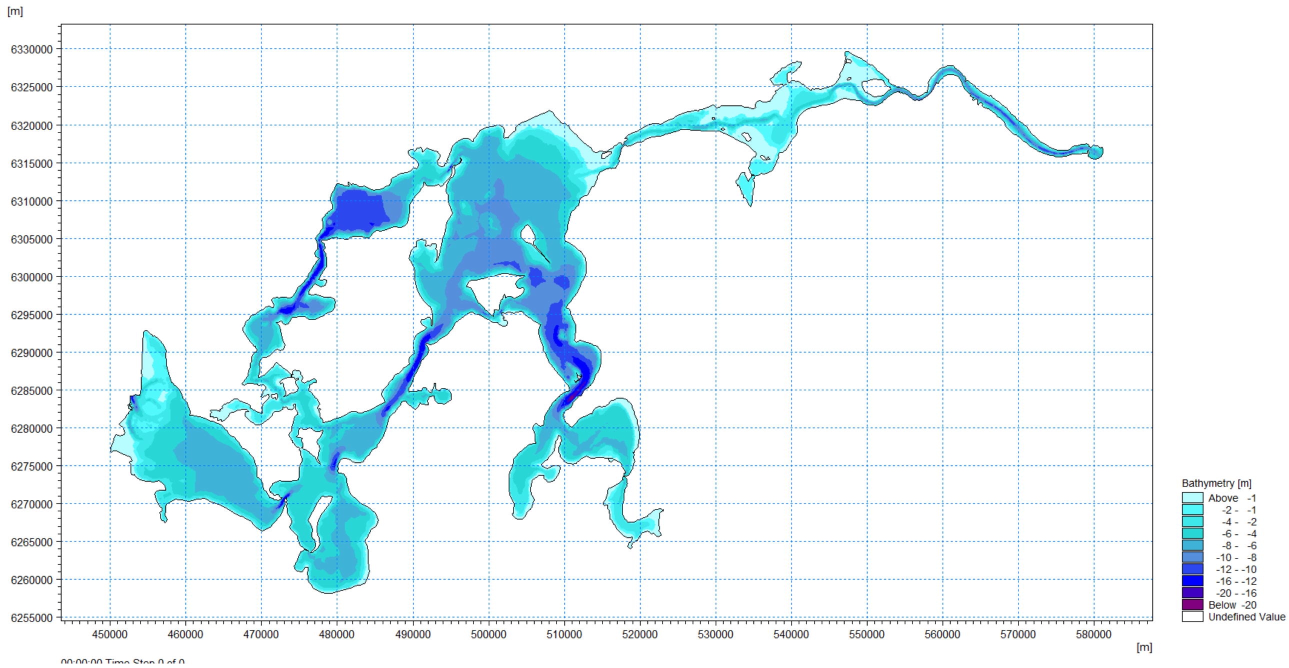


Figure 4-2 Limfjord Bathymetry

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 Limfjord model, a total of 20 model layers are applied. The water column from the surface to -5m below mean sea level (MSL) is resolved by five sigma-layers and the water column below is resolved by up to 15 z-layers, with a layer thickness of 1m. At depth >-20m the bottom layer adapts to the actual depth.

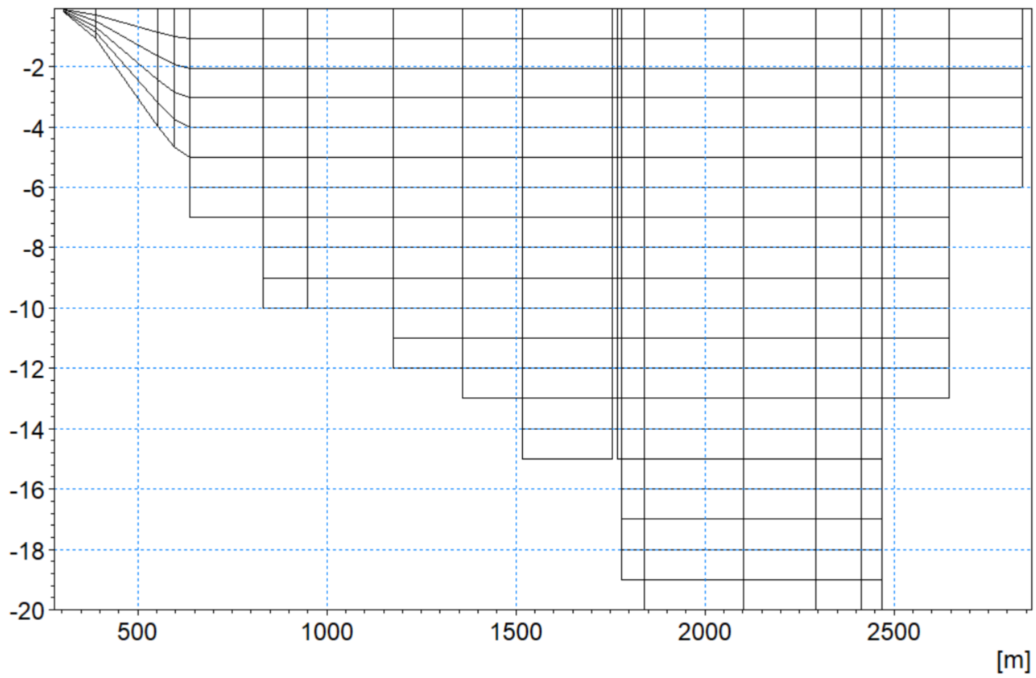


Figure 4-3 Example of cross section in Hvalpsund in the Limfjord showing the vertical model mesh consisting of five sigma layers down to -5m, z-layers of 1m resolution below -5m (here down to the local depth of -20m).

4.3 Model Forcings

4.3.1 Open Boundary Conditions

The model has two open boundaries: The western boundary that connects the Limfjord to the North Sea (Thyborøn) and the eastern boundary that connects the Limfjord to the Kattegat (Hals).

Model boundaries are described by water level, salinity and temperature.

For the Thyborøn boundary, water level data is taken from Kystdirektoratet measuring stations from Tyborøn Kyst and Thyborøn Havn. In order to improve the modelled tidal heights a correction of the tidal part of the water level boundary by 4 cm is undertaken to fit model's vertical datum. Measuring station RBK65 (located in the opening towards the North Sea) is used as a salinity and temperature boundary from 2000-2009 and from 2010-2017 data are extracted from DHI's operational North Sea model (the UKNS2 model), see DHI 2019b.

For the Hals boundary DMI data is used for water levels from measuring station at Hals. Measuring station NOR4011 is used as a salinity and temperature boundary from 2000-2009 and from 2010-2017 data are extracted from DHI's operational North Sea model (the UKNS2 model), see DHI 2019b.

4.3.2 Atmospheric Forcing

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

- Wind
- Atmospheric pressure
- Precipitation
- Air temperature
- 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 forward. 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.

Hourly wind measurement data for 2000-2009 is taken from DMI using measuring stations at Thyboron and Hals. DMI measurements from Thyborøn are used as atmospheric temperature measurements. Constant relative humidity of 85 % is used.

4.3.3 Freshwater Sources

The Limfjord 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 4-4.

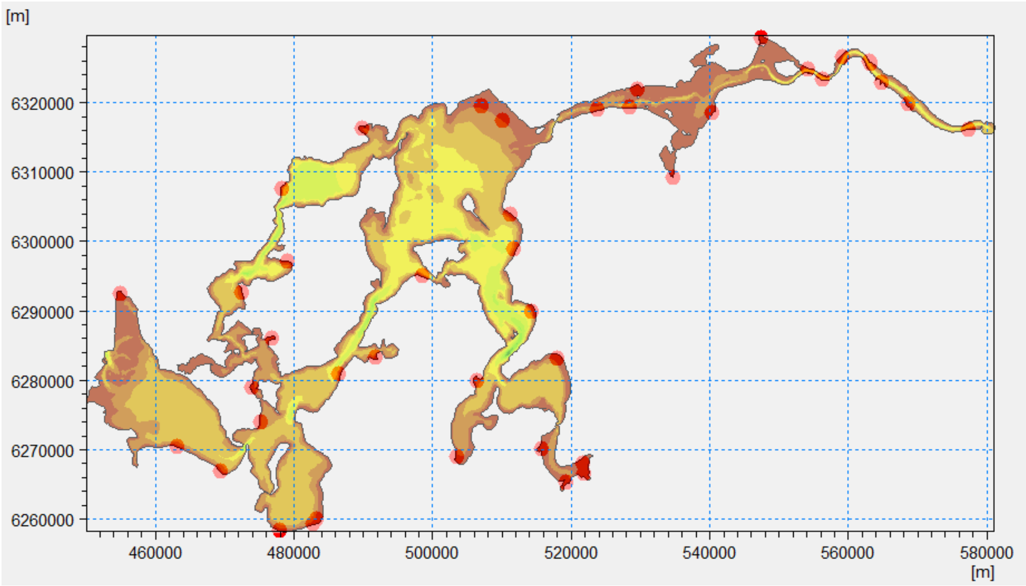


Figure 4-4 Distribution of fresh water sources applied in the Limfjord Fjord model.

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 fields (and partly temperature), however, the warm-up takes longer time and accordingly initial fields of this parameters are provided as input to the model. NOVANA data from stations within the Limfjord are used to create the initial salinity and temperature 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 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 Limfjord model.

Feature/Parameter	Setting/Value
Flooding and drying	Included with parameters: 0.005m, 0.05m and 0.1m
Wind friction coefficient	Linearly varying between 0.001255 and 0.002425 for wind speeds between 7 and 25m/s
Bed roughness	Constant value 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 = 1.0/0.01

6 Model Validation

6.1 Introduction

The model validation is the process of comparing observations and model results qualitatively and quantitatively in order to demonstrate the quality 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 of salinity and 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. For the validation period (2011-2016) 33 stations had sufficient data to be included in the model validation.

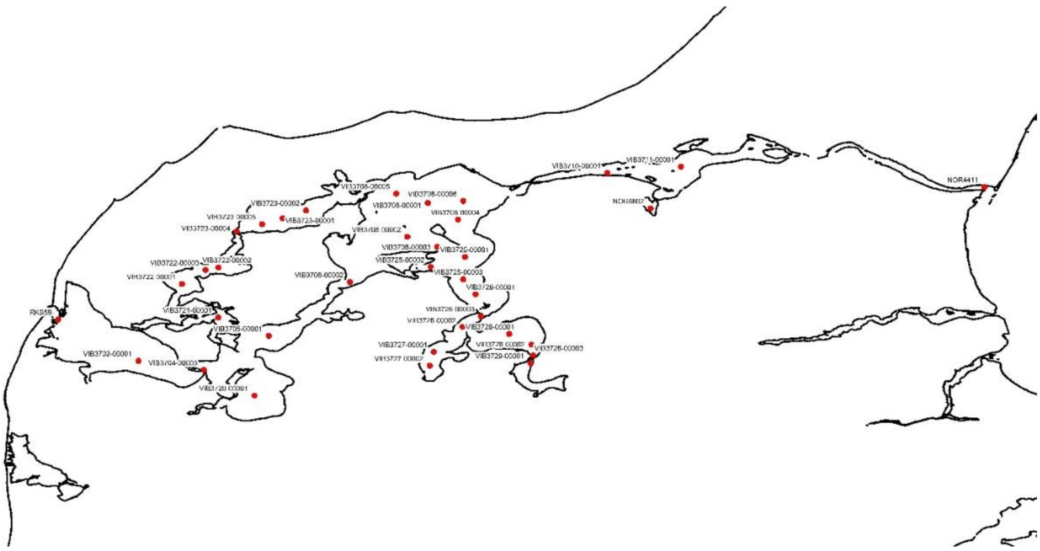


Figure 6-1 Location of monitoring stations for salinity and water temperature used in the model validation.

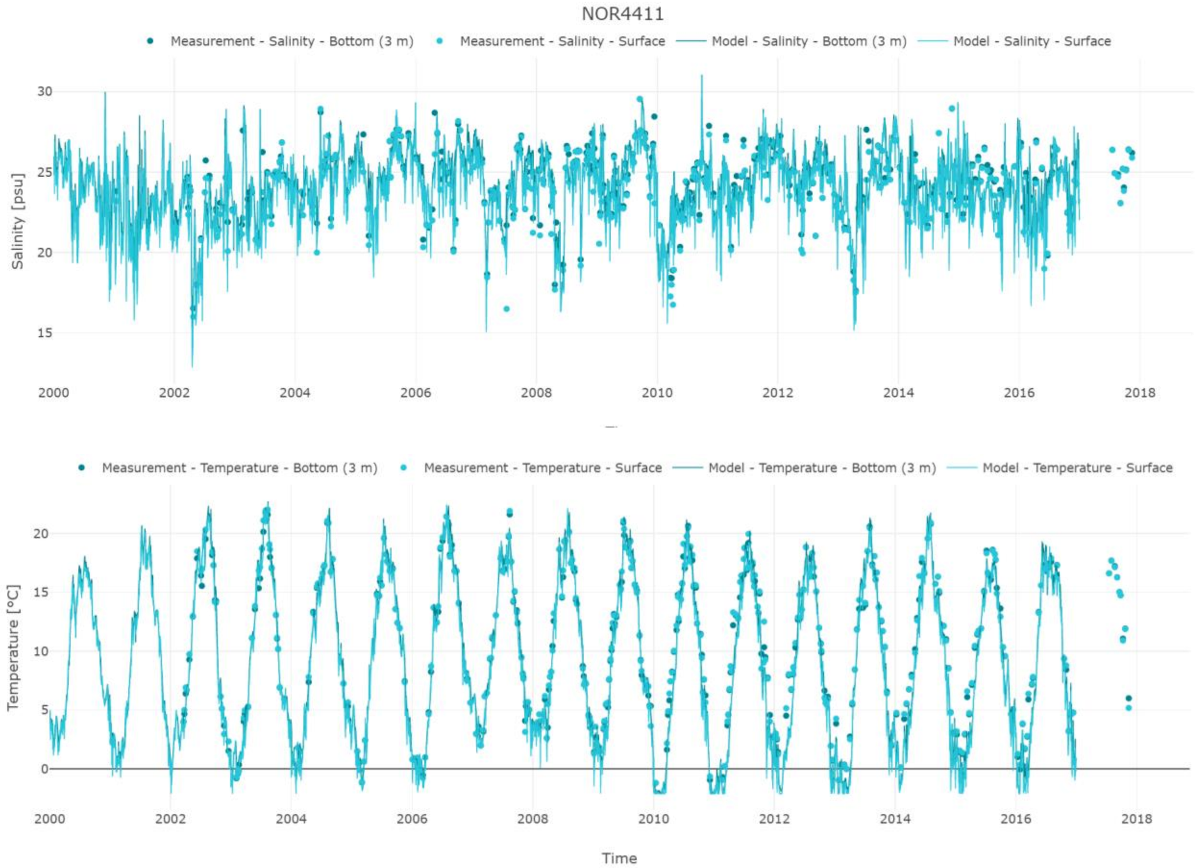
6.2 Model performance

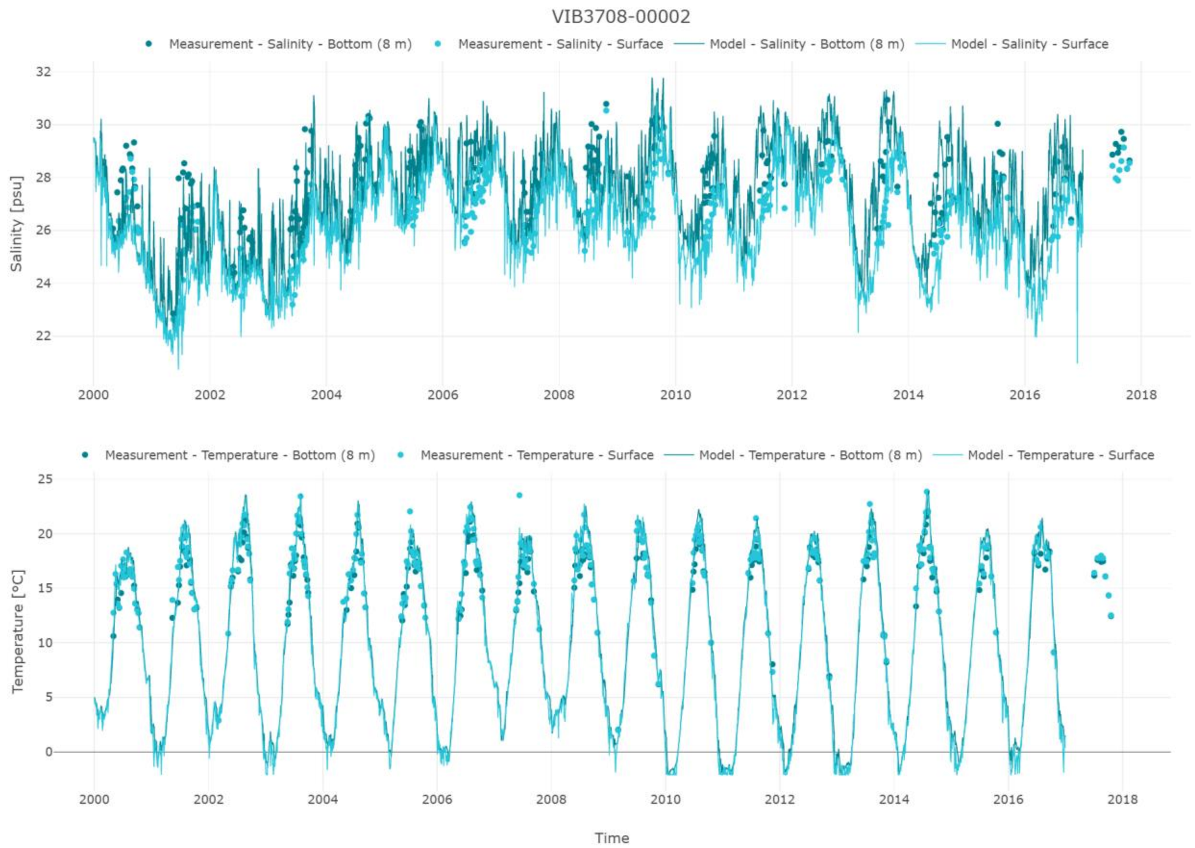
6.3 Salinity and Water Temperature

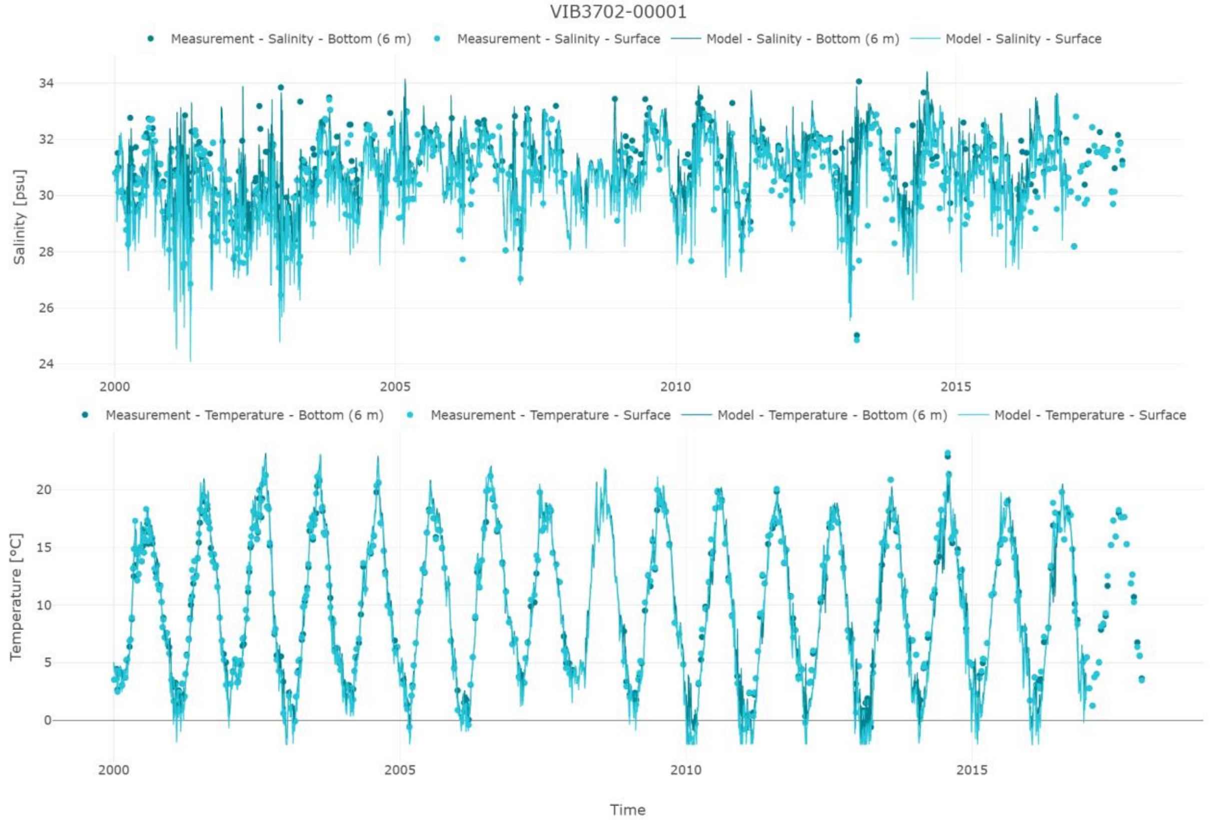
Error! Reference source not found. show examples of comparisons of modelled and measured water temperature and salinity at stations having measured data during the entire model period (2002-2016). The model reproduces well the variability and seasonality observed in the salinity and water temperature.

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.


NOR4411
Measurement - Salinity - Bottom (3 m)
Measurement - Salinity - Surface
Model - Salinity - Bottom (3 m)
Model - Salinity - Surface
Salinity [psu]
Measurement - Temperature - Bottom (3 m)
Measurement - Temperature - Surface
Model - Temperature - Bottom (3 m)
Model - Temperature - Surface
Temperature [°C]
Time


VIB3708-00002
Measurement - Salinity - Bottom (8 m)
Measurement - Salinity - Surface
Model - Salinity - Bottom (8 m)
Model - Salinity - Surface
Salinity [psu]
Measurement - Temperature - Bottom (8 m)
Measurement - Temperature - Surface
Model - Temperature - Bottom (8 m)
Model - Temperature - Surface
Temperature [°C]
Time



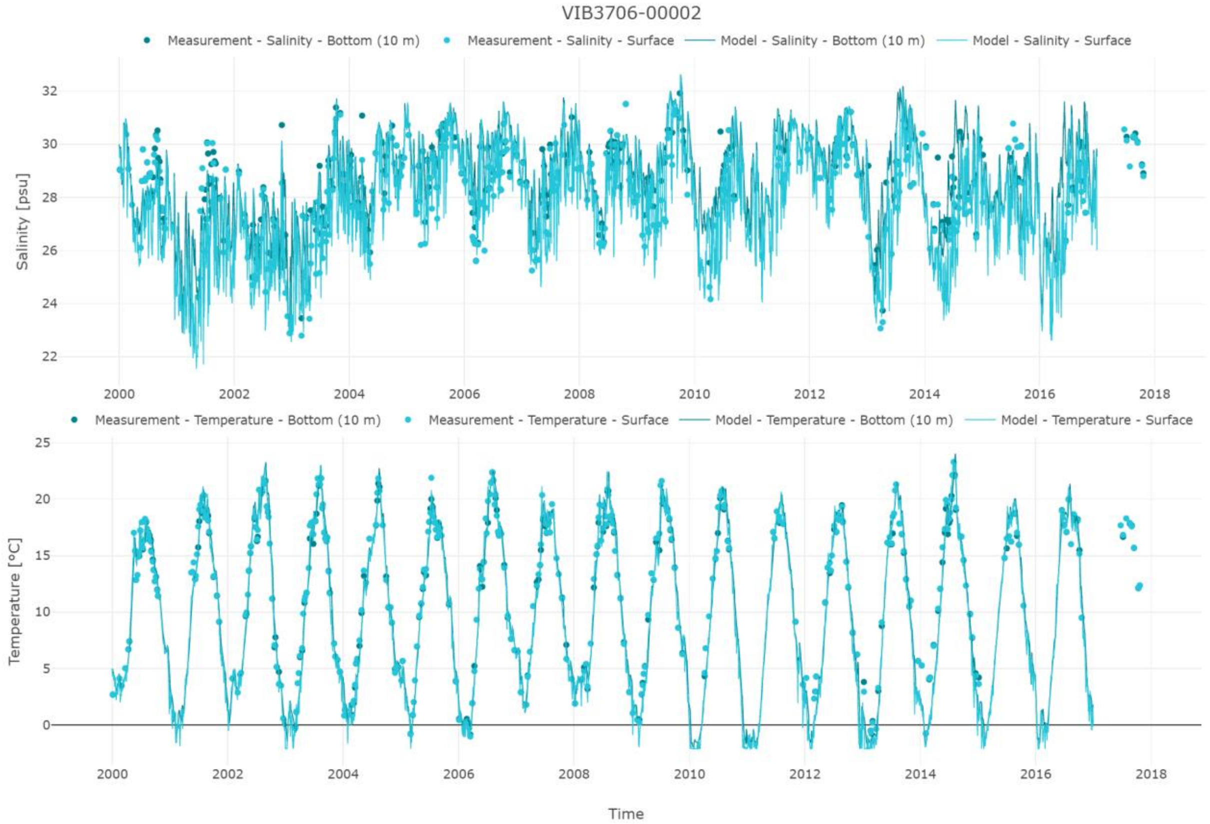


Figure 6-2 Comparison of measured and calculated water temperature and salinity at station NOR4401 (Hals), VIB3708 (Løgstør Broad), VIB3702 (Nissum Broad), VIB3706 (Kås Broad) for the model period 2002-2016. Data are also displayed at http://rbmp2021-2027.dhigroup.com.

In **Error! Reference source not found.** 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. The entire station network in the Limfjord 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. For salinity and temperature, the model performance was evaluated against the three different quality measures at 33 stations.

According to **Error! Reference source not found.** the modelled salinity meets ‘excellent’ or ‘very good’ in 65% of all measures at all stations. Similarly, the modelled water temperature (see Table 6-2) meets ‘excellent’ or ‘very good’ in 95% of all measures at all stations. Hence, for salinity the of ‘excellent’ og ‘very good’ for 3 out of 4 stations is not met entirely. Especially, the modelling efficient factor fails at a number of stations. Analyzing the overall modelled features (see http://rbmp2021-2027.dhigroup.com) and seasonality’s we still evaluate the model calibration as a high quality calibration, and hence, we conclude that the hydrodynamic model covering the Limfjord 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
NOR4411	-0.8	0.60	0.27	293
NOR6602	21.2	0.57	-0.58	267
VIB3702-00001	0.6	0.59	0.05	270
VIB3705-00001	0.7	0.50	0.00	177
VIB3706-00002	0.0	0.62	0.02	162
VIB3708-00001	-1.3	0.66	-0.13	336
VIB3708-00002	1.5	0.66	-0.48	128
VIB3708-00003	1.0	0.86	-0.04	56
VIB3708-00004	1.3	0.78	0.04	97
VIB3708-00005	0.4	0.77	0.29	108
VIB3708-00006	0.4	0.75	0.15	76
VIB3711-00001	-1.8	0.65	-0.01	276
VIB3720-00001	1.9	0.72	-0.86	68
VIB3721-00001	5.5	0.45	-1.82	72
VIB3722-00001	3.2	0.81	-1.94	105
VIB3722-00002	0.8	0.76	-0.52	150
VIB3722-00003	2.1	0.87	-0.71	114
VIB3723-00001	-1.4	0.80	0.20	154
VIB3723-00002	-0.8	0.91	0.50	118
VIB3723-00004	-1.0	0.83	0.31	150
VIB3723-00005	-0.7	0.92	0.45	116
VIB3725-00001	2.5	0.70	-0.26	174
VIB3725-00002	2.1	0.83	0.32	98
VIB3725-00003	3.4	0.86	0.14	132
VIB3726-00001	2.5	0.81	0.12	192

Station	P-Bias	Spearman Rank Correlation	Modelling Efficiency Factor	Number of observations
VIB3726-00002	3.5	0.88	0.49	174
VIB3726-00003	3.7	0.89	0.50	124
VIB3727-00001	3.9	0.83	0.20	329
VIB3727-00002	4.2	0.81	0.13	139
VIB3728-00001	6.5	0.72	-0.84	284
VIB3728-00002	3.7	0.74	-0.22	282
VIB3728-00003	1.0	0.72	0.12	220
VIB3729-00001	1.4	0.79	0.59	270

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
NOR4411	-16.0	0.98	0.86	293
NOR6602	-29.3	0.98	0.75	269
VIB3702-00001	-8.1	0.97	0.90	270
VIB3705-00001	-3.8	0.97	0.94	177
VIB3706-00002	-2.8	0.96	0.93	162
VIB3708-00001	-3.6	0.98	0.90	336
VIB3708-00002	7.0	0.86	0.75	128
VIB3708-00003	7.2	0.83	0.71	56
VIB3708-00004	8.7	0.88	0.43	97
VIB3708-00005	7.0	0.91	0.70	108
VIB3708-00006	6.1	0.87	0.76	76
VIB3711-00001	-18.9	0.98	0.85	276
VIB3720-00001	2.8	0.96	0.90	68
VIB3721-00001	0.2	0.90	0.86	72
VIB3722-00001	3.8	0.94	0.86	105
VIB3722-00002	6.0	0.89	0.70	150
VIB3722-00003	5.7	0.91	0.62	114
VIB3723-00001	7.7	0.91	0.68	154
VIB3723-00002	6.7	0.94	0.72	118
VIB3723-00004	7.0	0.88	0.63	150
VIB3723-00005	7.6	0.92	0.61	116
VIB3725-00001	8.9	0.91	0.55	174
VIB3725-00002	5.7	0.85	0.30	98
VIB3725-00003	9.0	0.92	0.53	132
VIB3726-00001	8.5	0.91	0.51	192
VIB3726-00002	9.4	0.88	0.57	174
VIB3726-00003	7.1	0.86	0.23	124
VIB3727-00001	1.8	0.94	0.78	329
VIB3727-00002	11.8	0.78	0.16	139
VIB3728-00001	5.4	0.91	0.75	284
VIB3728-00002	6.9	0.90	0.74	282

Station	P-Bias	Spearman Rank Correlation	Modelling Efficiency Factor	Number of observations
VIB3728-00003	6.5	0.92	0.69	220
VIB3729-00001	-11.1	0.94	0.73	270

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