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OFFSHORE AB

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Bilaga M14: Sediment Dispersal

Fyrskeppet Offshore

Sediment Dispersal

Fyrskeppet Offshore AB

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Appendix

1. Introduction

Fyrskeppet Offshore AB has appointed NIRAS to quantify the impact on the dispersal of sediment in the construction phase for two cases at the Fyskeppet Offshore Wind Farm (Fyrskeppet OWF): one with 187 turbines with 15MW rated power and the other with 187 turbines with 30MW rated power. The latter case constitutes a worst-case scenario for sediment dispersal.

The main difference between the two cases is the size of the gravity-based foundation (GBS) and the size of the turbine which have an effect of the requirement to seabed preparation.

2. Scope of Work

The purpose of the sediment dispersal study is to present the potential impact of the spreading of sediment due to dredging, jetting, etc. during the construction of Fyrskeppet OWF.

3. Abbreviation

GBS	Gravity Based Structure
IAC	Inter array cable
OSS	Offshore substation
OWF	Offshore wind farm
WTG	Wind turbine generator

4. Summary

To address the impact on the sediment dispersal a hydrodynamic and spectral wave model of the Gulf of Bothnia has been calibrated on public data of water levels, and project data of current, temperature, salinity and waves. Based on data from SMHI's 3D model of the Baltic Sea the year-to-year variations were investigated and the year 2021 was found to be close to an average year and thus to be used as a baseline for description of the potential impact. In general, the year-to-year variation is small and unlikely to impact the conclusion.

Baseline, general description:

The Bothnian Sea, where the project area of Fyrskeppet OWF is located, constitutes the southern part of the Gulf of Bothnia, and is separated from the Baltic Proper by a strait at the Åland Sea. Hydrographic conditions are characterised by a low salinity (3-6 PSU) and a weak vertical salinity gradient (halocline). Sea surface temperature varies from 0-2°C during the winter to somewhat over 20°C between June and August. Temperature is strongly stratified during the summer with a thermocline (zone of maximum temperature gradient) around 10-30m depth. Deeper temperature, below 30m, varies less during the year, between 2°C at the end of the winter to 7°C at the end of the autumn. Due to the absence of tides, water levels experience relatively small variations, generally between ±50cm around their average during the year. These variations are mostly driven by variations at the Åland boundary, wind and pressure differences (meteorological surge). Due to the limited variations in water levels, currents are generally weak, around 0.15m/s at the surface (maximum of 0.5m/s) and less than 0.07m/s below 30m, and mostly driven by wind as well as temperature and salinity differences. Average circulation in the Bothnian Sea is counter-clockwise with dominant

northward currents along the east coast, southwards along the west coast, and relatively large (≥10km radius) eddies at the centre of the sea. Waves are fetch limited with under 1m significant wave height on average over the year. Maximum waves are observed in October, 1.5m on average, with higher waves in the northward direction (long side of the sea).

The impact is evaluated for the sediment spill given by seabed preparation in the construction phase.

Construction Phase, Sediment Dispersal

Results are relatively close between the 15MW and 30MW cases, both in terms of total duration exceeding a given sediment concentration level (continuously or not) and sedimentation, and generally somewhat higher in the 30MW case due to larger gravity base structures (GBS). Surface (0-10m) sediment concentrations of 10mg/l cover 87% and 95% of Fyrskeppet OWF for at least 3 hours, 43% and 56% for 12 hours and 1% and 3% for 48 hours for the 15MW and 30MW case, respectively (Table 8.4 and Table 8.5). This indicates that sediment spilled at the surface dilutes relatively quickly. Virtually no part of Fyrskeppet OWF experiences sediment concentrations above 10mg/l for more than 72 hours in total over the construction phase. Surface sediment concentrations are mostly contained within Fyrskeppet OWF, with an increase in sediment concentrations of 10mg/l affecting very limited parts of the Natura 2000 area Finngrundet for less than 13 hours. Higher surface sediment concentrations (50mg/l) are contained within 1km of Fyrskeppet OWF. Hence, given the 2km buffer zone around the Natura 2000 area (bordering the south of Fyrskeppet OWF), the risk of surface sediment concentrations above 50mg/l spreading into the Natura 2000 area is low, while smaller concentrations could occur for less than 24 hours, depending on current speeds and directions. Due to the low current speeds at the bottom, sediments in the deeper layer settle quickly to the bottom and their impact is therefore spatially limited to the vicinity of the GBS, without yielding any increase in sediment concentrations within the lowest 5m above the seabed surrounding Fyrskeppet OWF, including the Natura 2000 area. Almost no areas of Fyrskeppet OWF in the lowest 5m above the seabed experience sediment concentrations greater than 10mg/l for more than a day, and very limited areas experience concentrations over 100mg/l for 3-6 hours. In terms of sedimentation, the installation of Fyrskeppet OWF for both the 15MW and 30MW cases generates moderate sedimentation (1mm to 5mm) in 1% to 13% of Fyrskeppet OWF area, while higher sedimentation affects less than 1% of Fyrskeppet OWF. Spilled sediment settles primarily near the GBSs and, due to low bottom current velocities, does not undergo resuspension and is generally stable. No increase in sedimentation is observed in the adjacent Natura 2000 area.

5. Methodology

To estimate the pressure on the hydrodynamics and the dispersal of sediment 3 types of numerical models are used:

1) A 3D hydrodynamic model to simulate the water level and currents;
2) A wave model to simulate the wave climate and
3) A sediment model to simulate the spread and deposit of the sediments dispersed due to the installation

Before any evaluation of potential impacts the 2 base models; the hydrodynamic model and the wave model, are calibrated toward the data collected by the project (wave, current, salinity and temperature) and publicly available water level data from Sweden and Finland.

Based on 10 years of data, the baseline is described and an average year is identified for input to the Construction Phase.

The numerical models used to simulate the baseline and the pressure from Fyrskeppet OWF are described shortly below and further information can be found here: https://www.mikepoweredbydhi.com/products.

Bathymetric data for the model domain will be extracted from C-Map which contains digitalized sea maps across the globe and EMODnet. Freely available boundary data of water level and wave conditions will be applied at the boundary towards the Baltic Sea combined with wind fields at the surface of the model domain. Wind data is anticipated to be obtained from ECMWF, ERA5 and wave data from SMHI.

Two models will be set up

1) A general model of the Gulf of Bothnia (regional model) and
2) A local high-resolution model forced by boundary data extracted from the regional model.

The combined MIKE3 HD & MIKE21 SW will be applied to assess the time series of the wave, current and water level conditions taking wave radiation stresses and wave transformation into consideration.

5.1.1. Hydrodynamic model

MIKE 3 HD FM (Hydrodynamics) is a hydrodynamic model with a flexible mesh. Based on tidal and current inputs along the open boundaries together with the wind conditions at the sea surface, the model simulates tide and depth-integrated current speed and direction throughout the model domain. The benefit of a flexible mesh is the possibility of using varying sizes of the mesh across the domain. Therefore, the focus area can have a high resolution, and areas further away can have a coarser resolution. This makes the model run faster, with a negligible impact on the simulation results.

5.1.2. Spectral wave model

MIKE 21 SW FM (Spectral Waves) is a spectral wave model which models wave growth and decay due to wind forcing, wave transformation, wave dissipation (from white capping, bottom friction and depth-induced wave breaking), refraction and shoaling.

5.1.3. Sediment model

MIKE 21/3 PT (Particle Tracking) is a so-called Lagrangian model which over time considers both the position and properties of the particles e.g., keeping track of the particle position in both x, y- and z-direction according to the mean current field. This is the opposite of a Eulerian model which does it cell-wise where e.g. the concentration will be an average of the volume over each cell. This type of model is extremely sensitive to the model resolution both horizontally and vertically, whereas the Lagrangian approach is independent of cell sizes.

The selection of MIKE 21/3 PT for modelling the sediment dispersal is due to the nature of the plumes created by dredging, drilling, ploughing and jetting. The plumes are initially narrow and occur in various water column depths. This is difficult to describe in a traditional model e.g., MIKE 21 MT mesh while maintaining a reasonable calculation time.

To assess the quantity and duration of spillage, it is important to understand the construction activities. Will they be carried out simultaneously or will they be carried out independently at short intervals from each other? This will have an impact on the modelling study as in the former scenario, a higher quantity of sediments will be spilled in a shorter duration and in the latter scenario, spillage will occur in smaller quantities but repeatedly at certain intervals.

6. Background data

In the present chapter, the background data used in the numerical modelling and the description of the morphological, oceanographic and hydraulic conditions site are presented. This includes Metocean data, grab samples and bathymetric surveys.

6.1. Fyrskeppet OWF, Project description

6.1.1. Fyrskeppet OWF Layout

The layout of Fyrskeppet OWF is illustrated in Figure 6.1. The footprint covers an area of 488 km^2, the total number of turbines are 187, there are 4 offshore substation and 450 km infield cables (380 km inter-array cable and 70 km redundancy cables). The Fyrskeppet OWF project, including the buffer zone with the adjacent Natura 2000 area, covers an area 533 km^2.

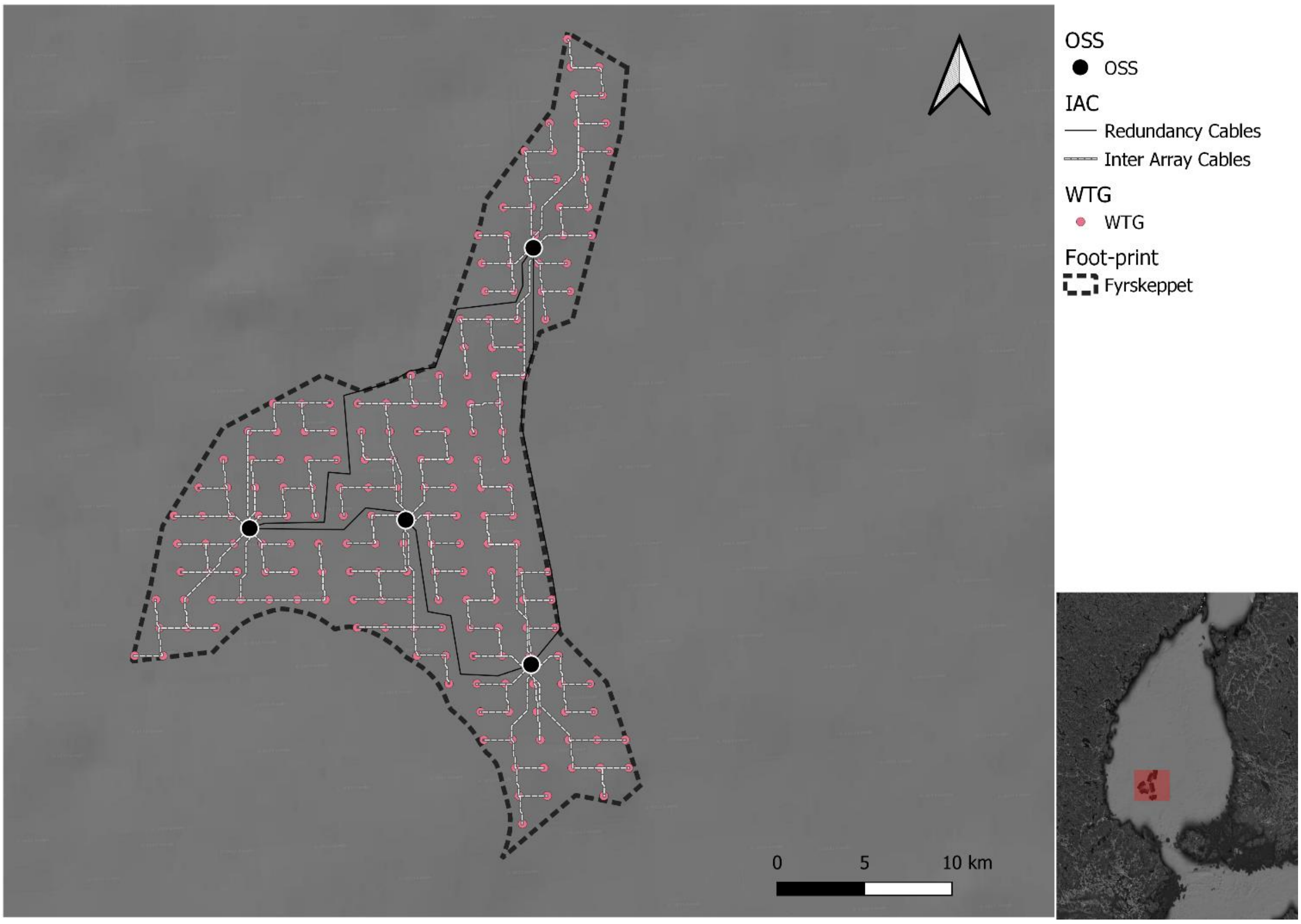

Figure 6.1: Fyrskeppet OWF layout: Map: Google Earth.

6.1.2. Dimensions

In Table 6.1 the dimensions of the wind turbines and supporting structures are listed together with the amount of dredged material and the gross spill. The 15% spill from the dredging of the gravity-based structures is 10% due to dredging spilled 2 m above the seabed and 5% overrun from the barge.

Moreover, a sketch illustrating the shape of the GBS can be found in Figure 6.2.

Table 6.1: Substructure dimension, spill percentage and gross spill

Case	**-**	**15MW GBS**	**30MW GBS**
Capacity	**MW/Unit**	**15**	**30**
Rotor diameter	**[m]**	**245**	**330**
Hub Height	**[m]**	**142.5**	**175**
Substructure	-	GBS	GBS
Capacity, total	MW	2805	5610
Nos	#	187	187
Bottom diameter, base	m	40	48
Top diameter, base	m	10.6	11.8
Dredging depth	m	3	3
Spill percentage, bottom	%	10%	10%
Spill percentage, overrun surface	%	5%	5%
Vol. to be removed	m^3/pos.	5700	7700
Dredged	#	100%	100%
Total drilled/dredged vol.	m^3	1065900	1439900
Spill, gross foundation	m^3	159885	215985
Length infield + redundancy cable	m	450000	450000
Trench 2m^3/m, Dispersed	m^3	1800000	1800000
Spill percentage	%	10%	10%
Spill, gross infield cable	m^3	180000	180000
No. OSS	#	4	4
Bottom diameter, base	m	48	48
Dredging depth	m	3	3
Spill percentage, bottom	%	10%	10%
Spill percentage, overrun surface	%	5%	5%
Vol. to be removed	m^3/pos.	7700	7700
Spill, gross OSS	m^3	4620	4620
Spill, gross	m^3	344505	400605
Spill, gross	ton	568433	660998

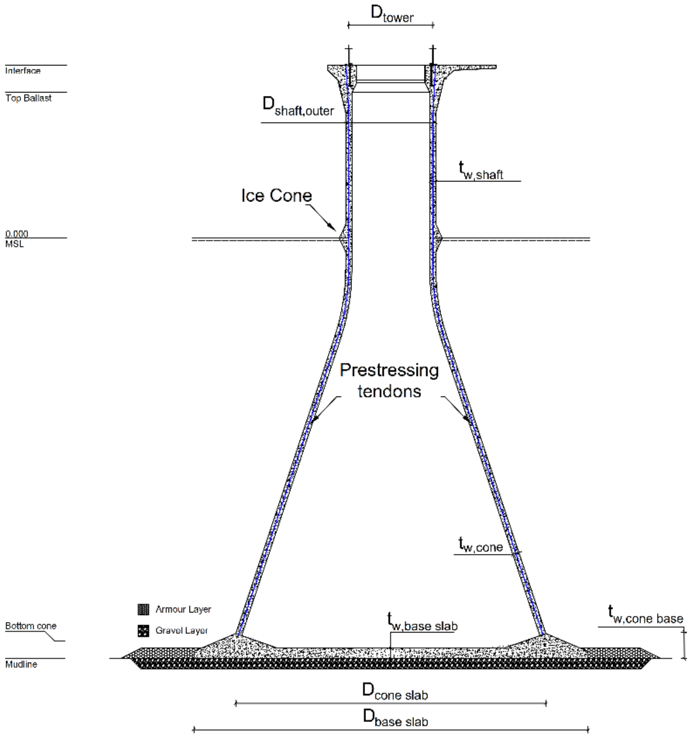

Figure 6.2: Sketch of the GBS

6.2. Bathymetry data

The water depths in the model are based on survey data provided by the project and EMODnet, (EMODnet, 2021) and on high resolution (50m) bathymetry data from the client based on field survey for Fyrskeppet OWF and presented in Figure 7.1 (together with the mesh).

6.3. Observations

6.3.1. Water levels

Water levels with an hourly resolution have been obtained from the SMHI stations Holmsund (lat: 63.6803, long: 20.3331), FORSMARK (lat: 60.4086, long: 18.2108), KALIX-STORÖN (lat: 65.6969, long: 23.0961) and SPIKARNA (lat: 62.3633, long: 17.5311), extracted for the years 2020-2022. The locations of the water level stations are displayed in Figure 6.3. Water levels for these stations are displayed in Figure 6.4.

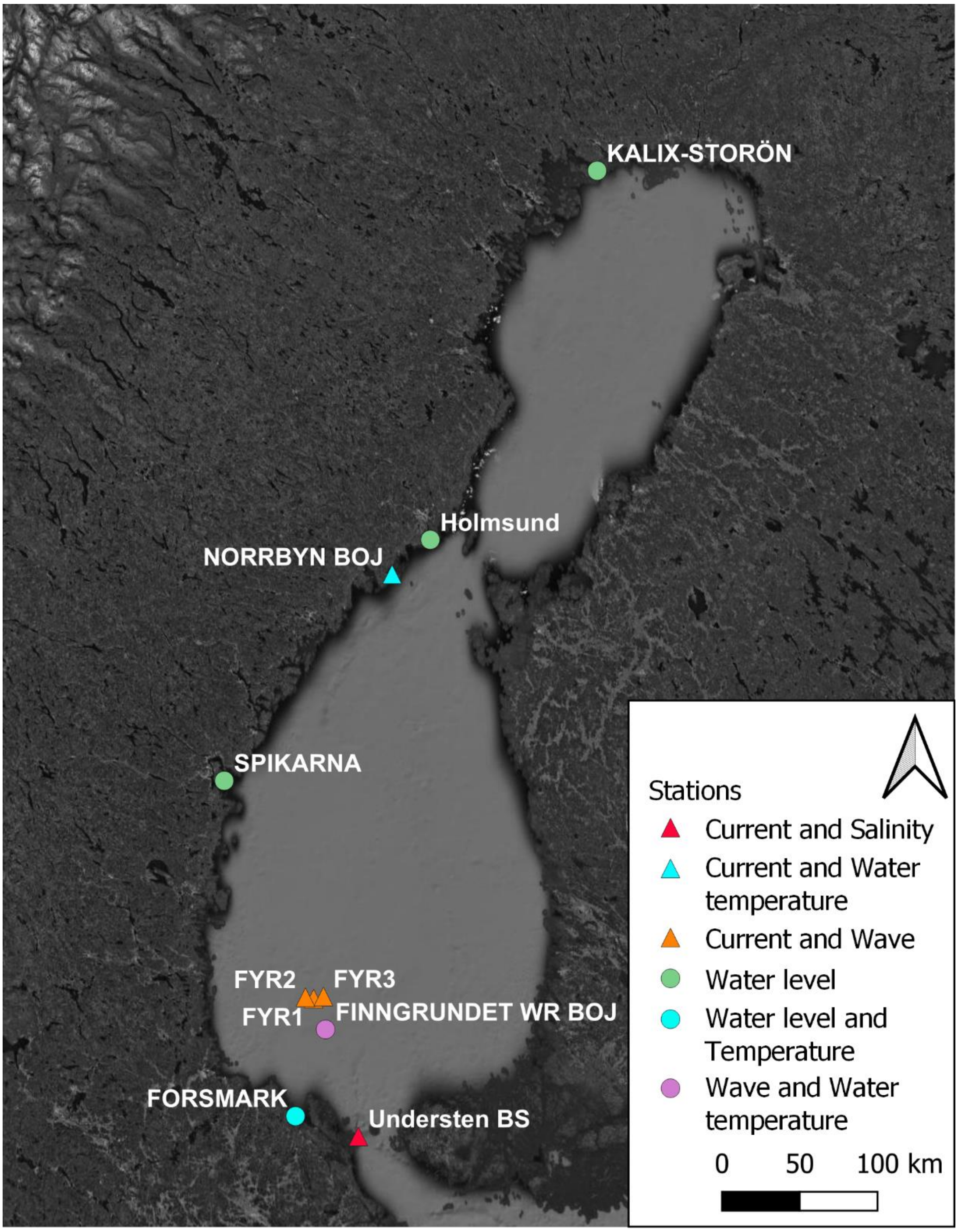

Figure 6.3: Location of water level, wave, current and water temperature monitoring stations used for calibration and validation of the hydrodynamic model. FYR1, FYR2 and FYR3 are project defined stations. Map: ESRI.

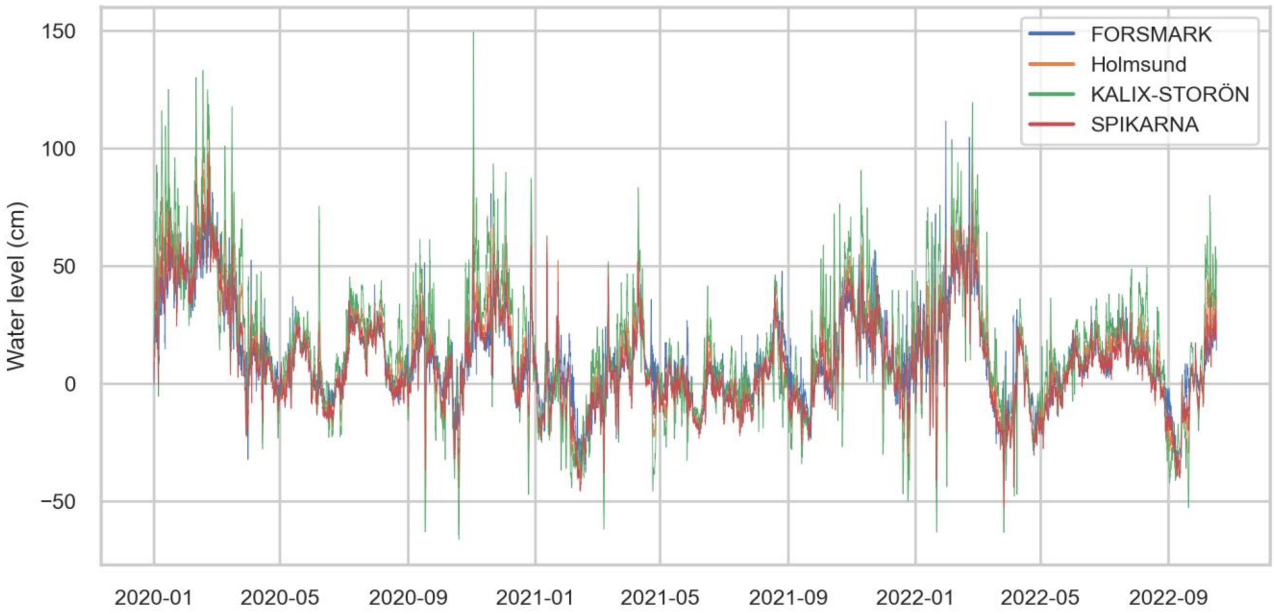

Figure 6.4: Water levels (cm) at the Forsmark, Holmsund, Kalix-Storön and Spikarna monitoring stations

6.3.2. Currents

Current speeds and directions with an hourly resolution have been obtained from the SMHI stations NORRBYN BOJ (lat: 63.499, long: 19.8044) at 5m, 15m and 25m depths for the period 2016-2021 and Understen BS (lat: 60.2715, long: 18.9302) at 219m depth for the year 2021.

Current speeds and directions with an hourly resolution have also been obtained from the project stations Fyrskeppet position 1 (61°4.924'N, 18°29.767'E), Fyrskeppet position 2 (61°5.498'N, 18°23.922'E) and Fyrskeppet position 3 (61°5.486'N, 18°36.863'E) for the period 2022/06/29 – 2022/10/01, extracted at 5m, 15m and 25m depths (FYR1, FYR2 and FYR3). The locations of the current stations are displayed in Figure 6.3. The current speeds and directions for the Fyrskeppet positions are shown in Figure 6.5 and Figure 6.6, respectively. The current speeds and directions for the SMHI stations are shown in Appendix 1.

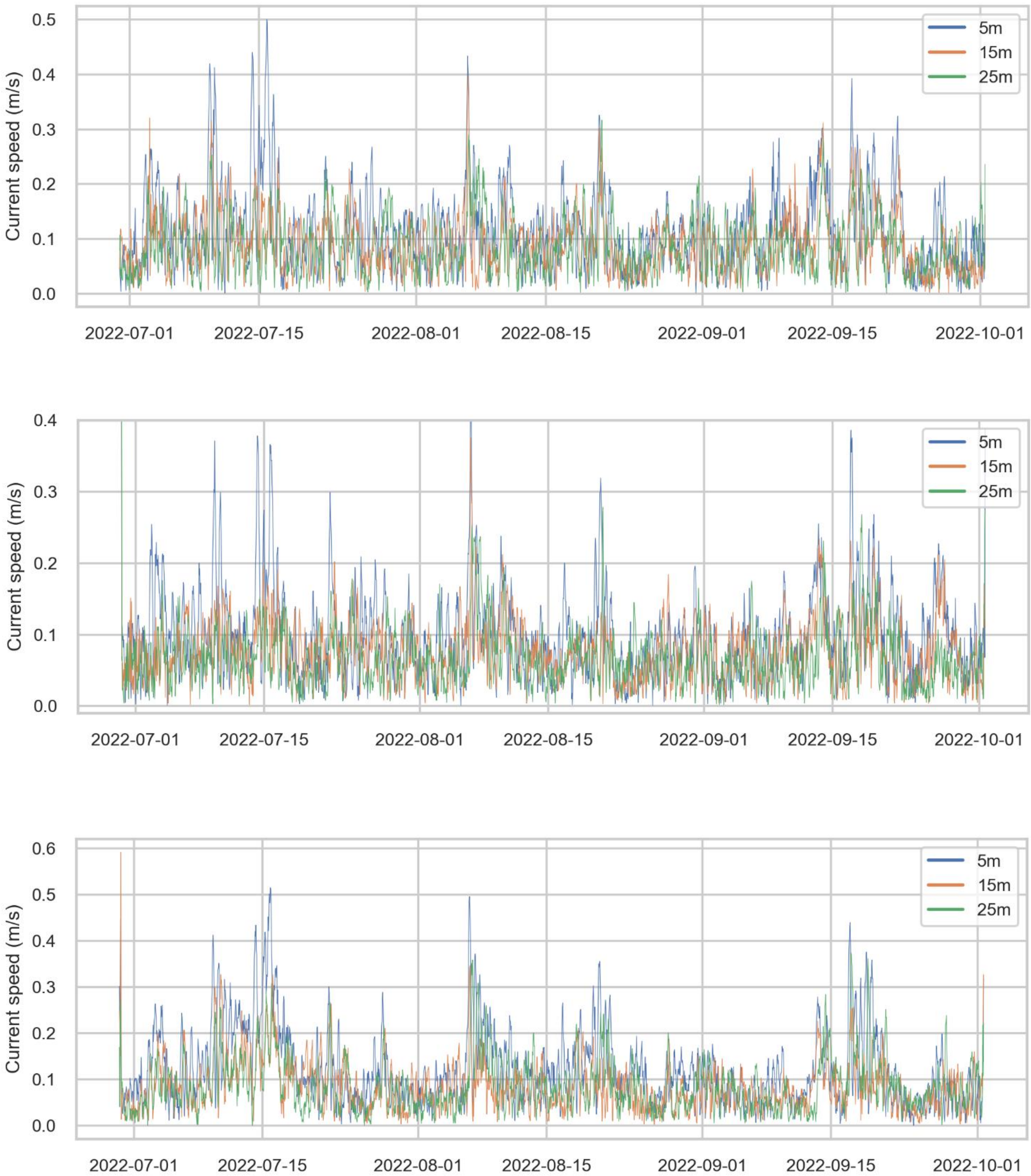

Figure 6.5: Current speeds (m/s) at 5, 15 and 25m for FYR1 (top), FYR2 (middle), and FYR3 (bottom).

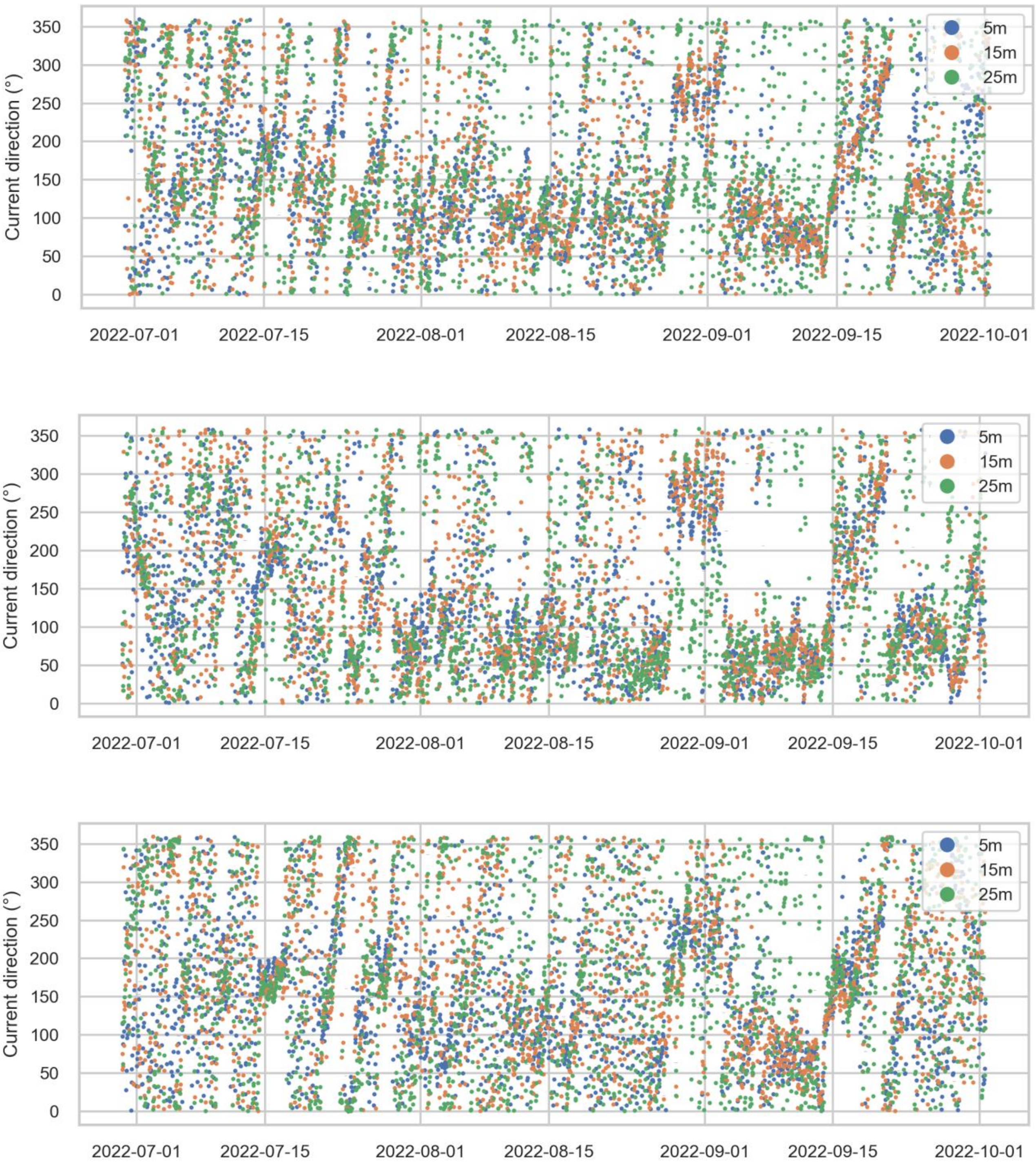

Figure 6.6: Current directions (°, going to) at 5, 15 and 25m for FYR1 (top), FYR2 (middle), and FYR3 (bottom).

6.3.3. Waves

Significant wave heights and mean wave directions with an hourly resolution have been obtained from the SMHI stations FINNGRUNDET WR BOJ (lat: 60.9, long: 18.6167) for the period 2020-2022.

Significant wave heights and mean wave directions with an hourly resolution have also been obtained from the project stations Fyrskeppet position 1 (61°4.924'N, 18°29.767'E), Fyrskeppet position 2 (61°5.498'N, 18°23.922'E) and Fyrskeppet position 3 (61°5.486'N, 18°36.863'E) for the period 2022/06/29 – 2022/10/01 (FYR1, FYR2 and FYR3). The locations of the wave stations are displayed in Figure 6.3.

Time series of significant wave heights and mean wave directions for the stations are displayed in Figure 6.7 and Figure 6.8.

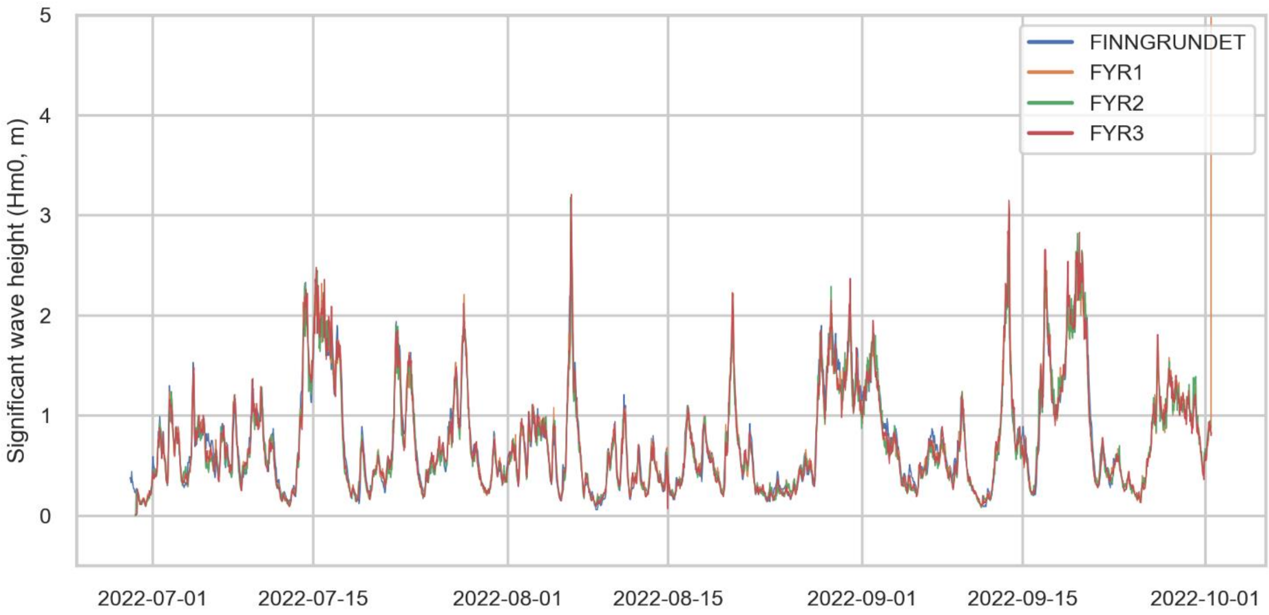

Figure 6.7: Significant wave height (Hm0, m) for the Fyrskeppet positions 1, 2 and 3, and SMHI station Finngrundet

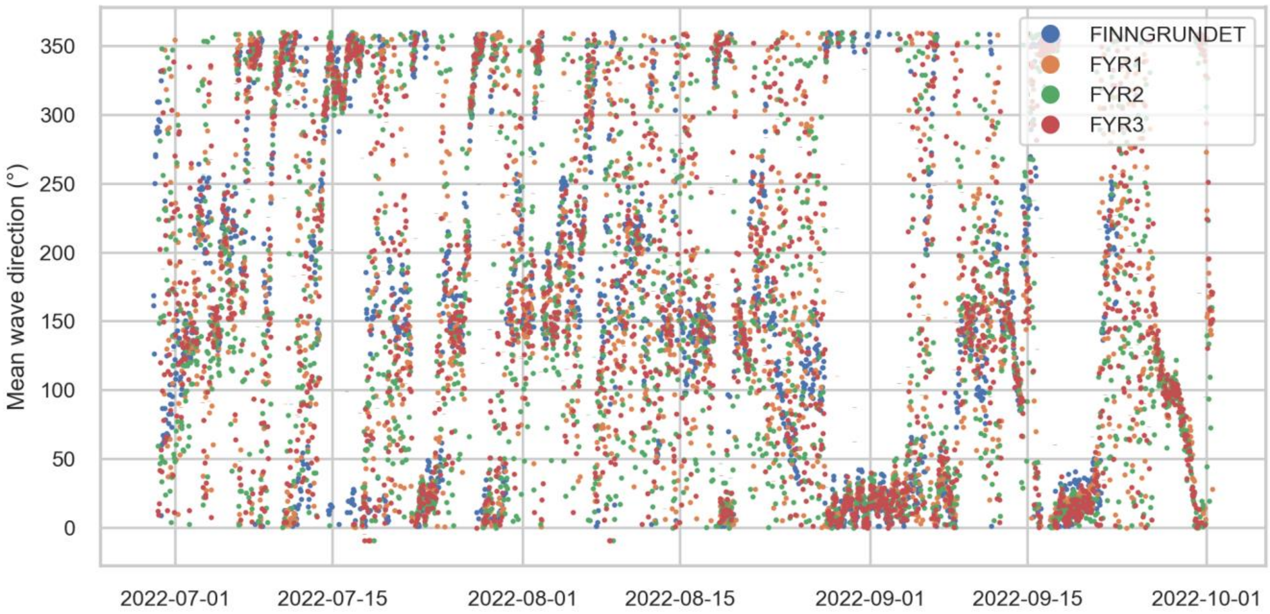

Figure 6.8: Mean wave direction (°, coming from) for the Fyrskeppet positions 1, 2 and 3, and SMHI station Finngrundet

6.3.4. Salinity and Temperature

Surface water temperatures (0m) with an hourly resolution have been obtained from the SMHI FINNGRUNDET WR BOJ (lat: 60.9, long: 18.6167), FORSMARK (lat: 60.41, long: 18.2108) and NORBYN (lat: 63.5642, long: 19.8331) stations for the period 2020-2022. Salinity at the surface (1m) from NORBYN BOJ and at the bottom (219m) from Understen BS has also been obtained from SMHI . The locations of the temperature and salinity stations are displayed in Figure 6.3. The time series of temperature and salinity are shown in Figure 6.9 and Figure 6.10, respectively.

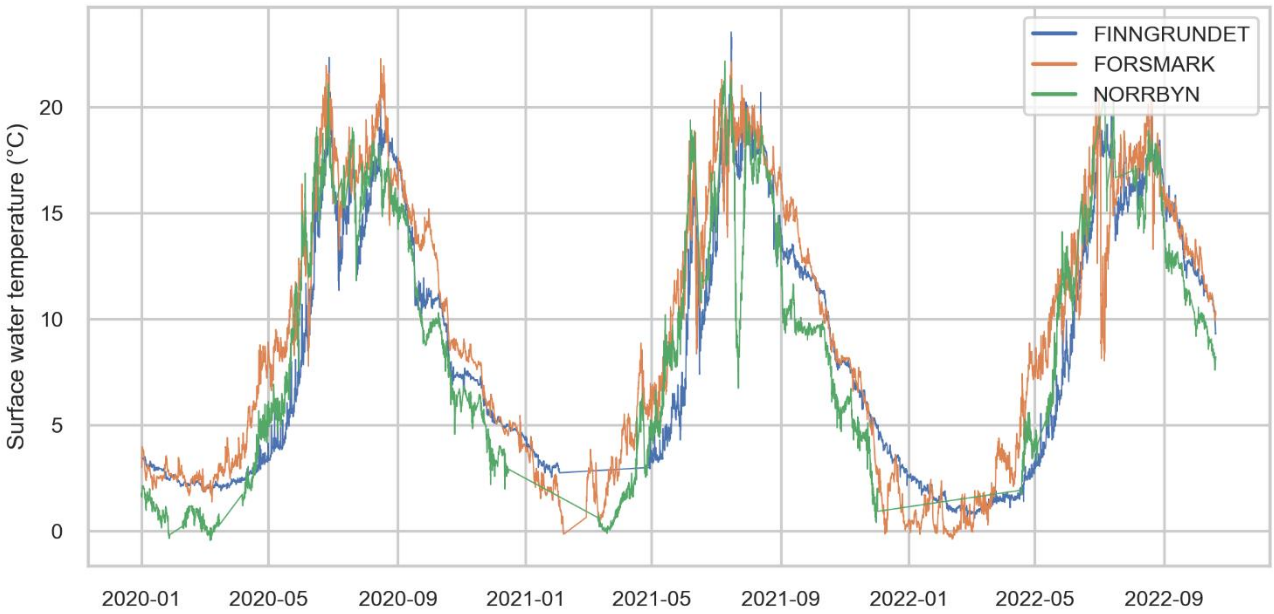

Figure 6.9: Surface water temperature (°C) at Finngrundet, Forsmark and Norrbyn monitoring stations

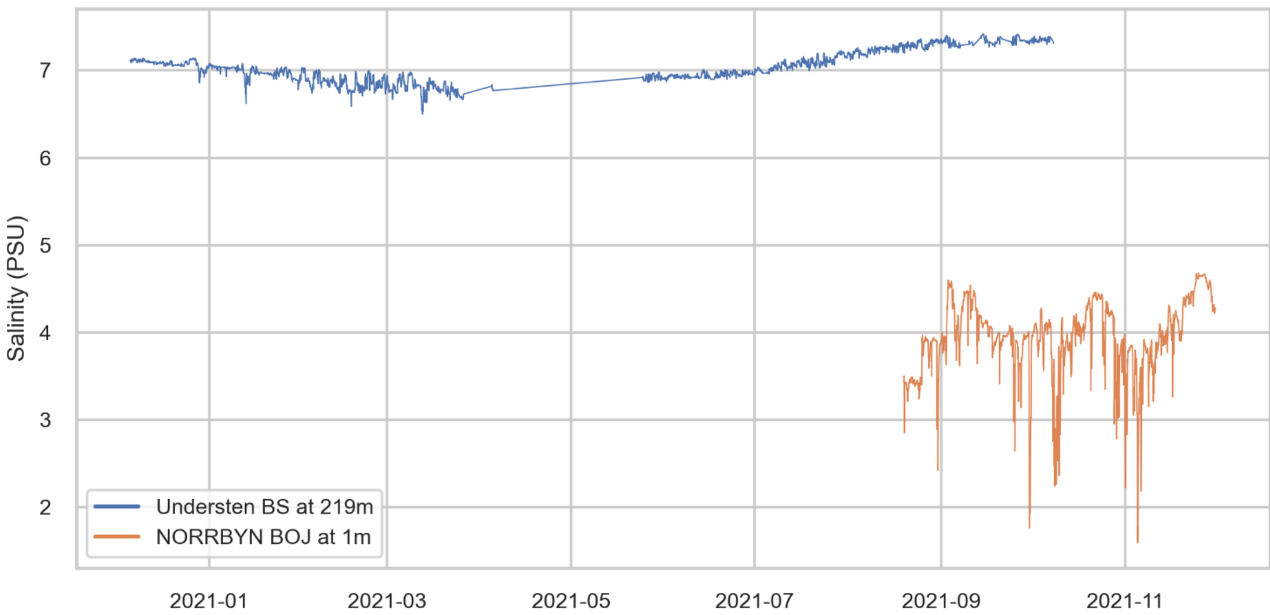

Figure 6.10: Salinity (PSU) at Understen BS (219m) and Norrbyn Boj (1m) stations

6.4. Hydrodynamic data from models

6.4.1. Water levels

Data from the 2km by 2km SMHI 3D Baltic Sea model are used at the Åland Sea boundary conditions to feed the Mike model (Copernicus, Baltic Sea Physics Analysis and Forecast, 2x2km, 2022) and (Copernicus, Baltic Sea Physics Reanalysis 4x4km, 2022).

6.4.2. Currents

To identify an average year for simulating impacts on hydrodynamics and sediment dispersal, SMHI 3D Baltic Sea model results at Fyrskeppet OWF (Copernicus, Baltic Sea Physics Analysis and Forecast, 2x2km, 2022) and (Copernicus, Baltic Sea Physics Reanalysis 4x4km, 2022) are presented in Appendix 4 and Appendix 5.

6.4.3. Salinity and Temperature

For initialisation and to feed the model at the boundary, data from SMHI's numerical model of the Baltic Sea are used, (Copernicus, Baltic Sea Physics Analysis and Forecast, 2x2km, 2022) and (Copernicus, Baltic Sea Physics Reanalysis 4x4km, 2022).

Data from selected years are presented in Appendix 2 and Appendix 3.

6.5. Wind, Air Pressure, Air Temperature, Net long and short-wave radiations

Atmospheric data in the form of instantaneous wind speed at 10 mMSL in x and y-directions, air pressure at the surface, air temperature at 2 m above the surface, relative air humidity, and net long and short-wave radiation at the surface have been extracted from ECMWF (ECMWF, 2022). The data have a horizontal resolution of 0.25 degrees and a temporal resolution of 1 hour.

6.6. Sea ice

The presence of sea ice is based on data produced by SMHI, (Copernicus, Baltic Sea Physics Analysis and Forecast, 2x2km, 2022) and (Copernicus, Baltic Sea Physics Reanalysis 4x4km, 2022) as ice thickness and concentration.

6.7. Run-off

The following major freshwater discharges (average discharge greater than 100m^3/s) to the Gulf of Bothnia are used as input to the model:

- Kokemäenjoki (Harjavalta station, lat: 61.34, long: 22.11; Finland)
- Oulujoki (Merikoski station, lat: 65.023, long: 25.47; Finland)
- Iijoki (Raasakka station, lat: 65.33, long: 25.41; Finland)
- Kemijoki (Taivalkoski station, lat: 65.93, long: 24.71; Finland)
- Tornionjoki (Karunki station, lat: 66.03, long: 24.02; Finland)
- Kalixälven (lat: 65.8, long: 23.25; Sweden)
- Luleälven (lat: 65.56, long: 22.05; Sweden)
- Piteälven (lat:65.30, long: 21.44; Sweden)
- Skellefteälven (lat: 64.71, long: 21.18; Sweden)
- Umeälven (lat: 63.74, long: 20.36; Sweden)
- Ångerman (lat: 63.03, long: 17.78; Sweden)
- Indalsälven (lat: 62.5, long: 17.5; Sweden)
- Ljungan (lat: 62.28, long: 17.4; Sweden)
- Ljusnan (lat: 61.2, long: 17.13; Sweden)
- Dalälven (lat: 60.62, long: 17.49; Sweden)

For the Swedish rivers, modelled and station-corrected daily discharges and temperatures have been obtained from the SMHI VattenWebb platform for the years 2020-2022. For the Finnish rivers, observed daily discharges have been obtained from the Finnish environmental institute Ymparisto, and water temperatures have been assumed similar to those of the Swedish river at the closest latitude. The discharges and temperatures of the main rivers are shown in Figure 6.12 and Figure 6.14, respectively, the total river discharge in Figure 6.13 and their location in Figure 6.11.

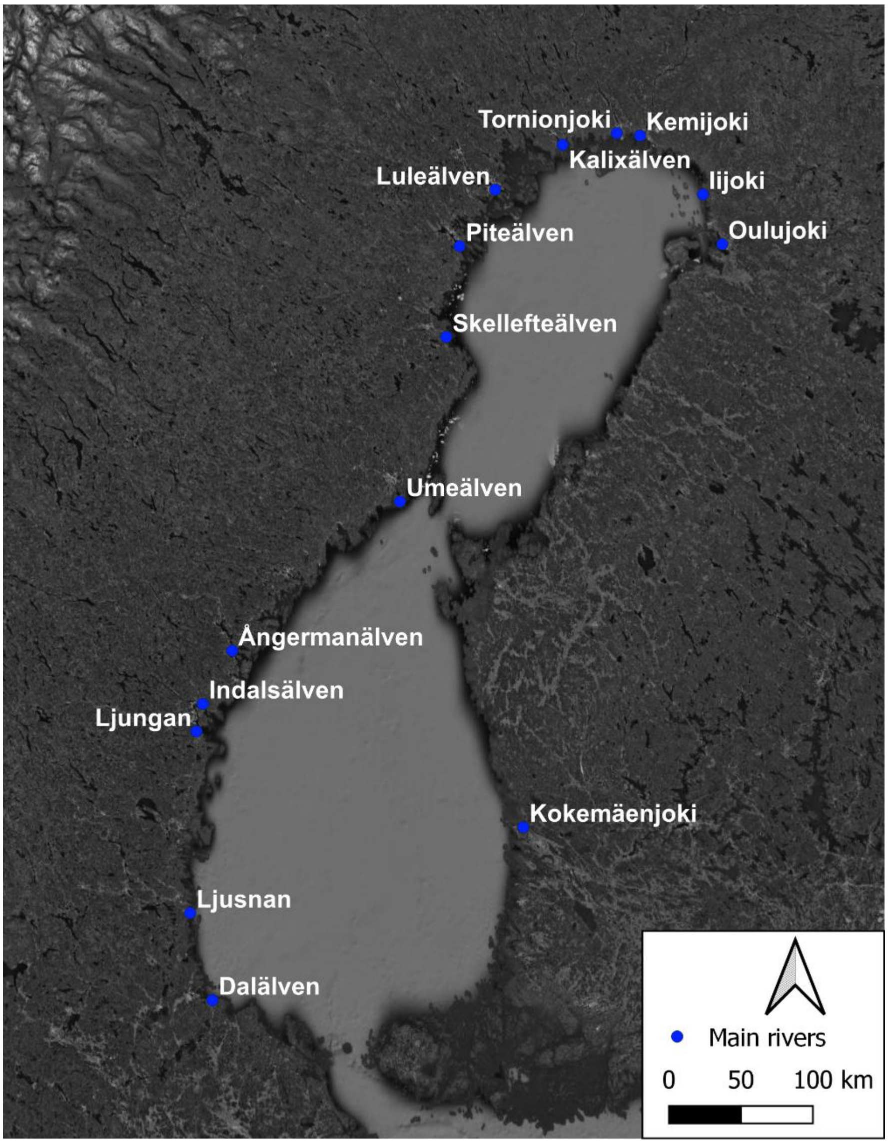

Figure 6.11: Location of the main rivers included in the model. Map: ESRI.

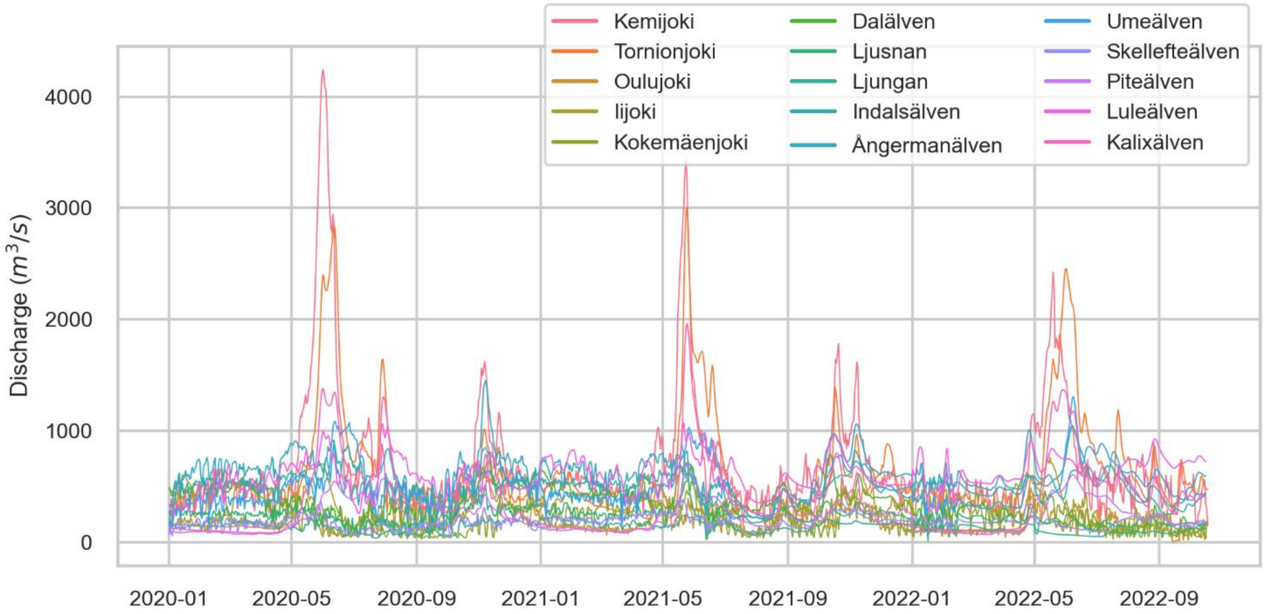

Figure 6.12: Daily discharges (m^3/s) for the main rivers considered in the model.

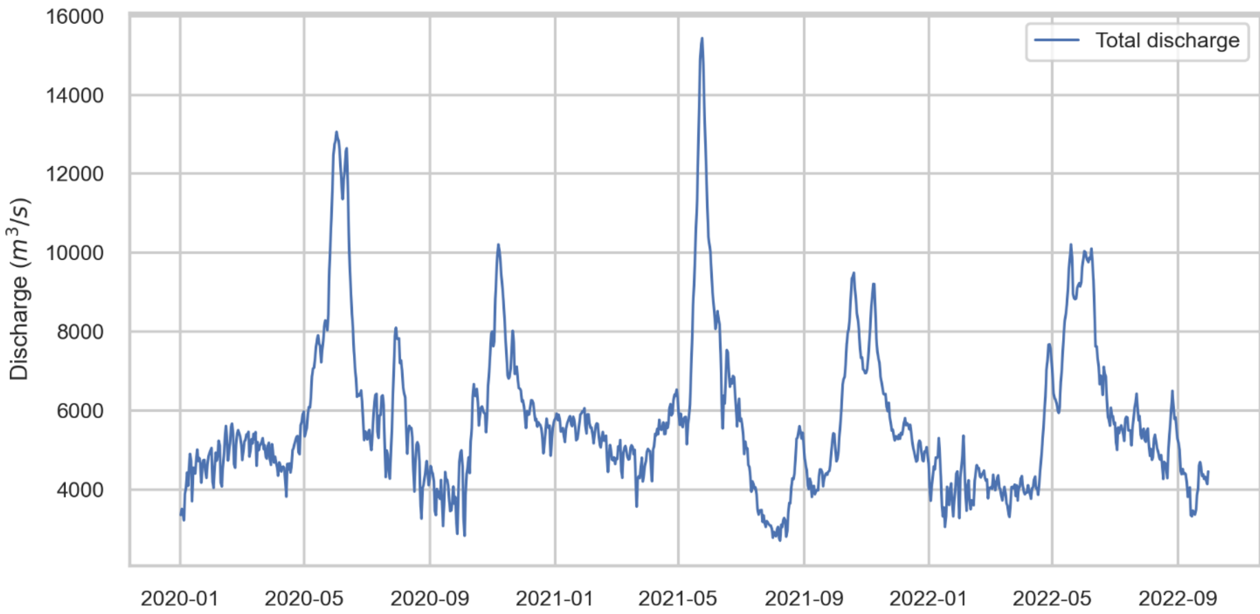

Figure 6.13: Total river discharge (m^3/s) into the model.

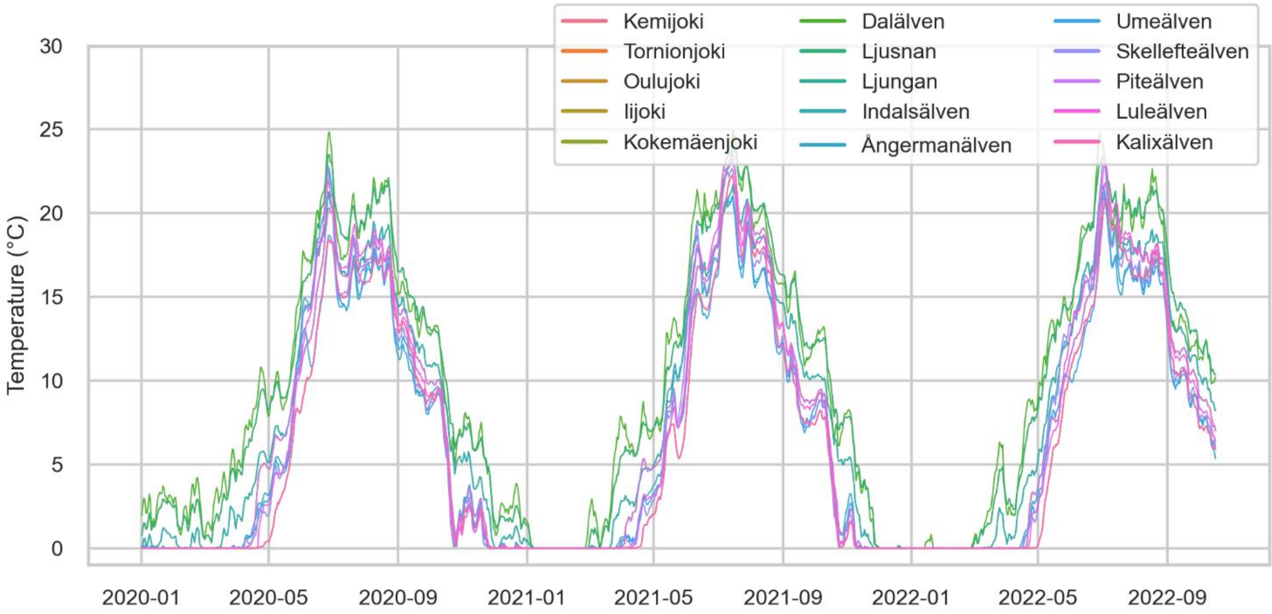

Figure 6.14: Daily water temperatures (°C) for the main rivers considered in the model.

6.8. Surficial sediments

The general image of the surficial sediments present in Fyrskeppet OWF and the surrounding area is based on data provided by the client as shapefiles, Figure 6.16.

The majority of the seabed within Fyrskeppet OWF consists of clary till and some small patched with glacial clay to the southeast and post-glacial clay to the southwest and west.

As no data with sufficient grain size resolution are available from the project the assumed grain distribution is based on data from (DHI/IOW Consortium, 2013) classified as Upper Glacial Till, Figure 6.15.

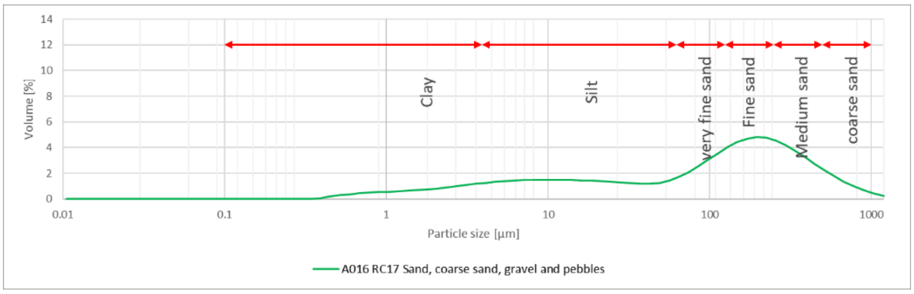

Figure 6.15: Assumed grain distribution, Sample A016 (DHI/IOW Consortium, 2013)

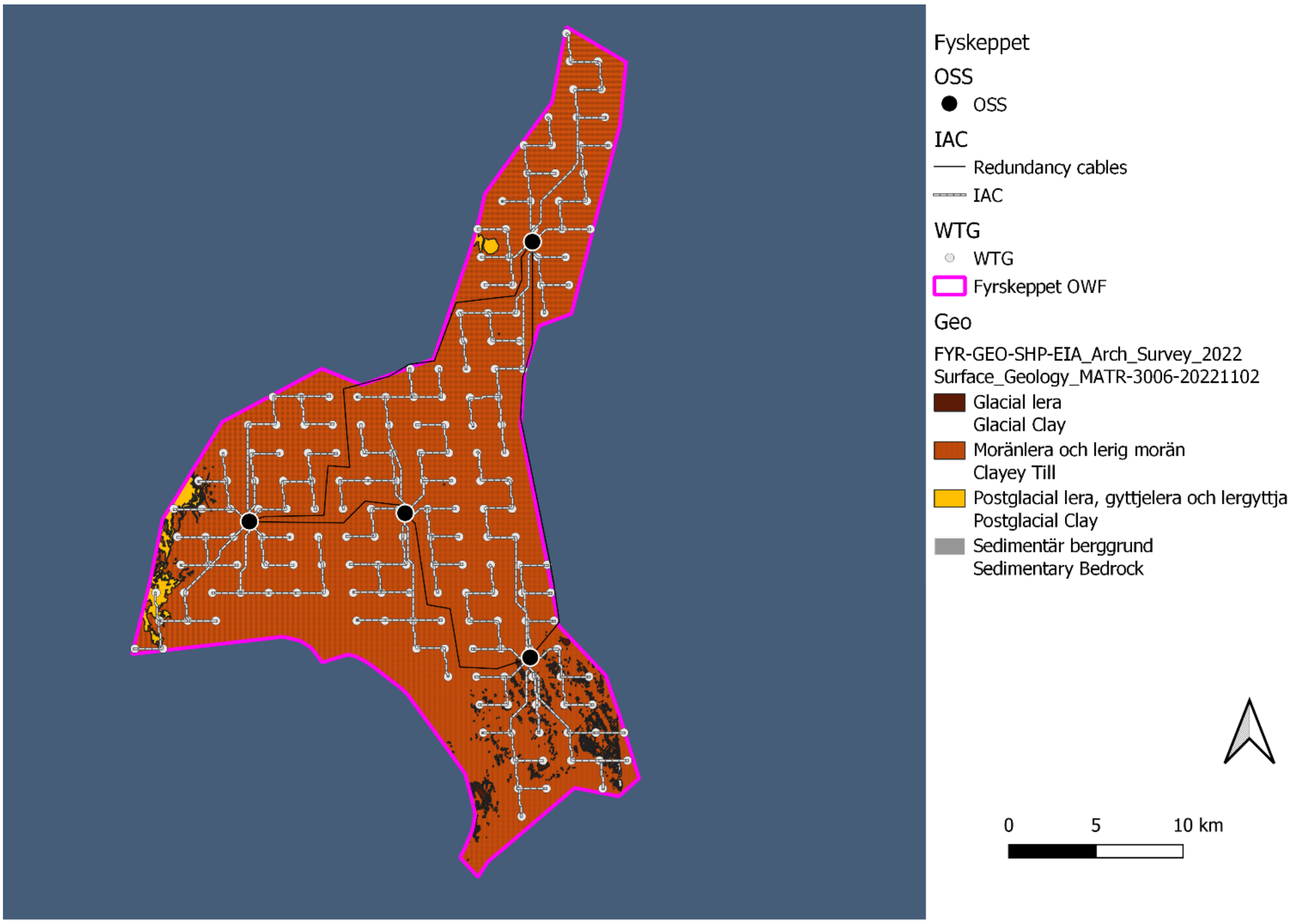

Figure 6.16: Sediment, sub-surface provided by the project.

6.9. Baseline description

The Bothnian Sea, where Fyrskeppet OWF is located, constitutes the southern part of the Gulf of Bothnia, and is separated from the Baltic Proper by a strait at the Åland Sea. Hydrographic conditions are characterised by a low salinity (3-6 PSU) and a weak vertical salinity gradient (halocline). Sea surface temperature varies from 0-2°C during the winter to somewhat over 20°C between June and August. Temperature is strongly stratified during the summer with a thermocline (zone of maximum temperature gradient) around 10-30m depth. Deeper temperature, below 30m, varies less during the year, between 2°C at the end of the winter to 7°C at the end of the autumn. Due to the absence of tides, water levels experience relatively small variations, generally between ±50cm around their average during the year. These variations are mostly driven by variations at the Åland boundary, wind and pressure differences. Due to the limited variations in water levels, currents are generally weak, around 0.15m/s at the surface (maximum of 0.5m/s) and less than 0.07m/s below 30m, and mostly driven by wind as well as temperature and salinity differences. Average circulation in the Bothnian Sea is counter-clockwise with dominant northward currents along the east coast, southwards along the west coast, and relatively large (≥10km radius) eddies at the centre of the sea. Waves are moderate due to the relatively small area of the sea (under 1m height on average over the year) and are maximum in October (1.5m on average), with higher waves in the northward direction (long side of the sea).

7. Hydrodynamic model

7.1. Bathymetry and mesh

7.1.1. Regional model

To account for regional circulation patterns, the regional 3D hydrodynamic model encompasses the whole Gulf of Bothnia (Bothnian Sea and Bothnian Bay). The boundary with the Baltic Proper has been placed at the narrowest zone of the Åland Sea. The regional model is used for calibration and validation of hydrodynamic processes, and to force the local pressure model (Figure 7.1). To maintain reasonable simulation times, the model has a relatively coarse horizontal resolution ($16km^2$) and is constituted of 14240 elements and 8182 nodes.

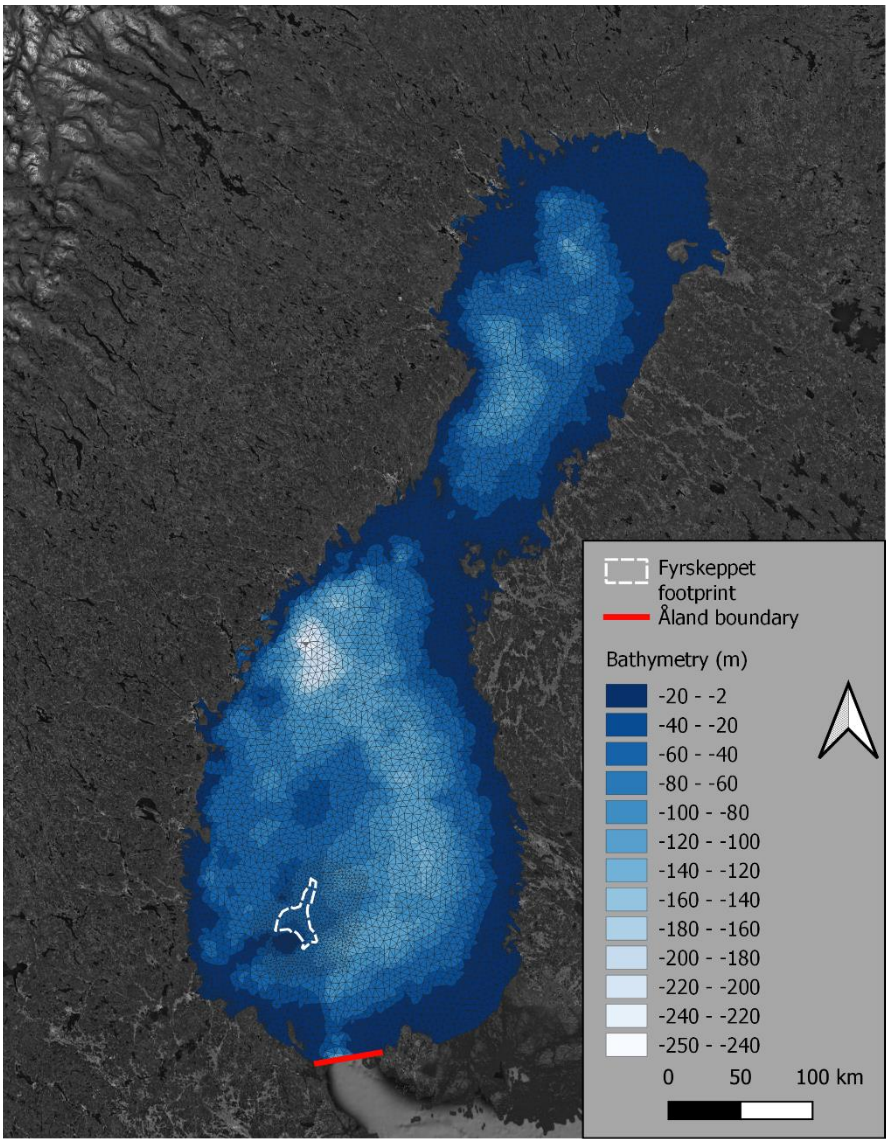

Figure 7.1: Mesh and associated bathymetry (MSL) of the regional hydrodynamic model for calibration and validation. Map: ESRI.

The horizontal resolution has been increased around the Fyrskeppet OWF project area to $5km^2$ for comparison with project specific monitoring data. To capture temperature and salinity stratification, which are more pronounced in the surface layer, the water column is divided into 10 vertical elements for depths up to 30 meters (hybrid sigma layers), giving a minimum vertical resolution of 3 meters. The part of the water column deeper than 30 meters is described using constant depth layers of 12 meters. The bathymetry in the Gulf of Bothnia varies between 0 meter at the coast to 250 meters for the north-western Bothnian Sea. The Bothnian Sea is separated from the Bothnian Bay by a relatively shallow area (the Quark, shallower than 40 meters). The Fyrskeppet OWF project area is generally shallower than its surrounding area, with depth varying between 20 to 80 meters.

7.1.2. Local model

To resolve the boundary conditions to the local sediment dispersal model around Fyrskeppet OWF, the local model encompasses the whole Bothnian Sea with higher resolution. The local model is constituted of 45104 elements and 23079 nodes, and its vertical resolution is similar to that of the regional model. The local model has a varying horizontal resolution, relatively coarse (25km^2) further than 100km from the Fyrskeppet OWF project area, where direct impacts are expected to be less strong, gradually increasing to 1km^2 within 50km of the project area and 0.25km^2 within the project area, where the impact is expected to be the strongest. It is forced by data from the SMHI model at the Åland boundary and results of the regional model at the northern boundary (red and orange lines in Figure 7.2).

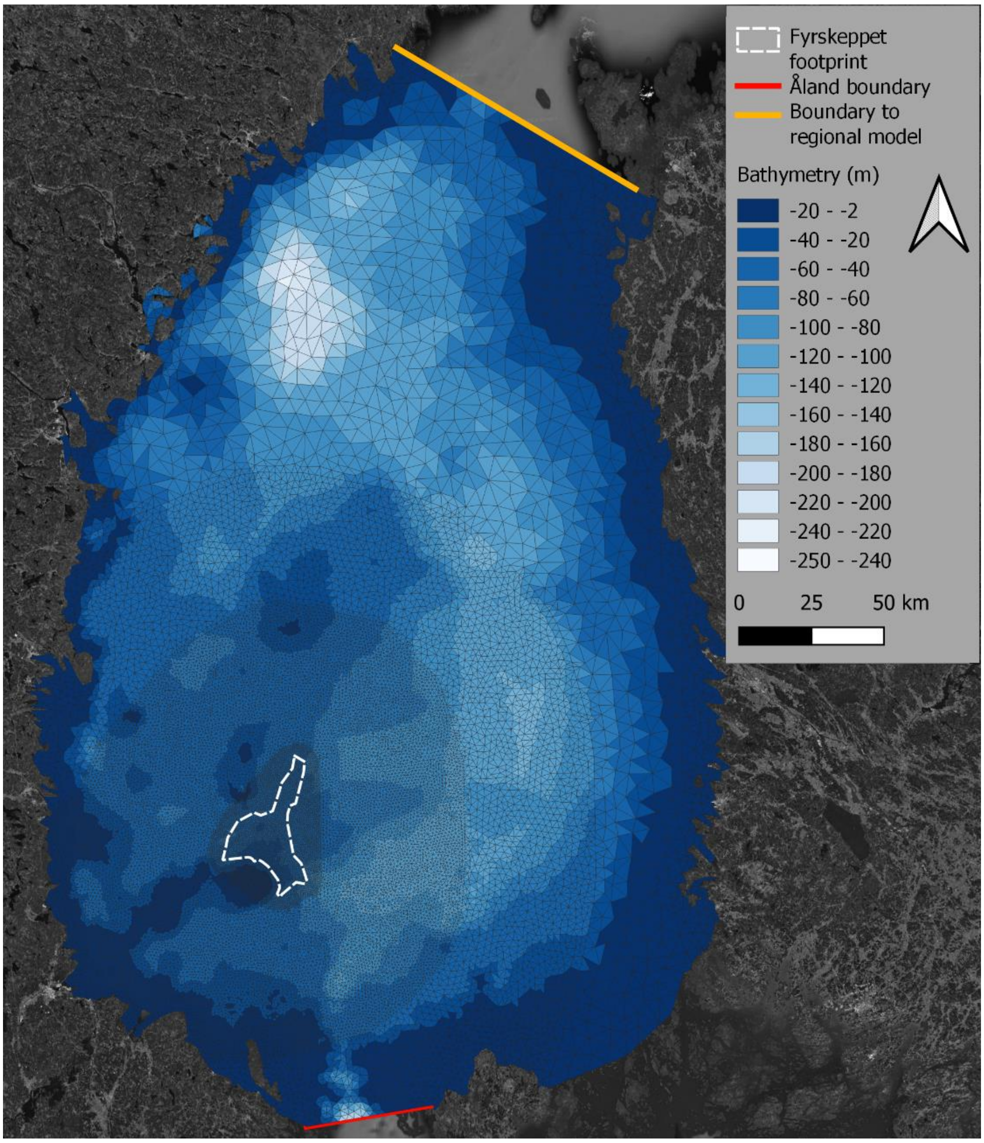

Figure 7.2: Mesh and associated bathymetry of the local model. Map: ESRI.

7.1.3. Local sediment model

To model sediment dispersal, the local sediment model represents the currents 40km around Fyrskeppet OWF. The local model is constituted of 74865 elements and 37574 nodes, and its vertical resolution is like that of the regional model. The local model has a varying horizontal resolution, coarser (2km^2) further than 30km from the Fyrskeppet OWF outer boundary, where negligible impacts of sediment dispersal can be expected due to the low currents, gradually increasing to 0.5km^2 between 30km and 15km of the project area, 0.2km^2 between 5km and 15km of the project, 0.08km^2 within 5km of the project area and 0.04km^2 within the project area, where the impact are of sediment dispersal are expected to be the strongest. It is forced by data from the local model at the surrounding boundary (orange lines in Figure 7.3).

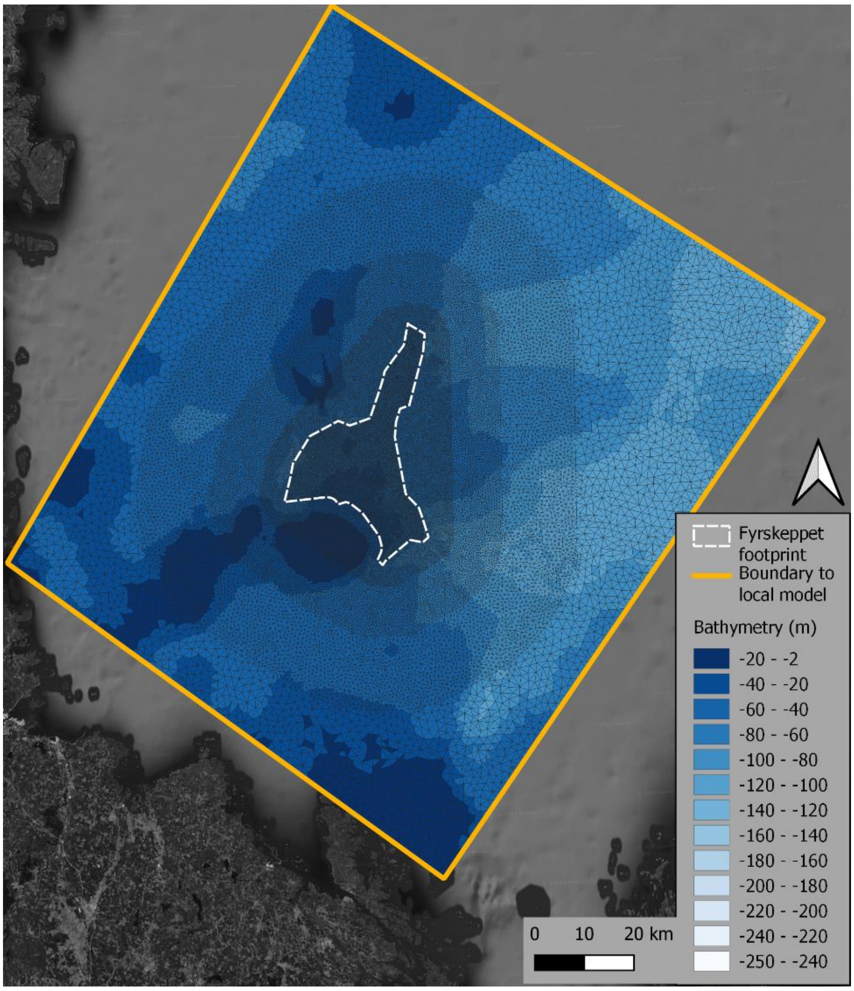

Figure 7.3: Mesh and associated bathymetry of the local sediment model for analysis of sediment dispersal. Map: ESRI.

7.2. Boundary data

The regional model at the open boundary towards the Baltic Sea is forced with modelled SMHI data regarding salinity, temperature, and water level. At the surface, ECMWF's ERA5 wind data in the form of wind fields, air pressure, precipitation and evaporation, and sea ice concentration and thickness from the Baltic SMHI model are considered. Heat exchange with the atmosphere has been taken into account via data from ECMWF's ERA5 of net short and longwave radiation, air temperature and humidity at the sea surface. Forcings from the catchment are also considered through the freshwater discharges temperatures from the major rivers listed in chapter 6.7.

To minimize the spin-up period the model is for the first time-step initialized with salinity, temperature and surface elevation from the Baltic Sea SMHI model.

7.3. Model setup and calibration

The regional model is forced at the southern boundary using specified water levels, and salinity and temperature profiles from the Baltic SMHI model. Water levels have been calibrated by adjusting the wind friction coefficients to get a reasonable agreement with observation data.

To account for salinity and temperature stratification, the vertical eddy viscosity is resolved using the k-ε turbulence model. Salinity and temperature profiles have been calibrated against available measurements within the Fyrskeppet OWF area by adjusting the vertical and horizontal dispersion coefficients, and surface temperatures have been calibrated through the light extinction coefficient determining the depth of the light penetration in the water column.

7.4. Identification of average year

Based on modelled temperature, salinity and currents at Fyrskeppet OWF from SMHI Baltic Sea model, presented in Appendix 2 to Appendix 5, an average year is identified by comparing yearly conditions. Interannual variation is generally low for salinity, temperature and currents, with a general counter-clockwise circulation pattern in the Bothnian Sea and south-eastward to southward currents at Fyrskeppet OWF.

The year 2021 has been chosen as an average year as it follows the general increase in salinity end of spring and the lower surface salinity end of summer. Temperature is highest in late summer with a thermocline going down to 15 meters. Thermocline depth in this area varies between 10-25m, so that 15m is on the lower side and indicates slightly reduced vertical mixing and worsened sediment dispersal conditions. Comparison between modelled currents by the 2km by 2km and 4km by 4km SMHI models indicate shifted currents from south to south-east in the finer version. The year 2021 experiences currents almost evenly spread around the south-eastward component (southward component for the 4km by 4km), which is also close to the average circulation pattern at Fyrskeppet OWF. The year 2021 was thereby chosen to investigate effects of Fyrskeppet OWF construction on sediment spreading.

7.5. Verification

For verification of the model, the period June to October 2022 (June is for warm-up of the model) where project specific data are available is selected.

The model is verified against

1) Observed water levels;
2) Observed current profiles and time series;
3) Observed salinity and temperature profiles, and temperature time series;
4) Observed wave data.

7.5.1. Water level, time series

Decreases in water levels are sometimes represented with a slight delay by the model, especially for the Forsmark, Spikarna and Holmsund stations, which could be due to discrepancies in the water level at the Åland boundary taken from SMHI model results (Figure 7.4). For the Kalix-Storön monitoring station, for which the water levels are more influenced by the wind than by the boundary conditions, the model overestimates some of the peaks, which could be due to differences between actual and reanalysis wind data from ERA5 used to force the model and to somewhat overestimated wind friction coefficients in the model.

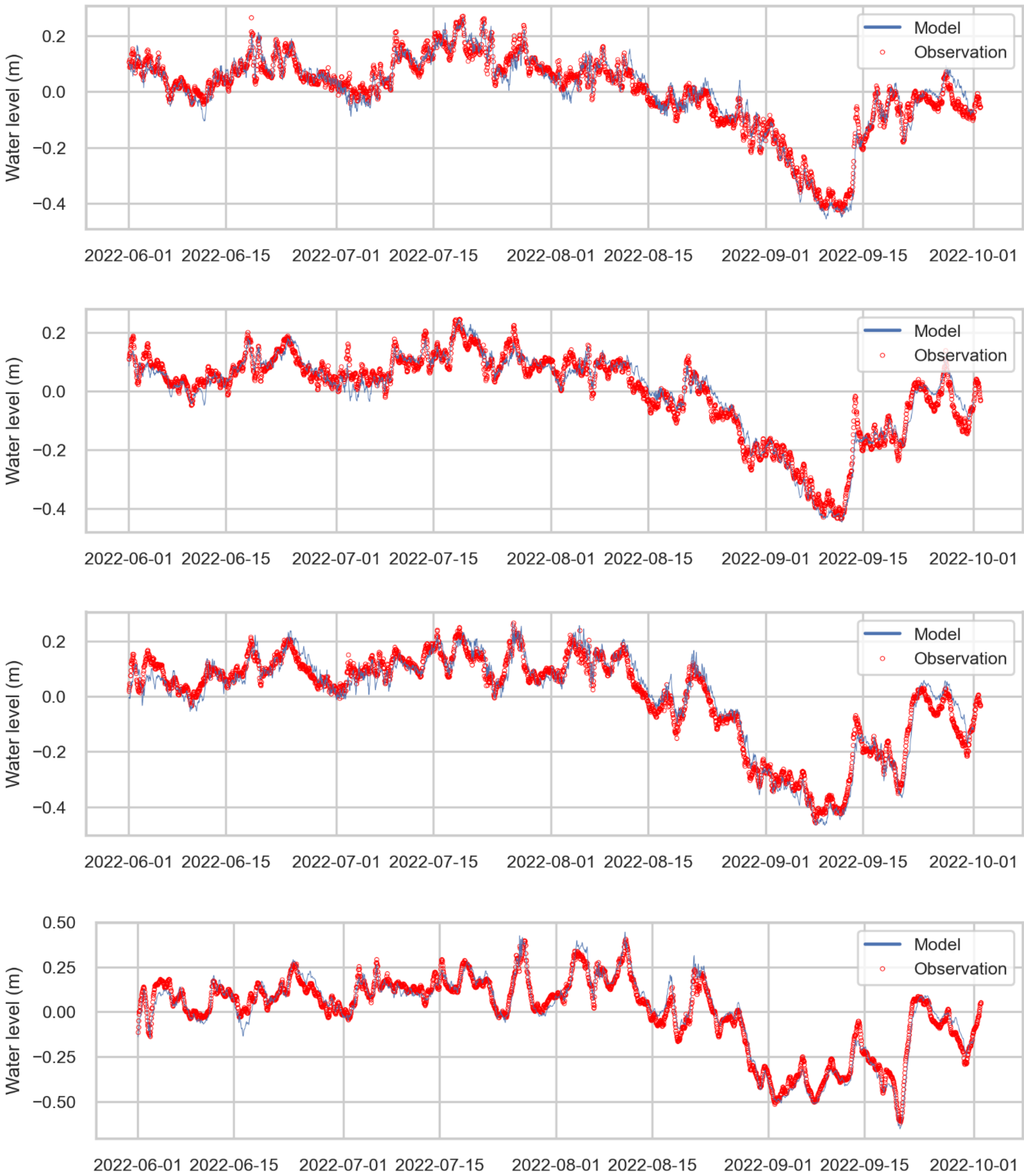

Figure 7.4: Comparison between observed water level in mMSL (red dots) and modelled water level (blue line) for the Forsmark (top row), Spikarna (second row), Holmsund (third row) and Kalix-Storön (bottom row) monitoring stations.

7.5.2. Current, time series

Time series of current speed are shown in Figure 7.5 and show a relatively good agreement between modelled and observed surface currents at -5m (correlation coefficient greater than 0.65 for all stations and RMSE around or lower than 0.05m/s), indicating that the wind driven currents are generally well captured by the model. Representation of the deeper currents at 15m and 25m is somewhat more challenging with correlation around or greater than 0.5 and RMSE around or lower than 0.05m/s for all stations. This could be due to a greater influence of currents driven by salinity and temperature differences and of the boundary conditions, as well as to a coarse representation of the bathymetry in the regional model. Time series of current directions are shown in Figure 7.6 and show that variations in surface current directions at 5m depth are well captured by the model (blue lines and circles). For the deeper currents at 15m and 25m depth, the average current direction is well captured by the model, while some shifts in current directions are not fully captured by the model.

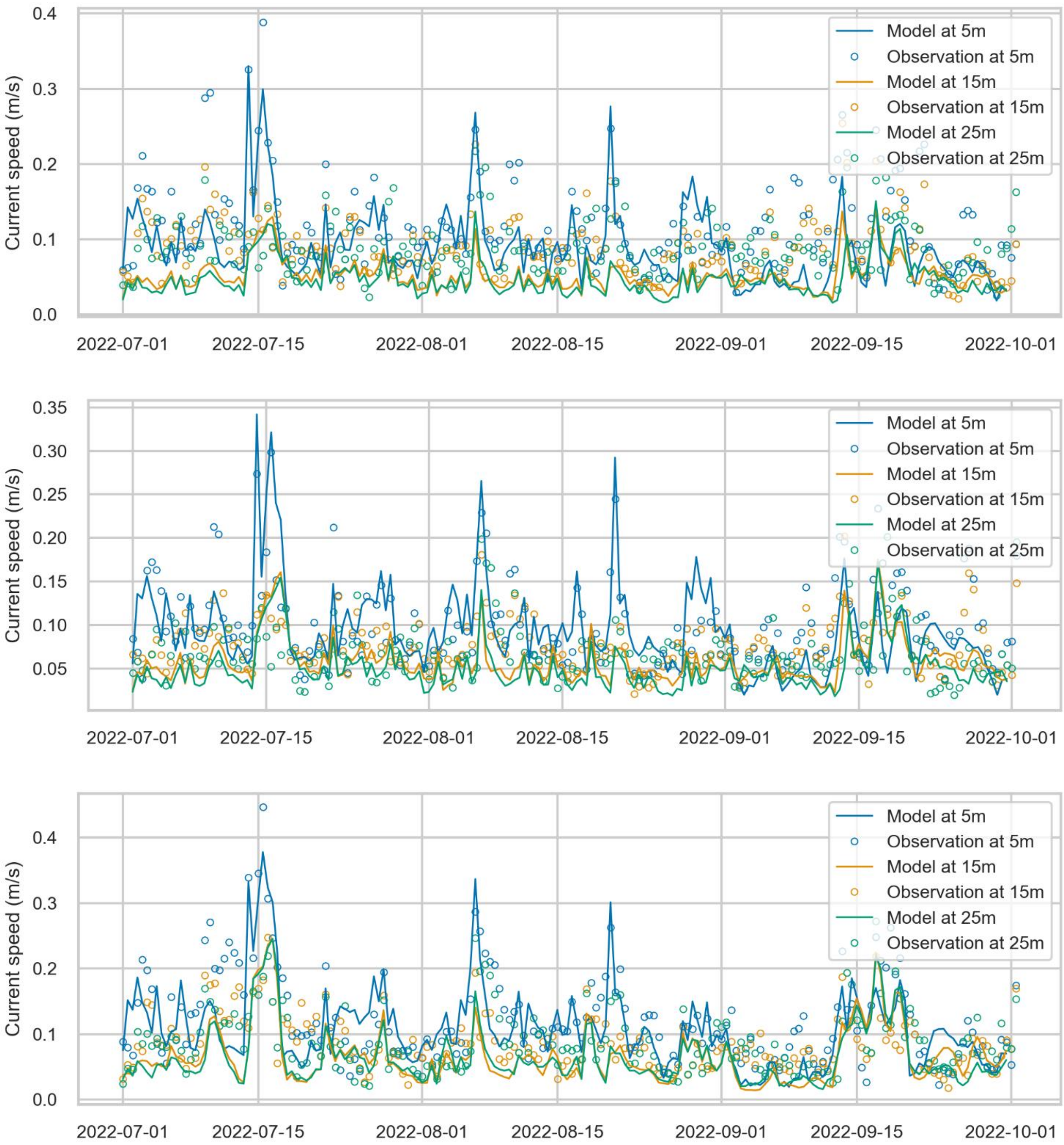

Figure 7.5: Comparison between observed (circles) and modelled (solid lines) current speeds (12-hour average, m/s) at 5-, 15- and 25-meter depths for the monitoring stations FYR1 (top row), FYR2 (second row), and FYR3 (third row).

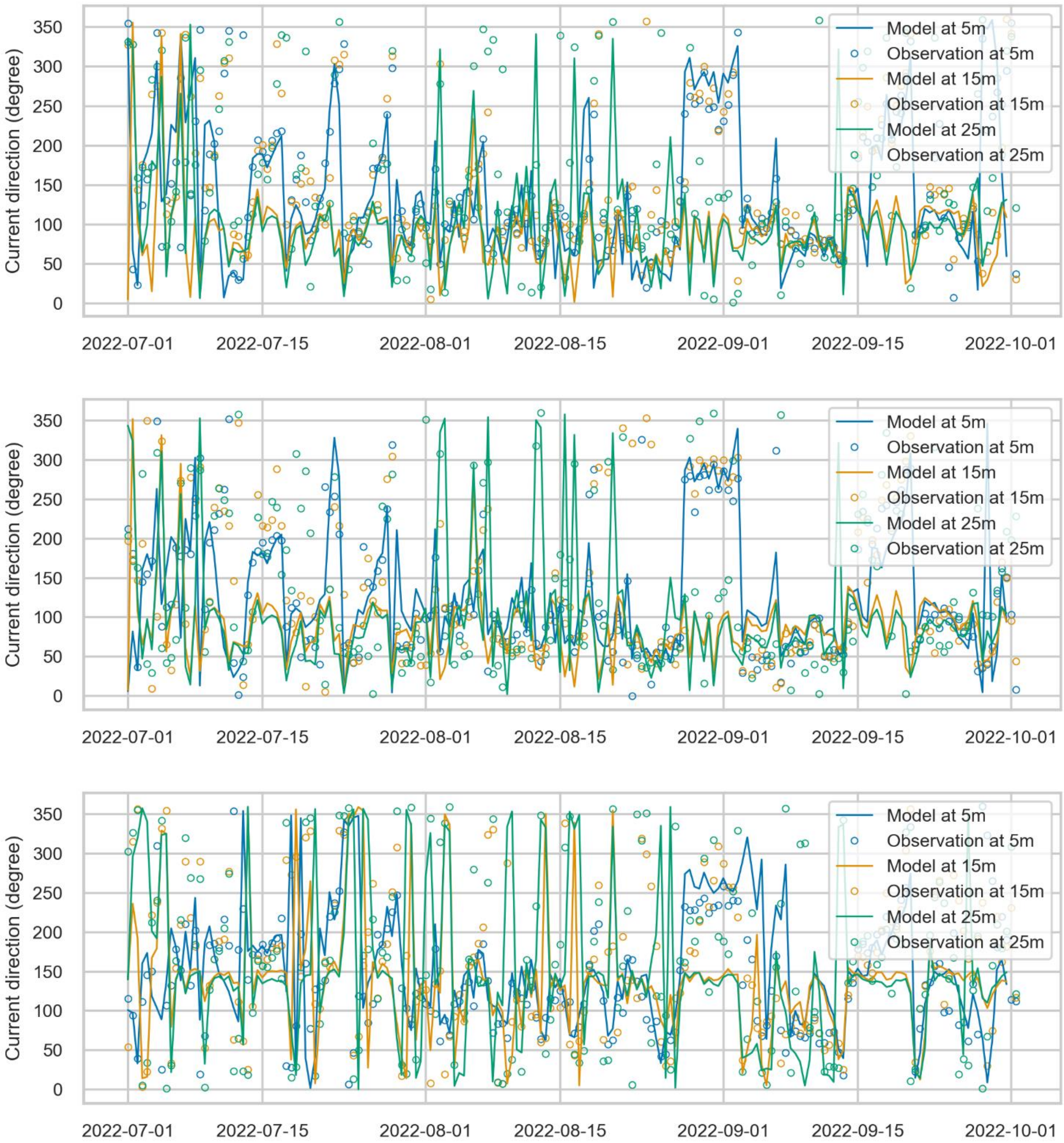

Figure 7.6: Comparison between observed (circles) and modelled (solid lines) current directions (12-hour average, degree) at 5-, 15- and 25-meter depths for the monitoring stations FYR1 (top row), FYR2 (second row), and FYR3 (third row).

7.5.3. Current roses comparison (observations, Mike model and SMHI model)

For FYR1, the current roses (Figure 7.7) show that the average east to southeast current direction is well captured by the present Mike model, with the southern component somewhat overestimated, while the SMIH model overrepresents the east and north-east direction. Averaged current speeds are somewhat underestimated by the Mike model, but less than by the SMHI model. For FYR2, the general eastern direction is captured by both the SMHI and Mike models, with the Mike model shifting currents southwards, while the SMHI model overestimates the northern component. Average current speeds lie within the observation range for both models but are somewhat underestimated by the SMHI model and the southeastern current speeds are somewhat overestimated by the Mike model. For FYR3, the SMHI model captures well the observed distribution of current direction. The dominant direction is also captured by the Mike model, but the southeastern component is overestimated, and the southern component is underestimated.

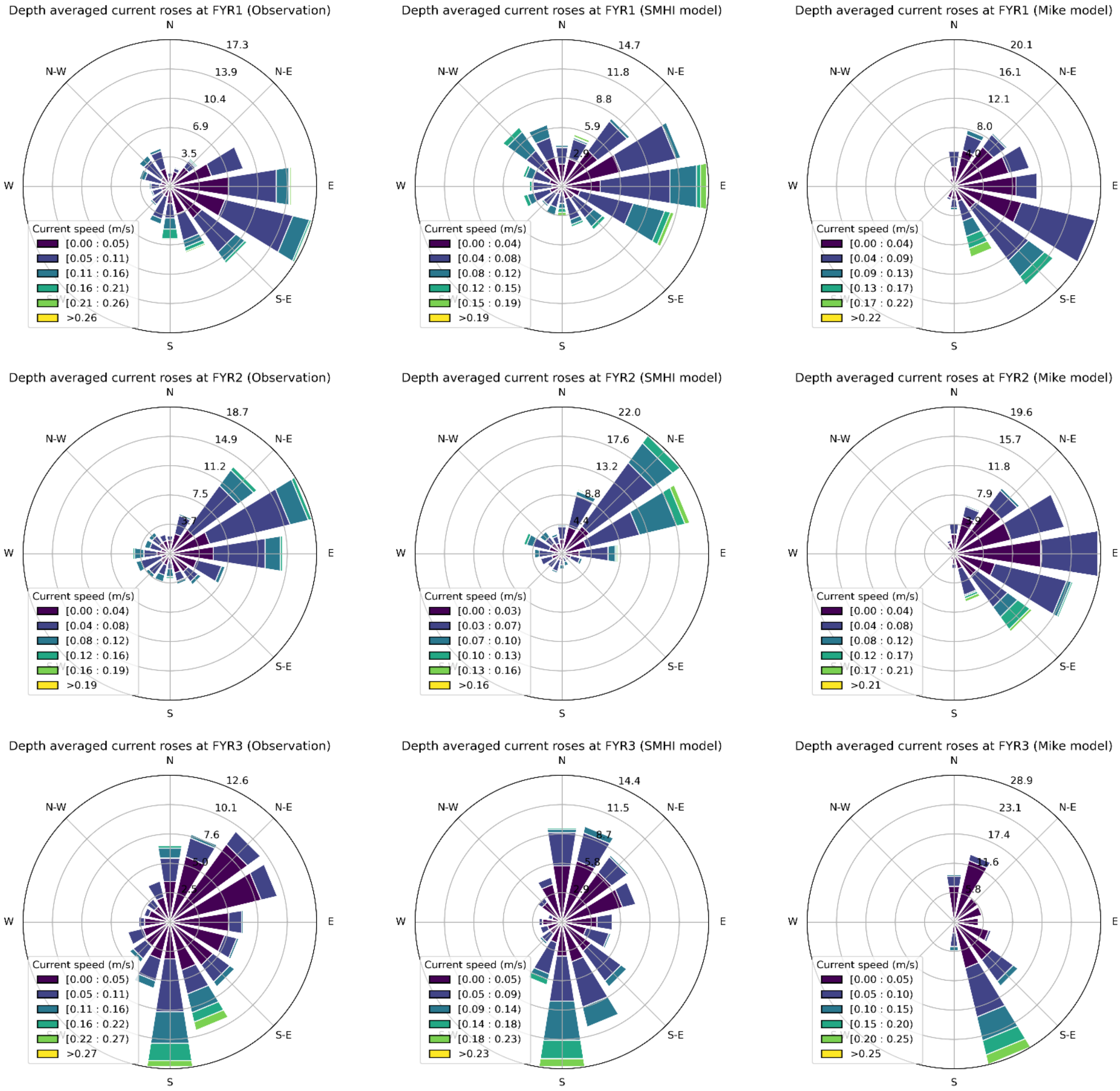

Figure 7.7: Current roses representing the distribution of directions of the depth-averaged current (towards) and associated current speeds for the observed current (first column) and currents modelled by the SMHI (second column) and the Mike (third column) models at Fyr1, Fyr2 and Fyr3.

7.5.4. Current profiles

Current velocity profiles for the stations FYR1, 2 and 3 averaged over the months of July, August and September are presented Figure 7.8. They show a general agreement between modelled and observed current speeds with higher speeds at the surface that decrease with depth down to 10m, increase slightly between 10 and 20m depth, and finally decrease slowly until the bottom.

This pattern is more pronounced in July (and August for FYR3) and well captured by the model and the flatter profiles of September are also well captured by the model, while the model overestimates surface currents in August, which could be due to the wind forcing data.

Current speeds are also somewhat underestimated by the model between 10-30m depth. Such moderate discrepancies can be expected because the model represents average current velocities for a given grid element (horizontal resolution of about 5km^2), whereas the observation represents currents at a discrete, point location. Comparison of modelled current time series, roses and profiles with observation data shows that, despite some discrepancies, the agreement is acceptable, and the model captures the general current dynamic and vertical patterns in the Fyrskeppet OWF project area and performs well against the SMHI model.

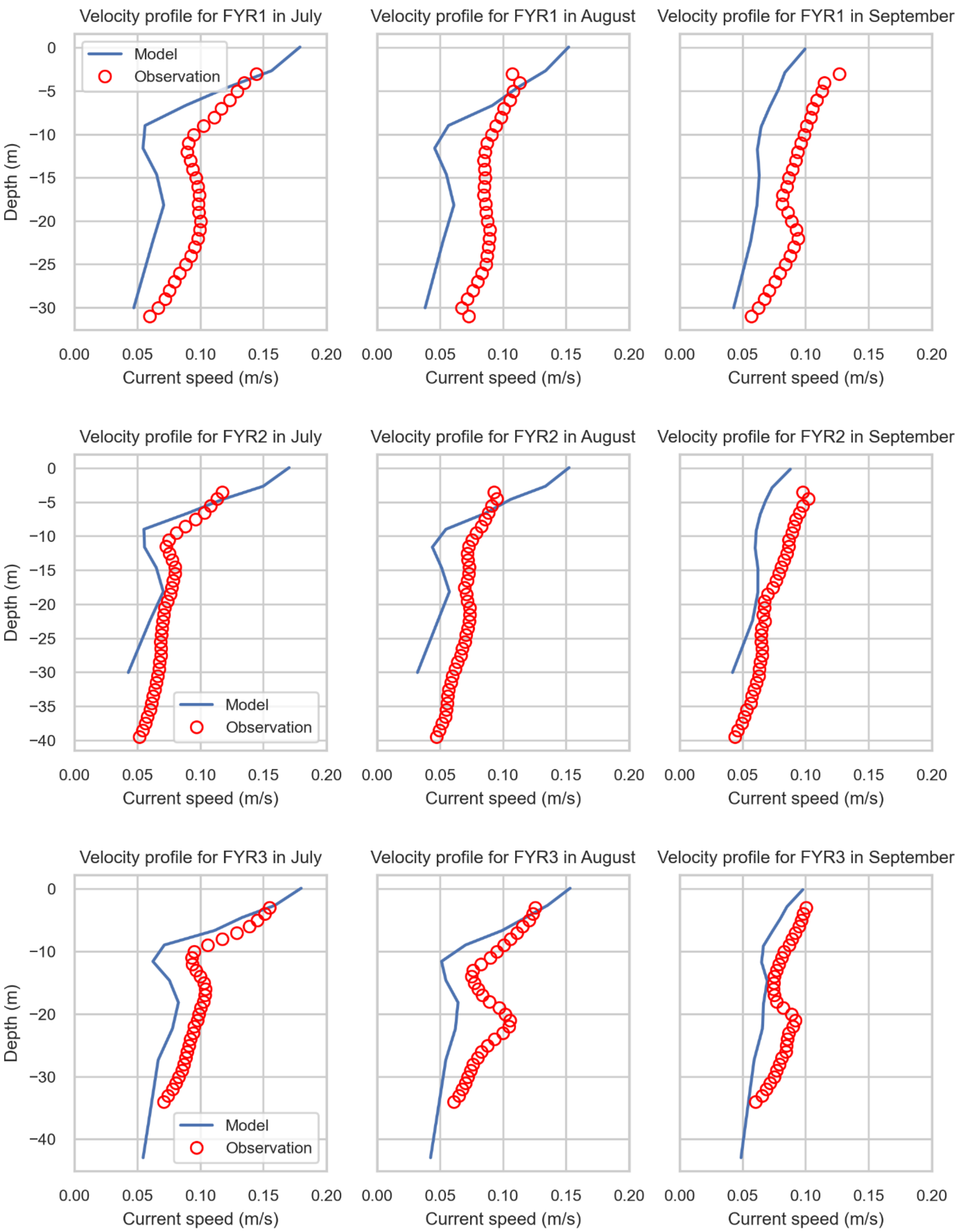

Figure 7.8: Comparison between modelled (blue line) and observed (red dots) monthly averaged current speed profiles in July (first column), August (second column) and September (third column) for the monitoring stations FYR1 (first row), FYR2 (second row) and FYR3 (third row).

7.5.5. Salinity and temperature profiles

Comparison of modelled salinity with observations in different parts of the project area shows that the salinity is well within the range of the observation values. Salinity stratification is somewhat overestimated in June, while it is well captured by the model in August, but with a modelled halocline (zone of maximum salinity gradient) occurring around 15m while the observed one lies around 20m.

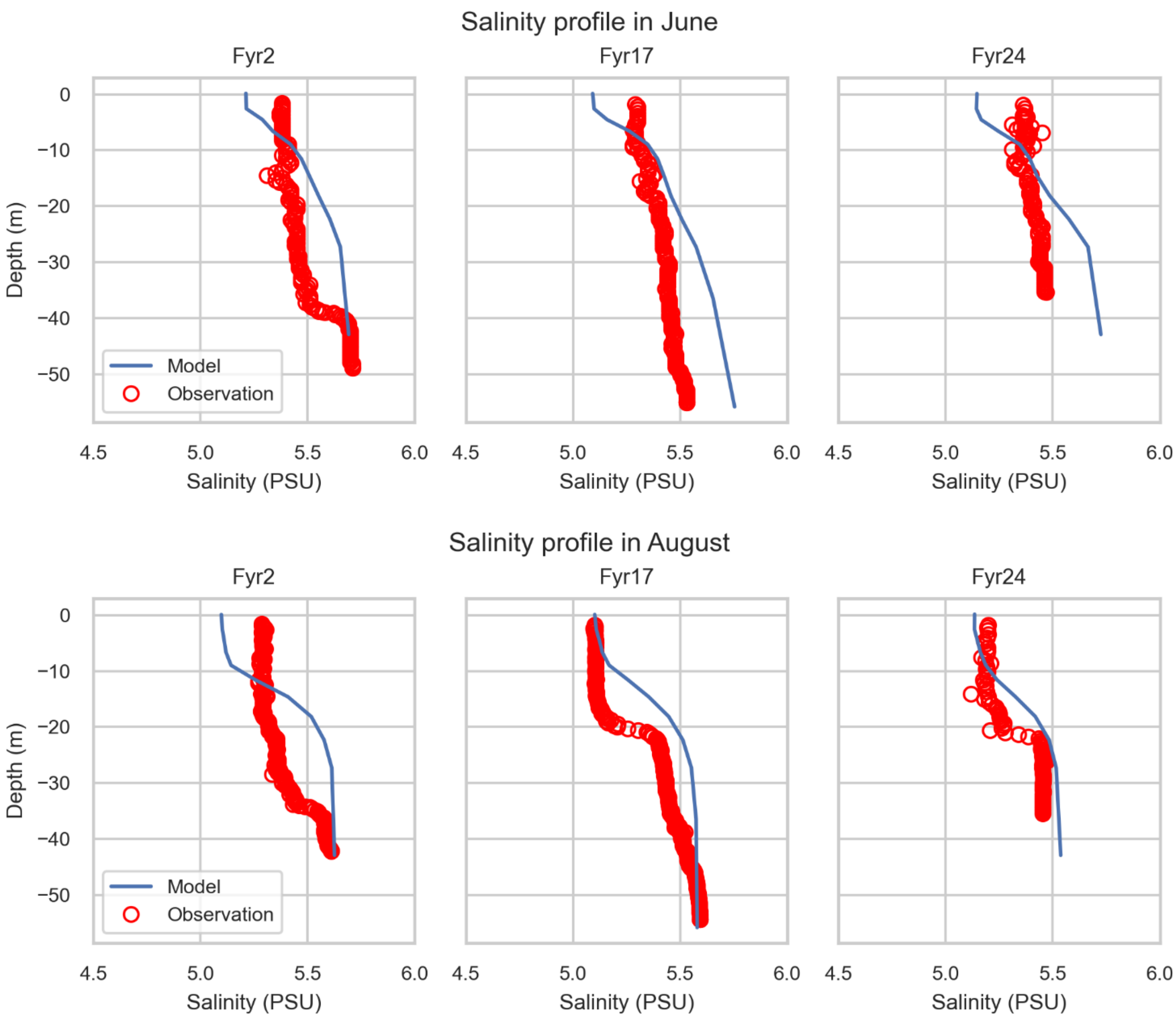

Figure 7.9: Comparison between modelled (blue line) and observed (red dots) salinity profiles at single dates in June (first row) and August (second row) for Fyr2, situated in the northern part, Fyr17, situated in the western part, and Fyr24 situated in the eastern part of the project area (Bladin, Rämö, Lavett, Vinterstare, & Vigouroux, 2022).

Temperature stratification (Figure 7.10) is well represented by the model both in June and August, with very good agreement for both the surface and bottom temperatures at the different stations. The thermocline is also in good agreement in June, while the modelled thermocline lies slightly too high in August. For Fyr2, the shape of the salinity and temperature profiles could indicate an upwelling, which would depend on variations of bathymetry that are not captured by the coarser regional model. The profiles of current, salinity and temperature thereby indicate a good ability for the model to represent the vertical stratification, suitable for analysis of sediment transport.

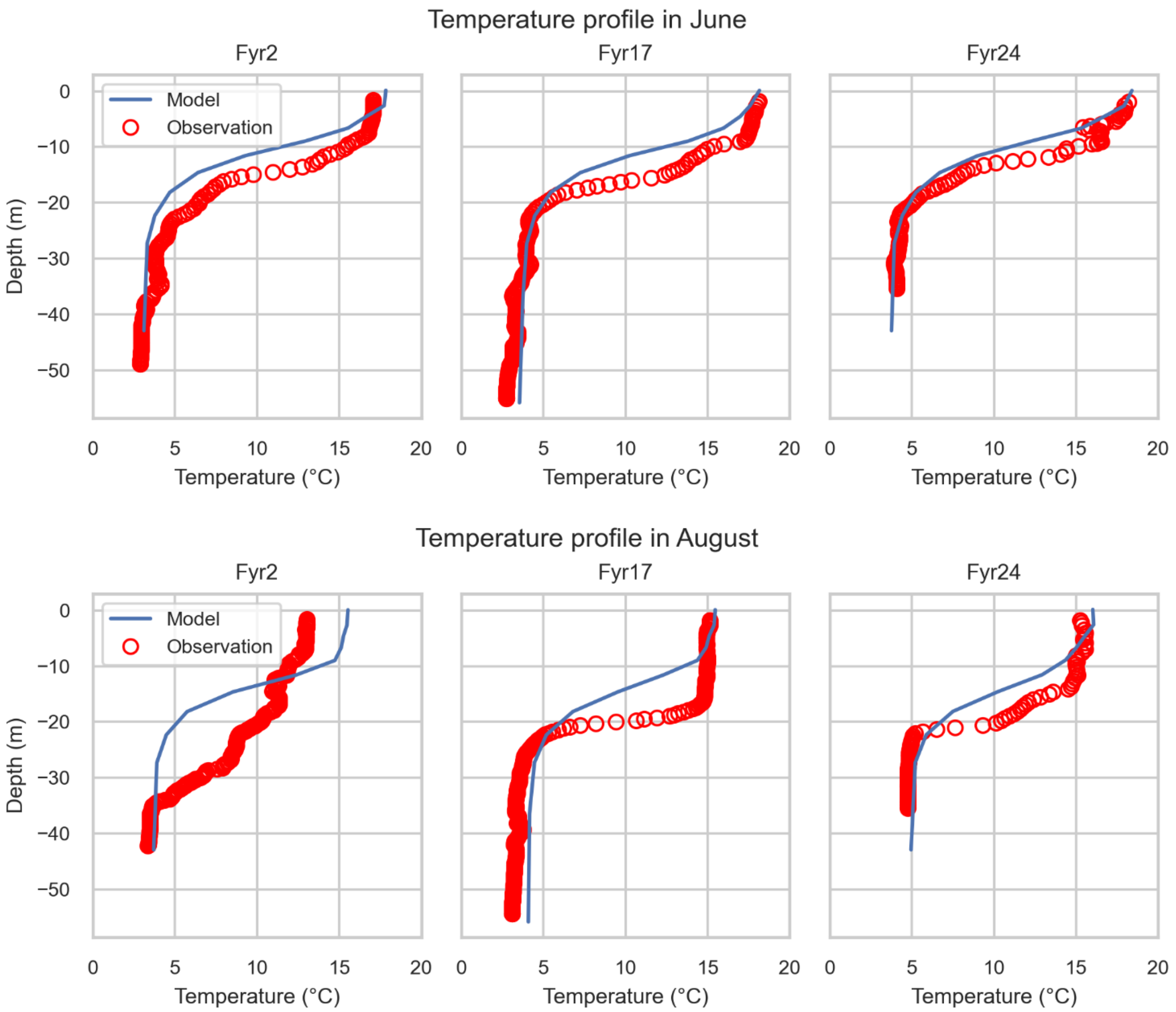

Figure 7.10: Comparison between modelled (blue line) and observed (red dots) temperature profiles at single dates in June (first row) and August (second row) for Fyr2, situated in the northern part, Fyr17, situated in the western part, and Fyr24 situated in the eastern part of the project area (Bladin, Rämö, Lavett, Vinterstare, & Vigouroux, 2022).

7.5.6. Temperature time series

Modelled surface temperature at Finngrundet shows very good agreement with observation both during the spring and summer periods with a correlation coefficient of 0.99 and a RMSE of 0.86°C. Most of the short-term variations are well captured by the model, while the temperature decreases slightly too quickly during the month of September.

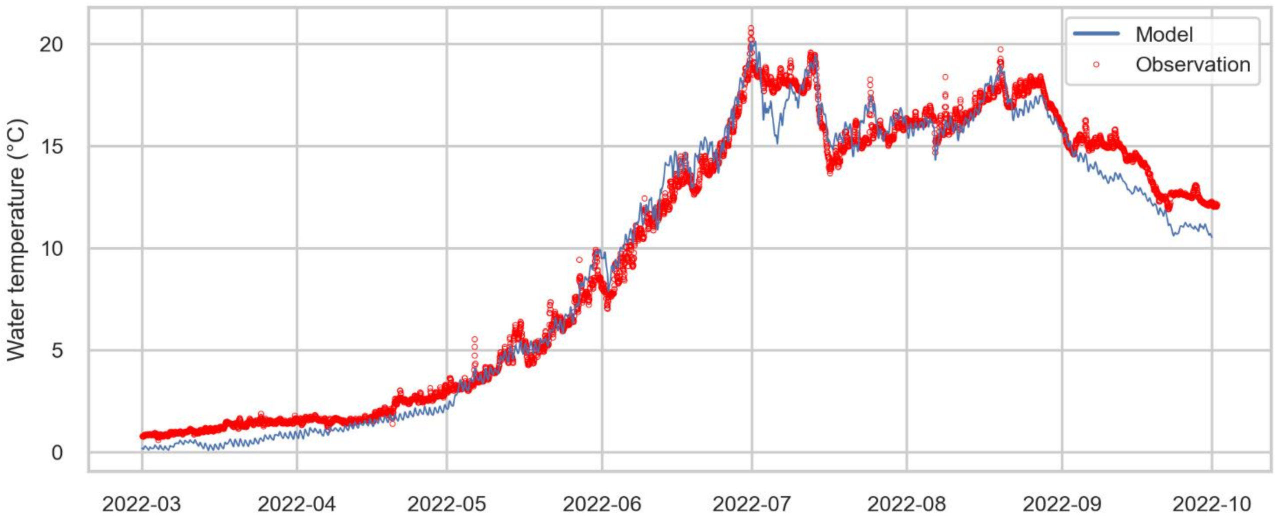

Figure 7.11: Comparison between modelled (blue line) and observed (red circles) surface water temperature time series at Finngrundet.

7.5.7. Waves, time series

Comparison between modelled and observed wave conditions are shown in Figure 7.12 only for Fyr1, since wave conditions are very similar between Fyr1, 2 and 3, and Finngrundet observations (Figure 6.7 and Figure 6.8). The figure shows a very good agreement between model results and observations, with a correlation coefficient of 0.94 and 0.85 and a RMSE of 0.19m and 0.62s for the significant wave height and the peak wave period, respectively. Main variations in mean wave direction are also well captured by the model, with some discrepancies under calmer conditions (low significant wave height). These results show a good ability of the model to describe wave conditions for the Bothnian Sea.

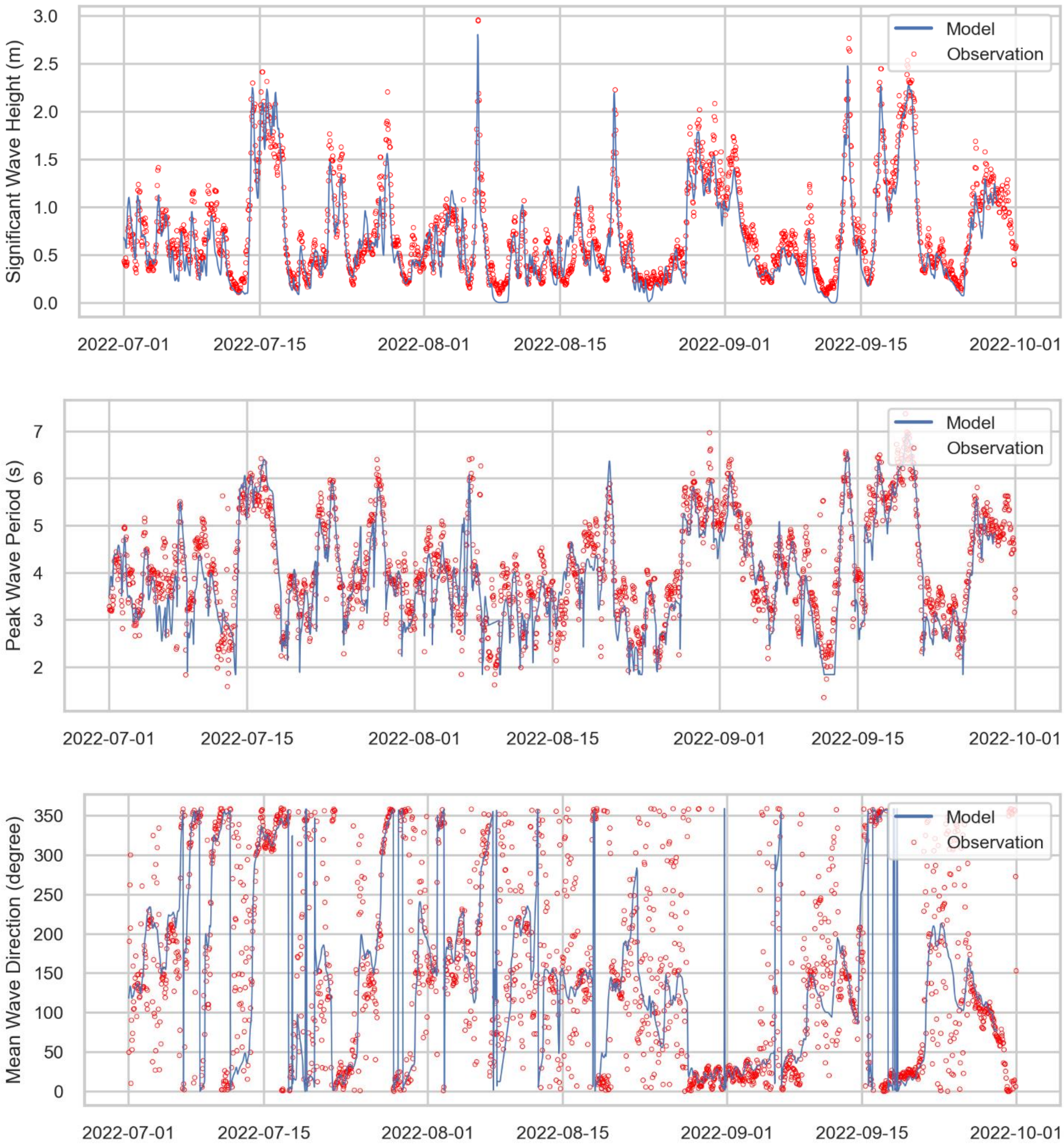

Figure 7.12: Comparison between modelled (blue lines) and observed (red circles) significant wave height (top row), peak wave period (second row) and mean wave direction (third row) for Fyr1

8. Sediment dispersal model

The input to the sediment model is described in the first three sections of this chapter and the outcome of the model in the last two sections.

8.1. Sediment sources and spill program

Three types of sources are considered:

1) Dredging of the 187 gravity-based substructures and 4 offshore substations with a dredge capacity of 300m^3/hour and a suction dredger that captures 90% of the dredged sediments. 10% (in consultant with the Client) of the dredged sediments are assumed to disperse near the bottom (released 2 meters over the sea-bed). The coarse sediment fraction settles next to the GBS (Gravity Base Structure), and the finer ones are available for transport in the surrounding waters.
2) 5% (in consultant with the Client) of the total suctioned sediments are assumed to overflow from the barge and are released at the surface and available for transport in the surrounding waters.
3) Burial of the inter array and redundancy cables in pre-excavated trenches with mechanical trencher/plough or a combination, with a volume of 400m^3/h (2 m^3/m trench with 200 m/h), where 10% (in consultant with the Client) of the sediments are assumed to be brought into suspension and released 2m over the seabed.

Two cases are considered:

1) The 15MW case where each of the 187 WTG can generate 15MW and the GBS has a base slab with a diameter of 40m, yielding an excavation of 5700m^3 for each GBS.
2) The 30MW case where each of the 187 WTG can generate 30MW and the GBS has a base slab with a diameter of 48m, yielding an excavation of 7700m^3 for each GBS.

Cable and offshore substation layouts are the same in both cases.

The installation programs for both cases are described Table 8.1 and Table 8.2, starting with the dredging of the GBS and offshore substations, and parallel installation of the foundations and laying of the inter array cables (IAC) and redundancy cables. Burial of the IAC and redundancy cables starts week 6 and 8, respectively. Dredging of the GBS foundations takes 3 more weeks in the 30MW case.

Table 8.1: Installation program for the 15MW case, starting May 1st and ending 28 weeks later, October 27th, 2021

15 MW Schedule Parallel 1:3																												
Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Dredging GBS WTG/OSS	x	x	x	x	x	x	x	x																				
Dredging GBS	x	x	x	x	x	x	x	x																				
Dredging GBS		x	x	x	x	x	x	x																				
OSS installation	x	x																										
GBS Installation		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x						
GBS Installation		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x						
GBS Installation			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x					
IAC laying and Pull-in		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
IAC laying and Pull-in											x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
IAC burial						x	x				x	x	x	x						x	x	x	x	x	x	x	x	x
Red.Cable Laying, pull in.		x	x	x	x	x	x	x	x	x																		
Red.Cable burial								x	x	x																		

Table 8.2: Installation program for the 30MW case, starting May 1st and ending 28 weeks later, October 27th, 2021

30 MW Schedule Parallel 1:3																												
Vecka	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Dredging GBS WTG/OSS	x	x	x	x	x	x	x	x	x	x																		
Dredging GBS		x	x	x	x	x	x	x	x	x	x																	
Dredging GBS		x	x	x	x	x	x	x	x	x	x																	
OSS installation	x	x																										
GBS Installation		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x						
GBS Installation		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x						
GBS Installation			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x					
IAC laying and Pull-in		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
IAC laying and Pull-in											x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
IAC burial						x	x				x	x	x	x						x	x	x	x	x	x	x	x	x
Red.Cable Laying, pull in.		x	x	x	x	x	x	x	x	x																		
Red.Cable burial								x	x	x																		

8.2. Sediment type

The expected types of sediments are defined along the cables per 200 m and at the substructures as described by SGU, Sveriges Geologiska Undersökning. Each sediment types are special joint to the sediment samples and an average grain distribution is calculated per sediment type.

The sediment model is an add-on to the hydrodynamic and wave model thus current data and shear stress are transferred by time step for advective transport of the sediment and deposition/resuspension of near-bottom sediments.

The sediment model itself contains information about:

1) The sediment types are split into 5 categories. The settling velocity is shown within brackets:
   a. Sand, 26.2% (0.015 m/s),
   b. Fine sand, 12.1% (0.00292 m/s),
   c. Coarse silt, 7.6% (0.00056 m/s),
   d. Fine Silt, 8.8% (7e-5 m/s) and
   e. Clay, 18.9% (3e-5 m/s).
2) For erosion a critical shear stress e.g., 0.3 N/m^2 (DHI/IOW Consortium, 2013);
3) Dispersion both horizontal and vertical;
4) A description of the sediment source in time and space.

8.3. Estimated spill

In total is the spill estimated to 190,702 m^3 for the 15MW and 220,832 m^2 for the 30 MW, Table 8.3.

Table 8.3: Total spill for the 15MW and 30MW case.

Sediemt:	sand	very fine sand/coarse silt	medium silt	fine silt	very fine silt/Clay	Sum
Case	[m3]	[m3]	[m3]	[m3]	[m3]	[m3]
15GW	68121	31339	19700	22681	48862	190702
30GW	78883	36290	22813	26264	56581	220832

8.4. Estimated sediment concentrations and associated durations

Figure 8.1 to Figure 8.4 (left) show the total duration during the construction period (continuous or not) of sediment concentrations in the surface layer higher than 10mg/l and 100mg/l for the 15MW and the 30MW cases. Sediment released at the surface as overrun from the barge are transported and dispersed with surface currents while sinking through the water column, is shown as plumes in these figures. Results are relatively similar between the 15MW and 30MW cases, with sediment concentrations of 10mg/l covering 87% and 95% for at least 3 hours, respectively (Table 8.4 and Table 8.5). Sediment disperses relatively fast, with 43% and 56% covered for 12h with sediment concentration of 10mg/l, 1% and 3% covered for 48h for the 15MW and 30MW case, respectively. Virtually none of Fyrskeppet OWF experiences sediment concentration for more than 72 hours all together. Most of Fyrskeppet OWF only experiences limited sediment concentrations (less than 50mg/l), with sediment concentrations of 50mg/l covering 21% and 26% of Fyrskeppet OWF for 3h and dissipating within 24h, while sediment concentrations of 200mg/l cover 3% and 4% of Fyrskeppet OWF for 3h and last less than 12h for the 15MW and 30MW cases respectively. None of Fyrskeppet OWF experiences sediment concentrations of 1000mg/l for any layout. Sediment concentrations of 100mg/l and higher are generally found in the immediate vicinity of the turbines (Figure 8.2 and Figure 8.4; left). Most of the surface sediment dilutes to negligible concentration within Fyrskeppet OWF area, however, some parts of the Natura 2000 area experience sediment concentrations of 10mg/l generally for less than 10h (up to 13h in both cases). Very few areas outside Fyrskeppet OWF experience surface sediment concentration of 50mg/l and above, generally confined to 1km around Fyrskeppet OWF. Thereby, given the buffer zone around the Natura 2000 area of 2km, the risk for sediment concentrations higher than 50mg/l spreading to the Natura 2000 area is low, while smaller concentrations could occur for less than 24h, depending on current speeds and directions.

Table 8.4: Area (km^2) and corresponding proportion of Fyrskeppet OWF experiencing sediment concentration equal or greater than 10, 50, 100 and 500mg/l for a duration greater than 3, 6, 12 and 24 hours in the top 10m layer for the 15MW case.

Sediment concentration (mg/L)	10				50			200		400	1000
Minimum duration (h)	3	12	48	72	3	12	24	3	12	3	3
Area (km^2)	462.8	229.7	3.6	0.1	111.0	17.9	0.2	16.4	1.4	3.0	0.0
Percentage (%) of Fyrskeppet OWF	86.7	43.0	0.7	0.0	20.8	3.3	0.0	3.1	0.3	0.6	0.0

Table 8.5: Area (km^2) and corresponding proportion of Fyrskeppet OWF experiencing sediment concentration equal or greater than 10, 50, 100 and 500mg/L for a duration greater than 3, 6, 12 and 24 hours in the top 10m layer for the 30MW case.

Sediment concentration (mg/L)	10				50			200		400	1000
Minimum duration (h)	3	12	48	72	3	12	24	3	12	3	3
Area (km^2)	504.9	298.1	15.5	0.2	138.2	28.8	1.6	19.6	2.7	3.4	0.0
Percentage (%) of Fyrskeppet OWF	94.6	55.8	2.9	0.0	25.9	5.4	0.3	3.7	0.5	0.6	0.0

Sediment concentrations are lower in the bottom 5 meters than in the surface layer (Figure 8.1 to Figure 8.4; right) and results for the 15MW and 30MW cases are similar. Somewhat higher concentrations and durations are observed in the 30MW case due to higher sediment releases from dredging and differences in timing compared with the 15MW case. Most of the area with sediment concentrations over 10mg/l over more than 3h are due to the dredging of the GBS and affect a limited area of Fyrskeppet OWF (26km^2 or 5% and 29km^2 or 6% of Fyrskeppet OWF area experience sediment concentration of 10mg/L for more than 3h for the 15MW and 30MW cases, respectively; Table 8.7 and Table 8.8). Due to the low current speeds, sediments sink to the bottom quickly, affecting less than 1.5% of Fyrskeppet OWF area after 12h, and none after 24h. Higher sediment concentrations of 50mg/l affect 11km^2 (2.1% of Fyrskeppet OWF) and 13.4km^2 (2.5% of Fyrskeppet OWF) during more than 3h for the 15MW and 30MW case, respectively, and less than 0.5% of Fyrskeppet OWF for 12h (both cases). Very high sediment concentrations of 500mg/l affect none of Fyrskeppet OWF. Due to the low currents throughout the water column, sediments released at the surface at the GBS location do not spread to large areas and settle relatively near the GBS. This yields spatially limited impacts of sediment concentrations, with no sediment spreading to the surrounding of Fyrskeppet OWF, including the Natura 2000 area. Almost no areas of Fyrskeppet OWF experiencing sediment concentrations over 10mg/l for more than a day, and very limited areas experiencing concentrations over 100mg/l for 3-6h.

Table 8.6: 15MW case - Area (km^2) and corresponding proportion of Fyrskeppet OWF experiencing sediment concentration equal or greater than 10, 50, 100 and 500mg/L for a duration greater than 3, 6, 12 and 24 hours in the lower 5m layer. Durations and concentrations generally not shown if corresponding area is zero.

Sediment concentration (mg/l)	10				50			100			500
Minimum duration (h)	3	6	12	24	3	6	12	3	6	12	3
Area (km^2)	25.8	14.0	4.5	0.1	11.0	5.3	1.1	1.4	0.6	0.1	0.0
Percentage (%) of Fyrskeppet OWF	4.8	2.6	0.8	0.0	2.1	1.0	0.2	0.3	0.1	0.0	0.0

Table 8.7: 30MW case - Area (km^2) and corresponding proportion of Fyrskeppet OWF experiencing sediment concentration equal or greater than 10, 50, 100 and 500mg/L for a duration greater than 3, 6, 12 and 24 hours in the lower 5m layer. Durations and concentrations generally not shown if corresponding area is zero.

Sediment concentration (mg/l)	10				50			100			500
Minimum duration (h)	3	6	12	24	3	6	12	3	6	12	3
Area (km^2)	29.4	17.7	7.8	0.5	13.4	7.6	2.6	1.6	0.6	0.1	0.0
Percentage (%) of Fyrskeppet OWF	5.5	3.3	1.5	0.1	2.5	1.4	0.5	0.3	0.1	0.0	0.0

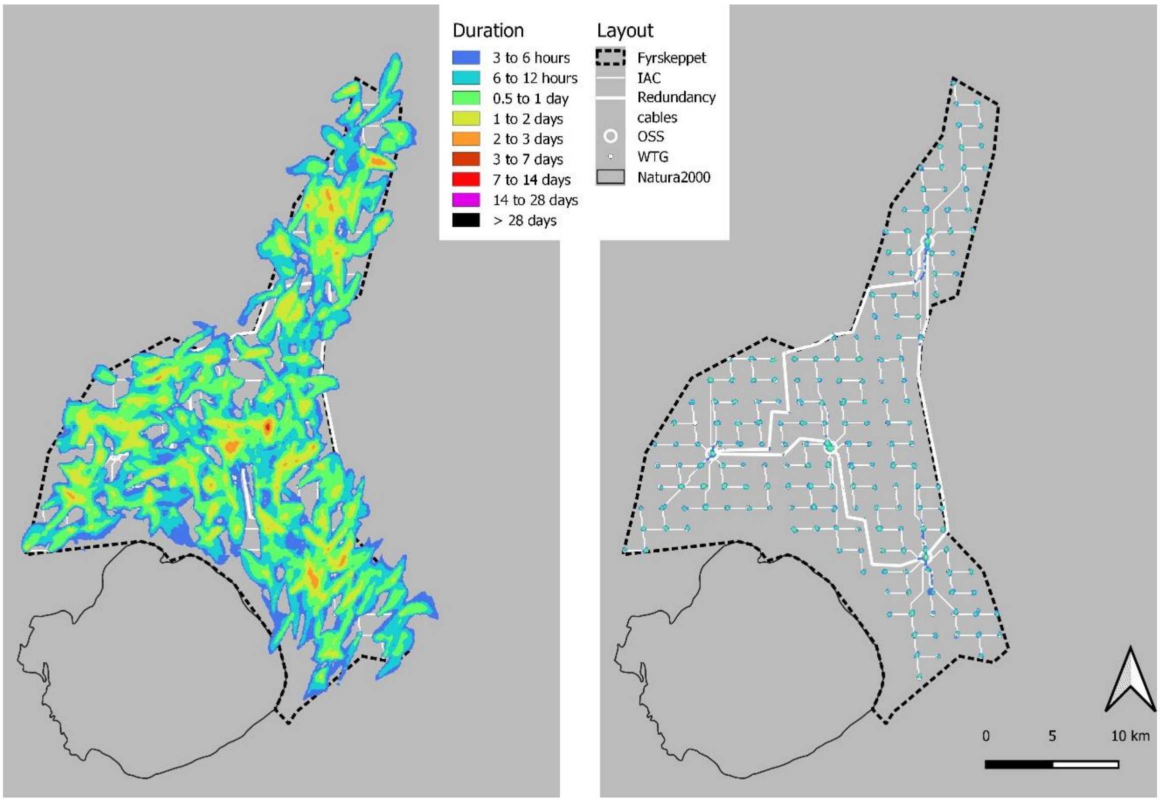

Figure 8.1: 15MW – Duration with sediment concentration of 10 mg/l. Left Average upper 10 m, Right Average lower 5 m.

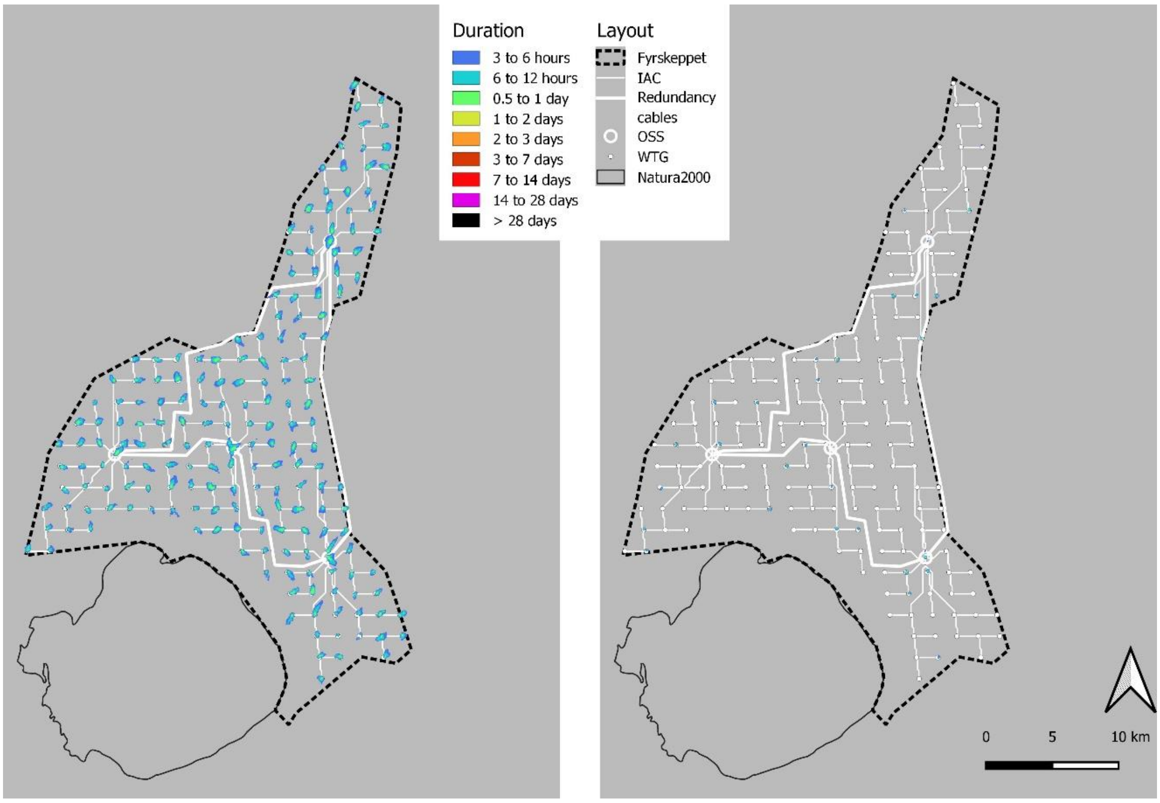

Figure 8.2: 15MW – Duration with sediment concentration of 100 mg/l. Left Average upper 10 m, Right Average lower 5 m.

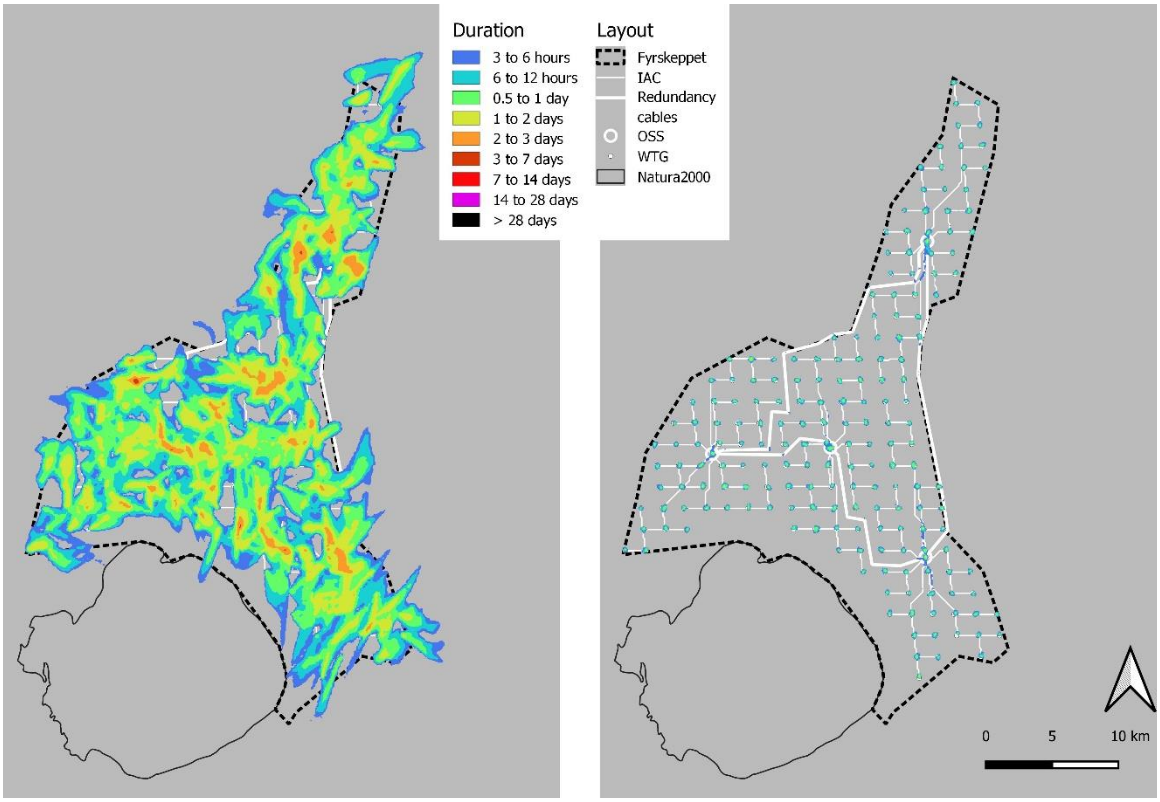

Figure 8.3: 30MW – Duration with sediment concentration of 10 mg/l. Left Average upper 10 m, Right Average lower 5 m.

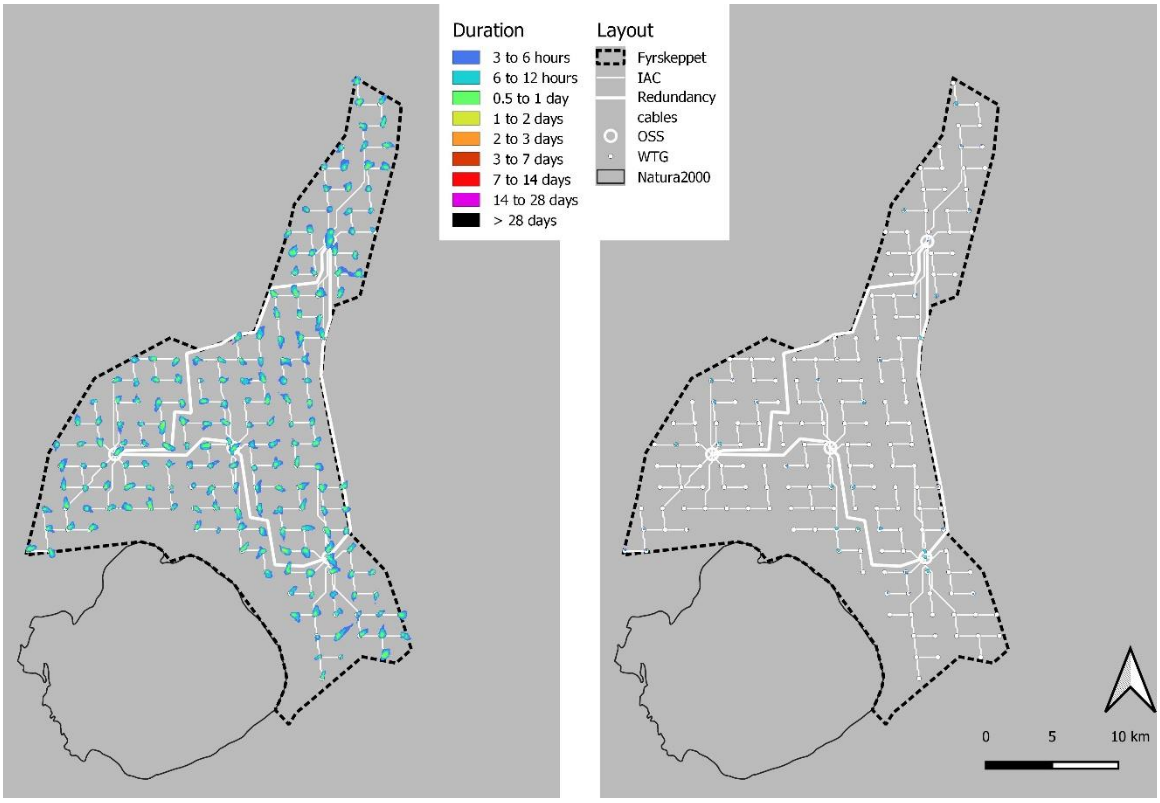

Figure 8.4: 30MW – Duration with sediment concentration of 100 mg/l. Left Average upper 10 m, Right Average lower 5 m.

8.5. Estimated sedimentation

Similarly, to the sediment concentration results, model results of sedimentation are very close between the 15MW and 30MW cases. Installation of inter array cables between the wind turbine generators and of redundancy cables between the offshore substations creates a moderate sedimentation of at most 1-2mm in both cases (Figure 8.5 and Figure 8.6). In both cases, moderate sedimentation (1-2mm) affects a moderate share of Fyrskeppet OWF, both from the cable and around the GBS (64km^2 or 12% of Fyrskeppet OWF and 69 km^2 or 13%, in the 15MW and 30MW, respectively; Table 8.8). Sedimentations of 5mm follow mostly the dredging operation for the wind turbine fundaments and installations of the offshore substations and affect 6.2km^2 and 9.2km^2 for the 15MW and 30MW cases, respectively, thereby representing limited proportion of Fyrskeppet OWF area (1.2% and 1.7%, respectively). Less than 0.5% of Fyrskeppet OWF experience sedimentation of 10mm and no area experience sedimentation of 25mm or more in any case. Due to the low bottom current speeds (around 5cm/s, Figure 7.8) and the substantial proportion of sand in the dredged sediments, resuspension of sediments sinking to the bottom is expected to be low and so the duration of sedimentation is expected to be high, as shown in Figure 8.5 and Figure 8.6 (left). This indicates that the sediments released are generally stable around the GBS locations. Installation of Fyrskeppet OWF for both the 15MW and 30MW cases generate moderate sedimentation (1mm to 5mm) in 1% to 13% of Fyrskeppet OWF area, while higher sedimentation only affects less than 1% of Fyrskeppet OWF. No increase in sedimentation is observed in the adjacent Natura 2000 area bordering the south of Fyrskeppet OWF.

Table 8.8: Area (km^2) and corresponding proportion of Fyrskeppet OWF experiencing sedimentation equal or greater than 1, 2, 5, 10 and 25mm over the construction period for the 15MW and 30MW cases.

Case	15MW					30MW				
Sedimentation (mm)	≥1	≥2	≥5	≥10	≥25	≥1	≥2	≥5	≥10	≥25
Area (km^2)	63.6	21.9	6.2	0.8	0.0	69.2	25.7	9.2	2.0	0.0
Percentage (%) of Fyrskeppet OWF	11.9	4.1	1.2	0.1	0.0	13.0	4.8	1.7	0.4	0.0

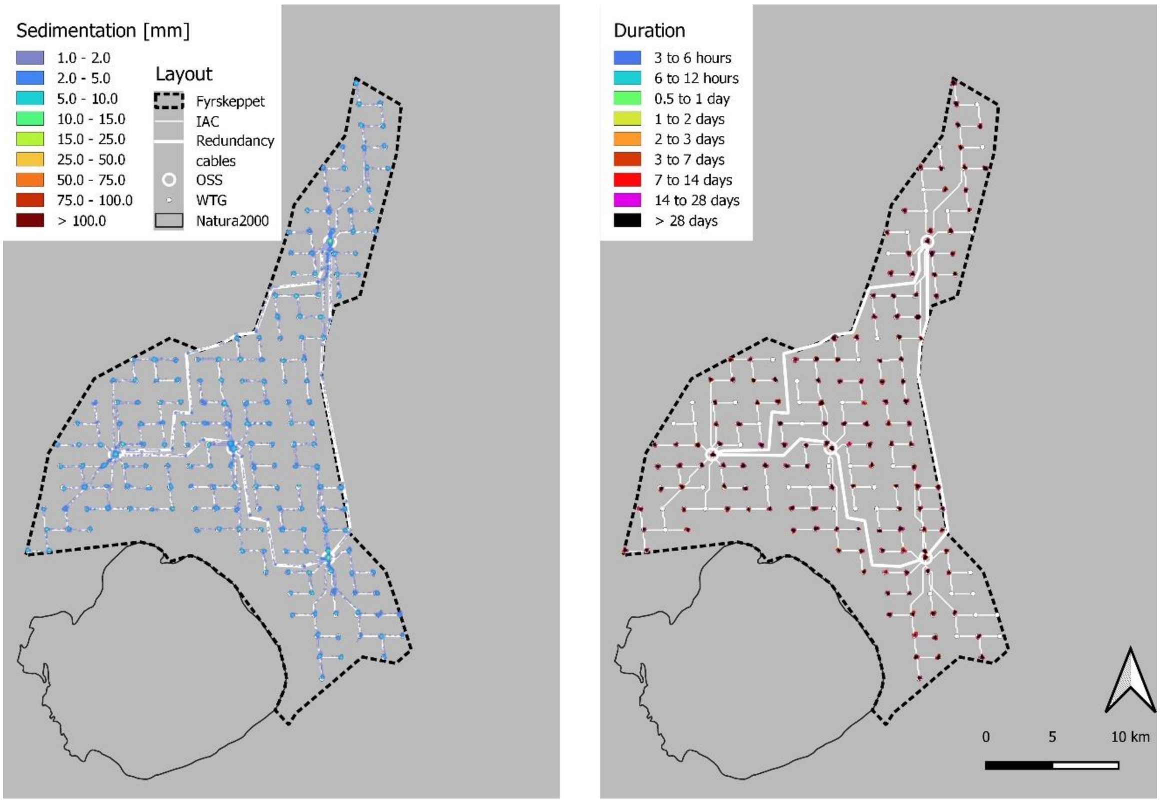

Figure 8.5: 15MW – Sedimentation. Left: End construction, Right: Duration with 10 mm or more of sedimentation.

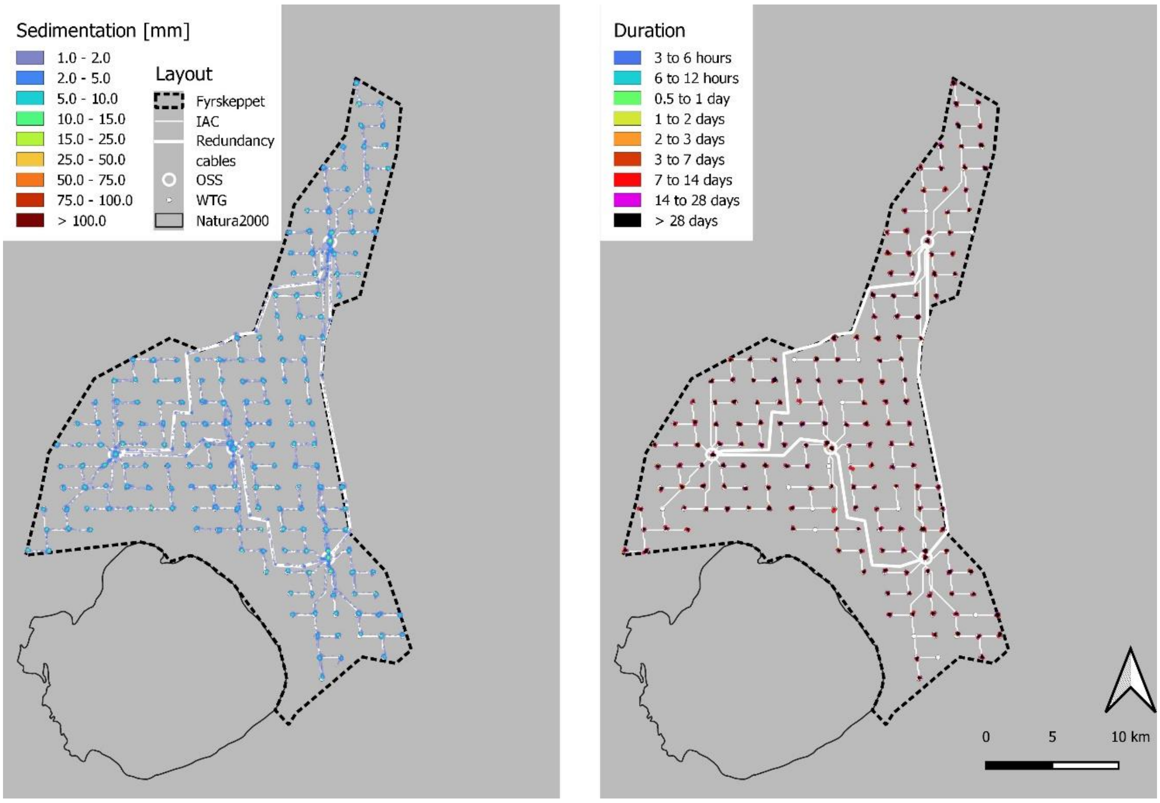

Figure 8.6: 30MW – Sedimentation. Left: End construction, Right: Duration with 10 mm or more of sedimentation.

9. References

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Appendix 1: Current speeds and direction for the SMHI monitoring stations

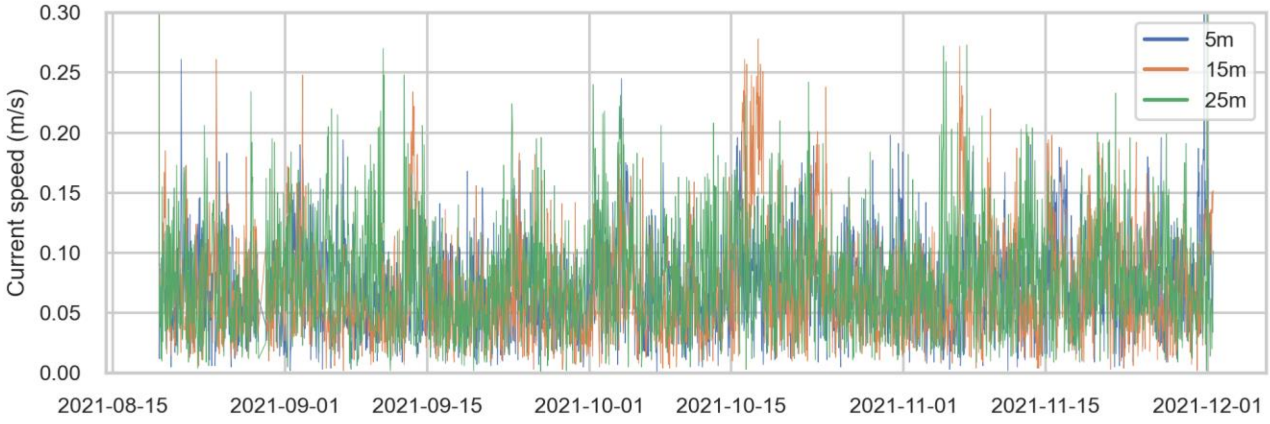


Figure 9.1: Current speed at 5, 15 and 25m depth at Norrbyn Boj monitoring station

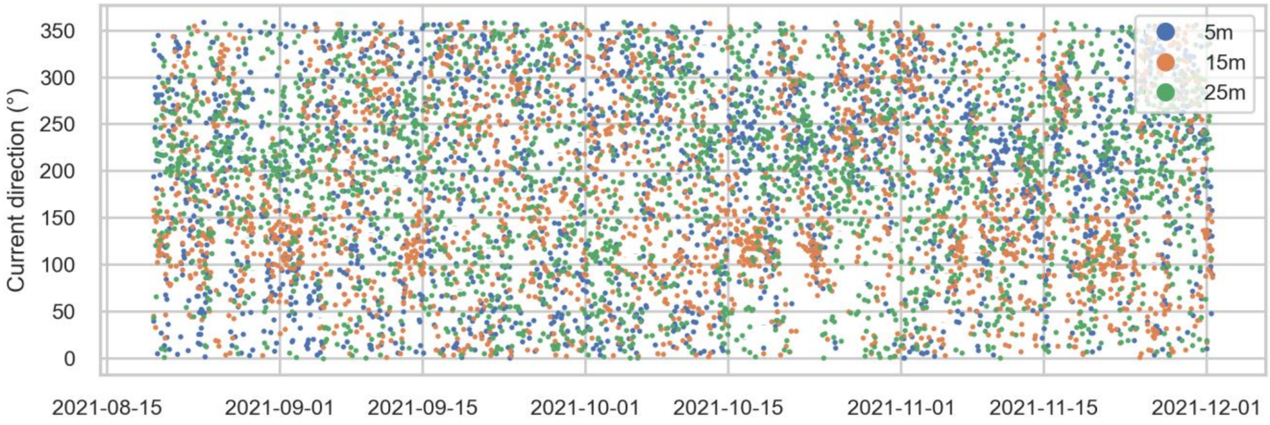


Figure 9.2: Current direction at 5, 15 and 25m depth at Norrbyn Boj monitoring station

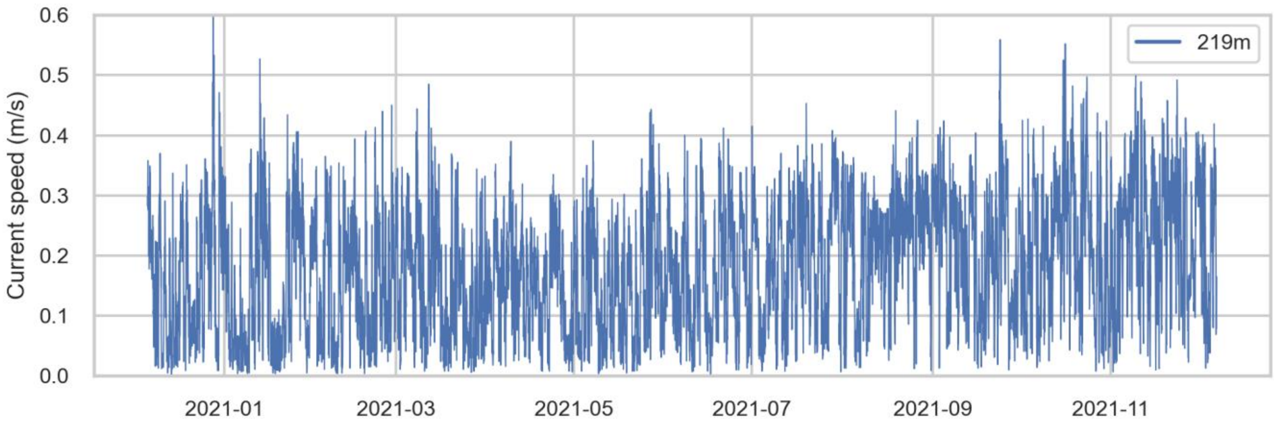


Figure 9.3: Current speed at 219m depth at Understen BS monitoring station

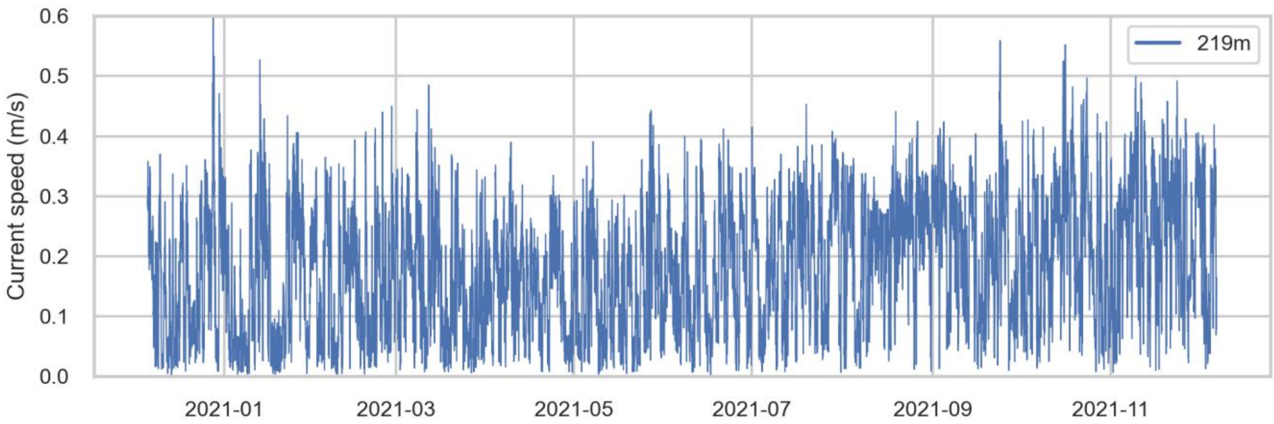
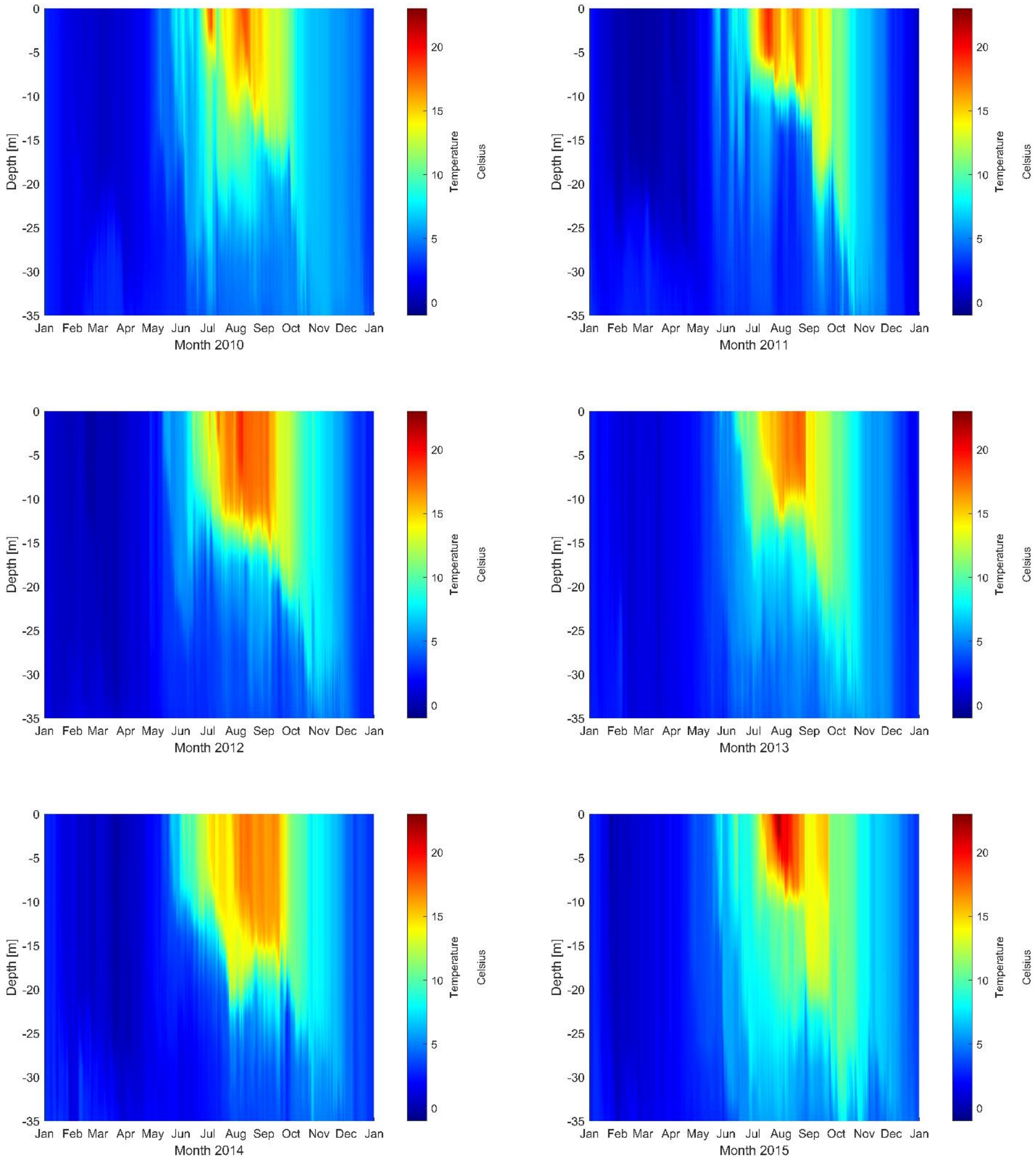
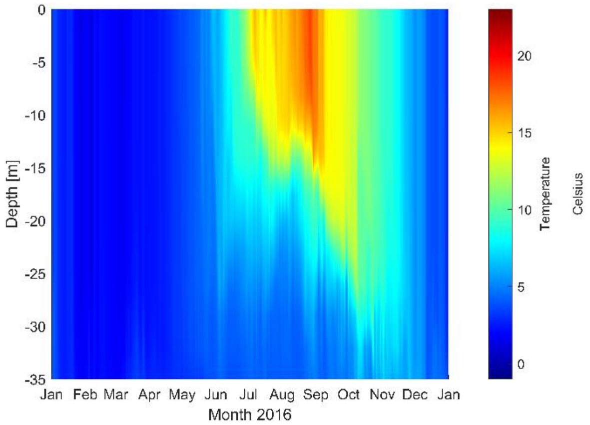


Figure 9.4: Current direction at 219m depth at Understen BS monitoring station

Appendix 2: Fyrskeppet OWF, Temperature profiles (SMHI, modelled 4x4km)

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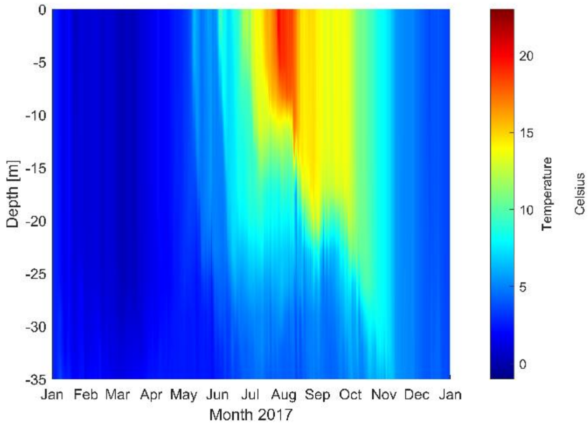
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan
Temperature
Celsius


Depth [m]
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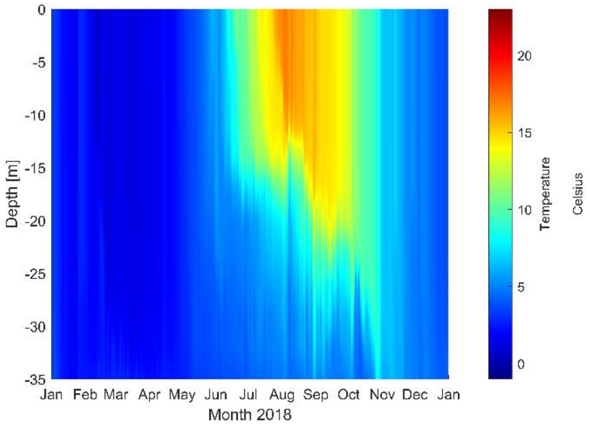
Temperature
Celsius


Depth [m]
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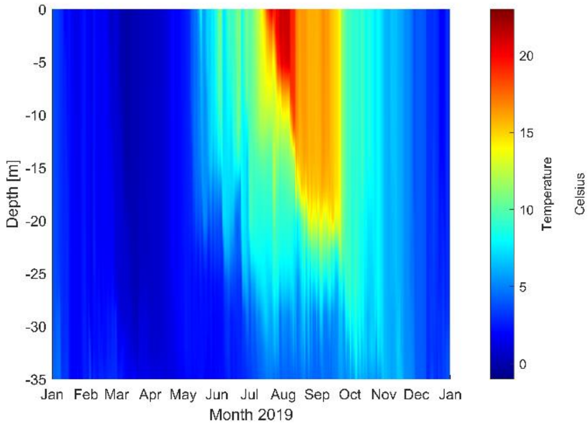
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan
Temperature
Celsius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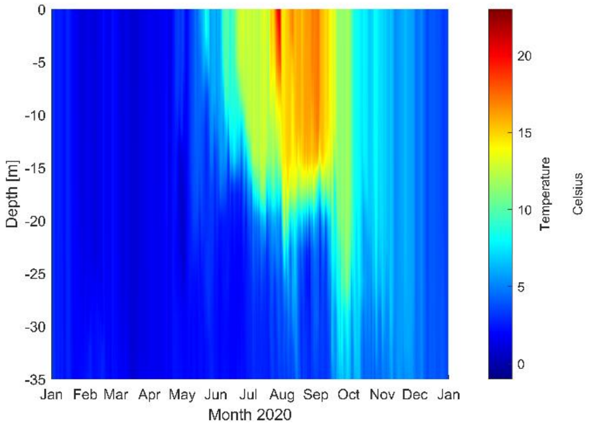
Temperature
Celsius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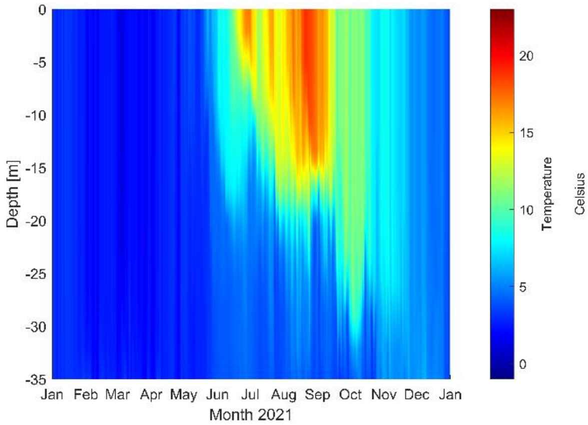
Temperature
Celsius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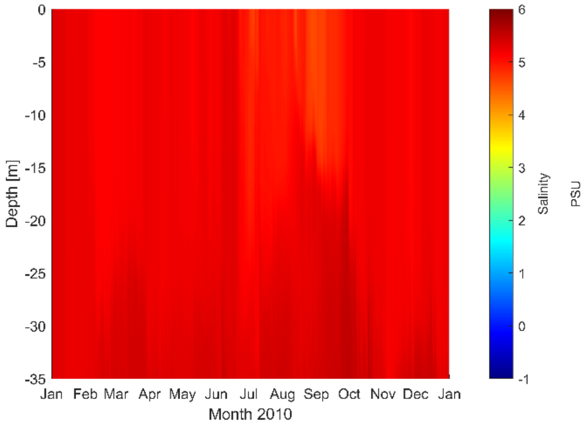
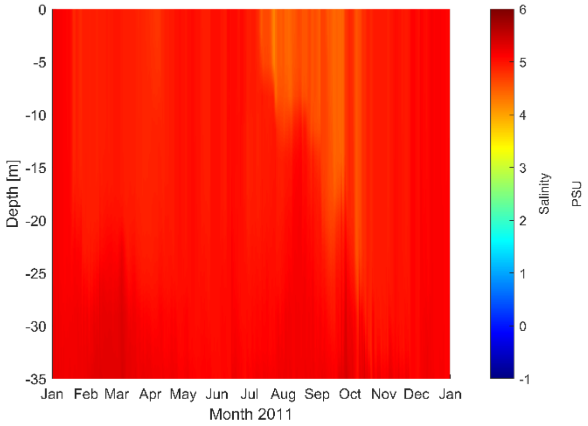
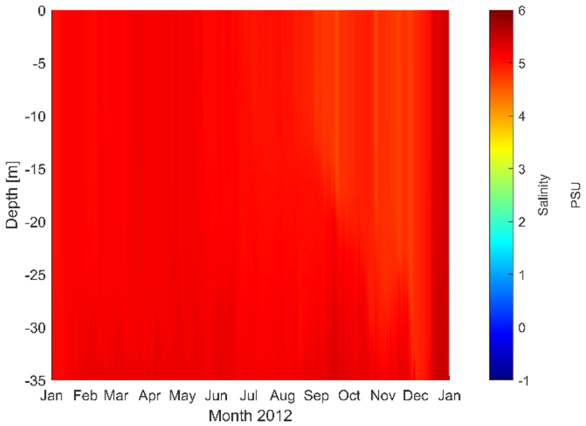
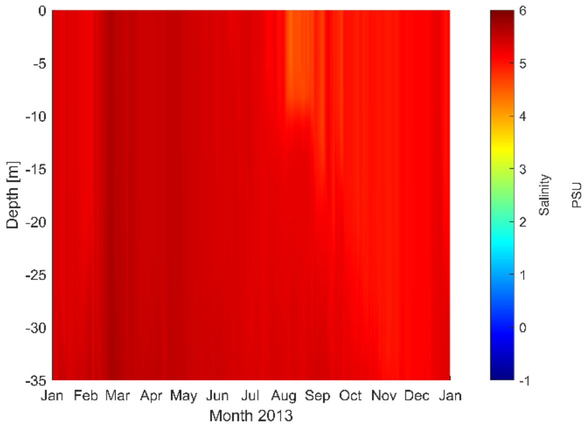
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan
Temperature
Celsius

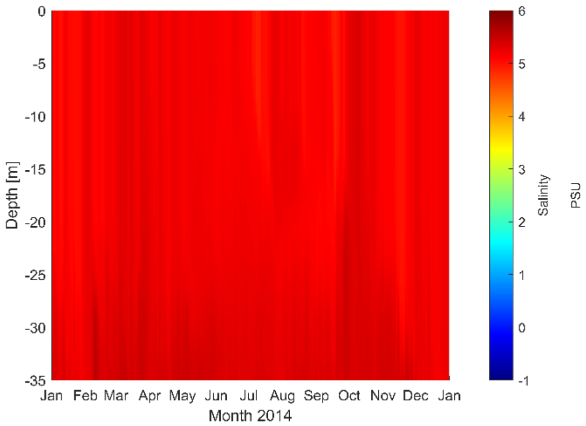
Appendix 3 Fyrskeppet OWF, Salinity profiles (SMHI, modelled 4x4km)

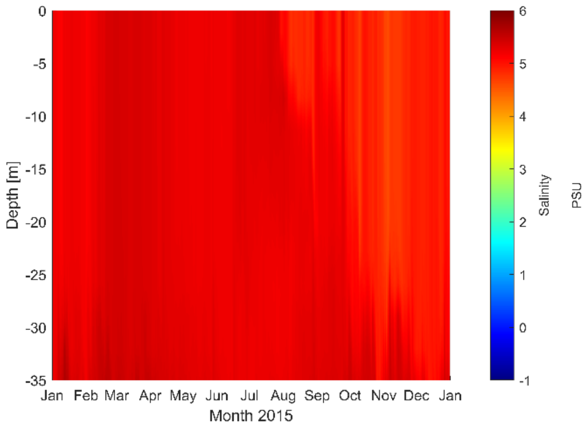


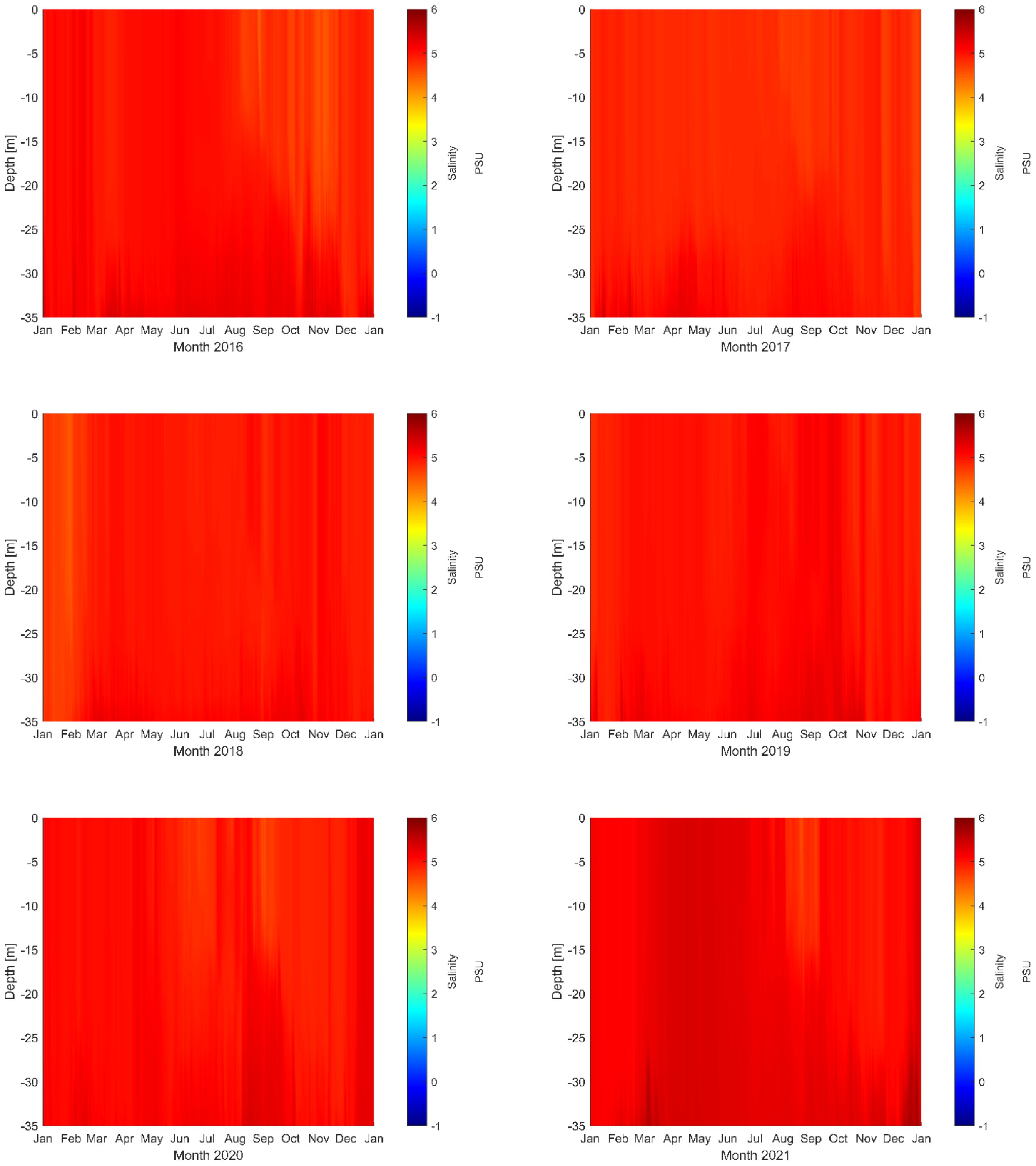











Depth [m]
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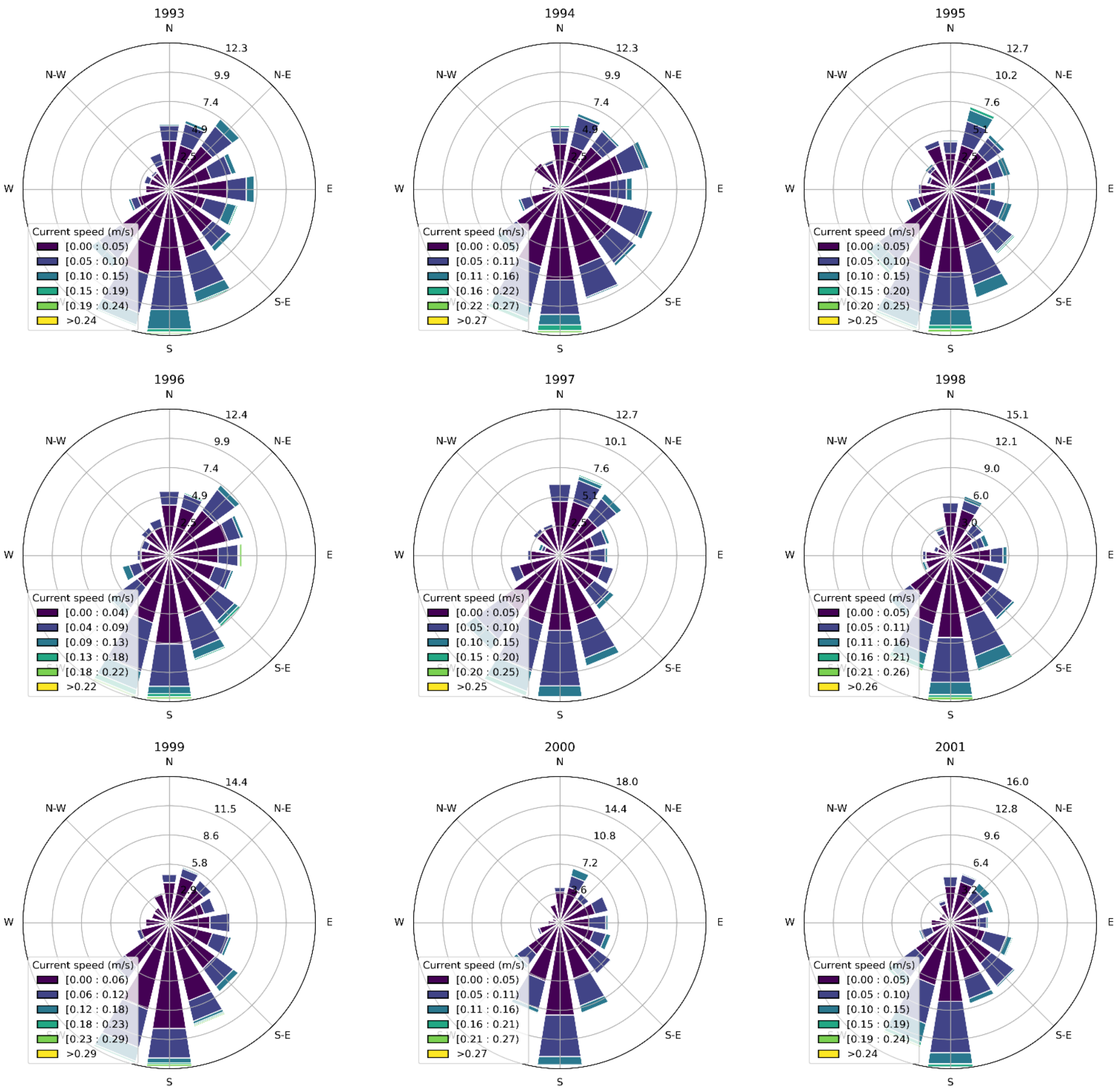
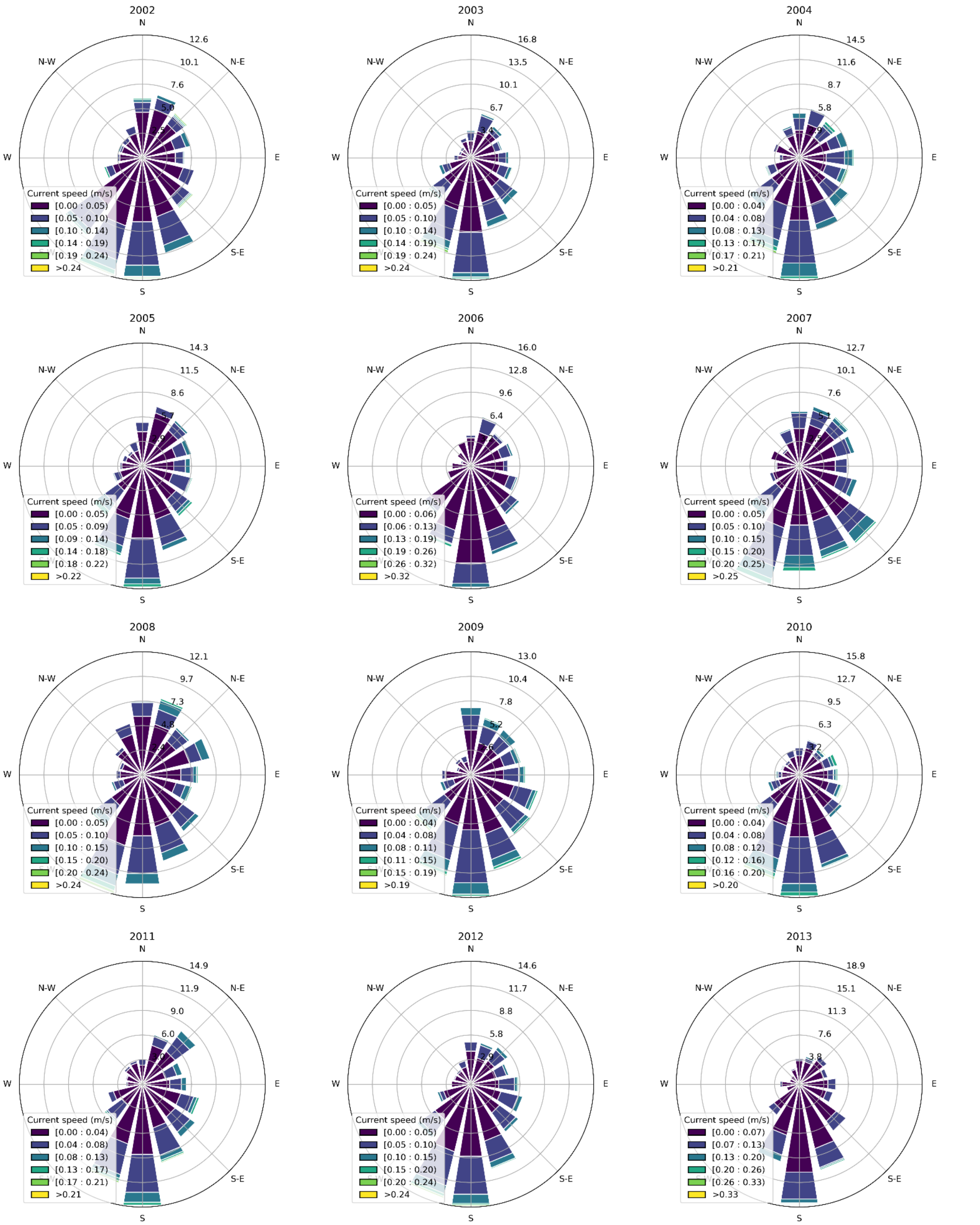
-5
-10
-15
-20
-25
-30
-35
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan
Month 2016
Month 2017
Month 2018
Month 2019
Month 2020
Month 2021
Salinity
PSU
6
5
4
3
2
1
0
-1

Appendix 4 Fyrskeppet OWF, Current roses (SMHI, modelled 4x4km)





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[0.05 : 0.10)
[0.10 : 0.14)
[0.14 : 0.19)
[0.19 : 0.24)
>0.24
2003
Current speed (m/s)
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[0.05 : 0.10)
[0.10 : 0.14)
[0.14 : 0.19)
[0.19 : 0.24)
>0.24
2004
Current speed (m/s)
[0.00 : 0.04)
[0.04 : 0.08)
[0.08 : 0.13)
[0.13 : 0.17)
[0.17 : 0.21)
>0.21
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Current speed (m/s)
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[0.05 : 0.09)
[0.09 : 0.14)
[0.14 : 0.18)
[0.18 : 0.22)
>0.22
2006
Current speed (m/s)
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[0.06 : 0.13)
[0.13 : 0.19)
[0.19 : 0.26)
[0.26 : 0.32)
>0.32
2007
Current speed (m/s)
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[0.05 : 0.10)
[0.10 : 0.15)
[0.15 : 0.20)
[0.20 : 0.25)
>0.25
2008
Current speed (m/s)
[0.00 : 0.05)
[0.05 : 0.10)
[0.10 : 0.15)
[0.15 : 0.20)
[0.20 : 0.24)
>0.24
2009
Current speed (m/s)
[0.00 : 0.04)
[0.04 : 0.08)
[0.08 : 0.11)
[0.11 : 0.15)
[0.15 : 0.19)
>0.19
2010
Current speed (m/s)
[0.00 : 0.04)
[0.04 : 0.08)
[0.08 : 0.12)
[0.12 : 0.16)
[0.16 : 0.20)
>0.20
2011
Current speed (m/s)
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[0.08 : 0.13)
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2012
Current speed (m/s)
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[0.05 : 0.10)
[0.10 : 0.15)
[0.15 : 0.20)
[0.20 : 0.24)
>0.24
2013
Current speed (m/s)
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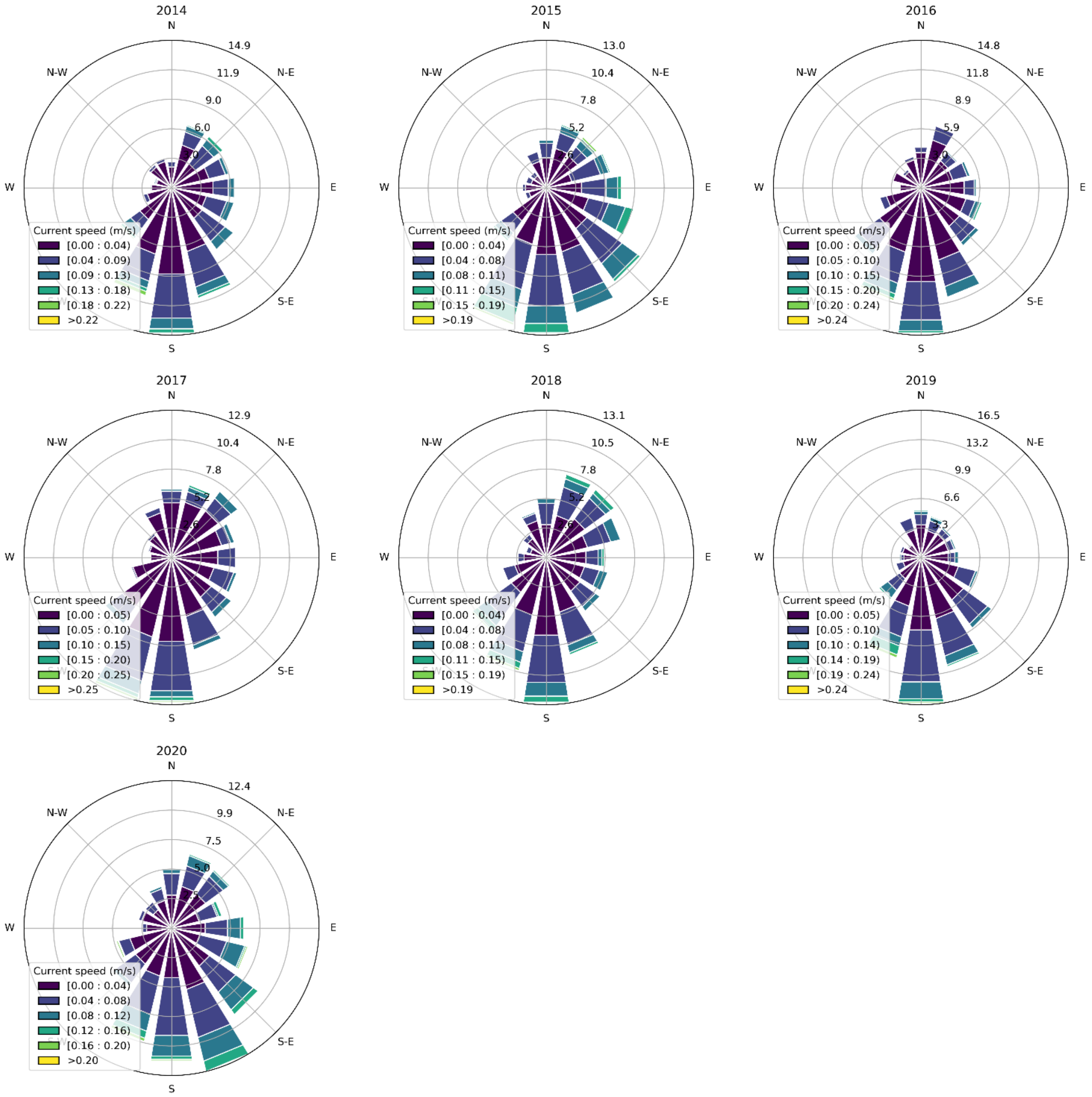
>0.33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N-E
E
S-E
S
W
N-W
14.9
11.9
9.0
6.0
Current speed (m/s)
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[0.13 : 0.18)
[0.18 : 0.22)
>0.22
2015
N
N-E
E
S-E
S
W
N-W
13.0
10.4
7.8
5.2
Current speed (m/s)
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>0.19
2016
N
N-E
E
S-E
S
W
N-W
14.8
11.8
8.9
5.9
Current speed (m/s)
[0.00 : 0.05)
[0.05 : 0.10)
[0.10 : 0.15)
[0.15 : 0.20)
[0.20 : 0.24)
>0.24
2017
N
N-E
E
S-E
S
W
N-W
12.9
10.4
7.8
5.2
Current speed (m/s)
[0.00 : 0.05)
[0.05 : 0.10)
[0.10 : 0.15)
[0.15 : 0.20)
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>0.25
2018
N
N-E
E
S-E
S
W
N-W
13.1
10.5
7.8
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Current speed (m/s)
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[0.11 : 0.15)
[0.15 : 0.19)
>0.19
2019
N
N-E
E
S-E
S
W
N-W
16.5
13.2
9.9
6.6
Current speed (m/s)
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[0.14 : 0.19)
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>0.24
2020
N
N-E
E
S-E
S
W
N-W
12.4
9.9
7.5
5.0
Current speed (m/s)
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[0.04 : 0.08)
[0.08 : 0.12)
[0.12 : 0.16)
[0.16 : 0.20)
>0.20

Appendix 5 Fyrskeppet OWF, Current roses (SMHI, modelled 2x2km)