DAM engineering

Simulation of spreading of fine sediment in Sørfjorden due to rock dumping

O16022/P3/C

Final report

2-5-2017

	PHONE	E-MAIL	WEB
Krohnåsvegen 56, 5239 Rådal, Bergen, Norway	+47 91900591	gerard.dam@damengineering.no	www.damengineering.no

DAM
engineering

DAM ENGINEERING
Krohnåsvegen 56
5239 Rådal, Bergen
Norway
+47 91900591
gerard.dam@damengineering.no
www.damengineering.no
Org nr. 914194067

The island Osterøy with Sørfjorden in the front (looking north); photo: Erlend Bjørtvedt (CC-BY-SA)

Name of document:	Simulation of spreading of fine sediment in Sørfjorden due to rock dumping
Author:	Gerard Dam
Status:	Draft report
Date:	2-5-2017
Reference:	O17009-P3-C
Project name:	E16 Indre Arna – Voss
Client:	Rådgivende Biologer AS

Table of contents

1 Introduction

Statens Vegvesen is planning to reconstruct the E16 road and rail track between Indre Arna and Voss in Hordaland, Norway. New tunnels will be constructed as part of the upgrade. Around 20 million m^3 of rock that comes out of the tunnels has to be deposited in and placed along the side of Sørfjorden, see Figure 1.1. The planned depositional area is shown in the inset figure.

The rock debris consists of all kinds of sizes. The larger rock parts will immediately sink to the bottom of the fjord, while the fine sediments can stay in suspension for a considerable amount of time and can be carried away by the currents. A large concentration of these fines has a potential negative ecological impact for amongst others fish (and fish farms) and has to be investigated in detail. It is estimated that around 1% of the rock contains fine sediments (around 200.000 m^3).

The consortium involved in the preliminary impact assessment (with amongst other Rådgivende Biologer AS and Reinertsen AS) has asked Dam Engineering for the simulation of the spreading of fine sediments with a numerical hydrodynamic model. This report describes the results of the investigation of the spreading of the fine sediments.

This report consists of a data analysis (Chapter 2), set-up and calibration of the hydrodynamic model (Chapter 3) and scenario simulations (Chapter 4). Finally a conclusion is given in Chapter 5.

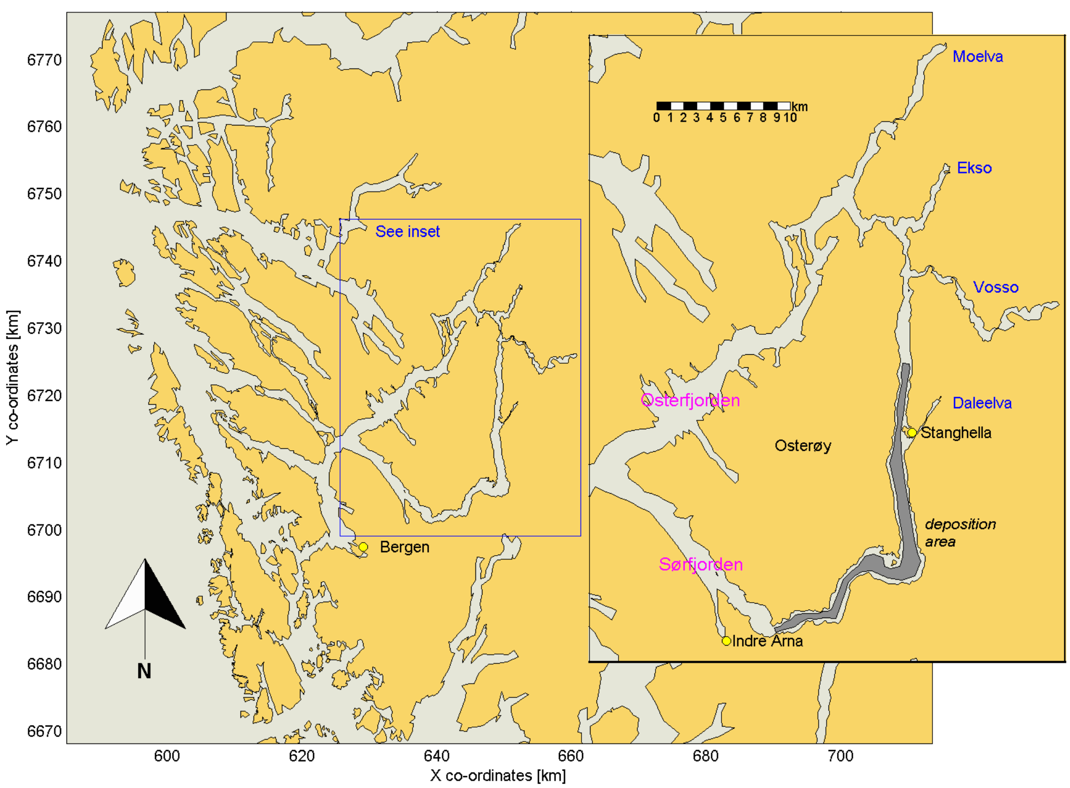


Figure 1.1: Overview of the project area

2 Data analysis of hydrodynamic processes

2.1 Introduction

Sørfjorden is connected to the sea through a series of other fjords (Figure 1.1). It is under influence of both the sea and fresh river runoff from the land.

A few processes are responsible for the hydrodynamics in Sørfjorden.

- Barotropic flows;
- Baroclinic flows;
- Wind driven currents

Each process will be described in the sections below. At the end of the chapter results of flow measurements in Sørfjorden are presented.

2.2 Barotropic flows; tide and storm surges

Barotropic flows are driven by sea surface variations between two locations. The tide is the most common known example of a barotropic flow.

Every 12,5 hours the fjord system around Osterøy is filled and emptied due to the tide. Bergen (and Sørfjorden) has an average tidal difference of 1.23m. At neap tide this tidal difference is smaller than during spring tide. This repeats in cycles of 14 days, see Figure 2.1. Normally the tidal waterlevels follows the rotation of the Sun and the Moon and is well predictable, this is called the astronomical tide. The real observed water level differs (sometimes) from the astronomical water level, since meteorological influences can affect the water levels. Wind and air pressure differences can cause a water level set-up or set-down. Usually during a storm the effects are the largest. In November 2016 both set-up and set-down events have occured (Figure 2.1).

Since Sørfjorden is very deep the tidal velocities associated with the filling and emptying of the basin are very low. The velocities are estimated to be in the order of several cm/s and are not expected to be the dominant process for the hydrodynamics in Sørfjorden.

2.3 Baroclinic flows; estuarine circulation

Baroclinic flows are driven by a difference in density stratification between two locations. The inflow of fresh water in fjords gives a potentially strong internal pressure gradient for baroclinic flows.

The fresh water inflow from rivers normally remains in a thin layer of several meters on top of the salt water. Figure 2.2 shows the average salinity profiles for 17 locations in Hordaland of 2015 for the upper 30m. Sørfjorden Innerst (location 17) is the location with the highest freshwater influence. The salinity in the top layer is 8 ppt. Several meters deeper there is a sharp transition between brakish and salt water. The profiles become more saline in the direction of the sea, due to the mixing of the fresh and salt water (Figure 2.2). Below the brakish water the salt water from the sea flows in the opposite direction because the brakish water needs to be replaced. In this way the so-called estuarine circulation is created. This estuarine circulation is thought to be one of the major influences on the hydrodynamics in this area and should be accounted for in the modelling.

The Sørfjorden and Ostfjorden system around Osterøy has a yearly fresh water runoff of average 10 km^3 (~317 m^3/s). The runoff has a spring peak in May/June of average 800 m^3/s due to the snow melt and a autumn peak in October of around 400 m^3/s (Johannessen et al., 2010). The largest river that is supplying fresh water is Vosso, with an average discharge of around 104 m^3/s, see Figure 1.1. Three other rivers that also contribute to the fresh water input are Daleelva (21 m^3/s average), Ekso (32 m^3/s average) and Moevla (45 m^3/s average). The average discharge of these rivers were determined from a 30 year period using the Hype model (http://hypeweb.smhi.se/). During periods of snowmelt and heavy rain these discharges can increase dramatically. These 4 rivers account for around 64% of the average freshwater runnoff for the Ostfjorden and Sørfjorden system. The rest is runnoff from minor catchment areas (e.g. the island Osterøy).

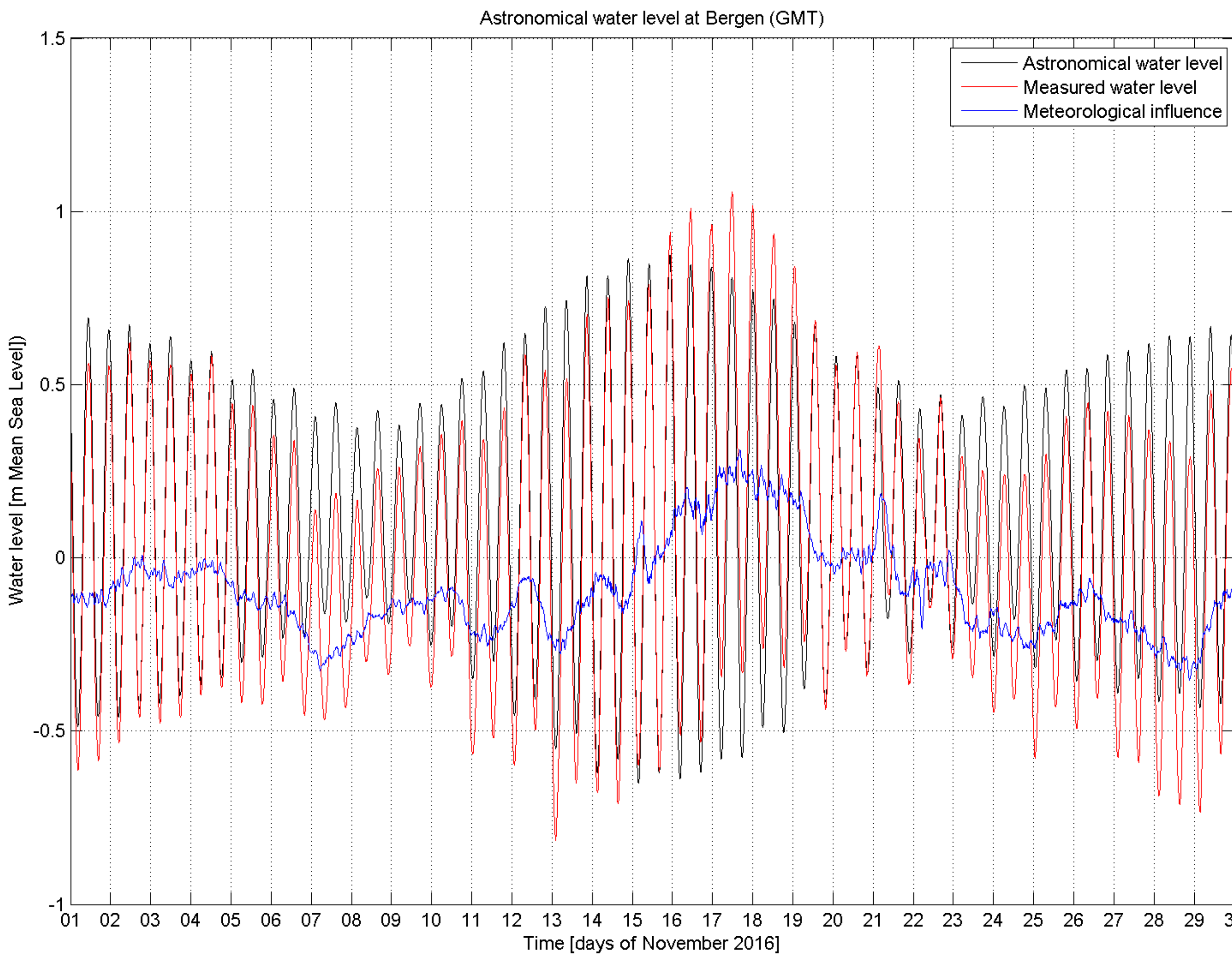


Figure 2.1: Astronomical water levels at Bergen for November 2016 (Data from kartverket.no/sehavniva/)

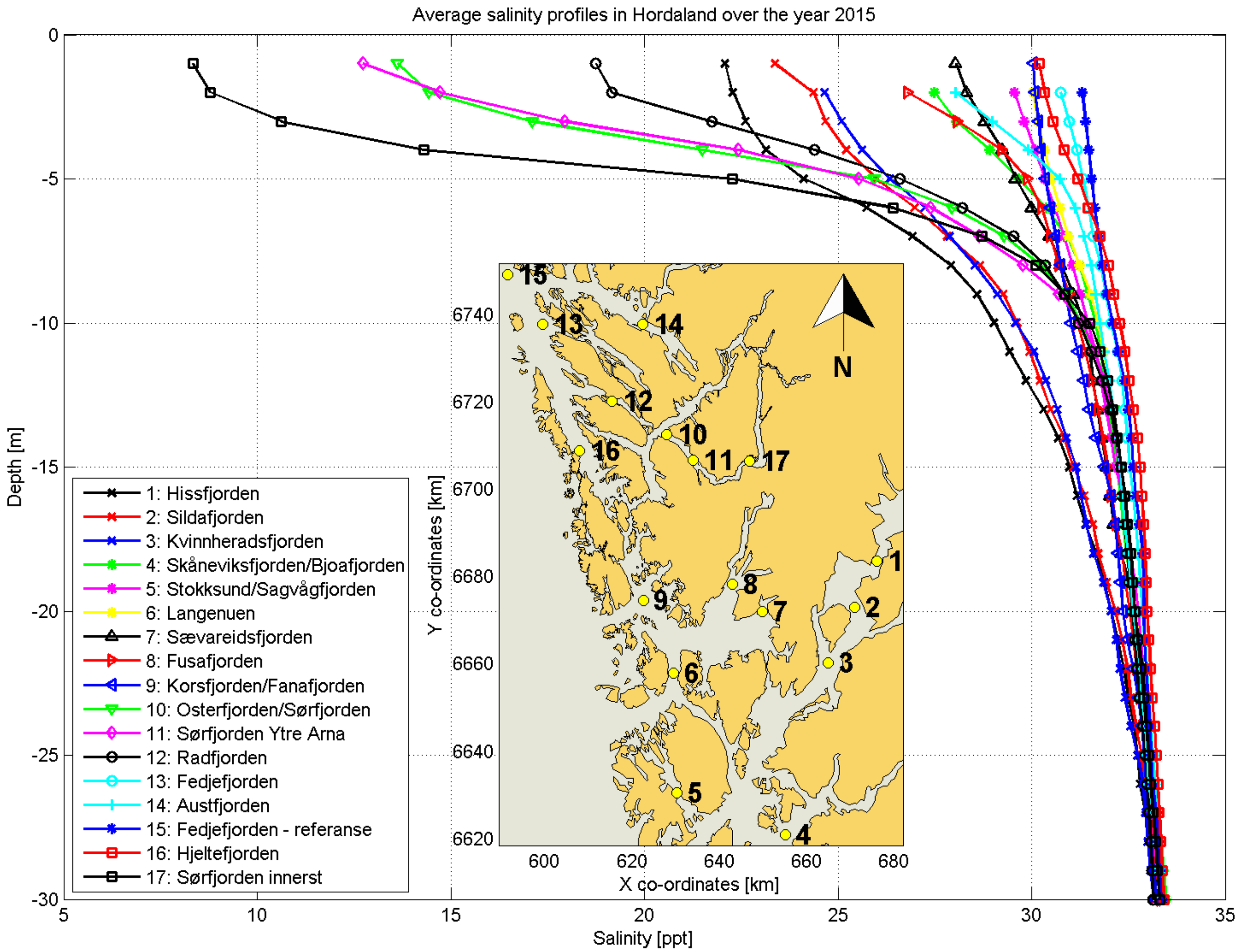


Figure 2.2: Average salinity profiles in Hordaland over the year 2015 (Data from Johnsen & Furset, 2016)

The salinity profile changes over the year depending on the fresh water input. Figure 2.3 shows measured profiles at “Sørfjorden innerst” for 2015 with an interval of approximately a month. Especially during the snow melt in May/June the top layer has the strongest stratification. Note that the year 2015 was a particularly wet year with a record rainfall in Bergen, so average profiles are expected to be less saline than average.

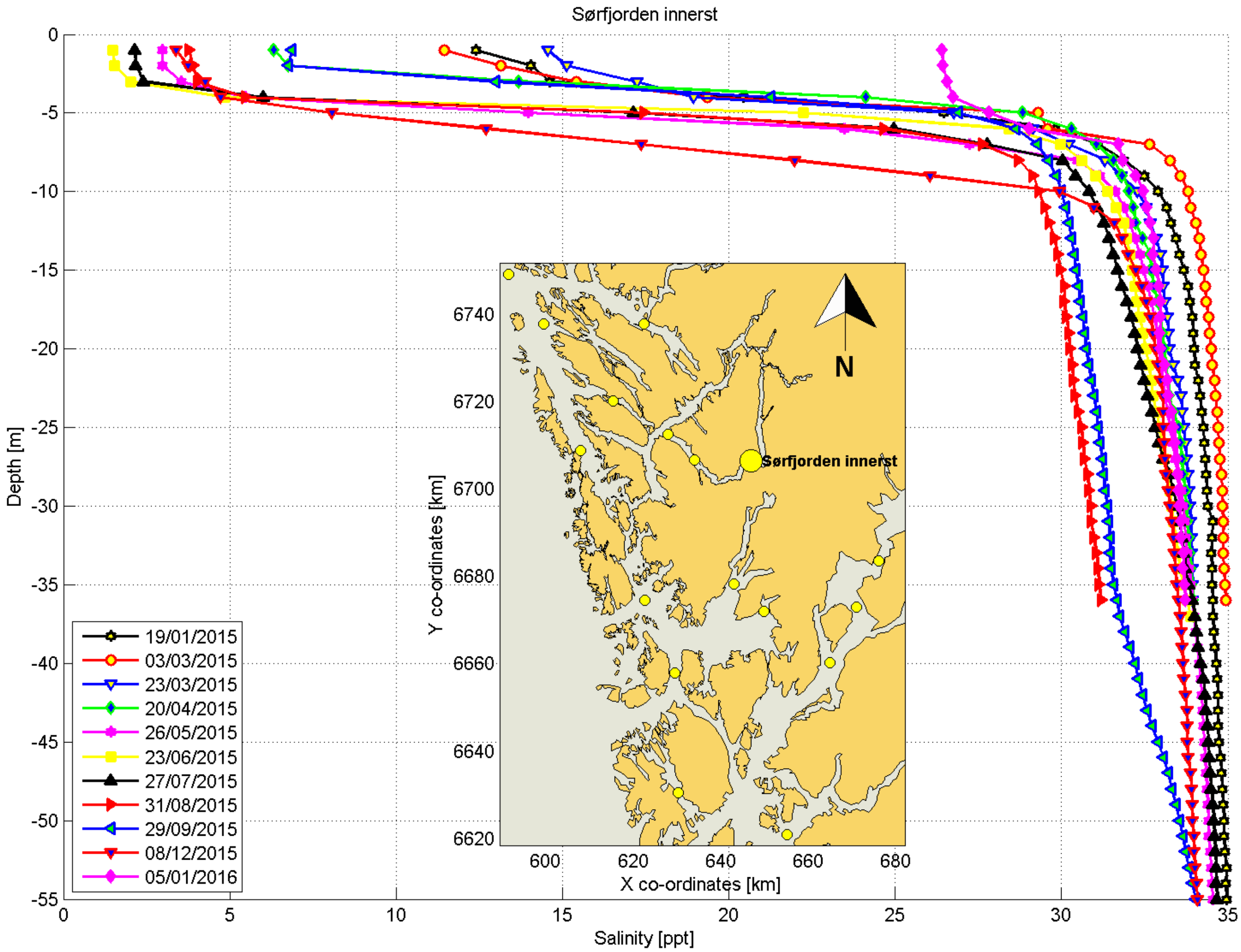


Figure 2.3: Salinity profiles at Sørfjorden innerst over the year 2015 (Data from Johnsen & Furset, 2016)

2.4 Wind driven currents

Wind causes a drag on the water surface and therefore causes wind driven currents. Wind can cause the highest currents in fjords. Asplin et al. (2014) shows that in Hardangerfjorden a storm with 15m/s causes a current of 0.7 m/s at 2m deep. At the surface the current can be over 1m/s during storms. The vertical current profile follows a logarithmic profile and is visible to 10-20m depth (Asplin et al., 2014).

2.5 Measurements of velocities in Sørfjorden from 2000-2002

Several flow measurements along the side of the fjord near fish farms were carried out in Sørfjorden from 2000-2002 (Tveranger (2000a, 2000b), Tveranger et al., (2001a, 2001b), Børsheim & Tveranger, 2002). Figure 2.4 shows the locations of these measurements. Measurements are carried out at three heights in the water column for several weeks. In Figure 2.5 the flow measurements are shown for 6 locations along the sides of the fjords.

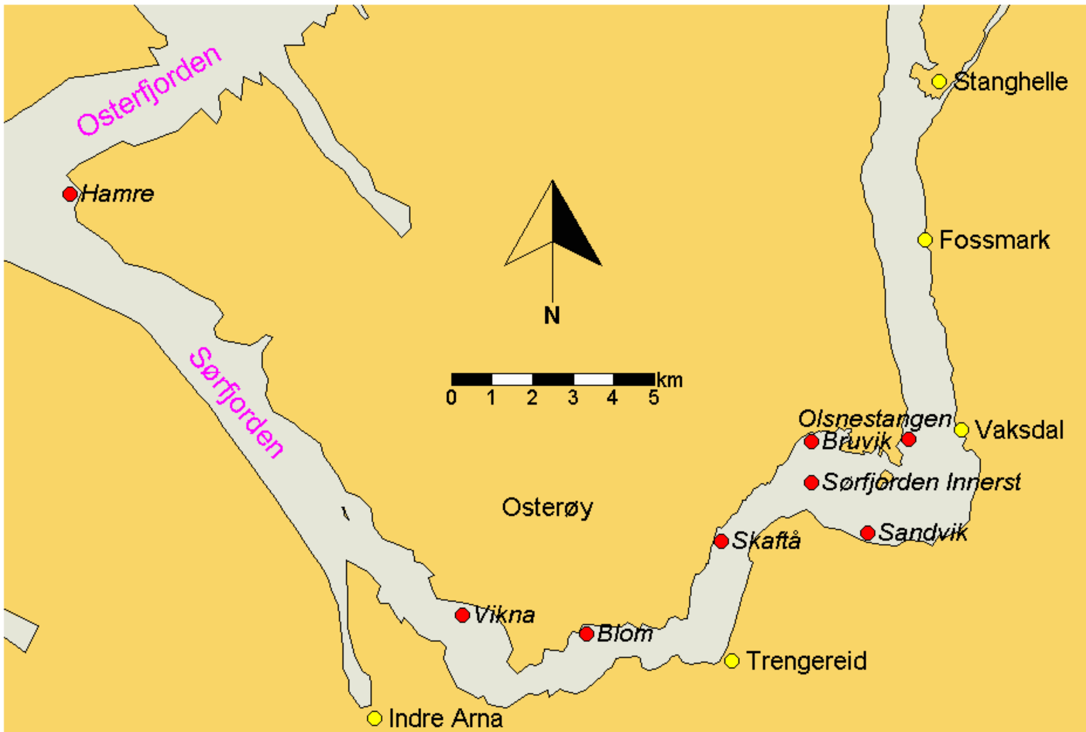


Figure 2.4: Overview velocity measurement locations (red dots)

Generally the flow velocities are highest in the upper water column and lower in the water column the velocities become smaller. The flow velocities are irregular with peaks up to 25 cm/s. There is no regular flow pattern detectable that would reveal tidal currents, i.e. a tidal dominated current signal has a regular sinusoidal shape. The direction of the flow generally is parallel with fjord and usually is dominant in the seaward direction.

The peaks in the flow velocity sometimes reveal an inverse flow at the surface; i.e. the current is directed into the fjord. This phenomenon has been reported at other locations, for example in Sandsfjorden, Rogaland (NIVA, 2013), but also in the USA in Chesapeake Bay (Elliot & Wang, 1978) and Prince William Sound (US Department of the interior, 2002). All sources claim that the inverse estuarine circulation has a weather related cause. This phenomenon can be explained by the fact that water near the head of the estuary is more saline than seawards, which triggers an inverse estuarine circulation. This can be attributed to weather effects in which deep saline water comes to the surface. The moments of an inverse estuarine circulation during these measurements coincide (roughly) with weather events in wind speed and water level set-up.

An example is at 13 February 2000. At both Olsnestangen and Bruvik there are measurements available which show the same (negative) peaks, which indicate a landward directed surface current. The 12th of February there was a peak wind speed of 12 m/s (with windcasts up to 21 m/s) measured at Bergen – Florida and is the most logical explanation for the occurrence of the peaks. There is no information further available how and if this negative estuarine salinity gradient occurs.

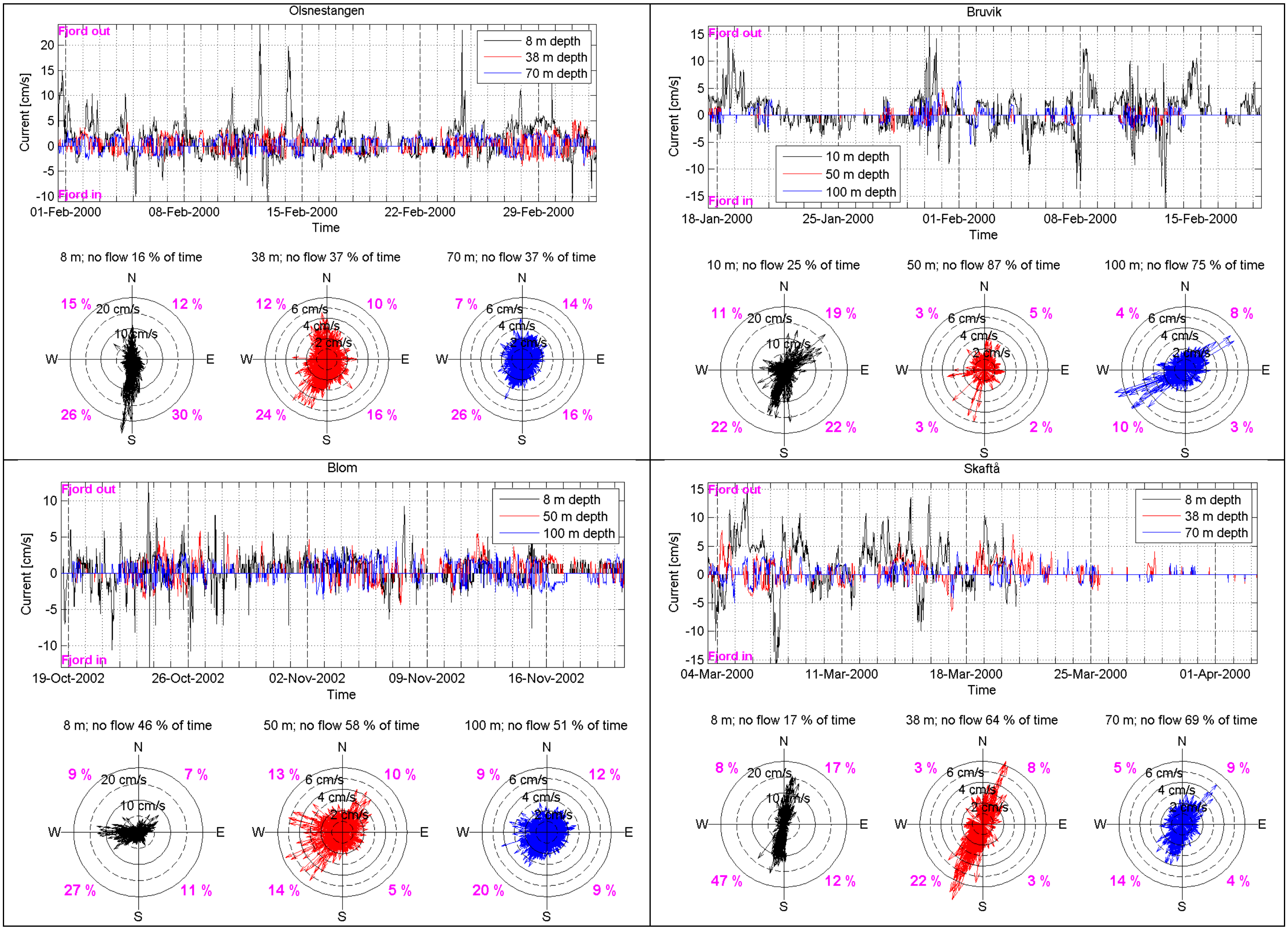


Figure 2.5: Velocity measurements at 4 locations in Sørfjorden: Olsnestangen, Bruvik, Blom and Skaftå

At Sandvik and Hamre there is also an overlapping period (Figure 2.6), but no correspondence between the two measurements has been detected. Sandvik is close to the southern bank of Sørfjorden and is therefore less sensitive to wind from a western and southern sector, while Hamre is more exposed to these winds. Velocity peaks at Hamre seems to correlate with high winds.

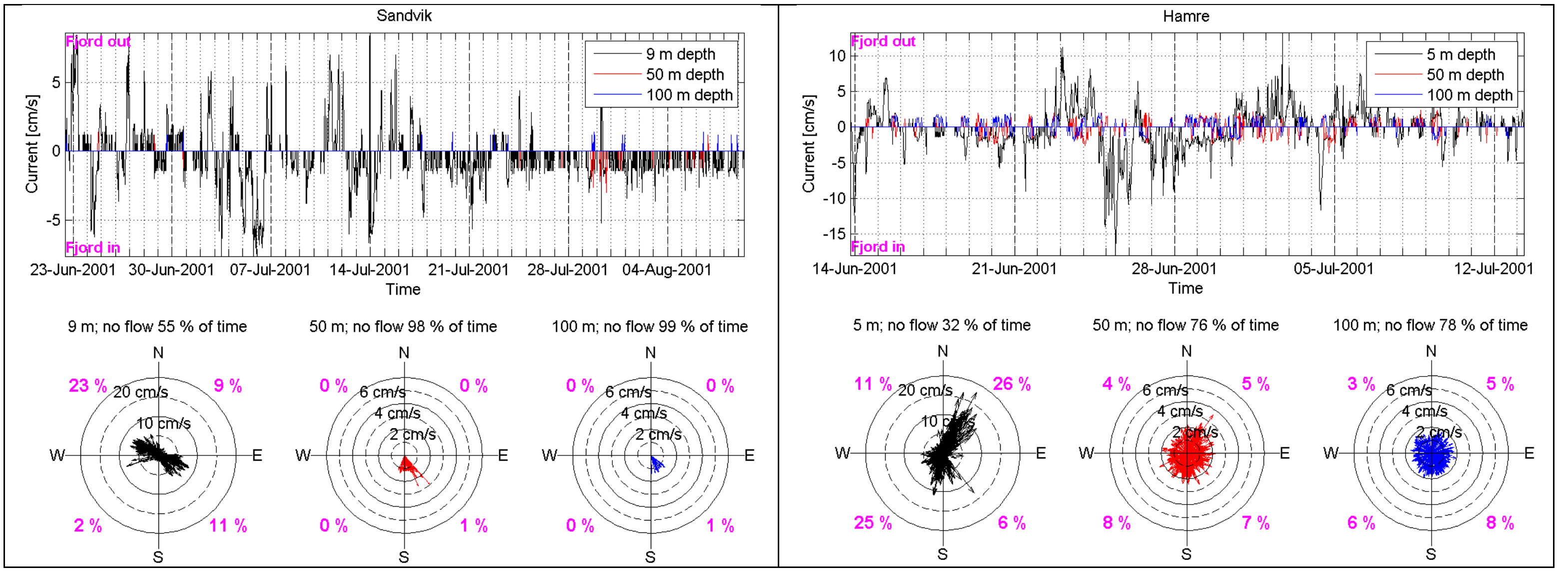


Figure 2.6: Velocity measurements at 2 locations in Sørfjorden: Sandvik and Hamre

2.6 Measurements of velocities in Sørfjorden in November 2016

As part of this project extra measurements were carried out at the location "Sørfjorden innerst", see Figure 2.4. The location was chosen because it is located in the middle of the area of interest and in the middle of the fjord. All other (older) measurements were carried out near the side of the fjord.

From November 4th to November 28th 2016 flow was measured at different heights. Also a Doppler profiler measured the flow in the upper 35 meter. Figure 2.1 shows the measured tide and meteorological influence on the tide of November 2016. The closest station for the wind measurement is Fossmark, which is located in Sørfjorden (Figure 2.4). The measured wind for November 2016 is plotted in Figure 2.7. Note that the wind direction is often north and south orientated, parallel with the fjord here.

The flow measured at -2m depth (Figure 2.8) shows that the first week the flow is directed seaward (fjord out), like the normal estuarine circulation. The flow has peaks and the averaged over this first week is slightly less than 10 cm/s. The direction is around 300 degrees, which is in a northwest direction. After November 11th the flow becomes irregular and multiple times the flow reverses with negative peaks (fjord in) up to 40 cm/s. The acoustic profiler at 8m depth also shows more or less the same behavior (Figure 2.8). At the time the flow reverses there is a southerly wind in Fossmark (Figure 2.7). This could mean that northward wind driven currents in the fjord near Fossmark, would drag also currents in the same 'fjord in' direction near the measurement location. Another possibility is that the wind generated currents stir up deep salt water at a location in the fjord (possibly the shallow sill near Stamneshella) that would reverse the estuarine circulation. Note that not all southerly winds generate a reverse flow.

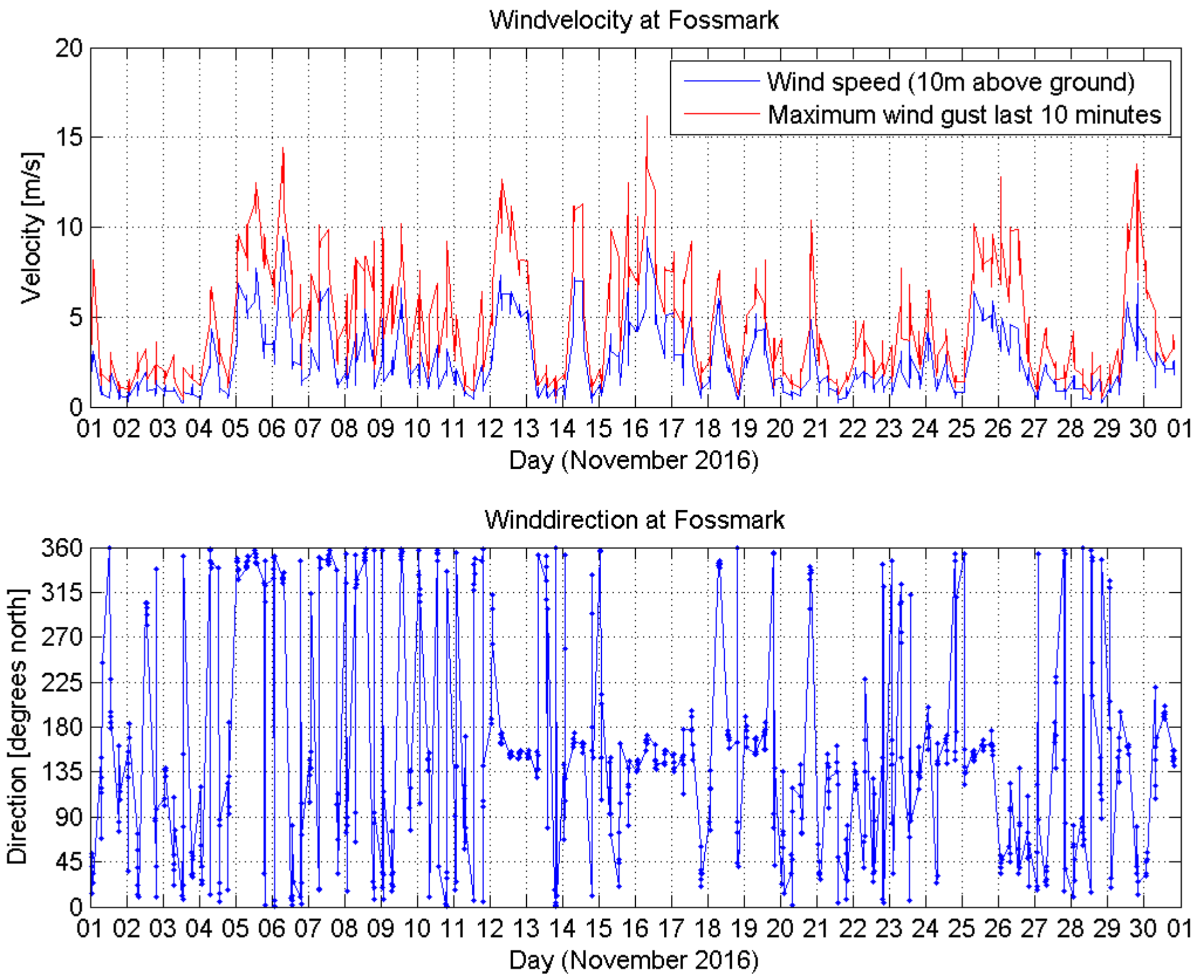


Figure 2.7: Wind measurements at Fossmark (Veafjorden); source: eklima.no

At 45m depth another point measurement was carried out (Figure 2.8). In the first days there is almost no flow, and the direction is around 200 degrees, which looks strange at first. In correspondence to the 2m measurement after November 11th the measurement at 45m depth also shows more irregular behavior. Several times after November 11th the direction comes back at a 200 degree direction. In the next chapter we will come back to this flow direction.

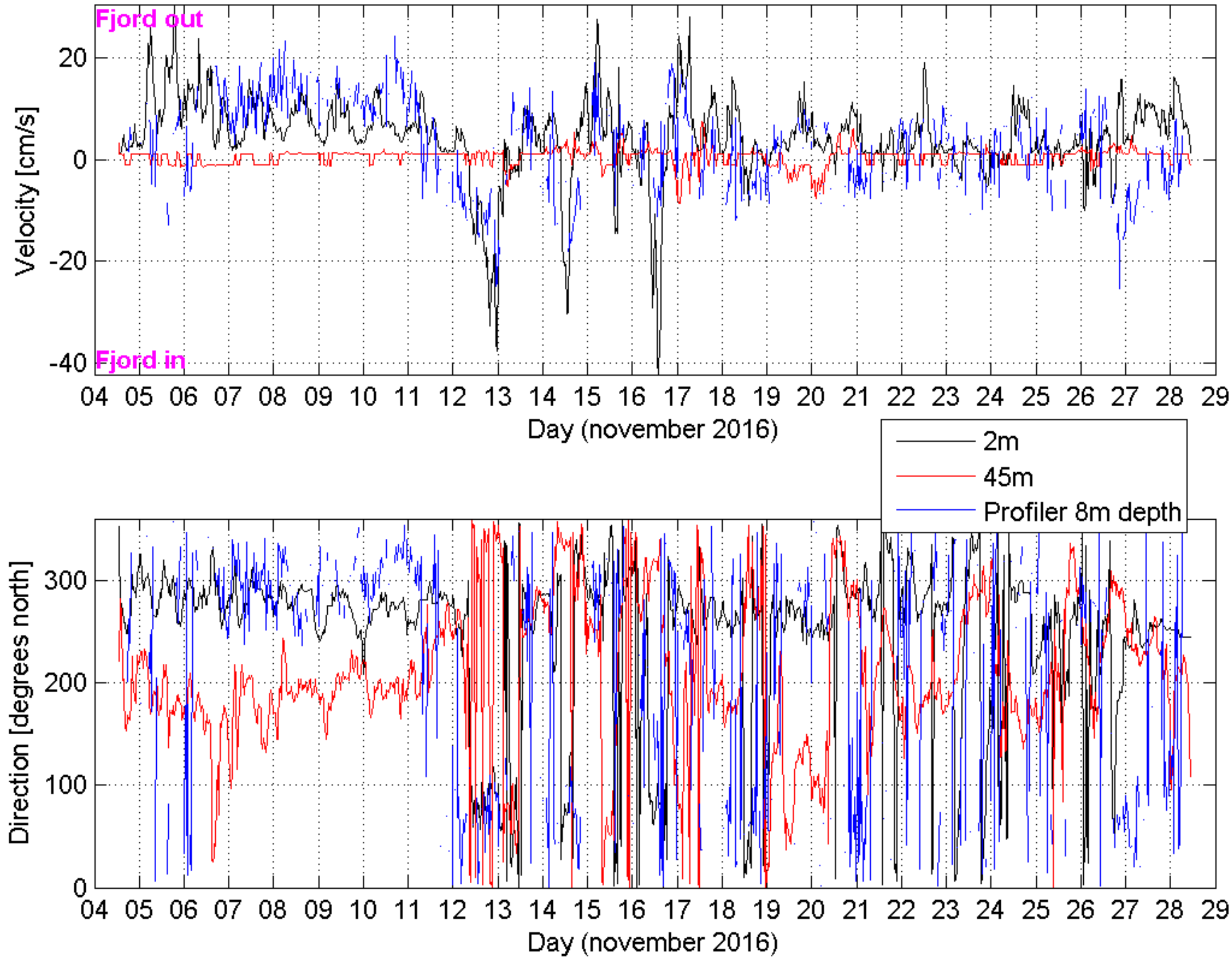


Figure 2.8: Velocity measurements at Sørfjorden Innerst November 2016: Upper part of water column

The measured flow at 80m and 270m shows irregular behavior at first sign (Figure 2.9). Slightly surprising is that at these depths a large flow is detected (up to 5-6 cm/s), especially at 270m depth, which is below the sill depth of this area. To get more insight in the behavior of the currents at 80 and 270m depth the drift of the velocity time series is plotted (Figure 2.10). A simple way of understanding this plot is to think of a track that a water particle would make in an open sea given the speed and direction of the measurement. The track starts at the beginning of the measurement from coordinate (0,0). The benefit of his plot is that dominant flow directions are revealed more easily than Figure 2.9. Figure 2.10 shows that both at 80m and 270m depth there is a net flow in northward direction. This can probably be explained by the curvature of the fjord, in which the flow makes spiral movements over the depth due to the bends of the fjord, see also next chapter. Also there are periods of days to more than a week in which the flow is dominant in one direction, for example at 80m depth from 12 to 21 November the flow is dominant in westerly direction. After that the flow is dominant in easterly direction for a week. So the flow is not so irregular, but the reason why the flow follows this behavior is unknown.

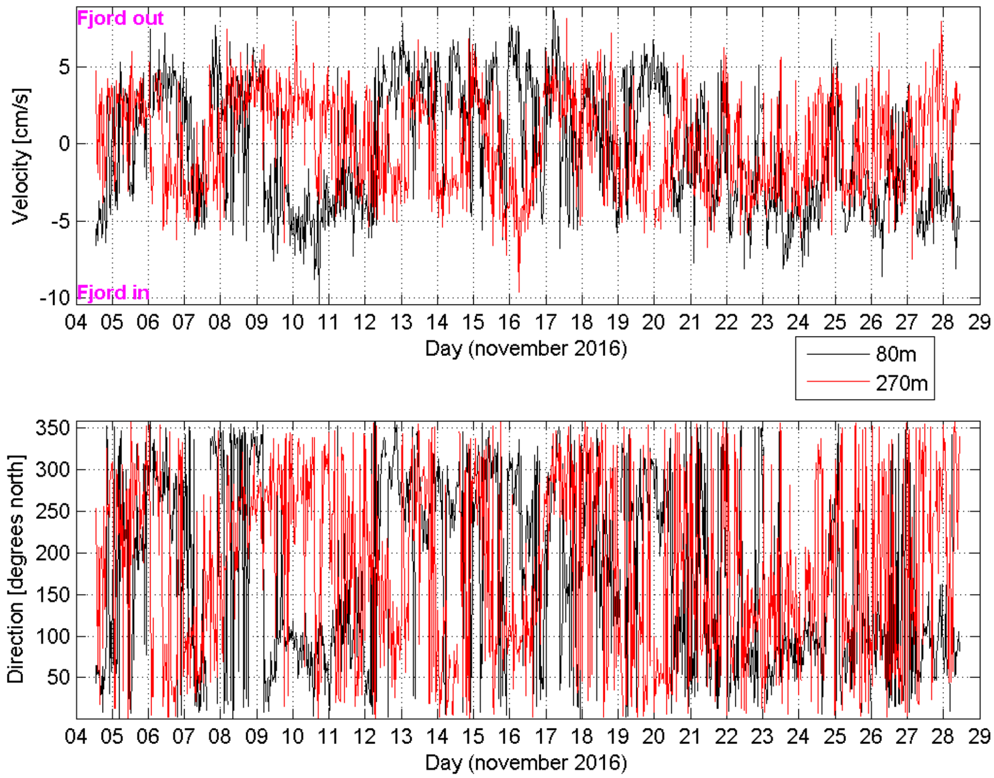


Figure 2.9: Velocity measurements at Sørfjorden Innerst November 2016: Lower part of water column

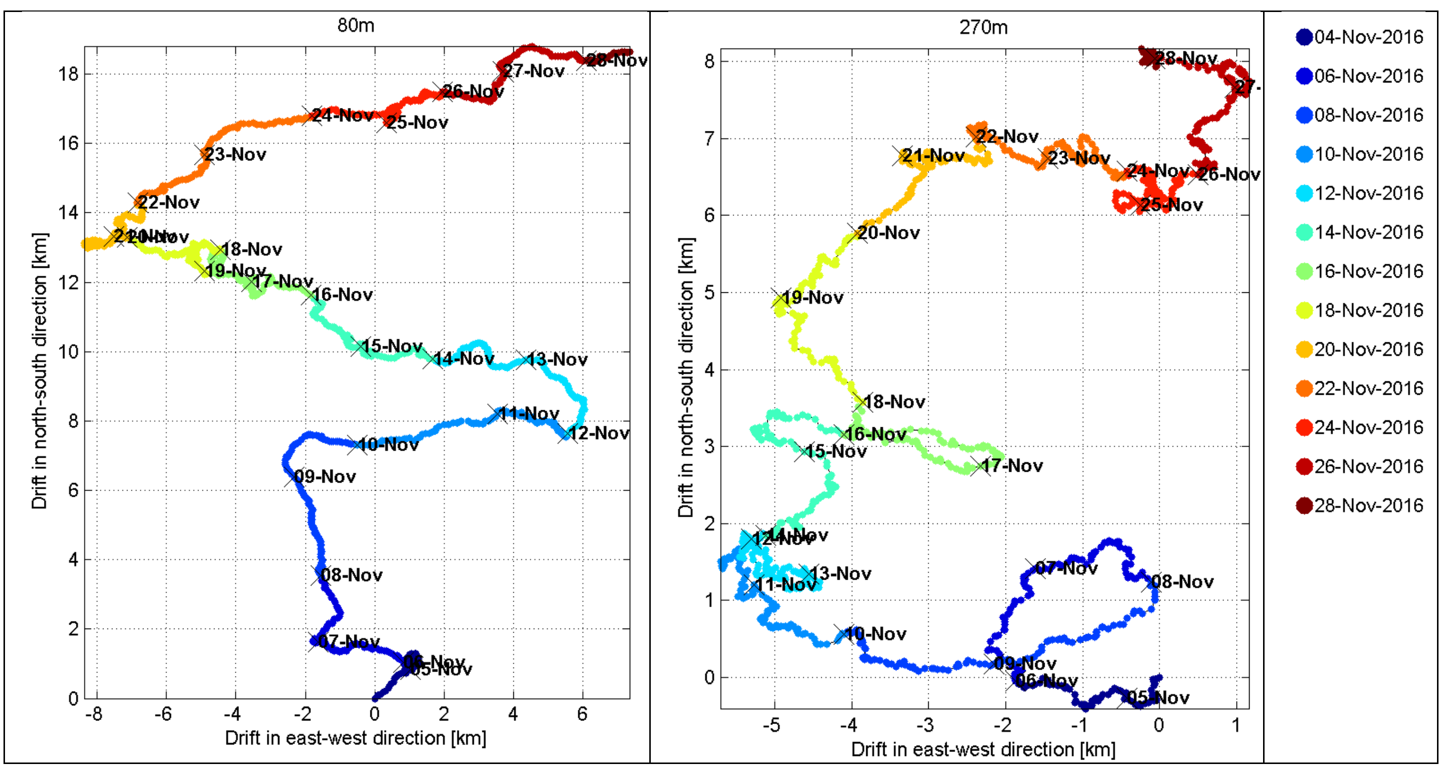


Figure 2.10: 'Drift' over 24 days for measurements at 80m and 270m depth

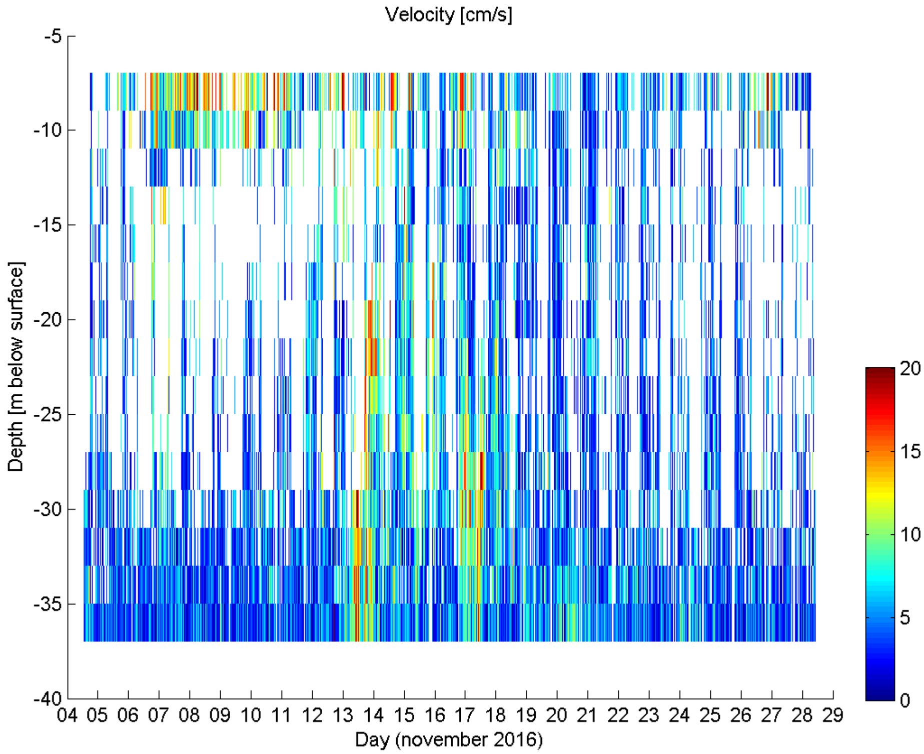


Figure 2.11: Velocity measurements with Acoustic Profiler at Sørfjorden Innerst November 2016

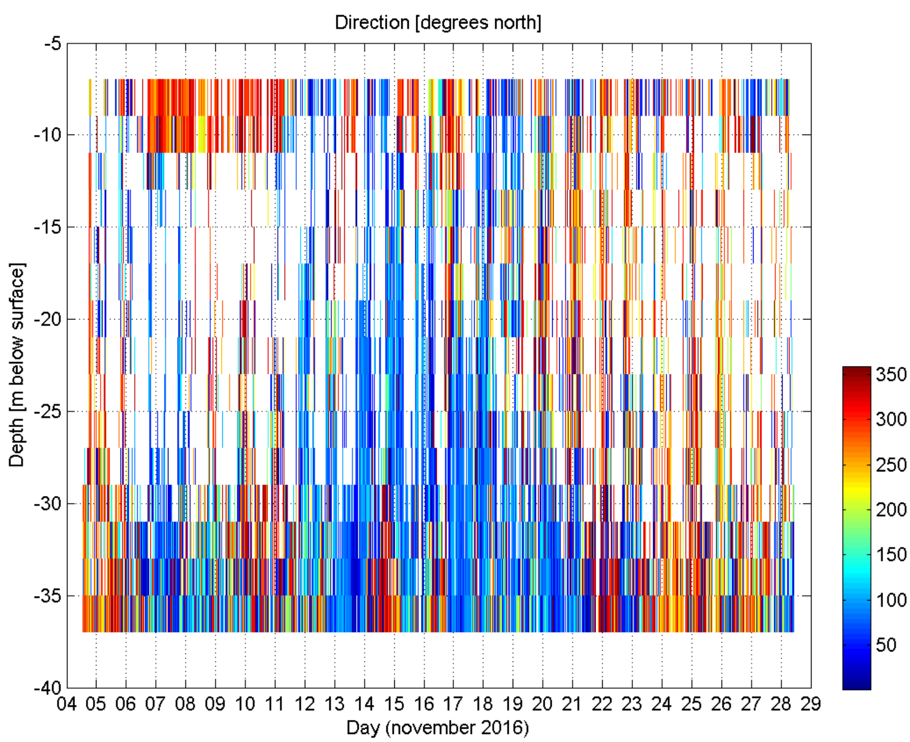


Figure 2.12: Velocity direction measurements with Acoustic Profiler at Sørfjorden Innerst November 2016

Figure 2.9 and Figure 2.10 show the measurements of the acoustic profiler. Where the measurement quality is too poor the outcome has been left blank. The profiler measurement show that the top layers generally have the largest currents and are usually in seaward direction until November 11th. After this period the outcomes show irregular behavior. At 13 and 17 November there are velocities of 10-20 cm/s at 20-35m depth that flow in landward direction, while in the upper column the velocities are less. This cannot be related to previous observed events and the source of these high currents is unknown.

2.7 Conclusion

The flow regime in Sørfjorden follows most of the time the normal estuarine circulation with an outflow to sea at the surface and an inflow at a lower depth between the upper layer and the sill depth.

Frequently a reverse flow at the surface is observed in Sørfjorden, i.e. a landward directed flow. This has both been observed in the period 2000-2002 and in the recent measurement campaign of November 2016. A clear explanation for these events cannot be given with the present data, but appears to have a correlation with northward directed winds, measured near Fossmark. It is likely that either wind causes wind driven currents and a circulation current in Sørfjorden or that wind causes upwelling of deep salt water in Sørfjorden that in turn causes an inverse estuarine circulation.

Surprisingly relative large currents have been measured at 80m and 270m deep. There is a net northward directed flow at these depths. Also there are periods of days to more than one week in which there is a net dominant direction.

3 Model set-up FINEL3D

3.1 Choice of model

The hydrodynamic model that will be used to simulate the hydrodynamics in Sørfjorden is the FINEL3d model. This is a 3D non-hydrostatic finite element model. The model is developed by the Technical University Delft and Svašek Hydraulics (Labeur, 2009, Labeur &Wells, 2007, 2009, 2010, Talstra, 2016). The FINEL3d model is equipped with sediment modules. The spreading of fine sediments due to advection, diffusion, sinking and resuspension can be taken into account. Point sources can be given where the sediment is released.

3.2 Computational grid

The benefit of this finite-element model is that it uses triangular shaped meshes. Triangles are especially useful when following complicated coastlines like Norway, since there is (almost) unlimited freedom in placement of the triangles. Another advantage of this model is that the coarseness of the grid is easily refined near the area of interest in three ways:

1) Horizontal refinement near the area of interest (or in narrow passages);
2) Increasement of the number of vertical layers near the area of interest;
3) Distribution of the vertical layers near the top of the water column with the highest salinity gradients.

Ad 1) The coverage of the horizontal grid is defined from the sea to the inner fjord of Sørfjorden. The reason behind this is that the salinity gradient of the upper layer between Sørfjorden and the sea is more easily defined. Also theoretically a sediment particle with a typical fall velocity of 1 mm/s and a horizontal velocity of 10 cm/s can travel 40 km for an area with a depth of 400m (without resuspension) before it settles on the bottom. Therefore a large area needs to be taken into account.

The fjord system around Bergen is taken into account in the grid, from Haugesund towards Florø. The grid size is 10km at sea, with a gradual refinement towards Sørfjorden. The gridsize in Sørfjorden is 150m, see Figure 3.1. In the next chapter scenario runs are carried out at several locations. At these locations the grid is locally refined further to 30-50m.

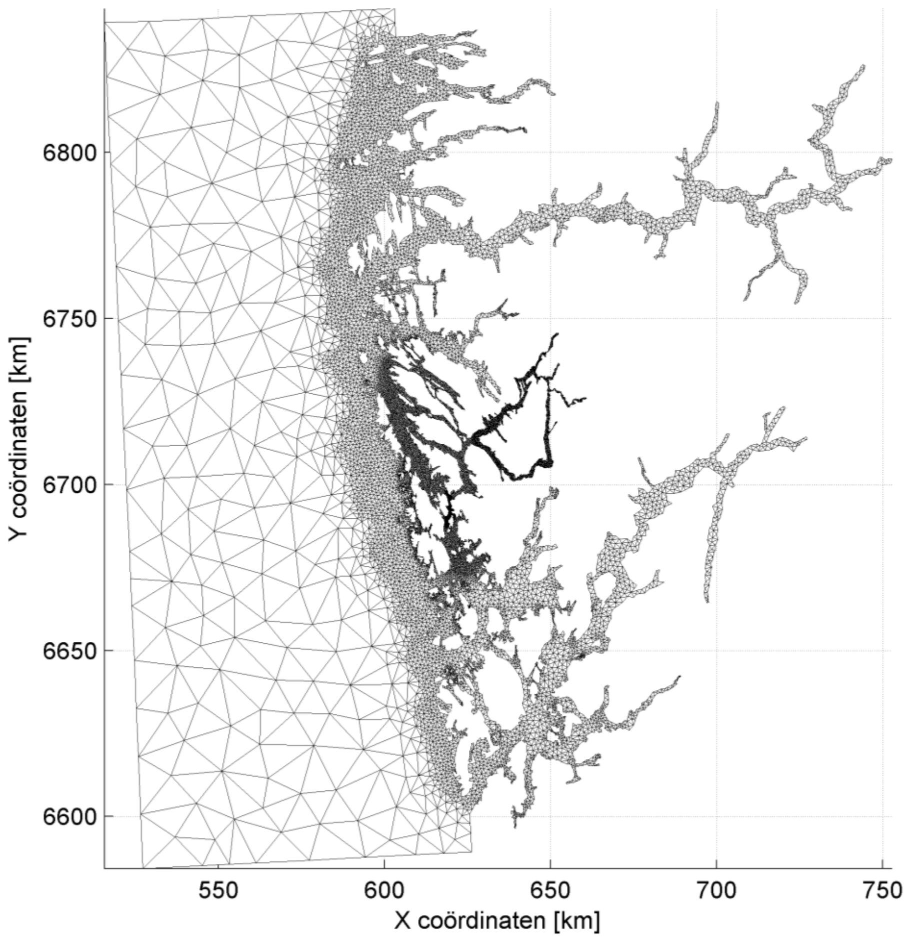


Figure 3.1: Computational grid of the FINEL3d model for the Sørfjorden project

Ad 2) FINEL3d gives the option to vary the number of layers throughout the domain. At sea it is not required to have a large detail in the vertical water column, therefore a limited number of layers suffice in this area. In Sørfjorden it is necessary to model the stratification correctly; therefore it is required to have a large numbers of layers here. At the sea the number of layers is 10, while in Sørfjorden the number of layers is 88. Between the sea and Sørfjorden the number of layers is gradually increased. Figure 3.2 shows the number of layers of the final model.

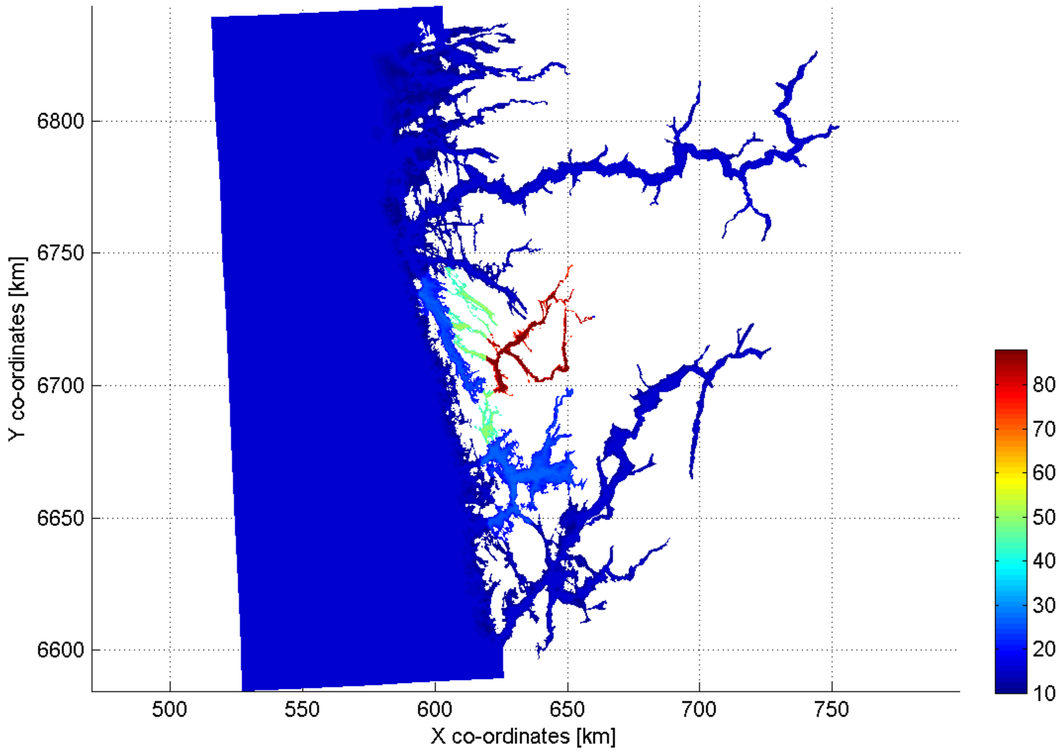


Figure 3.2: Number of vertical layers of the 3D grid

Ad 3) FINEL3D gives the possibility to vary the distribution of the vertical layers. This is especially useful in this area where there is a strong stratification in the upper few meters. The depth in Sørfjorden is around 400m and only the upper few meters contain fresh/brakish water with a sharp gradient between the upper and lower layer. Therefore more layers are required in the upper part of the water column and less in the downward part. The upper part of the model in the Sørfjorden area has a vertical resolution of 0.125m down to 8 meter. The vertical resolution is then gradually increased to 100m at the bottom. Figure 3.3 shows some 3D snapshots of the vertical layer distribution.

The vertical distribution of layers follows a combined z-layer (constant vertical layers) and sigma layer (follow the terrain) approach. In general the upper layers follow a horizontal distribution for the best reproduction of the salinity gradient (z-layers). In the upper 10m a vertical resolution of 0.125m is applied. The lower layers follow the bottom (sigma-layers). This becomes clear in Figure 3.3a.

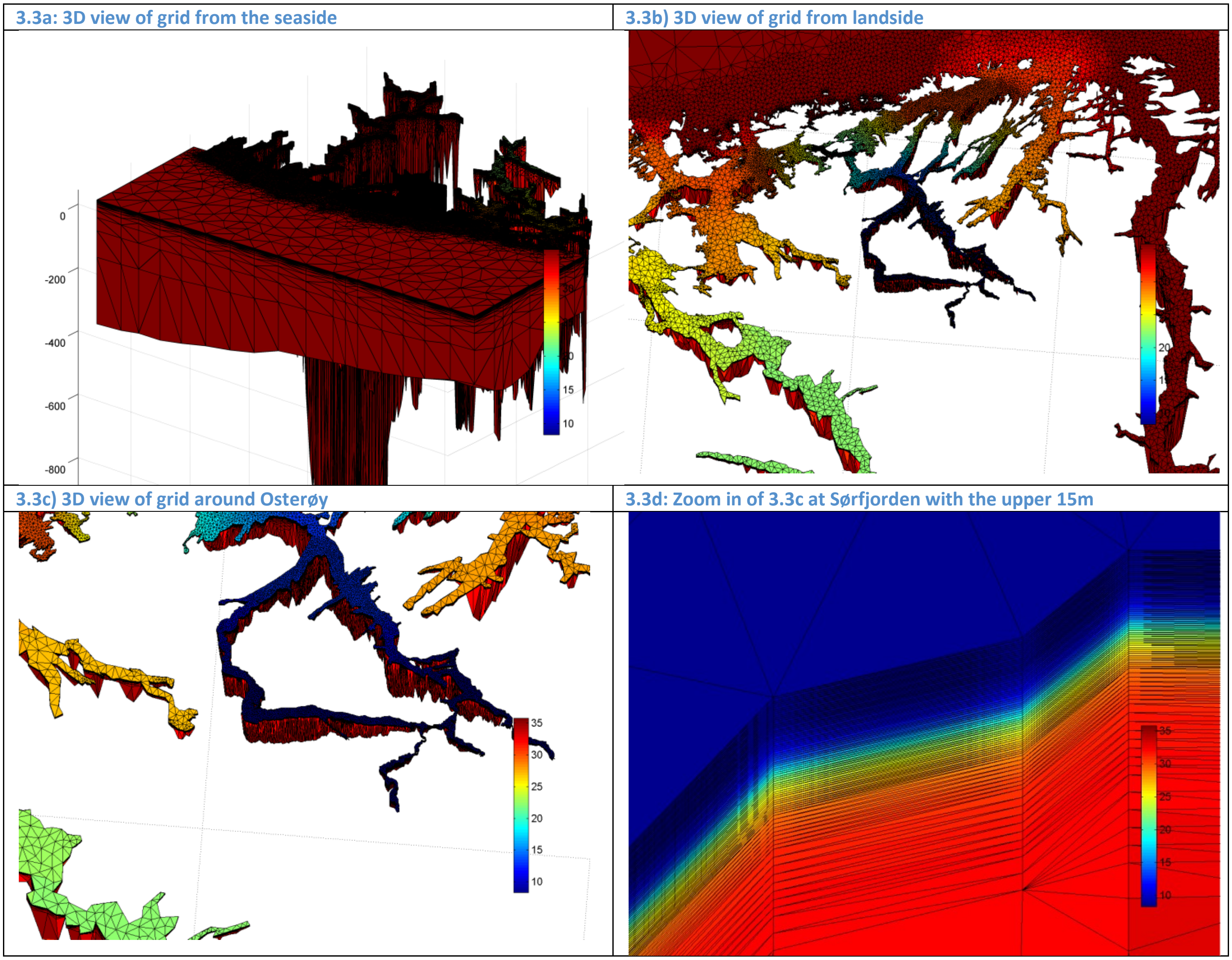


Figure 3.3: Snapshots of the 3D grid (in color the initial salinity distribution)

3.3 Bed level

Bed level data of the model consists of:

- Multibeam data of Sørfjorden with a 1m resolution (Mohn, 2016)
- Kartverket data of Hordaland with a variable resolution (downloaded from kartverket.no)
- EMODNET data for the seaside with a resolution of around 200m (downloaded from emodnet.eu).

The final bed level of the model is shown in Figure 3.4.

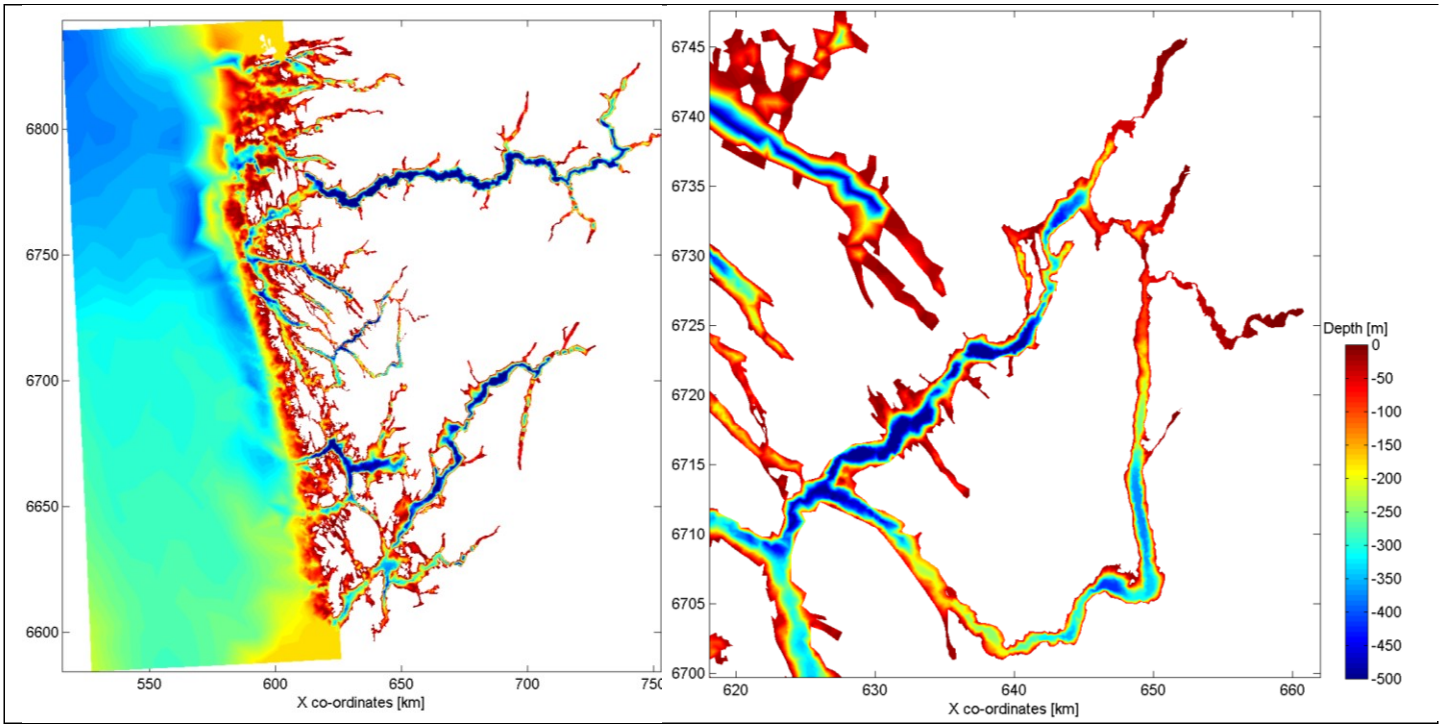


Figure 3.4: Bed level of the FINEL3d model with left: overall grid; right: detail around Osterøy

3.4 Boundary conditions

At the seaside astronomical tidal boundary conditions are applied. These boundary conditions are derived from the TPXO database with tidal constituents over the world.

3.5 Initial salinity distribution

Using the measured (averaged) profiles of 2015 (Figure 2.2) an initial 3D salinity distribution file is created (Figure 3.5). Between the locations the salinity is obtained by (lineair) interpolation between the profiles. Clearly visible is the relative fresh upper layer around Osterøy. Towards the sea the salinity in the top layer becomes more saline.

3.6 Fresh water input

The fresh water in the fjords comes from the rivers and in lesser degree rainfall on the water itself. The runoff of the largest river Vosso is well known and documented, however accounts only for around 1/3 of the fresh water input in the Sørfjorden/Osterfjorden system. Together these smaller rivers account a large part of the fresh water input in the system. Since it is impossible to schematize all smaller rivers separate in the model a new method is applied to ensure the input of the right amount of fresh water in the system. The new method consists of a 'rainfall' method. However the rainfall does not only account for the rain that falls on that grid element, but accounts also the fresh water runoff of a catchment area in the vicinity of that element. In this way also the local runoff of (small) rivers can be included, without schematizing all small rivers in the model. Catchment areas and yearly averaged run-off statistics were obtained from the website NVE (www.nve.no) and converted to fresh water input for the entire model domain.

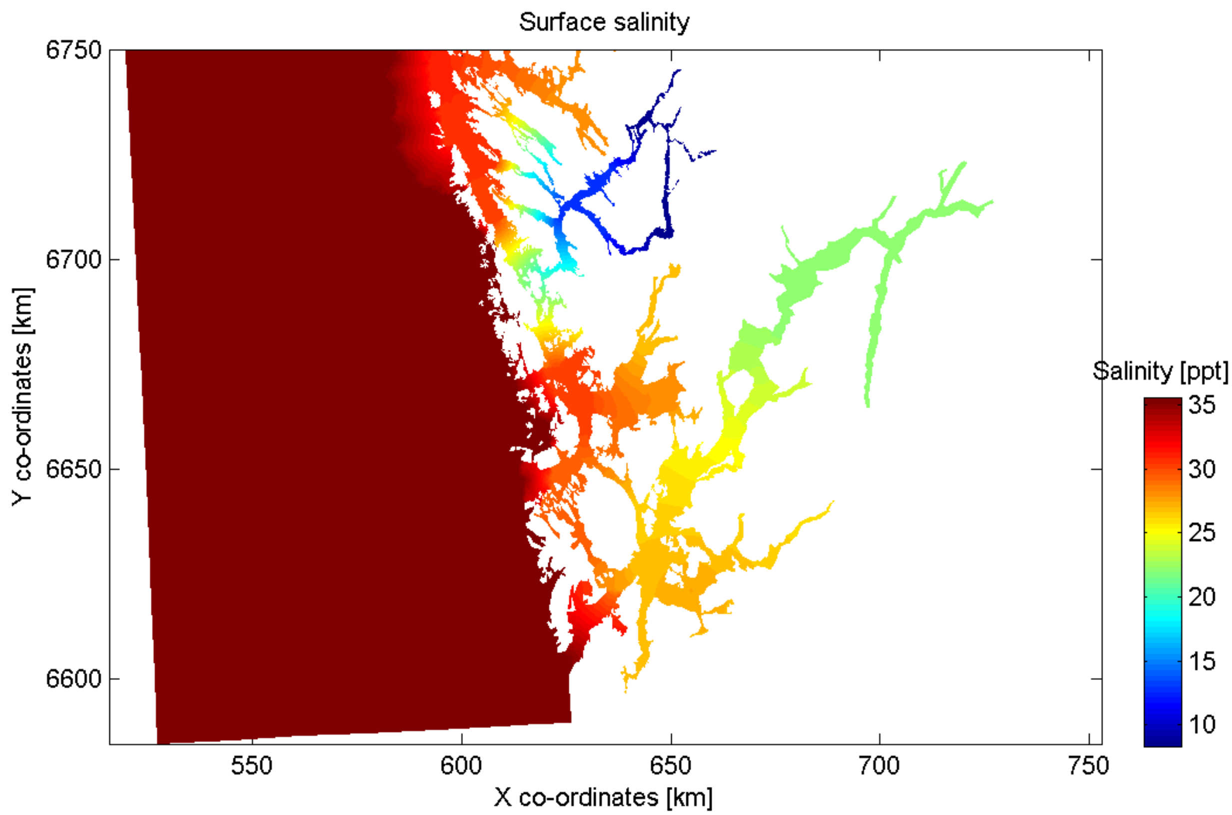


Figure 3.5: Initial salinity distribution at the top layer (average over the year 2015).

3.7 Calibration of the model

3.7.1 General

In this section the calibration of the model is described. The calibration period is November 2016, since detailed water level and flow measurements are available. Note that the model simulates the November period without meteorological forcing (wind and air pressure) and a constant fresh water input. This causes an (almost) stationary solution after the model spin-up, since tidal influences are small.

3.7.2 Tidal water levels

Figure 3.6 shows a comparison of tidal water levels between the FINEL3d model and measurements (http://kartverket.no/sehavniva/) for a 5 day period in November 2016 at Bergen. Note that this is a comparison between astronomical tides, so no meteorological influences are taken into account in the model at this stage. The model shows that it can calculate the water levels within 10 cm accuracy, which can be qualified as good. Tides will be included in the model simulations.

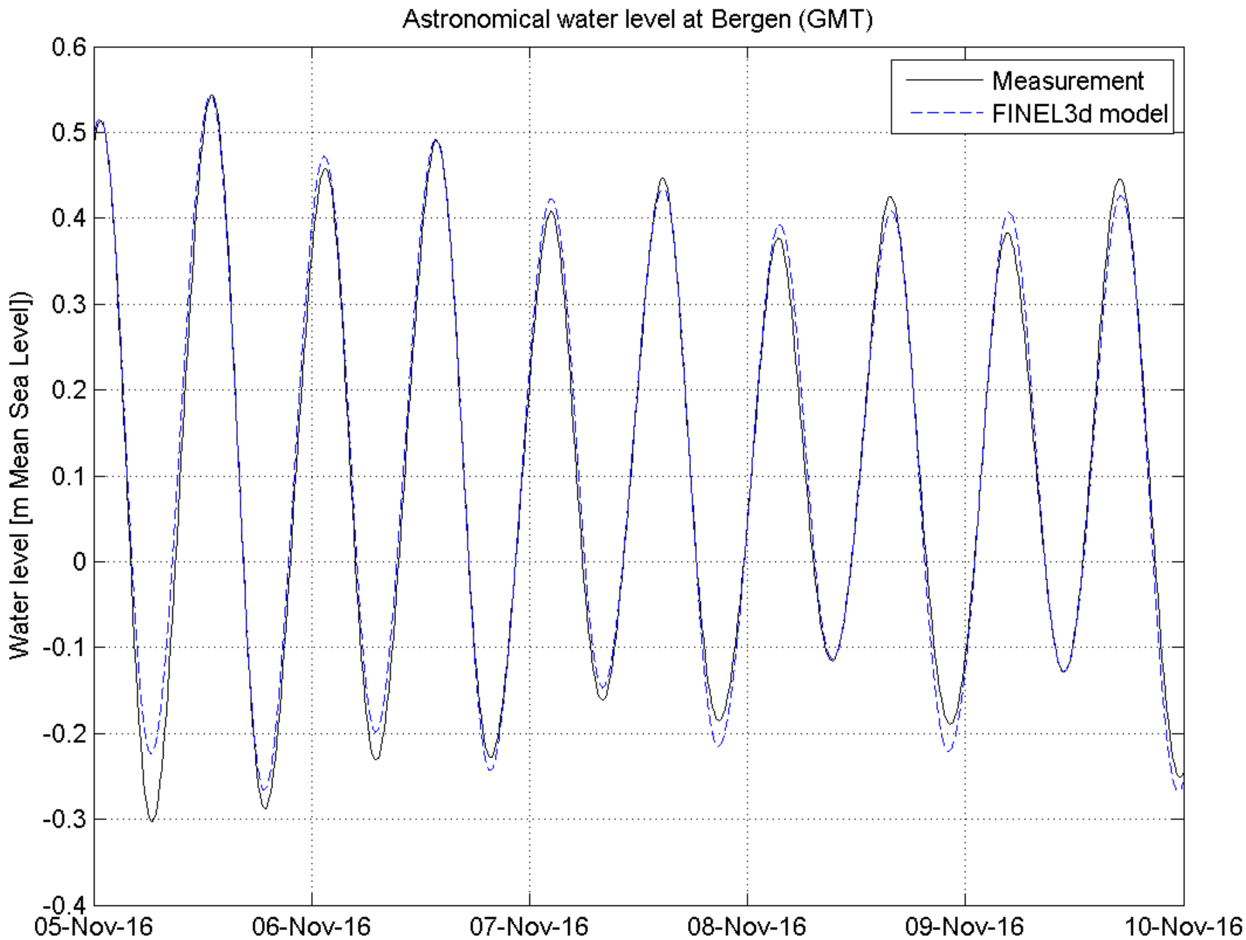


Figure 3.6: Water level comparison between measurement and FINEL3d model

3.7.3 Settings and sensitivity

The timestep of the numerical model is determined at 10 seconds. A higher timestep is numerical stable, but leads to unrealistic results. A lower timestep than 10 seconds leads to the same results.

Mixing is important in fjord systems. The estuarine circulation is dependent on the mixing coefficient. Generally the higher the mixing coefficient the higher the estuarine circulation. Several runs were carried out to investigate the sensitivity and to choose the right settings for the model. In the end a standard k-epsilon turbulence model was chosen with buoyancy effects.

A sensitivity analysis for the bottom and wall roughness revealed little or no sensitivity for the roughness coefficient.

The fresh water discharge is an important forcing in the model. To see the sensitivity the following plots show both the result of an average discharge (~300 m^3/s in Sørfjorden/Osterfjorden system) and a high rivier discharge (~900 m^3/s). The latter is equal to the peak fresh water input in May/June, during the snow melt. Figure 3.7 and Figure 3.8 show the surface flow for the average and high discharge respectively. The flow is directed to the sea; i.e. the normal estuarine circulation. Clearly visible is the influence of the fresh water discharge on the surface current. Generally with an average discharge the flow lies around 0.1 m/s in the middle of the fjord. With a high river discharge this increases to 0.2. Where the fjord is narrower the velocity increases to 0.3 m/s.

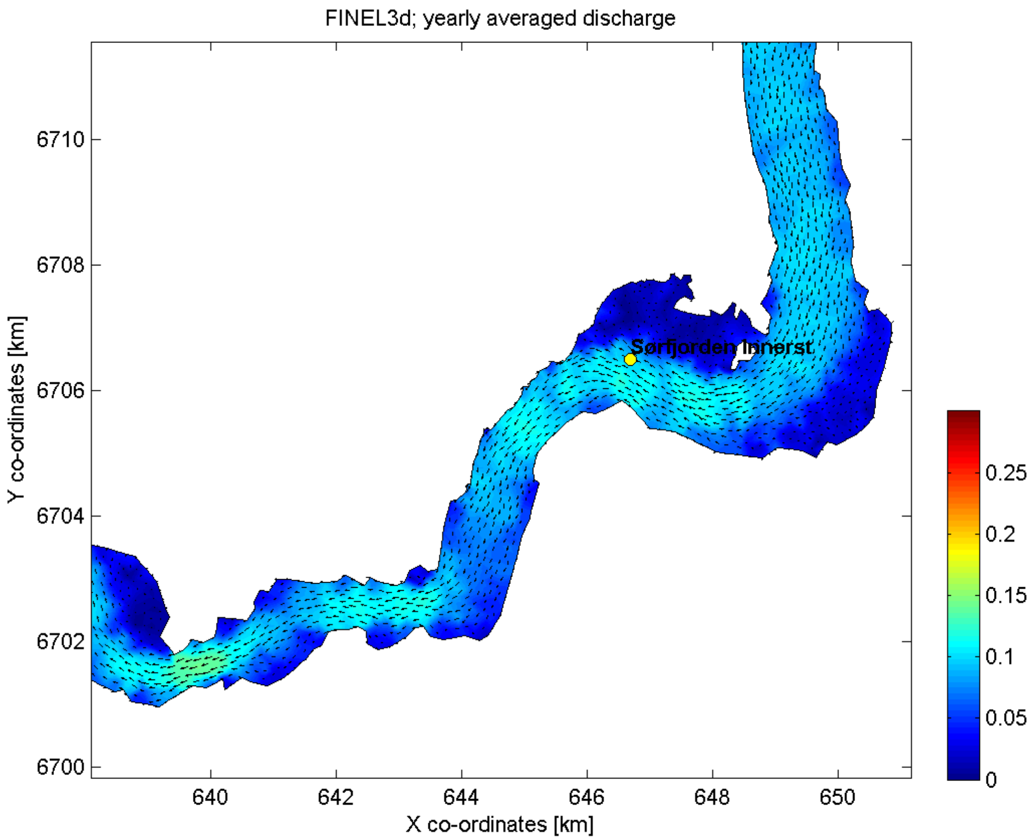


Figure 3.7: FINEL3d surface flow in Sørfjorden (m/s) with yearly average fresh water discharge (~300 m^3/s in Sørfjorden/Osterfjorden system)

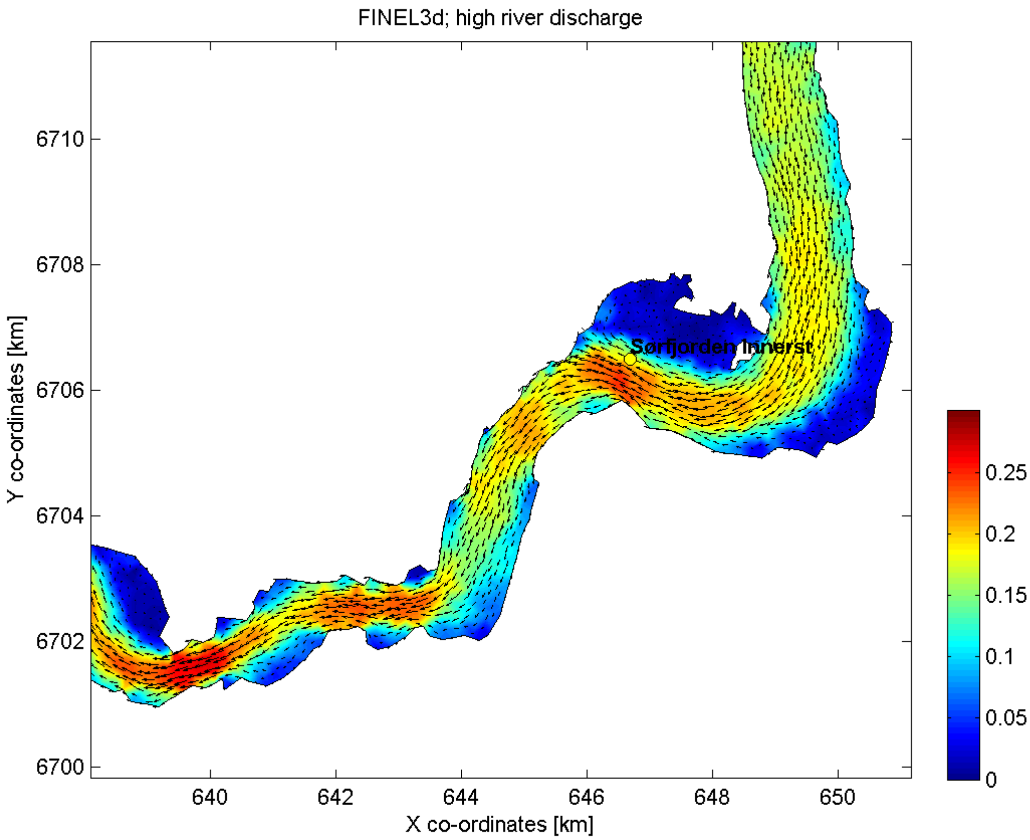


Figure 3.8: FINEL3d surface flow in Sørfjorden (m/s) with high fresh water discharge (~900 m^3/s in Sørfjorden/Osterfjorden system)

The model results at "Sørfjorden innerst" are compared with the measurement results as described in the previous chapter. The model results are compared for the period 6-9 November 2016, since this period shows a more or less "stable" flow pattern with a normal estuarine circulation. After November 11th the flow becomes too irregular and lies beyond the scope of this study.

Figure 3.9 shows the results of the model and measurements at 2m deep. Since the model has layers of 0.125m in the upper 10m, the exact depth can be used for comparison. The simulation with the average fresh water discharge shows good comparison with the average measured velocity (~7-8 cm/s). The peaks in the velocity measurement cannot be reproduced and is probably weather or discharge related (and this variation is not included in the model). The high river discharge gives a velocity close to 15 cm/s here. The direction of the flow is around 300 degrees in both the model and measurements. Figure 3.7 and Figure 3.8 clearly show why the velocity direction here is in a northwest direction.

Figure 3.10 shows the results at 45m depth. The current meter almost is zero here, but interestingly the direction of the current meter is directed in a southernly direction (180 degrees). The model also gives a southernly directed flow here (~200 degrees), with a small tidal variation. The explanation for this phenomenon is given in Figure 3.11, where a south-north crosssection through the fjord is taken from the model results. In the upper layer the 'normal' brakish water outflow can be seen with arrows in a net northward direction (300 degrees). Below this layer there is a return current visible in the model results with a net southward directed flow. This can be attributed to the curvature of the fjords here. The curvature of the fjords here make that there is upwelling and downwelling along the sides of the fjords and this creates a spiral flow. The southerly directed flow below the brakish layer is the result of that.

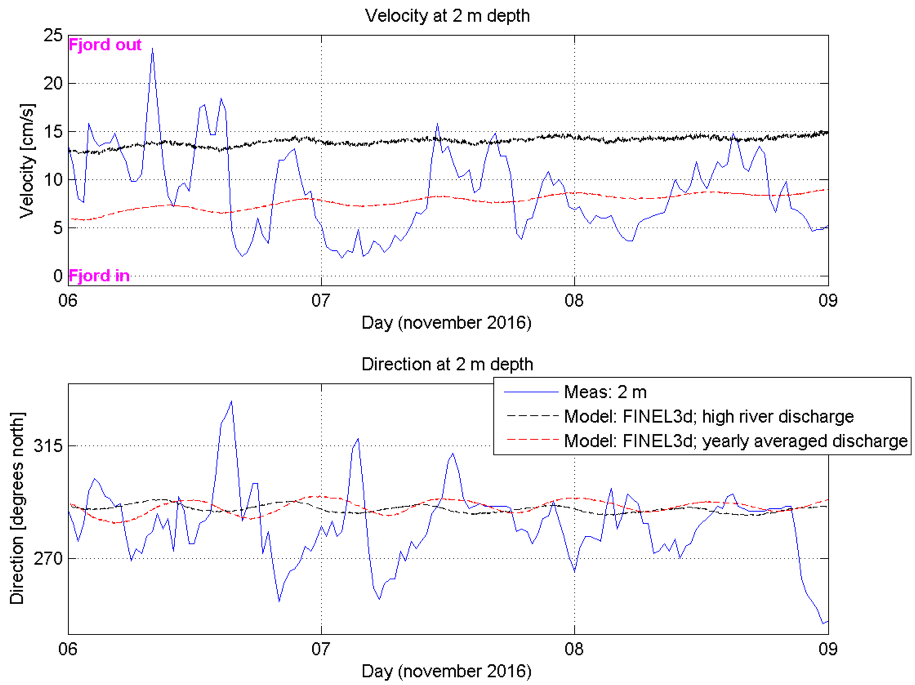


Figure 3.9: Velocity comparison between measurement and FINEL3d model at 2m depth

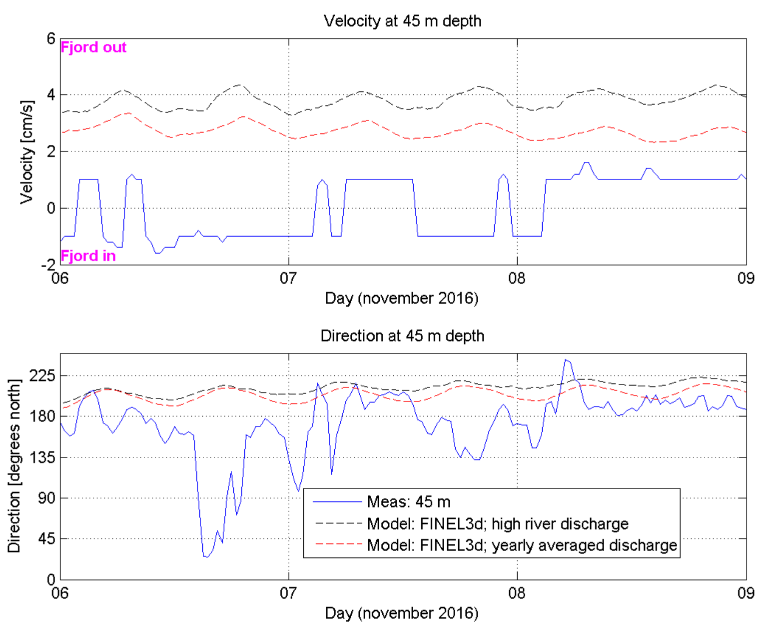


Figure 3.10: Velocity comparison between measurement and FINEL3d model at 45m depth

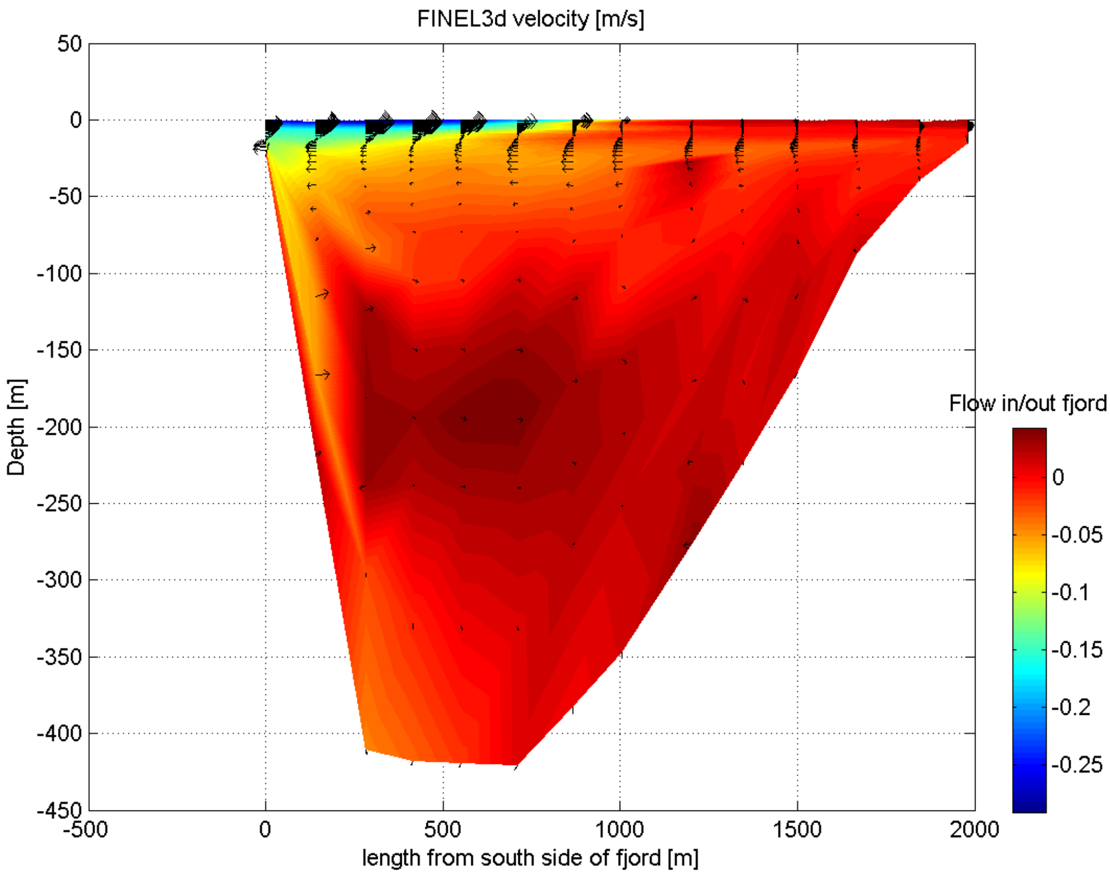


Figure 3.11: South-north crosssection through fjord at Bruvik from model results (and Sørfjorden innerst measurement location). Arrows indicate north (left-right)-south (right-left) and vertical flow; colors indicate east (negative)-west (positive) flow.

3.8 Conclusion

Conclusion from this chapter is that successfully a 3D hydrodynamic model has been set up that can capture the most important processes for the simulation of the hydrodynamics in Sørfjorden: tidal levels can be simulated correctly and the estuarine circulation can be captured correctly.

4 Scenario simulations

4.1 Introduction

This chapter describes the results of the scenario simulations in which fine sediment is released in the water and spread over time.

The following scenarios are defined:

1) Bruvik with the sediment source at -2m depth
2) Bruvik with the sediment source at -10m depth
3) Fossmark with the sediment source at -2m depth
4) Stanghella with the sediment source at -2m depth

See Figure 4.1 for the locations of the scenarios

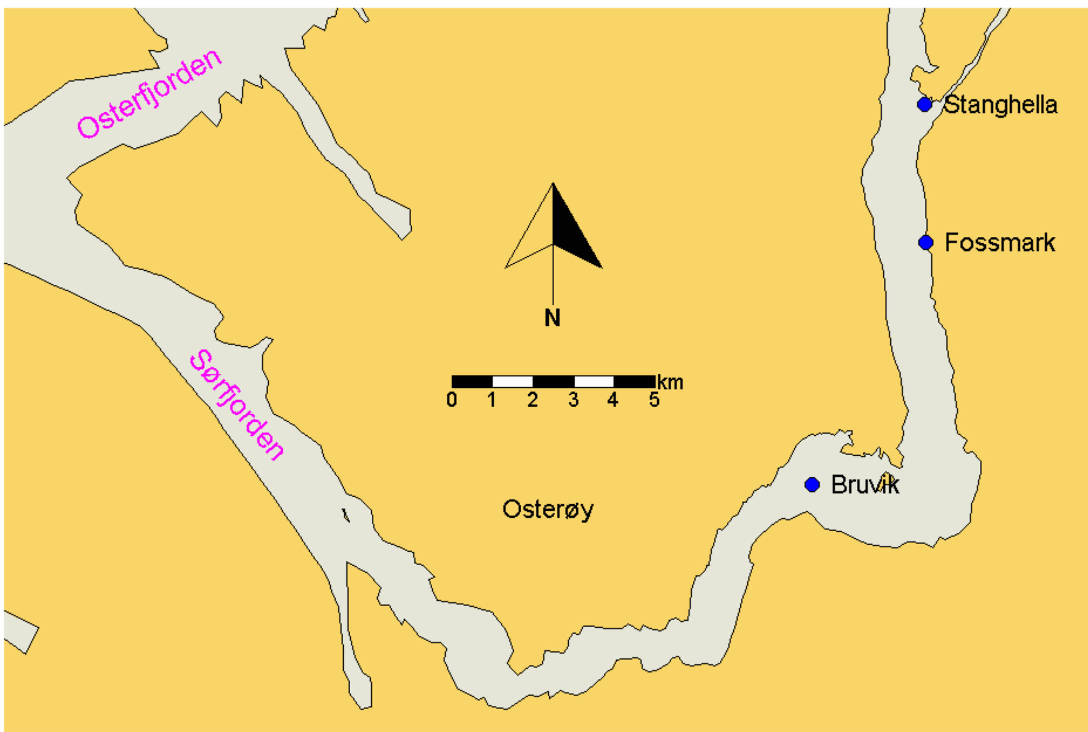


Figure 4.1: Overview scenario locations (blue dots)

Every scenario simulates both a silt and clay fraction. Silt is defined as sediment particles with a particle size between 2 and 63 µm, while clay is defined as particles less than 2 µm. The most important difference here is that the clay fraction has a smaller fall velocity in water. The fall velocity of silt is defined at 1 mm/s. The fall velocity of clay is set constant at 0.02mm/s according to Sutherland et al. (2014). Hereby is the assumption that silt and clay are not forming flocs, which would increase the fall velocity. According to Sutherland et al. (2014) flocculation of clay particles occurs in salinities over 10 ppt. Since it lies beyond the scope of this study to incorporate this into the model a constant fall velocity suffices at this moment. This assumption represents thus a maximum spreading situation of the silt and clay.

The sediment module works with settling and erosion (resuspension) according to the formulas of Krone (1962) and Partheniadis (1965). These formulas have been applied in many cases over the world and incorporated in many models for fine sediment.

The settings of the sediment module are chosen within realistic values. The settings are (Table 4.1):

Table 4.1: Settings of the sediment parameters

Parameter	Symbol	Value	Remarks
Settling velocity sediment silt fraction	$w_{s\ silt}$	1 mm/s	No flocculation assumed
Settling velocity sediment clay fraction	$w_{s\ clay}$	0.02 mm/s	No flocculation assumed
Erosion flux	M	0.001 m/s	In case of resuspension of sediment from bottom
Critical shear stress for deposition	Tau_s	0.75 Pa	
Critical shear stress for erosion	Tau_e	0.25 Pa	
Density of sediment	ρ_{sed}	1400 kg/m^3	Only relevant when sediment settles at bottom
Porosity	n	0.3	Only relevant when sediment settles at bottom

At the moment of writing of this report no detailed information is available of how much silt and clay is released during the dumping of the rock. Therefore the same values for all scenarios are defined, so the scenarios can be compared qualitatively. Since the formulas are linear, the outcomes can be scaled at a later moment in time, when more information is available about the amount that will be released. For now the following amounts are defined for all scenarios:

- Silt: constant release of **1 kg/s** at source
- Clay: constant release of **0.1 kg/s** at source

The scenarios are carried out with a constant high river discharge, as described in the previous chapter. The outcomes are shown after a continuous release of around 50-120 hours. At this stage the outcomes are mostly stationary, i.e. they don't change much anymore over time. Tidal filling and emptying of the fjord is also included in the model runs.

4.2 Scenario 01: Bruvik at -2m and Scenario 02: Bruvik at -10m depth

In line with the measurement campaign and the calibration the first 2 scenarios are chosen at the measurement location "Sørfjorden innerst". In the rest of this chapter the name "Bruvik" is used for the scenario simulations at this location.

Figure 4.2 shows the results of the maximum concentration over the depth for Scenario 01 and 02 after 51 hours. This means that over the entire depth the maximum concentration is determined per 2D gridpoint at that time. This tells how the silt is spread in horizontal direction, but does not give information how it is spread in the vertical direction. The silt concentration generally stays much closer to the source for both scenarios than the clay fraction. The clay fraction settles less fast to the bottom and therefore it is carried away further due to the higher currents in the upper water column. For Scenario 01 the sediment is carried away further than Scenario 02 because at -2m the currents are higher than -10m. The silt fraction of Scenario 02 spreads much more equal around the source than Scenario 01, because the silt is also affected by the landward directed flow below the brakish layer. The clay concentration of Scenario 01 is carried away towards the northern side of the fjord; there it mostly follows the outward directed flow. A small part is deflected land inwards, due to the backflow at the northern shore at Bruvik (also visible in Figure 3.8). In Scenario 02 the clay fraction is more spread over the entire width of the fjord.

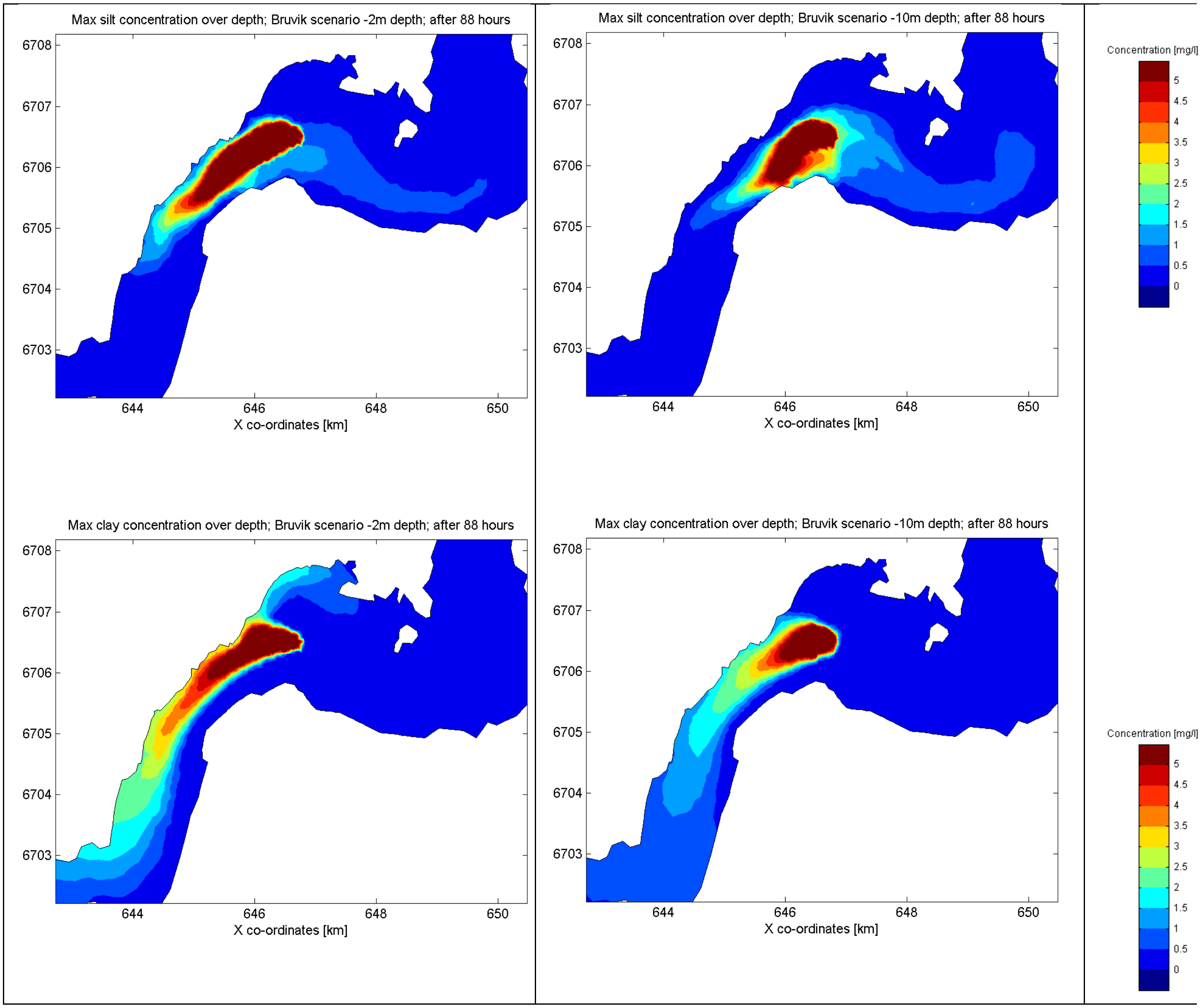


Figure 4.2: Maximum concentration over depth; Scenario 01: Bruvik -2m and Scenario 02: Bruvik -10m

Figure 4.3 defines a 15.5 km long cross-section through Sørfjorden. Figure 4.4 shows the silt and clay concentrations along this cross-section for Scenario 01 and 02. The silt that is released from the source first is advected with the seaward directed currents of the toplayer. While the sediment sinks further to around 15 meters the direction of the flow changes and the sediment is transported landward. Because the sediment is released at a lower location Scenario 02 shows less sediment transport in the direction of the sea than Scenario 01. The silt settles within a distance of 4 to 5 km from the release location on the bottom (Figure 4.5). Silt released at -2m (Scenario 01) settles more seaward to the bed than silt that is released at -10m (Scenario 02).

The clay fraction has a small settling velocity and stays therefore for a long time in a thin layer in the upper surface of the water column (Figure 4.4). Because the velocities for Scenario 02 are smaller than Scenario 01 more clay settles from this upper layer to the deeper layer. This results in higher concentrations for Scenario 02 in the deeper part of the fjord (km 4-10 in Figure 4.4). Here it will also settle to the seabed (Figure 4.6), while for Scenario 01 more clay is further transported in seaward direction.

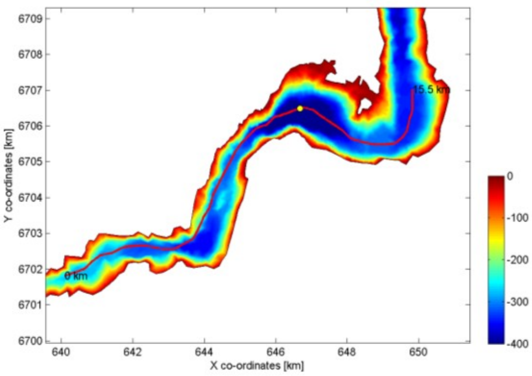


Figure 4.3: Location of cross-section of Figure 4.4

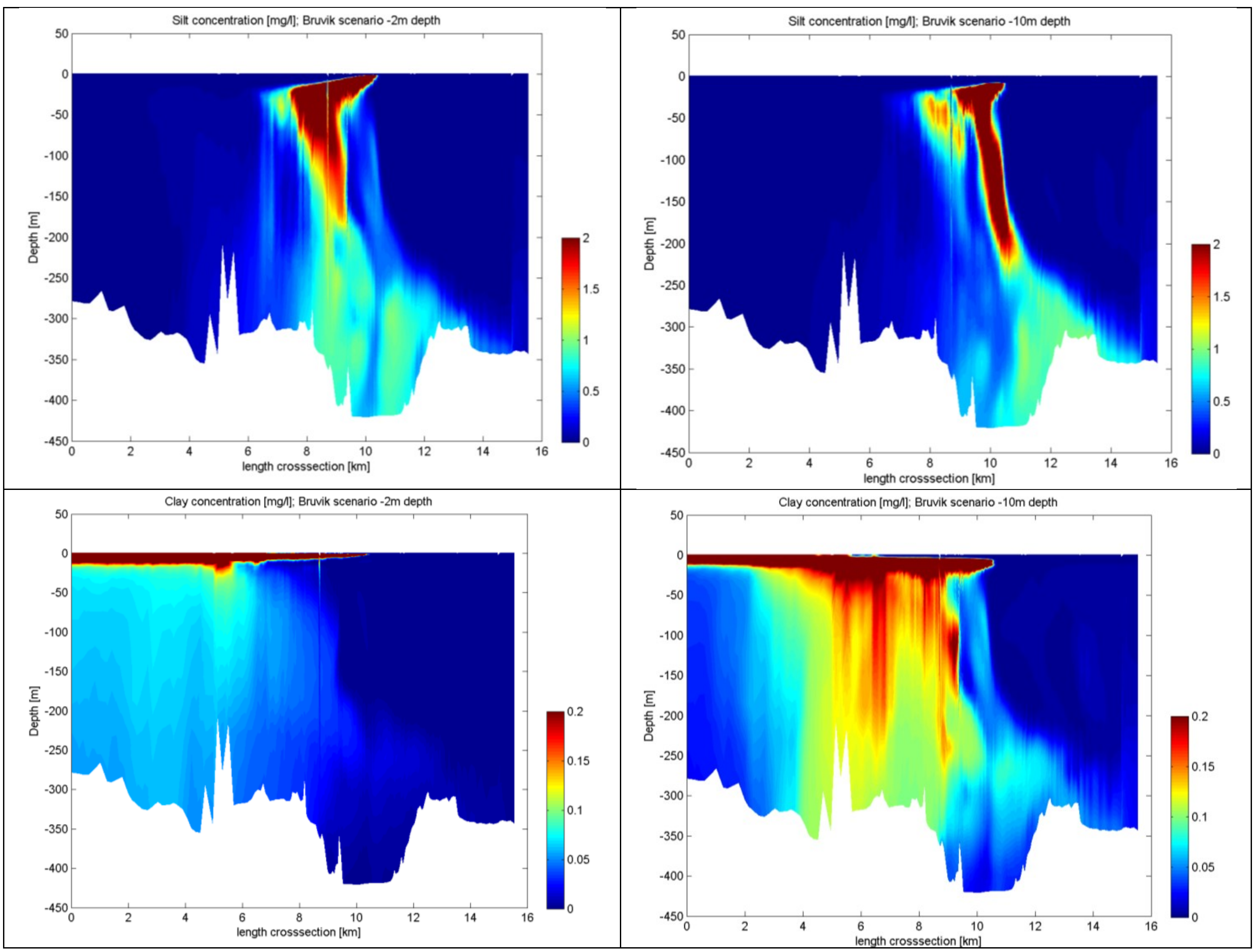


Figure 4.4: Cross-section with silt and clay concentrations; Scenario 01: Bruvik -2m and Scenario 02: Bruvik -10m

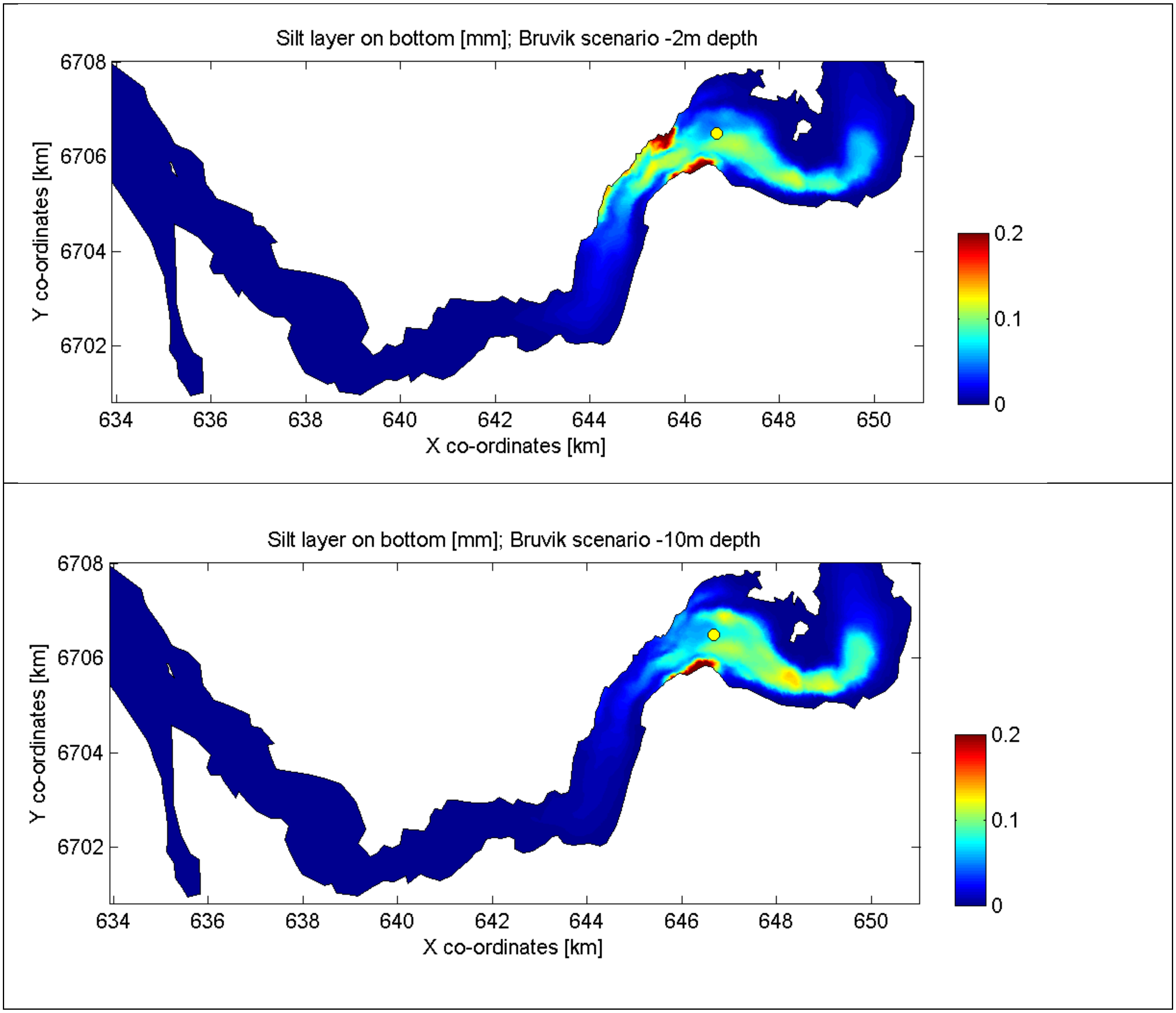
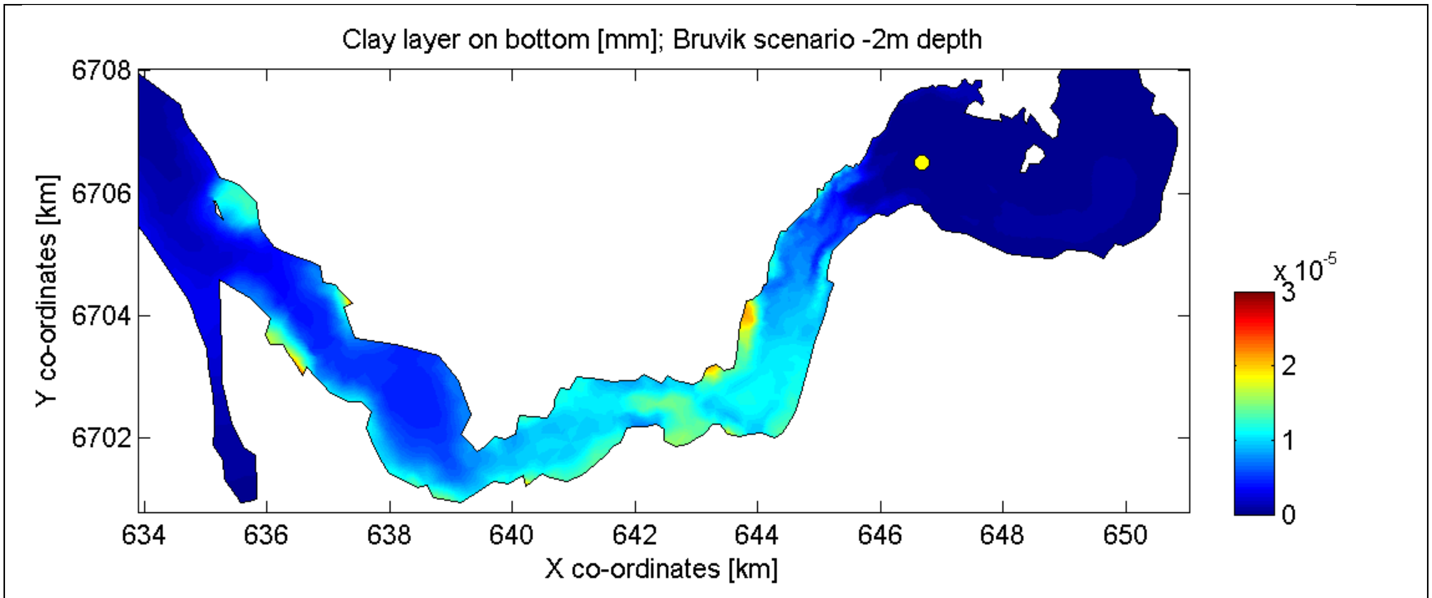


Figure 4.5: Silt layer thickness on bottom [mm]; Scenario 01: Bruvik -2m and Scenario 02: Bruvik -10m



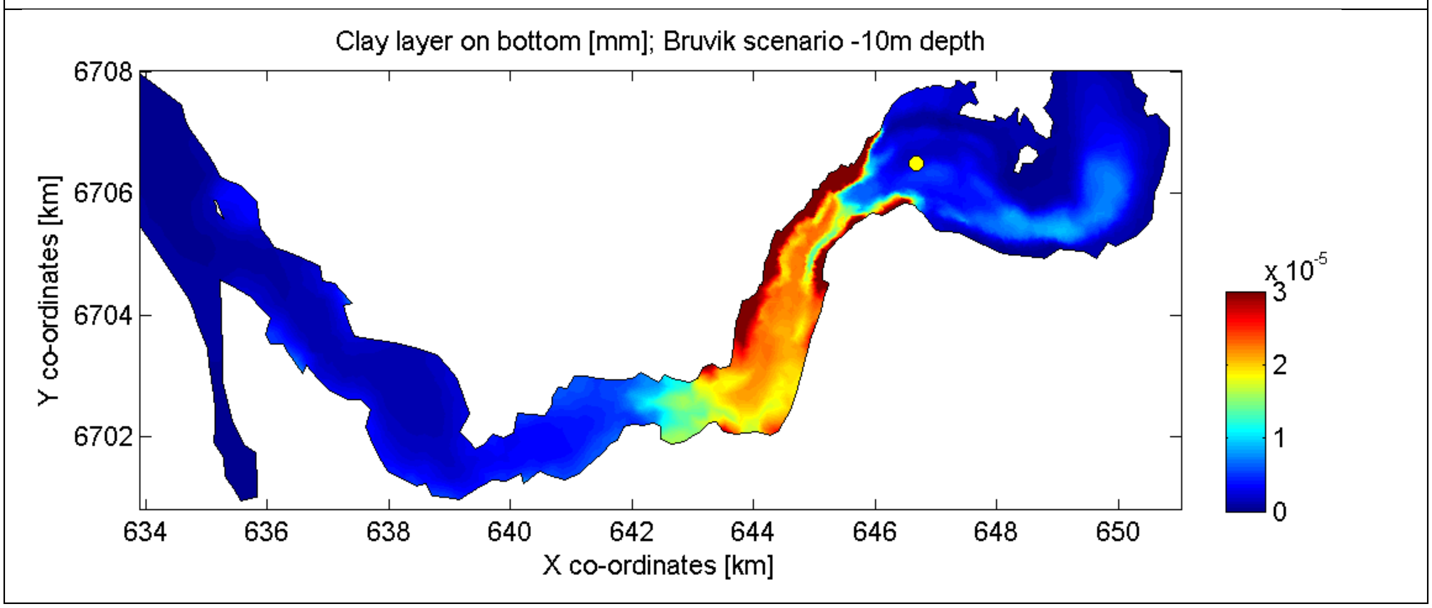


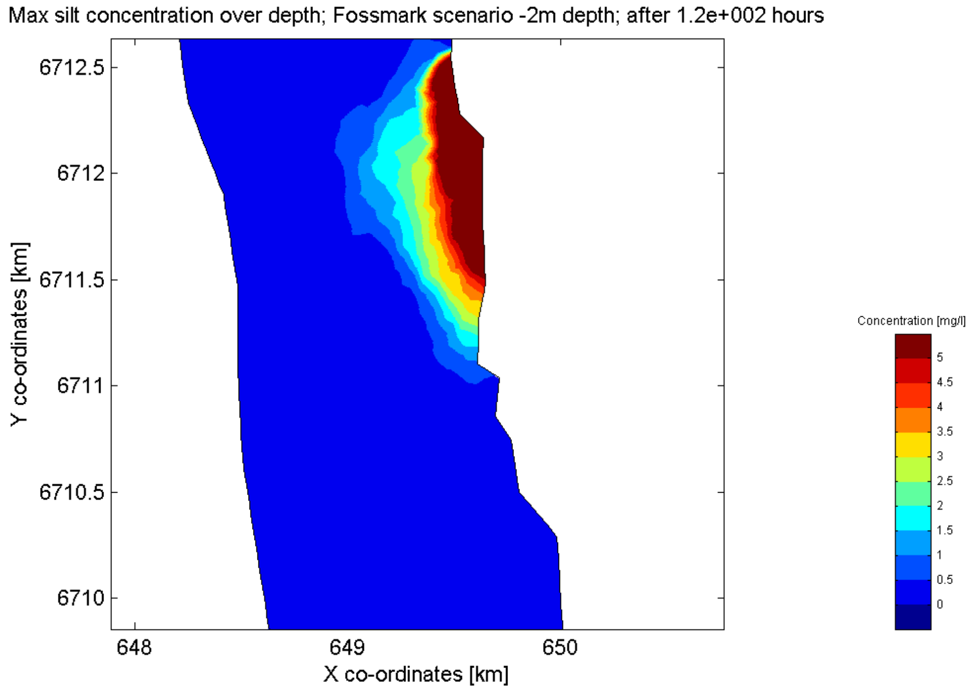
Figure 4.6: Clay layer thickness on bottom [mm]; Scenario 01: Bruvik -2m and Scenario 02: Bruvik -10m

4.3 Scenario 3: Fossmark -2m

Figure 4.7 shows the maximum concentration over the depth of the Fossmark scenario. The source here is at -2m depth, so the sediment is carried away by the brakish toplayer in the seaward (in this case southerly) direction. The sediment stays attached to the eastside of the fjord. The clay is carried away further by the current than the silt fraction.

Figure 4.8 defines a cross-section at the eastside of the fjord. Figure 4.9 shows the silt and clay concentration along this cross-section. Silt that is released first flows with the brakish outflow in seaward direction. At around -15m depth the flow and the sediment transport direction reverses. The silt transport is now transported landward, although the velocity is less strong. Most silt settles within 2km from the source at the eastside of the fjord. A small part settles further in the deeper fjord.

A large part of the clay fraction stays in a thin layer in the upper water for a considerable amount of time (Figure 4.9). It settles mostly in the shallow areas at the eastern side of the fjord, but a considerable amount also is transported further seaward.



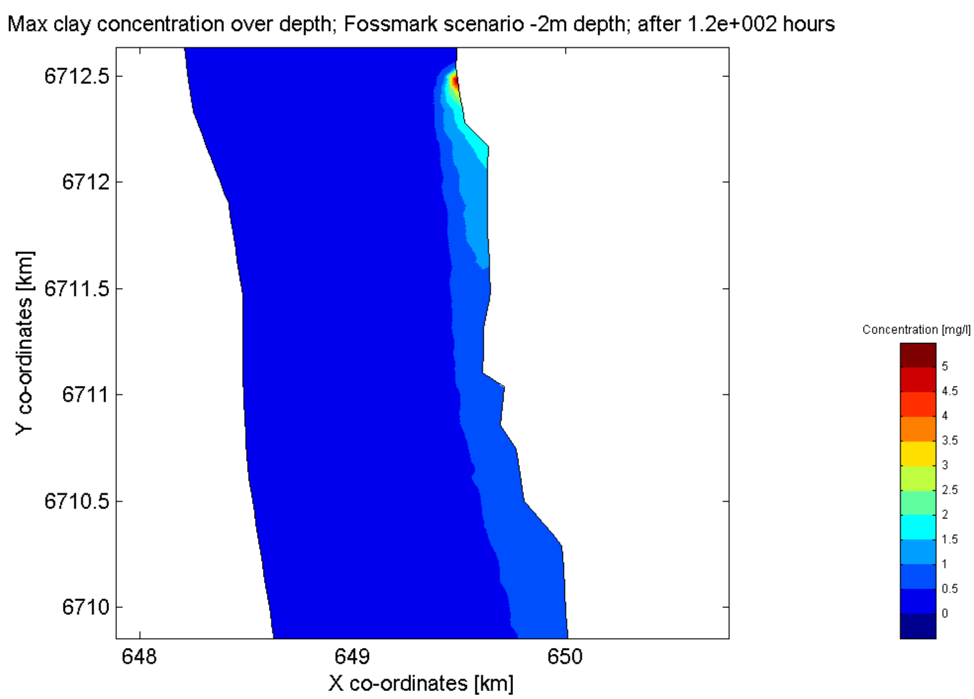


Figure 4.7: Maximum concentration over depth; Scenario 03: Fossmark -2m

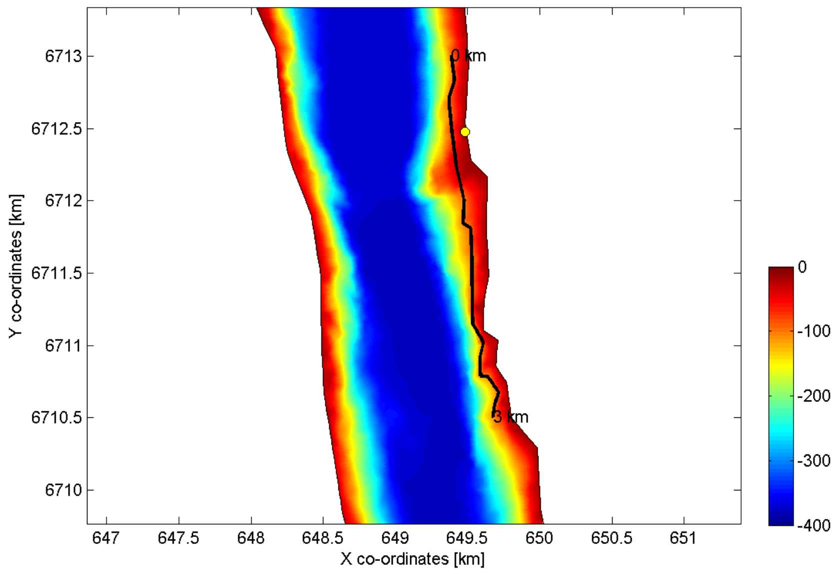


Figure 4.8: Location of cross-section of Figure 4.9

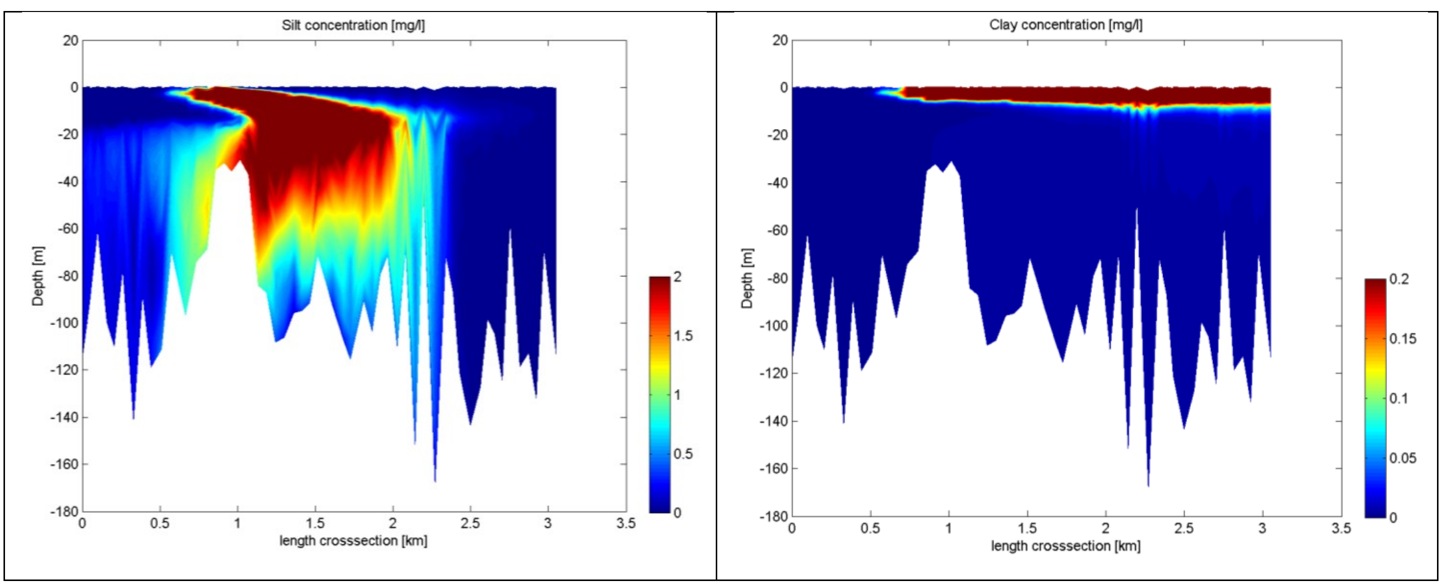


Figure 4.9: Cross-section with silt and clay concentrations; Scenario 03:Fossmark -2m

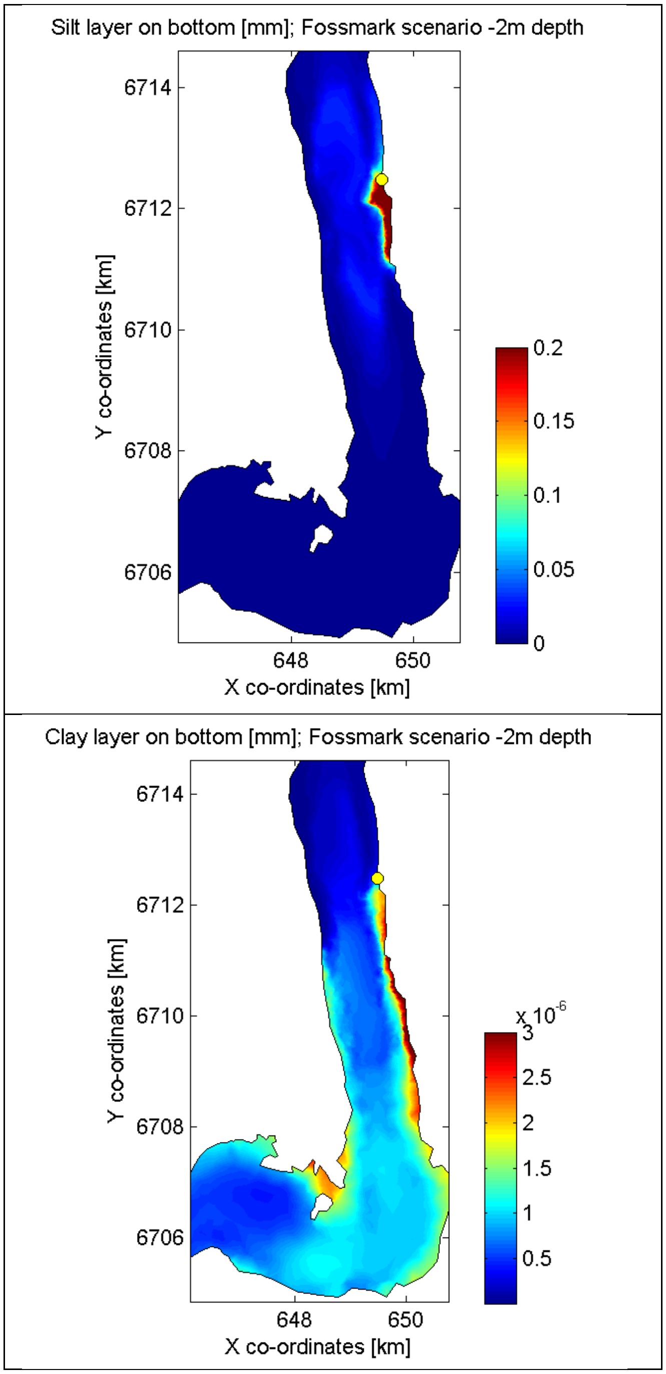


Figure 4.10: Silt and clay layer thickness on bottom [mm]; Scenario 03: Fossmark -2m

4.4 Scenario 4: Stanghelle

At Stanghelle there is a shallow area in the fjord around 2m deep. Possibly a part of the rock will be placed here. This simulation is to show the possible effect of the spreading of the fine sediments due to that infilling. Figure 4.11 shows the maximum concentration over the depth for this scenario, while Figure 4.12 shows the sediment thickness layer. The concentration and thus the build-up of sediment on the bed stays close to the source. This is explained by two facts:

1) The velocities here are too low to keep the sediment in suspension. With only 2m deep the sediment settles quickly to the bottom.

2) Due to the fresh outflow of the river and saline water of the fjord close by, there is a small estuarine circulation here in the mouth of the river. This estuarine circulation catches the sediment in its vertical cell and creates a so called Estuarine Turbidity Maximum (ETM). This is a well known phenomenon of large estuaries like the Scheldt, Elbe or other estuaries and is attributed to the fresh outflow and the salt backflow in the lower layer.

Whether this happens in reality remains to be seen. Bed level information here is too scarce to make a good bathymetry for the model, therefore the flow velocities at the source might not be good enough.

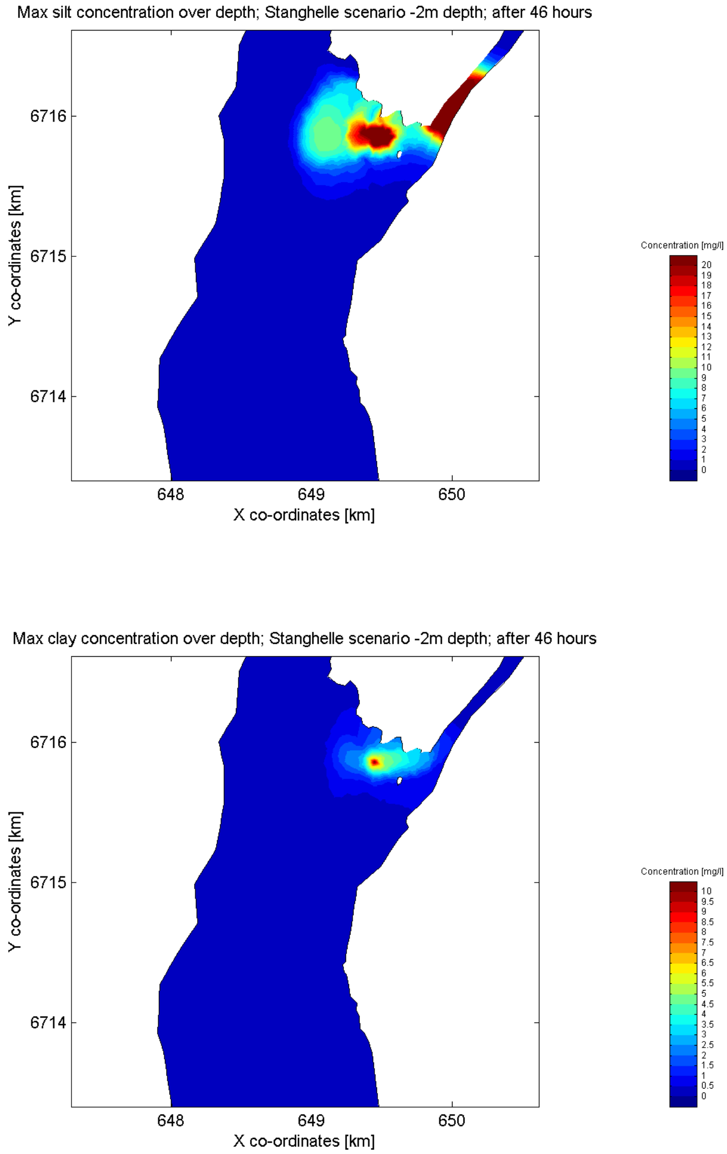
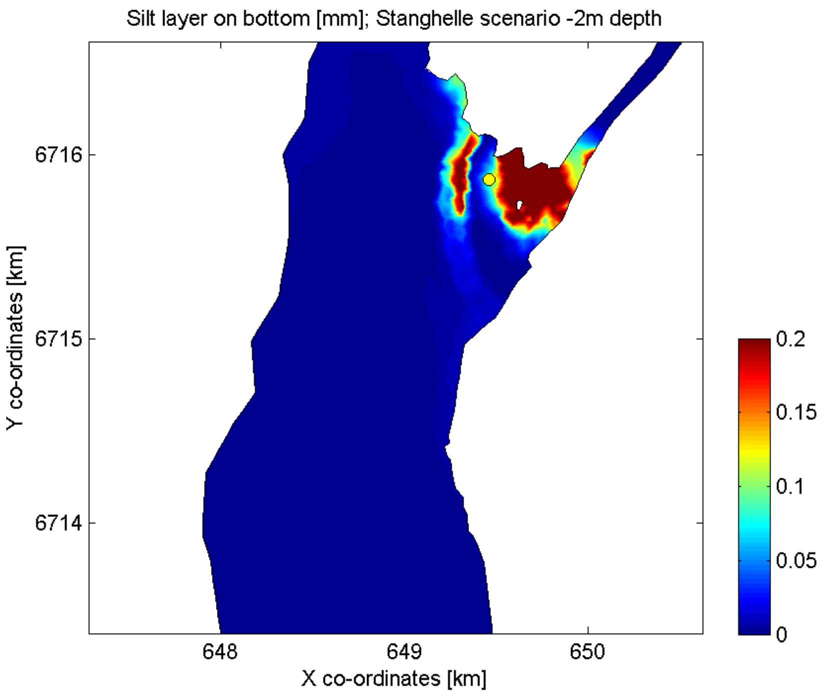


Figure 4.11: Maximum concentration over depth; Scenario 03: Stanghelle -2m



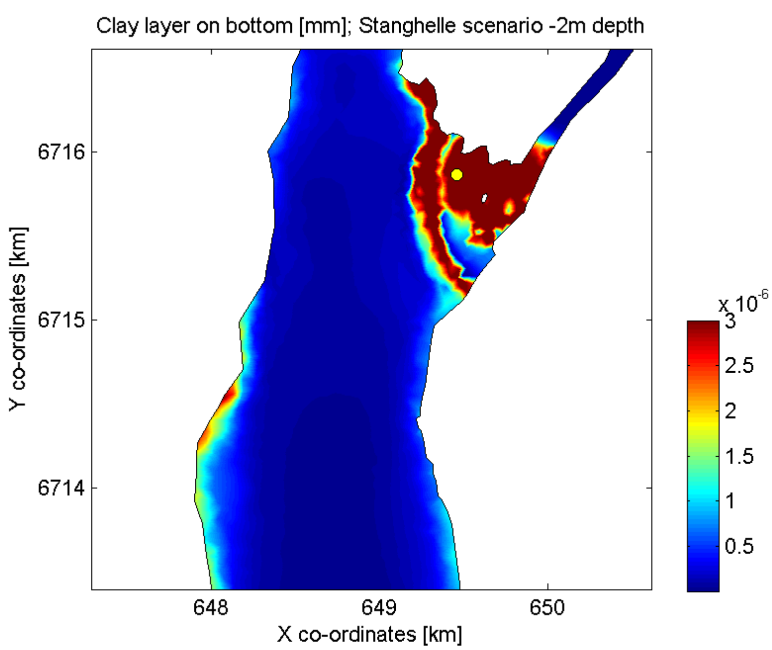


Figure 4.12: Silt and clay layer thickness on bottom [mm]; Scenario 03: Fossmark -2m

5 Conclusions and recommendations

5.1 Conclusions

In this report a study is performed on the spreading of fine sediment due to rock dumping in Sørfjorden (near Osterøy) for the construction of the new E16 and rail connection between Indre Arna and Voss.

A 3D finite element model called "FINEL3d" has been set up for the entire fjord area near Bergen, the grid is refined in 3 steps to have a maximum resolution near the area of interest of 50m in horizontal direction and vertical layers of 0,125m in the upper 10m where the largest salinity gradients occur.

The calibration of the flow measurements in the upper layer shows a good comparison in both magnitude and direction. The model shows a vertical velocity cell that can be attributed to the bending of the fjord here. This is confirmed by the measurements.

Four scenario simulations with a continuous release of sediment (silt and clay) are carried out. The scenarios are:

1) Bruvik with sediment source at -2m depth
2) Bruvik with sediment source at -10m depth
3) Fossmark with sediment source at -2m depth
4) Stanghelle with sediment source at -2m depth

The lessons that are learned from these scenario runs are:

- It is better to release the sediment as deep as possible (Scenario 1 versus Scenario 2).
- The clay fraction can be carried away over long distances (many km), while silt remains relatively close to the source (Scenario 1, 2 and 3)
- The sediment stays relatively close to the side of the fjord when it is transported here due to the current (Scenario 1) or when it is released there (Scenario 3).

5.2 Recommendations

- The results of the simulations should be adjusted to the actual release amount of sediment if there is more information available about this. The simulations do not need to be carried out again, since the results of the outcomes are scalable, i.e. if the release of sediment is 10kg/s instead of 1kg/s, the concentrations of the simulations can be multiplied with a factor 10. At that stage the results should be interpreted quantitative and should be concluded if the concentrations pose potential problems for ecology and other user functions of Sørfjorden.
- The scenario runs are carried out with a normal estuarine circulation without meteorological effects. In reality the flow reverses often due to these meteorological effects. It is recommended to include this in further scenario runs.

6 References

Asplin, L., Sandvik, A.D., Albretsen, J (2014), Strømhastigheter ved lokalitet Skorpo I Hardangerfjorden 10. August 2014, samt generelt om strøm, Havforskingsinstituttet

Børsheim, K., Tveranger, B., Johnson, G.H., (2002) Miljøvurdering av oppdrettslokaliteten Blom I Sørfjorden i Osterøy commune, Rådgivende Biologer rapport 617.

Elliot A.J., Wang, D.P., (1978), The effect of meteorological forcing on the Chesapeake Bay: the coupling between an estuarine system and its adjacent coastal waters. Hydrodynamics of Estuaries and Fjords. Proceedings of the 9th Int. Colloqium on Ocean Hydrodyn.

Johannessen, P., Sætre, R., Kryvi, H., Hjelle, H., (2010) Bergensfjordene, natur og bruk, Havforskingsinstituttet, Uni Research, Universitetet I Bergen, Bergen kommune.

Johnsen, G.H., Furset, T.T. (2016), Overvåking av fjordområdene I Hordaland. Vannkvalitet 2014-2015, Rådgivende Biologer rapport 2231.

Krone, R.B. (1962), Flume studies of the transport of sediment in estuarial shoaling process. University of California.

Labeur, R.J., (2009), Finite element modeling of transport and non-hydrostatic flow in environmental fluid mechanics, PhD thesis, Technical University Delft.

Labeur, R.J., Wells, G.N., (2007), A Galerkin interface stabilisation method for the advection-diffusion and incompressible Navier-Stokes equations, Computer methods in Applied Mechanics and Engineering 196, pp. 4985-5000.

Labeur, R.J., Wells, G.N., (2009), Interface stabilized finite element method for moving domains and free surface flows, Computer methods in Applied Mechanics and Engineering 198, pp. 615-630.

Labeur, R.J., Wells, G.N., (2010), Energy stable and momentum conservation interface stabilised finite element method for the incompressible Navier-Stokes equations, SIAM Journal of Scientific Computations, 34(2), pp. A889–A913.

Mohn, H., (2016) Sørfjorden, skyggerelief 1:25000, bunnkart fra oppmåling med multistråleecholodd, Nearshore Survey AS.

NIVA, (2013) Resipientundersøkelse i Sandfjorden i Rogaland og modellering av partikkelspredning fra Norsk Stein sitt anleg. Rapport L.NR. 6523-2013

Partheniades, E.A. (1965), Erosion and deposition of cohesive soils. J. of Hydr. Div. Vol 91., no. HY 1.

Sutherland, B.R., Barrett K.J., Gingras M.K., (2014) Clay settling in fresh and salt water. Envoron Fluid Mech. Doi 10.1007/s10652-014-9365-0.

Talstra, H., (2016) User manual FINEL3d, Svašek Hydraulics.

Tveranger, B., (2000a) Jakta fiskeoppdrett AS vurdering av strømmålingane ved Olsnestangen I Sørfjorden, Sunnhordland Havbruksring

Tveranger, B., (2000b) Oster fjordfarm AS vurdering av strømmålingane ved Bruvik i Sørfjorden, Sunnhordland Havbruksring

Tveranger, B., Brekke, E., Johnsen, G.H., (2001a) Straummålingar for Bognøy Fiskeoppdrett AS ved Sandvik I Sørfjorden, Vaksdal commune, Rådgivende Biologer rapport 506.

Tveranger, B., Brekke, E., Johnsen, G.H., (2001b) Miljøvurdering av oppdrettslokalitet ved Hamre I Osterfjorden I Osterøy commune, Rådgivende Biologer rapport 510.

US Department of the interior; Bureau of Land management (2002). Renewal of the federal grant for the trans-alaska pipeline system right-of-way. BLM/AK/PT-03/005+2880+990.