Fortescue Future Industries - FFI

Seawater Cooling Concept Report

Seawater Cooling Concept Report (Variation order)

NOR1101-0200-PR-REP-0001

NOR1101-0200-PR-REP-0001

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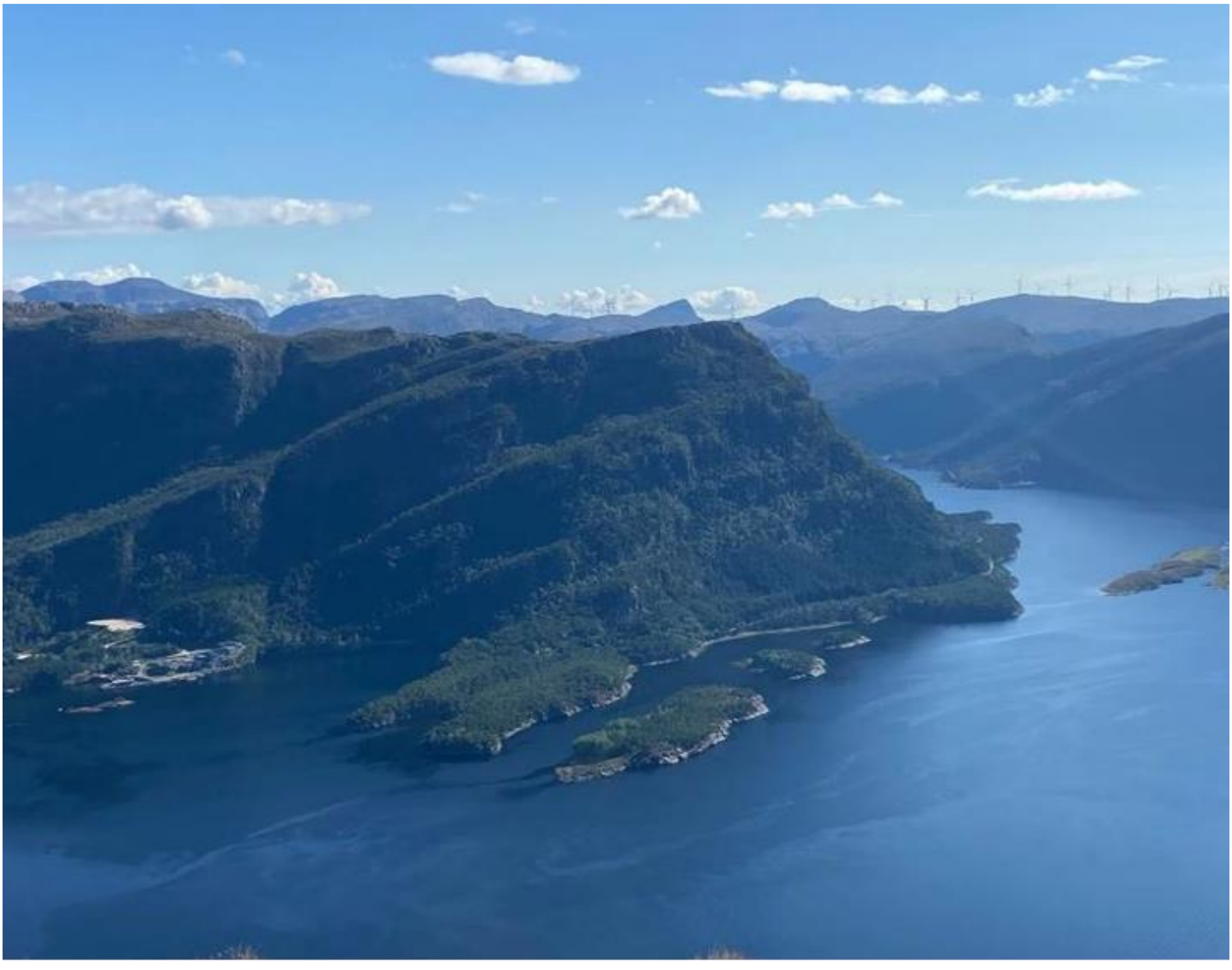

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Summary

As a part of the planning process for utilization of cooling water from the sea, Norconsult was assigned to evaluate that good international industry practice and International Finance Corporation/World Bank Group (IFC) requirements is achieved for both intake velocities and discharge temperature. Dispersion modelling was performed to study how discharge of cooling water can affect sea water temperatures followed by a marine biology assessment on the effects on the marine natural environment.

The area affected by a temperature increase of 3° C (IFC/World Bank Criteria) is in the pelagic zone at about 35-45 m depth within 7 m in horizontal distance from the discharge point. The organisms living in this zone are pelagic zooplankton and fish with the ability to avoid this area. The potential negative effect of the temperature increase due to discharge water is therefore very small. And the technical solution is thusly considered to follow good international industry practice and IFC requirements for impact on the marine environment and organisms.

In this Cooling Concept Study the intake and discharge lines for seawater has been optimized to reduce the impact on the marine environment. This have been achieved by outlining design principles that reduce intake speed and the intake is relocated to a site with more advantageous seabed conditions.

The results and conclusions are valid for the prerequisites given in this report. If major changes in intake and discharge fluxes, dimensions and placement of pipelines or temperatures and constituents of discharge water are planned a new assessment should be performed.

1 Introduction

This report assimilates the findings from the work packages related to an improved solution for sea water cooling. The included work encompass data from baseline surveys, public databases and engineering undergone in the prefeasibility study (PFS). Marine Biology assessments and dispersion models are used to document the results.

As a part of the planning process for utilization of cooling water from the sea, Norconsult was assigned to evaluate that good international industry practice and IFC (IFC Word Bank Group Environment, Health, and Safety Guidelines - General EHS Guidelines - wastewater and ambient water quality) requirements for both intake velocities and discharge temperature criteria will be achieved. Considerations included are: That the temperature of cooling water prior to discharge does not result in an increase greater than 3° C of ambient sea temperature at the edge of a scientifically established mixing zone which is based on ambient water quality, receiving water use, marine habitats, and assimilative capacity.

Solutions to get the intake speed down to 0.15 m/s aligned with good international industry practice is also assessed and commented on. Based on a PFS study of intake and discharge pipelines and further considerations within this assignment, dispersion modelling was performed to study how discharge of cooling water can affect sea water temperatures followed by a marine biology assessment on the effects on the marine natural environment.

As part of this additional work within the cooling concept, the longitudinal profile of intake and discharge lines for cooling water was drawn up. The report also includes a description of the principle for the intake and discharge arrangement and the principle of securing the pipes in the landfall area at Holmaneset.

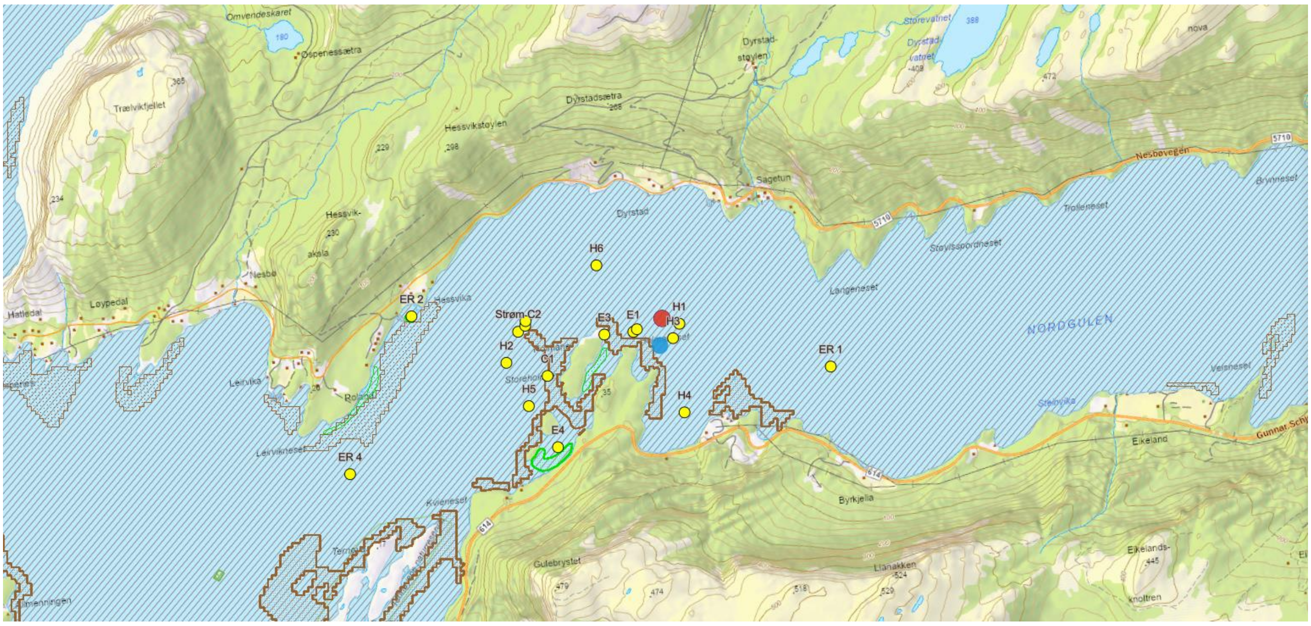


Figure 1. Overview of the project area with intake (red dot), discharge point (blue dot) and hydrography stations (yellow dots). Brown areas indicate kelp distribution, green areas indicate eelgrass meadows and the grey stippled area covering the whole fjord indicates that there is cod and other fish that use the area for spawning.

2 Pipelines for intake and discharge of cooling water

2.1 Pipeline dimensions and depths of intake and discharge

As stated in the Prefeasibility Phase Report, Doc. No. NOR1101-0000-EG-REP-0002, rev. A, the outcome of the cooling system evaluation was that seawater cooling will be the optimal solution in terms of overall cost and footprint requirements. The seawater cooling system consists of an open loop comprising 3 x 50% intake lines and 3 x 50% discharge lines. A pumping station where seawater is pumped from a self-displacement well through heat exchangers, connects the open loop with two closed cooling water loops, one low temperature loop and one high temperature loop. Only two of the three pipes for intake and discharge will be used simultaneously, the third is for redundancy and maintenance.

As described in the Cooling System Evaluation Report, Doc. No. NOR1101-0220-PR-REP-0001, each of the 3 seawater intake pipes has an outer diameter of Ø1400 and the material is PE100 SDR13.6. The intake depth is approximately 80 m. At this depth there is a low growth of algae, and no chemical injection is envisaged for the seawater cooling system. After exiting the seawater heat exchangers, the seawater from the two closed loops is mixed and discharged with elevated temperature through 3 x 50% discharge pipes. Treated and untreated waste- and reject water from the site shall be combined with cooling water discharge, in order to avoid many small discharges. However, the amount is marginal in relation to the amount of cooling water; only approx. 31 m3/h reject water compared to 11,800 m/h cooling water, i.e. 0.2% of the cooling water quantity. For more information, see the Wastewater Management Strategy (NOR1101-0200-WM-STR-0001).

Each of the discharge pipe size has an outer diameter of Ø1000 and the material is PE100 SDR13.6. The discharge depth is approximately 40 m. The temperature increase of the seawater across the heat exchangers is set to approximately 12K.

The flowrate of seawater is approximately 11 800 m^3/h for both loops combined.

All pipes are assumed to be held down by prefabricated concrete weights at regular intervals.

2.2 Pipeline routes

The drawings NOR1101-0600-PP-DPP.0001.002 (rev. 1) and NOR1101-0600-PP-DPP.0001.004 (rev. A) show the plan and longitudinal profile of the intake and discharge lines, respectively.

In the revision 1 of the plan drawing NOR1101-0600-PP-DPP.0001.002 the intake route has been changed since rev. 0 of the drawing to get a better longitudinal profile, i.e. avoid the steepest slopes on the seabed. The drawing also shows a mutual distance between the inlet pipelines of approximately 10 m and between the outlet pipelines of approximately 35 m. The length of each intake line is approx. 300 m, and the length of each discharge line is approx. 140 m. Horizontal distance between the nearest intake and discharge line is approx. 100 m.

The figure below shows the proposed pipeline routes:

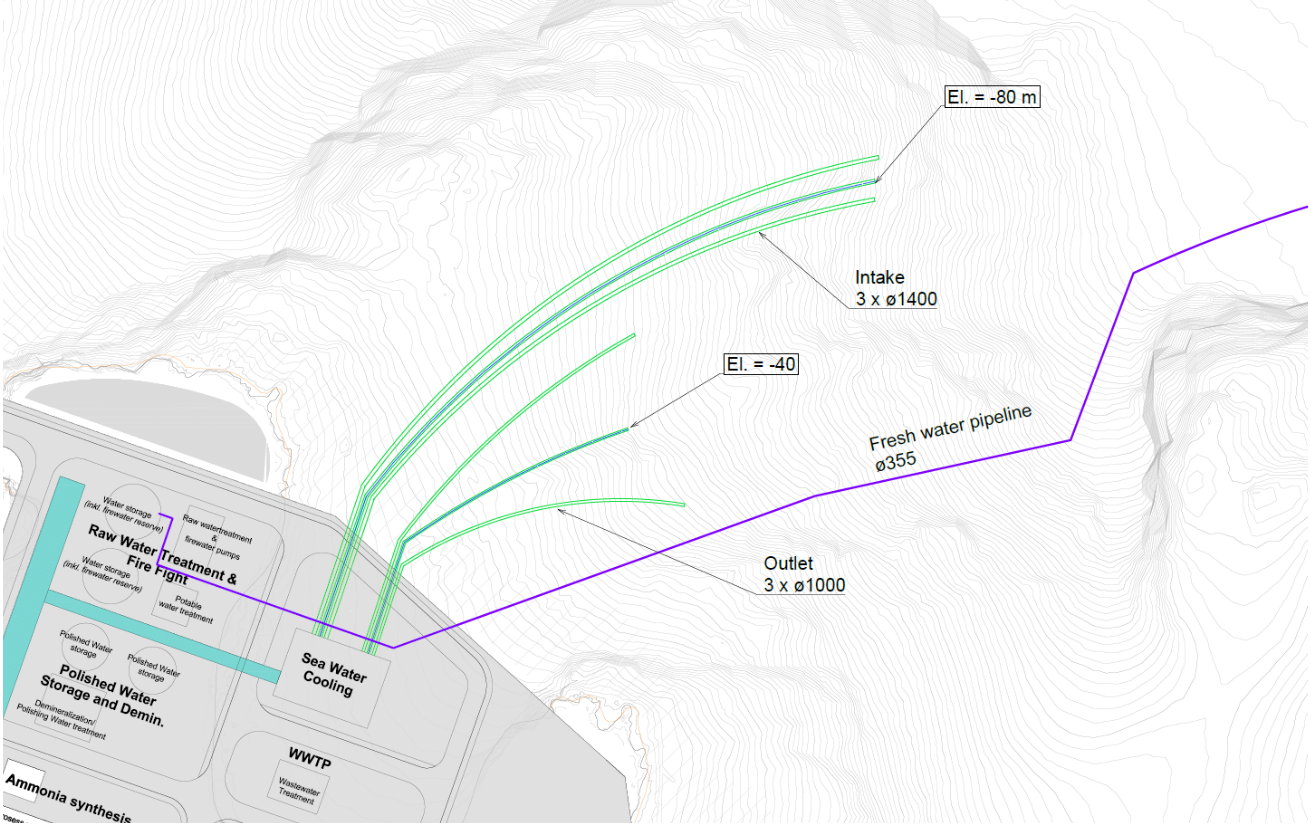


Figure 2: Proposed routes inlet and outlet of sea water

2.3 Intake and discharge arrangements

An example of an intake arrangement is shown in the next figure:

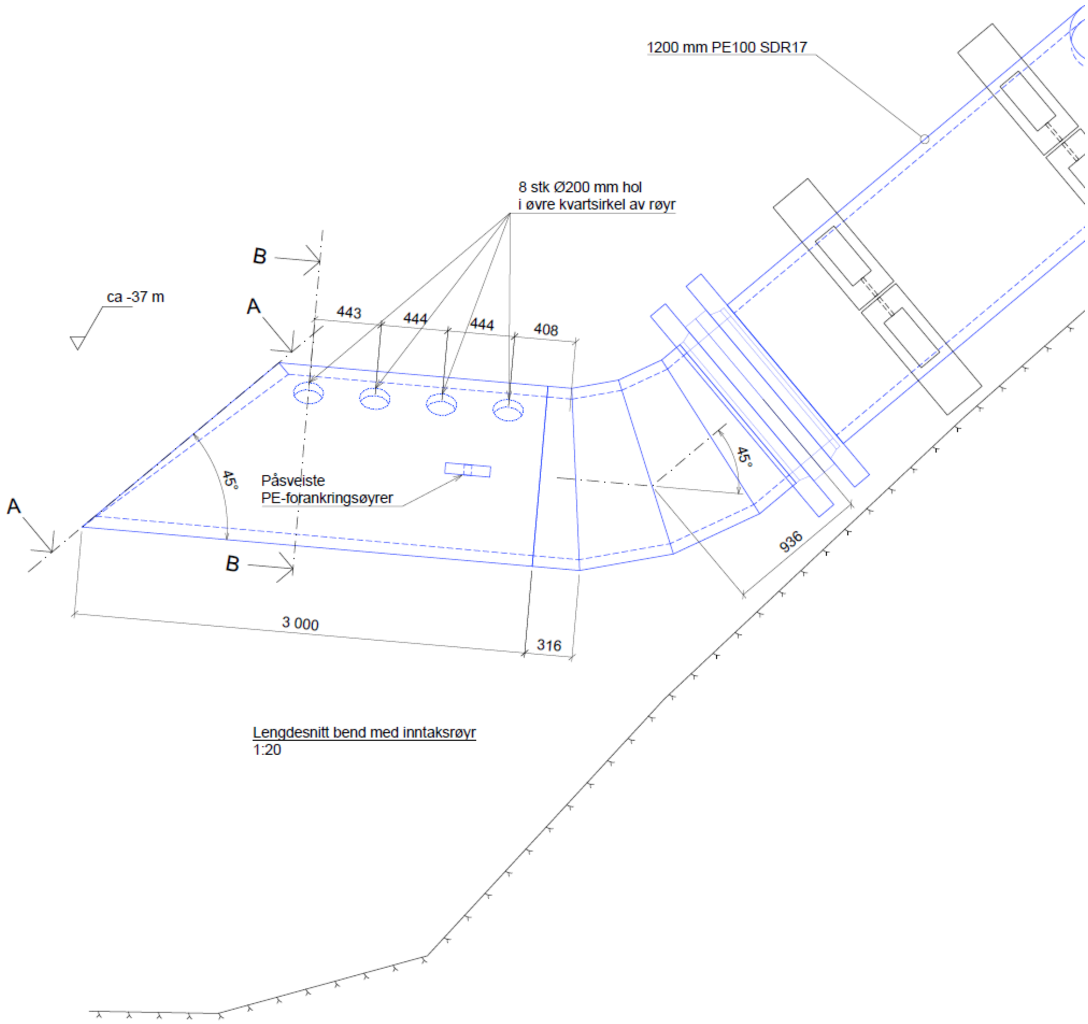


Figure 3: Example from intake line Ø1200 to a fish farming facility

As can be seen from the figure above, the intake pipe is raised slightly from the seabed by using a bend at the very end, which is a common solution for this type of intake of seawater. A similar solution can be used for the discharge lines, possibly with a bend that is to a greater extent directed upwards, e.g. 30 degrees relative to the horizontal.

As also can be seen from the figure, the end of the intake pipe is cut at an angle, this to reduce the intake speed at the end of the pipe. For the same purpose, some Ø200 mm holes have also been drilled in the top of the pipe end. A similar solution can be used for the Holmaneset pipes to reduce the inlet velocity at the pipe end. Without such bevel cutting and drilling of holes in the top, the inlet velocity at the end of each of the two active pipes Ø1400 will be approx. 1,46 m/s. With the mentioned measures the inlet area will increase and the inlet velocity will be reduced to approx. 0,9 m/s. Further expansion of the intake area at the end of the pipe can be done by fitting pipe extensions that can give an intake velocity as low as 0.15 m/s to avoid fish or other things being dragged into the inlet. Good international industry practice may lead to 0.15 m/s as the maximum intake velocity to reduce potential impingement/entrainment impacts.

The figure below shows a principle solution for this. Further detailing must take place in the next phase.

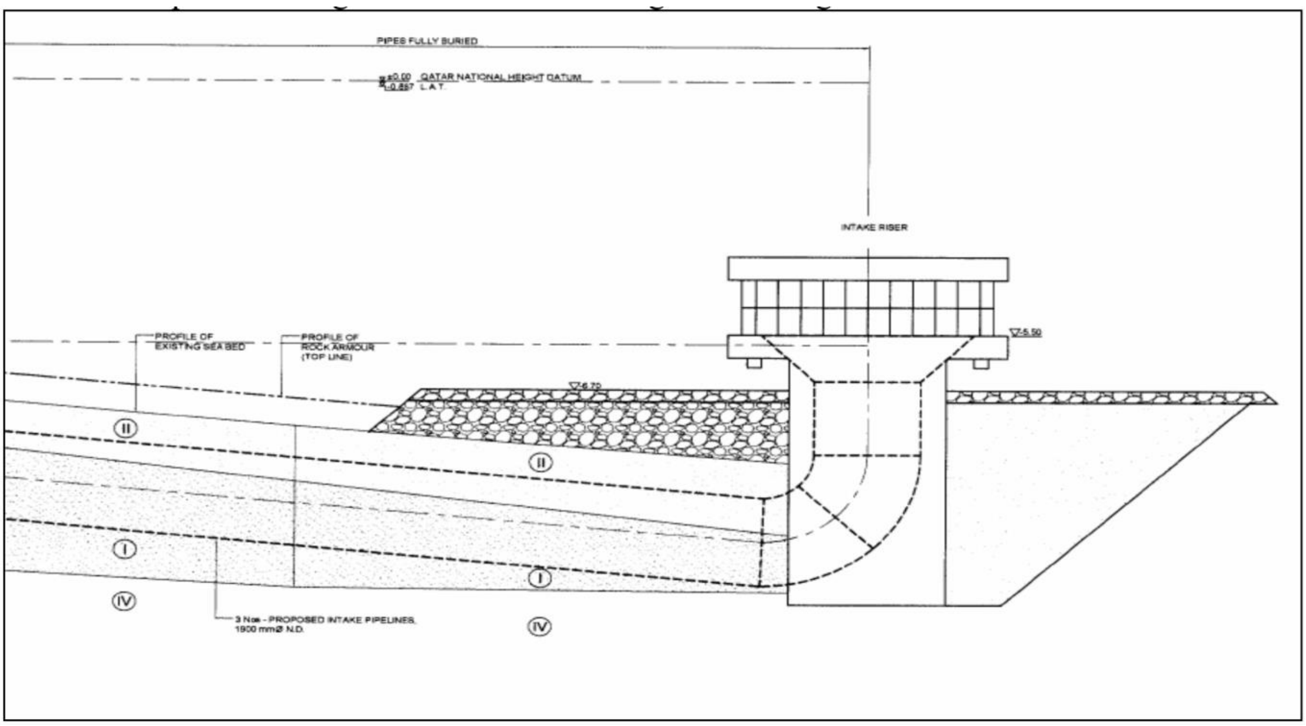


Figure 4: Example from intake line with pipe extension at the end to reduce the intake velocity to a minimum

It is considered likely that intake velocity limited to 0.15 m/s will require grates on the intake. The challenge will be to find inspection and maintenance methods which do not cause disproportionately large operating disadvantages at a depth of 80 m in relation to the advantages such a low intake rate provides. Additional grates may be placed in a sump or other accessible point on land upstream of the heat exchanger. Detailed design of the intake and final clarification of how low the intake speed should be is assumed to belong to the next project phase.

It is not considered necessary to have grates on the outlet, here the water should flow out freely. Diffuser heads to improve dilution can however be considered in the next project phase.

2.4 Landfall protection of the pipes

On land for the first few meters from the north side of the Sea Water Cooling Building, the intake pipes and discharge pipes will be well protected in a deep trench.

As can be seen from the length profile on the drawing NOR1101-0600-PP-DPP.0001.004, all six pipes will lie relatively shallow for the first few meters in the sea, and here the following protective measures will be applicable:

- Excavation/blasting with backfilling of stone over the pipes

- Laying the pipes on the seabed with protection with concrete mattresses

- Laying the pipes on the seabed with protection with both concrete mattresses and stone masses over the matresses.

Further assessment of protection measures in the sea belongs to the next project phase.

3 Marine biology

Holmaneset is situated in the water body Nordgulen fjord (ID 0282010400-C), which is characterised as “protected fjord influenced by fresh water”. The ecological status is registered as “moderate” and the chemical status poor, (Vann-nett.no).

The seafloor around the suggested outlet site has not yet been surveyed but from the current profile measurements close to the same site we have a few pictures from the seafloor close by which indicates that the seafloor here consists of soft bottom with gravels and some turf algae. These registrations are from about 40m depth.

Potential conflict areas for the intake and outlet of cooling water are registered occurrences of spawning grounds for cod, eelgrass meadows and kelp forests.

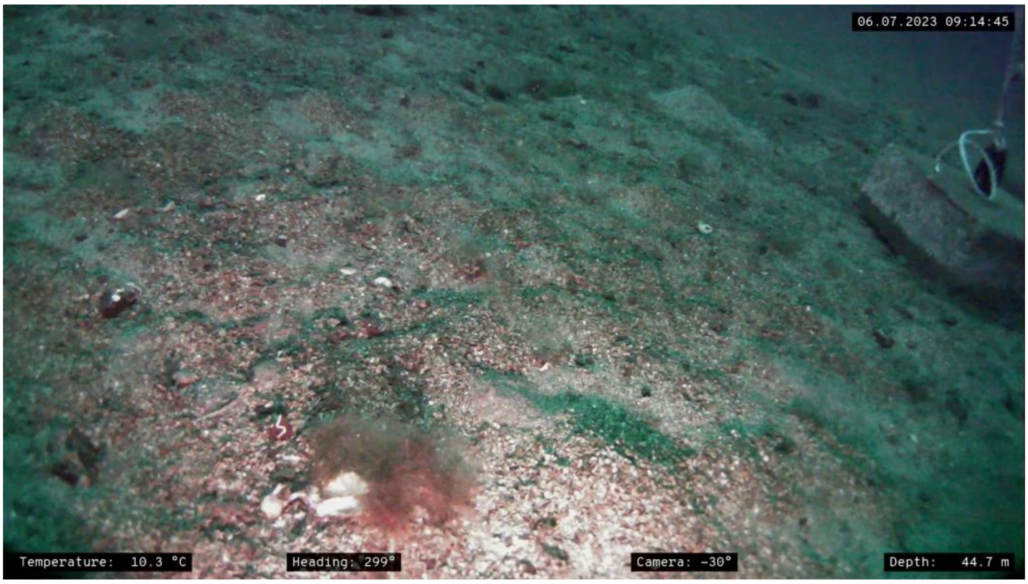


Figure 5: Seafloor environment at 44m depth close to the outlet area. (Photo: Norconsult AS)

3.1 Spawning grounds for cod

Figure 6: Cod spawning ground (stipled area) Fiskeridirektoratet.no. The red dot indicates the intake point, and the blue dot indicates the outlet point.

All of the fjord Nordgulen is registered as spawning ground for cod (*Gadus morhua*). However, a more site specific distribution is not available, but the registrations is verified by field investigations by Institute for Marine Research and classified to be of “regional importance”.

Atlantic cod spawn pelagic and exhibit notable temperature sensitivity during their spawning process. The females release their eggs into the aquatic environment while males simultaneously release sperm for external fertilization. This reproductive strategy augments the prospects of successful fertilization but concurrently exposes the eggs and ensuing larvae to diverse environmental influences. After fertilization, the eggs undertake passive transport facilitated by oceanic currents. The development of the eggs and the subsequent larval stage of Atlantic cod are greatly influenced by ambient water temperatures, with colder conditions being ideal for both growth and viability. After hatching, Atlantic cod larvae are small in size and enter a pelagic phase, making them vulnerable to predation and susceptible to environmental challenges. As they progress to a more advanced juvenile stage, they eventually settle on the seabed.

Successful egg and larval development in *G.morhua* require specific cold-water conditions within the range of 5°C to 7°C and high salinity (González-Irusta et al., 2016). Consequently, Atlantic cod typically spawn during the year's colder months, specifically from February to April. Deviation from this optimal temperature range can have adverse effects on the normal development of Atlantic cod eggs and larvae. An increase in water temperature of 4°C corresponded to a substantial reduction in larval survival, resulting to a 75% decline (Havforskningsinstituttet; Oomen et al., 2022). Elevated water temperatures can disrupt the development, and in severe instances, such conditions may prove fatal for the eggs and larvae. Larval cod exhibit heightened vulnerability during their early life stage. Only a minority of these larvae endure the initial development phase to evolve into fry and subsequently larger fish. Minor fluctuations in the survival rate of cod larvae can exert substantial repercussions on the overall cod population. Moreover, the presence of warmer waters due to environmental factors can introduce significant alterations in the timing and success of Atlantic cod spawning. These changes in spawning dynamics can exert profound repercussions on the overall health and sustainability of Atlantic cod populations.

Spawning Atlantic cod exhibit great variability in the habitat used for spawning in-depth, current patterns, and general geographic locations, such as within fjord systems or on the continental shelf (Grabowski et al., 2012). The choice of spawning depth, which can vary from 20 meters to 200 meters, is often driven by temperature and other environmental factors. *G.morhua* seek out areas with temperatures within their preferred range to optimize the survival and development of their eggs and larvae.

3.2 Eelgrass meadows

Figure 7: Eelgrass beds in the project area. The map shows eelgrass beds (green dotted fields) registered in naturbase.no and verified by Ramboll 2023. The red dot indicates the intake point, and the blue dot indicates the outlet point.

Mapped eelgrass (*Zostera marina)* meadows have been registered in the area, and some occurrences overlap directly with the project area. The eelgrass at Litleholmen is considered *very important* (with national importance, A-value) and the eelgrass at Holmensundet *important* (with regional importance, B-value), both occurrences mapped and registered in 2013 by the Institute of Marine Research (IMR) on behalf of the

Norwegian Environment Agency and Norwegian Fisheries Directorate. [17]. (Ref. Ramboll, 2023) The eelgrass meadow between Storholmen and Holmaneset appeared dense and viable in certain places, despite the surveys being carried out late in the year. The distribution area corresponded well with previous registrations in the Naturbase database [17], however the meadow was partly fragmented in some places. In some places there was apparent growth of filamentous (thread-shaped) algae on the leaves of the eelgrass.

Eelgrass is a submerged aquatic angiosperm commonly inhabiting coastal and estuarine ecosystems. Z. marina usually grows in protected areas without too much wave exposure and is dependent on good light conditions. The species is therefore usually found in relatively shallow areas, usually at a depth of 2-5 metres, but it can also grow deeper if there are good conditions. Eelgrass exhibits a well-defined temperature tolerance spectrum and tolerates temperatures between − 1.5 and 30 °C but has an optimum temperature of 15.3 ± 1.6 °C for growth and 23.3 ± 1.8 °C for photosynthesis (Lee et al., 2007). Sustained exposure to elevated temperatures can impede the crucial process of photosynthesis and elicit stress responses within the plants, ultimately affecting growth rates and overall vitality. Nonetheless, eelgrass exhibits a degree of resilience to temperature fluctuations outside this favored range, particularly when assessing brief temporal deviations or acclimation. Eelgrass is a tolerant plant that can withstand a lot of disturbance, but only up to a certain point. If the disturbance becomes so great that it exceeds the threshold value of what the meadow can tolerate, then the positive feedback loops can be changed to negative. This means that there will be less eelgrass holding the sediments, which will give more resuspension in the water column, making the light conditions worse. As a possible outcome, the habitat will no longer be suitable for the growth of the eelgrass, and the meadow will eventually die out and disappear.

3.3 Kelp forests

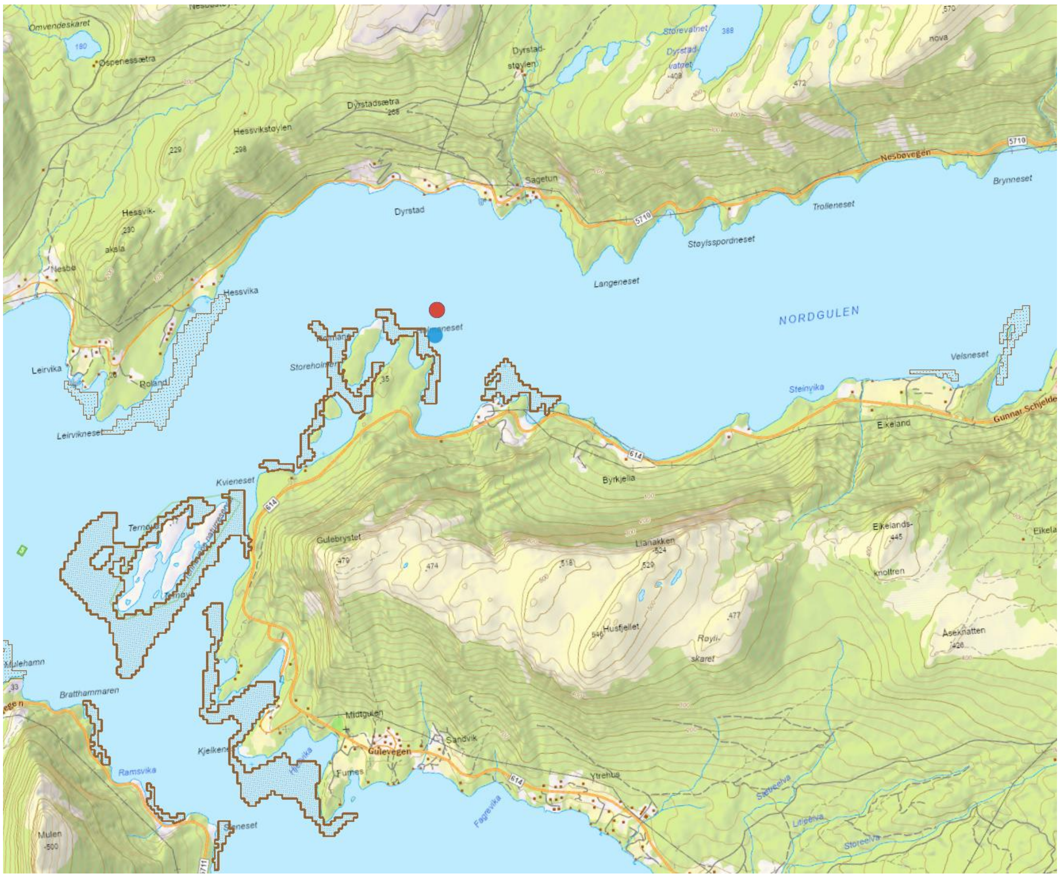


Figure 8: Kelp forest (sugar kelp) in the project area. The map shows kelp (brown dotted fields) registered in naturbase.no and verified by Ramboll 2023. The red dot indicates the intake point, and the blue dot indicates the outlet point.

Many areas along the coast of the Nordgulen fjord is inhabited by the red listed habitat type northern sugar kelp forest (*Saccharina latissima*) (Endangered, EN (N)), according to previous registrations. Some of these occurrences overlap directly with the project area and are considered as *very important* (e.g. Midtgulen) [21]. (Ref. Ramboll).

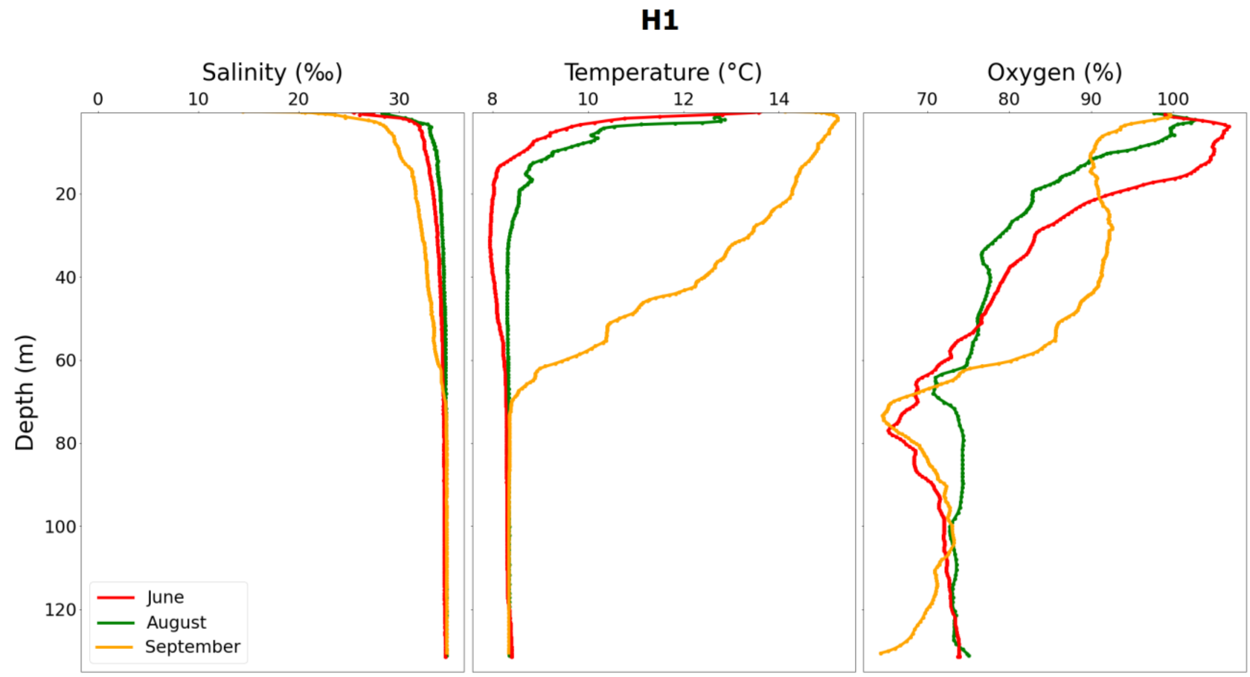
The visual seabed surveys performed early in November 2022 (Ramboll) confirm previously registered occurrences of the marine habitat type large kelp forest consisting of sugar kelp (*Saccharina latissima*) in the area of investigation. Especially on the outside of the islands Litleholmen, Meholmen and Storholmen there were dense and intact occurrences of sugar kelp Northeast and east of Holmaneset the observed sugar kelp forests were dense and occurred down to at least 10 m depth. Unpublished data from the dive transect conducted in August indicates that the lower depth range for sugar kelp is about 24m and that it is dense from around 16m and upwards. In the area between Storholmen and Holmaneset, the occurrences of sugar kelp were more dispersed, with a few individual algae lying flat on the seabed, of which most were covered by ether sediments or some sort of epiphytic organism.

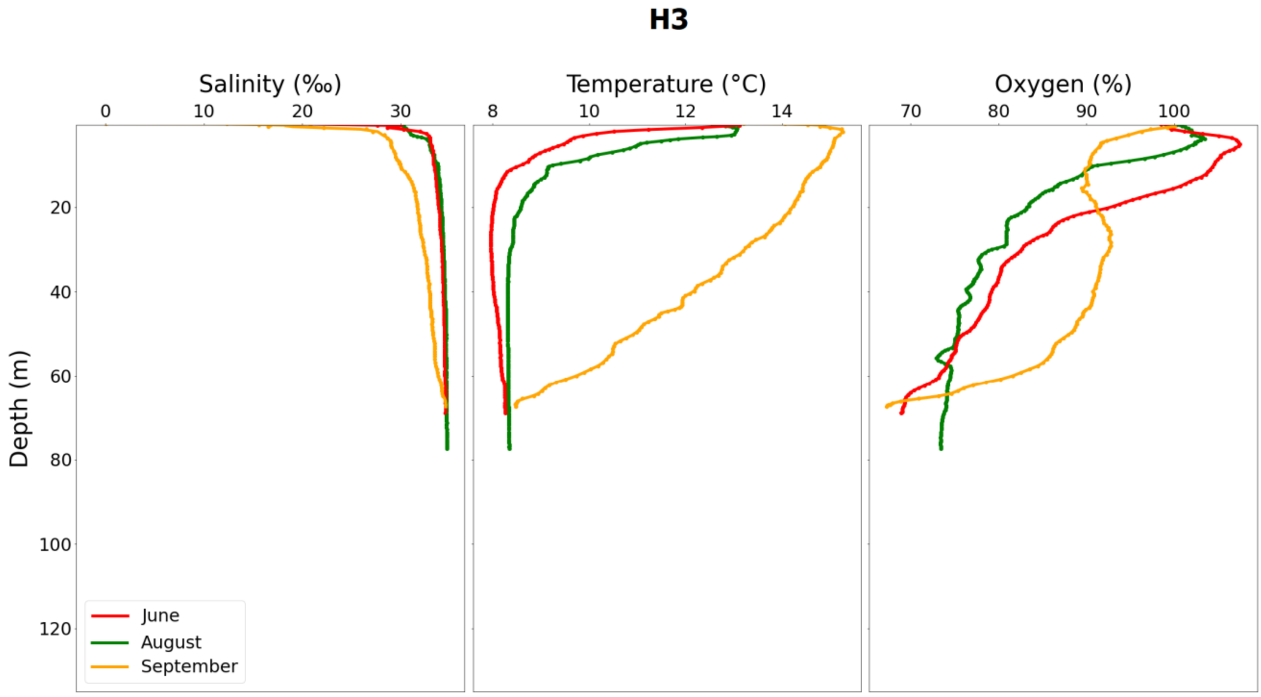
Saccharina latissima prefer semi-exposed to sheltered habitats attached to rocky substrate, and can be found between 1 – 30 meters, although usually dominating the upper parts (Moy and Christie, 2012). The vegetative growth of sugar kelp starts during winter, and throughout the early spring the sugar kelp utilizes the energy, in form of chrysolaminaran, conserved during the summer. Bolton and Lüning (1982) showed that the optimum temperature for *S. latissima* is between 10 – 15°C. Optimal salinities ranging from 23 and up to 31 PSU (Werner et al., 2003 in Bruton et al., 2009; Peteiro and Freire, 2013). Optimal water velocity presumably lies between 0.158-0.171 m s-1 (velocity 0.2 m s-1 during early growth), beyond which growth rate could be declined (Peteiro et al. (2019), Le François et al., 2023). Furthermore, Lüning (1980) suggested that the distribution is mainly determined by summer temperatures.

Laboratory observations have revealed that when the ocean temperature becomes too high, Norwegian sugar kelp will spend more energy on respiration than what they are able to generate through photosynthesis. This increase in metabolism will deplete their reserves and they will become more vulnerable (Andersen et al., 2013). Andersen et al. (2013) showed that when *S. latissima* is retained at 20°C over time, it starts to show evidence of reduced photosynthetic ability. In addition, Bolton and Lüning (1982) demonstrated that sugar kelp can only sustain 23°C for a few days before dying. Thus, changes in temperature will reduce sugar kelps resilience, and the presences in south Norway may become unstable. Another consequence of changing temperatures is an advantage to competitors. In contrast to sugar kelp, turf benefits from high water temperatures, and may rapidly achieve vegetative dominance (Lotze and Worm, 2000) (Ref. some taken from Torp, 2018.)

3.4 Hydrography

Based on the hydrography measurements Conductivity, Temperature, Salinity (CTD) from June, July, August, and September 2023 (NOR1101-0200-WM-REP-0008), three data profiles were generated for hydrography measurements stations (H1, H3, H6, E1), located near the originally proposed locations for discharge and cooling water intake (Figure 9, Figure 1).


H1
Salinity (‰)
0
10
20
30
Temperature (°C)
8
10
12
14
Oxygen (%)
70
80
90
100
Depth (m)
20
40
60
80
100
120
June
August
September


H3
Salinity (‰)
0
10
20
30
Temperature (°C)
8
10
12
14
Oxygen (%)
70
80
90
100
Depth (m)
20
40
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120
June
August
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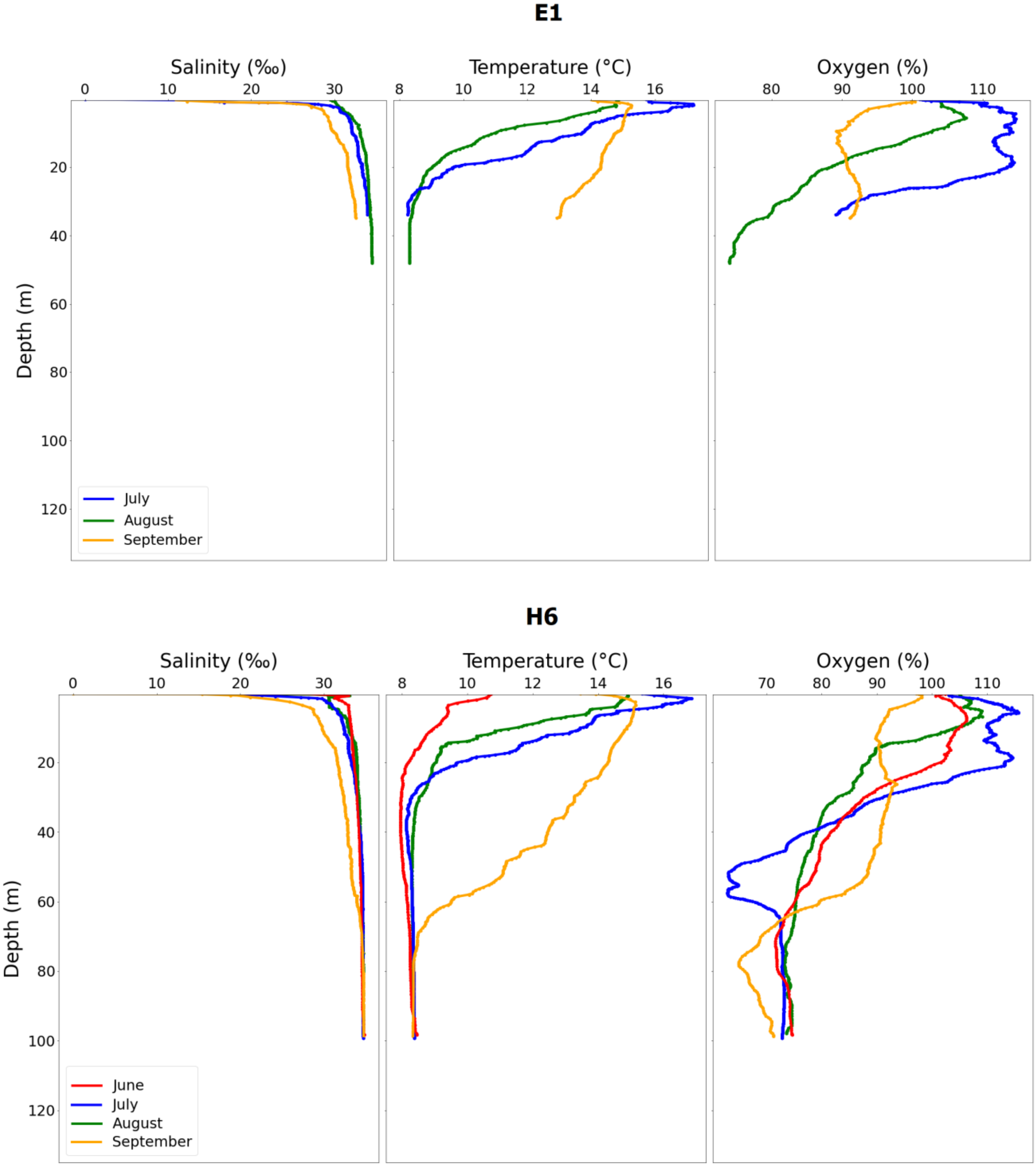


Figure 9 - Water column distribution of salinity, temperature, and oxygen. The profiles are based on CTD data collected in June, July, August, and September 2023 at the locations H1, H3, H6, E1 for water sampling and hydrography measurements. The legend corresponds to the sampling points (labelled in accordance with the map (Figure 1).

As discernible from the plotted data, CTD profiles related to salinity display similar depth distribution patterns across the four sampling locations. In September, there is a slight decrease in salinity observed in all stations within the upper 80 meters of the water column.

Further, the salinity plots show a narrow surface layer of more fresh water, which is expected due to the freshwater runoff in the innermost part of the fjord. Under this top layer the salinity is rather constant throughout the water column.

The oxygen levels in the deep waters are good at all stations throughout the summer.

4 Dispersion modelling of discharge water

4.1 Models, model setup, site characteristics and ambient sea conditions

Effluent mixing and dilution in the ambient water will depend on discharge characteristics and ambient conditions. The processes are generally analyzed and modelled into two separate domains, called near-field and far-field dispersion, in which different physical mechanisms dominate.

In the near-field region, discharge characteristics primarily dominate the mixing behavior. This region typically extends over a few meters up to a few hundred meters from the discharge point. The effluent discharging into the ambient water generates an intense shear flow due to velocity discontinuity between the effluent and the ambient flow, causing turbulent mixing. Such velocity discontinuity may arise from an initial momentum flux, from a buoyancy flux leading to vertical acceleration or from a combination of both. Entrainment of ambient fluid dilutes the effluent, and hence decreases differences in concentration of pollutants or fluid properties (density, salinity, temperature) between the effluent and the ambient water. The ambient conditions do also influence the mixing process. Ambient currents deflect the effluent trajectory into the current direction, inducing further dilution. Ambient density stratification, instead, has a negative effect on dilution since it inhibits vertical acceleration and diffusion.

In the far-field, the ambient conditions dominate the mixing processes. The established plume is passively advected by the ambient current. The plume dilutes and increase its dimensions as it mixes with ambient water due to ambient turbulence and buoyancy processes.

To evaluate how the discharged cooling water mixes and dilutes close to the discharge point, the Visual Plumes model tool was used. Visual Plumes is an openly available model tool developed by the EPA (United States Environmental Protection Agency) for calculating initial dispersion and dilution on a small scale (typically 0–100 m from the point of emission). This study uses the UM3 model within Visual Plumes. The UM3 is a near field model suited for simulating the phase until the plume reaches the density of the ambient water, or reaches the surface, or impinges to the seafloor (Figure 10). UM3 is a Lagrangian model that quantifies forced entrainment, the rate at which mass is incorporated into the plume in the presence of current. In UM3 it is assumed that the plume is in steady state, which implies that successive elements follow the same trajectory. The steady state assumption means cumulative impacts of continuous discharge is not accounted for. The calculations will for instance not include impacts of more or less diluted discharge water returning to the plume.

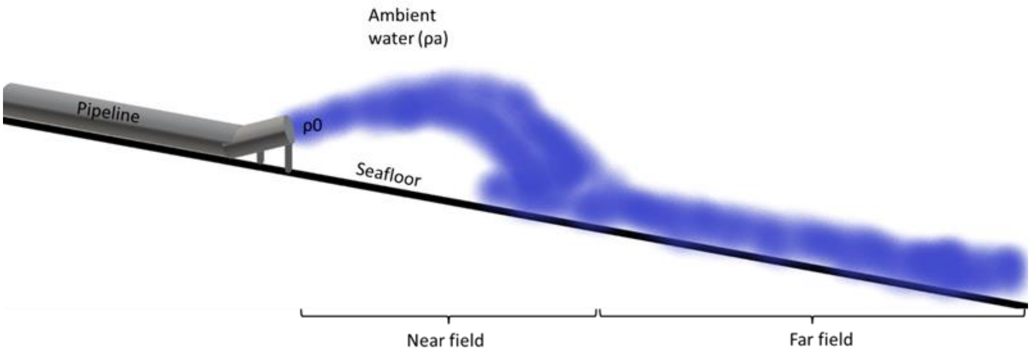


Figure 10: Example sketch of dispersion of discharge water with higher density (ρ0) than that of ambient water (ρa).

Table 1 shows the input parameters (volume-fluxes, temperature, salinity, pipeline dimension, emission depth and directions) employed in the model calculations. The parameters are derived from Figure 2 and an assumed dispersion flux of 11800 m^3/h, adjusted upward from a previous estimate of 11000 m^3/h (Cooling System Evaluation Report, Doc. No. NOR1101-0220-PR-REP-0001). With 2 of 3 outlet pipelines in concurrent operation the flux per pipeline is 5900 m^3/h. There are plans for adding a 300-400 times smaller wastewater flux to the discharge pipelines (Wastewater Management Strategy Report, Doc. No. NOR1101-0200-W-STR-0001). The amounts of pollutants in the wastewater are expected to be small (Wastewater Management Strategy Report, Doc. No. NOR1101-0200-W-STR-0001) and when mixed in efficiently diluted. The wastewater density properties and impacts of constituents in the wastewater are therefore assumed negligible-small and not addressed in the sea dispersion modelling. In the UM3 model calculations the pipeline outlet is set to be directed perpendicularly outward from the coastline parallel to the horizontal plane. The lower end of the pipeline outlet is situated 1 m above the seafloor. UM3 also requires information about the physical conditions in the ambient water of the recipient. For this, data from the NorFjords 160 model close to the intake and discharge points are used (Table 1, Table 2).

Table 1: Input parameters for discharge water applied in the Visual Plumes UM3 calculations.

Discharge flux per pipeline	Inner pipeline diameter	Depth	Inclination relative to horizontal plane	Temperature*	Salinity*
5900 m^3/h	820 mm	40 m	0°	12° C above intake water	Same as intake water

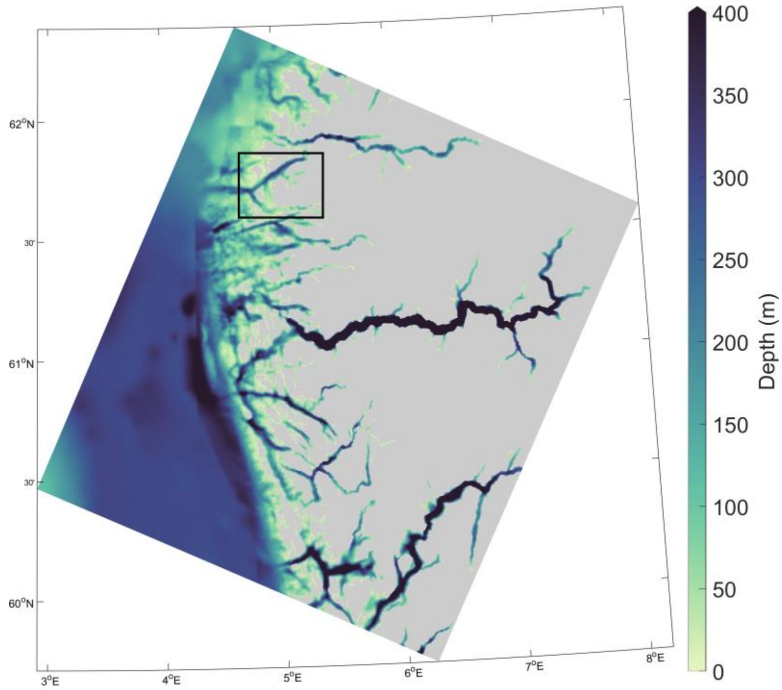
*NorFjords 160 model data near the intake point for April 2017–March 2021 is used.

Table 2: Input data on ambient conditions near the discharge point. For all cases NorFjords 160 model data for April 2017–March 2021 is used.

Cases	Temperature	Salinity	Current speed	Current direction relative to discharge direction
Base	Monthly means (Figure 13)	Monthly means (Figure 13)	Monthly means (Figure 14)	Perpendicular
Sens 1	Monthly means (Figure 13)	Monthly means (Figure 13)	Monthly means (Figure 14)	Opposite
Sens 2	Monthly means (Figure 13)	Monthly means (Figure 13)	Monthly 5th percentile	Same (parallel)

The NorFjords hydrodynamic model (Asplin, et al., 2020; Dalsøren, et al., 2020) was developed based on ROMS (Regional Ocean Modeling System; http://myroms.org; Haidvogel, et al., 2008, and Shchepetkin & McWilliams, 2005) by the Norwegian Institute of Marine Research (IMR) in collaboration with the Norwegian Meteorological Institute for Norwegian coastal and fjord areas, as well as nearby seas. NorFjords has been evaluated against observations at numerous locations along the Norwegian coast and fjords and is in good agreement with the measurements in time and space in most places (Asplin, et al., 2020; Dalsøren, et al., 2020; HI, 2021).

The data analyzed in this work is derived from IMRs historical results archive. NorFjord's results with 160 m horizontal resolution are available for the period April 2017-June 2023 with a time resolution of one hour from 13 sub-areas which together cover the entire Norwegian coast, including fjords and nearby sea areas. The model domain used here extends from Stord in the south to Stad in the north (Figure 11). 35 vertical layers cover the water column from the surface to the bottom. 160 m horizontal resolution smooths the coastline, small islands and bathymetry (Figure 11), but is usually capable of reproducing the main features in fjords like Nordgulen which is quite open, and the circulation is mostly driven by large scale forcings like river runoff, wind, tides, and interaction with the Norwegian Coastal Current (NCC) along the coast. This interaction and influence from nearby fjords (mainly Midtgulen) are important and NorFjords 160 resolves this seamlessly as it covers both the coast and fjords. The model results show good agreement with a few available CTD measurements data in Nordgulen performed some years ago (Cooling System Evaluation Report, Doc. No. NOR1101-0220-PR-REP-0001). The NorFjords data in Nordgulen will also be compared to an ongoing sea monitoring survey (Baseline Water Monitoring Program Plan & Scope Report, Doc. No. NOR1101-0200-WM-PLN-0001) in a separate upcoming report. This will include evaluation of model performance close to the intake and discharge points.



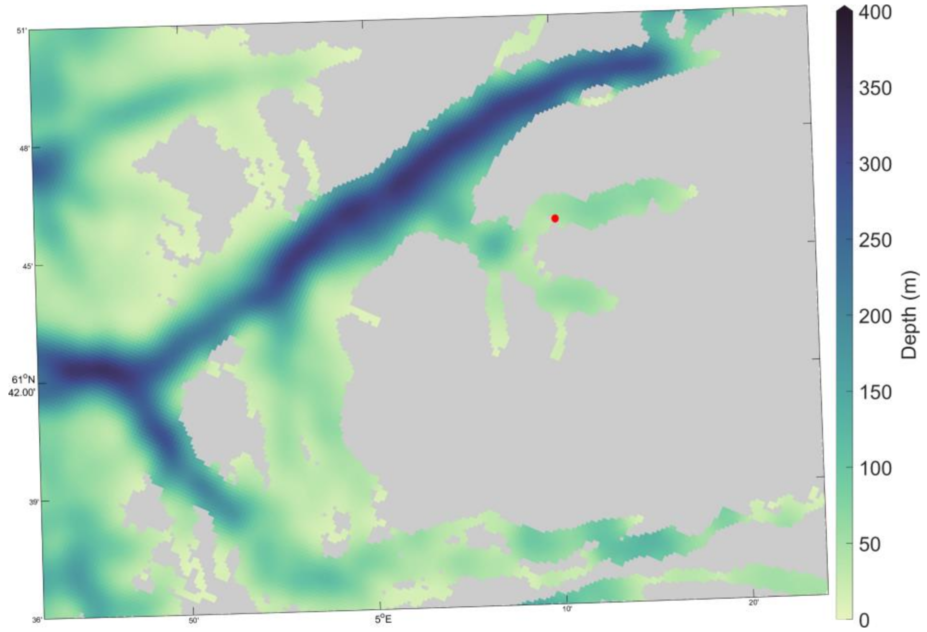


Figure 11: Upper: Model domain and bathymetry in the NorFjords160 model. Lower: Region inside black frame in upper figure, the red point shows the position of Holmaneset.

Figure 129 shows temperatures and salinities in NorFjords160 close to the intake points. The expected temperatures and salinities below 60 m depth show quite small seasonal variations relative to those in the water masses above and are in the range 6-11° C and 34-35 psu, respectively. The reason for rather narrow range and small seasonal variation below 60 m depth is limited deepwater exchange in the basins inside the sill northwest of Storholmen in outer Nordgulen (Cooling System Evaluation Report, Doc. No. NOR1101-0220-PR-REP-0001). The deepwater in the basin where the intake is placed is mainly replaced in periods with inflow at sill level of relatively dense cold coastal water of high salinity. The quite low and stable temperatures of the deepwater found both in the model and measurements (Cooling System Evaluation Report, Doc. No. NOR1101-0220-PR-REP-0001) are the main reason for proposing intake of cooling water at 80 m depth (Figure 2). The NorFjords160 temperatures and salinities at 75 m depth is applied as properties of the intake water in the input to the dispersion modelling (Table 1).

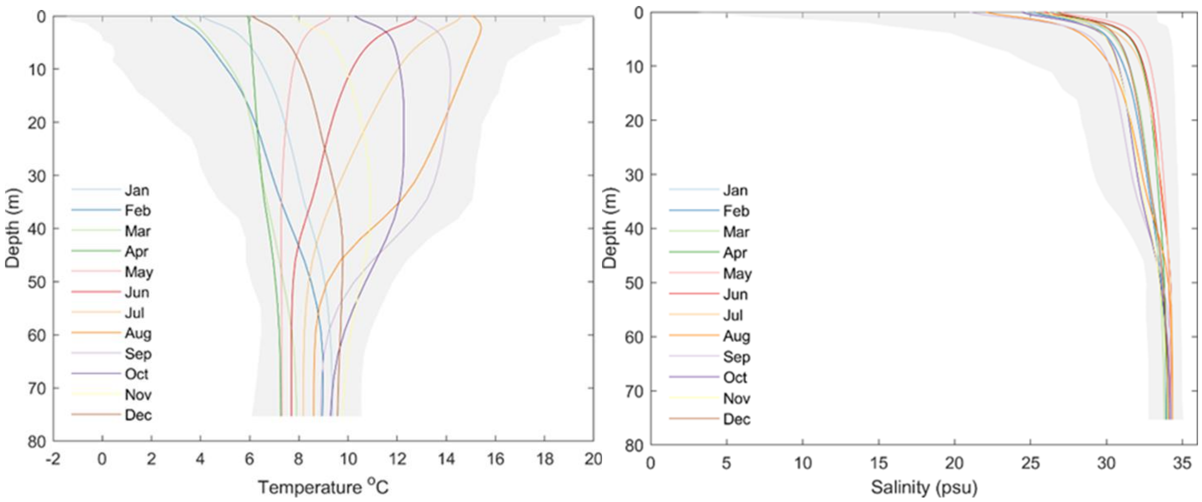


Figure 129: Temperature (left) and salinity (right) profiles based on NorFjords160 hourly data close to the intake point. Colored lines show monthly averages over the period April 2017-March 2021. The grey shaded area shows the full ranges from minimum to maximum temperatures and salinities.

Figure 13 shows temperature and salinity profiles in NorFjords 160 close to the discharge points. The profiles are quite similar to those at the intake points. This is due to the proximity to the intake points and since all intake and discharge points belong to the same basin with very homogenous properties of the deepwater below 50-60 m depth. The selection of a discharge depth of 40 m aims to avoid that the discharge water affects the stable quite low temperatures of the deepwater and its frequency of exchange with other parts of the fjord as this could impact temperatures of the intake water and marine environment. 40 m is also chosen to minimize pipeline clogging due to algae growth and limit temperature impacts in the biological productive zone near the sea surface. As shown in Figure 13, in Nordgulen there is a thin surface layer with brackish water due to large freshwater runoff to the fjord and discharge at 40 m depth also limits the chance that the discharge water reaches the surface. The NorFjords 160 temperatures and salinities at 40 m depth are applied to represent the ambient conditions at the discharge points in the dispersion modelling.

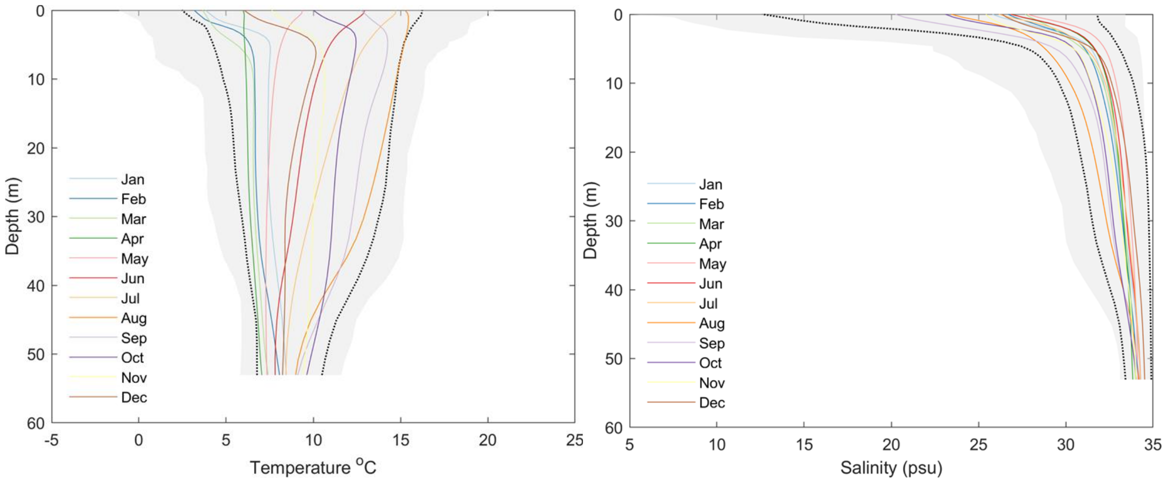


Figure 13: Temperature (left) and salinity (right) profiles based on NorFjords160 hourly data close to the discharge point. Coloured lines show monthly averages over the period April 2017-March 2021, dotted lines 5th and 95th percentiles, and the grey shaded area the complete ranges.

As discussed above the discharge parameters are more important for the near-field dispersion than the ambient conditions. For ambient temperature and salinity, the ranges at the discharge point at 40 m depth are quite small (Figure 13), and monthly averages are therefore used in the model base case calculations. The same is the case for temperatures and salinities from the intake points (Figure 129). Ambient currents have a relatively larger range (Figure 14, Figure 15) and vary both in direction and strength. Figure 15 shows that the currents at the discharge point are mainly directed along the coastline, perpendicular to the pipeline direction (Figure 2). This is a favorable circumstance as it maximizes dilution. The basis calculations assume a discharge direction perpendicular to that of the current. Calculations are made both for monthly average current speeds (base case) and lower mixing/dilution cases in sensitivity studies. The first sensitivity study (‘Sens 1’, Table 2) tested whether ambient currents towards the coastline (more seldom occurring, Figure 15), could result in inward flow leading to a plume ascending upwards along the sloping coastal seafloor impacting benthic organisms. The second sensitivity study (‘Sens 2’, Table 2) studies situations with low current speeds (5th percentile) in the same direction as the discharge away from the coastline. For such a case (also quite seldom occurring, Figure 15) dilution would in theory be less efficient.

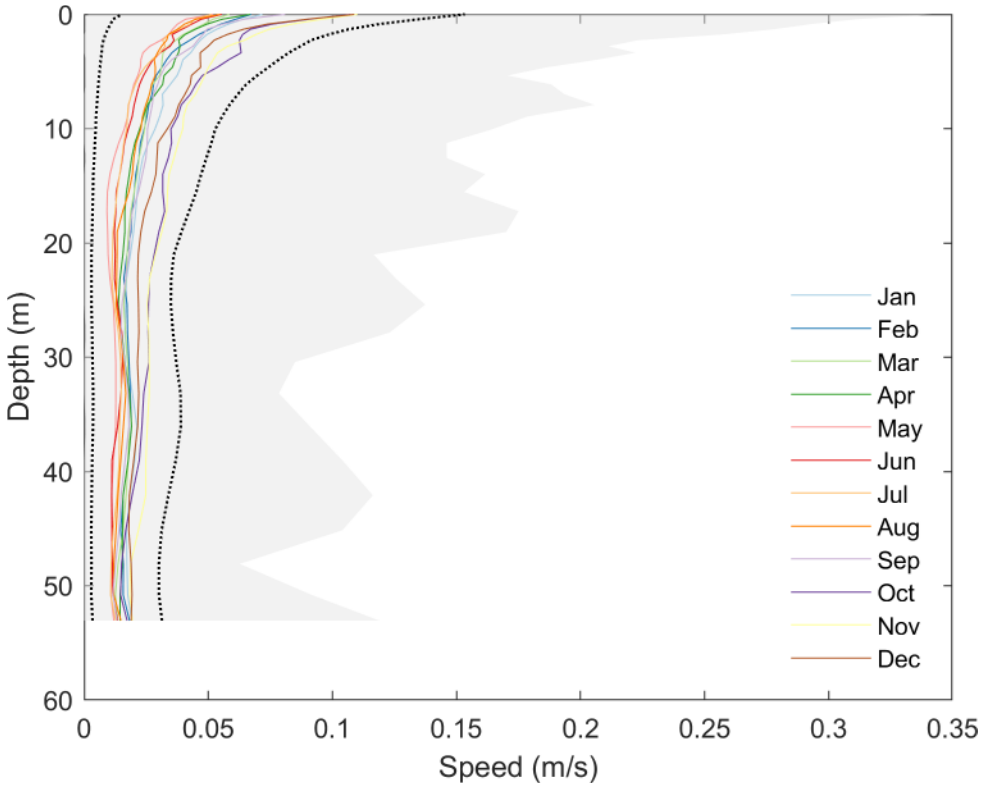


Figure 14: Speed profiles based on NorFjords160 hourly data close to the discharge point. Coloured lines show monthly averages over the period April 2017-March 2021, dotted lines 5th and 95th percentiles, and the grey shaded area the complete range.

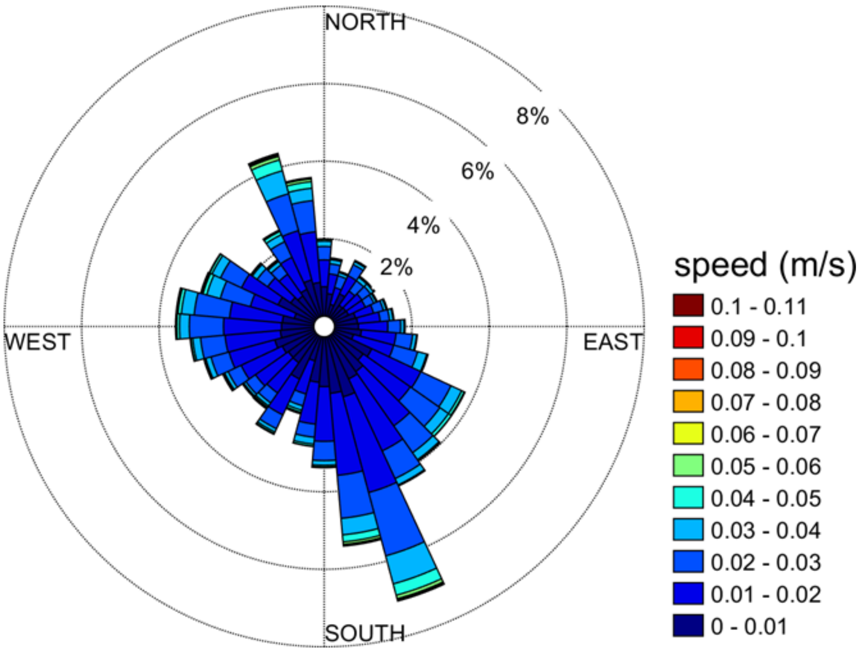


Figure 15: Modelled current from NorFjords 160 near the discharge point at 40 m depth for the period April 2017–March 2021. Speed, direction (flow towards), and percentage of time for 10° direction-intervals based on hourly model data.

4.2 Dispersion modelling results

Figure 1610 and Figure 1711 show the near field dispersion for various months in the base case (applying monthly mean temperature and salinities, and monthly mean perpendicular (along coastline) current for ambient conditions, Table 2). As the seasonal variation range of these ambient variables is quite small near the outlet point, and since the dispersion is much more dependent on the discharge flux (assumed constant over the year) and pipeline dimension, seasonal differences are small. Due to slightly positive buoyancy (net result of higher temperatures (positive buoyancy impact) and higher salinities (negative buoyancy impact) in the discharge water compared to the ambient seawater) the discharge flow initially slowly ascends. Due to its initial upward buoyancy the density of the plume at its maximum rise is higher than that of the ambient seawater. At this stage its momentum is lost, and the plume therefore starts to sink approaching the ambient density and slightly surpasses it reaching a lower density resulting in small buoyant turbulent oscillations in the outer part of the plume appearing as irregularities of the upper outer boundary (Figure 1610). Throughout its outflow, the plume expands and dilutes. Although expanding, the plume dimensions are still quite narrow (plume diameter typically just above 30 m, Figure 1610, Figure 1711) at the end of the near field-phase. However, mixing with ambient seawater is efficient enough to lead to a large decrease in plume temperature levels (Figure18). At the end of the near-field process, the average temperature over the plume transect is only about 0.3° C above ambient conditions (Figure18, lower panel). With regards to the IFC World Bank Criteria the average plume temperature is less than 3° C above the ambient seawater within a horizontal distance of 7 m from the discharge point (Figure18 upper right panel). Less than 1° C difference is reached within 25 m.

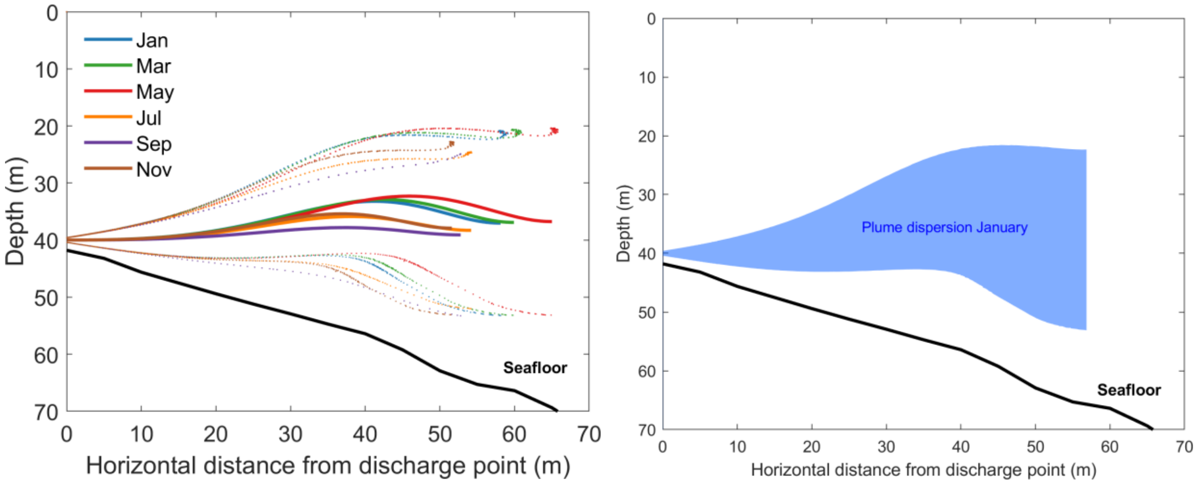


Figure 1610: Vertical view of plume dispersion in the UM3 model for the base case. The slope of the seafloor is based on the longitudinal profiles of the discharge lines (NOR1101-0600-PP-DPP.0001.004 (rev. A)). Left: Seasonal dispersion characteristics. Colored lines: Plume centerline. Colored dotted lines: Plume boundaries. Right: Another way to present plume dispersion (blue). Dispersion in January until final few meters of near-field phase where oscillations at the upper outer boundary occur (left figure).

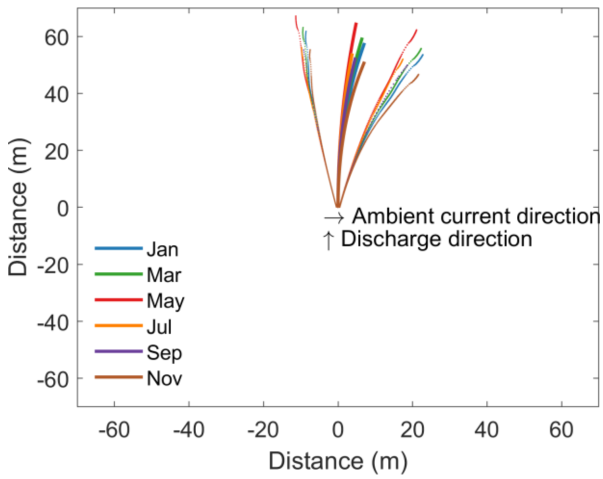


Figure 1711: Horizontal view (e.g. downward view from the sea surface) of plume dispersion in the UM3 model.

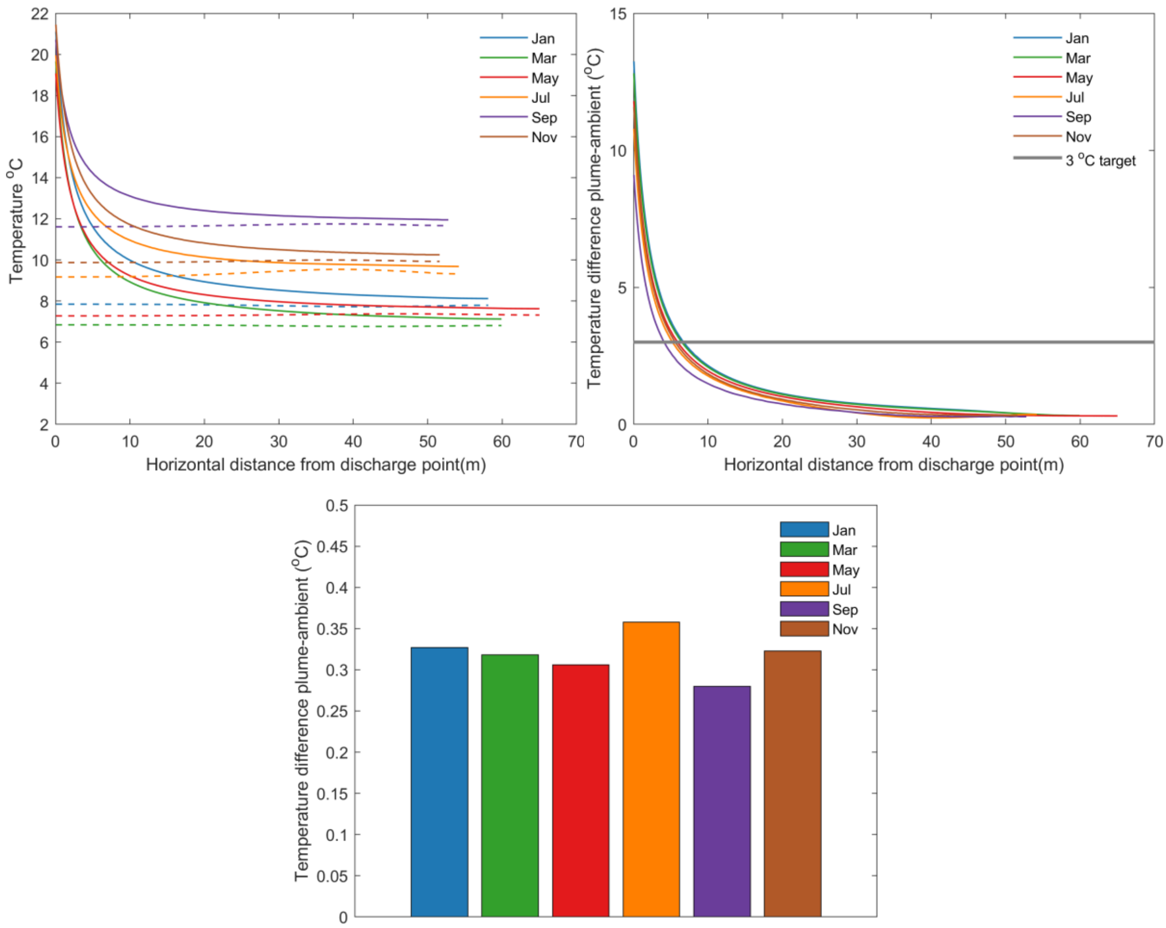


Figure18: Temperature impacts. Upper left: Lines: Average temperature across plume transect. Dashed lines: Temperatures of the ambient seawater. Upper right: Temperature difference between plume (average over cross section) and the ambient seawater. Lower: Temperature difference between plume (average over cross section) and the ambient seawater at the end of the near-field phase (end of coloured lines upper left figure).

The velocity of the discharge water is much larger than the current speeds in the ambient seawater. For the base case the plume therefore mainly flows in the outlet direction (Figure 1711) away from the coastline with slight sideway deflection due to ambient currents perpendicular to the discharge direction (along the coastline). The first sensitivity study ('Sens 1', Table 2) tested whether ambient currents towards the coastline (more seldom occurring, Figure 15, could result in inward flow leading to a plume ascending upwards along the sloping coastal seafloor impacting benthic organisms. But also, for this case the plume flows in the discharge direction away from the coastline (Figure 1912). This is due to the aforementioned much larger velocity of the discharge water compared to the ambient water. The vertical dispersion (not shown) and temperature signals (Figure 2013) are very similar to that for the base case. The second sensitivity study ('Sens 2', Table 2) represents a period with low current speeds in the same direction as the discharge away from the coastline. For such a case (also quite seldom occurring, Figure 15) dilution would in theory be less efficient. But again, the difference to the base case is small (Figure 2013). This underpins that the dispersion characteristics (pipeline dimension, discharge flux) are more decisive for the dispersion in the near-field phase than the ambient current speeds and directions.

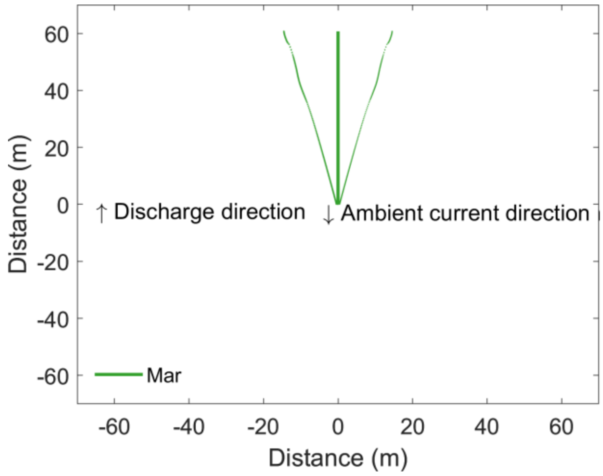


Figure 1912: Horizontal view of plume dispersion for the 'Sens1' case in March.

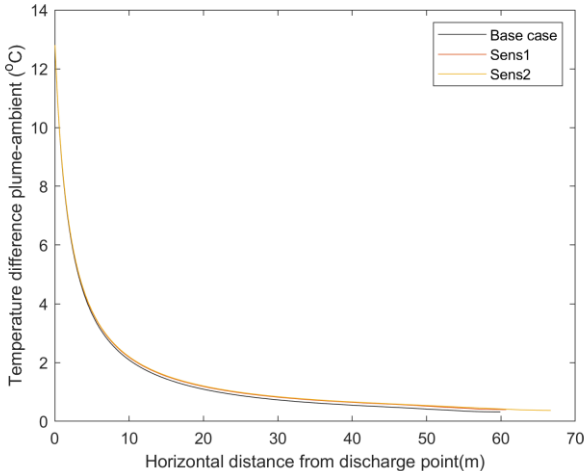


Figure 2013: Temperature difference between plume (average over cross section) and the ambient seawater in March for 'Base case' and sensitivity studies.

Two of three discharge pipelines will be in concurrent operation. If pipeline outlets are situated too close to each other plume interaction would result in larger temperature increases than those calculated for the single plume above. Based on the horizontal extent of the discharge plume from one outlet (Figure 1711, Figure 1912) pipeline outlets should be placed 50 m apart to avoid plume interaction. To be able to place all three discharge pipeplines between the intake pipelines and freshwater pipeline (Figure 2) the distance between the outlets may for practical reasons be down to 30 m (conservative estimate). Based on the results for one plume this is considered acceptable, if interaction it will be mixing of two quite dissipated outer plume boundaries where excess temperatures are low. Placing the outlets at maximum possible distance from each other will limit the temperature impacts but result in a slightly larger impact zone than for more closely placed pipeline outlets.

As earlier discussed, the amount of pollutants in the wastewater added to the clean cooling water are expected to be small and when mixed in very diluted as the wastewater flux is 300-400 times lower. Anyway, it could be of interest to have an impression of how the physical dilution of a dissolved pollutant would be in the sea recipient. This is shown in Figure 2114, at the end of the near field phase mixing with ambient seawater will dilute dissolved effluents in the discharge water by up to factors 30-40. This is the maximal physical dilution factor as the actual dilution never will be larger than the difference between the discharge concentration and the concentration of the pollutant in the recipient.

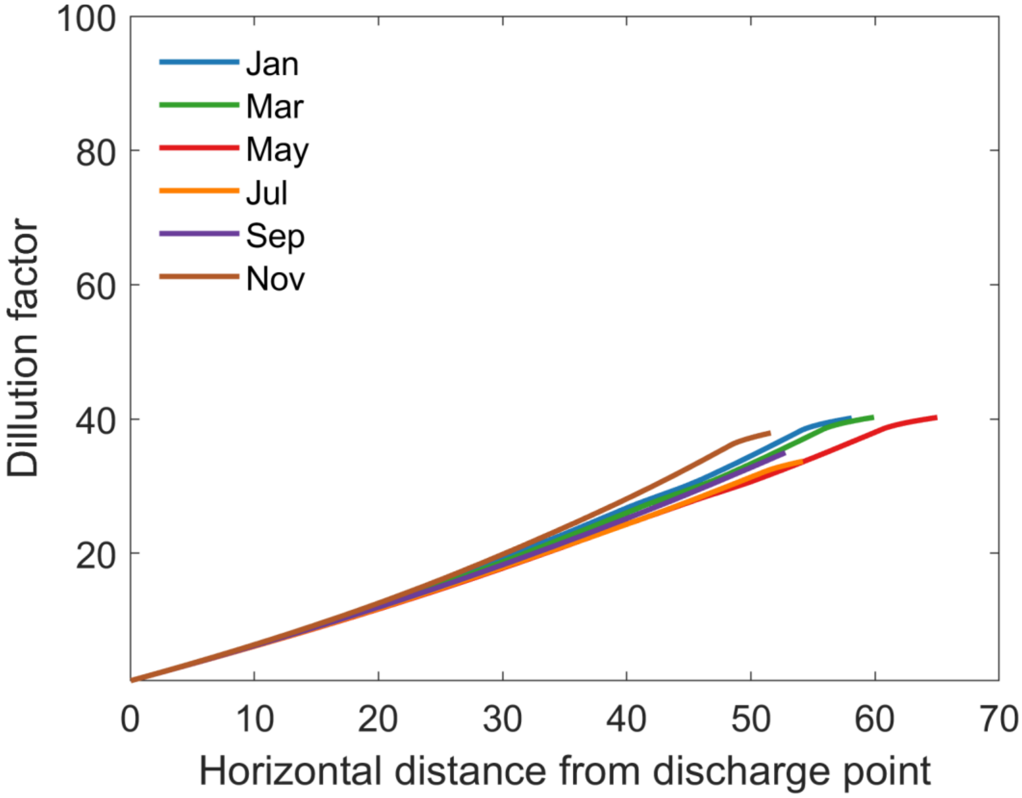


Figure 2114: Dilution due to mixing with ambient seawater.

5 Conclusions

Dispersion modelling was based om a total dispersion flux of 11800 m^3/h, outlet at 40 m depth, intake of cooling water at 80 m depth and temperatures of the discharge water 12° C above that of the intake water. With 2 of 3 outlet pipelines in concurrent operation the flux per pipeline is 5900 m^3/h. Based on dispersion modelling from one outlet and the horizontal circumference of the dispersion plume it is recommended that the distance between the pipeline outlets should be at least 30 m. This will limit the level of the temperature increase in the recipient but result in a slightly larger impact zone than for more closely placed pipeline outlets. Throughout its outflow, the discharge plume expands and dilutes. Mixing with ambient seawater leads to rapid and large decrease in plume temperature. With regards to the IFC World Bank Criteria the average plume temperature is less than 3° C above the ambient seawater within a horizontal distance of 7 m from the discharge point. Less than 1° C difference is reached within 25 m. 50 m in horizontal distance from the outlet the vertical extension of the plume is typically from 20-50 m depth, and the average temperature over the plume transect is less than 0.5° C above temperatures in the ambient seawater.

The kelp forest around Holmaneset starts about 50 m from the outlet points. Unpublished data indicate that the depth limit for sugar kelp on the northern tip of Holmaneset is 24m and below this, there is mostly turf algae. In addition to the efficient dispersion and rapid temperature decline in the discharge plume (temperature increase less than 0.5° C 50 m away), the modelling shows dispersion away from the coastline and low chance of inward flow with a plume ascending upwards along the sloping coastal seafloor towards the sugar kelp. Pictures taken from 43 m depth close to the outlet points show turf algae on the seafloor and indicate that some algae can also grow at these depths. These turf algae are opportunistic species and may benefit from increased temperatures in the water column; however, if the plume water affect the seafloor this will only be in a range of a few meters from the outlet, and the speed of the plume will then most likely disperse the turf algae as they have no holdfasts and live floating, not attached. The main concern with the impact of turf algae is their ability to compete with more stable algae and deprive them of light. At 40 m depth, there is no other seaweed, which is therefore not considered a problem.

The nearest seagrass bed in the area is the one in Holmesundet (ID BM00105387), more than 350 m away from the outlets and out of the impact range.

The whole Nordgulen Fjord is registered as a cod spawning area, but we do not have information about more specific sites. Zooplankton samples are collected from some sites in the fjord this summer, but the analysis results are not yet ready. However, cod is known to spawn from February to April and has the best survival rates at temperatures between 5° and 7° C. The spawning cod can select spawning areas according to their preferences. The model indicates that the average temperatures for February to April at the release site for the cooling water are already in the upper limit of these preferences, mostly above 7° C (). It may, therefore, be likely that this site is not one of the preferred spawning points and that cod spawns in other and deeper parts of the fjord. An increased temperature will severely affect the survival rates of the eggs, and if the temperature elevation constantly occurs, it can be assumed that spawning cod will avoid this specific area for spawning. Therefore, the discharge water will not affect the spawning of cod.

The average plume temperature is less than 3° C above the ambient seawater within a horizontal distance of 7 m from the discharge point. The area affected by this will be in the pelagic zone at about 35-45 m depth. The organisms living in this zone are pelagic zooplankton and fish with the ability to avoid this zone. The potential negative effect of this temperature increase is therefore very small and considered acceptable for the marine environment and organisms.

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