TR A7249- Unrestricted

Report

Modeling operation of a pumped-storage plant in Lake Suldalsvatn

Consequences on temperature and currents distributions

Author(s)
Julie Charmasson

SINTEF Energy Research
Energy Systems
2012-09-25

CEDREN – Centre for Environmental Design of Renewable Energy: Research for technical development and environmental impact of hydro power, wind power, power lines and implementation of environment and energy policy.

SINTEF Energy Research, the Norwegian Institute for Nature Research (NINA) and the Norwegian University of Science and Technology (NTNU) are the main research partners. A number of energy companies, Norwegian and international R&D institutes and universities are partners in the project.

The centre, which is funded by The Research Council of Norway and energy companies, is one of eleven Centre for Environment-friendly Energy Research (FME). The FME scheme consists of time-limited research centres which conduct concentrated, focused and long-term research of high international quality in order to solve specific challenges in the field of renewable energy and the environment.

SINTEF

SINTEF Energi AS
SINTEF Energy Research
Address:
Postboks 4761 Sluppen
NO-7465 Trondheim
NORWAY
Telephone: +47 73 59 72 00
Telefax: +47 73 59 72 50
energy.research@sintef.no
www.sintef.no/energi
Enterprise /VAT No:
NO 939 350 675 MVA

KEYWORDS:
Suldalsvatn
Pumped-storage
Temperature
Currents

Report

Modeling operation of a pumped-storage plant in Lake Suldalsvatn

Consequences on temperature and currents distributions

VERSION	DATE
Version 1	2012-09-25

AUTHOR(S)
Julie Charmasson

CLIENT(S)	CLIENT'S REF.
CEDREN	

PROJECT NO.	NUMBER OF PAGES/APPENDICES:
12X67315	40 + Appendices

ABSTRACT
In a context of climate change, use of renewable energies should highly increase in the coming decades. Existing reservoirs and hydropower plants could be used to balance intermittent energy sources such as wind power and solar energy by pumping water from the downstream reservoirs and storing it in the upstream ones when electricity demand is low, and releasing it to generate electricity in high demand periods. Lake Suldalsvatn, located on the Western coast of Norway, is the lowermost reservoir of Ulla-Førre, the largest hydropower plants system in Northern Europe. Today, it receives turbinated waters from Kvilldal and Suldal hydro power plants, and supplies water to Hylen power plant. In the future, new operational regimes could include the alternation of pumping phases and production phases through installation of a new pumped-storage power plant. Lake Blåsjø located at a higher elevation could be used as upstream reservoir to store water pumped from Lake Suldalsvatn. This report describes results of a study investigating changes in temperature and current distribution in Lake Suldalsvatn under pumped-storage regime. The 3D-hydrodynamic model GEMSS was used to calculate flow velocity, water level fluctuations, and water temperature for two different pumped-storage scenarios. The results of simulations show that intense vertical mixing through the water column is expected during operation of a pumped-storage power plant, leading to colder temperature in the downstream river Suldalslågen during summer and autumn. In addition strong currents appear next to the pumped-storage plant.

		SIGNATURE
PREPARED BY Julie Charmasson	For Julie Charmasson:	Håkon Sundt
CHECKED BY Tor Haakon Bakken		Tor Haakon Bakken
APPROVED BY Magnus Korpås		Magnus Korpås

REPORT NO.	ISBN	CLASSIFICATION	CLASSIFICATION THIS PAGE
TR A7249	978-82-594-3530-9	Unrestricted	Unrestricted

Document history

VERSION	DATE	VERSION DESCRIPTION
Version No.	2012-09-25	Final report

Table of contents

APPENDICES

List of figures

List of tables

1 Introduction

As a part of the EnviPEAK project, the sub-project EnviPEAK_A5_Hydro Reservoirs and Lakes investigates changes in the hydrodynamic processes of downstream lakes and reservoirs as a consequence of hydro-power production. The regulation affects flow pattern, erosion, temperature and ice conditions.
This report presents the results of a study which analyses hydrodynamics consequences of setting-up a pumped-storage power plant in Lake Suldalsvatn. Scenarios and set-up are based on a previous analysis regarding the use of Norwegian hydropower plants and reservoirs to balance intermittent energy sources in Europe [2].

In the report the term pumped-storage power refers to a hydropower plant which alternatively pumps water from a reservoir located at a certain altitude to a reservoir at higher altitude, and releases water from the higher reservoir into the lower one to generate electricity.

2 Material and methods

2.1 Study site description

Lake Suldalsvatn (**Table 1**) is a narrow and deep lake located in South-West of Norway, in the heavily regulated river basin of Ulla-Førre. Suldalsvatn is located at the lowest altitude (56 m a.s.l) in the complex Ulla-Førre system (**Figure 1**). The regulated catchment area of approx. 2000 km^2 consists of a large number of interconnections[1] (total length of tunnels: 100 km) between 16 different reservoirs (total volume: 3500 Mm^3), and hydropower plants basically located at the three different altitudes (60, 600 and 1000 m a.s.l). Four hydropower plants (HP), among which two have a pumping station, have an average annual electricity production of 4500 GWh. Two additional small pump stations contribute to the storage of water.

Table 1. Lake Suldalsvatn's characteristics

Volume	44.86	Mm^3
Area	28.7	Km2
Max length	29.5	Km
Max width	2.8	Km
Average depth	156	m
Max depth	376	m

[1] Source: Statkraft Energi AS

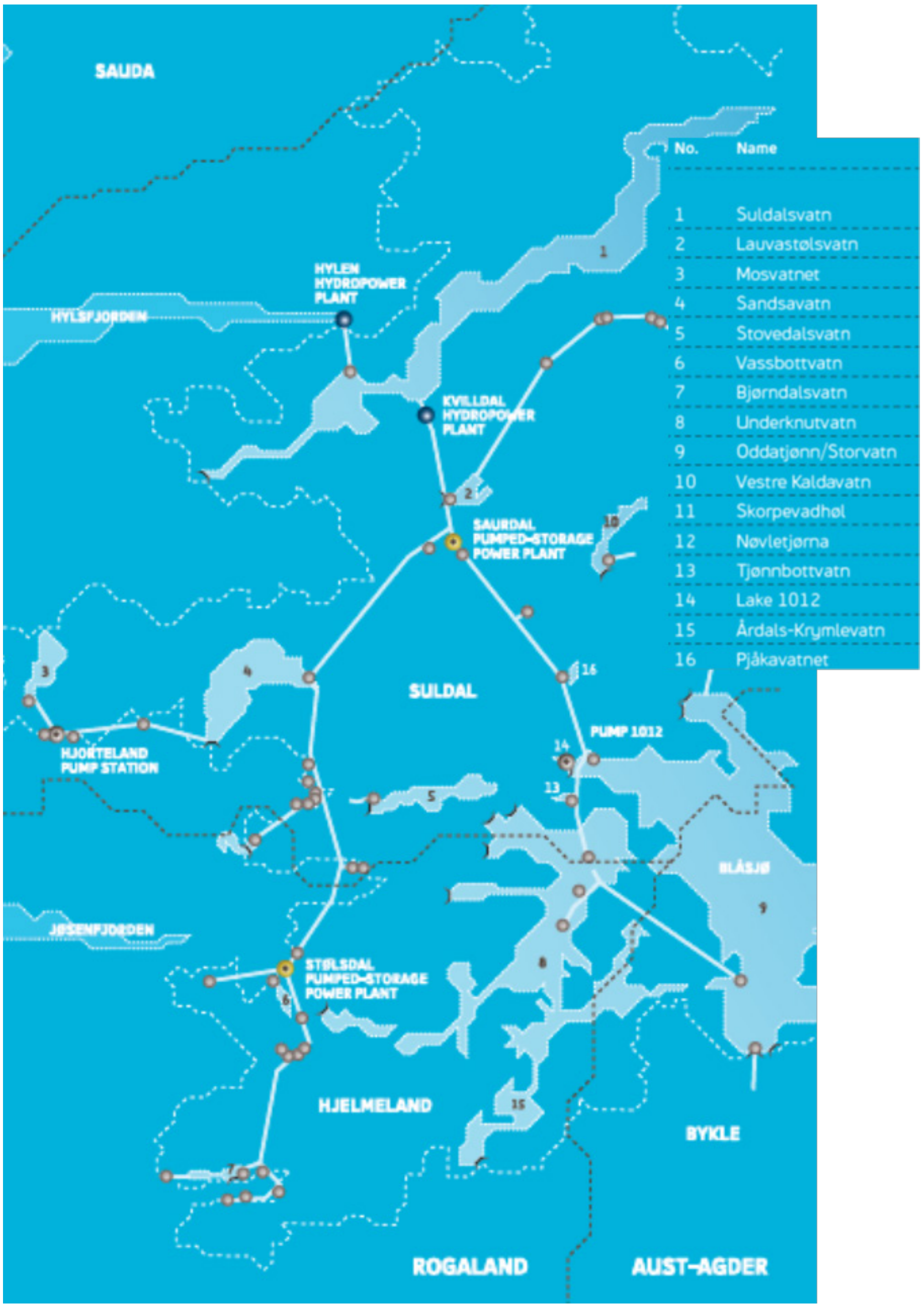


Figure 1. Ulla-Førre hydro-power plant system. It is constituted of 2 hydro-power plants (Kvilldal and Hylen), 2 pumped-storage plants (Saurdal and Stølsdal), and 2 pump stations (Hjorteland and Pump 1012). Water is provided by 15 lakes linked together with about 100 km of tunnels. *Source Statkraft.*

SINTEF

2.2 Current hydrodynamic regime

Water flows

Lake Suldalsvatn is regulated and the available water volume lies between the lowest (LRWL) and the highest regulated water levels (HRWL), located at 67 and 69 m a.s.l, respectively. Three hydro-power plants are located on Lake Suldalsvatn. The smallest one is Suldal I&II power plant, run by Hydro, receiving water from the north-eastern catchment and releasing it into Lake Suldalsvatn, with a capacity of 310 MW. The mean annual discharge for 1998-2005 is 59 m³/s, while the maximum discharge is 170 m³/s. Kvilldal power plant, run by Statkraft, is located on the southern shore of the lake. It has a capacity of 1240 MW and releases water into Lake Suldalsvatn from the southern catchment and the uppermost reservoirs (mainly Lakes Sandsavatn and Blåsjø). The mean annual discharge for 1998-2005 is 68 m³/s, while the maximum discharge is 259 m³/s. Hylen power plant, run by Statkraft, is the only intake in Lake Suldalsvatn. It withdraws water between 61 and 51 m a.s.l and releases it into the fjord Hylsfjorden. The mean annual discharge for 1998-2005 is 111 m³/s, while the maximum discharge is 273 m³/s. Suldalslågen River is a natural stream flowing out of Lake Suldalsvatn into the fjord Sandsfjorden. The average flow is about 16 m³/s during the low flow season (November to April) and 57 m³/s during the high flow season (May to October). In addition, Lake Suldalsvatn receives lateral inflows from the neighbouring catchments, distributed around the lake and estimated at 23.8 m³/s for 1998-2005.

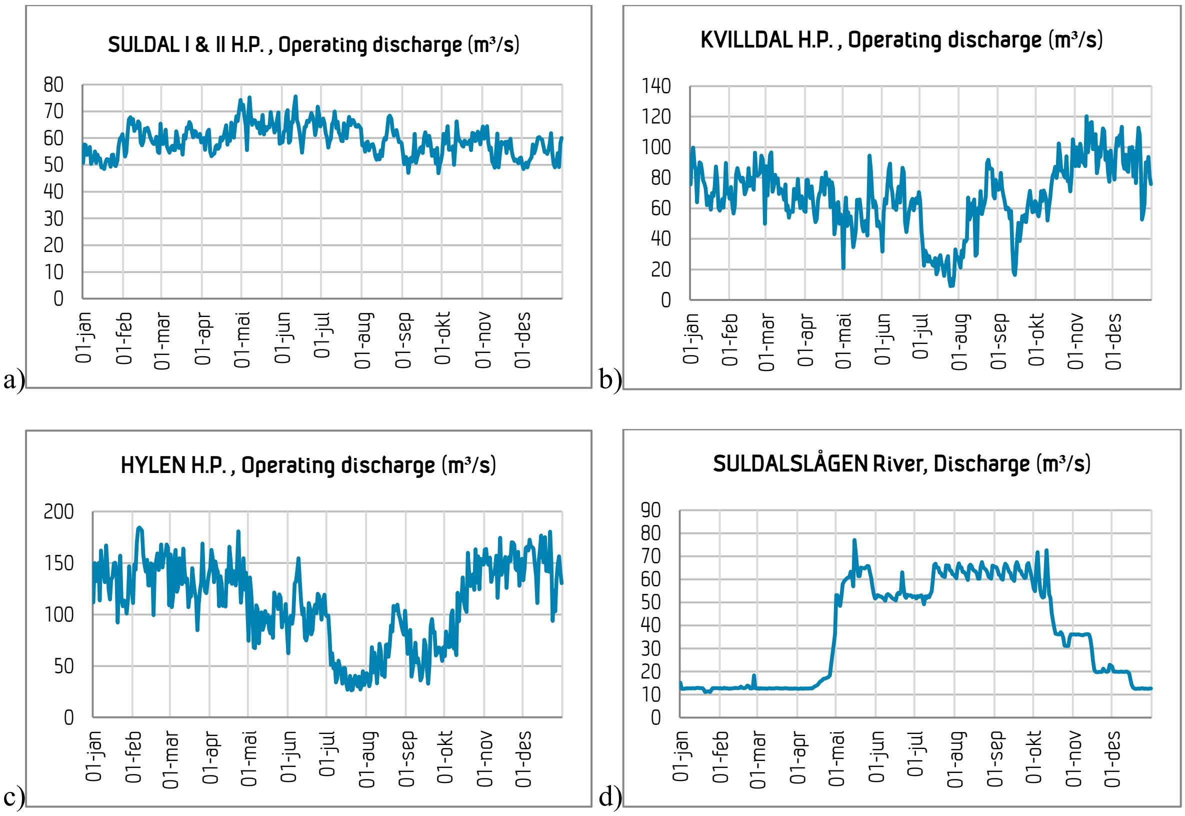


Figure 2. Mean discharge for 1998-2004 released by Suldal I & II (a), Kvilldal (b), and Hylen (c) power plants. Mean water flow for 1998-2004 discharged into Suldalslågen River (d).

Stage

The mean water level varies between 67.58 and 68.15 m a.s.l, based on the 1998-2004 time series (**Figure 3**). It shows a low stage season from November to April, and a high stage season from May to October. Daily fluctuations, with a mean value of 9 cm /day are relatively small compared to the altitude difference between LRWL and HRWL of 2 m. Ninety-five per cent of daily variations are inferior to 24 cm /day.

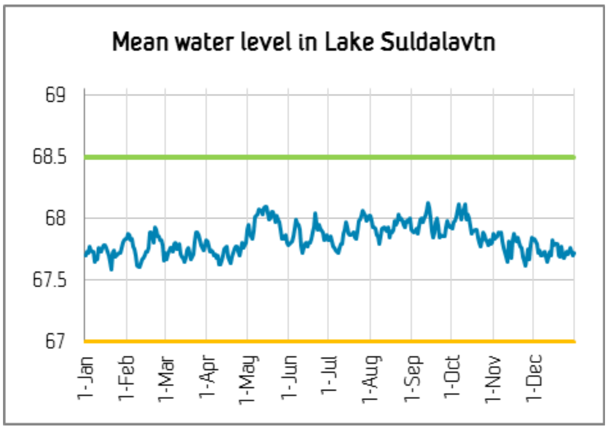


Figure 3. Mean observed water level in Lake Suldalsvatn for 1998-2005 (blue line). Altitudes of LRWL (green) and HRWL (orange).

Water temperature

Lake Suldalsvatn is generally thermally stratified from May to November. Stratification period and length are highly dependent on the meteorological conditions and inflows, and thus vary from year to year. Observations in 2001 show that the lake is stratified (Summer stratification) during more than 7 months (**Figure 4, Figure 5**), and the temperature difference between the surface and the 50 m-deep layers reaches 11ºC at its maximum in July. Two seasonal turnovers, in spring and fall, allow a complete mixing in the first fifty meters of the water column (where observations are available). In 2001, an inverse stratification took place in winter and lasted one month. Observations in the layers between the surface and 50 m show daily fluctuations of temperature of several degrees Celsius.

Temperature conditions in Lake Suldalsvatn act directly on water temperature in the downstream river Suldalslågen. Observations from 1998 to 2005 (**Figure 6**) show that temperature varies between 2ºC at the coldest point in February, and 11 to 16ºC depending on the year at the warmest point in August.

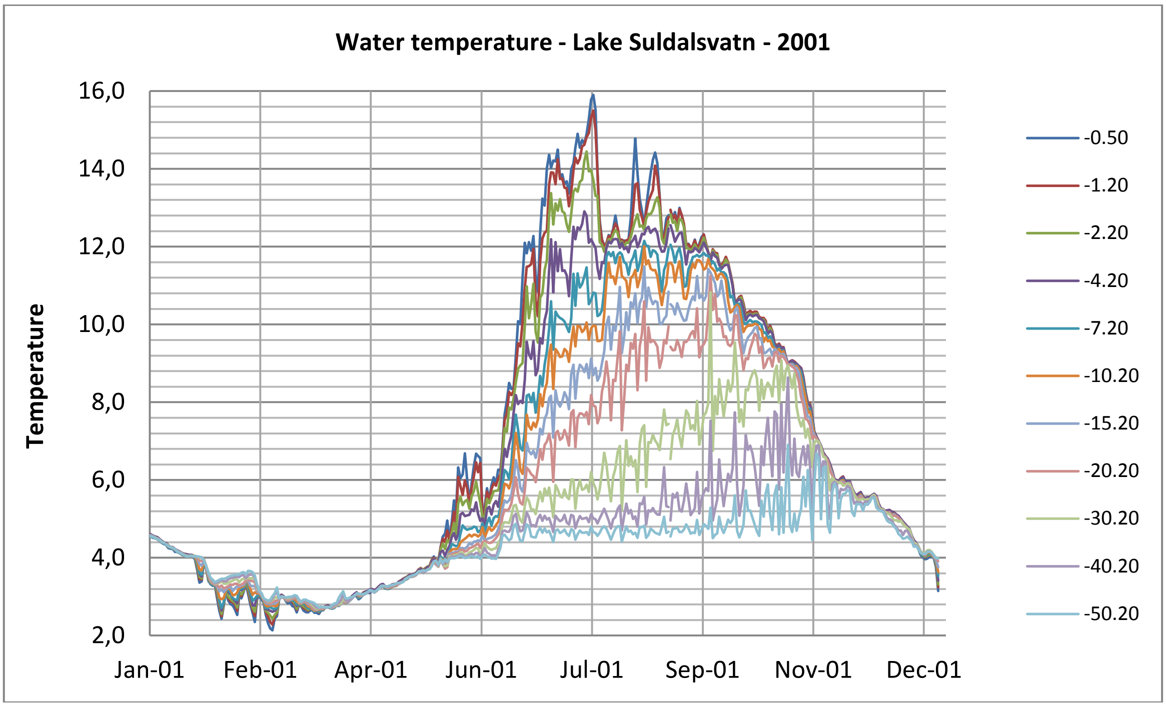


Figure 4. Daily averaged temperature observed for layers at -0.5, -1.2, -2.2, -4.2, -7.2, -10.2, -15.2, -20.2, -30.2, -40.2, and -50.2 m under the surface in 2001. NVE station nº 36.73.3.1003.2.

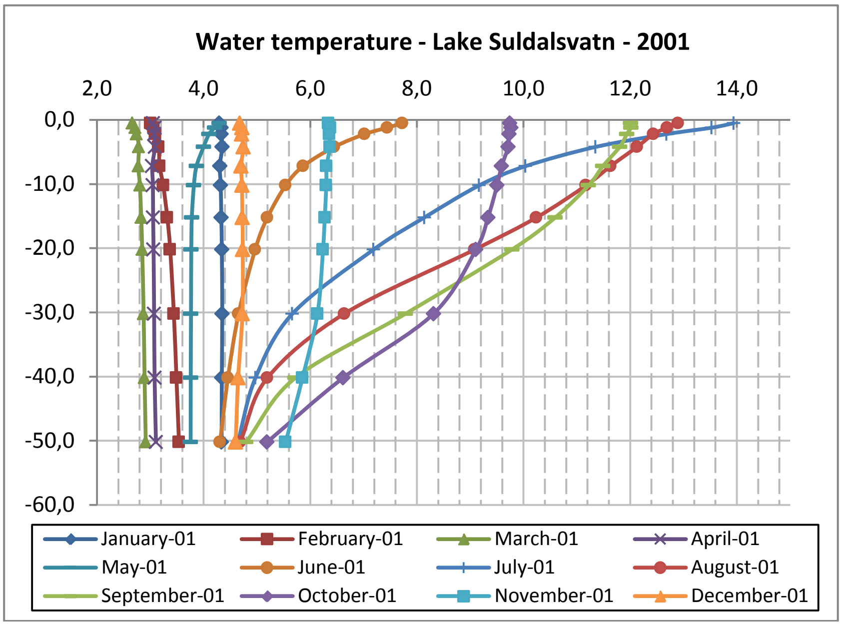


Figure 5. Monthly averaged vertical profiles of temperature observed in 2001 at NVE station nº 36.73.3.1003.2.

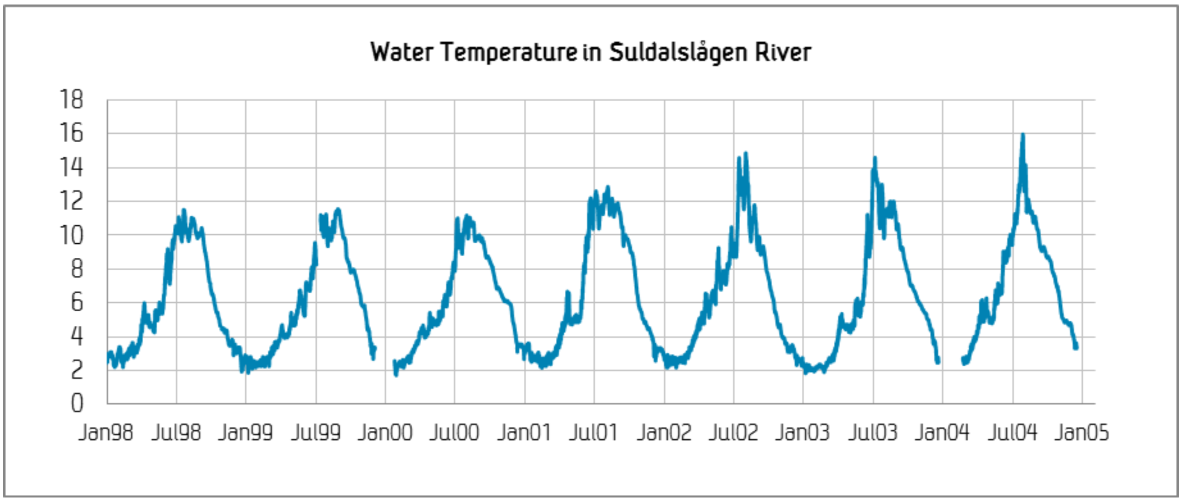


Figure 6. Water temperature observed in Suldalslågen River for 1998-2005. Observations are registered by a temperature logger located at the outlet of the lake. *Source Statkraft*.

Meteorological conditions

In 2001, observations show that air temperature (**Figure 7**) is positive from April to November, and reaches a maximum of 21 ºC in July. Temperature is oscillating between positive and negative values from Mid-November to end of March, and reaches a minimum of -13 ºC in January.

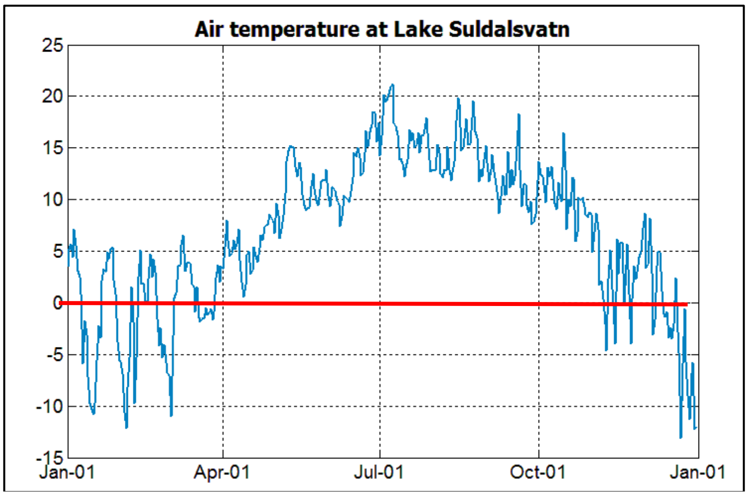


Figure 7. Observed air temperature in 2001 at Prestvika meteo station (owned by Statkraft), located at Lake Suldalsvatn.

The wind rose plot (**Figure 8**) shows the distribution of wind speed and distribution observed in Suldalsvatn from 1999 to 2005. Wind blows mainly from two directions: North-East and North-West, which correspond to the longitudinal and transversal directions. Wind speed is considered as weak (under 0.5 m/s) in about thirty-nine per cent of the days. It ranges between 0.5 and 5 m/s in fifty-three per cent of days, and it is over 5 m/s in 6 per cents.

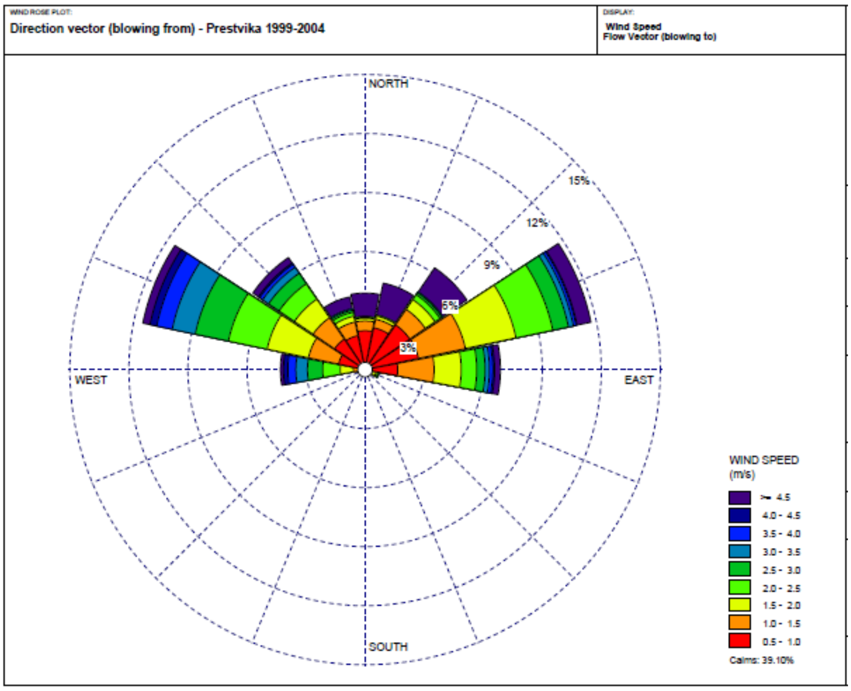


Figure 8. Distribution of wind speed and direction (blowing from) observed at Prestvika meteo station *(Stakraft)* for 1999-2005.

2.3 Model set-up

In order to assess the hydrodynamics changes due to the installation of a pump-storage power plant, the three-dimensional (3-D) hydrodynamic model GEMSS® was applied to Lake Suldalsvatn. GEMSS® is a general-purpose modeling package for simulating 3-D flow, transport, sediments and biological processes in water systems such as rivers, lakes, reservoirs, estuaries, wetlands and coastal regions. The GEMSS® model was is developed by ERM's Surface water Modeling Group in Exton, Pennsylvania (http://www.erm-smg.com). The numerical model solves the hydrostatic hydrodynamic equations and transport equations in 3-D (x, y and z) and computes time-varying velocities, water surface elevations, and water quality constituent concentrations in water-bodies. The vertical momentum dispersion coefficient and vertical shear is presently evaluated from a Von Karman relationship modified by the local Richardson number [1]. The latter is defined as the ratio of vertical buoyant acceleration to vertical momentum transfer. The computations are done on a horizontal and vertical grid that represents the water-body bounded by its water surface, shoreline, and bottom. Various finite difference numerical schemes are available for the solution of the equations. Included in the computations are boundary conditions formulations for friction, wind shear, turbulence, inflow, outflow, surface exchange, and water quality kinetics. For the details of model capabilities, the reader is referred to the user’s manual [1].

Two different hydrodynamic model grids are set-up and used, depending on the physical parameters which were analysed. One grid with a coarse horizontal resolution is used to calibrate the model, and simulate long periods for temperature conditions. It contains 54 x 90 x 36 grid cells (X, Y, Z), 11 048 of which are active cells. The horizontal discretization of each computational cell (Dx, Dy) is 262 x 322 m². The vertical discretization consists in 36 layers of increasing thickness from 2 to 20 m. The second grid is curvilinear (non-orthogonal) and follows the shoreline. It has a slightly finer horizontal resolution, and is used to simulate currents around hydropower plants. The it contains 99 x 106 x 36 grid cells (X, Y, Z), The vertical discretization is the same as the coarse grid. As the computational cost of the second grid being much higher than the coarse grid, it has been decided to run only short-period simulations to evaluate the distribution of the currents in Lake Suldalsvatn.

Table 2. Thickness and depth of the simulated layers.

	Layer number		
	1 to 15	16 to 25	26 to 36
Layer thickness (meters)	2	5	20
Layer depth	0 to 30	30 to 80	80 to 300

The first layer number represents the surface layer.

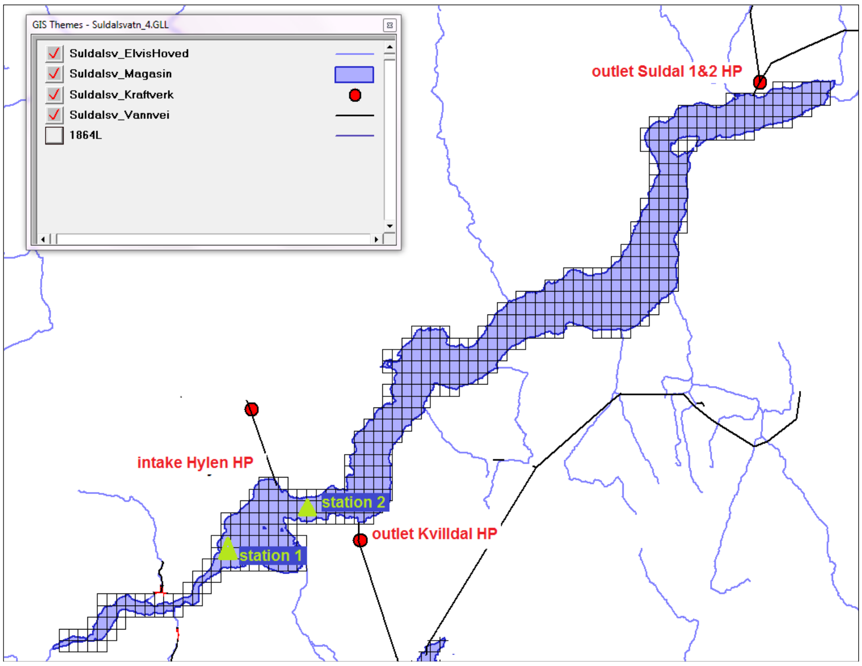


Figure 9. Coarse computational grid of Lake Suldalsvatn.

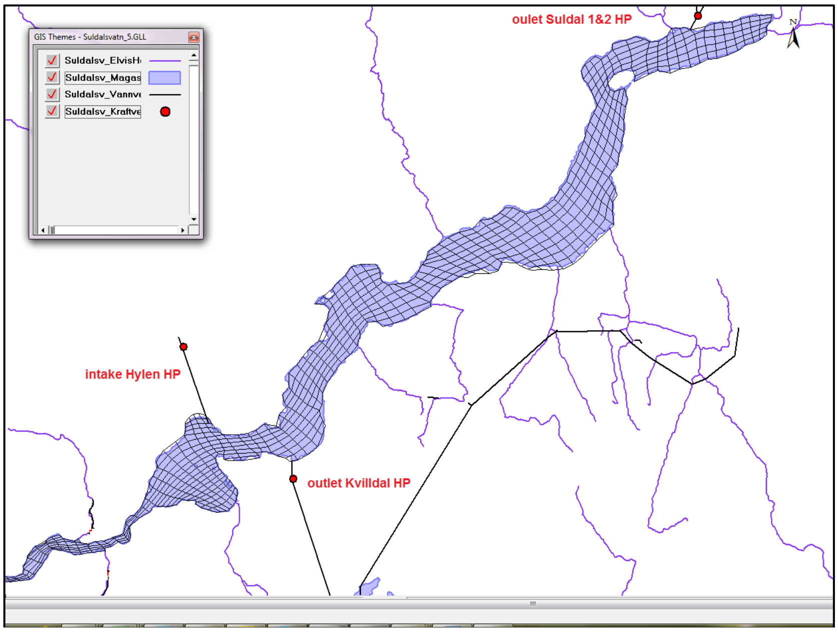


Figure 10. Curvilinear computational grid of Lake Suldalsvatn.

Input data to the numerical model consist of meteorological data (wind speed, wind direction, air temperature, cloud cover, dew point) and flows data (inflows discharge, inflows temperature, outflow discharge). Solar radiation is computed by a specific module within the model. All input data have hourly resolution, which allow the simulation of day/night variations.

Table 3. Input data characteristics.

Input data	Source	Station	Comments
Meteorological data			
Wind	Statkraft data	*Station Prestvika*	*Local meteo station*
Air temperature	Statkraft data	*Station Prestvika*	*Local meteo station*
Precipitation	Statkraft data	*Station Prestvika*	*Local meteo station*
Cloud cover	Met.no	*Station 46610 Sauda*	
Dew point temperature	Met.no	*Station 46610 Sauda*	
Pressure	Met.no	*Station 46610 Sauda*	
Temperature			
Kvilldal HP	NVE data base	*Station 36.64*	
Suldal HP	NVE data base	*Station 36.64*	
Lateral inflow	NVE data base	*Station 36.68*	Unregulated river Hamrabøåna
Discharge			
Kvilldal HP	Statkraft data	*Measured*	
Suldal HP	Hydro data	*Measured*	
Lateral inflow	Statkraft data	*Estimated*	
Suldalslågen River	Statkraft data	*Measured*	

A large number of simulations have been run in order to calibrate the model. Vertical measurements of temperature between depths 0 and 50 m, from 2 NVE stations (Station 1 and Station 2) for 2000, 2001 and 2002 were used as references for calibration. Several internal parameters related to hydrodynamics, computational scheme, water quality, meteorological, etc., as well as some boundary conditions, have been varied to best fit with observations. The model was particularly sensitive to following parameters: transport and constituent computation scheme, and solar radiation input. In addition, the model provides reasonable results from one year after the starting simulation date.

In this report results from the following simulations are presented and discussed:

- Simulation of the observed situation in 2001-2002 (**3**)
- Simulation of a hypothetical scenario, Pump1, including a pumped-storage plant (**4.1)**
- Simulation of a second hypothetical scenario, Pump 2, including a pumped-storage plant (**4.2**).

3 Validation of the model

3.1 Temperature conditions

Lake Temperature

Temperature data within Lake Suldalsvatn are available for 1999 – 2002. Two loggers located in the southern part, west of Kvilldal HP of the lake automatically registered temperature values every hour at eleven depths from the surface to 50 m. Station 1 is located by the downstream outlet of the lake (**Figure 9**), while Station 2 is close to the outlet of Kvilldal HP.
Comparison between observations and results of the simulations showed that the model is able to simulate the main temperature variations through the water column in Lake Suldalsvatn for the years 2001 and 2002.

Table 4. Vertical location of temperature loggers.

	Measurements depth										
Station 1	-0.5,	-1.2,	-2.2,	-4.2,	-7.2,	-10.2,	-15.2,	-20.2,	-30.2,	-40.2,	-50.2
Station 2	-1,	-1.5,	-2.5,	-4.5,	-7.5,	-10.5,	-15.5,	-20.5,	-30.5,	-40.5,	-50.5

When comparing the observed and simulated temperature at both Station 1 and 2 (**Figure 11 to Figure 14**), the following features are well simulated:

- Length of the vertical stratification period is approximately 6 months.
- Autumnal turnover (full mixing of the water column).
- The uppermost layer (at a depth of -1 meter) has a simulated temperature close to observations.

However some of the simulated characteristics do not fit accurately to observations.

- The temperature of mixed water column in autumn is slightly colder in the simulations.
- The weak inverse stratification (temperature is increasing from the surface towards the bottom) which occurs generally from January/February to March/April is too strong (up to 4 degree C difference) and lasts 3 to 4 months in the simulation.
- The difference in vertical temperature profiles between the two stations is hardly visible in the simulation while observations show a higher vertical gradient of temperature in Station 1 than in Station 2 due to intensive mixing induced by the HP's outlet.

The simulated vertical profile is a combination of observations at both Stations. The layers located from the surface to a depth of 15 m corresponds to observed temperature at Station 2, while the layer below 20 m are close to observed temperature at Station 1. It means that the model allow a strong mixing of the uppermost layers.

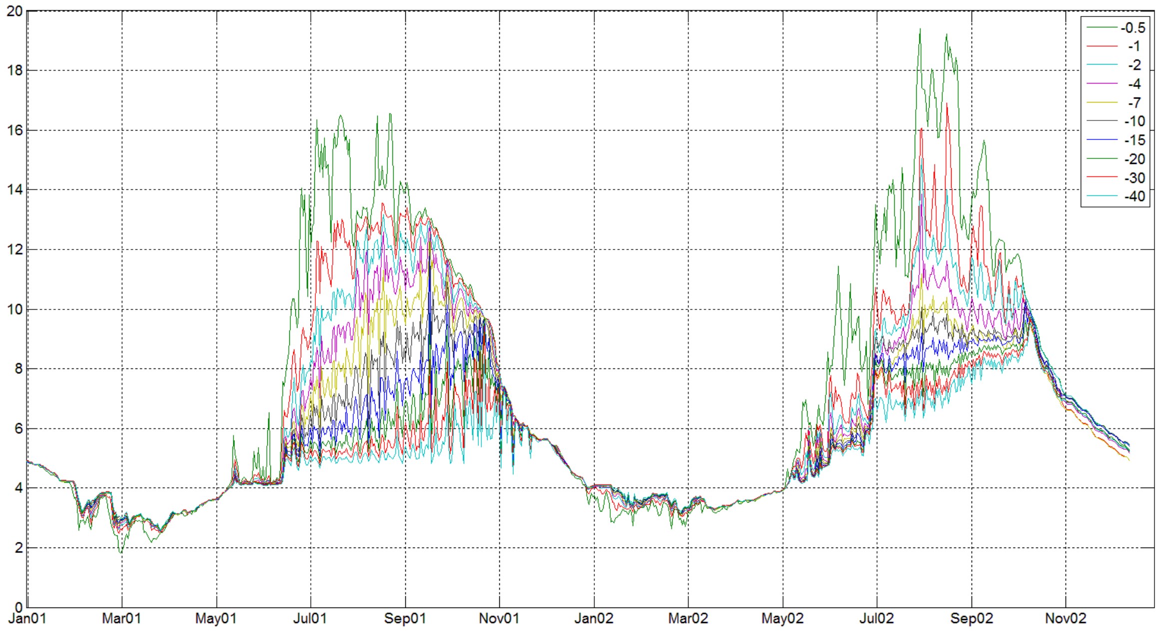


Figure 11. Station 1. Observed temperature of layers located at depths 0.5 to 40 m for 2001 and 2002.

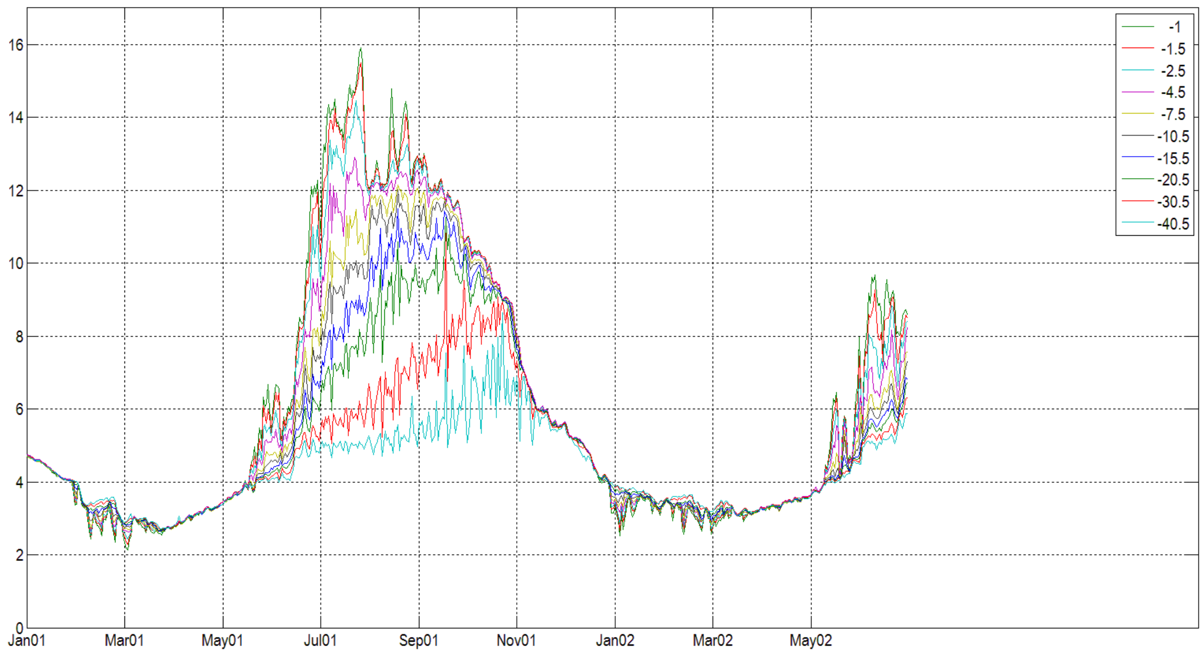


Figure 12. Station 2. Observed temperature of layers located at depths 1 to 40 m for 2001 and beginning of 2002.

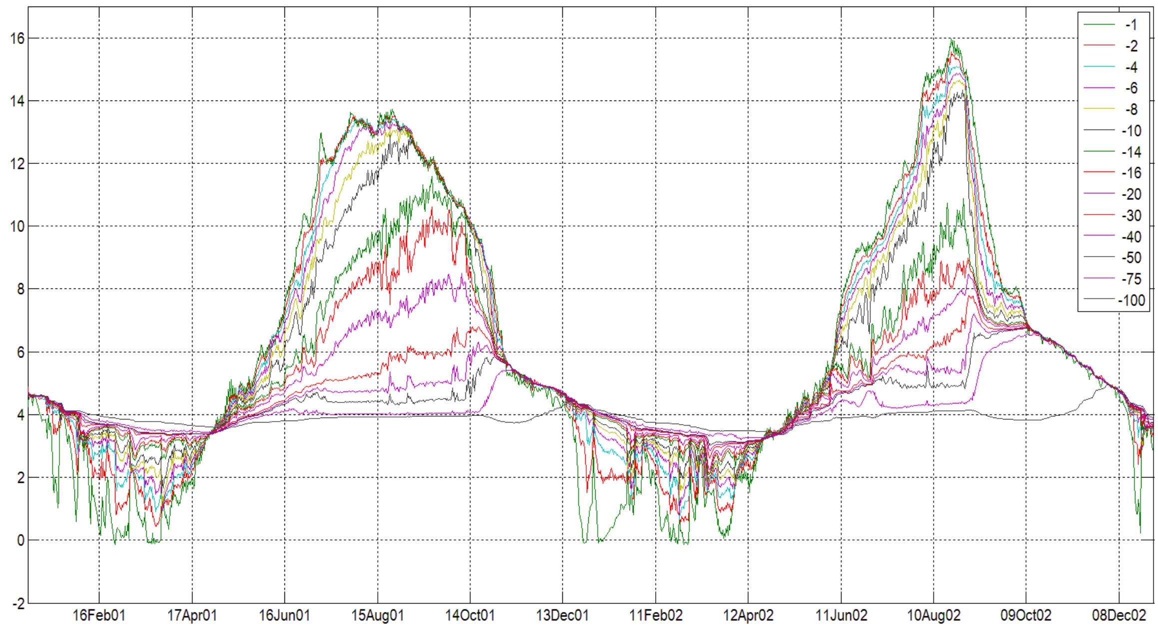


Figure 13. Station 1. Simulated temperature of layers located at depths 1 to 100 m for 2001 and 2002.

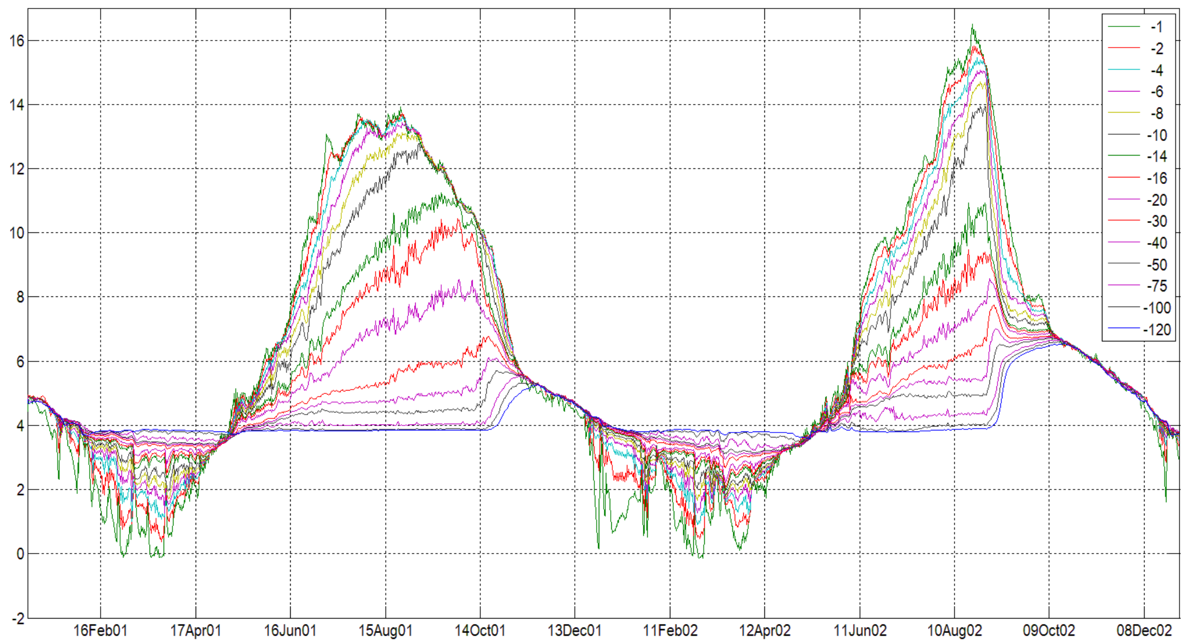


Figure 14. Station 2. Simulated temperature of layers located at depths 1 to 120 m for 2001 and 2002.

Downstream river temperature

Observed temperature in the river is highly correlated to observed temperature in the lake, with some differences (**Figure 15**).

- River temperature is warmer than the mixed water column temperature in the lake in spring. It is colder in autumn. Indeed, temperature conditions in the river are in general more influenced by air temperature fluctuations than temperature conditions in the lake are, because of lower volumes of water and a larger part of the water body exposed to the surroundings.
- River temperature is colder than the surface layer in summer, certainly because of more turbulent mixing, and also because of geographical characteristics of the lake's outlet, which is particularly shaded by vegetation and topography.
- River temperature is close to upper layers' temperature at the end of summer, when stratification weakens.

When comparing the observed temperature in the downstream river (Suldalslågen River) and the simulated temperature at the downstream outlet of the lake (southernmost lake boundary which provides characteristics of the water flowing out), we can see that the model provides relatively good temperature values for the river depending on the year. It reflects some of the features which were described above (**Figure 16**). However, the observed river temperature is warmer than the lake mixed water column temperature in autumn, due to an inaccuracy of the model in modelling the correct mixed water column temperature as explained below.

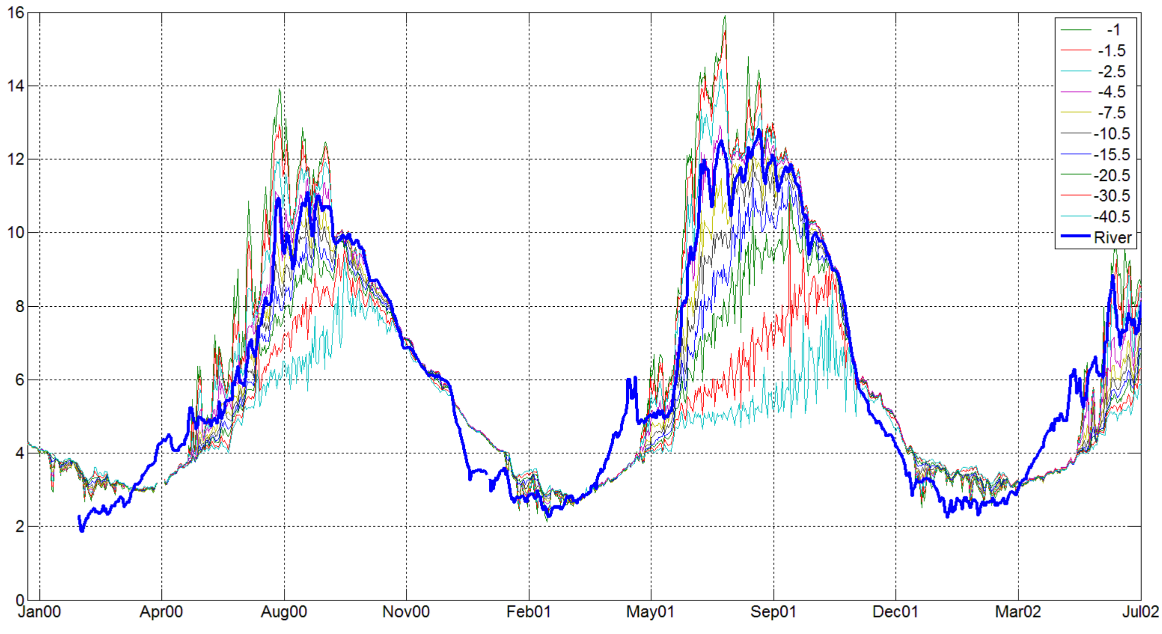


Figure 15. Observed temperature in the downstream river (blue tick line) and observed temperature of layers at depths 1 to 40.5 m, at Station 1, in the southern part of the lake.

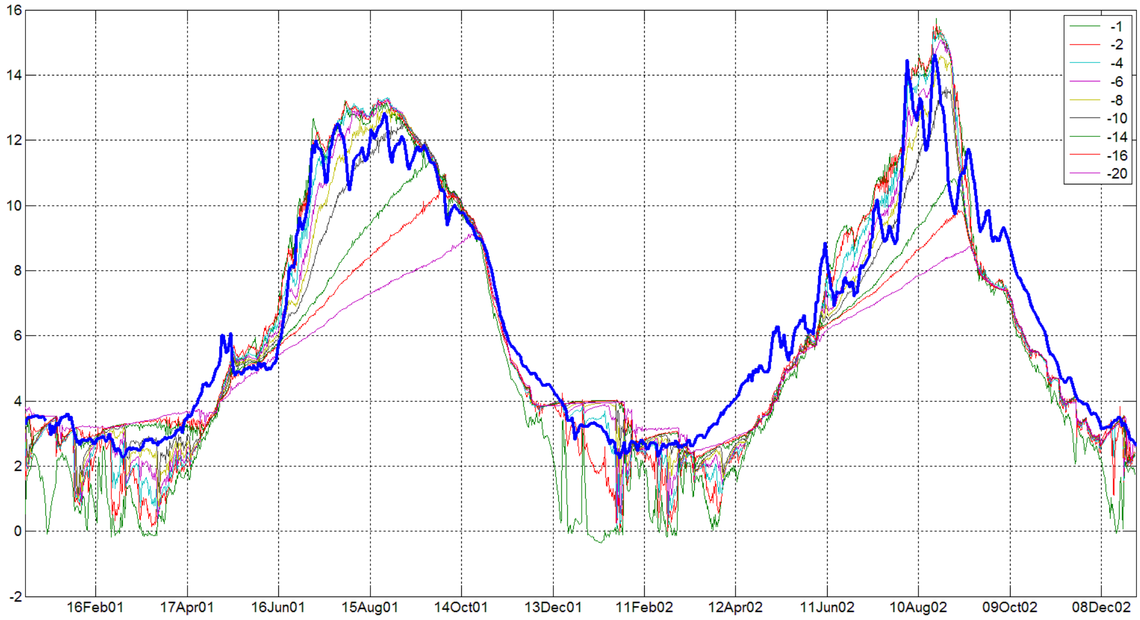


Figure 16. Observed temperature in the downstream river (blue tick line) and simulated temperature of layers at depths 1 to 20 m at the downstream outlet of the lake (southern boundary).

3.2 Map of currents

In natural lakes, currents are mainly driven by wind (surface and upper layers) and topography (intermediate and lower layers). Lake Suldalsvatn is used as a reservoir, and hydro-power related inflows and outflows induce also currents. In summer, wind is on average low and blows often towards South-West, while in in autumn/winter period, it is often stronger and blows towards North-East direction. Results of simulation at depths of 2 and 10 m are shown in **Figure 17 to Figure 22.**

a) Summer

The typical situation is wind blowing in South-West direction, and the 3 HP (Kvilldal HP, Suldal HP, Hylen HP) are running.

Layer at a depth of 2 m

The typical currents pattern just below the surface is (**Figure 17 and Figure 18**):

- A clockwise gyre next to Suldal HP, in the northern part of the lake, due to the inflow from the HP.
- Main current is flowing in South-West direction through the whole lake, following the topography
- A clockwise gyre next to Hylen HP, in the southern part of the lake, due to the HP's intake.
- A anticlockwise gyre in the southern pool of the lake, next to Kvilldal River.

Layer at a depth of 10 m

Looking carefully at the area located next to Hylen and Kvilldal HP which have their intake, outlet respectively at depths between 8 and 16 m the strongest currents can be identified (**Figure 19.**).

- The outflow from Kvilldal HP spreads northwards. While most of it turns westwards in a counter clockwise gyre and flows in downstream direction, a small part flows in the opposite direction, towards North-East part of the lake.
- The outflow from Kvilldal HP continues in the same direction until it encounters Hylen HP intake where it divides. One part flows in a clockwise gyre formed in front of the HP, and it is partly withdrawn through the intake. The second part continues the way downstream boundary.
- Like in the upper layers, there is a counter clockwise gyre in the southern pool of the lake, next to Kvilldal River.

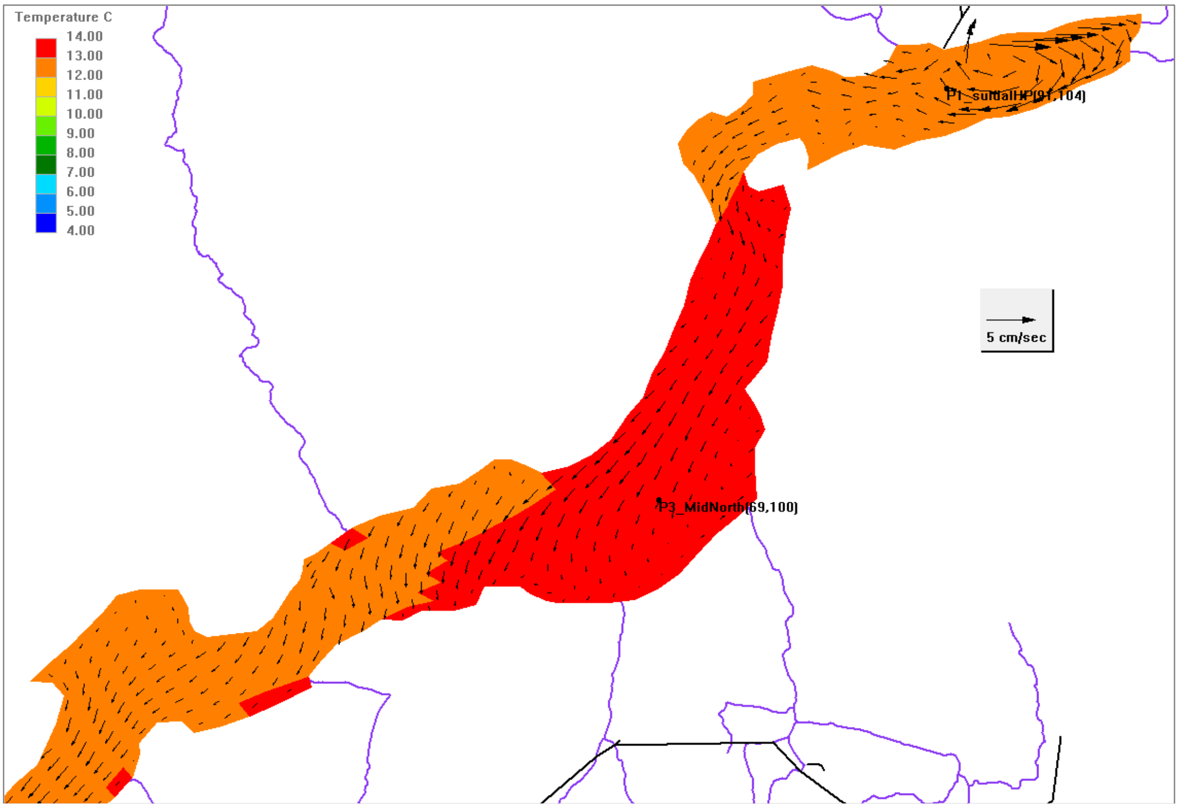


Figure 17. Main currents at a depth of 2 m in the North part of Lake Suldalsvatn in a typical summer situation. Arrows represents the horizontal velocity.

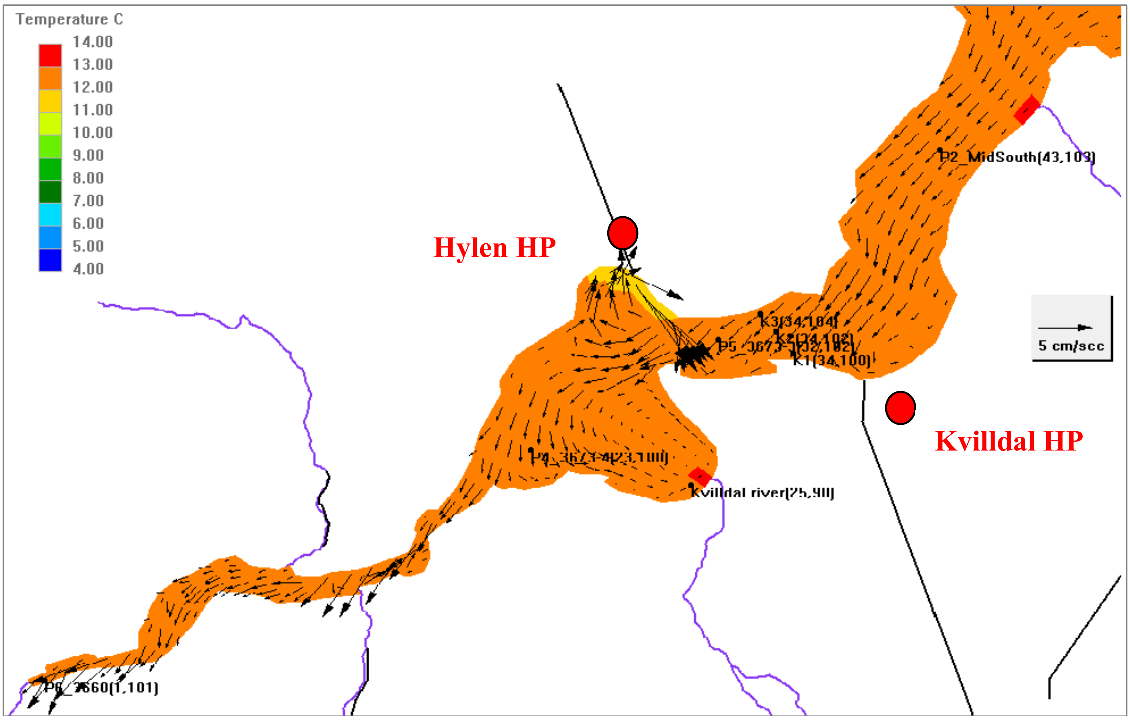


Figure 18. Main currents at a depth of 2 m in the South part of Lake Suldalsvatn in a typical summer situation. Arrows represents the horizontal velocity.

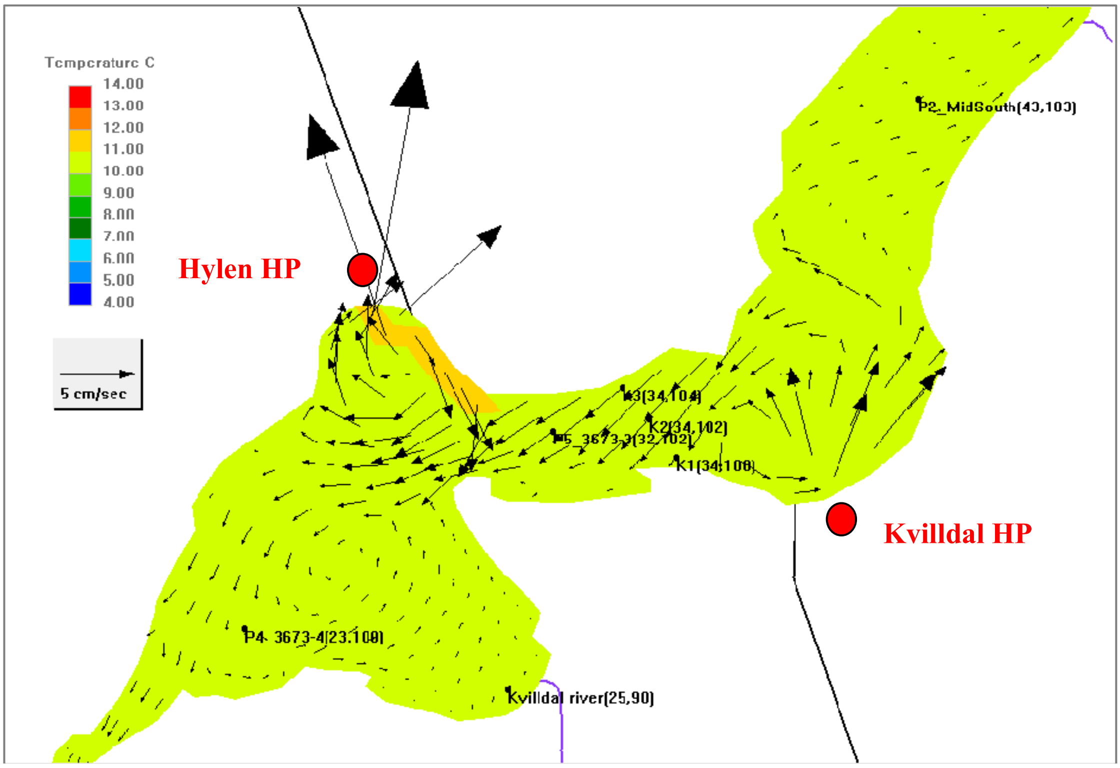


Figure 19. Main currents at a depth of 10 m in the South part of Lake Suldalsvatn in a typical summer situation. Arrows represents the horizontal velocity.

b) Autumn-winter

The typical situation is wind blowing in North-West direction, and the 3 HP (Kvilldal HP, Suldal HP, Hylen HP) are running.

Layer at a depth of 2 m

The typical currents pattern just below the surface is (**Figure 20 and Figure 21**) :

- Main current is flowing in North-West direction through the whole lake, following the topography
- A clockwise gyre next to Hylen HP, in the South part of the lake, due to the HP's intake.

Layer at a depth of 10 m

Looking carefully at the area located next to Hylen and Kvilldal HP, which have their intake, outlet respectively, at this level main currents can be identified (**Figure 22**).

- The outflow from Kvilldal HP spreads northwards and mixes with the wind-driven current flowing in South-West direction in this specific are, because of topography. The outflow from Kvilldal HP continues in the same direction until it encounters Hylen HP intake where it divides. One part flows in a clockwise gyre formed in front of the HP, and it is partly withdrawn through the intake. The second part continues the way towards the downstream boundary of the lake.
- Like in the upper layers, there is a counter clockwise gyre in the southern pool of the lake, Kvilldal River discharges.

SINTEF

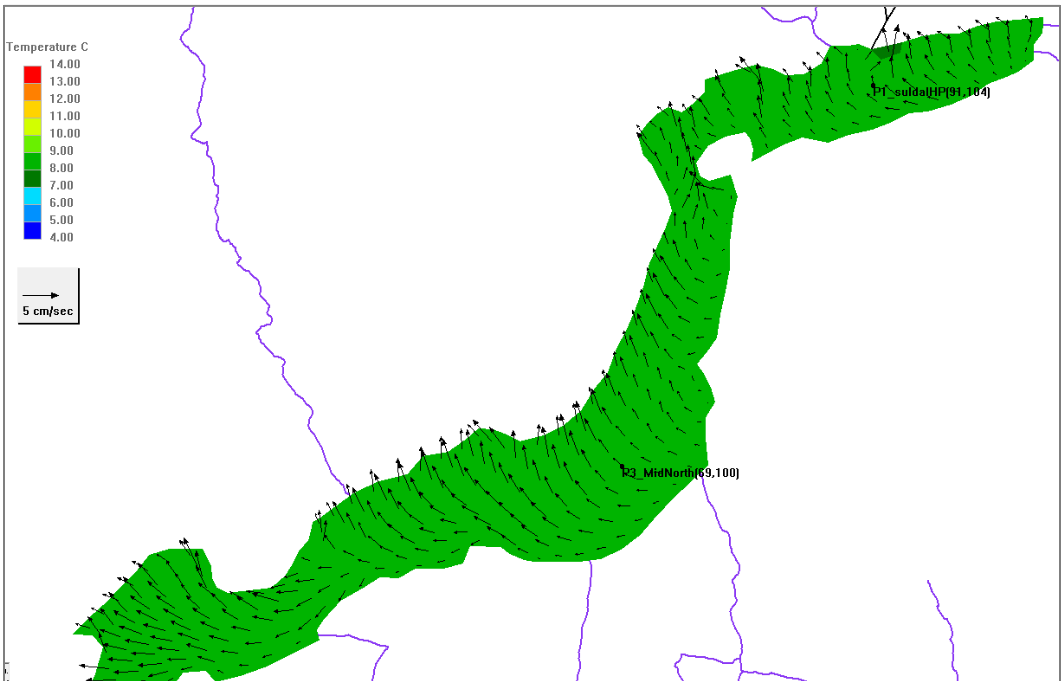


Figure 20. Main currents at a depth of 2 m in the North part of Lake Suldalsvatn in a typical autumn/winter situation. Arrows represents the horizontal velocity.

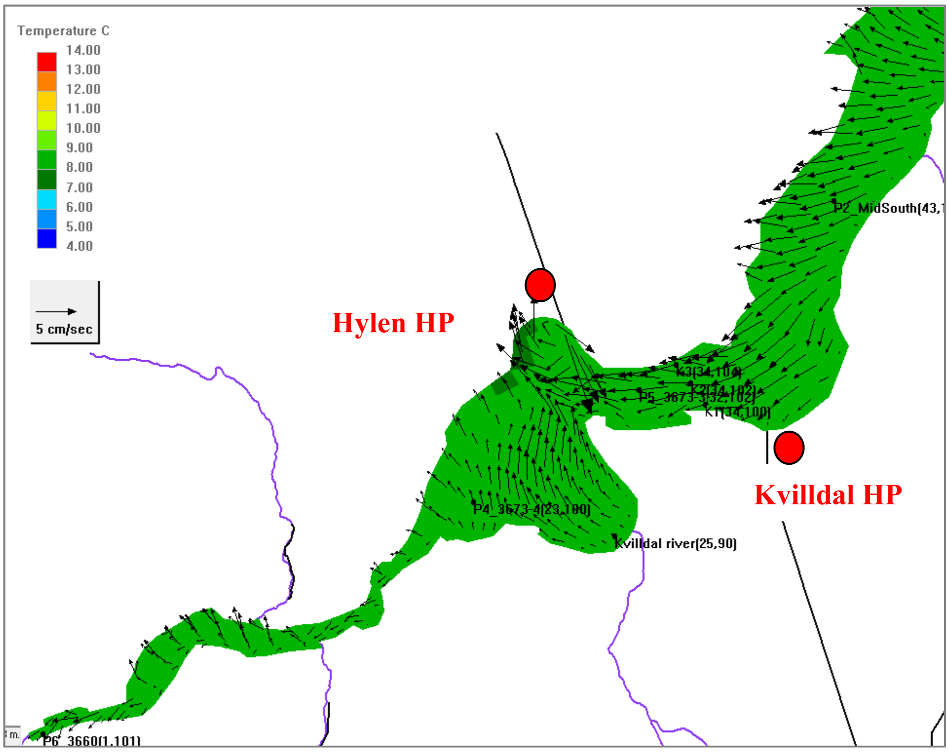


Figure 21. Main currents at a depth of 2 m in the South part of Lake Suldalsvatn in a typical autumn/winter situation. Arrows represents the horizontal velocity.

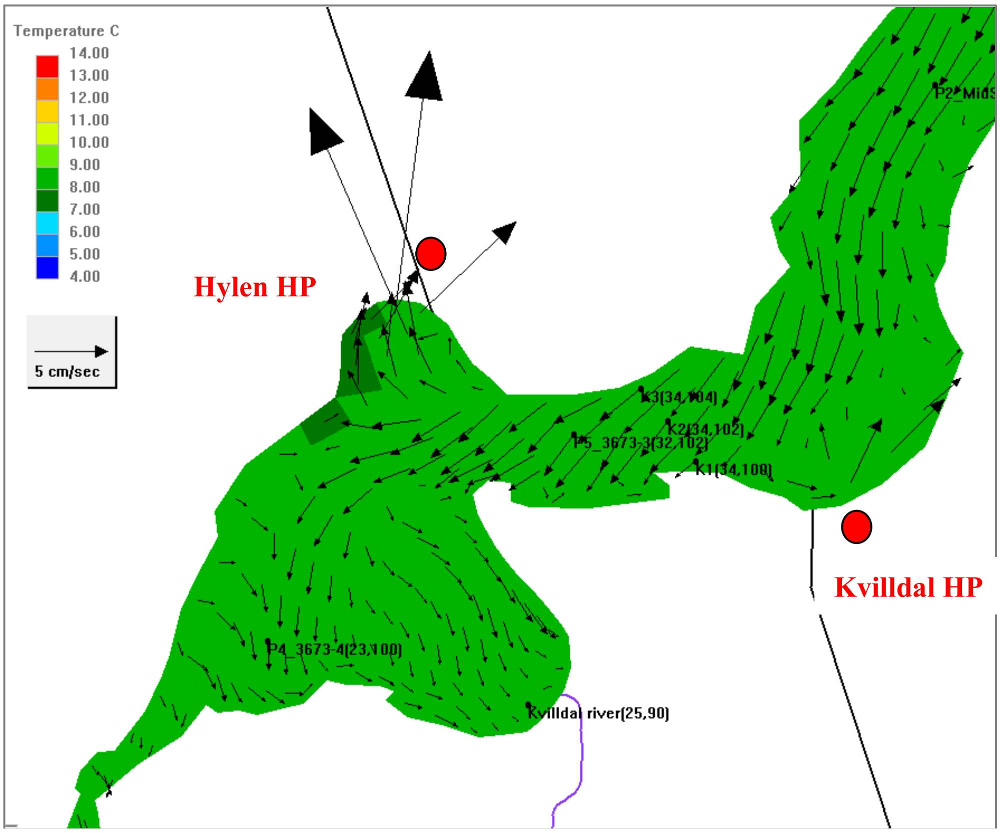


Figure 22. Main currents at a depth of 10 m in the South part of Lake Suldalsvatn in a typical autumn/winter situation. Arrows represents the horizontal velocity.

Previous field observations to map the currents in Lake Suldalsvatn [3], and a study of currents in the neighbourhood of Kvilldal and Hylen HPs carried out with a numerical model [4] have shown similar patterns and contribute to validate the model. In particular, the outflow from Kvilldal HP takes a swing northwards before it flows westwards in the direction of the downstream river Suldalslågen. The counter clockwise circulation off Kvilldal HP is due to the right topographic angle of the shore at this location. A small part of the outflow is flowing northwards until it meets the main current. Since the outlet of Kvilldal HP is located near the middle-point of the recirculation, it only contributes for a small share to the northwards current. When Hylen HP is running at middle or full capacity, the main part of tail-waters from Kvilldal HP will be withdrawn at the intake. Since the intake is submerged, the highest velocities are found at depths of 10-20 m.

Ice cover

At both stations 1 and 2, observations show that the temperature of the uppermost layer remains above 2 ºC during the observations period, leading to no winter ice cover at these locations. Nevertheless, it does not give information about ice cover presence in other parts of the lake, especially in the more shallow regions where ice is expected in winter.
The results of the model regarding the modelling of winter period remain far from observations. Further work to calibrate the model for the specific winter period is required.

4 Scenario including pumped-storage: hydrodynamics consequences

The pumping scenarios consist of setting-up a new pumped-storage power plant (PSP) next to the existing hydropower plant Kvilldal. The PSP is supposed to be day/night reversible, meaning producing electricity and release tail water into the lake (production phase) during day; and withdraw water from the lake and pump it to a higher reservoir (pumping phase) during night (**Table 5**). The amount of water released (300 m^3/s) and withdrawn (253 m^3/s) are based on a previous analysis of case Suldalsvatn [2]. The length of both the production and pumping phases is chosen in order to have a daily balanced water budget for the PSP (same amount of water released and withdrawn into the lake within one day).

The model set-up established to simulate the current situation without PSP (2.3 and 3) is preserved. The new PSP is set-up in addition to the current situation set-up, at a distance of about 250 m from the existing Kvilldal HP (**Figure 23**). Two scenarios are run, each one having a different temperature scenario for water released into Lake Suldalsvatn.

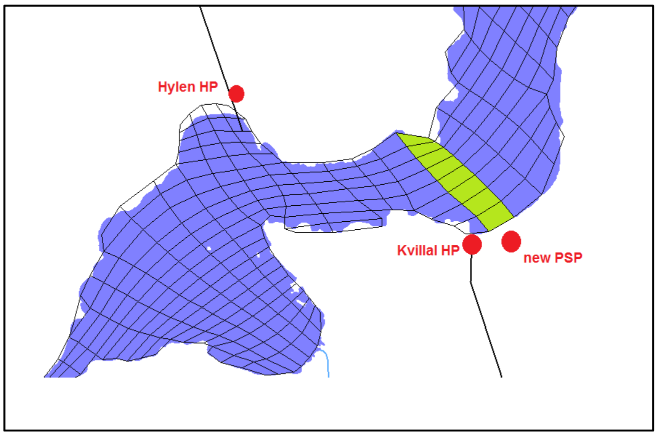


Figure 23. Location of the new pumped-storage plant. In green, a vertical section located in front of the PSP.

Table 5. Characteristics of the production and pumping phases

	Production phase	Pumping phase
Discharge (m^3/s)	300	253
Length (hour)	11	13
Time of the day	8h-18h	19h-7h

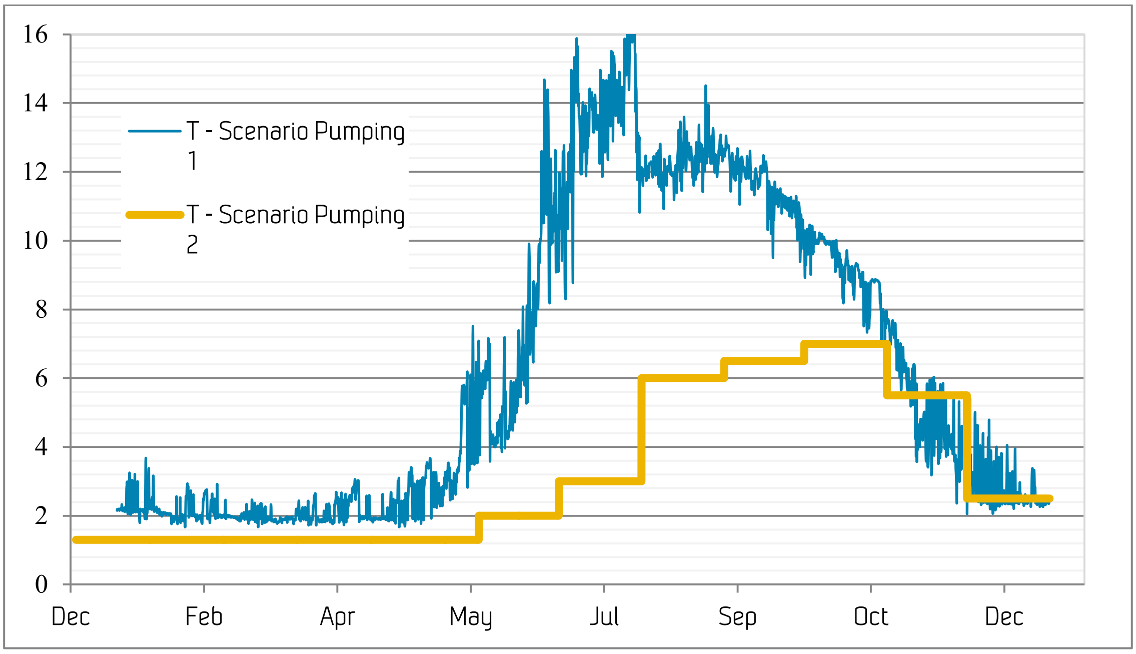


Figure 24. Temperature of water released during production phases in the pumping Scenario 1 (blue line), and the pumping Scenario 2 (orange line).

4.1 Pumping Scenario 1

In Pumping Scenario 1 (Sc1), it is assumed that during production phases, the water released by the new reversible PSP, has the same characteristics as the water released today by Kvilldal HP (**Figure 24**). Water originates from different storage reservoirs located at different altitudes, depending on availability of water. Observed temperature variations in 2001 are set-up as input for both simulated years 2001 and 2002.

4.1.1 Consequences of PSP operation on the temperature of the lake

In Pumping Scenario 1, the length as well as the stability of the summer stratification is highly reduced. Effects are particularly strong for 2001, which was a year with a long stratification period. The length of the stratification is reduced to 4-5 months, from May-June to end of October, depending on the year. The vertical mixing is stronger in that scenario than in the current situation. As a result, upper layers (between the surface and the depth of 20 m) have a colder temperature, while intermediate and low layers have a warmer temperature. The surface layer is about 3 ºC colder at the time when it reaches its maximum. A the end of summer, the difference between both scenarios reaches between 3.5 and 4 ºC depending on the year, since the stratification ends up about 2 months early in Pumping Scenario 2. Layers at depth of 14 m until the bottom are more mixed than today and their temperature reaches 9 ºC at the end of summer.

Changes in lake's temperature affect also the downstream river Suldalslågen, with a certain variability according to the season: strong differences in summer and autumn, with a gap of 3 to 4 ºC between today and Scenario 1; relatively small differences in winter and spring, with a gap of 0 to 0.5 ºC.

In winter and spring, temperature in the river is slightly warmer compared to the today situation, since temperature in the upper layers of Lake Suldalsvatn is slightly warmer in Sc1. However, since the temperature variation induced by pumped-storage in winter/spring is in the same range as uncertainties of the model to simulate lake's temperature for that period, it is no possible to evaluate how strong changes are.

In summer, the lake temperature's rise is delayed of approximately 2 weeks, leading to a slightly later rise in the river. During the whole summer, the temperature in the river is colder by 2 to 4 ºC, due to an intense vertical mixing which cools down the layers above a depth of 20 m. Then, the situation is reversed: from September-October, temperature in the river is warmer by about 1 ºC.

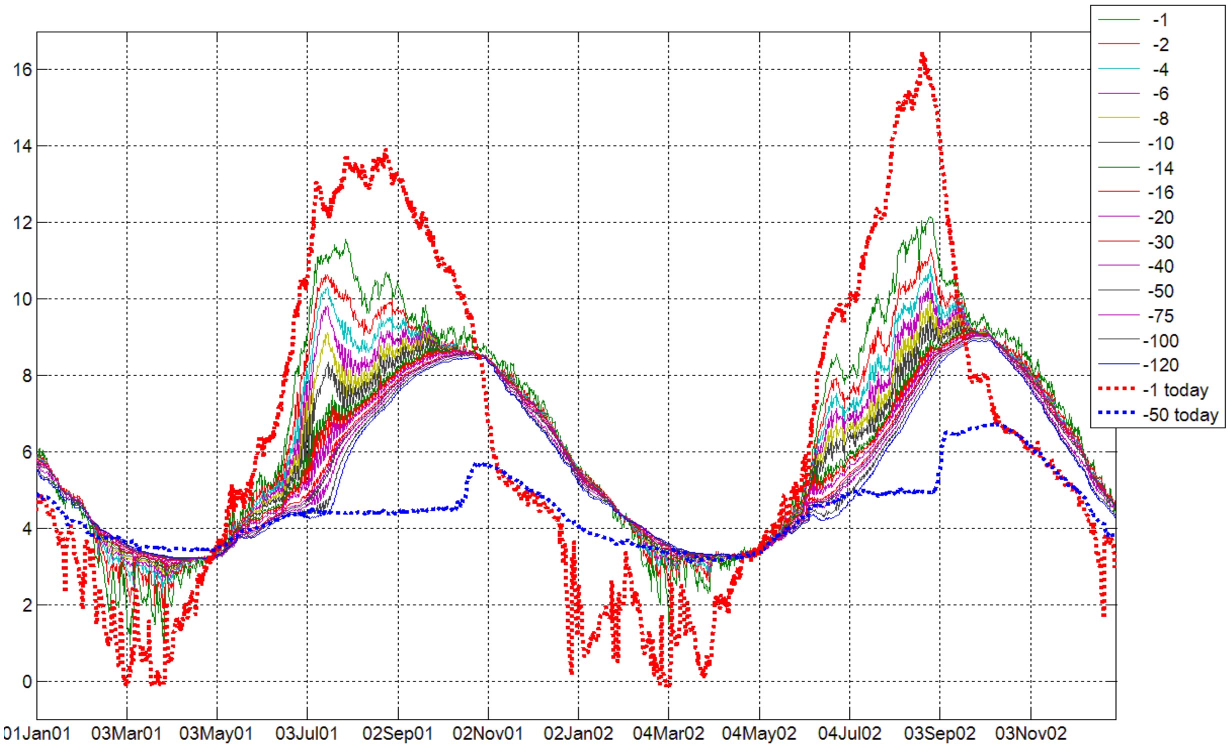


Figure 25. Simulated temperature of layers at depths 1 to 120 m in the southern part of the lake from Pumping Scenario 1 (continuous lines), and simulated temperature of layers at 1 and 50 m for today's situation (dot lines).

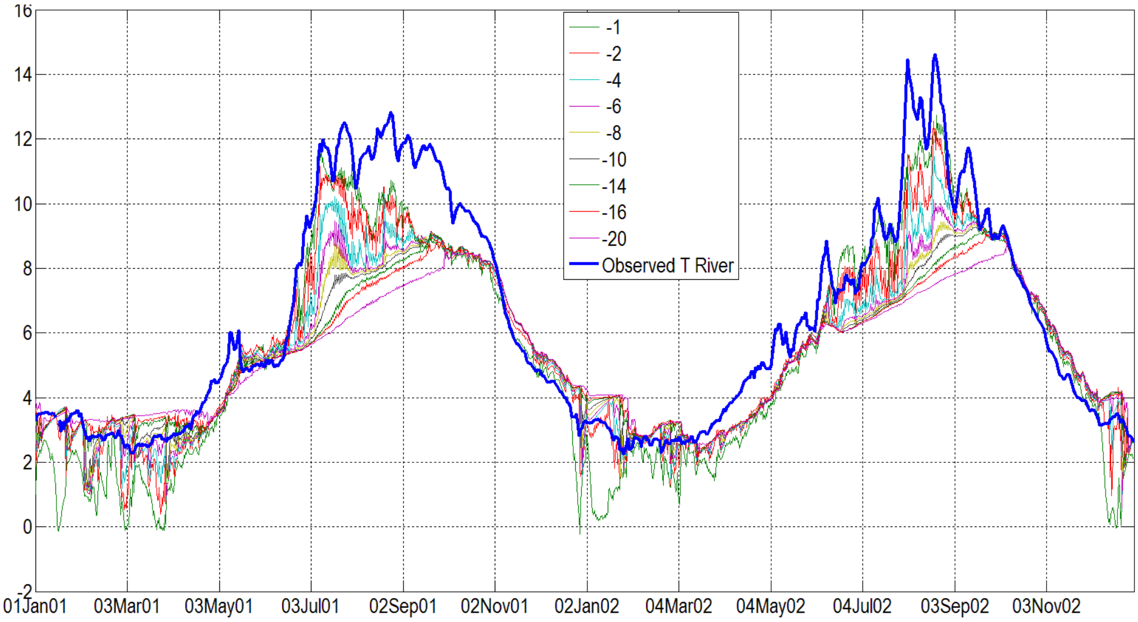


Figure 26. Simulated temperature of layers at depths 1 to 20 m at the downstream outlet of the lake from Pumping Scenario 1 (continuous lines), and observed temperature in Suldalslågen River (thick blue lines).

4.1.2 Consequences of PSP operation on currents

4.1.2.1 Horizontal distribution of currents near the PSP

In scenarios including a PSP, there is alternation of 2 distributions of currents as a consequence for alternation of production phase and pumping phase. A new tunnel is set-up at depths 8 to 16 m, like tunnels of the existing HP Hylen and Kvilldal. The map of currents at a depth of 10 m (**Figure 27 to Figure 30**) is described here.

a) Summer

The typical situation is wind blowing in South-West direction and the 3 HP (Kvilldal HP, Suldal HP, Hylen HP) and the new PSP are running.

During production phases, the distribution of currents at a depth of 10 m (**Figure 27**) is similar to the map of currents observed today. Some features differ as follows:

- The velocity of the flow released in Lake Suldalsvatn is twice larger
- A current flowing towards the upstream boundary (North-East) of the lake is observed
- A clockwise gyre with low currents is observed in the southern pool of the lake, where Kvilldal River discharges.

During pumping phases, new currents appear in the area located around Hylen and Kvilldal HPs. at a depth of 10 m (**Figure 28**):

- Water masses from opposite directions (North-East, and South-West) flow towards the PSP, into a clockwise gyre before being withdrawn
- In the area located between Hylen and Kvilldal HP, the strong westwards current observed today has disappeared.

b) Autumn

The typical situation is wind blowing in North-West direction and the 3 HP (Kvilldal HP, Suldal HP, and Hylen HP) and the new PSP are running.

During production phases, the distribution of currents at a depth of 10 m (**Figure 29**) is similar to the map of currents observed today, except the velocity of the flow released in Lake Suldalsvatn which is twice larger.

During pumping phases, at a depth of 10 m, the main changes appear in the area located between Hylen and Kvilldal HPs (**Figure 30**): the strong westwards current observed when no PSP is running is broken and replaced by 2 currents flowing in opposite directions, North-East, and South-West, towards the PSP and Hylen HP, respectively.

N.B.: The results of simulation providing high local flow velocities in the neighbourhood of the hydropower plants might be affected by the choice of horizontal grid resolution. Further investigation with a finer grid is necessary to assess values of these flows. The circulation however should remain the same with a finer grid.

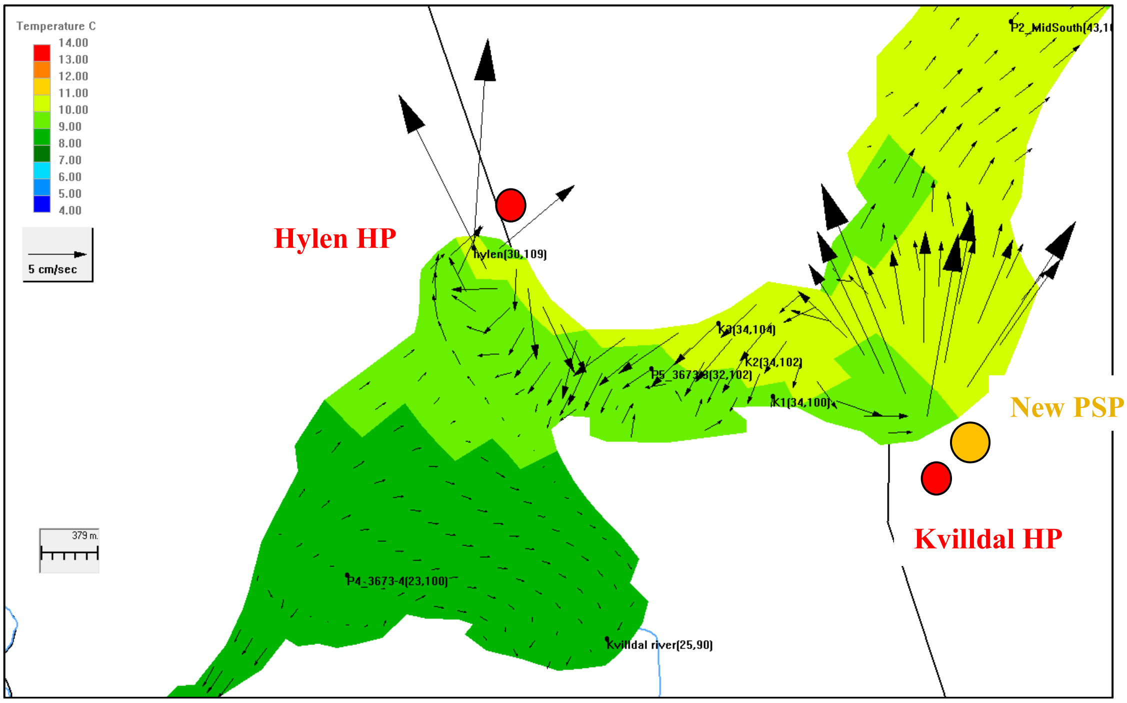


Figure 27. Pumping Scenario 1. Production phase. Main currents at a depth of 10 m in the South part of Lake Suldalsvatn in a typical summer situation. Arrows represents the horizontal velocity (Time of simulation 11 August 16h00).

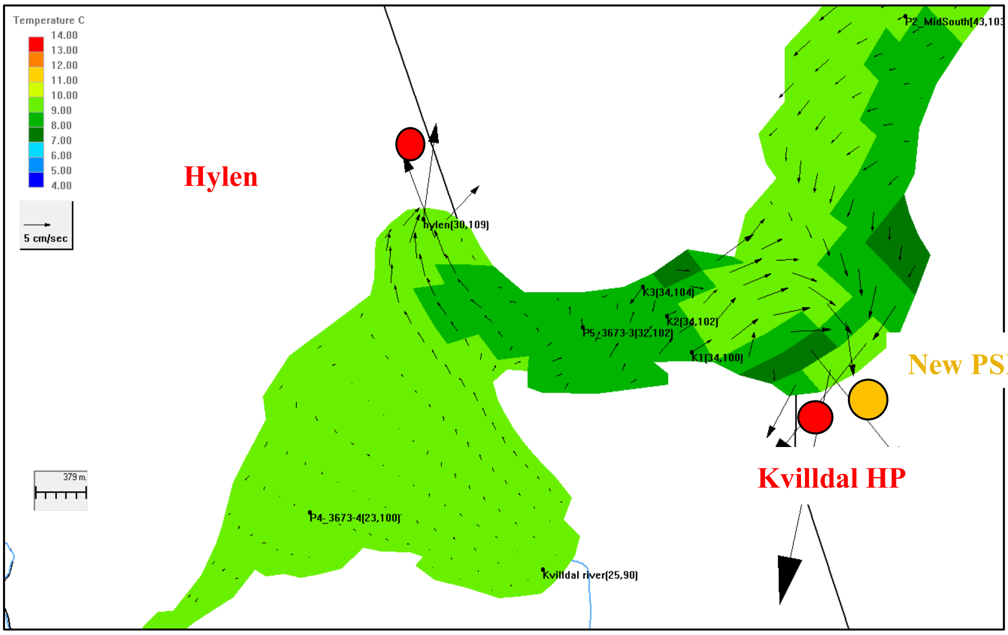


Figure 28. Pumping Scenario 1. Pumping phase. Main currents at a depth of 10 m in the South part of Lake Suldalsvatn in a typical summer situation. Arrows represents the horizontal velocity (Time of simulation 12 August 03h00).

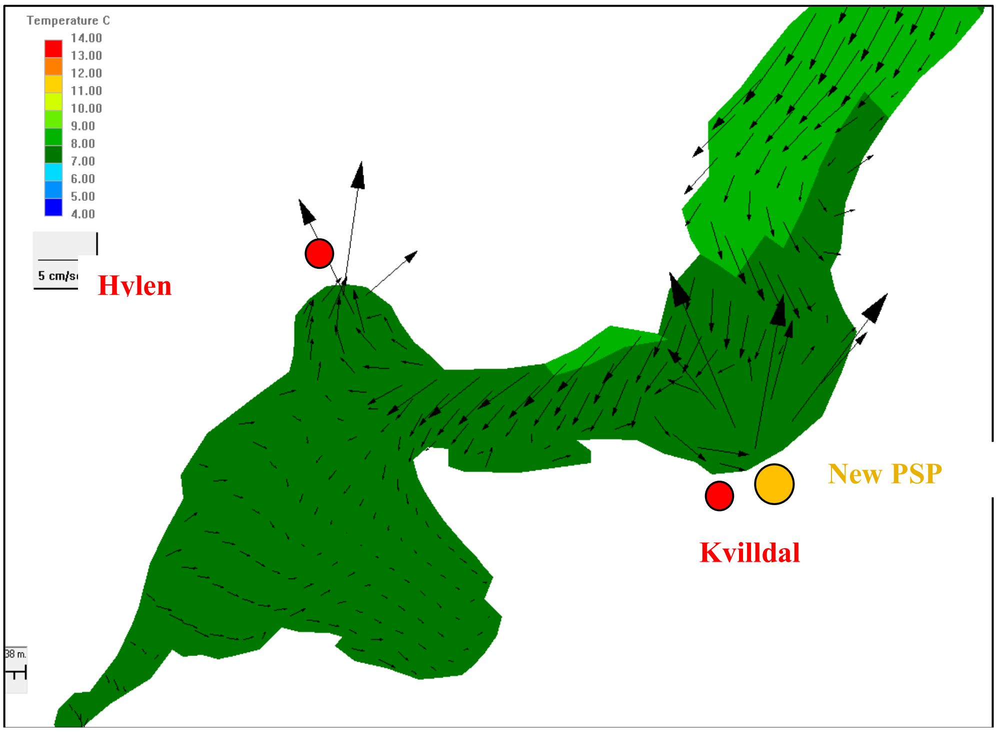


Figure 29. Pumping Scenario 1. Production phase. Main currents at a depth of 10 m in the South part of Lake Suldalsvatn in a typical autumn situation. Arrows represents the horizontal velocity (Time of simulation 22 October 16h00).

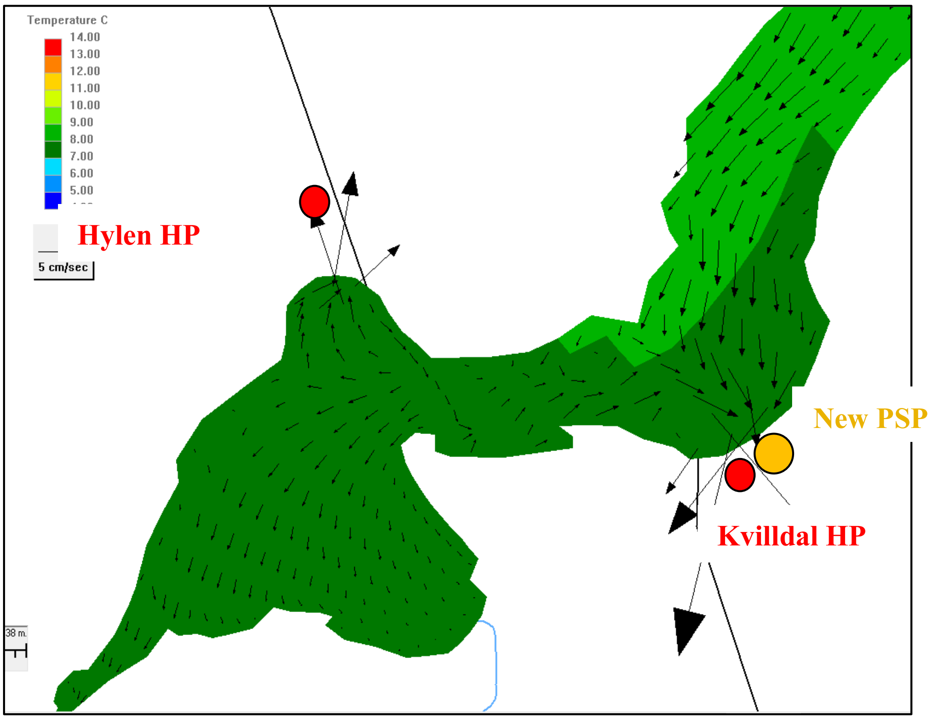


Figure 30. Pumping Scenario 1. Pumping phase. Main currents at a depth of 10 m in the South part of Lake Suldalsvatn in a typical autumn situation. Arrows represents the horizontal velocity (Time of simulation 22 October 03h00).

4.1.2.2 Vertical distribution of currents near the PSP

A new vertical circulation is induced in the area located in front of the PSP, where distribution of currents is directly induced by the operation of the PSP. The main characteristics of the vertical circulation are the same in summer or autumn. Graphs presented in this section of the report correspond to the autumnal situation. To understand the water masses circulation in the area, a vertical slice located in front the PSP (**Figure 23**) is plotted.

During production phase, the release of water induces a current which flows from the PSP towards the North direction (**Figure 31**). This current takes place between the layers 5 and 11 (depths of 6 and 18 m respectively) at the outlet of the PSP; its intensity decreases while it flows Northwards and plunges at depths of 30 m. To balance this jet, a surface current flows towards the PSP.

During pumping phases, the withdrawal of water induces a horizontal current which flows towards the PSP (Southwards) in the upper layers. Far from the PSP, water masses forming the current are located in the first ten meters; when approaching the PSP, the flow intensifies and thickens until layers at 30 m, gathering layers with different temperature, and thus densities. A return Northwards flow establishes at depths of 30 to 75 m to compensate the water masses movement of the upper layers. The transition between both currents is realized by a down-welling at the PSP intake (accumulation and sinking of higher density layers beneath the lower density ones).

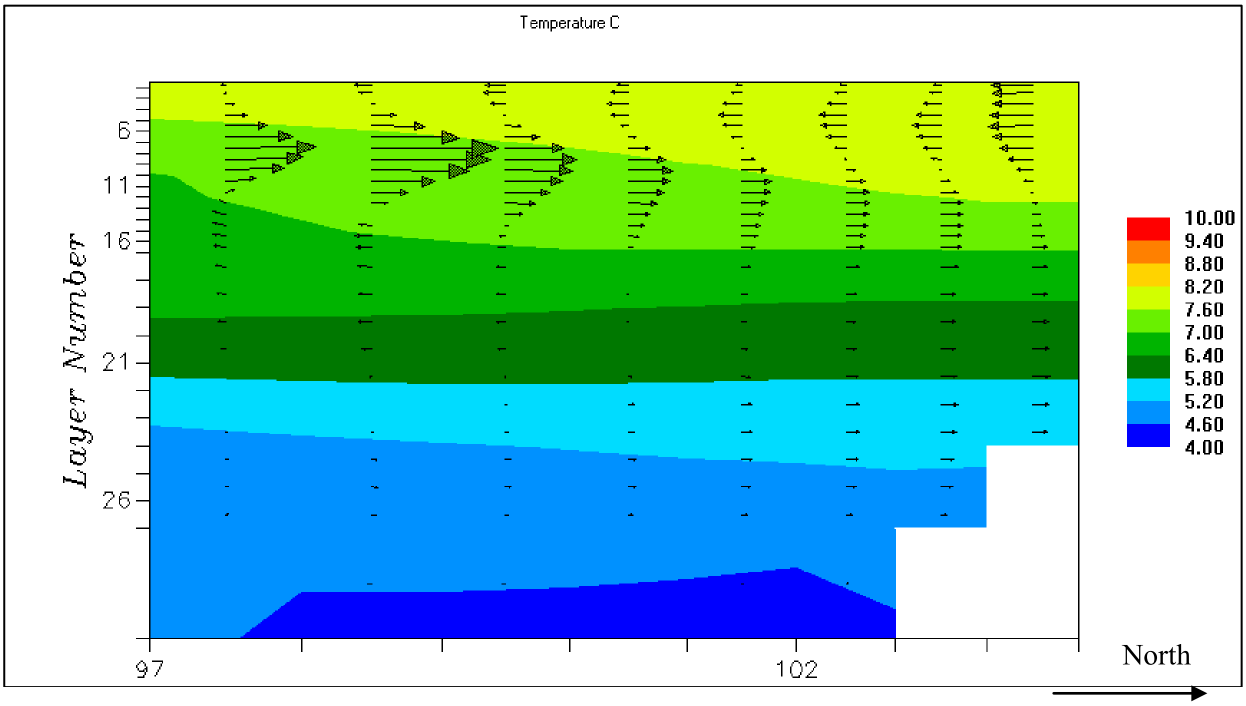


Figure 31. Pumping Scenario 1. Production phase. Vertical slice along the North direction (x=36, y= {97: 105}) showing velocity vectors (arrows) and temperature values (colour scale) in a typical autumn situation during production. The Y-axis represents the layer number (n°6: - 8m; n°11: - 18m; n°16: - 28m; N°21: - 50m; N°26: -75 m). (Time of simulation: 22 October 16h00).

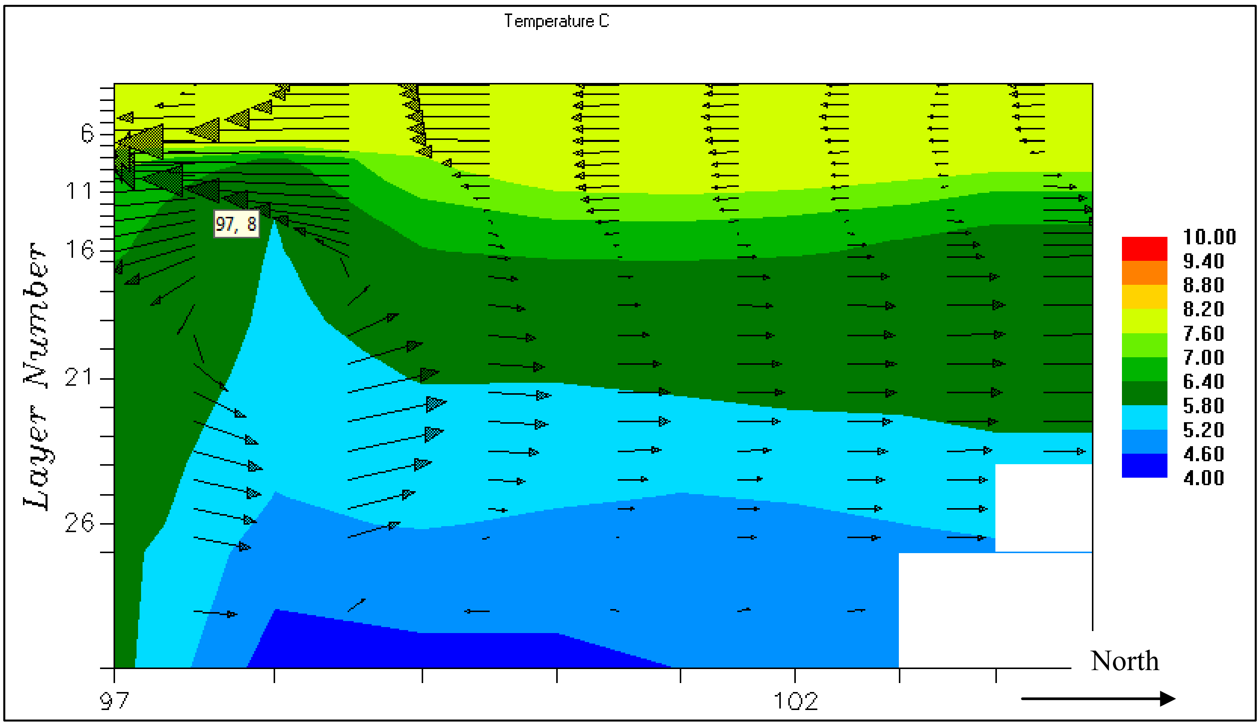


Figure 32. Pumping Scenario 1. Pumping phase. Vertical slice along the North direction (x=36, y={97: 105}) showing velocity vectors (arrows) and temperature values (colour scale) in a typical autumn situation during pumping. The Y-axis represents the layer number (n°6: - 8m; n°11: - 18m; n°16: - 28m; N°21: - 50m; N°26: - 75 m). (Time of simulation: 22 October 03h00).

4.2 Pumping Scenario 2

Consequences of pumping and releasing water in Lake Suldalsvatn are highly dependent on the characteristics and the amount of water which is withdrawn and released in the lake. One possible solution in the planning of a PSP on Lake Suldalsvatn would be to use Lake Blåsjø as the upper reservoir and build a direct connection between both lakes. Therefore in Pumping Scenario 2 (Sc2), a different temperature scenario is assumed for water released by the PSP during production phases (**Figure 24**). It is based on the mean annual temperature variations observed in Lake Blåsjø. The same temperature pattern is set-up as input for both simulated years 2001 and 2002.

4.2.1 Consequences on Lake's temperature of operating a PSP

The same consequences of operating a PSP as found in Scenario 1 are present in Scenario 2.

Both the length and the stability of the summer stratification are highly reduced (**Figure 33**). Effects are stronger for 2001, which was the year with a more stable stratification. The length of the stratification period is reduced to about 4 months, from July to end of September. Like in Sc1, the vertical mixing is higher than today and leads to a weaker vertical gradient of temperature through the water column. Since the water released in Sc2 is colder than in Sc1 during the whole year, results show that all layers, except the surface layer (down to -2 m) are colder in Sc2. In 2001, the layer at a depth of 6 m reaches only 8 °C in Sc2, but 10 °C in Sc1. Intermediate and lower layers reach 7 °C in Sc2 at their maximum at the end of the stratification period, but 8.5 °C in Sc1. However the vertical gradient is stronger in Sc2 than in Sc1: the upper layers are warmed by the solar radiation and reach approximately the same temperature as in Sc1; the lower layers have a limited warming due to the release of cold water by the PSP.

Changes in lake's temperature affect also the downstream river Suldalslågen, mainly during summer and autumn. As for Sc1 the delay in the formation of the stratification induces that temperature in Suldalslågen River is 2 to 4 °C colder in Sc2 than today during this delay period. In July and August the temperature in the river, roughly represented by the layer at a depth of 4 m, is colder in Sc2 than in Sc1: in 2001, it roughly ranges between 6 and 8 °C in Sc2, and between 8 and 10 °C in Sc1; in 2002 the river temperature has approximately the same range, 6 to 12 °C in Sc2, and 7 to 12 °C in Sc1. From September to November temperature in the river is 3 to 5 °C colder than today in Sc2 (1 to 3 °C for Sc1), due to the combination of an earlier autumnal turnover and a colder mixing temperature of water.

Temperature of the water withdrawn by Hylen HP would certainly be affected by changes in temperature in Lake Suldalsvatn. Colder water released then into the sea through Hylsfjorden is expected. Since the currents distribution maps show that some of the water released by Kvilldal HP flows almost directly (while mixing with the surrounding water) to Hylen, intake temperature of the withdrawn water could be even more affected in Sc2 than in Sc1.

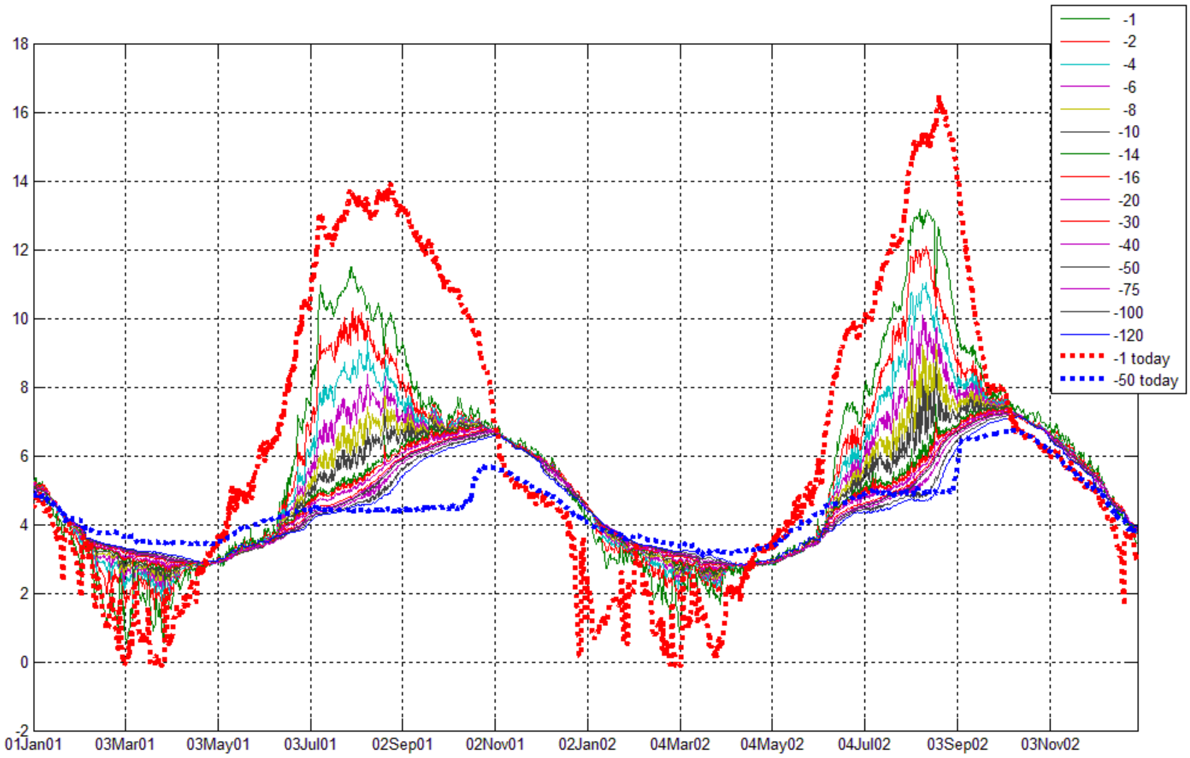


Figure 33. Simulated temperature of layers at depths 1 to 120 m in the southern part of the lake from Pumping Scenario 2 (continuous lines), and simulated temperature of layers at 1 and 50 m for today's situation (dot lines).

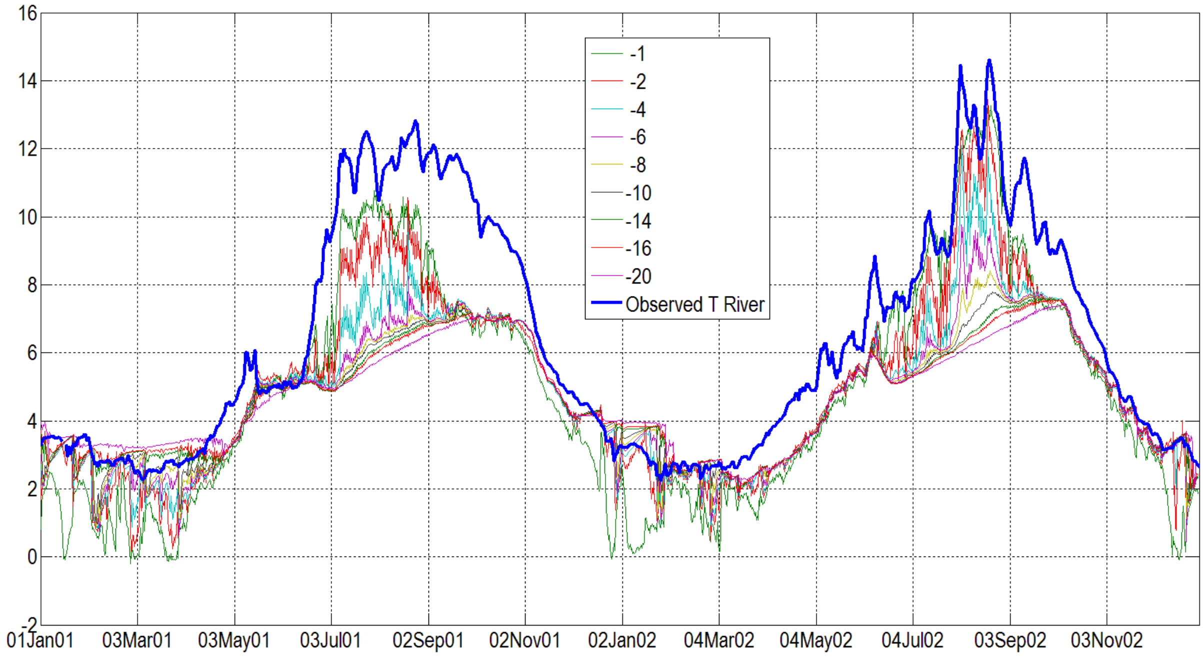


Figure 34. Simulated temperature of layers at depths 1 to 20 m at the downstream outlet of the lake from Pumping Scenario 2 (continuous lines), and observed temperature in Suldalslågen River (thick blue lines).

4.2.2 Consequence on currents of operating a PSP

The new patterns in both the horizontal and vertical distributions of currents induced by the operation of the PSP in Scenario 2 are similar to the ones described for Scenario 1 (**4.1.2**).

5 Conclusion

Simulation of hypothetic scenarios with a 3-D numerical model showed that large changes in temperature and currents distributions would appear in case of installation and operation of a pumped storage plant.
A more intense vertical mixing is expected in the whole lake, due to the release as well as the pumping of water which destabilize the water column. As a consequence, Scenario 1 show that upper layers at depths above 20 m could be colder than today, and intermediate and lower layers at depths below 20 m warmer, leading to a weaker/less stable vertical gradient in temperature. The stratification period will be shortened by 2 months. The amplitude of the mixing depends on the temperature of the water release by the PSP during production phases. Thus Pumping Scenario 2 show a shorter stratification period with a less stable water column than Scenario 1, as well as colder temperatures.

In this study, 300 and 253 m^3/s have been selected as discharge values for the production and pumping phases respectively. Since the value of the discharge, as well as the location of the outlet (depth), and its size (diameter) affect also the mixing of the surrounding waters, results presented in this report are valid for the specific configuration set-up. Additional simulations varying geometrical parameters of the outlet/intake of the PSP should be run to select a technical solution that would minimize consequences in Lake Suldalsvatn.
The study also showed that temperature in the downstream river is directly affected by the operation of a PSP, particularly during summer and autumn. Due to the importance of water temperature for species living in this river, some solutions should be envisaged. Today the overflow from Suldalsvatn passes the dam and discharges into the river. A possible solution is to have flexible outlet to select water with the most adequate characteristics in order to better match the ecological requirements.

A more detailed study is also necessary to evaluate the impacts of strong currents on ice cover in Lake Suldalsvatn, especially in the area located next to the PSP. Especially a finer horizontal, as well as vertical grid could be set-up for additional investigations and assessments of the currents.

Finally, some uncertainties of the model results need to be further investigated (horizontal variation of temperature within the lake, velocities values, and simulation of winter period). Additional field observations (temperature loggers, currents mapping, ice mapping, sediments sampling) are required to have a complete validation of the model and assess all the possible impacts/changes induced by a new regulation using a PSP.

References

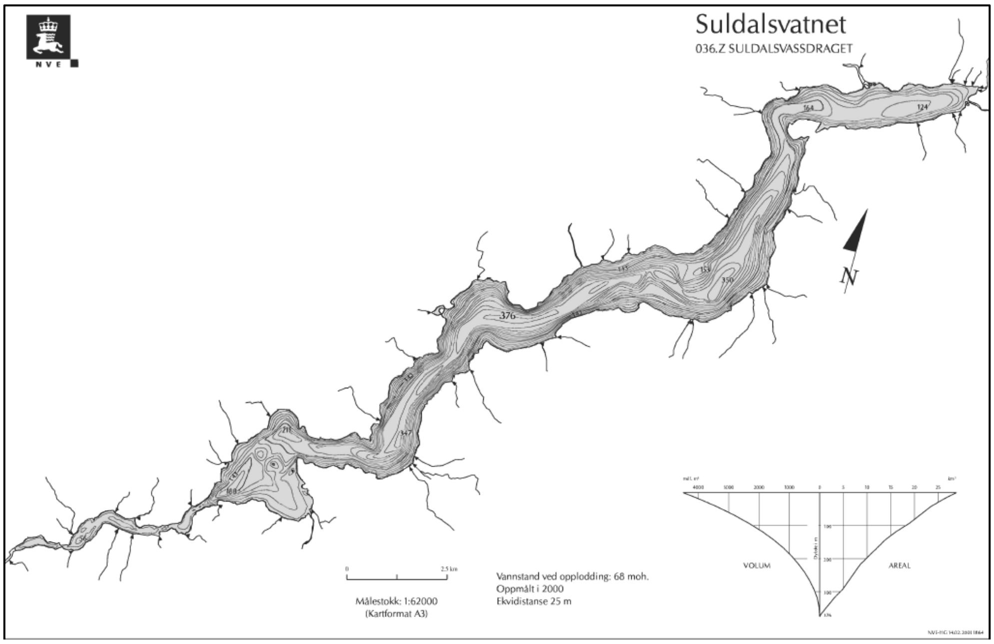
[1] ERM (2006), GEMSS Development Team, Surfacewater Modeling Group (SMG). GEMSS-HDM, Hydrodynamic and Transport Module. Technical Documentation.

[2] Solvang, Harby and Killingtveit (2010). Increasing balance power capacity in Norwegian hydroelectric power stations, A preliminary study of specific cases in Southern Norway. SINTEF Report TR A7195.

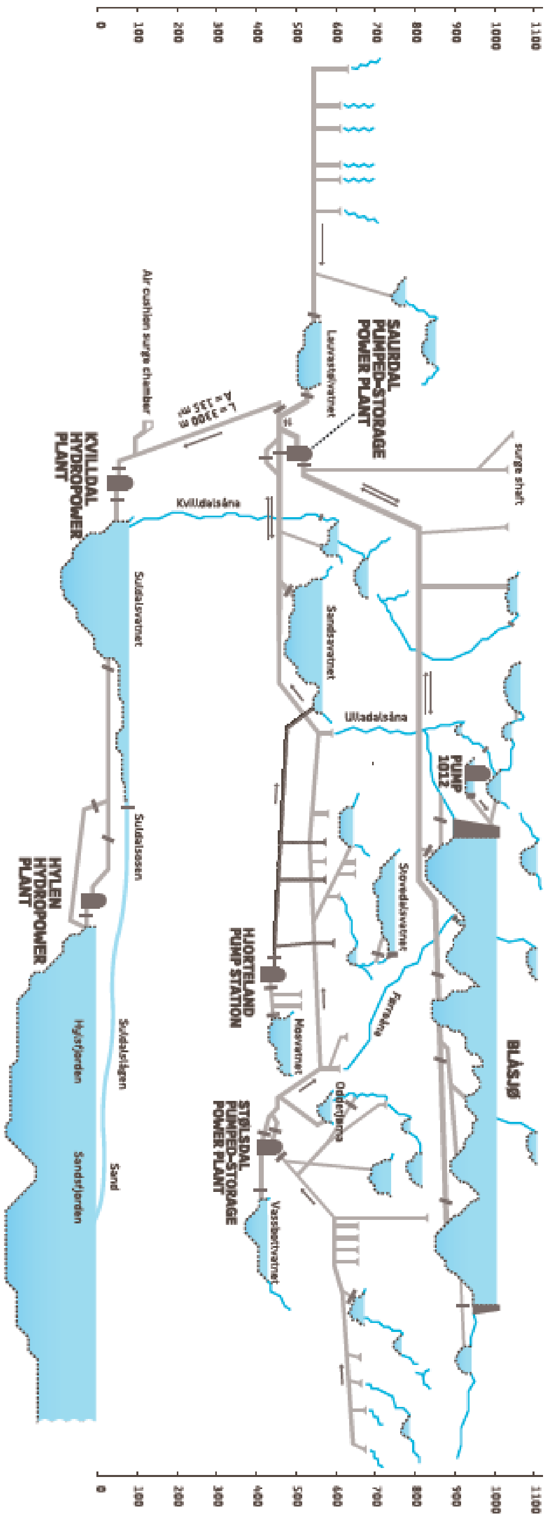
[3] Berge F.S. (1985). Strømnigsforhold i Suldalsvatn, feltforsøk høsten 1984. NHL SINTEF. Report STF60 A85051.

[4] Ellingsen E. (1994). FUS Prosjektet Ulla Førre. Strømingsmønsteret i Suldalsvatn (en numerisk modell). Statkraft Engineering.

Appendixes



Topography of Lake Suldalsvatn. Source NVE.



Vertical distribution of Ulla-Førre hydropower plants' system.

Technology for a better society

www.sintef.no