TR A7621- Unrestricted

Report

Numerical Modelling of Water temperature conditions in Lake Vassbygdvatn

Scenarios to increase water temperature in Aurlandselva

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2016-12-20

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KEYWORDS:
Hydropower
Water temperature
Aurlandselva
Numerical model
Vassbygdvatn
Mitigation
Brown trout
Atlantic Salmon

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VERSION
1

DATE
2016-12-20

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CLIENT(S)
E-CO Energy

CLIENT'S REF.
Bjørn Otto Dønnum

PROJECT NO.
502000131-4

NUMBER OF PAGES/APPENDICES:
44 + Appendices

ABSTRACT

The present study is part of the Environmentally Designed Operation of Regulated Rivers (EnviDORR) project whose main objective is to develop optimal solutions to increase both Atlantic salmon and hydropower production in regulated rivers. The main goal of this study is to investigate win-win solutions for increasing water temperature in Aurlandselva river. A 3D numerical model of Lake Vassbygdvatn was set-up in order to study alternative mitigation measures for increasing water temperature at the lake's surface, and in the downstream Aurlandselva River as a consequence. Four different scenarios were simulated for the period May to October for two different climate years: 2006, warm and dry, and 2007, cold and wet year. Mitigations measures consisted in alternative operational strategies of the hydropower system, manipulation of inflow/outflow of Vassbygdvatn and physical changes in the outlet structure of the hydropower plant. Significant increase of water temperature in Aurlandselva was obtained only in the scenario which includes a limited run of Aurland 1's hydropower plant during 10 to 30 days from May, June or July. The largest rises in temperature were obtained for the longest limited run period after stratification formation.

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REPORT NO.	ISBN	CLASSIFICATION	CLASSIFICATION THIS PAGE
TR A7621	978-82-594-3681-8	Unrestricted	Unrestricted

Document history

VERSION	DATE	VERSION DESCRIPTION
Version No 0.1	2015-12-15	Draft
Version No 0.2	2015-12-15	Updated version
Version No 1	2016-12-20	Updated version

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Acronyms

m a.s.l: meters above sea level

LRWL: Lowest regulated water level

HRWL: Highest regulated water level

1 Background

The study is part of the Environmentally Designed Operation of Regulated Rivers (EnviDORR) project.

The objective of EnviDORR project is to develop optimal solutions to increase both Atlantic salmon and hydropower production in regulated rivers.

The present study focuses on Lake Vassbygdvatn and its downstream regulated river Aurlandselva.

The Aurland water course, located on the Western coast of Norway, is heavily regulated due to hydropower development. The lower part of the water course, especially Aurlandselva River, but also Vassbygdelvi River upstream Vassbygdvatn, holds important anadromous trout populations (*Salmo Trutta*) and a very weak salmon population (*Salmo Salar*), and is popular and valuable for game fishing (Jensen, 1990). Due to the hydropower development the hydrological regimes (both flow and water temperature) have been significantly altered in both these streams (Tvede, 1994) giving impacts on the biological system. As the water is short-cutted from the high-altitude reservoir Viddalsvatn, diverted into the hydropower system (tunnel, penstock and the turbines of Aurland I) and released in Vassbygdvatn, this lake receives much colder water than prior to the regulation. Without the diversion the water would be naturally heated by solar radiation and heat exchange with the ambient air on its way down to Vassbygdvatn.

It is well known that water temperature is an important factor for several biological processes and an increase in water temperature would especially contribute to growth in juvenile fish in summer (Cassie, 2006).

The present study aims at seeking new and mutually beneficial and improved solutions for both the environment and the hydropower production. One of the main tasks has been to analyse the water temperature regime under the present manoeuvring of the hydropower system and how possible alternative operational strategies could increase the downstream water temperature at specific periods of the year.

In order to reach such a situation, a set of different mitigating measures like alternative operational strategies of the hydropower system, manipulation of inflow/outflow of Vassbygdvatn and physical changes in the outlet structure of the hydropower plant have been simulated and investigated with a 3D numerical model.

2 Study site description

2.1 Aurland's hydropower plant system

Table 1. Characteristics of Lake Vassbygdvatn

Volume	Mm^3	79.5
Area	Km2	1.83
Average depth	m	42
Max depth	m	65
Theoretical residence time	days	25
HRL	m a.s.l	55.4
LRL	m a.s.l	54

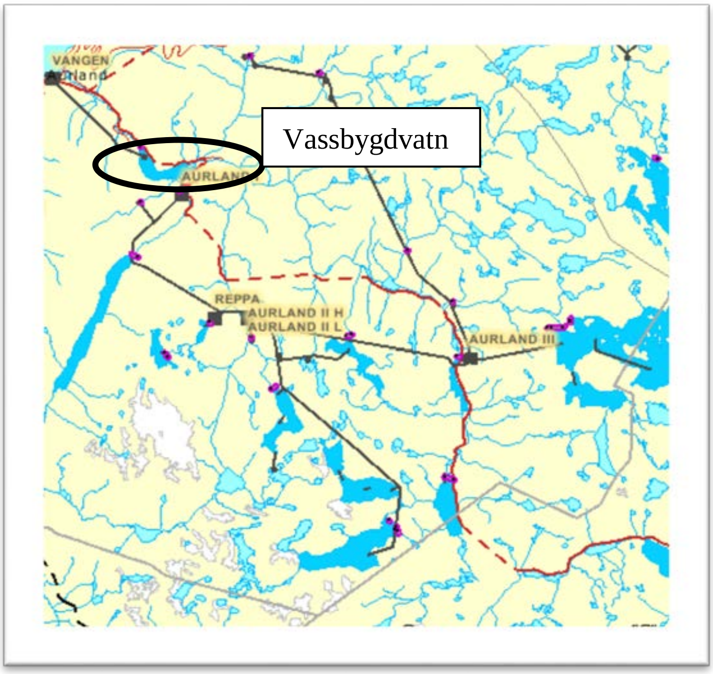

Figure 1. Overview of the most important elements in the today's regulated river system of Aurland. (Source: NVE Atlas - http://arcus.nve.no/website/nve/viewer.htm).

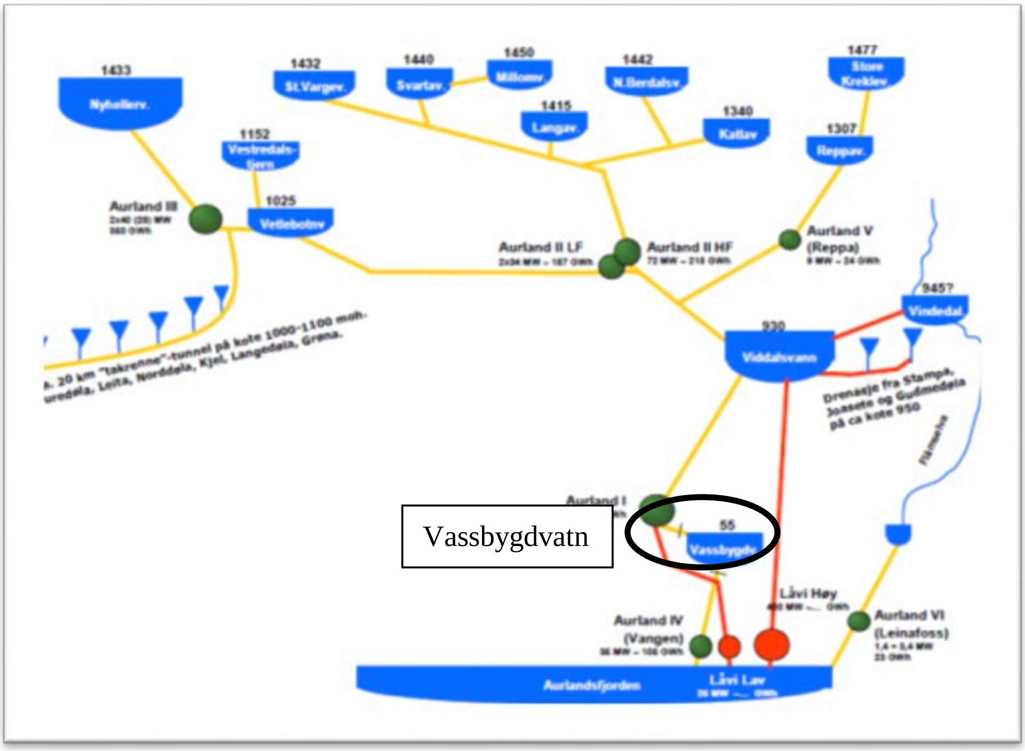

Figure 2. Scheme of Aurlands' hydropower plant system. It is constituted of seven hydropower plants and more than fourteen reservoirs.

Lake Vassbygdvatn (**Table 1**) is a small (Area: 1.8 km^2) and relatively shallow (mean depth: 42 m) regulated lake located in South of Norway at the lowest altitude (55 m a.s.l) in the complex Aurland's system (**Figure 1, Figure 2 and Figure 3**). The regulated catchment area consists of a large number of interconnections between 14 different reservoirs and hydropower plants basically located at the three different altitudes (50, 900 and 1400 m a.s.l).

The water level in Lake Vassbygdvatn varies between the lowest (LRWL: 54 m a.s.l) and the highest regulated water level (HRWL: 55.4 m a.s.l).

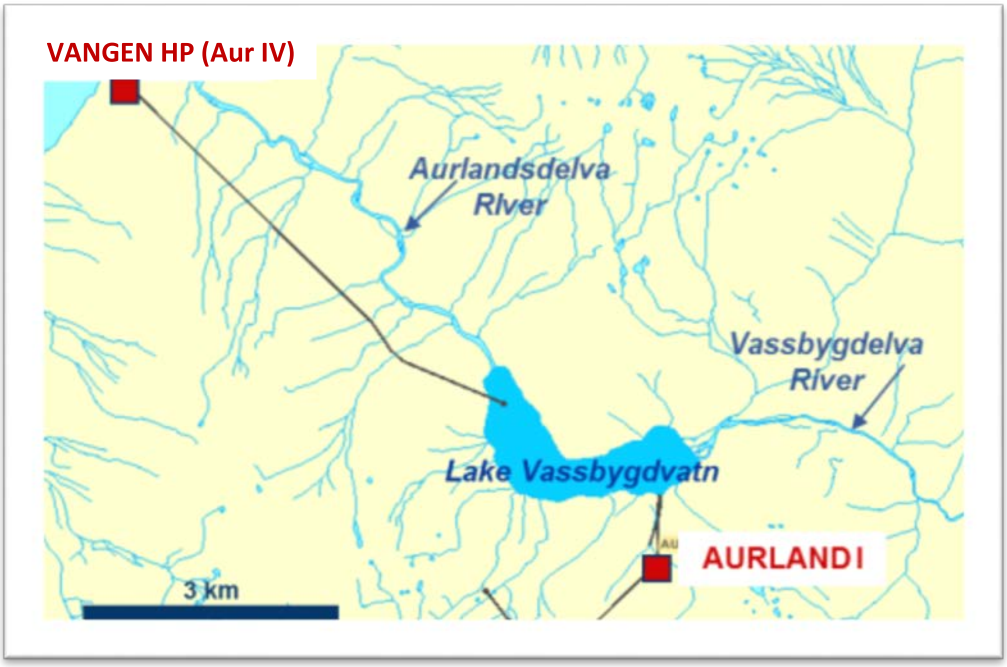

Figure 3. Overview of the most important elements in the today's regulated Lake Vassbygdvatn. (Source: NVE Atlas - http://arcus.nve.no/website/nve/viewer.htm).

2.2 Inflows and outflows

Inflows

- **Vassbygdelvi River** is a stream which discharges on the eastern shore of the lake.
- **Aurland I (AuI)** is the outlet of a hydropower plant (installed capacity of 3 x 280 MW) located on the south-eastern shore of the Lake Vassbygdvatn. Water is withdrawn from the upper lake Viddalsvatn and released in Lake Vassbygdvatn between 48 m a.s.l. and the surface.
- **Lateral inflows** from the neighbouring catchment are distributed around the lake.

Outflows

- Overflow from the dam in Lake Vassbygdvatn discharges in **Aurlandselva River** at the northern-east part of the lake through an adjustable weir. From 1st May to 15th Sept the weir is lowed down to insure the minimum flow in Aurlandselva river.
- The intake to **Aurland IV (Vangen)** is located close to the dam. Water is withdrawn from an intake opening between 38 and 45.5 m a.s.l.

Table 2. Inflows and outflows characteristics

	Name	Type
Inflow	Aurland I	Hydropower plant
	Vassbygdelvi	River
	Lateral inflow	Run-off
Outflow	Aurland IV (Vangen)	Hydropower plant
	Aurlandselva	River

Table 3. Technical characteristics of intakes and outlets

	Location of the tunnel's bottom	Diameter
Aurland I	48 m a.s.l	9.1 m
Vangen (Aurland IV)	38 m a.s.l	7.5 m

2.3 Climate variability

Physical conditions in Lake Vassbydgvatn have a natural variability from year to year due to climate conditions variability.

Downstream river temperature

Measured yearly averaged water temperature at the outlet of the lake (upstream reach of Aurlandselva River) is shown in **Table** 4 and in **Figure 4**.

The 2002-2013 averaged temperature at the outlet is 4.9 °C.

- **2006 is qualified as warm year.** The yearly averaged temperature is 5.8 °C in 2006.
- **2007 and 2012 are qualified as cold years.** The yearly averaged temperature is 4.5 °C in 2007, 4.1°C in 2012.

Table 4. Measured averaged water temperature at the outlet of Lake Vassbygdvatn (upper reach of Aurlandselva River)

2002-2013	°C
AVERAGE	**4.9**
2002	**4.7**
2003	**5.0**
2004	**5.0**
2005	**4.8**
2006	**5.8**
2007	**4.5**
2008	**5.1**
2009	**4.8**
2010	**4.7**
2011	**5.1**
2012	**4.1**
2013	**4.9**

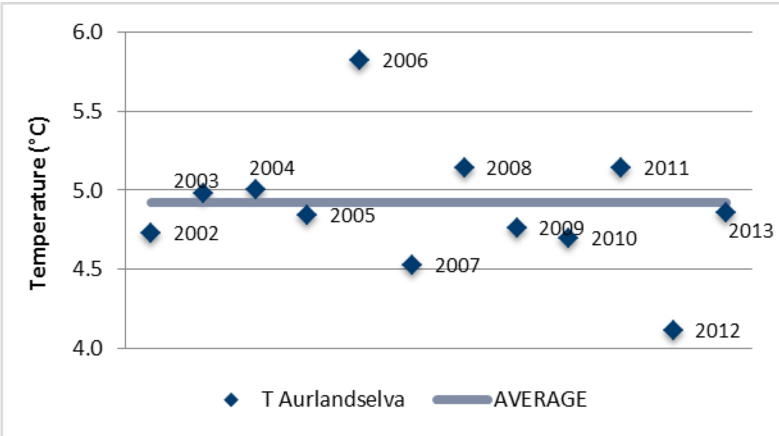

Figure 4. Measured yearly average and 12 years-average water temperature at the outlet of Lake Vassbygdvatn

Measured summer averaged water temperature (July and August) at the outlet of the lake (upstream reach of Aurlandselva River) is shown in **Table 5** and in **Figure 5**
The 2002-2014 averaged temperature at the outlet is 9.2 °C.

- **2003, 2006, 2010, 2014 are qualified as warm summer years.** The yearly averaged temperature is 10.0 °C in 2003, 10.6 °C in 2006, 9.8 °C in 2010 and 10.2 °C in 2014.
- **2007 and 2012 are qualified as cold years.** The yearly averaged temperature is 8.2 °C in 2007, 7.9 °C in 2012.

Figure 6 shows daily water temperature at the outlet of Lake Vassbygdvatn (upper reach of Aurlandselva River for 2006 (a) and 2007 (b). Water temperature averaged for 2002-2013 is also plotted.

Table 5. Measured July-August averaged water temperature at the outlet of Lake Vassbygdvatn

2002-2014 AVERAGE	°C 8.5
2002	8.0
2003	9.3
2004	8.2
2005	7.8
2006	9.6
2007	8.0
2008	8.7
2009	8.3
2010	8.8
2011	8.0
2012	7.3
2013	8.3
2014	9.6

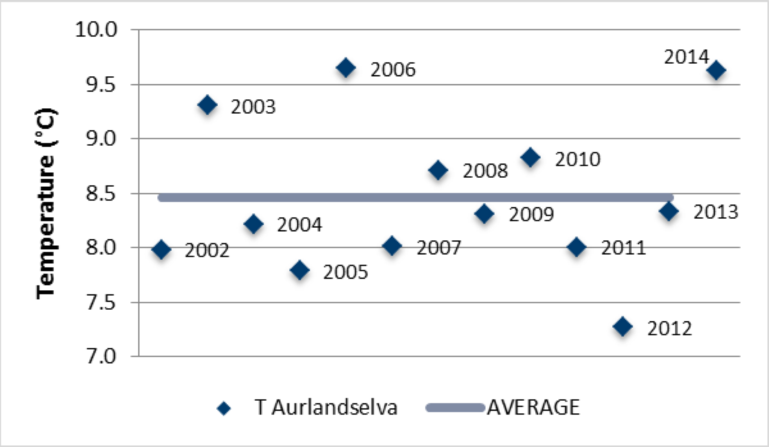

Figure 5. Measured July-August Yearly average and 14 years-average water temperature at the outlet of Lake Vassbygdvatn

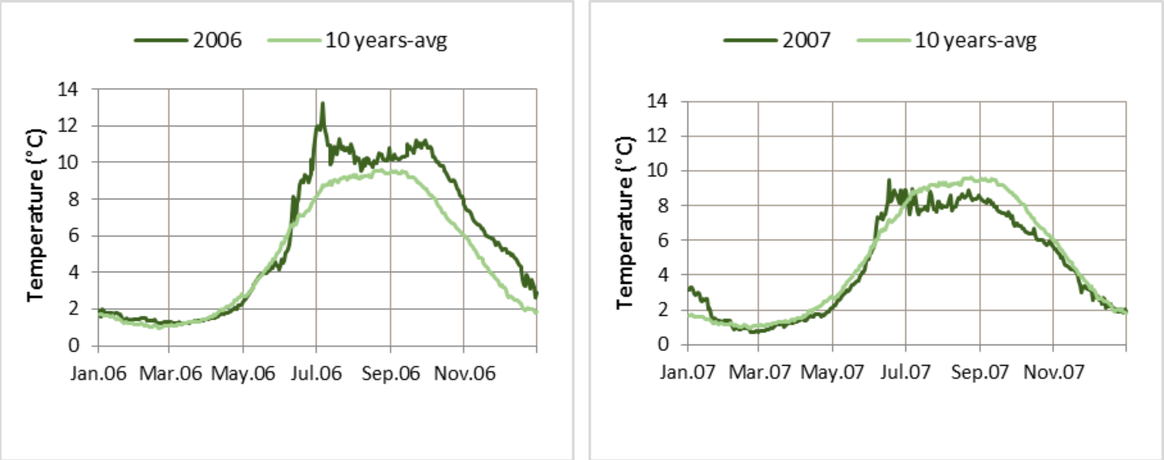

Figure 6. Measured daily averaged water temperature at the outlet of Vassbygdvatn into Aurlandselva for 2006 (left) and 2007 (right). The 2002-2013 daily average is also plotted on the graphics.

Inflow discharge from Vassbygdelvi River (upstream Lake Vassbygdvatn)

Measured yearly averaged discharge in Vassbygdelvi is shown **Table** 6 and in **Figure 7.** The 2004-2013 averaged discharge in Vassbygdelvi is 3.9 m^3/s.

- **2005, 2007, 2011 are qualified as wet years** compared to the 2004-2013 average. The yearly averaged discharge is 5.2 m^3/s in 2007 and 4.6 m^3/s in 2011.
- **2004, 2006 and 2010 are qualified as dry years**. The yearly averaged discharge is 2.7 m^3/s in 2004, 2.7 m^3/s in 2006, 2.9 m^3/s in 2010.

Table 6. Measured yearly averaged and 10 years averaged discharge in Vassbygdelvi (m^3/s).

2004-2013 AVERAGE	3.9
2004	3.2
2005	4.3
2006	2.7
2007	5.2
2008	3.8
2009	4.0
2010	2.9
2011	4.6
2012	4.2
2013	4.0

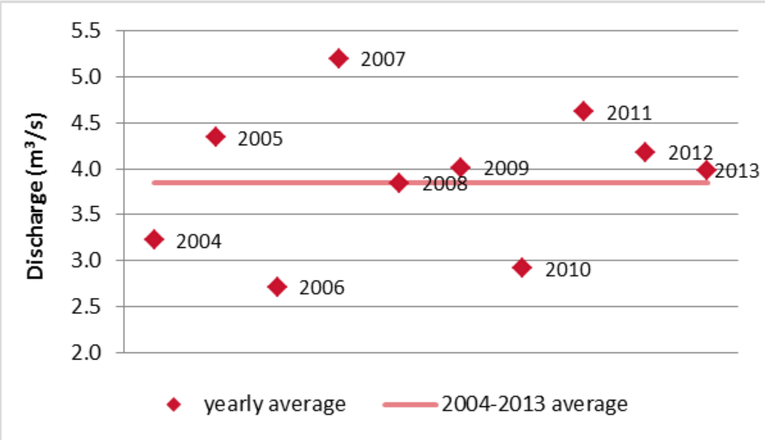

Figure 7. Measured yearly averaged and 10 years averaged discharge in Vassbygdelvi River

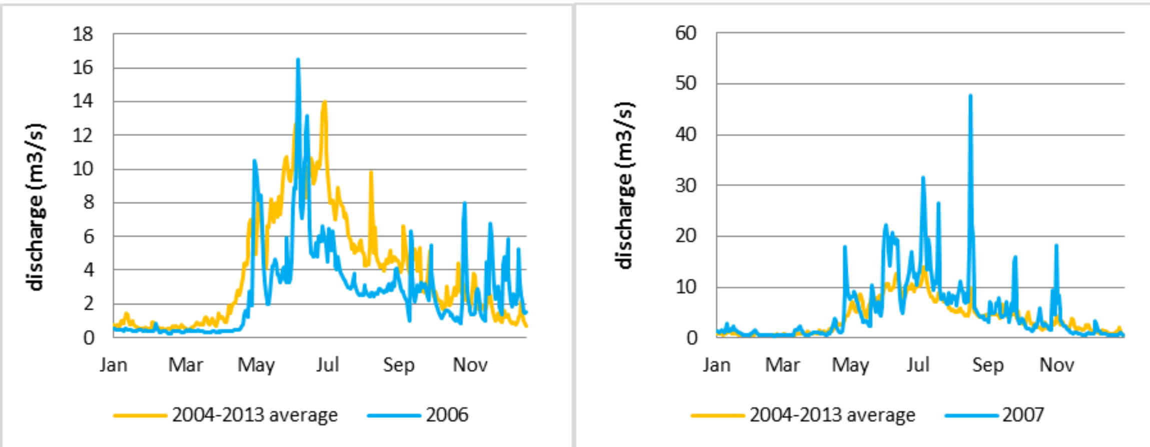

Figure 8. Measured daily averaged discharge in Vassbygdelvi for 2006 (right) and 2007 (left). The 2004-2013 daily average is also plotted on the graphics.

2006 and 2007 are chosen for simulation of mitigation measures in order to take into account year to year variability. 2006 is defined as warm and dry, 2007 is defined as cold and wet.

2.4 Minimum flow in Aurlandselva

The required minimum flow in Aurlandselva varies over the seasons (**Figure 9**, red line). The historical daily averaged measured discharge from 1908 to 1980 (before regulation) is plotted in blue.
The minimum flow varies as follows:

- From 1st January to 15th June and from 15th October to 31th December, it is 3 m^3/s.
- From 16th June to 15th July, it is 25 m^3/s.
- From 16th July to 15th august, it is 30 m^3/s.
- From 16th August to 14th September it reduces gradually to 3 m^3/s.

The current restrictions for minimum flow are included in all simulations of mitigation measures,.

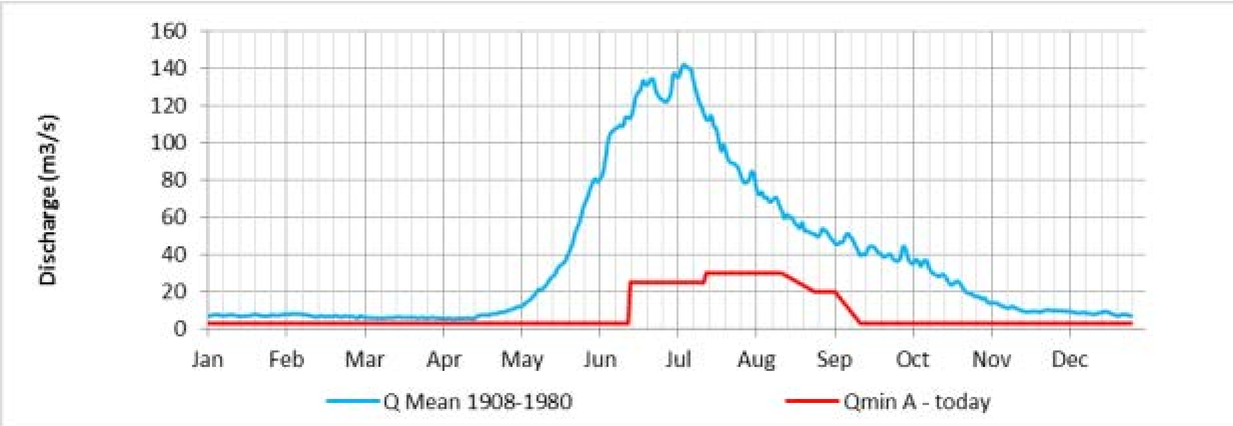

Figure 9. Historical average discharge in Aurlandselva (blue line). Current and alternative minimum discharge in Aurlandselva (red line).

2.5 Relationship between water temperature in the lake and in the downstream river

Water temperature in the uppermost reach of Aurlandselva is affected by surface temperature in Lake Vassbygdvatn. There is a strong correlation between water temperature in the upper reach of Aurlandselva and surface water temperature in the centre of lake (**Figure 10** and **Figure 11**).

Since water temperature in Aurlandselva is strongly affected by surface temperature in Lake Vassbygdvatn, simulations of mitigation measures investigate the possibility of increasing surface temperature in the Lake.

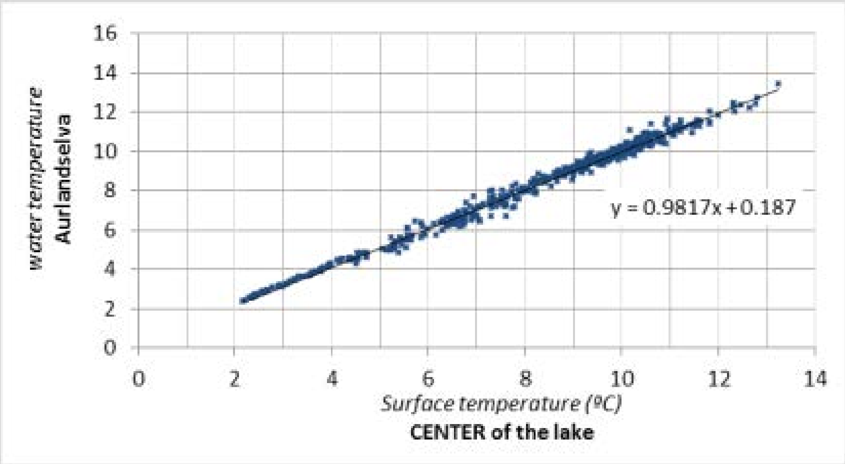

Figure 10. Measured water temperature in Aurlandselva versus measured surface water temperature in th lake (measurement station located in the centre). Data points are from 2003 to 2006.

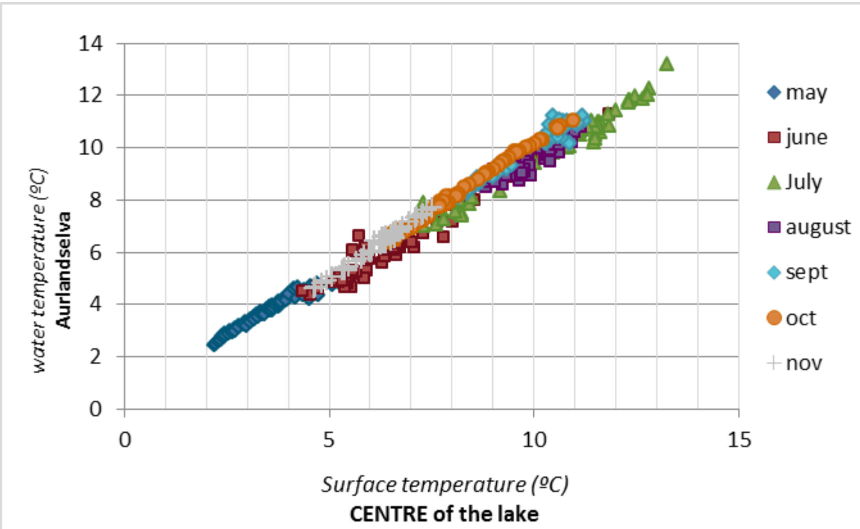

Figure 11. Measured water temperature in Aurlandselva versus measured surface water temperature in the lake (measurement station located in the centre). Data points are classified according of date of measurements. Date points are from 2003 to 2006.

2.6 Water temperature in Lake Vassbygdvatn

Measurements of temperature in Lake Vassbygdvatn are available from April to November for 2005, 2006, 2010, and 2013.

In spring, Lake Vassbygdvatn is well- mixed and temperature is homogeneous. Stratification occurs every summer from June to September. Due to more intense solar radiation in summer, surface temperature increases and heat is partially transferred to layers located under the surface, down to 20-30 m. In autumn seasonal overturn occurs due to less intense solar radiation and stronger winds. Water temperature is homogeneous and decreases until the next spring.

Length, time period, and intensity (temperature difference between layers) of stratification is variable between years**. Figure 12** shows a shorter and less intense stratification for 2005 than 2006.

Short and weak stratification leads to cold surface temperature in Lake Vassbygdvatn (**Figure 12**).

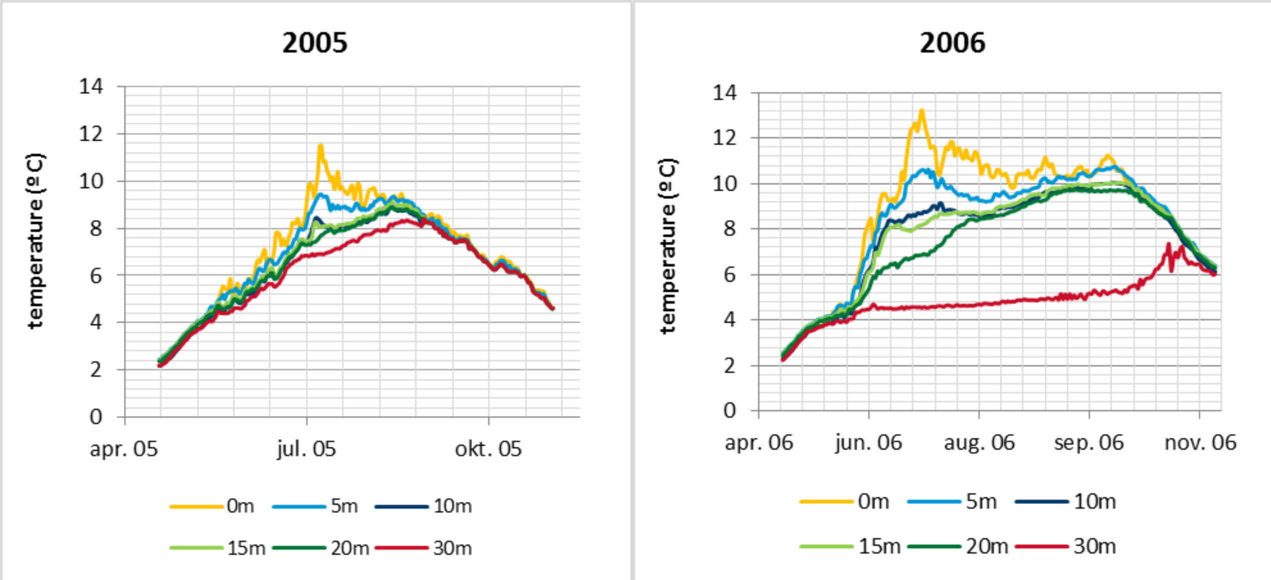

Figure 12. Measured water temperature at several depths in Lake Vassbygdvatn for 2005 (left) and 2006 (right)

3 Model set-up and calibration

3.1 Model set-up

In order to assess hydrodynamic changes due to alternative operational strategies the three dimensions (3D) hydrodynamic model GEMSS® was applied to Lake Vassbygdvatn.

GEMSS® is a general-purpose modelling package for simulating 3D-flow, transport, water quality, 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 (ERM, 2006). 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 (ERM, 2006).

Computational grid

The computational grid (**Figure 13**) was built using bathymetric map of Lake Vassbygdvatn. The grid contains 49 x 9 x 27 grid cells (X, Y, Z). The size of the grid allows simulation of accurate temperature distribution while computational costs are still reasonable.

Input data

Input data to the numerical model consist of:

- Bathymetric map
- Meteorological data (wind speed, wind direction, air temperature, cloud cover, dew point, precipitation, atmospheric pressure)
- Flow data (inflows discharge, inflows temperature, outflow discharge).
- Solar radiation is computed by a specific module within the model.

Sources for input data are shown in

Table 7. Meteorological data are from met.no, water temperature data are from NVE, except measurements in Lake Vassbygdvatn (from E-CO), discharge data are from NVE and E-CO.

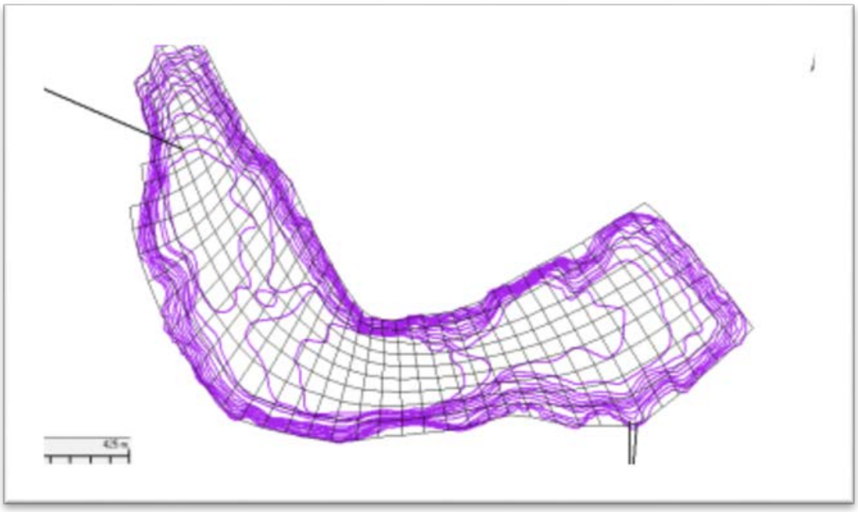

Figure 13. Curvilinear computational grid

Table 7. Input data source and station.

Input data	Source	Station	Comments
Bathymetry data			
Bathymetric map	NVE	*Vassbygdvatn*	
Meteorological data			
Wind	Met.no	*Lærdal*	
Air temperature	Met.no	*Lærdal*	
Cloud cover	Met.no	*Lærdal*	
Dew point temperature	Met.no	*Lærdal*	*some missing data*
Pressure	Met.no	*Lærdal*	
Precipitation	Met.no	*Aurland*	*Local meteo station*
Temperature			
Aur1 HP	NVE data base	*Station 72.23*	
Vassbygdelvi River	NVE data base	*Station 72.25*	
Lateral inflow	x	x	*Estimated*
Aurlandselva	NVE data base	*Station 72.64*	
Vassbygdvatn	E-CO		
Discharge			

Aurlan 1 HP	E-CO		
Vassbygdelvi River	NVE data base	*Station 72.64*	
Lateral inflow	E-CO	x	*Estimated*
Aurlandselva	NVE data base	*Station 72.7*	
Vangen HP	E-CO		

Note 1: Most of the input data have hourly resolution, which allow the simulation of day/night variations.

Note 2: Comparison between Lærdal Station from *met.no* and local measurements in Aurland show very little difference for air temperature.

Note 3: Wind conditions should be preferably measured locally. Due to lack of wind measurement station by Lake Vassbygdvatn, wind speed and wind direction from Lærdal meteorological station were used and calibrated.

Note 4: Lateral inflow discharge was estimated from water balance for Lake Vassbygdvatn

Note 5: Lateral inflow temperature was scaled and calibrated from water temperature of Vassbygdelvi

Note 6: Missing dew point temperature data was estimated from air temperature and relative humidity with the following equation (Lawrence, 2005):

$$\mathrm{Tdp} = \mathrm{Ta} - \frac{(100 - \mathrm{RH})}{5}$$

where,

Tdp = Dew point temperature in degrees Celsius;

Ta = Air temperature in degrees Celsius; and

RH = Relative humidity in percent.

3.2 Model calibration

Model calibration consisted of adjusting and scaling physical and numerical model parameters in order to reproduce Lake Vassbygdvatn behaviour as accurate as possible.
Since the present study focuses on mitigation measures in Aurlandselva in summer, model calibration was done against water temperature only.

Observed data used for model calibration were:

- Water temperature in Aurlandselva (outlet of Lake Vassbygdvatn) for 2005, 2006 and 2007
- Water temperature from 0 down to 30 m depth in Lake Vassbygdvatn for 2005, 2006.

Model calibration against measurements was carried out for years with different temperature and discharge conditions. 2005 is a weak stratified year, 2006 is a strong stratified year (paragraph 2.6). 2005 and 2007 are considered as cold and wet years (paragraph 0).

Several internal parameters related to hydrodynamics, computational scheme, water quality, meteorological, etc., as well as some boundary conditions, have been adjusted to best fit with observations. The model was particularly sensitive to following parameters:

- water balance for Lake Vassbygdvatn
- initial conditions for water temperature in Lake Vassbygdvatn,
- water temperature of lateral inflows,
- air temperature,

- solar radiation input.

Water temperature in Lake Vassbygdvatn

After calibration, the model was able to reproduce lake behavior in terms of water temperature. Observed and simulated water temperature profiles were similar and seasonal stratification was well reproduced by the model (**Figure 14** and **Figure 15**). Mean absolute difference between observed and predicted values for layers from 0 m down to 30 m ranged from 0.21 to 0.5 °C in 2005 and was maximal at the surface (**Table 8**). It ranged from 0.31 to 0.67 °C in 2006 and was maximal at 10 m. Considering data quality and the model set-up, the average residual and mean absolute error are considered small and indicate that calibration is satisfying.

Note 1: Residual is defined as difference between observed and predicted value.

Note 2: Absolute error is defined as absolute value of residual

Note 3: Mean is computed when observed data is available: Mai to November.

Table 8. Comparison of observed and simulated water temperature at several depths in Lake Vassbygdvatn for 2005 and 2006.

2005			2006		
Depth	**Average residual**	**Mean Absolute error**	**Depth**	**Average residual**	**Mean Absolute error**
0m	0.19	0.50	**0m**	0.30	0.39
5m	0.15	0.26	**5m**	0.37	0.41
10m	0.41	0.41	**10m**	0.62	0.67
15m	0.13	0.25	**15m**	-0.16	0.36
20m	0.06	0.21	**20m**	-0.09	0.31
30m	0.07	0.22	**30m**	0.61	0.62

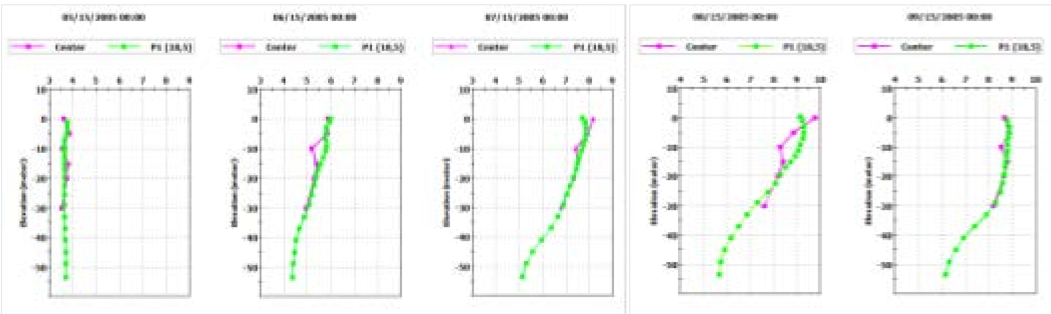

Figure 14. Water temperature profiles in May, June, July, August and September 2005 from field measurements (pink, --Δ--) and from simulated results (green, --□--). The station was located in the middle of the lake.

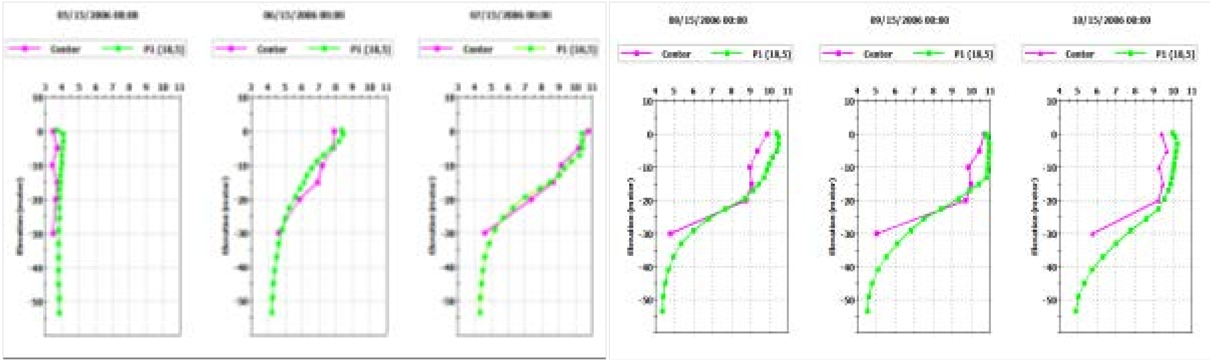

Figure 15. Water temperature in May, June, July, August, September and October 2006 from field measurements (pink, --Δ--) and from simulated results (green, --□--). The station was located in the middle of the lake.

Water temperature in Aurlandselva River

After calibration, the model was able to reproduce seasonal and daily water temperature variations in Aurlandselva (**Figure 16).** Mean absolute difference between observed and predicted values ranged from 0.35 to 0.5 °C for all three years (**Table 9**).

Table 9. Comparison of observed and simulated water temperature in Aurlandselva in 2005, 2006 and 2007.

	Average residual	Mean Absolute error
2005	0.19	0.50
2006	0.30	0.39
2007	0.14	0.35

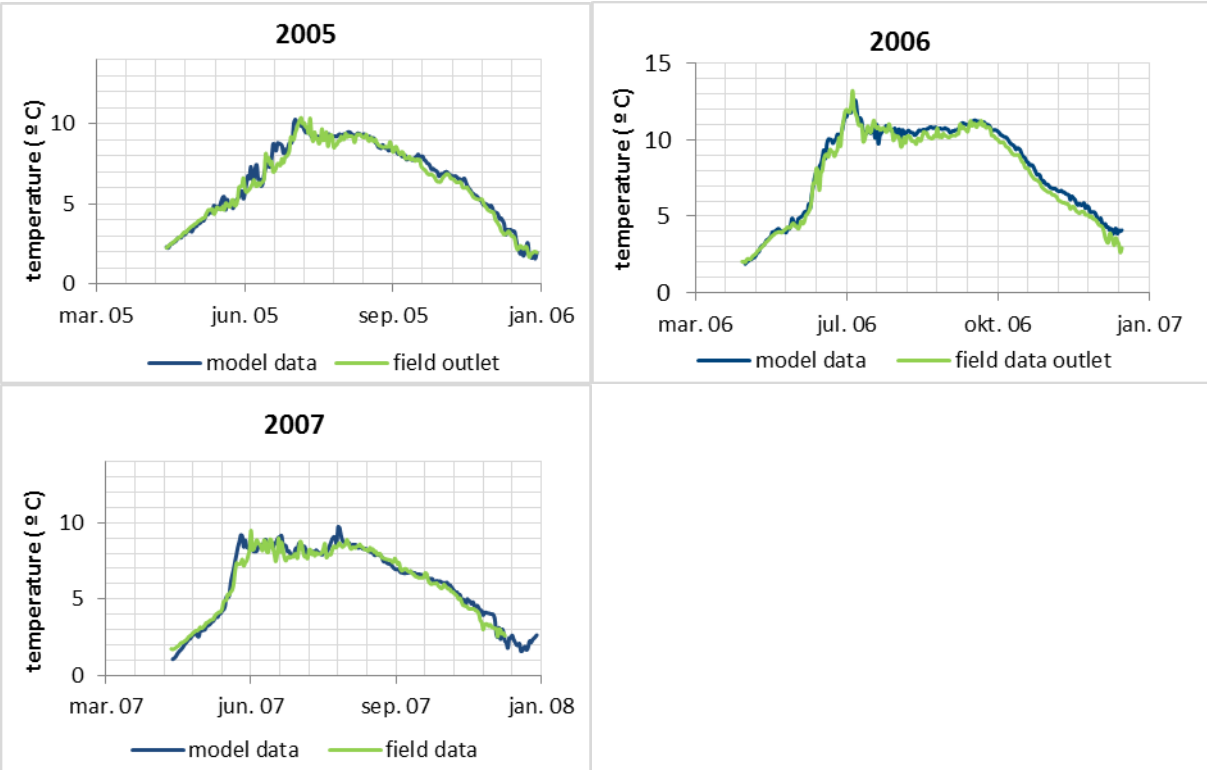

Figure 16. Measured (green) and predicted (dark blue) water temperature for the downstream river Aurlandselva in 2005, 2006, 2007.

Simulated water temperature in Lake Vassbygdvatn and in Aurlandselva River for 2005 and 2006 calibrated against water temperature are considered as reference situation for the respective years, and will be used for comparison with results from simulated scenarios.

4 Simulated mitigation measures: results of simulated scenarios

Four scenarios (**Table 10**) were simulated for investigating mitigations solutions for increasing water temperature in Aurlandselva River.
The choice of scenarios was based on discussion with the hydropower plant company E-CO (scenarios 1 and 3), with biological experts (scenarios 4). Scenarios 2 was proposed by SINTEF Energi based on its own expertise (**see 4.2.1**).
2006 and 2007 were simulated, as they represent natural variability in terms of climate (warm and dry for 2006, and cold and wet for 2007).

In order to be consistent, <u>simulated temperature</u> obtained from modelled scenarios will be compared to <u>simulated temperature</u> obtained from modelled years 2006 and 2007 without scenarios (also called "reference situation"). Comparison of modelled results between them, (and not modelled scenarios versus observed reference situation) allows excluding the existing gap between observed and modelled temperature which remains after calibration.

Consequently, comparison of model results from scenarios to model results from reference situation provides the <u>relative</u> temperature increase (or decrease) which could occur if mitigation measures defined by the respective scenarios were put in place during the studied years.

Table 10. Name and description of simulated scenarios.

Name	Description	Simulated years	Scenarios name
Scenario 1	Run of Vangen HP in Summer	2006, 2007	A1, A2, A3
Scenario 2	Limited run of Aurland I HP in summer	2006, 2007	B1, B2, B3 C1, C2,C3 D1,D2,D3
Scenario 3	Modification of Aurland I's tunnel outlet	2006, 2007	E1, E2, E3
Scenario 4	Increase of Vassbygdelvi discharge	2006, 2007	F1, F2, F3, F4

4.1 Scenario 1: Run of Vangen hydropower plant in summer

4.1.1 Description of scenario 1

Today, Vangen hydropower plant is stopped between 1st May and 1st September as shown in **Figure 17** .

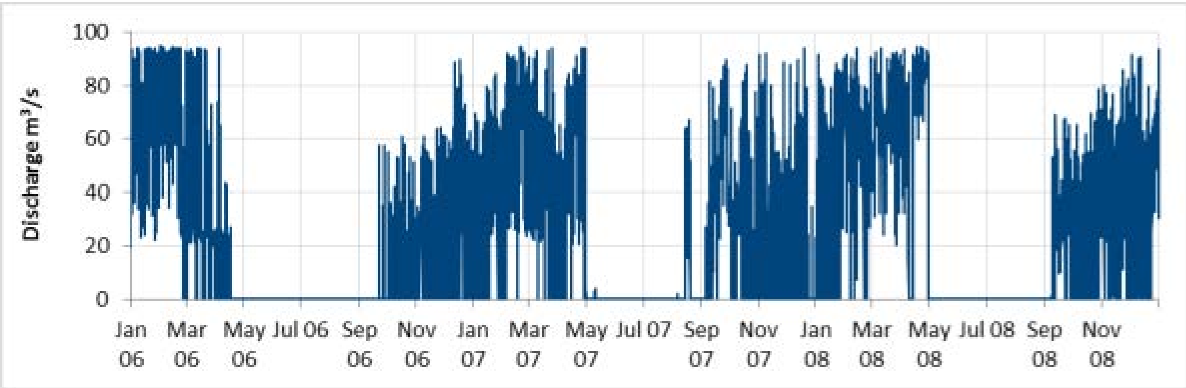

Figure 17. Discharge for Vangen (Aurland 4) hydropower plant from 2006 to 2008.

Scenario 1 consists of running Vangen (Aurland 4) hydropower plant from May to September.

In scenario 1 Vangen HP runs <u>only</u> if <u>both</u> the following conditions are met:

- Minimum discharge *Qmin* described in **2.4** (also called environmental flow) in Aurlandselva is respected
- Available discharge for Vangen must be superior to the technical requirements for running Vangen. Three technical discharge limits have been tested:
  - 22.61 m^3/s (minimum discharge to run Vangen)
  - 42 m^3/s (best discharge point).

When conditions for running Vangen HP are met, the following assumptions are made:

- **Discharge in Aurlandselva is set to *Qmin*** the required minimum flow ,

- **Remaining flow in Aurlandselva is allocated to Vangen** so that the discharge in Vangen is computed as the current discharge value in Aurlandselva minus the minimum discharge requirement in Aurlandselva.
- **Inflows (Aurland I, Vassbygdelvi, lateral run-off) are kept to the same values** as measured in 2005 and 2006.
- Thus, the water level in Lake Vassbygdvatn follows the same variation than measured in 2005 and 2006.

Table 11. Matrix of simulations for Scenario 1. Simulations names are given according to the simulated year and the requirement of minimum technical discharge in Vangen HP.

SCENARIO 1	Minimum flow for running Vangen HP (m^3/s)	
	22.61	**42.00**
2006	A2_06	x
2007	A2_07	A3_07

Scenarios were run for summer (April- November) 2006 and 2007. 2006 is considered as a warm and dry year, with seasonal stratification well-developed in Lake Vassbygdvatn. 2007 is considered as a wet and cold year with more mixed water column.
Five simulations were run. They are described in **Table 11.**

4.1.2 Amount of water available into Vangen HP (Aurland IV)

Computations of available water for Vangen HP in summer from 2004 to 2013 are presented in **Table 12**. Statistics are computed to evaluate the percentage of summer days when Vangen HP could run and to characterise the discharge flowing into Vangen HP for these days. Summer days are counted from 1st May until 1st September.

Table 12. Computations of available water for Vangen

Minimum discharge Vangen			2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	MEAN
22.6	**Conditions met to run Vangen**	**%**	**13.7**	**19.1**	**17.6**	**55.0**	**30.5**	**45.0**	**16.0**	**22.1**	**29.8**	**24.4**	**27.3**
	Q Vangen	**mean**	**46.3**	**35.5**	**27.7**	**40.8**	**35.1**	**31.0**	**30.1**	**44.7**	**37.9**	**40.4**	**37.0**
		min	25.3	23.3	23.1	22.9	22.6	22.9	23.5	22.8	22.6	22.6	22.6
		max	90.9	53.6	36.7	82.8	58.3	49.6	38.8	81.9	56.9	70.0	90.9
	Water through Vangen	**Mm3**	**72**	**77**	**55**	**254**	**121**	**158**	**55**	**112**	**128**	**112**	**114**
42.0	**Conditions met to run Vangen**	**%**	**7.6**	**5.3**	**0.0**	**20.6**	**5.3**	**4.6**	**0.0**	**9.2**	**10.7**	**11.5**	**7.5**
	Q Vangen	**mean**	**57.5**	**45.9**	**x**	**54.8**	**51.2**	**45.8**	**x**	**62.7**	**50.3**	**51.9**	**52.5**
		min	43.6	43.3	x	42.2	42.5	42.7	x	44.7	42.7	42.7	0.0
		max	90.9	53.6	0.0	82.8	58.3	49.6	0.0	81.9	56.9	70.0	90.9
	Water through Vangen	**Mm3**	**50**	**28**	**0**	**128**	**31**	**24**	**0**	**65**	**61**	**67**	**45**

Example of for reading the statistics table is given below for 2004:

- If technical threshold for Vangen HP is set to Q_{tech}=22.6 m^3/s:
    - In 13.7 % of summer days Vangen is running
    - Average flow through Vangen for days with Vangen running is Q_{Vangen}= 46.3 m^3/s.
    - Total amount of water allocated to Vangen for May-September V_{Vangen}=72 Mm^3
- If technical threshold for Vangen HP is set to Q_{tech}=42 m^3/s:
    - In 7.6 % of summer days Vangen is running
    - Average flow through Vangen for days with Vangen running is Q_{Vangen}= 57.5 m^3/s.
    - Total amount t of water allocated to Vangen for May-September V_{Vangen}=50 Mm^3

Conclusions from reading **Table 12** are:

- ➔ The lower the minimum technical discharge in Vangen HP is, the more often Vangen can run;
- ➔ The lower the minimum technical discharge in Vangen HP is, the lower the average discharge through Vangen is;
- ➔ The lower the minimum technical discharge in Vangen HP is, the larger the total water amount through Vangen during the period summer is.
- ➔ The total amount water through Vangen is computed based on same water level (WL) variations in Lake Vassbydgvatn than the registered WL in the associated years (2004-2013). *The amount of water through Vangen could be considerably increased when assuming that WL in the lake decreases to LRWL during the studied period.*

Figure 18 shows the simulated amount of water available for Vangen HP during 2004 to 2013 summers. The total amount of water decrease when the required technical discharge increases for Vangen. Trends of inter annual variations are similar for both all technical discharge. The highest available volume occurs in 2007, while no water is available in 2006 and 2010.

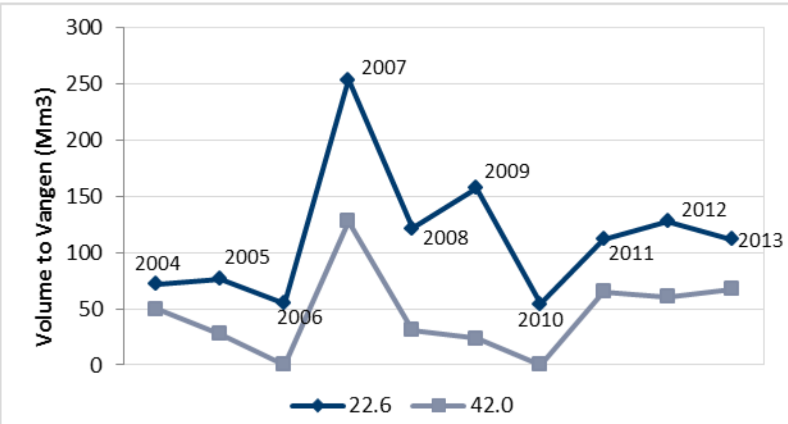

Figure 18. Computed amount of water available for Vangen from 2004 to 2013 with a minimum discharge in Vangen of Q_{tech} = 22.6 m^3/s (dark blue) and Q_{tech} = 42 m^3/s (light blue).

4.1.3 Model results

Scenarios A2 and A3 have been implemented and simulated. Results from simulated scenarios were compared to results from reference situation in order to evaluate if scenario 1 could be relevant for mitigating water temperature in Aurlandselva (Reference situation corresponds to simulated water temperature for 2006 and 2007 calibrated against measurements).

Results from simulations of scenarios A2, and A3 show that running Vangen in summer would mainly almost not affect water temperature in the layers located at the surface. Changes would be insignificant in the downstream river for 2005 and 2006.

4.1.3.1 Simulation of Scenario 1 for 2006

In Scenario A2, Vangen runs during 17.6 % of summer days, and 55.10^6 m^3 of water goes to Vangen. Scenario A3 is not relevant in 2006 due to lack of water and the impossibility to run Vangen HP and respect the environmental restrictions in Aurlandselva at the same time.

Negligible changes occur for water temperature in Aurlandselva when simulating scenario A2 (**Figure 19**). The highest average difference between scenario A2 and the reference scenario is 0.37 °C and occurs in June (**Table 13**).
Water temperature in Lake Vassbygdvatn is almost not modified with scenarios A2. Stratification characteristics remain similar to reference situation (**Figure 20**).

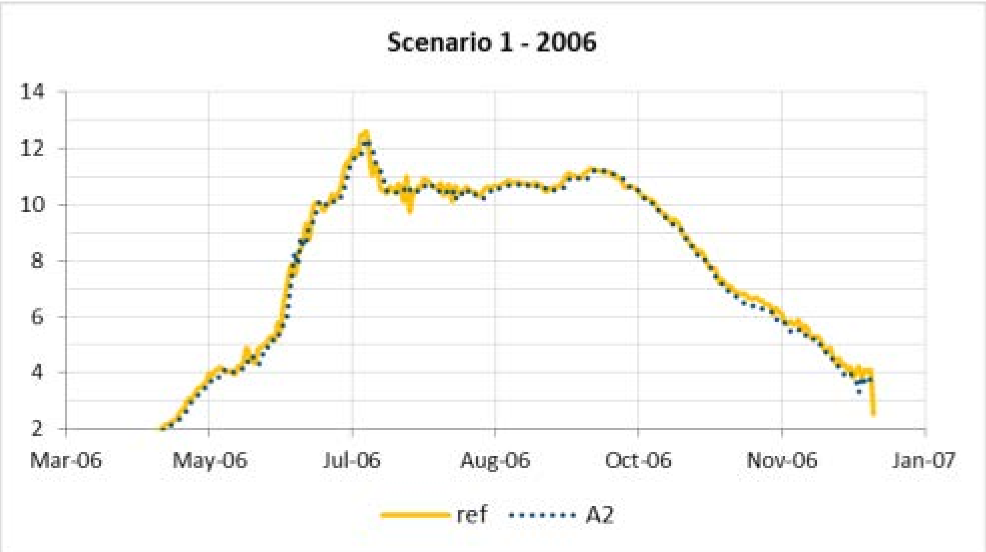

Figure 19. Simulated 2006 time series of Aurlandselva water temperature for scenario A2 (dashed black), compared to reference scenario (orange). Reference situation corresponds to simulated water temperature for 2006 calibrated against measurements.

Table 13. Monthly averaged temperature difference in Aurlandselva obtained for 2006 from scenario 1 A2 (A2_06), compared to reference situation (Reference situation corresponds to simulated water temperature for 2006 calibrated against measurements.).

	A2	
	Mean Absolute difference	Average residual
May-Oct	**0.21**	
May	0.21	*-0.18*
June	0.37	*-0.23*
July	0.28	*0.01*
Aug.	0.16	*-0.10*
Sept	0.10	*-0.07*
Oct	0.09	*-0.04*

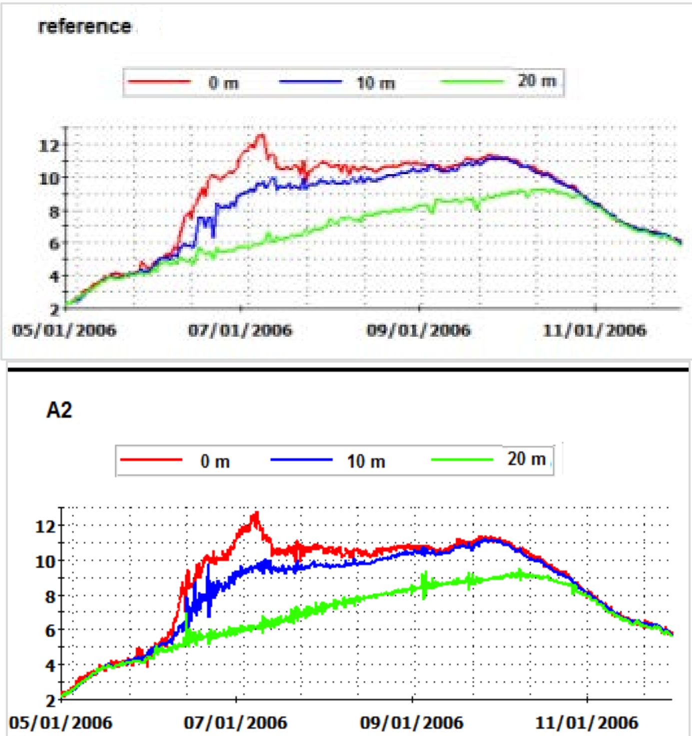

Figure 20. Simulated time series of water temperature for Vassbydgvatn at 0 m, 10 m, 20 m depth, for reference situation (top), A2 (bottom). Reference situation corresponds to simulated water temperature for 2006 calibrated against measurements.

4.1.3.2 Simulation of Scenario 1 for 2007

In Scenario A2, Vangen runs during 55 % of summer days, 254.10^6 m^3 of water goes to Vangen. The amount of water through Vangen in 2007 is more than five times larger than in 2006. In Scenario A3, Vangen runs during 20.6 % of summer days and 128.10^6 m^3 of water go to Vangen.

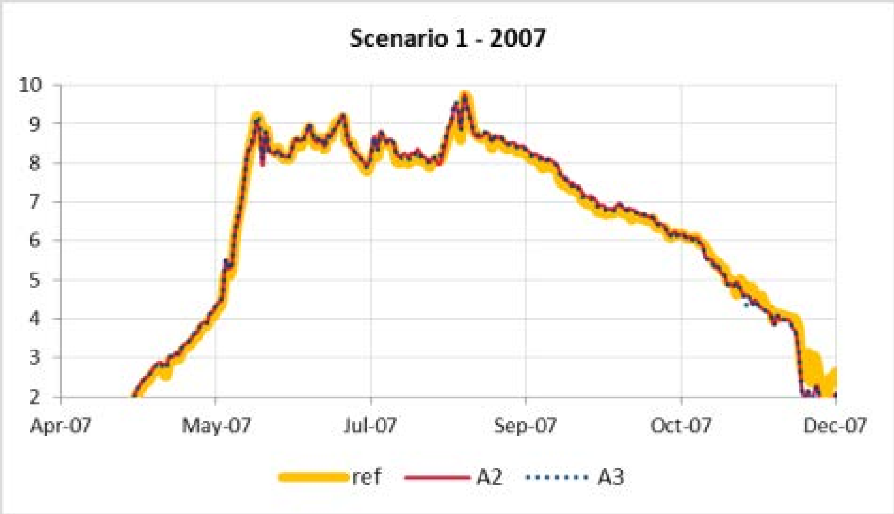

Figure 21. Simulated 2007 time series of Aurlandselva water temperature for scenario A2 (red), and A3 (dashed black), compared to reference scenario (orange). Reference situation corresponds to simulated water temperature for 2007 calibrated against measurements.

Table 14. Monthly averaged temperature difference in Aurlandselva obtained for 2007 from scenario 1 A2 (A2_07), and scenario 1 A3 (A3_07), compared to reference situation (Reference situation corresponds to simulated water temperature for 2007 calibrated against measurements.).

	A2		A3	
	Mean Absolute difference	**Average residual**	**Mean Absolute difference**	**Average residual**
May-Oct	**0.16**	**0.16**	**0.15**	**0.15**
May	**0.13**	*0.13*	**0.12**	*0.12*
June	**0.10**	*-0.01*	**0.08**	*0.03*
July	**0.12**	*0.10*	**0.09**	*0.09*
aug	**0.12**	*0.09*	**0.13**	*0.11*
Sept	**0.17**	*0.17*	**0.11**	*0.11*
Oct	**0.08**	*0.08*	**0.06**	*0.05*

Negligible changes occur for water temperature in Aurlandselva when simulating scenario A2, and A3 (**Figure 21**). The highest average difference between scenario A2 and the reference scenario is 0.17 °C and occurs in September. It is 0.13 °C and occurs in August for Scenario A3 (**Table 14**).

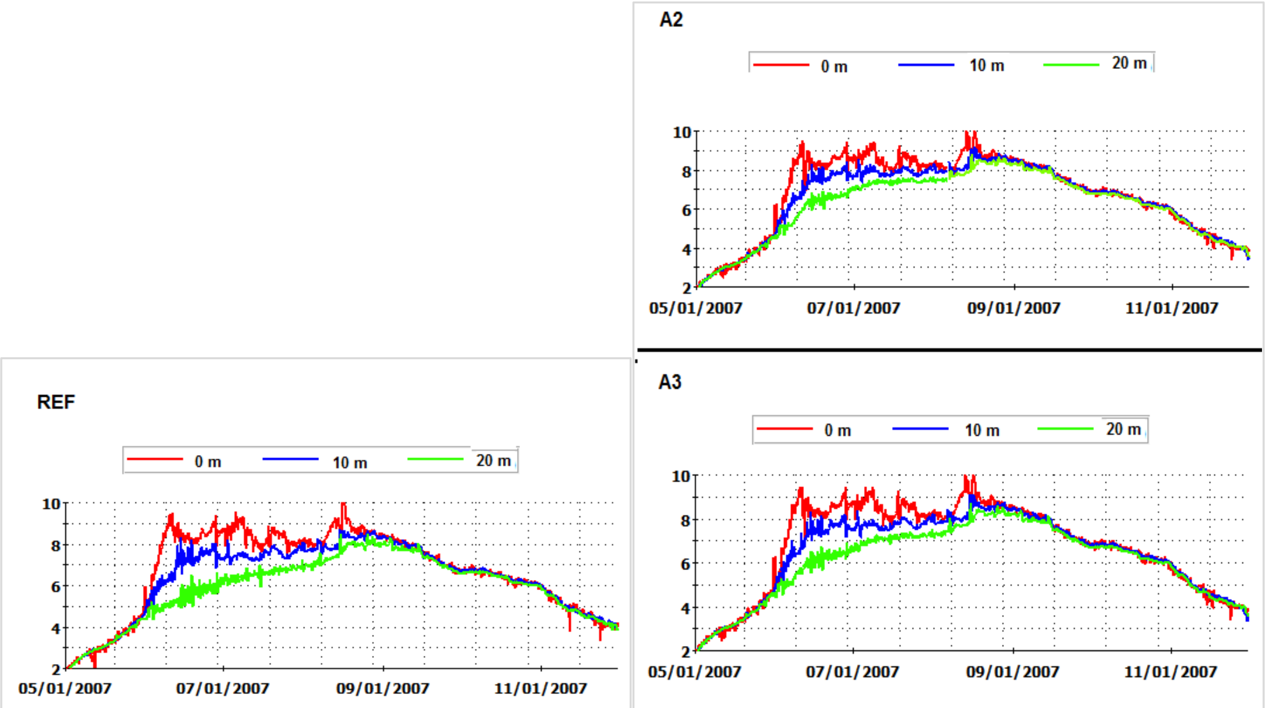

Figure 22. Simulated time series of water temperature for Vassbydgvatn at 0 m, 10 m, 20 m depth, for reference situation (top left), scenario A2 (top right) and A3 (bottom right).

When simulating scenarios A2, and A3, water temperature in Lake Vassbygdvatn is slightly modified for layers located at 10 m and 20 m under the surface.

In scenario A2, on the 1st July water temperature is 1 °C warmer than reference situation at 20 m, and 0.5 °C warmer than reference at 10 m, while surface temperature is similar to reference scenario (**Figure 22**). As a consequence stratification is considered as weaker.

Same behaviour is found for scenario A3 with decreasing intensity.

4.2 Scenario 2: Limited run of Aurland I hydropower plant in summer

4.2.1 Impact of Aurland I on water temperature in Aurlandselva

Figure 23 shows summer water temperature in Aurlandselva and Aurland I discharge for the period 2002-2014. There is a strong impact of Aurland I on water temperature in Aurlandselva: the higher the discharge in Aurland 1 is, the cooler the water temperature is. In other words, water temperature in Aurlandselva is warmer for years with lower discharge in Aurland 1. Consequently, a scenario which includes a limited run of Aurland 1 was simulated.

We note that water temperature in Aurlandselva is also influenced by other factors than Aurland I discharge. For example, in 2011, 2012, and 2013, the discharge in Aurland I is close to the 2003-2013 average discharge, while the summer water temperature in Aurlandselva varies by 1.5 C between these years. This suggest that others factors like climate conditions also have also an impact on water temperature in Aurlandselva.

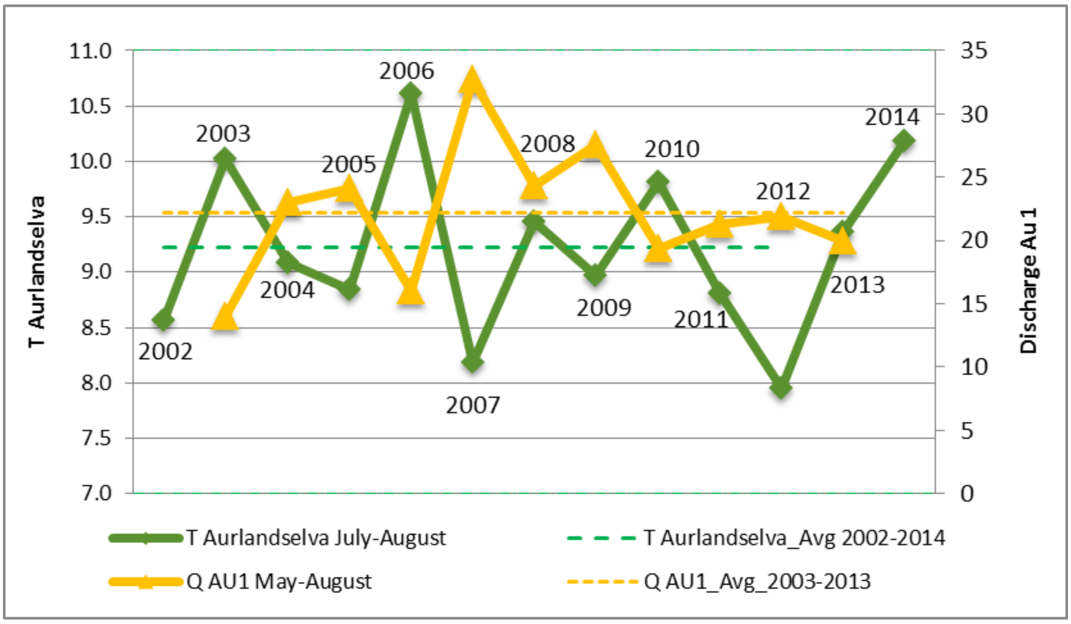

Figure 23. Summer water temperature in Aurlandselva is plotted for each year for 2002-2014 (green). Summer discharge from Aurland 1 is plotted for each year for 2003-2013 (yellow).

4.2.2 Description of scenario 2

The second scenario consists in limiting Aurland I hydropower production during 10, 20 or 30 days from Mai, June or July. Aurland I is used only to respect the minimum flow conditions in Aurlandselva an to maintain lake water level above LWRL.

The following assumptions are made when simulating scenario 2:

- Vangen hydropower plant is stopped in summer (as today),
- Aurland I is in limited run during 10, 20 or 30 days from Mai, June or July if all conditions are met,
- Environmental restrictions for Aurlandselva are respected (minimum flow described in **2.4**)
- Remaining discharge in Aurlandselva (discharge exceeding minimum flow) is used to preserve water volume in Lake Vassbydgvatn (it compensates reduction of water from Aur I),
- Lake water level is kept within the range {54, 55.4} m, i.e. {LRWL- HRWL},
- If necessary the remaining water volume in Lake Vassbygdvatn within the range {54, 55.4} m is used to compensate the lack of water from Aurland I.
- In some cases, the stop of Aurland I can not be compensated by retaining Aurlandselva water in the lake and the lake water level could fall under the LRWL. Therefore, Aurland I is allowed to run and to realease water until the lake water level reaches the LRWL. The Aurland I discharge is computed accordingly.

In the following paragraph, Aurland 1 "limited run" means that Aurland I runs only to respect the minimum flow in Aurlandselva.
Scenarios were run for summer (April- November) 2006 and 2007. Nine simulations were run for each year. They are described in **Table 15.**

Table 15. Matrix of simulations for Scenario 2. Simulations names are given according to date and length of Aurland limited run

SCENARIO 2		Length		
Limited run of Aurland I		10 days	20 days	30 days
Month	Mai	B1	B2	B3
	June	C1	C2	C3
	July	D1	D2	D3

4.2.3 Model results

Results of simulations for scenario 2 show that a limited run of Aurland 1 could lead to increased water temperature in Aurlandselva in wet years. Significant effects occur already when Aurland 1 is limited for 10 days. The longer Aurland I HP has a limited run the higher the temperature increases are.
However, no significant temperature increase is noticed if Aurland 1 HP is limited before stratification formation.
In very dry years, lack of water may not allow any long limited run for Aurland 1. Consequently temperature increase cannot always occur.

Aurland 1 HP plays a specfic role for electricty production and ancillary services (frequence regulation). Any restriction or limitation of the production would therefore require an impact assessement prior to implementation in order to evaluate the feasability of such a measure.

Results of simulations for 2006

When simulating scenario 2 for 2006, Aurland 1 HP often had to produce (electricity) to avoid any falling under the LRWL in the lake. **Table 16** gives Aurland 1's production expressed in percentage of reference production (Reference production is the actual production for 2006).

Aurland 1's production was 88 % and 96 % of reference production in scenarios B and scenarios C respectively.

As a consequence, model set-up for scenarios C and D are almost similar to the reference situation since Aurland 1 could hardly be limited. As expected, results from simulated scenarios indicate very little increase of water temperature in Aurlandselva for scenario C (June) in **Figure 24**. No increase can be discernible for scenario D (July).

However temperature increase is noticed for scenarios B (May). In May, stratification is not established in Lake Vassbygdvatn and water column is still well-mixed preventing any important increase of surface layers. Limited run of Aurland 1's production during this period (only 3 % of reference production) does stimulate moderate temperature increase in lake surface water.

Table 16. Assumed production in Aurland 1 HP for each 2006 scenario. Production is expressed in percentage of reference production (reference situation is defined by simulated results of today's situation).

2006	Assumed production in % of reference production
B (B1, B2, B3)	4
C (C1, C2, C3)	88
D(D1, D2, D3)	96

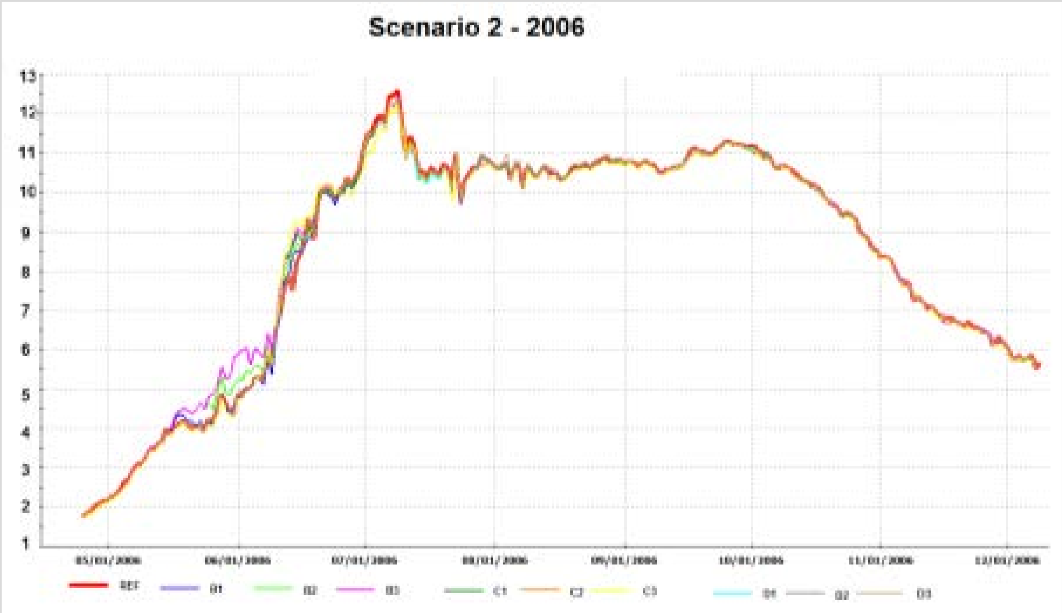

Figure 24. Simulated time series of water temperature in Aurlandselva for 2006 scenarios B1, B2, B3, and C1, C2, C3 and D1, D2, D3, compared to 2006 reference scenario (red).

Results of simulations for 2007

Table 17. Assumed production in Aurland 1 HP for each 2007 scenario. Production is expressed in percentage of reference production (reference situation is defined by simulated results of today's situation).

2007	Assumed production in % of reference production
B (B1, B2, B3)	3
C (C1, C2, C3)	22
D(D1, D2, D3)	27

When simulating scenario 2 for 2007, Aurland 1 HP had to run in some days to avoid any falling under the LRWL. **Table 17** gives Aurland 1's production expressed in percentage of reference production. Reference production is the actual production for 2007.

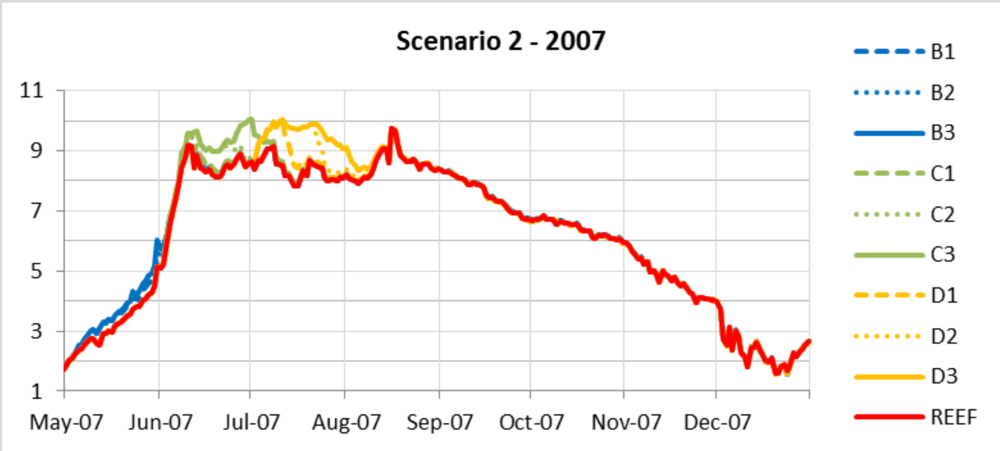

Figure 25. Simulated time series of water temperature in Aurlandselva for 2007 scenarios B1, B2, B3 (blue), C1, C2, C3 (green) and D1, D2, D3 (orange), compared to 2007 reference scenario (red).

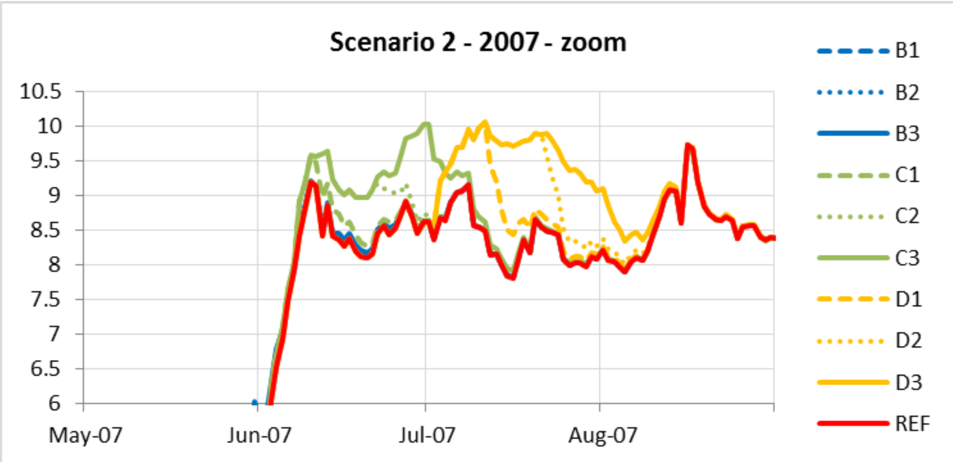

Figure 26. Simulated time series of water temperature in Aurlandselva for 2007 scenarios B1, B2, B3 (blue), C1, C2, C3 (green) and D1, D2, D3 (orange), compared to reference scenario (red).

Results from simulated scenarios show that a limited run of Aurland leads to significant increase of water temperature in Aurlandselva (**Figure 25** and **Figure 26, 25, Table 18**).

Effects are more intense:

- **If the limited run starts in July rather than June and May**: increase up to 1.20, 0.67 and 0.37 °C for scenarios D (July), C (June), and B (Mai) respectively;
- **If the limited run lasts 30 days, rather than 20 and 10 days**: increase is 1.20, 0.94, and 0.49 °C for scenario D3, D2, and D1 respectively.

Increase of temperature occurs during the month of limited run and lasts about one additional week.

All values given in Table 18 are the <u>relative</u> increase in water temperature when comparing simulated scenarios and simulated reference situations.

We point out that in some cases (scenarios B and C) a significant temperature increase can occur when limiting the production in Aurland 1. In these cases, Aurland 1's electricity production is about one quarter of the actual 2007 production.

Table 18. Monthly averaged temperature difference for Aurlandselva obtained for 2007 from scenario 2 B1, B2, B3, scenario 2 C1, C2, C3, and scenario D1, D2, D3 compared to reference situation (Reference situation corresponds to simulated water temperature for 2007 calibrated against measurements.). Uncertainties are given by CE-QUAL's model limitations: ± 0.02 °C.

2007	Averaged absolute difference	B1	B2	B3	C1	C2	C3	D1	D2	D3
	May-Oct	0.05	0.06	0.07	0.03	0.06	0.11	0.07	0.12	0.17
	May	0.27	0.34	0.37	0.00	0.00	0.00	0.00	0.00	0.00
	June	0.06	0.08	0.11	0.21	0.48	0.67	0.00	0.00	0.00
	July	0.01	0.01	0.01	0.01	0.02	0.22	0.49	0.94	1.20
	aug	0.00	0.01	0.01	0.00	0.00	0.01	0.02	0.05	0.18
	Sept	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01
	Oct	0.01	0.02	0.01	0.00	0.01	0.02	0.01	0.01	0.01
	Nov	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.01

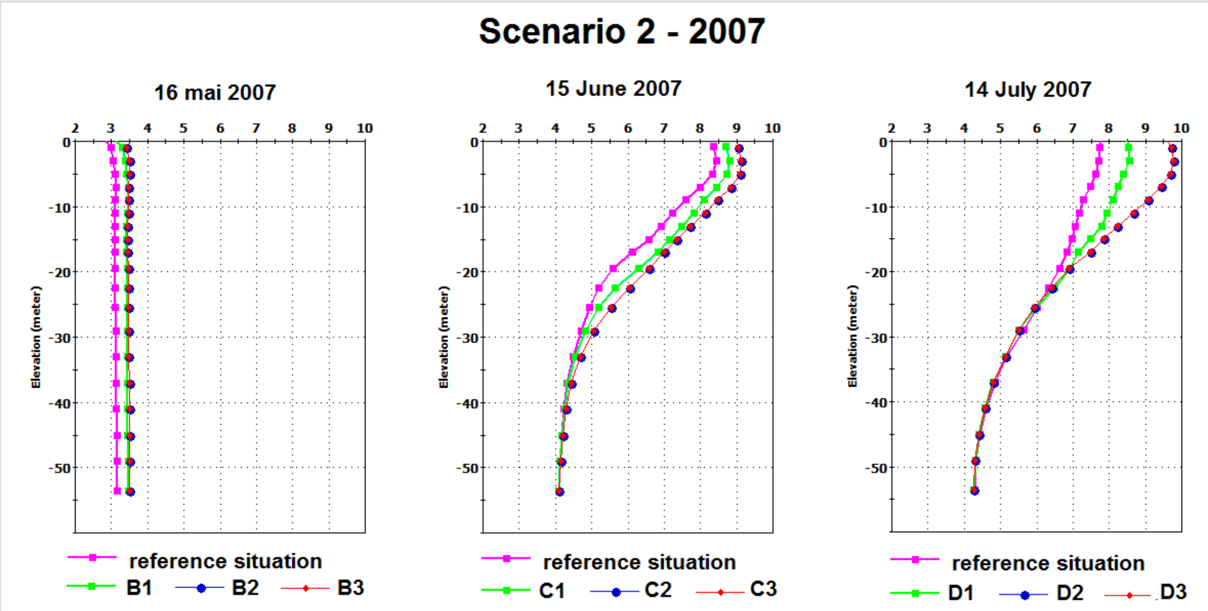

Figure 27. Simulated vertical profile of water temperature in Lake Vassbygdvatn for 2007 from scenarios 2 B1, B2, B3, (left) , scenarios 2 C1, C2, C3, (centre), and scenarios D1, D2, D3 (right), compared to reference situation (reference situation is defined by simulated results from today' situation). Vertical profiles are plotted for the following dates: 16 May, 15 June, and 14 July 2007.

Simulated vertical profiles confirm that Aurland 1 limited run leads to increased water temperature in Lake Vassbygdvatn (**Figure 27**).

If the limited run occurs before the formation of stratification in the lake, all layers benefit from this limitation of production (**Figure 27 left**), but the increase is smaller.

If the limited run occurs when stratification forms or after stratification is established, the degree of increase is more significant (**Figure 27, centre and right).** The later in summer Aurland 1 is limited, the less the deep layers benefit from limited production, and the larger is the increase for the surface and thus for temperature in Aurlandselva.

4.3 Scenario 3: Modification of Aurland I's outlet location

4.3.1 Description of scenario 3

Scenario 3 consists in modifying the location of Aurland 1's tunnel in Vassbydgvatn.

Today tailwaters from Aurland 1 are released between 6 m deep and the surface (48 -54 m a.s.l.) and are generally colder than Vassbydgvatn waters they encounter at the same depth (**Figure 28**). Aurland 1's waters are also colder than water in Aurlandselva (**Figure 28 and** Figure 26**Figure 29)**. Scenario 3' objective is to simulate mitigation measures with different depths (12 m, 21 m, and 27 m) for Aurland 1's tunnel. These simulations are carried out in order to understand the potential influence of the outlets' location. Due to technical reasons, modifying the depth of the outlet's location will not be possible with the current Pelton turbine.

Simulations were run for summer (April- November) 2006 and 2007. Three simulations were run for each year. They are described in **Table 19.**

Table 19. Matrix of simulations for Scenario 3. Simulations names are given according to location of Aurland 1 tunnel's bottom.

SCENARIO 3	Depth of tunnel's bottom		
	12 m	**21 m**	**27 m**
Name	E1	E2	E3

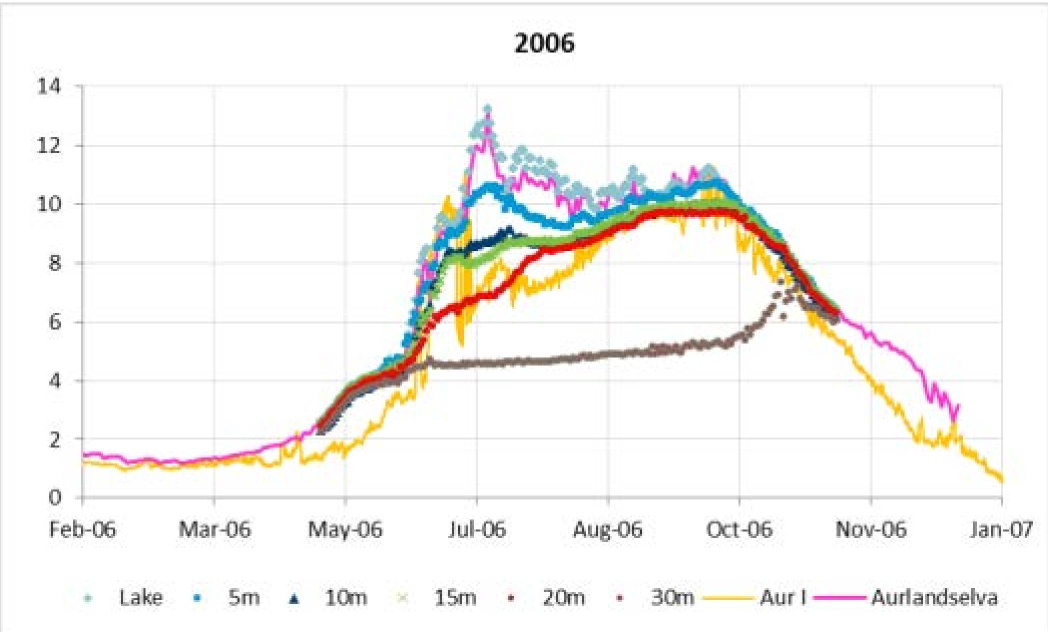

Figure 28. Measured water temperature in Lake Vassbygdvatn at several depths in 2006 (markers) and in Aurlandselva (purple solid line). The yellow line represents temperature of water released by Aurland 1 HP.

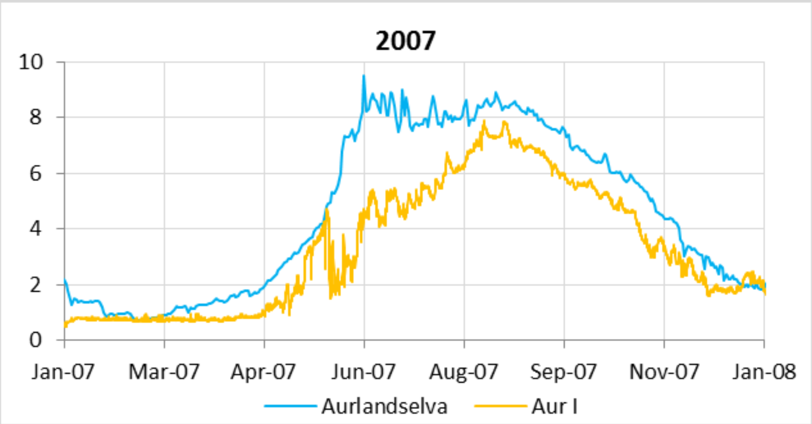

Figure 29. Measured water temperature for 2007 in Aurlandselva (blue line), and at the outlet of Aurland 1 HP (yellow).

4.3.2 Model Results

Results from scenarios E1, E2, and E3 indicate that modification of Aurland 1's tunnel outlet does not significantly contribute to increase water temperature in Aurlandselva.
(**Figure 31** and **Figure 32**).

Water temperature increase in Aurlandselva ranges from 0.01 (May, scenarios E1, E2, E3) to 0.51 (August, scenario E3). Scenarios E2 and E3 give slightly higher temperature increase than E1 (**Table 20**, but values are still insignificant in relation to model uncertainties.

However, layers located under the lake surface and down to 50 m endure temperature change in scenarios E2 and E3 (**Figure 32**). E1 gives water temperature close to reference situation.
E2 and E3 induce more vertical missing in Lake Vassbygdvatn, resulting in reduced temperature for layers above 25 to 30 m, and higher temperature for layers under 30 m.
At 10 m, in July, water is about 2 °C colder in 2006, and about 1.3 to 1.4 °C colder in 2007 (
Table 21).

Table 20. Monthly averaged in Aurlandselva temperature difference obtained for 2006 and 2007 from scenarios 3 E1, E2 and E3, compared to reference situation.

2006	Averaged absolute difference	E1	E2	E3	2007	Averaged absolute difference	E1	E2	E3
	May-Oct	**0.06**	**0.25**	**0.28**		**May-Oct**	**0.06**	**0.22**	**0.24**
	May	0.01	0.01	0.01		**May**	0.01	0.01	0.01
	June	0.03	0.12	0.12		**June**	0.11	0.43	0.42
	July	0.18	0.44	0.45		**July**	0.09	0.38	0.34
	Aug.	0.06	0.46	0.51		**Aug**	0.09	0.27	0.33
	Sept	0.04	0.40	0.48		**Sept**	0.03	0.14	0.20
	Oct	0.04	0.08	0.14		**Oct**	0.02	0.12	0.14

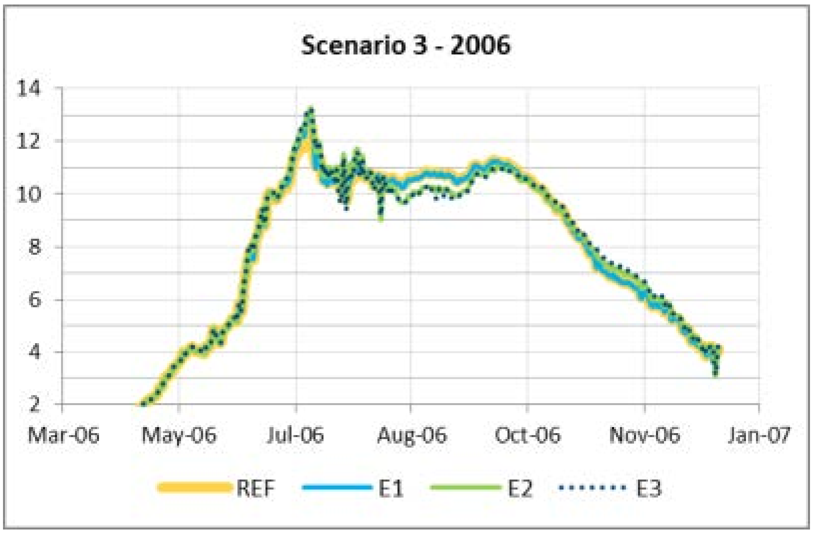

Figure 30. Simulated time series of water temperature in Aurlandselva from 2006 scenarios 3 E1 (blue), E2 (green) and E3 (dashed black), compared to reference scenario (yellow).

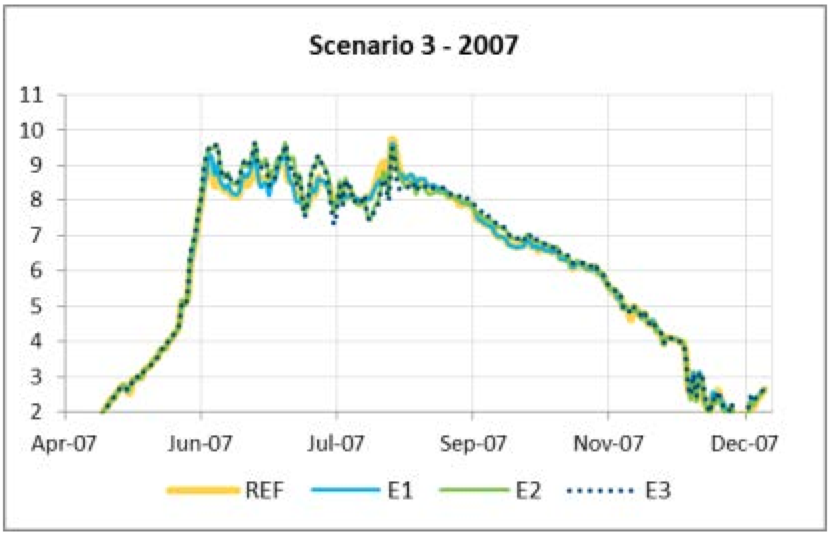

Figure 31. Simulated time series of water temperature in Aurlandselva from 2007 scenarios 3 E1 (blue), E2 (green) and E3 (dashed black), compared to reference scenario (yellow).

Table 21. Monthly averaged temperature difference for layers at 10m and 20 m obtained for 2007 from scenarios 3 E1, E2 and E3, compared to reference situation (Reference situation corresponds to simulated water temperature for 2006 calibrated against measurements.).

2007	10m				20m			
	Averaged absolute difference	**E1**	**E2**	**E3**	**Averaged absolute difference**	**E1**	**E2**	**E3**
	May-Oct	**0.06**	**0.46**	**0.44**	**May-Oct**	**0.05**	**0.44**	**0.34**
	May	0.01	0.01	0.01	May	0.00	0.01	0.01
	June	0.15	**0.61**	**0.62**	June	0.10	**0.63**	**0.62**
	July	0.06	**1.42**	**1.29**	July	0.06	**1.18**	**0.84**
	aug	0.09	**0.48**	**0.38**	aug	0.10	**0.55**	0.22

Sept	0.02	0.14	0.20	Sept	0.02	0.14	0.24
Oct	0.01	0.11	0.13	Oct	0.01	0.10	0.12

Table 22. Monthly averaged temperature difference for layers at 10m and 20 m obtained for 2006 from scenarios 3 E1, E2 and E3, compared to reference situation (Reference situation corresponds to simulated water temperature for 2007 calibrated against measurements.).

2006	**10m**				**20m**			
	Averaged absolute difference	**E1**	**E2**	**E3**	**Averaged absolute difference**	**E1**	**E2**	**E3**
	May-Oct	**0.19**	**0.78**	**0.86**	**May-Oct**	**0.12**	**0.23**	**0.25**
	May	0.01	0.02	0.02	May	0.01	0.01	0.02
	June	0.06	0.17	0.17	June	0.02	0.13	0.14
	July	0.66	**2.01**	**2.19**	July	0.09	0.33	0.29
	Aug	0.30	**1.84**	**1.97**	Aug	0.27	0.40	0.29
	Sept	0.08	**0.55**	**0.65**	Sept	0.23	0.29	0.51
	Oct	0.04	0.08	0.15	Oct	0.11	0.21	0.26

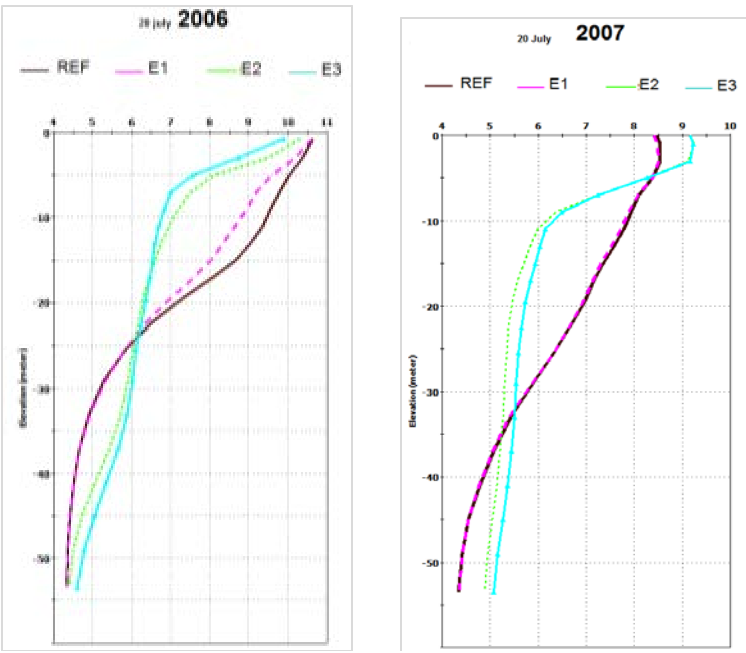

Figure 32. Simulated vertical profile of water temperature in Lake Vassbygdvatn for 2006 (left) and 2007(right) from scenarios 3 E1 (pink), E2 (green), and E3 (turquoise), compared to reference situation (black). Reference situation is defined by simulated results from today' situation. Vertical profiles are plotted for the following dates: 20 July 2006, 20 July 2007.

4.4 Scenario 4: Increase of discharge in Vassbygdelvi

4.4.1 Description of Scenario 4

Scenario 4 consists in increasing Vassbygdelvi discharge by 2, 4, 6, and 8 m³/s from May to August.

New discharge values for Vassbygdelvi are computed by added 2, 4, 6, or 8 m³/s to the observed discharges in 2006 and 2007. **Figure 33** shows time series of discharge in Vassbygdelvi used in simulations F1, F2, F3, and F4, compared to reference situation.
In all simulations, water temperature for Vassbygdelvi is set to observed water temperature for the corresponding years.

Discharge to Aurland 1 and Vangen, and WL in Lake Vassbygdvatn are kept to the same values than observed values for 2006 and 2007.
The additional inflow from Vassbygdelvi flows out from the lake into Aurlandselva.

Scenarios were run for summer (April- November) 2006 and 2007. Four simulations were run for each year. They are described in **Table 23.**

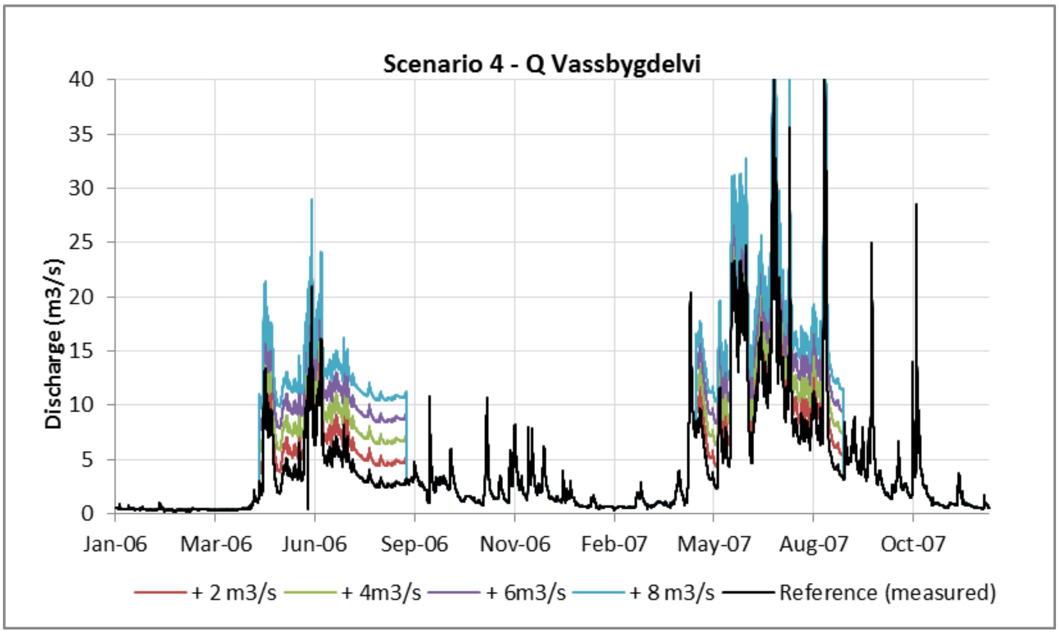

Figure 33. Time series of Vassbygdelvi discharge for scenarios 4 F1 (red), F2 (green), F3 (purple), and F4 (blue), compared to reference situation.

Table 23. Matrix of simulations for Scenario 4. Simulations names are given according to discharge increase in Vassbygdelvi.

SCENARIO 4	**Discharge in Vassbygdelvi**			
	+ 2 m³/s	**+4 m³/s**	**+ 6 m³/s**	**+8 m³/s**
Name	F1	F2	F3	F4

4.4.1 Model results

Results from simulated scenarios F1, F2, F3, and F4 show that increasing (up to + 8 m³/s) does not contribute to significant water temperature increase in Aurlandselva.

Simulated time series of water temperature in Aurlandselva for scenarios F1 to F4 for 2006 and 2007 show that water temperature time series from scenarios is very similar to the reference situation (**Figure 34).** May-October average absolute difference between simulated time series and reference time series ranges from 0.15 to 0.19 °C in 2006 and from 0.04 to 0.13 °C in 2007. In 2006, the highest difference is 0.32°C, and occurs in July for scenarios F1 and F2. In 2007, the highest increase is 0.22 °C and occurs in August for scenarios F3. Differences in water temperature between values from simulated scenarios and the reference situation are considered negligible.

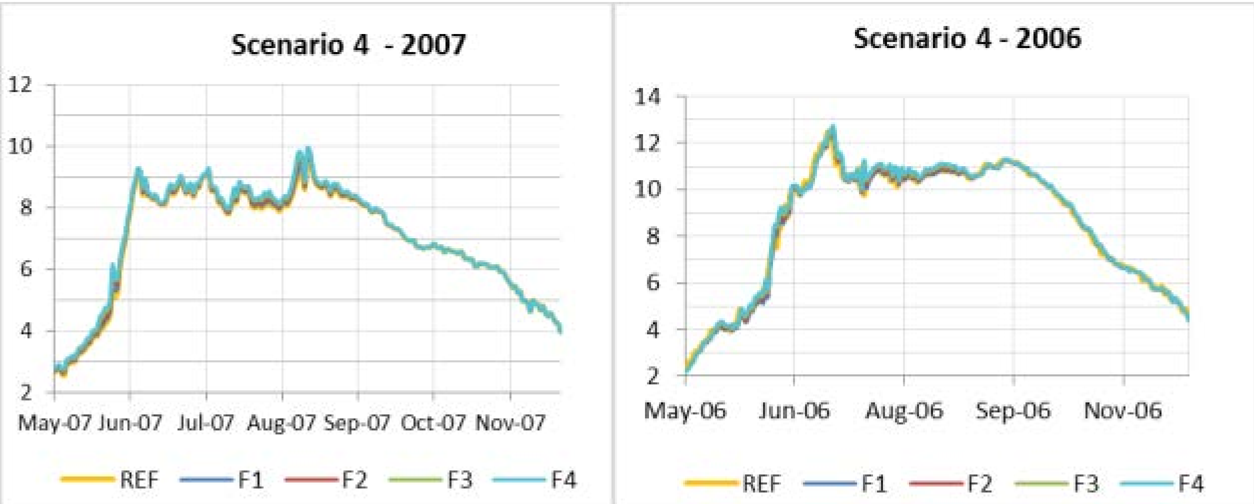

Figure 34. Simulated time series of water temperature in Aurlandselva from 2006 (left) and 2007 (right) scenarios 3 F1 (blue), F2 (red) and F3 (green), and F4 (turquoise), compared to reference scenario (yellow).

Table 24. Monthly averaged temperature difference in Aurlandselva obtained for 2006 from scenarios 3 F1, F2, F3, and F4 compared to reference situation (Reference situation corresponds to simulated water temperature for 2006 calibrated against measurements.).

2006	Averaged absolute difference	F1	F2	F3	F4
	May-Oct	**0.17**	**0.18**	**0.19**	**0.15**
	May	0.16	0.15	0.15	0.11
	June	0.29	0.29	0.31	0.27
	July	0.32	0.31	0.32	0.19
	Aug.	0.11	0.15	0.22	0.25
	Sept	0.07	0.07	0.09	0.08
	Oct	0.08	0.08	0.08	0.03

Table 25. Monthly averaged temperature difference in Aurlandselva obtained for 2007 from scenarios 3 F1, F2, F3, and F4 compared to reference situation (Reference situation corresponds to simulated water temperature for 2007 calibrated against measurements).

2007	Averaged absolute difference	F1	F2	F3	F4
	May-Oct	**0.04**	**0.09**	**0.13**	**0.12**
	May	0.06	0.12	0.18	0.18
	June	0.06	0.11	0.15	0.13
	July	0.06	0.11	0.16	0.16
	Aug.	0.08	0.15	0.22	0.21
	Sept	0.01	0.03	0.04	0.04
	Oct	0.00	0.00	0.01	0.01

5 Conclusion

A numerical model of Lake Vassbygdvatn was set-up in order to study alternative solutions for increasing water temperature at the lake's surface, and in the downstream Aurlandselva River as a consequence. Four different scenarios were simulated to investigate possible mitigations for the period May to October. Mitigations measures consisted in:

- Running Vangen hydropower plant in summer unlike it is today (scenario 1),
- Restricting Aurland 1 hydropower plant for 10 to 30 days in summer (scenario 2),
- Modifying the depth of Aurland 1's tunnel outlet in Lake Vassbygdvatn (scenario 3),
- Increasing the discharge in Vassbygdelvi (scenario 4).

Simulations were run for two different climate years: 2006 being warm and dry, with strong stratification in Lake Vassbygdvatn; 2007, being a cold and wet year, with weak stratification in the lake. In total 37 simulations were run and studied.

Significant increase of water temperature in Aurlandselva was obtained only in scenario 2 which includes a limited run of Aurland 1's hydropower plant during 10 to 30 days from May, June or July. The largest rises in temperature were obtained for the longest limited run period after stratification formation.

Further work

In the case of Aurlandselva River, priority is given to mitigation measures which would contribute to increase of water temperature especially during cold years.

The main reason for Aurland 1's waters to be cold compared to Aurlandselva temperature is that water is withdrawn in the upper mountain reservoir (Viddalsvatn, more than 900 m a.s.l) where climate conditions are more severe than in Lake Vassbygdvatn and downstream. The location of the intake in upper reservoir could also be investigated as alternative solution. Measurements from 2009 show that in summer surface water ins Viddalsvatn is warmer than the deep water where the intake is located. Intake with variable depth needs toot be further investigated. The study could be based on field measurements from 2009, completed by additional measurements at several depths and over several summers. Temperature loggers located at several depths have been installed in Vidalsvatn in 2016. Results from these measurements should be analysed.

Simulations from scenario 2 showed that limited run of Aurland 1 can be a suitable mitigation measure. This measure could be applied especially during cold years to maintain Aurlandselva temperature above critical threshold for fish. However, Aurland 1 HP plays a specfic role for electricty production and ancillary services (frequence regulation). Any restriction or limitation of the production would therefore require an impact assessement prior to implementation in order to evaluate the feasability of such a measure.
As a continuation to findings from these simulations, it would be valuable to establish a method for defining "cold" and "wet" years. In addition, supplementary scenarios can be investigating to determine the more appropriate win-win solution for both the hydropower company and the targeted fish population. A limitation of Aurland 1 production during the whole year seems to not be necessary and efficient but reduced production in specific period might be very profitable for water temperature increase.

A new pump will be installed in order to transfer water between two reservoirs located at higher altitude than Vassbygdvatn. The pump will be installed in Fossane (Aurland 3). The use of the pump will be strongly dependent on market electricity prices.
A study of impacts of Aurland 3 pump's operation should be carried out to assess how the pump affects water temperature conditions in Vassbygdvatn, and in Aurlandselva.

APPENDIX

Table 26. Data quality of input data to the numerical model

Meteorological data				
		Good	**Uncertain**	**Very uncertain**
Air temperature			x (± 1 C)	
Wind direction			x	
Wind speed				
Dew point temperature			x	
Cloud cover			x	
Humidity			x	
Pressure			x	
Solar radiation			x	
Precipitation			x	
Inflows				
		Good	**Uncertain**	**Very uncertain**
Au I	Temperature	x		
	Discharge	x		
Lateral (distributed inflow – runoff)	Temperature		X	
	Discharge			x
Vassbygdelvi	Temperature	x		
	Discharge	x		
Outflows				
		Good	**Uncertain**	**Very uncertain**
Vangen	Discharge	x		
	Temperature	x		
Out Vassbygdvatn	Wlevel	x		
	Discharge	x		

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