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ANALYSIS OF ENVIRONMENTAL IMPACTS OF A PUMP-STORAGE SYSTEM BETWEEN TWO NORWEGIAN RESERVOIRS CONSIDERING CLIMATE SCENARIOS

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A mia sorella Chiara,

e a tutta quanta la mia famiglia

Abstract

In Norway, pumped-storage hydropower plants are supposed to increase in number in the future, thanks to the great availability of water in the whole country, the number of existing traditional hydropower plants, and the changes of the energy market associated with the increasing use of intermittent renewable sources. However, environmental impacts on reservoirs from hydropower regulation are considerably less studied than impacts on rivers. Upgrading traditional power plants to pumped-storage ones can affect the environmental conditions in the reservoirs. The main objective of this master thesis is to investigate the current methodology, and explore new approaches, to identify and evaluate the environmental impacts of short-term water level fluctuations on two reservoirs connected by a pumped-storage hydropower plant.

A case-study in southern Norway has been chosen (the Øyarvatn and Roskreppfjorden reservoirs belonging to the Sira-Kvina system), as part of the HydroConnect project currently carried out by SINTEF Energi Research Institute and co-founded by the Norwegian Council (RCN Project no. 320794). To achieve this goal, an interdisciplinary approach has been followed, connecting hydro-morphological aspects of the reservoirs and future climate scenarios with a medium-term optimal price-based scheduling model, to obtain detailed water level data for the reservoirs. A selection of the indices currently developed under the Norwegian hydromorphological classification system for lakes and reservoirs (HYMO) have been applied. At the same time, some new indices have also been proposed and tested. A comparison between results obtained for a reference period and considering future climate scenarios has been carried out as an initial step to a task of the HydroConnect project. In addition, the effect of introducing ramping constraints on water level variations have been evaluated.

Results show that the extent and intensity of the dewatered areas due to short-term water level fluctuations depend on the reservoir volume and morphology. Pumping operation mode will increase the number of peaking events per year. In Øyarvatn reservoir, which is smaller than Roskreppfjorden, pumping operation will result in a smaller but more frequently impacted dewatered area. Implementing ramping constraints can help reducing the environmental impact in both reservoirs. Further analyses on the impact generated by hydropower production are needed to suggest ramping constraints allowing for more sustainable hydropower operations (considering both economic and environmental perspectives).

This work can be considered as a starting point for evaluating potential impacts generated by traditional and pumped-storage power plants, both in present and future climate scenarios, and supporting the identification of environmental constraints.

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Chapter 1

INTRODUCTION

1.1 Hydropower in Norway and PSHPs

Nowadays, Renewable Energies Sources (RES) importance is worldwide in the limelight. Most of these RES, like wind or solar power, are subjected to variability due to their intrinsic nature. In contrast, hydropower energy is the only able to store energy surplus. Pumped Storage Hydropower Plant (PSHP) is the largest energy battery available worldwide and allow to better integrate in the energy grid the volatile energy outputs from solar and wind power. When energy prices are high, the system operates as a traditional power plant, generating energy through a turbine. When energy prices are low, it is possible to exploit the pump, bringing the water from the lower to the upper reservoir. Recent studies identify a potential to increase pump hydro capacity by retrofitting already existing conventional hydropower plants, non-powered dams, disused mines and underground caverns. This could potentially increase global pump hydro capacity by almost 50 per cent (from 160 GW to about 240 GW) by 2030 [27].

In Norway, which has almost half of Europe's reservoir storage capacity and where the main energy source is hydropower, there are ten active PSHPs at the moment, mainly located in the southern part of the country [21]. These active PSHPs are open-loop pump systems, which means that either the upper or the lower reservoir is connected to flowing water source such as a river. They are designed to operate when the demand for electricity is low. So, a PSHP facility stores energy by pumping water from the lower reservoir to the upper one. In periods with high electrical demand, water is then released back to the lower reservoir through a turbine, generating electricity. The cost for construction of new PSPs in Norway is expected to be low, because current power plant could take advantage from the existing tunnel system, reducing the investment only to pumping units and powerhouse extension. Pumped Storage Hydropower Plants (PSHPs) represent a valuable solution to achieve ambitious decarbonization objectives.

Future climate scenarios and their impact on hydropower production is an important factor to consider, since this kind of energy is strongly influenced from the weather. Changes in temperature, as precipitation amount and distribution during the year can lead to changes in inflows pattern. This aspect directly influences water availability and therefore will have an impact on the optimization of the operational regime of hydropower plants under traditional and pumping operations. Studies from the Norwegian Water Resources and Energy Directorate (NVE) show that runoff will vary more from year to year, increasing the uncertainties to optimize hydropower operations.

1.2 Environmental impacts on shoreline

This system has many energetic benefits, but also environmental implications. Pump activation is subjected to price variability, and can vary many times during a single day, and so water level in the two involved reservoirs. This can have an important impact on the littoral zone, defined as a transitional area, where aquatic and terrestrial components interact, creating habitats with high biodiversity levels [37]. Water level variation is one of the most hydro-morphological pressures, which can cause desiccation and stress for species [22].

Art. 4 in EU Water Framework Directive (WFD) states that Member States not only have to implement necessary measures to prevent deterioration of the status of water bodies, but also shall protect, enhance and restore all bodies of surface water [8]. Due to large variability in lake's morphological structure, geographical position, reservoir's purpose and biological communities, it is difficult to evaluate criteria for evaluation of water status and, consequently, measures to adopt in order to reach a good quality status.

In Norway the current reference guide is an Hydromorphological (HYMO) classification system, published in 2019 [3], whose aim is to evaluate the current hydromorphological classification, and find indices easily measurable for all Norwegian reservoirs, given the current availability of data, state of modelling tools and monitoring techniques. This classification system is divided into 5 classes, ranging from *Near natural* to *Severely modified*, and consists of 17 hydromorphological parameters. Many of these can be calculated based on hydrological data and bathymetric maps. As the aim of the study was to provide a classification system for all reservoirs in Norway, natural and regulated, the main requirement for all the defined parameters is that they should be easily measurable. Some of them focus on the entire lake (e.g. degree of regulation, total volume change, short term water level variations) while some others are focused on littoral zone (dewatered littoral zone versus total littoral zone, loss in lateral connectivity along the shoreline). The shorter time resolution is on daily basis, due to general detail level of data.

1.3 HydroConnect project and objective of the present work

In this context, the *HydroConnect* [12] project takes place. This project is carried out by SINTEF Energi, co-founded by the Norwegian Research Council, and has different research partners; University of Trento is one of them. Future environmental impacts on involved reservoirs need to be analyzed, considering different price and inflow evolution, and the present work is part of this research.

How would PSHPs behave in terms of water level (WL) fluctuations and consequent dewatered areas compared to traditional operational systems considering hypothetical future climate scenarios? To answer this question, the following steps-questions will be answered:

Q1. How could the introduction of PSHP influence water level fluctuations in the involved reservoirs, considering a medium term optimization scheduling model for hydropower production and comparing the traditional operating mode and the pumping one?

Q2. What would be the influence on the littoral zone, in terms of dewatered areas in the two reservoirs, considering the two different operating modes?

Q3. Is there a way to mitigate the potential negative effects by adding a ramping constraint to the operational schedules?

Q4. How could the change of the hydrological regime affect these considerations in the future, considering different emission scenarios in climate projections?

In addition, this thesis aims to find an easy and reproducible method to identify physical impacts on reservoir's shoreline in large lakes, considering short-term water level variations, generated by artificial regulation. This method is based on morphological features of the littoral zone, and requires spatial analyses.

Chapter 2

STUDY CASE

2.1 Sira-Kvina hydropower system

The hydropower plant analyzed in this study is part of Sira-Kvina hydropower scheme. This scheme is located in the southern part of Norway, in Agder Country, in the south-western part of Norway. The utilized hydropower resources are the Sira and Kvina watercourse, respectively 152 km and 151 km length. While Sira River has its origin in the Sirdal mountain range, on the border area between Agder and Rogaland countries, the Kvina River has its source north of Lake Roskreppfjorden.

The entire scheme is a combined development obtained by transferring water from the Kvina River to the Sira watercourse, after make it pass through different power plants along its natural course. The two watercourses develop separately in their upper section, joining then in Tonstad power plant, which has his outlet in at the north of Sirdalsvatn/Lundevatn reservoir.

Thanks to the location in the southern part of Norway, and to the large amount of water exchange possibilities, this power plant secures electric supply to both regional public and industrial needs.

The total capacity of the system is 3042 Mm^3, which gives an option for energy storage of approximately 6300 GWh, produced thank to seven different hydropower plants, which corresponds to about 5% of Norway's power production.

The portion of the entire Sira-Kvina hydropower system analyzed in this thesis is located in the upper section of Kvina watercourse, with its two reservoirs Roskreppfjoprden and Øyarvatn.

2.2 Roskreppfjorden and Øyarvatn

Here we refer to two reservoirs, which are part of this huge hydropower scheme: Roskreppfjorden and Øyarvatn. They are both located in the upper part of Kvina watercourse, as shown in *Figure 2.1*. After a brief description regarding the two involved power plants, the reservoirs' description is provided.

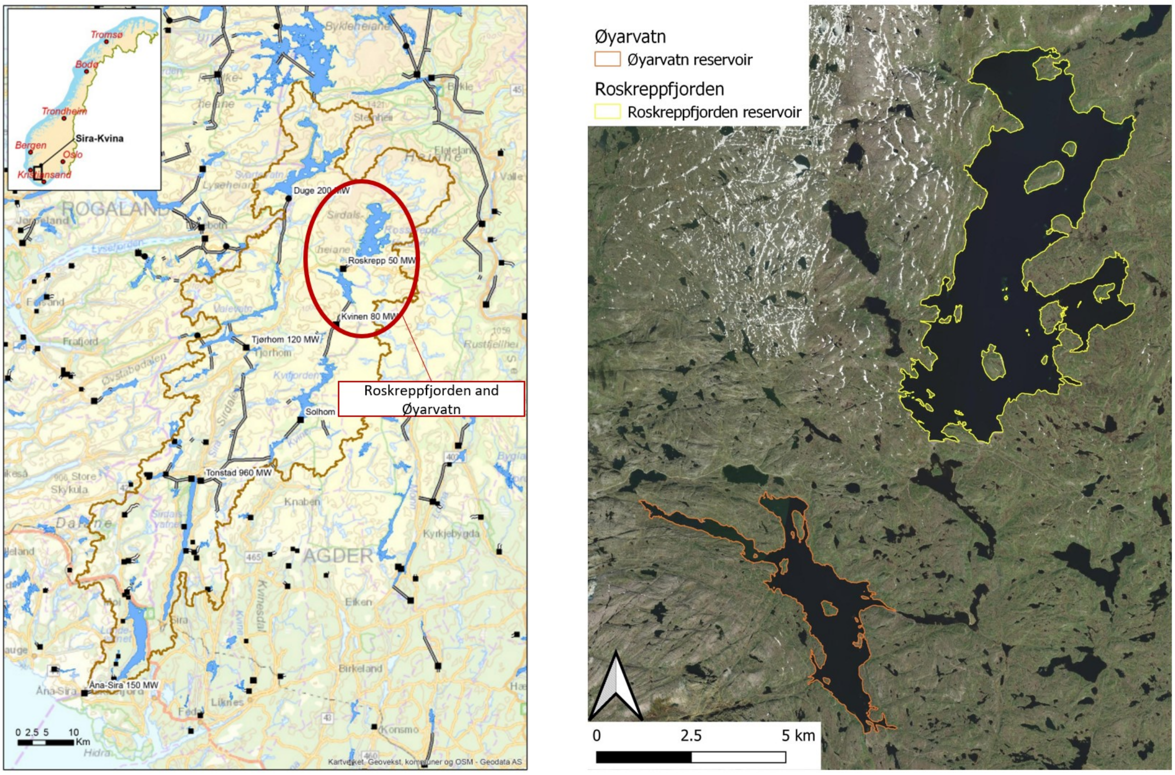


Figure 2.1: Sira-Kvina Hydropower system (NVE Rapport nr. 28/2021 [20]) and Rorkreppfjorden and Øyarvatn reservoirs.

2.2.1 Roskreppfjorden Power Plant

This first power plant is located on the southern part of Roskreppfjoprden, which has its HRWL at 929 m above sea level (asl). The related power plant is the smallest one in the Sira-Kvina company, even if the lake is one of the biggest in the area involved in Sira-Kvina power production. The hydraulic head is approximately 90 m, and the output power is 50 MW. The average annual production is 105 GWh, and the production is for now mostly during the winter, as the price of electricity is higher. The following *Table 2.1* resumes its characteristics.

Through this power plant, water flows into Øyarvatn through a short drainage tunnel, before embarking on the next stage down to Kvinen power plant.

Table 2.1: Characteristics of the Roskrepp Power Plant [33].

Production	Power	In Operation	Head	Municipality
105 GWh	50 MW	1979	83 m	Sirdal

2.2.2 Kvinen Power Plant

The Kvinen power Plant is located by Høenvatn lake in Sirdal municipality, Vest-Agder county. A Francis turbine is installed in the plant, associated with a generator, with an installed output of 80 MW, and an average production of 215 GWh, mainly during winter, since this power plant is closely linked to the production at Roskrepp Power Plant. Its characteristics are resumed in *Table 2.2*.

Table 2.2: Characteristics of the Kvinen Power Plant [32].

Production	Power	In Operation	Head	Municipality
215 GWh	80 MW	1981	116 m	Sirdal

2.2.3 Reservoirs' characteristics

Both Roskreppfjorden and Øyarvatn have an irregular elongated shape, mainly developed in in north-south direction. Roskreppfjorden is the biggest one, since its volume is around 684 Mm^3, while Øyarvatn water volume is 104 Mm^3, approximately one sixth of the upper one. Data regarding their catchments can be found in NEVINA website [16], which allows to identify them selecting a closure point along the river network. Øyarvatn's catchment is bigger than Roskreppfjorden's one, since the upper lake is included in it, with all its catchment. This website was used in this work to download the data used in our analysis.

Table 2.3 resumes the reservoirs' characteristics, and *Figure 2.2* shows the two catchment extensions.

Table 2.3: Roskreppfjorden and Øyarvatn characteristics.

Parameter	Roskreppfjorden	Øyarvatn
HRV	929 m asl	820 m asl
LRV	890 $masl$	837 $masl$
Volume	684 Mm^3	104 Mm^3
Reservoir area at HRV	29.75 km^2	8.08 km^2
Reservoir area at LRV	11.02 km^2	3.87 km^2
Regulation area	18.73 km^2	4.21 km^2
Catchment Area	271 km^2	402 km^2
Available volume for regulation	635.10 Mm^3	95.58 Mm^3

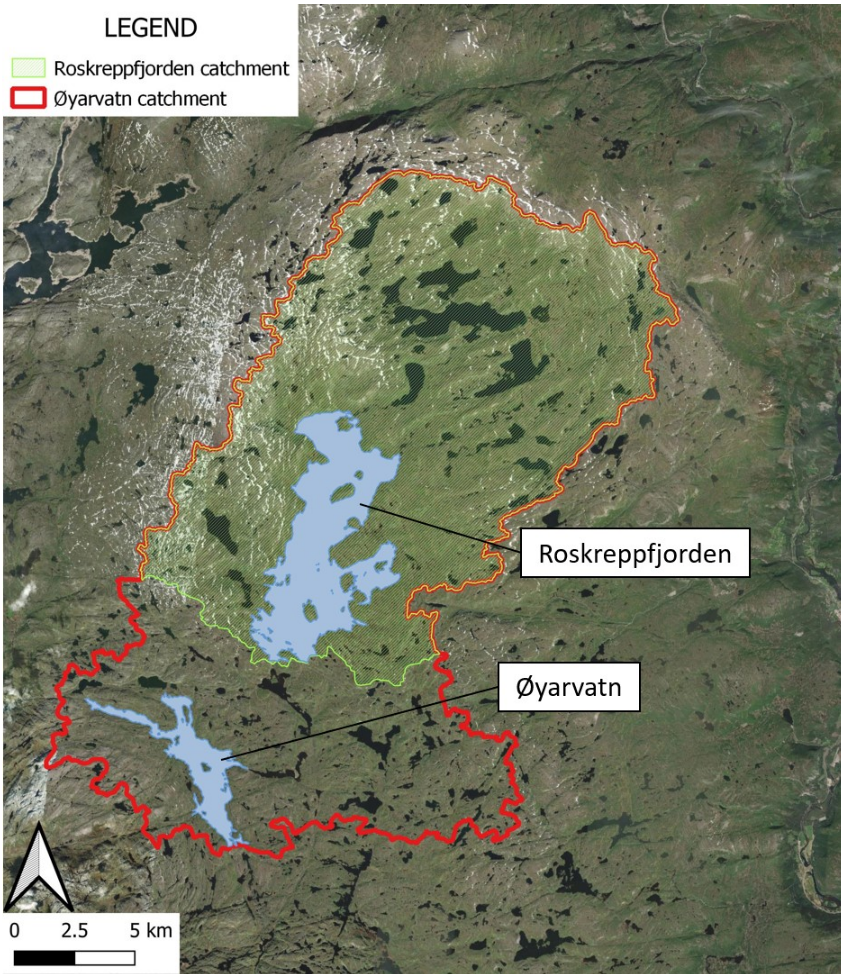


Figure 2.2: Rorkreppfjorden and Øyarvatn catchments.

Chapter 3

RELEVANT MODELLING AND ASSESSMENT APPROACH

Since a proper method to evaluate the environmental impact of pumped-storage system between two reservoirs has been never implemented, this is the main focus of this work. This implies a interdisciplinary approach, and the application of different modelling tools to reach the final scope. All the modelling tools used to reach the scope are free and open source, so the present approach is applicable each time the input data are available.

In this Chapter information on different models and assessment approach used for this study are provided. First, *Section 3.1* briefly gives a general background on climate models and climate modelling in Norway. After that, *Section 3.2* is dedicated to the structure of the *Hydrologiska Byråns Vattenbalansavdelning* (HBV) hydrological model. Inflows predicted by this model are then the fundamental ingredient of the optimization scheduling model presented in *Section 3.3*, which allows to predict water level fluctuations for the two lakes. This part of the thesis will provide answers to sub-questions **Q1**, **Q2** and **Q4** initially presented (*Section 1.3*). The last *Section 3.4* gives a brief overview for what regards the hydromorphological classification system currently used in Norway, with the aim to compute some of the proposed parameters and some new ones that can be proposed and evaluated based on detailed availability of data.

3.1 Climate models and projections

Here a general background regarding climate models and projection is given, followed by a general background on Norwegian climate modelling.

3.1.1 Global and Regional Climate models

Climate scenarios are referred to possible Representative Concentration Pathways (RCPs), and each of them represents a greenhouse gas concentration trajectory. During the IPCC Fifth Assessment Report (2014) [2] 4 different RCPs were identified. Each RCP has a different code (RCP2.6, RCP4.5, RCP6.0, RCP8.5), and represents a concentration trajectory, depending on the efforts that are supposed to be taken in the future to limit greenhouse gas emissions(highest effort under RCP2.6, lowest effort under RCP8.5).

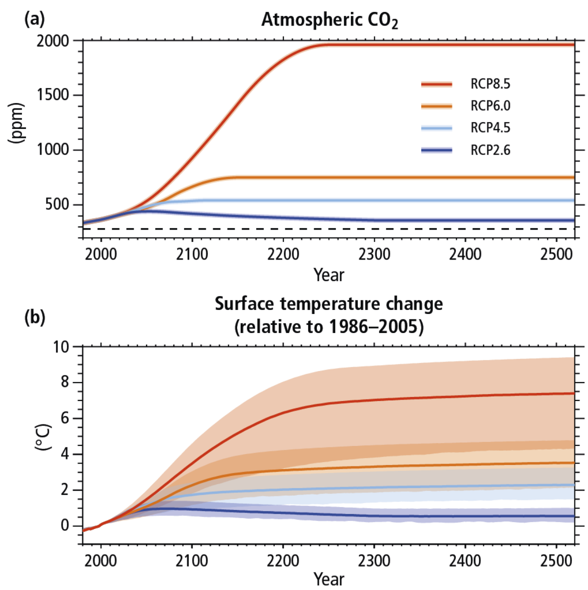


Figure 3.1: **(a)** Atmospheric CO_2 and **(b)** Surface temperature for different RCPs [2].

Global and Regional Climate Models (respectively GCM and RCM) are referred to proper emission scenarios. Both of them have similar mathematical structure in order to represent and predict meteorological variables, but RCMs are focused on a limited region. They are dynamically downscaled from the global dataset, having a resolution of 50 km $\times$ 50 km, or even less [7]. This make RCMs a powerful tool to investigate effects of climate change in specific areas, because they carry with them higher resolution and better simulation of regional and even local conditions (*Figure 3.2*, [24]).

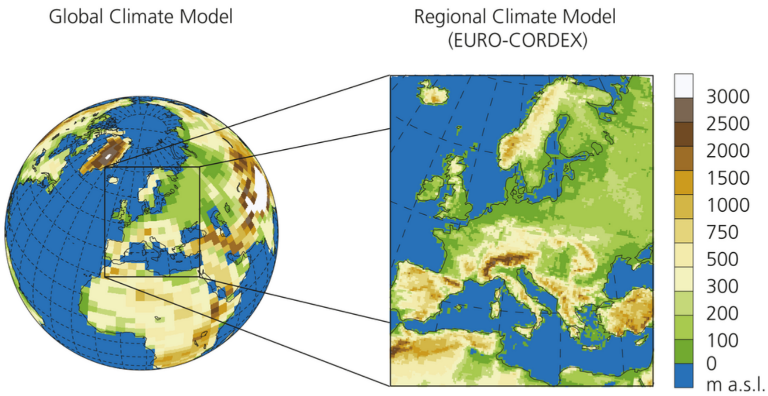


Figure 3.2: Structure of a Regional Climate Model compared to a Global Climate Model. [35]

3.1.2 Norwegian climate models

For this study, Norwegian climate predictions are needed. They can be freely downloaded from the Norsk KlimaServicecenter (KSS) website [18], and they are the official Norwegian climate projections. They are based on the EURO-CORDEX program, which realized a new high-resolution regional climate change ensemble for Europe [13]. Thank to Norwegian Climate Center, data have been downscaled to a 1 km × 1 km grid size, as shown in Figure 3.3 using an empirical quantile mapping method (EQM) to bias-correct and downscale precipitation and temperature projections for Norway, [36]. *Figure 3.3* shows the different spatial resolution obtained from global, regional and national climate projections.

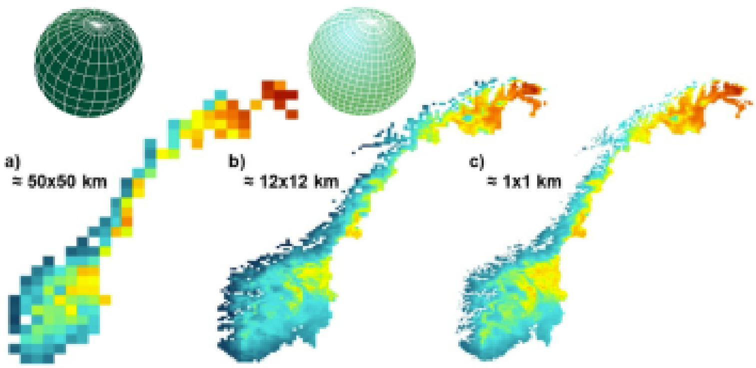


Figure 3.3: Degree of detail (spatial resolution) in a) global climate projections, b) regional climate projections and c) national climate projections.[19]

From Norsk KlimaServicecenter (KSS) [18] it is possible to download climate data for the two main Representative Concentration Pathways: RCP 4.5 and RCP8.5, choosing ten different combinations of GCM and RCM, and data can be downloaded for the time period 1971-2100. For this thesis, mean air temperature and rainfall have been downloaded for Adger region, for period 1981-2009 and 2022-2050, both for RCP4.5 and RCP8.5, for the climate combination MPI-CCLM model.

Table 3.1: Climate combination used for HBV model.

GCM	RCM	Reference Period	Future Period	Downloaded series
MPI	CCLM	1981-2005	2022-2050	Precipitation, MeanT

3.2 Hydrological HBV model

For predicting future inflows, an hydrological model is needed. The Hydrologiska Byråns Vattenbalansavdelning (HBV) model is a conceptual precipitation-runoff hydrological model, originally developed during the early 1970s by Bergström [5] at the Swedish meteorological institute, and used in Norway since 1974. The model was created to compute runoff in Scandinavian catchments, including options of snow storage and snow-melting. It has been modified over time depending on different needs, and many versions have been so far developed. In this work the PINEHBV Version 1.0 from Trond Rinde is adopted[26].

The HBV model is a mathematical conceptual deterministic model, meaning that it is based on some considerations of the physical structure and processes in the catchment. Its deterministic approach is reflected in the fact that identical sets of output are obtained given identical initial conditions and parameters.

As input data, the model requires a series of daily values of precipitation and mean air temperature, as far as monthly estimates of potential evapotranspiration. The model requires a series of ten equal elevation zones. Areas within each zone are given in km^2, and they are taken from the hypsometric curve [14].

It has to be calibrated by using initial field parameters regarding the catchment itself before it can be used for practical applications, since it contains a certain number of parameters which need to be assigned values to. After calibration, the model has to be validated with observed runoff. Then it can be used for several analysis, in this study it will be used for runoff forecasting for the future analyzed period, in order to estimate inflows for the two catchment of interest.

3.2.1 Model calibration

For calibration of HBV model, it is important to choose an unregulated catchment nearby the study area with similar characteristics to the one we are interested in. In this case, runoff is naturally produced,undisturbed and not controlled by power plant production. This can help for further model validation, for which also observed runoff data are needed.

For the analysis it was chosen Gjuvvatn catchment, which is located upstream with respect Roskreppfjorden and Øyarvatn, in north direction. It is not regulated and does not belong to Sira-Kvina hydropower scheme. A gauge station in the southern part of the catchment is present, which measures daily runoff.

In addition to that, elevation rates distribution is similar both to Roskrepp and Øyarvatn catchment, which makes Gjuvvatn catchment suitable for model calibration and validation.

Input data series

The model requires, as input data series, daily precipitation and mean air temperature.

Three series of input data have been run on in HBV model for calibration, in order to choose the one which gives the best result in terms of simulated runoff. Input data series runoff is taken from Gjuvvatn station itself [30], which is located in Valle municipality, in Adger region. In Table 3.2 reference data about Gjuvvatn gauge station and the catchment area (*Figure 3.4*) are shown.

Table 3.2: Gjuvvatn station information.

Station name	ID	LAT (°N)	LON (°E)	H (m asl)	Catchment area (km^2)
Gjuvvatn	25.24.0	59.159	7.125	952	97.0

In addition to runoff field data, precipitation and air temperature are required from HBV model. As previously said, different data series combinations have been tested for calibration. One of them is the gridded observations from the open portal seNorge.no [29], while the other two are downloaded from KSS[17].

The first dataset's timeseries, is selected choosing the closure point of Gjuvvatn catchment form the map. The full daily complete timeseries of precipitation and mean air temperature can be downloaded starting from the first selected timestep. Data have been downloaded from 1981.

The following *Table 3.3* resumes informations and data downloaded from KSS. They have been coupled two by two, because they do not carry data both for rainfall and temperature. In addition to that it is worth to notice that all these stations are no more active, so data download series are at least til 2009 long.

Name and coordinates of selected stations, data type and reference period downloaded are shown in *Table 3.3*, as far a map in *Figure 3.5*, in which different colors represent different measurement type (green for Precipitation, orange for Temperature). From now we will refer

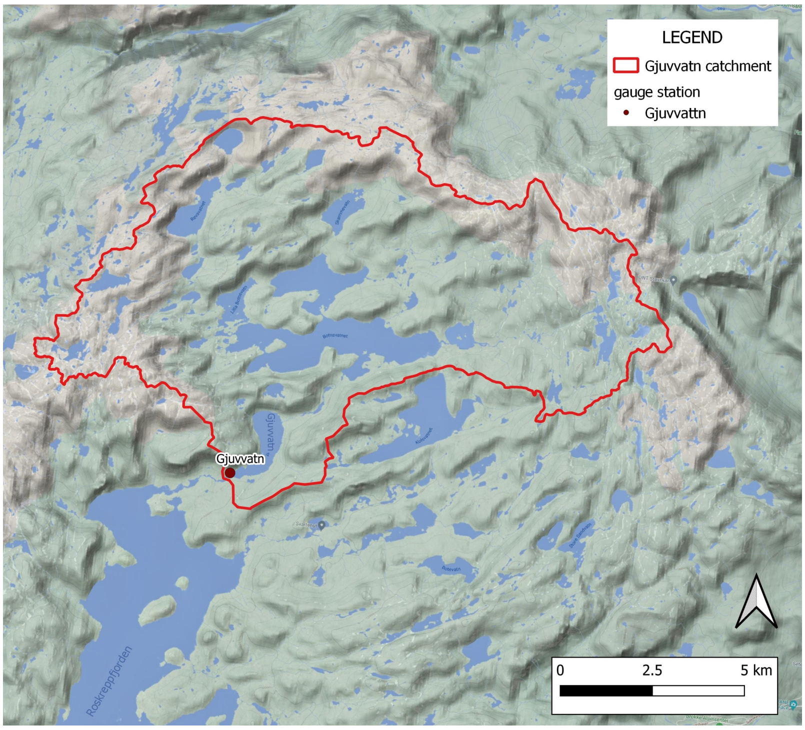


Figure 3.4: Gjuvvatn catchment and gauge station

to the first couple (Brokke Kraftstasjon, Sirdal Roskrepp) as **KSS1**, while the third and fourth statione (Øvre Sirdal and Sirdal Duge) will be named **KSS2**.

Table 3.3: Station information and data downloaded from KSS.

Station name	ID	LAT (°N)	LON (°E)	H (masl)	Measure	Period
Brokke Kraftstasjon	SN40200	59.0276	7.5103	275.00	Precipitation	01-01-1987 - 30-12-2009
Sirdal Roskrepp	SN42600	59.0276	7.0833	840.00	Temperature	02-06-1995 - 23-06-2004
Øvre Sirdal	SN42950	58.9455	6.9183	582.00	Precipitation	01-01-1981 - 23-06-2004
Sirdal Duge	SN43000	59.1193	6.8938	760.00	Temperature	01-01-1990 - 30-12-2009

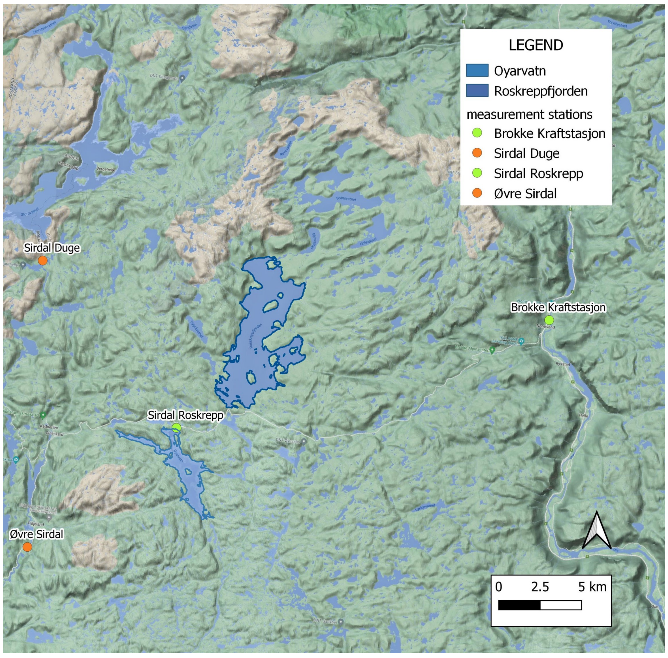


Figure 3.5: Precipitation and temperature stations downloaded from KSS.

Once data are available, HBV model calibration has been ran for the three datasets. The three runoff datasets were compared with the observed runoff available from measurement stations. HBV model include the computation of Nash-Sutcliff Efficiency coefficient (NSE) [15], which allows to evaluate the performance of the model. The closer to 1 the NSE coefficient is, the better the simulation of the model. The NSE is defined as

$$NSE = 1 - \frac{\sum(Y_i - Y_{i,sim})^2}{\sum(Y_i - \bar{Y})^2}\,, \tag{3.1}$$

where Y_i indicates the observed runoff, $Y_{i,sim}$ is the simulated one and $\bar{Y}$ is the mean of the observed data.

Figure 3.6 and *Figure 3.7* show the simulated discharge compared with the observed one, and the observed versus simulated cumulative runoff, for the three different datasets used in this analysis.

From plots and numerical data results, the first timeseries (SeNorge) was selected as the best one for model calibration, not only because there were some period of missing data in the other two and because stations provided by KlimaSeviceSenter are no more active, but also because the NSE index (Nash-Sutcliffe goodness of fit criteria) were lower with respect to the NSE from SeNorge dataset (*Table 3.4*).

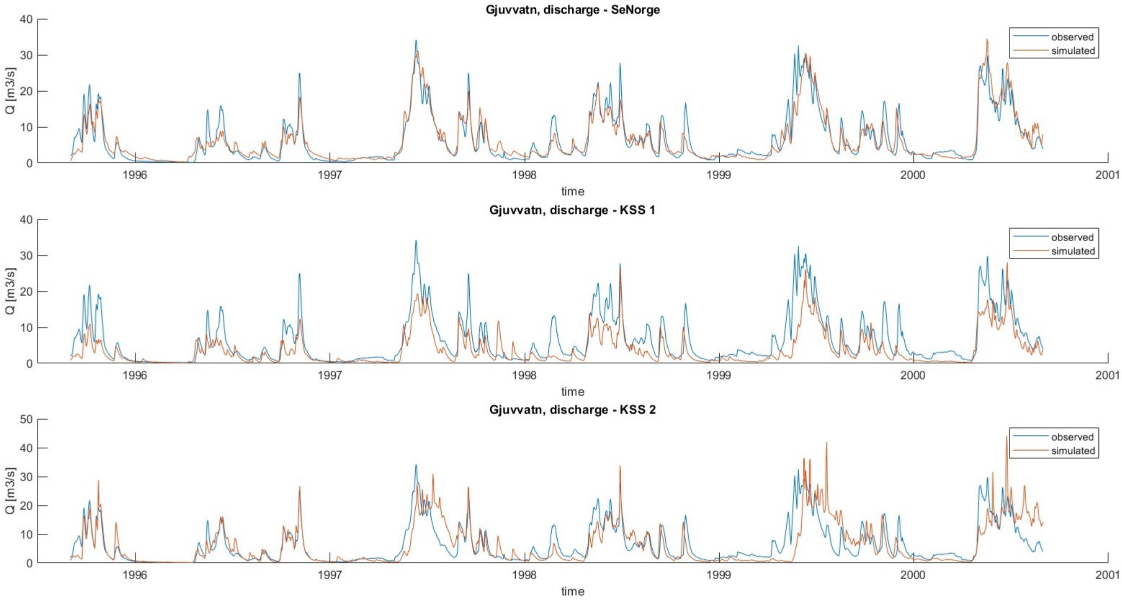


Figure 3.6: Gjuvvatn, observed and simulated discharge.

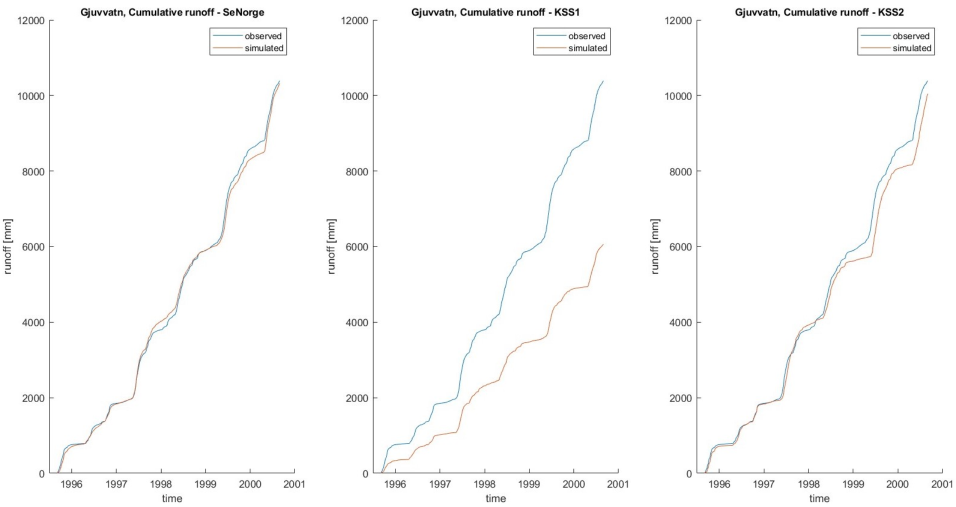


Figure 3.7: Gjuvvatn, observed and simulated cumulative runoff catchment and gauge station.

Table 3.4: NSE index for the different datasets.

Dataset	NSE [−]
SeNorge	0.867
KSS1	0.790
KSS2	0.818

3.2.2 Historical runoff reconstruction and future runoff prediction

Once the model is calibrated and validate for Gjuvvatn catchment, it can be used to simulate runoff for Roskreppfjorden and Øyarvatn, for the reference period. The basic assumption is that the runoff generation for the full Roskrepp catchment is similar to the Gjuvvatn one. The final step consists of using it to predict future runoff for the same catchments.

First, input data series of (P,T) for period 1981-2009 downloaded from SeNorge and used for calibration and validation have been ran into HBV model, to get historical runoff to Roskreppfjorden catchment. *Figure 3.8* presents the comparison between measured data from Sira-Kvina that have been provided to SINTEF Energi inflows given to SINTEF from Sira-Kvina company for Roskreppfjorden (orange line) and the HBV modelled runoff (green line). The first series has a large high-frequency variability in its values, and some of them do not look realistic. For this reason, runoff simulated with HBV model has been used.

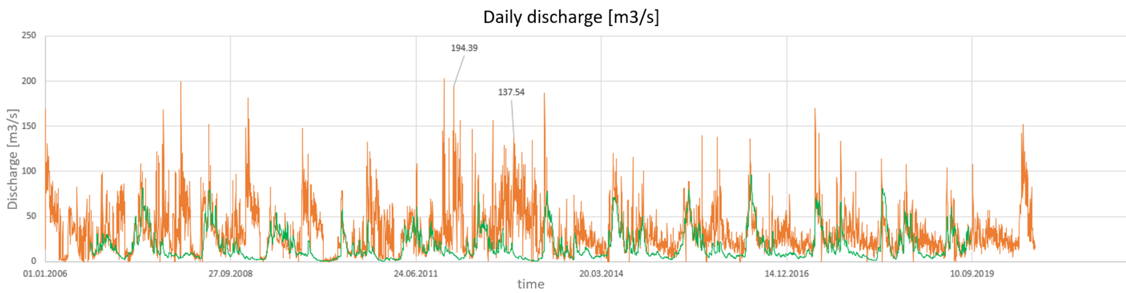


Figure 3.8: Roskreppfjorden, back-calculated inflows versus HBV simulated inflows.

In this work, the process has been carried on with the climate model combination MPI-CCLM, as reported in *Table 3.1*, and two different emission scenarios were considered, RCP 4.5 and RCP 8.5. This choice has been taken since the patterns for precipitation and temperature for this combination better reflects the observed ones. *Figure 3.9* and *Figure 3.10* represent temperature and precipitation for the whole combination possibilities.

After calibrating the model for Gjuvvatn catchment, the assumption made is that both Roskrepp and Øyarvatn catchment have similar morphological structure (elevation distribution, lake percentage, forested areas) between each other and also similar to Gjuvvatn catchment itself (*Annex A.1* for morphological characteristics of the two catchments). So, except for the dimensions of Roskrepp and Øyarvatn catchment, which are bigger than Gjuvattn and imply changes in confined parameters in HBV model, the parameters obtained in model calibration are assumed to remain the same for further simulations.

Finally, future inflow prediction is needed for the two catchments. For this task, a delta-change method is used [34]. Average monthly difference in temperature and monthly change in precipitation between historical and future climate scenarios have been computed. These quantities are the Delta changed input for hydrology. This assumption leads to change only a limited number of parameters in HBV model according to the other two catchments and run the

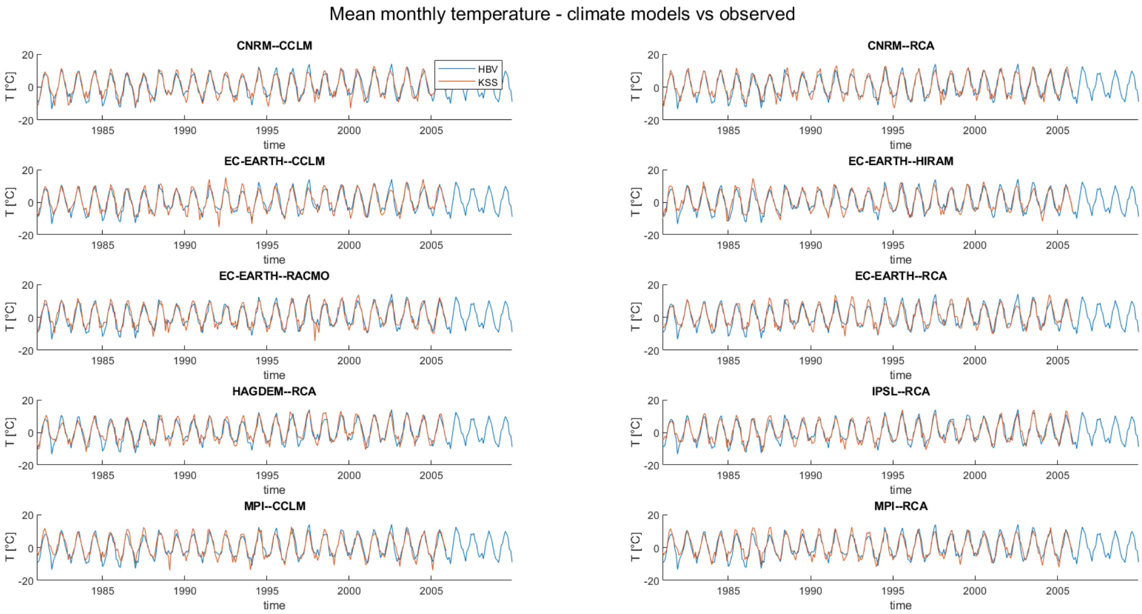


Figure 3.9: Mean monthly temperature. Observed data versus KSS data.

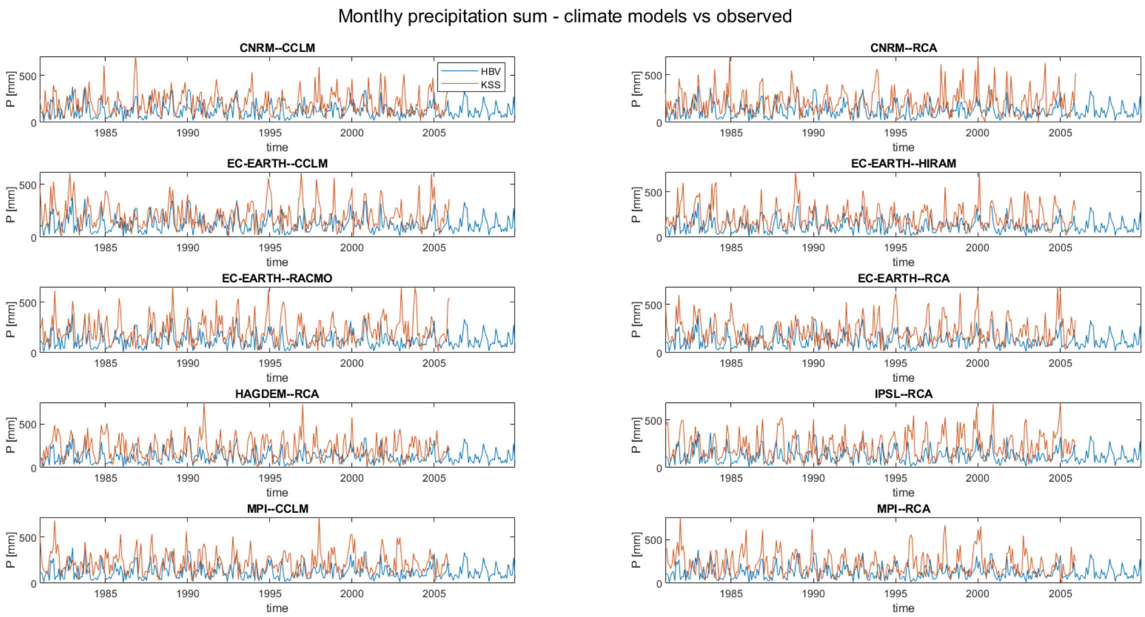


Figure 3.10: Monthly precipitation sum. Observed data versus KSS data.

model to find inflows for Roskrepp and Oyarvatn for the future period 2022-2050. First, climate data for precipitation and mean air temperature series for period (2022-2050) are downloaded from KSS. Comparing them with the historical ones (also reconstructed from KSS), ΔT $[°C]$ and ΔP [%] have been computed for the two climate scenarios. Multiplying the initial observed data by the obtained deltas, a new time series for precipitation and temperature has been obtained. It has been run into HBV model and the final output is the future predicted discharge Q_{*FUT}. *Figure 3.11* illustrates the work flow used to get future runoff for Roskrepp catchment.

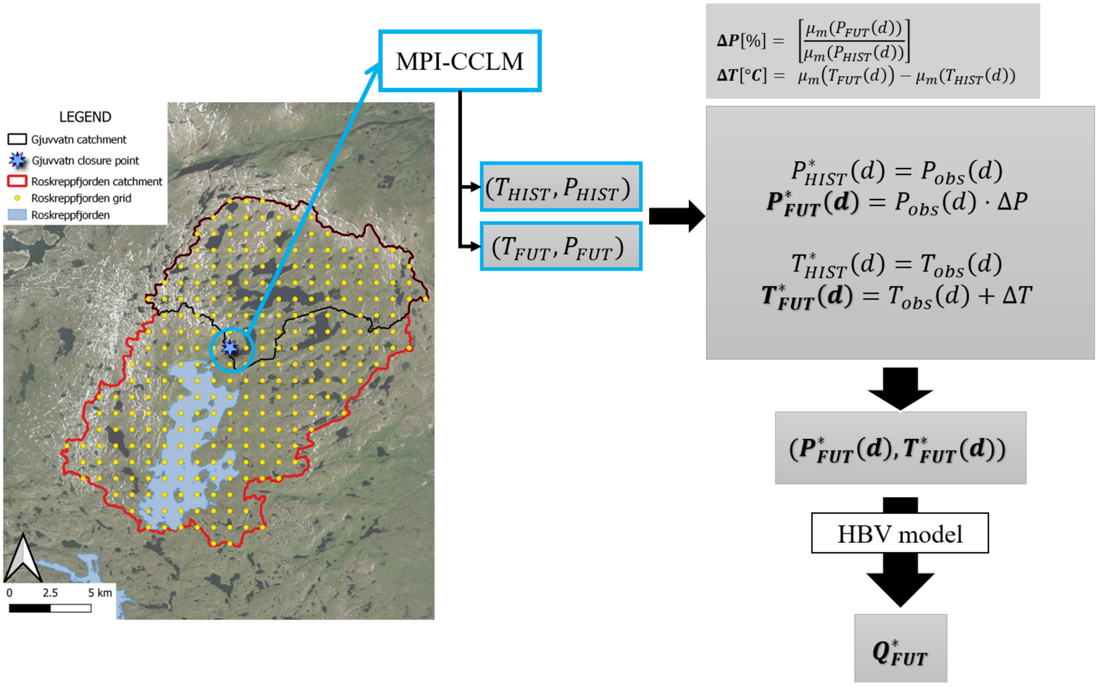


Figure 3.11: DeltaChange flow work.

The results for Delta-change method are shown in *Figure 3.12*, and *Figure3.13*, while *Table 3.5* resumes numerical deltas obtained.

Table 3.5: Monthly temperature deltas for temperature and precipitation.

Month	$\Delta T_{4.5}$	$\Delta T_{8.5}$	$\Delta P_{4.5}$	$\Delta P_{8.5}$
Jan	0.46	0.44	0.96	0.96
Feb	1.76	2.38	1.03	1.04
Mar	0.08	0.69	0.93	1.01
Apr	0.35	0.44	1.08	1.29
May	0.42	0.95	1.09	1.09
Jun	0.62	1.48	1.13	1.10
Jul	0.53	0.43	1.08	1.12
Aug	0.82	1.00	0.96	0.97
Sep	0.96	1.23	1.13	1.11
Oct	1.59	1.69	0.80	0.90
Nov	1.33	1.58	1.05	1.10
Dec	0.83	1.73	0.82	0.99

Future inflows are influenced by the expected climate change. Both for RCP 4.5 and RCP

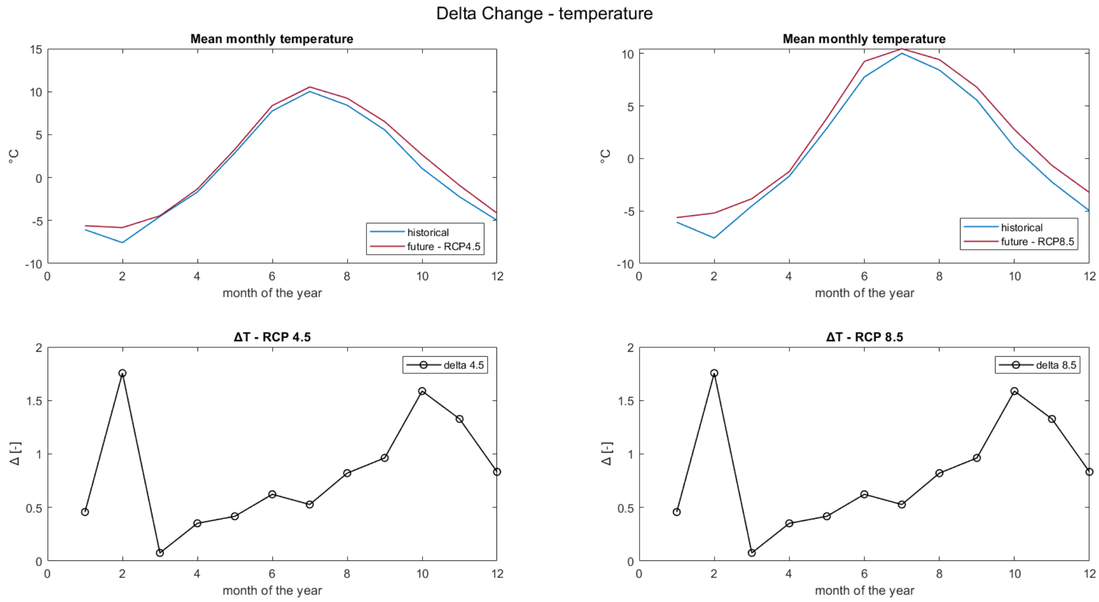


Figure 3.12: Monthly ΔT.

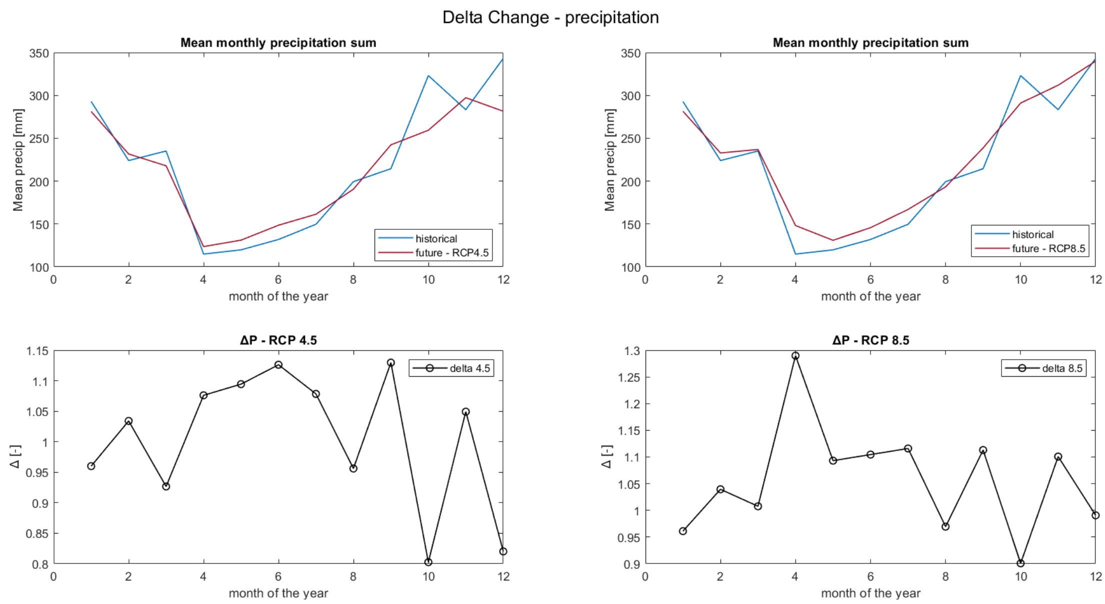


Figure 3.13: Monthly ΔT.

8.5, inflows are lower in the central part of the year, while there is the tendency to increase during winter (beginning of the year and end part of the year).

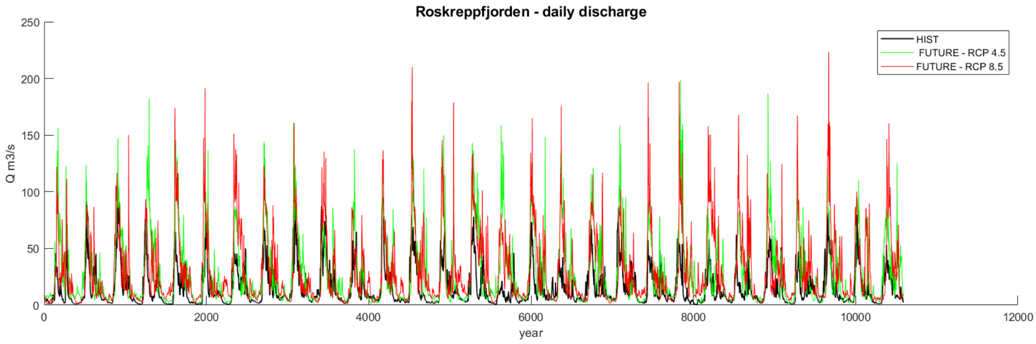


Figure 3.14: HBV model, daily runoff for historical reference period and future climate scenarios RCP 4.5 and RCP 8.5.

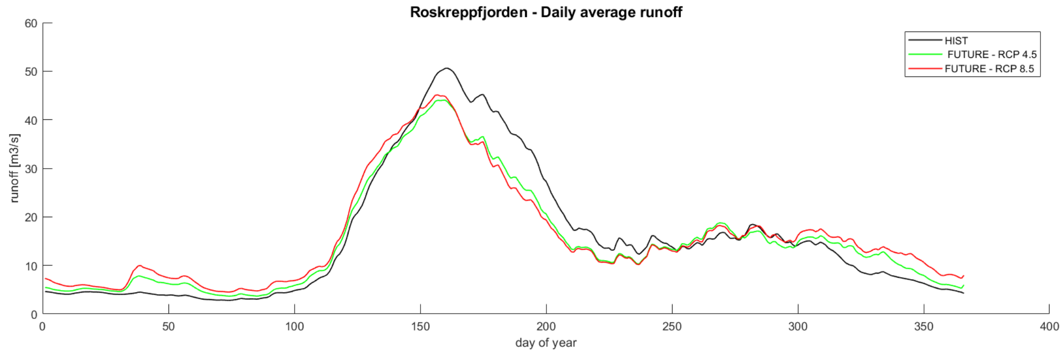


Figure 3.15: HBV model, daily average runoff for historical reference period and future climate scenarios RCP 4.5 and RCP 8.5.

To reduce complications of creating new scenarios by considering two sets of inflows (one for each catchment), inflows that will be further used as input for the optimization model are the ones modelled for Roskreppfjorden. For Øyarvatn, its inflows have been scaled by a factor $\gamma = 0.417$. This factor is based on the current practice, carried out also from the hydropower optimization models[1].

3.3 Optimization scheduling model

To simulate the hydropower system and the flow exchange between Roskreppfjorden and Øyarvatn, a model is needed. The choice is to use an optimization scheduling model, implemented for traditional Hydropower system by Linn Emelie Schäffer [28], and recently updated in order to simulate pumping operation [1]. The last version has been used. The entire model aims to provide a an optimal stochastic scheduling model that maximizes the revenue of a pumped storage hydropower plant operating under different scenarios and respecting several technical and environmental constraints ([1]).

Input data needed for the model are:

- Weekly inflows, given as volume quantity, in [Mm^3];
- A relationship between volume [Mm^3] with respect to the Walter level [m asl] for each catchment;
- Weekly prices, in [euro/MWh].

Inflows simulated with HBV model, both for reference period and for the two future climate scenarios, have been transformed into weekly inflows, and given as input into the scheduling model. So, outputs could be considered as the result of realistic inflow input. Plots in *Figure 3.16* represent weekly inflows for some of the analyzed years, while *Figure 3.17* represents the complete timeseries for the historical reference period. (See *Annex* B.1 for the pattern of future weekly inflows for RCP 4.5, *Figure B.1* ,and RCP 8.5, *Figure B.2*).

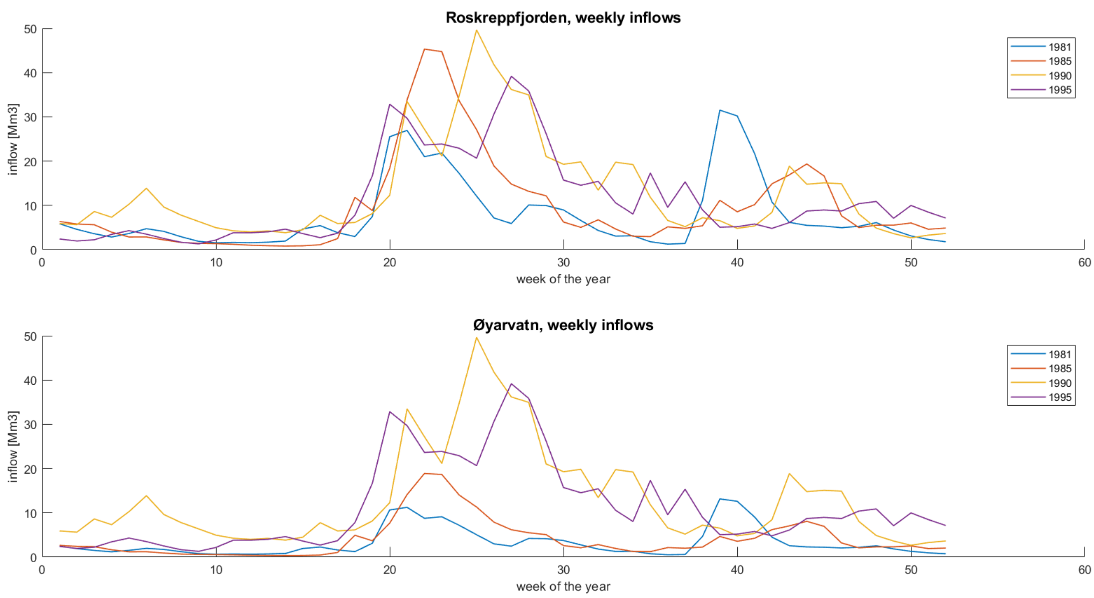


Figure 3.16: Weekly inflows for years 1981, 1985, 1990.

By assuming the bathymetry for the two reservoir reconstructed in Donini's master thesis [6], it was possible to give a more detailed curve than the one previously proposed in Alic's master thesis [1] (see *Figure 3.18*).

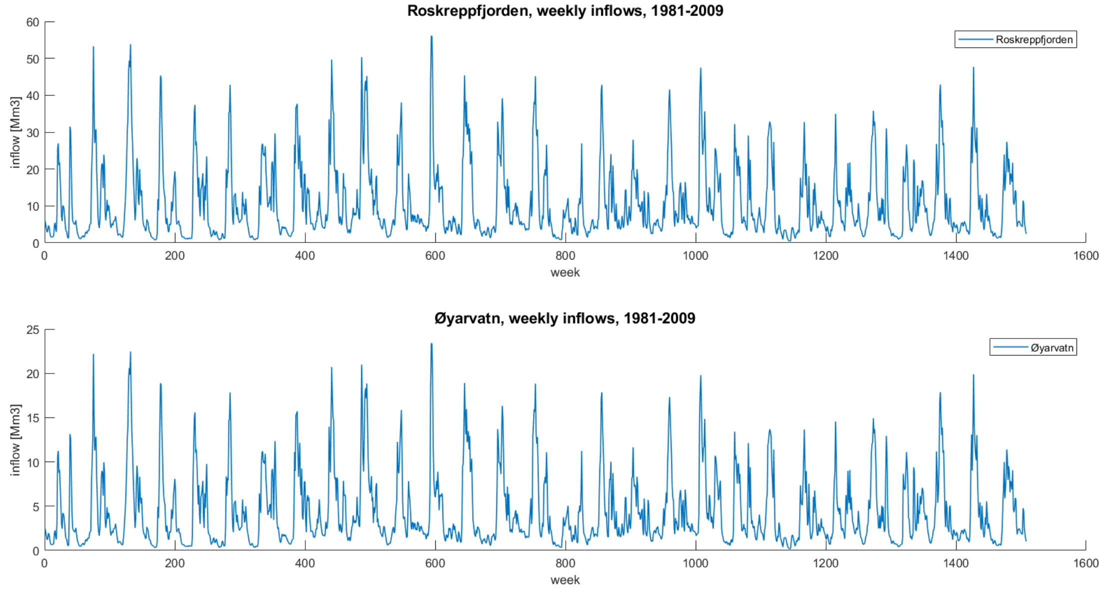


Figure 3.17: Weekly inflows for the full timeseries 1981-2009.

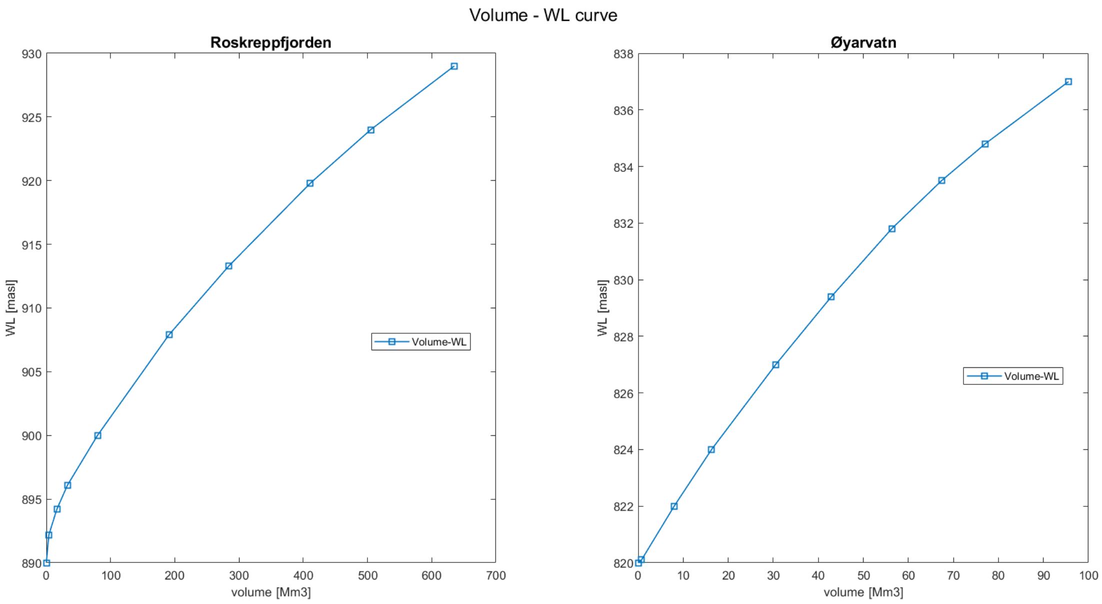


Figure 3.18: Volume - water level curves for Roskreppfjorden and Øyarvatn.

As it is visible from the two plots, the curves range from minimum water level (890 m asl for Roskreppfjorden and 820 m asl for Øyarvatn) till the maximum capacity of the catchment, that is 929 m asl for Roskreppfjorden and 837 m asl for Øyarvatn).

Another modification has been implemented to the model, in order to simulate output scenarios for specific inflows given as input in a deterministic way. So outputs for specific real years are possible, and also the comparison between differences in results that arise from different meteorological conditions.

An important component inside the model are weekly prices and infra-weekly prices variations. Weekly prices given as input are based on weather conditions recorded in period 1981-2010, and reflect a possible scenario in the power energetic system for year 2030. Results of those analysis are available from the 2022 project *SINTEF project: New environmental restrictions - overall impact on the power system*[31]. Infra-weekly price variations matrix are important also, as they modify and split each original weekly price for 56 sub-interval inside each week. An initial weak infra-weekly price variation has been replaced with a stronger one (*Figure 3.19*). This implies to simulate more intense pumped-storage operations in the two reservoirs due to the stronger differences between low and high prices.

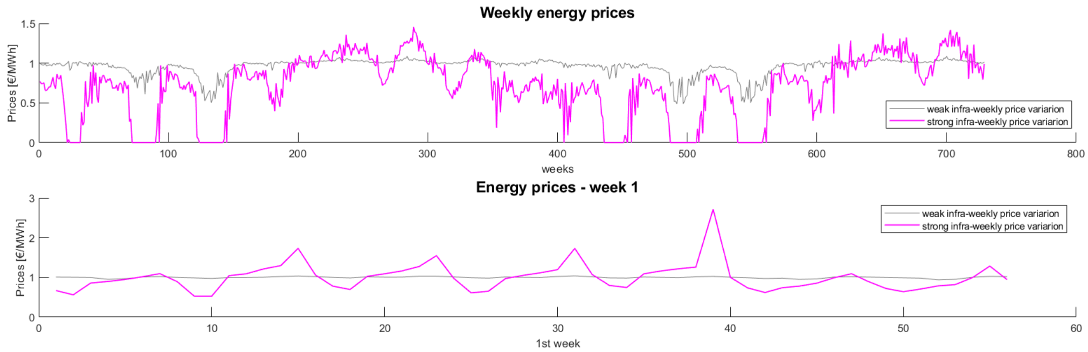


Figure 3.19: Weekly energy prices, general and detail for week 1.

3.4 HYMO parameters and new proposed indices

Here some of the indices proposed in HYMO[3] report are calculated, while some others are added to the classification, thanks to the availability of detailed data.

3.4.1 HYMO parameters

The parameters proposed in the current classification follow the main requirement of the HYMO system, that is, creating an easy classification system that could be applied to lakes and reservoirs in Norway. Very often some parameter data are hardly available, and for this classification system the majority of parameters can be calculated using bathymetric maps, when available, and hydrological data. The parameters presented in *Figure 3.20* resumes the currently hydromorphological classification system, with the corresponding class-borders, based on a five-class classification system. It consists of a set of 17 hydromorphological parameters, and describes the most important hydromorphological processes and alterations in Norwegian lakes and reservoirs.

No	Parameter	Near-natural	Slightly modified	Moderately modified	Extensively modified	Severely modified
100	Change in annual inflow	<5 % regulation upstream	5-20 % regulation upstream	20-50% regulation upstream	50-90% regulation upstream	>90% regulation upstream
101	Upstream barriers affecting sediment processes	<5 % reduction in distance to natural upstream barrier	5-10 % reduction in distance to natural upstream barrier	10-50 % reduction in distance to natural upstream barrier	50-90 % reduction in distance to natural upstream barrier	>90 % reduction in distance to natural upstream barrier
200	Water level changes	<2 meters	2-3 meters	3-10 meters	10-50 meters	>50 meters
201	Total volume change	<5 % change from natural volume	5-10 % change from natural volume	10-30 % change from natural volume	30-70 % change from natural volume	>70 % change from natural volume
202	Change in retention time	<5 % change in retention time	5-20 % change in retention time	20-50 % change in retention time	50-100 % change in retention time	>100 % change in retention time
203	Change in date of filling	<3 days change compared to filling by starting date	3-10 days change compared to filling by starting date	10-20 days change compared to filling by starting date	20-70 days change compared to filling by starting date	>70 days change compared to filling by starting date
204	Change in date of emptying	<3 days change compared to emptying by starting date	3-10 days change compared to emptying by starting date	10-20 days change compared to emptying by starting date	20-70 days change compared to emptying by starting date	>70 days change compared to emptying by starting date
205	Water level change at filling date	<5 % relative deviation from natural water level	5-10 % relative deviation from natural water level	10 – 30 % relative deviation from natural water level	30-70 % relative deviation from natural water level	>70 % relative deviation from natural water level
206	Water level change at emptying date	<5 % relative deviation from natural water level	5-10 % relative deviation from natural water level	10 – 30 % relative deviation from natural water level	30-70 % relative deviation from natural water level	>70 % relative deviation from natural water level
207	Short term water level variations (days)	<0.1 meters change during one day (90-percentile day during a year)	0.1-0.5 meters change during one day (90-percentile day during a year)	0.5-1 meter during one day (90-percentile day during a year)	1-2 meters during one day (90-percentile day during a year)	>2 meters during one day (90-percentile day during a year)
208	Short term water level variations (weeks)	<0.3 meter within a week (90-percentile of a week during a year)	0.3-1 meter within a week (90-percentile of a week during a year)	1-3 meters in a week (90-percentile of a week during a year)	3-5 meters during one week (90-percentile week during a year)	>5 meters during one week (90-percentile week during a year)
210	Dewatered areas	<5 % dewatered compared to natural surface area	5-10 % dewatered compared to natural surface area	10-40 % dewatered compared to natural surface area	40-90 % dewatered compared to natural surface area	>90 % dewatered compared to natural surface area
211	Relative lake level fluctuation	<5 % in relative lake level fluctuations	5-50 % in relative lake level fluctuations	50-100 % in relative lake level fluctuations	100-150 % in relative lake level fluctuations	>150 % in relative lake level fluctuations
212	Dewatered littoral zone versus total littoral zone (ratio)	<5 % affected by dewatering	5-10 % affected by dewatering	10-40 % affected by dewatering	40-90 % affected by dewatering	>90 % affected by dewatering
213	Loss in lateral connectivity along the shoreline	<5 % of shoreline affected	5-20 % of shoreline affected	20-50 % of shoreline affected	50-90 % of shoreline affected	>90 % of shoreline affected
214	Riparian zone changes	<5 % of riparian vegetation affected (measured as % of shoreline)	5-20 % of riparian vegetation affected (measured as % of shoreline)	20-50 % of riparian vegetation affected (measured as % of shoreline)	50-90 % of riparian vegetation affected (measured as % of shoreline)	>90 % of riparian vegetation affected (measured as % of shoreline)
220	Change in substrate qualities	<5 % spawning substrate lost	5-10 % spawning substrate lost	10-40 % spawning substrate lost	30-90 % spawning substrate lost	>90 % spawning substrate lost

Figure 3.20: Proposed HYMO hydromorphological classification system and the corresponding class borders, following a five-class system. All parameters refer to changes in the hydromorphological state from natural conditions or degree of hydromorphological alterations.

From HYMO Report, following indices have been chosen:

1. **Short term water level variations (days) (P.207)**: This parameter is calculated on daily basis, taking a timeseries of water level for each reservoir. In this case, positive and negative daily water level fluctuations are divided to have a more detailed estimation, even if it can be assumed that positive and negative daily water level fluctuation have the same

effect on the reservoir;

2. **Dewatered areas (P.210)**: This parameter reflects the severity of regulation. To calculate this parameter, the surface area at the highest and lowest water level is derived from maps. Large dewatered areas can have large ecological impact on flora and fauna living in the shoreline part, and also aesthetic negative impact.

$$DewA = \frac{A_{LRL}}{A_{HRV}} \; [\%] \tag{3.2}$$

3. **Dewatered littoral zone versus total littoral zone (ratio) (P.212)**: This parameter is similar to the **P.210**, but only referred to littoral zone. Loss in littoral zone is calculated as percentage with respect to the total area of littoral zone. Since the considered system is a regulated one, we considered as littoral zone the full area going from the HRL to the LRL, and so the parameter is:

$$L = \frac{A_{LIT,dry}}{A_{LIT,tot}} \cdot 100 \; [\%] \tag{3.3}$$

where $L[\%]$ is the total loss in littoral zone, and $A_{LIT,dry}[m^2]$ and $A_{LIT,tot}[m^2]$ are respectively the dry portion of littoral zone at each timestep and the total available littoral zone.

3.4.2 New proposed indices

Since detailed data from the bathymetry and scheduling model are available, it is possible to go more in detail with the analysis.

Indices related to water level

Changing the operating mode from traditional to pumped-storage, water level in the two reservoirs is affected a lot in its pattern. Differences are supposed to be seen firstly in number and intensity of peaks. Low-prices conditions without any ramping constraints allow to pump water from the lower to the upper reservoir. For this reason, higher number of peaking events with lower intensity is expected in pumped-storage operating mode. Moreover, maximum and minimum rate of change is supposed to be modified, as the duration of each peaking event.

So some new indices related to water level are proposed and evaluated for this specific study-case, comparing traditional and pumped-storage operating mode:

WL.1: Distribution and number of peaking events;

WL.2: Duration of peaking events;

Dewatering indices

Water level changes in different pattern are supposed to change distribution of wet areas during time for the two catchments. Greater number of water level fluctuations in pumped-storage mode imply that some areas will be frequently dry off and get wet after a while. This aspect can have strong implication from the biological point of view. Considering fish's spawning period for example, there is the risk that some areas in the regulation reservoir zone, that are wet during the initial spawning period, become dry immediately after fishes lay their eggs. If the dry period is too long, there is the risk not to have time enough to have new fish active. For this reason water water level during winter should not go below the minimum water level in the first spawning season.

Secondly, supposing that small fishes can be affected by water level fluctuations. So water level fluctuations in this period can be investigated.

So following indices are proposed, for the two different operating scenarios:

DeW.1: Percentage of wet period compared with the entire analyzed period. This is calculated within the regulation area, so between HRL and LRV;

DeW.2: Median wet period, limiting the analysis for 365 days;

DeW.3: Period 5-30 days. This index can be used to highlight areas, within regulation zone, that are wet for a period longer than 5 and shorter than 30 days more than once a year on average. This aspect could be a hint in detecting critical areas e.g. for small fishes hatched that can find refuges but that in less than 30 days will be dewatered (note that this duration is yearly average, but could be focused on a specific period of the year, depending on the type of fauna considered, and the 5-30 days should be considered only as a example without a specific scientific support);

DeW.4: Comparison between minimum water level in October and the water level in the following period from November to March, during each year;

DeW.5: Short-term water level fluctuations in period March-April during each year. This index can be uses to evaluate magnitude of variation within water level during first spring months. This period can be critical for small alevins, that mainly live in very shallow waters [4], and could die in case of stressful condition of continuing oscillating water level.

Chapter 4

SET UP OF QGIS PROCEDURE

To analyze impacts on environmental conditions generated by hydropower operations, it is important to know morphological characteristics of the two reservoirs. Particularly, it is necessary to focus the attention on their regulation areas, which represent the part directly interested by hydropower operation. This area can be inundated and dewatered depending on water availability and production pattern. For general characterization and map production $QGIS$ 3.22.12 has been used.

During fieldwork, which took place from 11^{th} to 14^{th} October 2022, it was possible also to have an idea of the reservoirs bottom morphology and substrate, thanks to an underwater camera.

4.1 Morphological comparison

First, a morphological comparison between the two reservoirs is presented, to give an overview of their bathymetry and slope of their shores. Since the hydropower scheme involves both reservoirs, it is clear that morphological differences between the two are relevant. As first, *Figure 4.1* show bathymetry of the two reservoir, that was surveyed by Donini, G.[6] under HydroConnect Project. The high contrast underlines deeper areas (light blue and blue) with respect to the shoreline part (orange/red coloured) of two reservoirs. For Roskreppfjorden, the deepest measured point is around 866 masl, so 63 meters depth, located in the southern part of the reservoir. Øyarvatn's maximum depth is around 71 meters, clearly visible in map more in the north-eastern part of the lake.

Roskreppfjorden (*Figure 4.1*a) is around six times bigger than Øyarvatn (*Figure 4.1*b), and deeper in its central part. The two maps also highlight the irregularity shape of two lakes and numerous islands that are never inundated, since their elevation is higher than the water level reached for HRV. It is worth to notice that both reservoirs have some branches and insulated areas. For Roskreppfjorden the biggest one is located in the southern part of the lake, while in

Øyarvatn there are two lateral branches in the northern part.

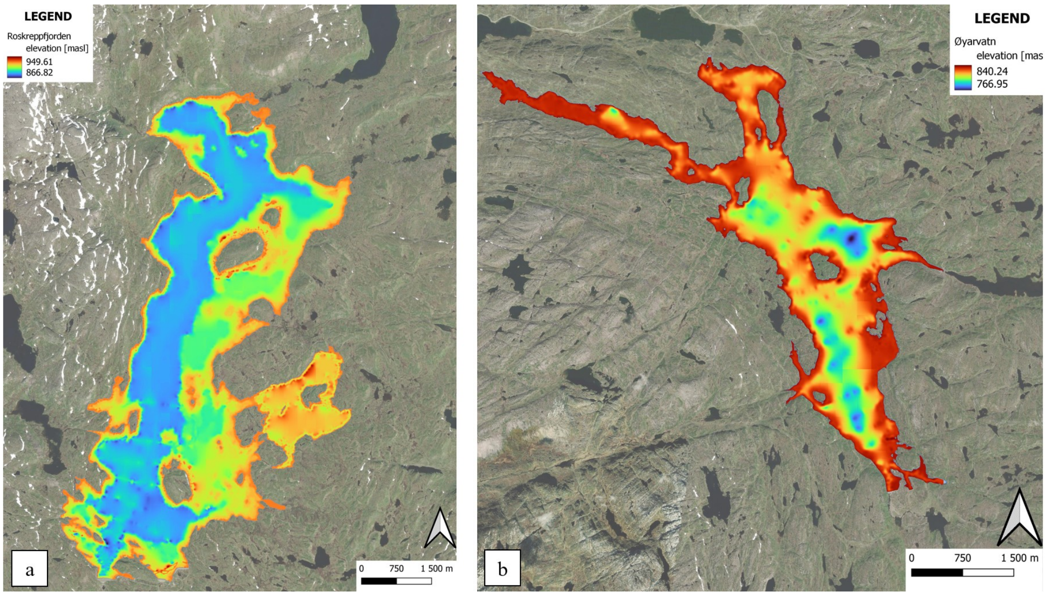


Figure 4.1: Roskreppfjporden and Øyarvatn: bathymetry.

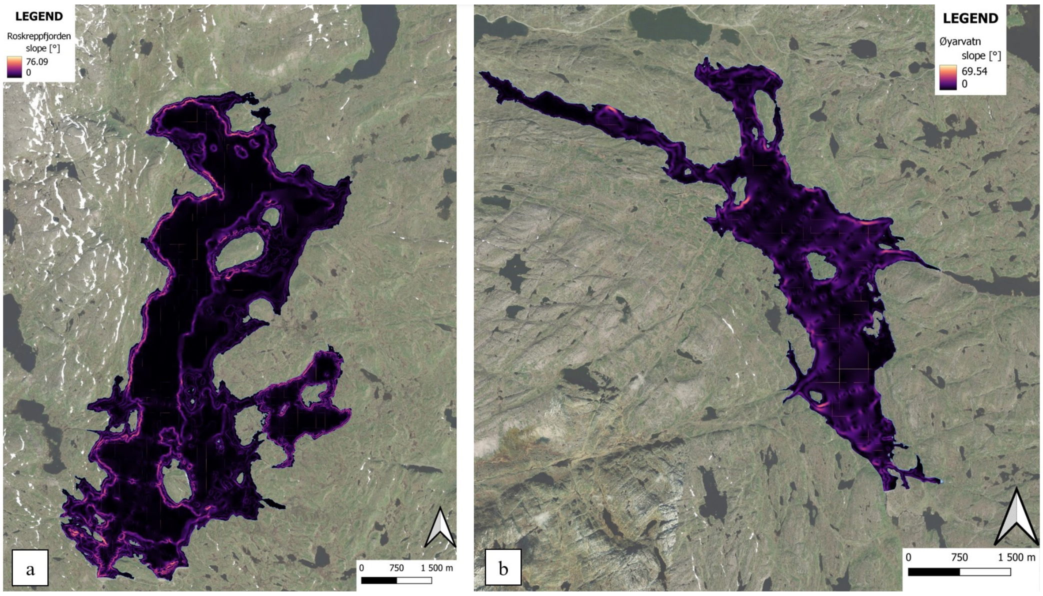


Figure 4.2: Roskreppfjporden and Øyarvatn: slope.

Then, the slope has been computed, as shown in *Figure 4.2*. The steepest areas are distributed along the shoreline, as expected. Combining data obtained from elevation and slope, some flat areas and *plateau* are visible for the two lakes, around their HRV. For Roskreppfjorden, these are mainly located in the eastern part of the reservoir, while in Øyarvatn they are more developed in its northern-west zone.

4.2 Grid creation and centroids extraction

As the two catchments are artificially regulated, the main interest lies on their regulation zone. So the area in between maximum and minimum water level was selected, and will be object of analysis in this Chapter. This area has been grid-divided, in order to group together areas with same characteristics of elevation and slope. 100 meters square grid cells are shown in *Figures 4.3-4.4*.

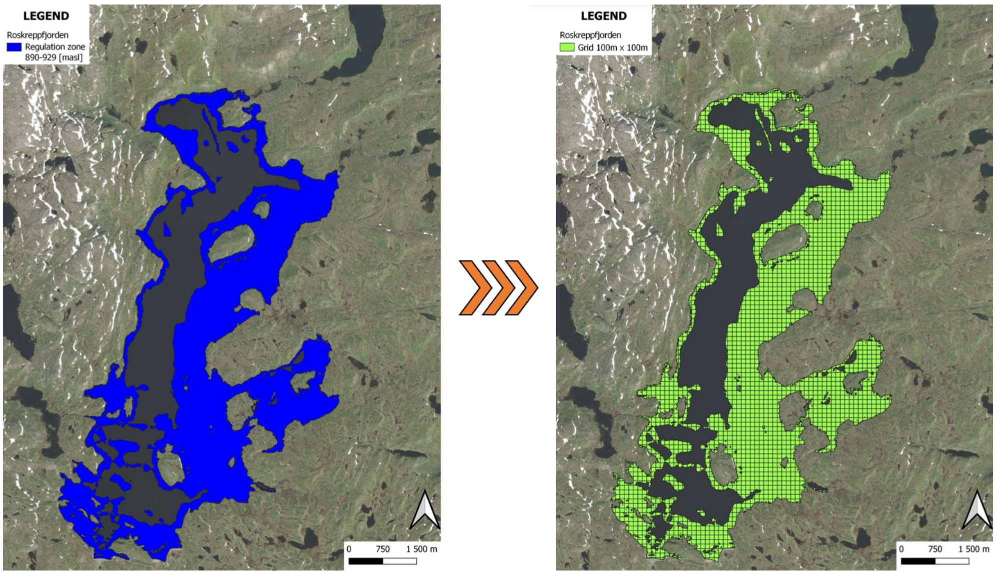


Figure 4.3: Roskreppfjporden: regulation zone and square grid 100 m × 100 m.

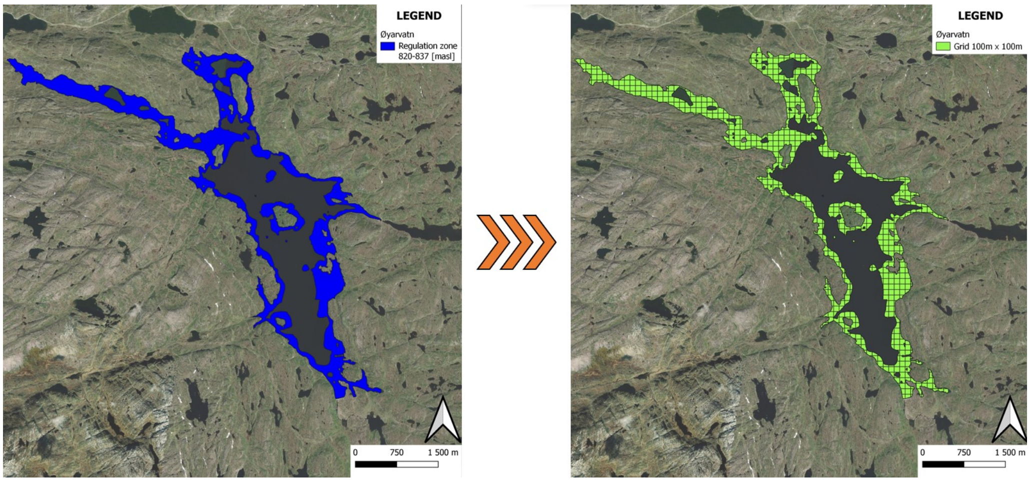


Figure 4.4: Øyarvatn: regulation zone and square grid 100 m × 100 m.

Then, *Zonal Statistics* tool has been used. Elevation layer has been overlapped with the polygon square grid vector layer previously created, to obtain mean elevation for each 100 m × 100 m square within regulation zone. Same process has been done for slope. Results are shown in *Figures 4.5 - 4.6*, in which elevation and slope have been divided in ten equal classes.

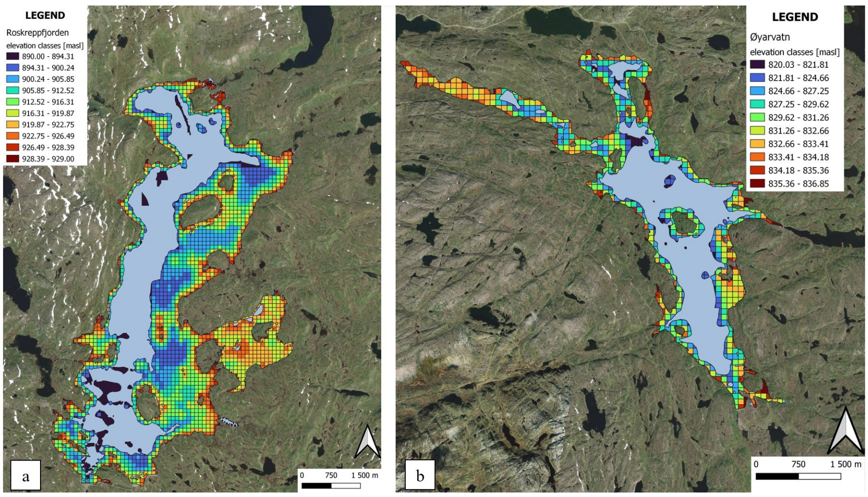


Figure 4.5: Roskreppfjporden and Øyarvatn: elevation classes for the littoral zone.

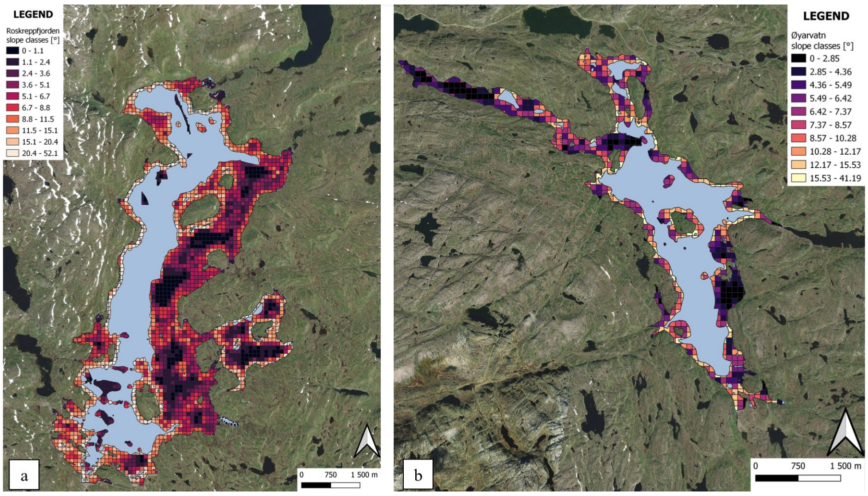


Figure 4.6: Roskreppfjporden and Øyarvatn: slope classes of the littoral zone.

Histograms in *Figures 4.7-4.8* show elevation and slope distribution in littoral areas of the two lakes.

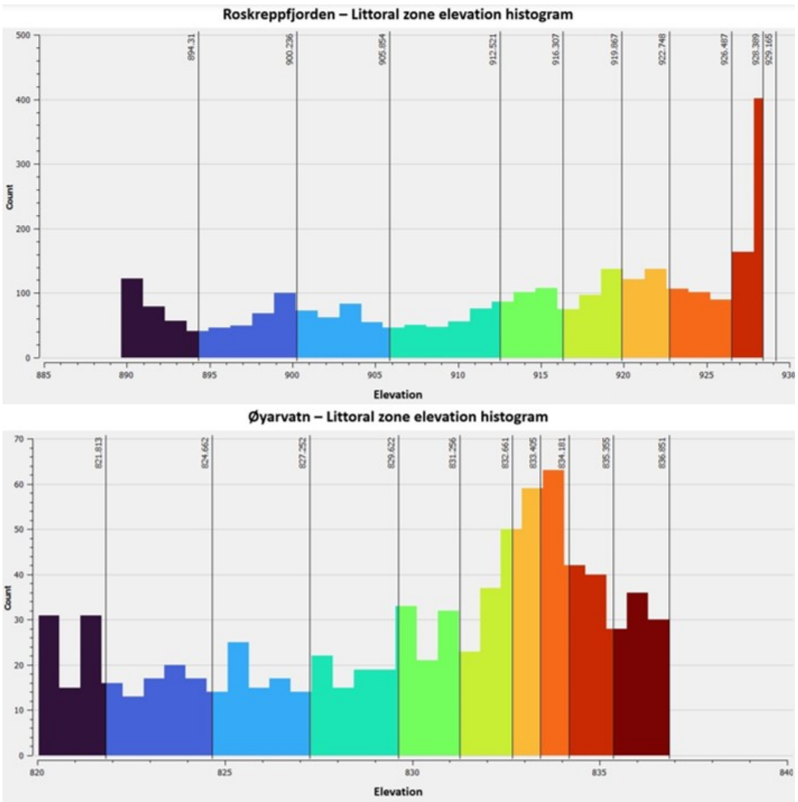


Figure 4.7: Roskreppfjporden and Øyarvatn: elevation classes distribution in the littoral zone.

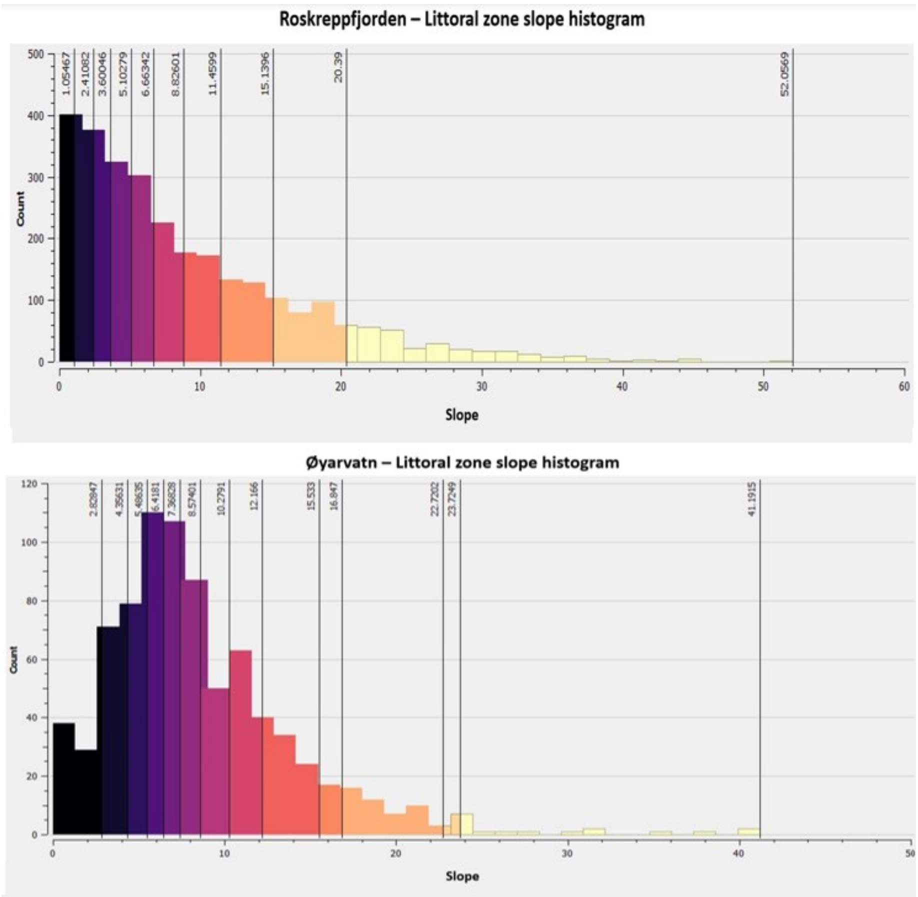


Figure 4.8: Roskreppfjporden and Øyarvatn: slope classes distribution in the littoral zone.

Further calculations and analysis have been carried out using mean elevation value for each 100 m × 100 m square. For this reason, points representing centroids of this geometry have been created (*Figure 4.9-a - 4.9-b*).

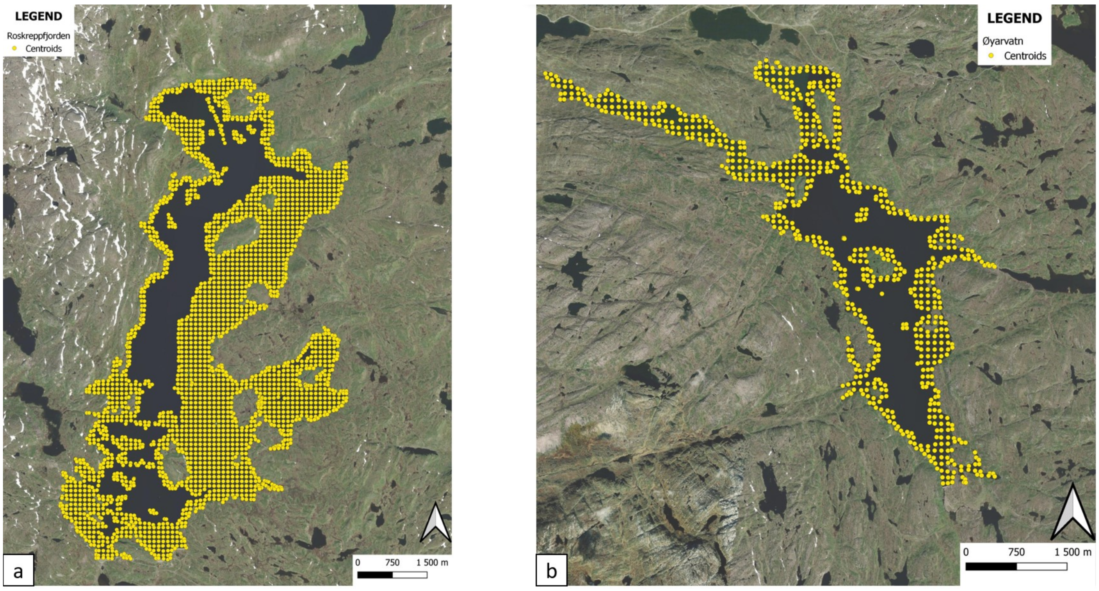


Figure 4.9: Roskreppfjorden and Øyarvatn: centroids.

4.3 Dynamic visualization

In order to support environmental decisions regarding how water level variations will impact the shore area of the reservoirs and have a better understanding of the spatial and temporal resolution, the tool *Dynamical Temporal Control* in *QGIS* [23] has been tested to visualize the two selected year (See *Chapter 5.4*). This simple method could help identified the most impacted shore areas within the reservoir and at different periods of the year. Using separate fields for Start-Date and End-Date, features will be rendered if these values overlap the map canvas temporal.

This could be of special value when the visualization can be overlap with other information such as biological data and potential areas for fish spawning or sheltering areas for juveniles.

4.4 Shoreline characterization

Using an underwater camera from NTNU it has been possible to have a first view on the characteristics of the morphological structure and substrate type of the regulation zone in the two reservoirs.

Figure 4.10: Underwater camera placed in Roskreppfjorden. Roskreppfjorden dam is visible on the background.

Visual observations have been carried out for a little portion of the two reservoirs. Results have been recorded into short video-clip, and in Figure 4.11-4.12 two screenshots of the substrate are shown, one for each of the two lakes. where it was possible to observed that in Roskreppfjorden the substrate had a more rounded shape, and has higher content of finer sediments particularly in the area inspected close to the near shore and the dam. Some visible underwater vegetation was also observed at the surroundings of the dam. In Øyarvatn, substrate had more sharpen and angle shape in the near shore and the substrate had less content of finer sediments. Further investigations about the substrate type which are being initiated in a recent project funded by the Norwegian Research Council (FunkyFish)[9] will facilitate to have a better understanding of the substrate classification in reservoirs and possibly find which characteristics can be associated to it (such as slope or exposure to water level variations).

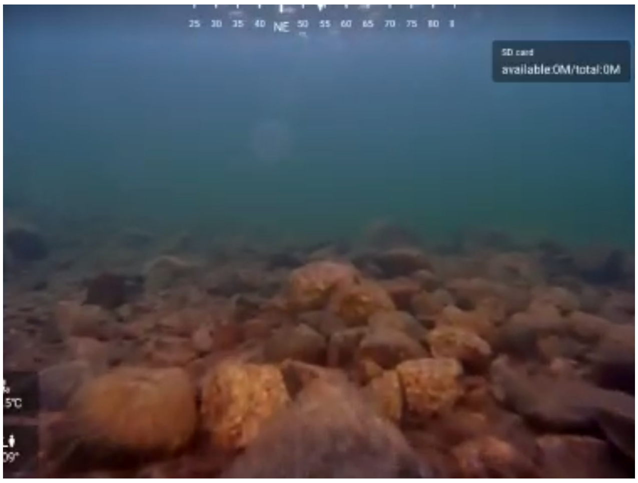


Figure 4.11: Roskreppfjorden, bottom nearby the shoreline.

Figure 4.12: Øyarvatn, bottom nearby the shoreline.

Chapter 5

RESULTS

The results of the study are presented in this chapter. First of all, results coming from the optimization scheduling model in terms of water level pattern and water level variations are shown, that is, the basis for further analysis. In fact, different operating mode reflects on water level variations in the two reservoirs. Their different behaviour under this aspect is, for the most part, due to their different reservoir dimension. Øyarvatn, as previously said, is around six times smaller than Roskreppfjorden. This means that even low changes in water level during time will be more visible with respect to Roskreppfjorden. Secondly, shoreline steepness (i.e. elevation and slope) in reservoirs is very different: their steepness is inversely proportional to extension, and so narrower littoral areas correspond to steepest portion of reservoirs. Finally, the very irregular shape of the two lakes, with lateral branches and internal islands, reflects in different inundated areas during time, depending on position of those areas and water level at each timestep.

Some of the indices proposed from HYMO classification are computed for the two lakes, in order to classify them based on an existing classification, currently in use in Norway. In addition to that, some new indices are proposed, since the availability of detailed data, both for bathymetry an water level variation allows to investigate the study case more in detail. All the calculation are proposed both for the complete time series and for some specific years. The idea is that not only the general behaviour is important, but also the one for particular years. For this reason, two significantly different years have been chosen, one with relative high water level and the other with a very low one.

Finally, some considerations regarding result obtained for the future climate scenarios will be taken into analyzed.

An important aspect that has to be highlighted is that, for now, any ramping constraints is included in the calculation. This means that water level fluctuations are generated by price variations. So they can be as abrupt as the price variations are, as any constraint is limiting them.

5.1 Results from Optimization model

Given as input weekly inflows and prices for the two lakes, the scheduling model is able to provide different output scenarios, with 3 h timestep resolution. The output format represents years 52 weeks long, and each of them is made of 56 3h-timesteps (*Figure 5.1* and *Figure 5.2*). Water levels for future climate scenarios are reported in *Annex B.1* (*Figures B.3, B.5, B.4, B.6*).

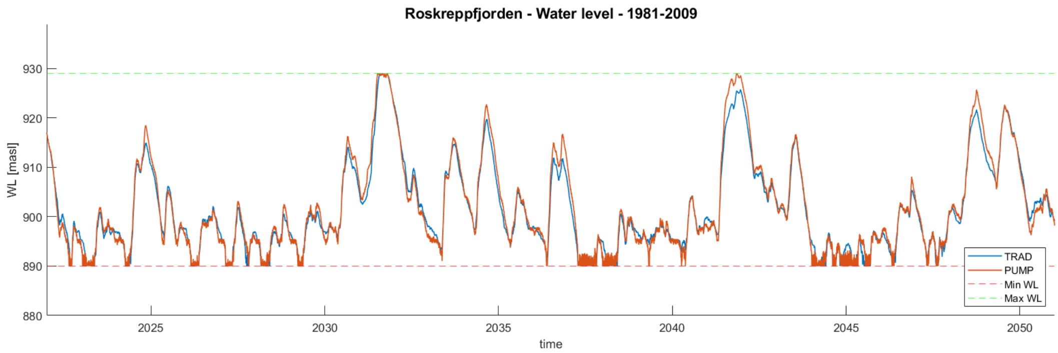


Figure 5.1: Roskreppfjporden: water level for period 1981-2009.

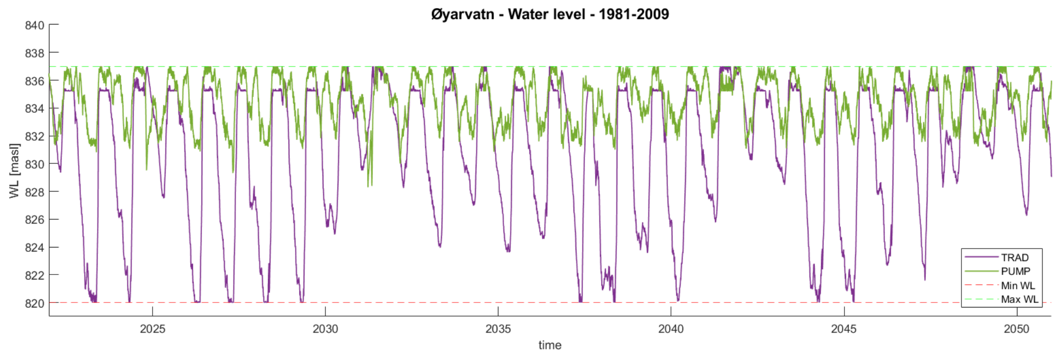


Figure 5.2: Øyarvatn: water level for period 1981-2009.

At a first look, the main aspect that can be noticed, is that water levels in Roskreppfjorden do not change a lot comparing the traditional and pumped-storage operating modes. On the contrary, water levels in Øyarvatn differ a lot from an operating mode to the other. This can be explained since Øyarvatn is smaller than Roskreppfjorden, so fluctuations in water level are much more visible.

Water level variations are also available as result of the model, with the same time-resolution. These are visible in *Figures 5.3* and 5.4. At first look, it is evident that change in operating mode is reflected on fluctuations in water level. Even here differences are more evident for the smaller reservoir, comparing traditional and pumping.

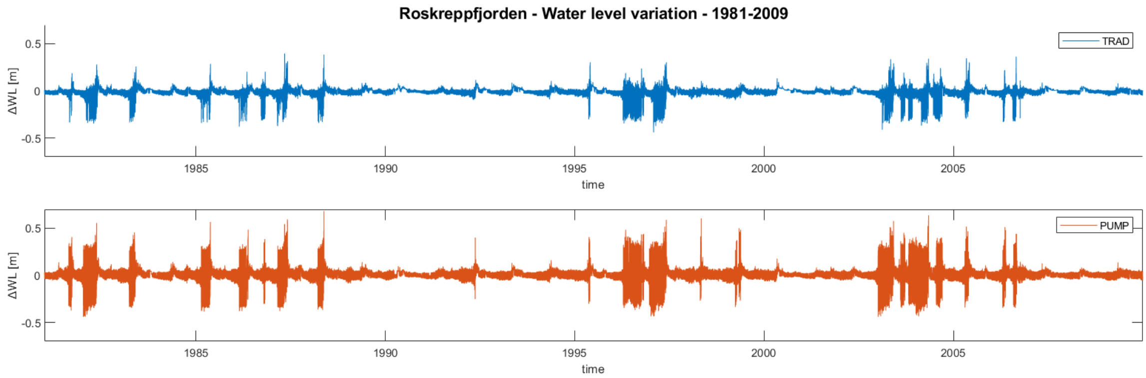


Figure 5.3: Roskreppfjporden: water level variations for period 1981-2009.

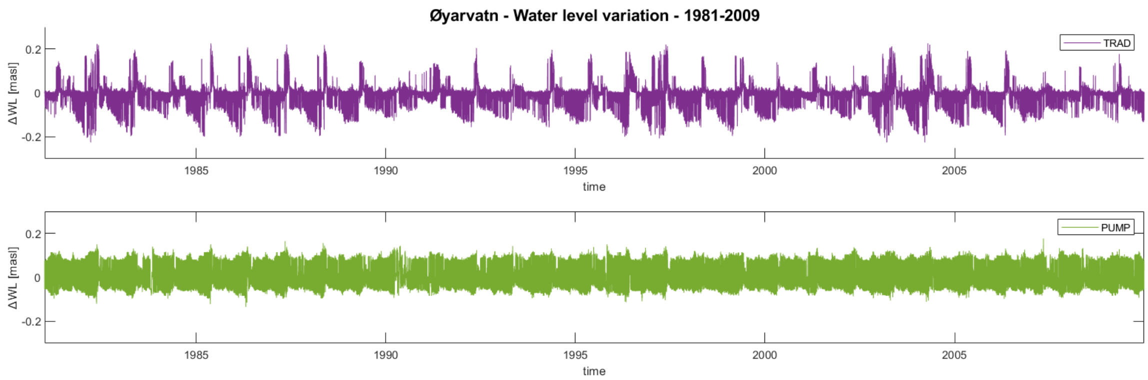


Figure 5.4: Øyarvatn: water level variations for period 1981-2009.

5.2 Specific years selection

Together with the full timeseries analysis, some specific hydrological years are selected, to be analyzed more in detail. The choice was made visually, trying to take in consideration possible differences in inflows and price pattern, which respectively reflect water available from the system and energy prices, remembering also that low energy prices primarily mean more possibilities for pump to work (so a year with lower prices mean potentially possibilities to have more frequent water level fluctuation due to pumping operations).

The choice to analyse hydrological years instead of solar ones was taken looking at the yearly inflow pattern, to see whether it can be related to water level variations in regulated reservoirs. Years have been selected from the historical reference period, and then pairing them with the corresponding future ones, to make them being comparable in terms of inflows, since price scheme is the same. Selected years 1989-1990 and 2003-2004 for the historical reference period (see *Figure 5.5* and *Figure 5.6*), and 2030-2031 and 2044-2045 for the future period, RCP 4.5 and RCP 8.5.

As could be expected, in a regulated system like the one in object, prices are the main driver

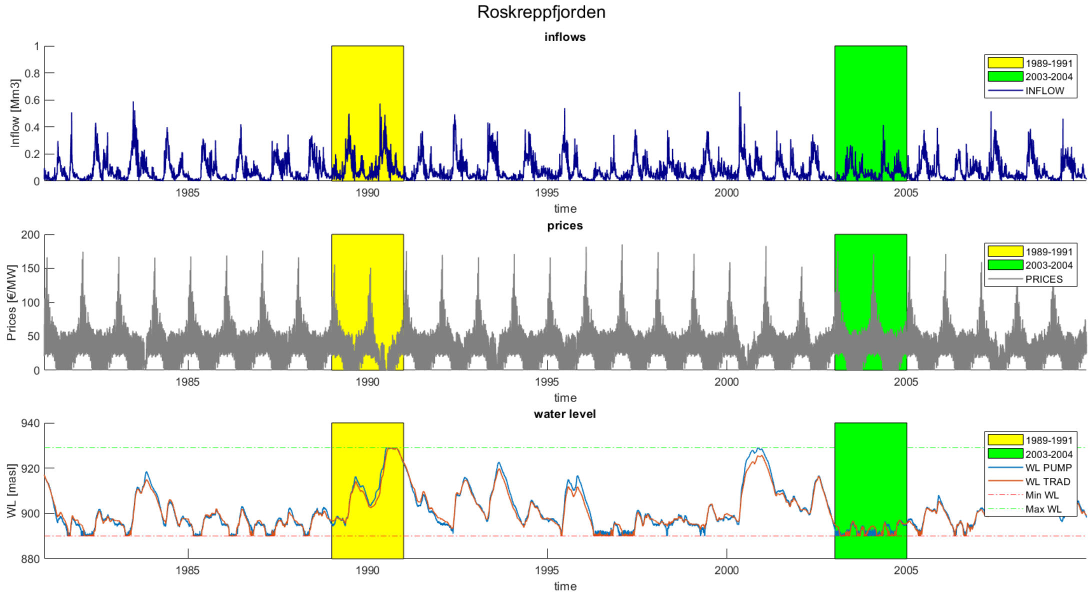


Figure 5.5: Roskreppfjorden: inflow, prices and water level for period 1981-2009 and selected years.

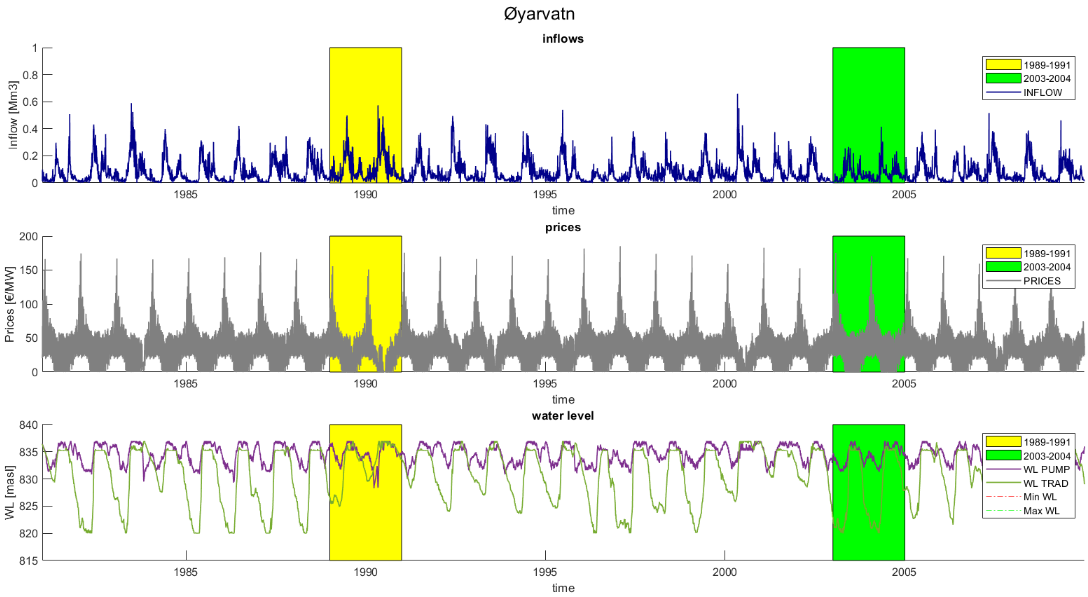


Figure 5.6: Øyarvatn: inflow, prices and water level for period 1981-2009 and selected years.

which influence hydropower operations, so the inflow pattern is only bashfully reflected in the resulting water level pattern.

Water level pattern for 1989-90 and 2003-04 for the two reservoirs is shown in *Figure 5.7* and *Figure 5.8*.

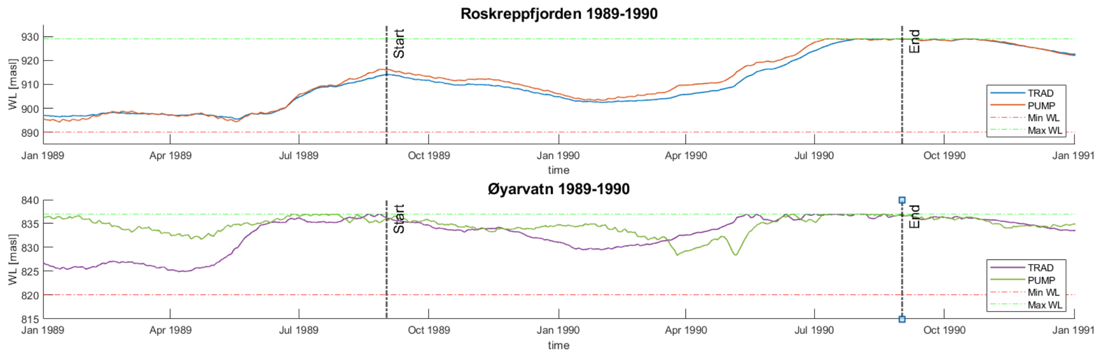


Figure 5.7: Water level, Roskreppfjorden and Øyarvatn, 1989-1990.

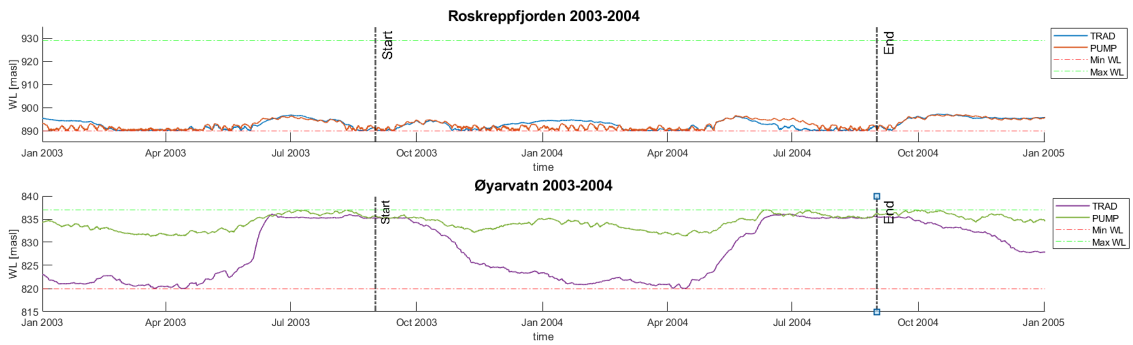


Figure 5.8: Water level, Roskreppfjorden and Øyarvatn, 2003-2004.

5.3 General statistics for Traditional and Pumped storage mode

This section analyses indices proposed in *Chapter 3* in the two catchments, for the historical reference period. They are divided into three main categories, as their measurement purpose is different. The first part, dedicated to HYMO parameters, considers two of the proposed indices resumed in *Figure 3.20*, while the following sections aim to show that more indices can be defined and computed for this specific case, taking into account a larger availability of data.

5.3.1 HYMO parameters

Short term water level variations (days) (P.207)

This parameter is the first indicator for the alteration level in a regulated catchment. The following *Table 5.1* resumes class borders for HYMO classification.

The pie charts in *Figure 5.9* and *Figure 5.10* consider mean daily water level fluctuations, divided into positive and negative, for Roskreppfjorden and Øyarvatn. For the entire historical

Table 5.1: Short term WL variations (days).

Parameter	N.N.	S.M.	M.M.	E.M.	Se.M.
Short term WL variations (days)	$< 0.1\ m$	$0.1 - 0.5\ m$	$0.5 - 1\ m$	$1 - 2\ m$	$> 2\ m$

reference period, it is clear that in the both cases water level variations are pretty small, and the two catchments can for this reason be classified as near natural or slightly modified, which limits are 0.1 and 0.1-0.5 meters changes during a day respectively.

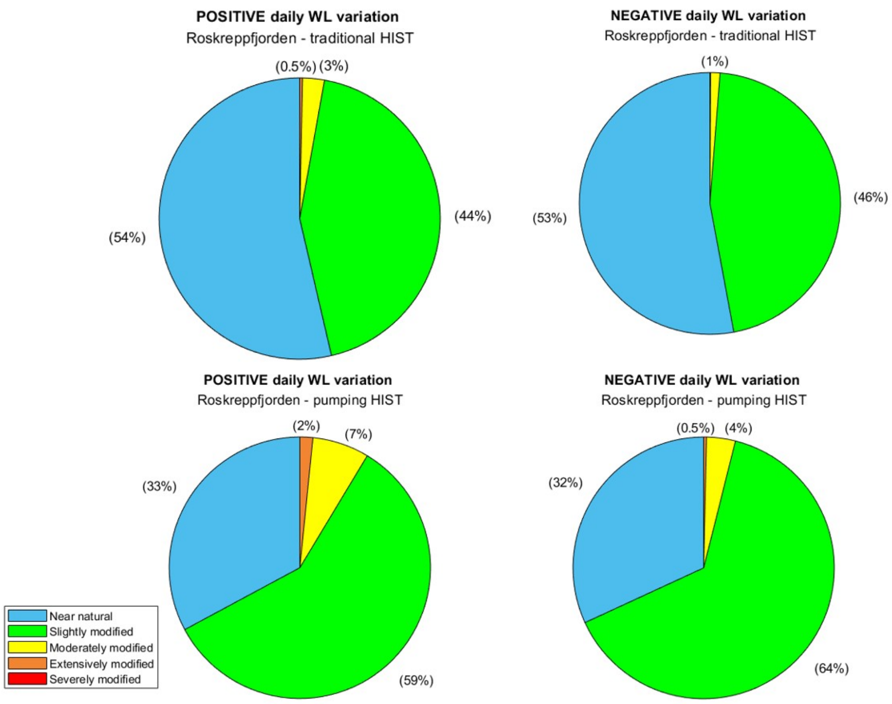


Figure 5.9: Roskreppfjorden, daily water level fluctuations, period 1981-2009.

Both for Roskreppfjorden and Øyarvatn, switching from traditional to pumping mode, there is an increase of positive and negative water level fluctuation within range 0.1-0.5 m. The main difference between the two catchment lies in water level fluctuation in the range 0.5-1 m and 1-2 m. While for Roskreppfjorden there is a slight increase of this kind of variations, for the second catchment they decrease becoming less than 1% in an hypothetical change of the operating mode from traditional to pumping.

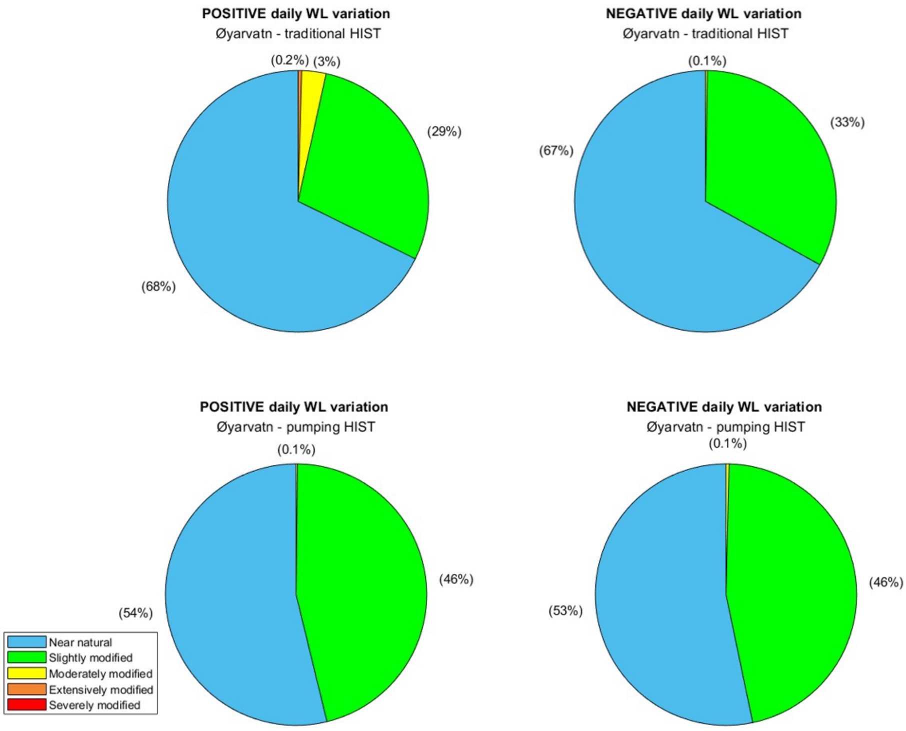


Figure 5.10: Øyarvatn, daily water level fluctuations, period 1981-2009.

Dewatered areas (P.210)

This parameter simply depends on the extension of regulation area with respect to the entire catchment area. Class-borders are resumed in *Table 5.2.*

Table 5.2: Dewatered areas.

Parameter	N.N.	S.M.	M.M.	E.M.	Se.M.
Dewatered Area	$< 5\%$	$5 - 10\%$	$10 - 30\%$	$30 - 70\%$	$> 70\%$

In both cases, the dewatered areas are less than 5% compared with the entire catchment area. Because of this reason, they can be classified as severely modified catchment. In detail:

$$\textbf{Roskreppfjorden}: \; DewA = \frac{A_{LRV}}{A_{HRV}} = \frac{2.88e^9}{2.98e^9} = 0.966 = 96.6\% > 70\% \rightarrow \textbf{Severely Modified} \quad (5.1)$$

$$\textbf{Øyarvatn:} \; DewA = \frac{A_{LRV}}{A_{HRV}} = \frac{8.04e^8}{8.08e^8} = 0.9948 = 99.5\% > 70\% \rightarrow \textbf{Severely Modified} \quad (5.2)$$

Dewatered littoral zone versus total littoral zone (ratio) (P.212)

This parameter is only referred to littoral zone. As previously mentioned, in this case the littoral zone corresponds to the entire regulation area of the two catchments. To compute the dewatered littoral zone, *Equation 3.3* is used. *Table 5.3* resumes the classes boundary used in the HYMO report for classification.

Table 5.3: Dewatered littoral area versus total littoral area (ratio).

Parameter	N.N.	S.M.	M.M.	E.M.	Se.M.
Dewatered Littoral Zone	$< 5\%$	$5 - 10\%$	$10 - 40\%$	$40 - 90\%$	$> 90\%$

Results of the analysis for the two reservoirs are reported in *Figure 5.11* and *Figure 5.12*, where the black line represents the percentage dewatered littoral zone and class-borders are visible with coloured boxes.

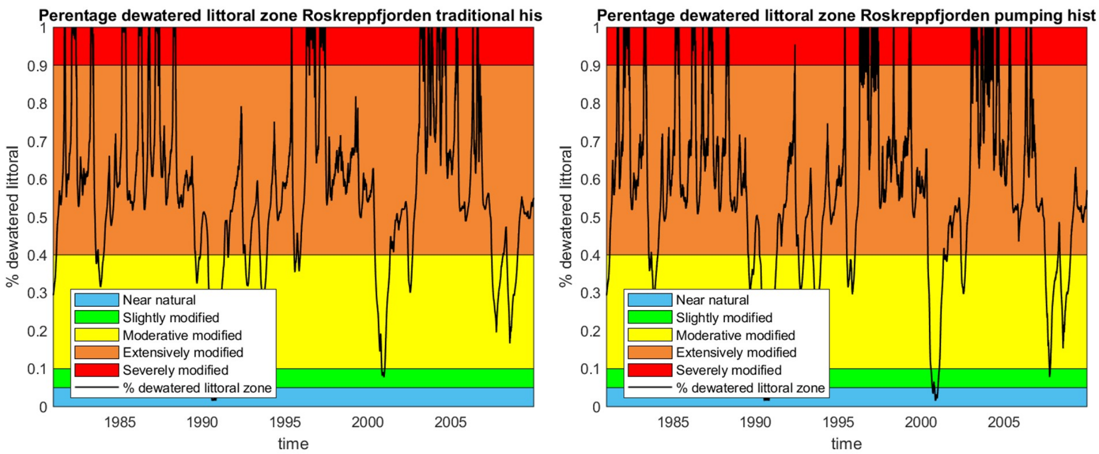


Figure 5.11: Roskreppfjorden, percentage dewatered littoral zone compared to the total littoral zone, period 1981-2009.

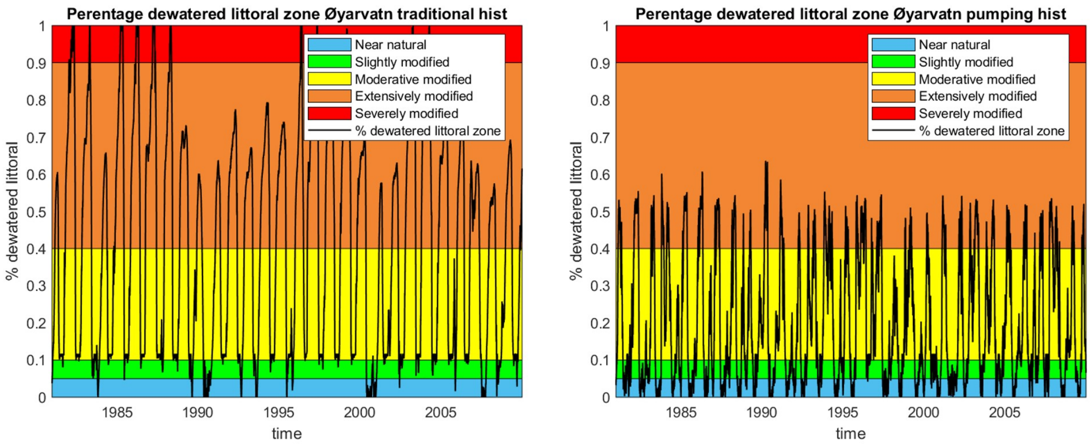


Figure 5.12: Øyarvatn, percentage dewatered littoral zone compared to the total littoral zone, period 1981-2009.

Comparing the two operating mode, differences in the percentage of dewatered littoral zone are more visible for Øyarvatn than for Roskreppfjorden. Again, the reason lies in the very different dimensions of the two reservoirs, and consequently in the extension of their littoral zone. The downstream catchment has a littoral zone that is approximately four times smaller than the upstream one, so it is more influenced by the operating mode. Switching from traditional to pumping mode for Øyarvatn would help in preserving littoral zone from being largely dewatered more frequently and for longer periods during years. Even with more frequent water level fluctuations in pumping mode, this catchment would benefit in terms of dewatered areas.

5.3.2 New proposed indices related to water level

To analyse more in detail distribution of peaks during years and month, such as their intensity and duration, some indices related to water level are here presented.

Distribution and number of peaking events (WL.1)

Changes in distribution and number of peaks over the years in the reference period are a direct consequence of adding the pump to the current system.

In this case, since the minimum timestep is 3-hours, even very small local maximum are detected as peaking event for water level timeseries, and so number of peaking events depends on data frequency. To solve this, the peaking detection has been analysed using the mean daily water level timestep. Then a minimum peak prominence (that is, how much the peak stands out due to its intrinsic height and its location relative to other peaks) has been chosen for each lake, providing a better identification of peak number and peak duration. Different methods have been tested to overcome the challenges of overestimating peak events, while the number of peaks might slightly differ, results show that peaks under pumping double compared with the traditional scenario.

Table 5.4 shows number of peaks counted for each reservoir, both for traditional and pumping mode.

Table 5.4: Number of peaking events.

Mode	Roskreppfjorden	Øyarvatn
TRADITIONAL	81	87
PUMPING	177	223

In this case, number of peaking evens is supposed to double for the two lakes, switching from traditional to pumped-storage mode. Dividing the results for total number of years, an average number of peaks per year is obtained. This number is around 2.7 for traditional mode, and 6.5 in pumping mode.

Duration of peaking events (WL.2)

The distinctive tract of the increased number of peaking events that occur adding the pump to the system is characterized by a smaller duration of peaks themselves. Following plots

The plots in Figures 5.13-5.14 represent, on the y-axis, the time that is passing between an increasing water level and successive decrease, for the two reservoirs considering both traditional and pumped-storage operating mode. This aspect is again more visible for Øyarvatn (see *Figure 5.14*). Another aspect is evident from the plots: the peaks' amplitude decreases a lot in the pumping mode with respect to the traditional one.

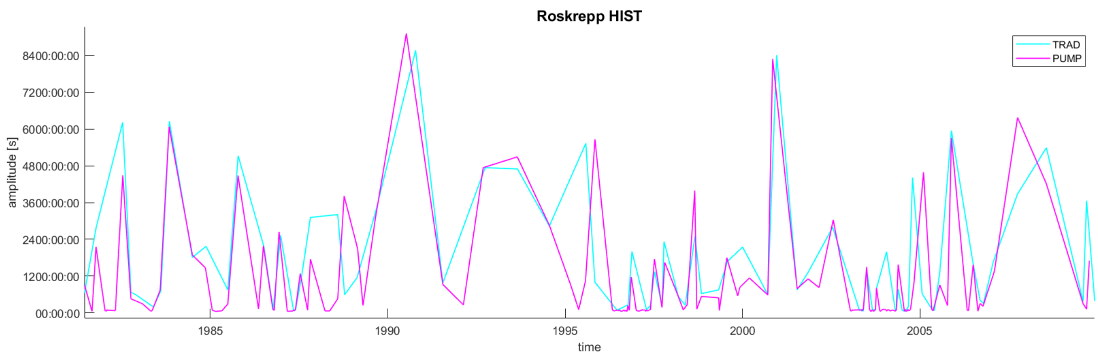


Figure 5.13: Roskreppfjorden, duration between a rapid increase and decrease, traditional scheme.

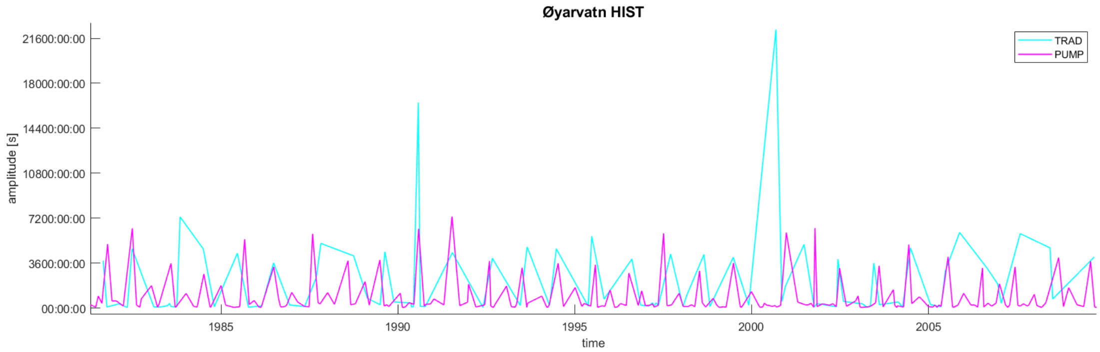


Figure 5.14: Roskreppfjorden, duration between a rapid increase and decrease, traditional scheme.

5.3.3 New proposed dewatering indices

These indices allow to visualize, in form of maps or bar plots, some quantities that are supposed to be relevant not only from morphological but also from the biological point so view. In fact, even if in this specific case there is lack of data regarding this second aspect, they can be used for situations where more data about biological activities are available. To compute the following indices, needed data are hypsometric curves of the two reservoirs, timeseries of water level and elevation of pixels that lie within the littoral zone. These data are available from bathymetric maps and timeseries for water level in the two reservoirs.

Percentage of wet period compared with the entire analysed period (Dew.1)

Considering the regulation zone, and the whole timeseries, a first general comparison is possible: what is the percentage of time that water level is higher than the elevation of a certain pixel, compared with the full time series. This could help in identifying areas that are dry most of the time, and is a first possibility to compare traditional scheme and pumped-storage one. *Figure 5.15* and *Figure 5.15* show results comparing the two operating modes for the whole historical reference period, but it is possible to obtain the same kind of maps for specific selected years, obtaining a comparison for shorter period.

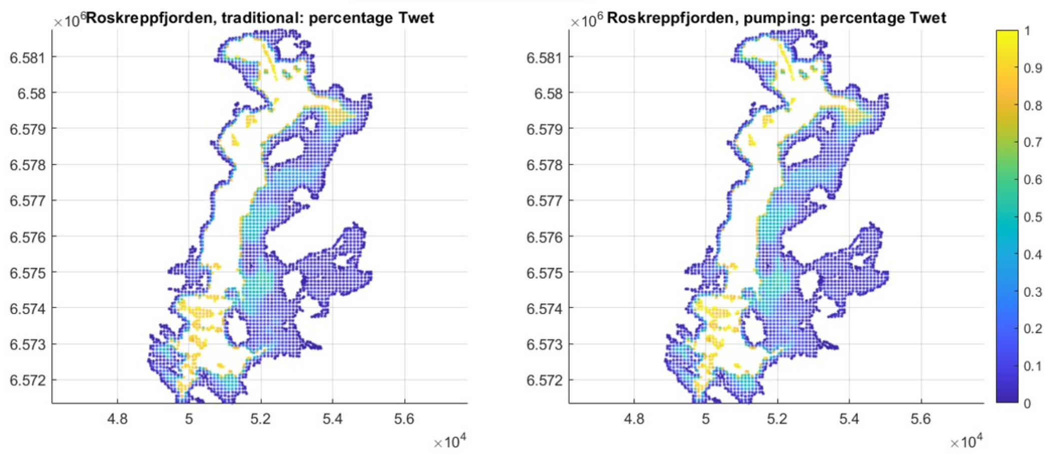


Figure 5.15: Roskreppfjorden, percentage of wet period compared with the entire timeseries.

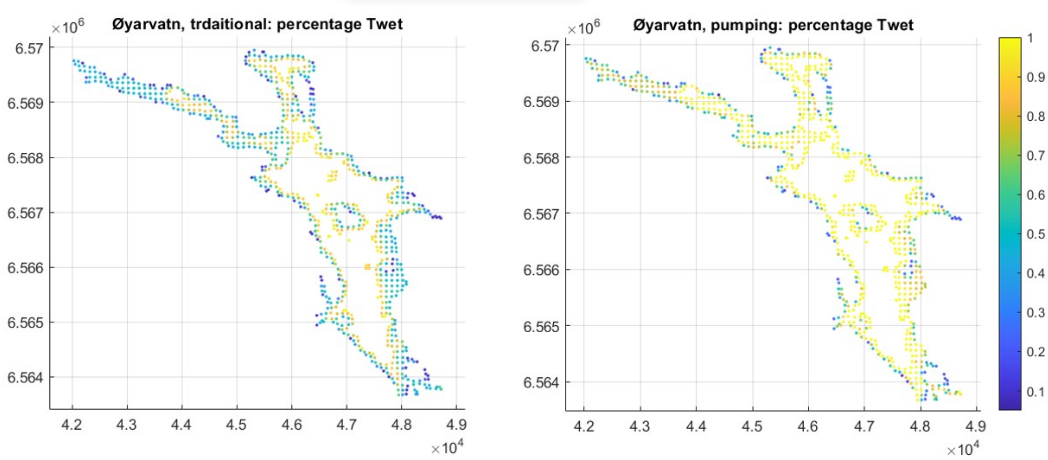


Figure 5.16: Øyarvatn, percentage of wet period compared with the entire timeseries.

As previously mentioned, the biggest differences are visible for Øyarvatn (Figure 5.16) in which water level pattern changes a lot from traditional to pumping mode, as shown in *Figure 5.1* and 5.2.

Median wet period, limiting the analysis to 365 days (Dew.2)

Another interesting information, easily obtainable, is the median time for pixels in the regulation zone being wet. To better visualize results, the color bar can be limited within range 0-365 days. Results are presented in *Figure 5.17* for Roskreppfjorden and 5.18 for Øyarvatn.

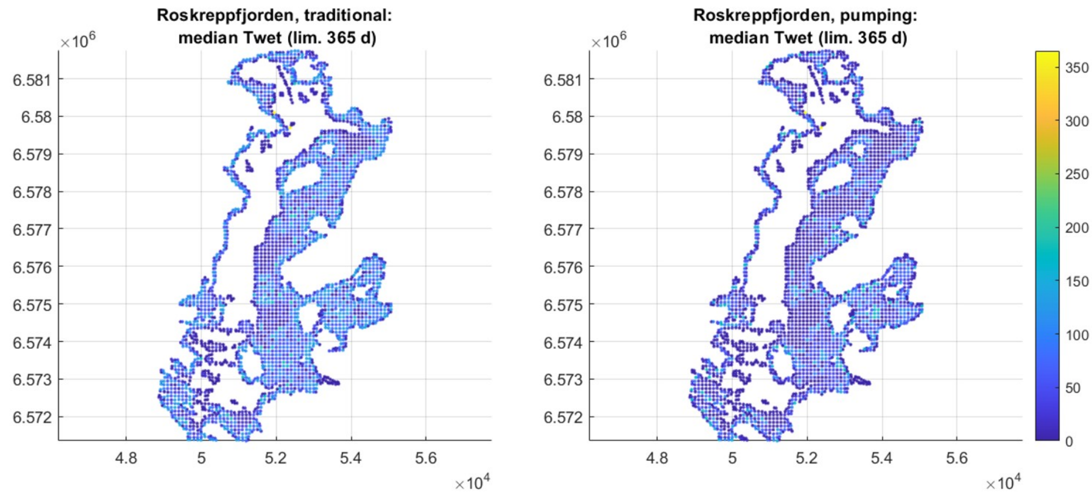


Figure 5.17: Roskreppfjorden, median Twet (limit 365 days).

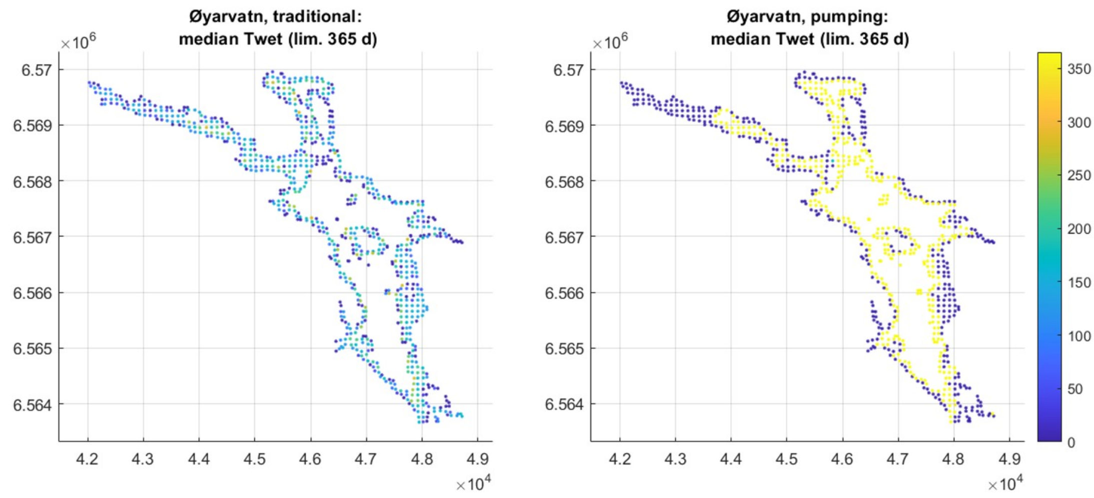


Figure 5.18: Øyarvatn, median Twet (limit 365 days).

Even in this case there is higher contrast in results for Øyarvatn, where the higher median T_{wet} period is around 150 days in traditional mode, compared with almost 365 days (or almost continuously wet regions) in pumped-storage mode. Referring to this second operating mode, the reservoir can be divided into two clearly distinct region: the inner region, which is approximately always wet, and the external one, which becomes wet only when water level reaches the HRV. This is consistent with the water level pattern in Øyarvatn for this second scheme, that rarely drops under 825 m asl. Less evident is the difference in Roskreppfjorden: for traditional mode median T_{wet} is on average a bit higher than the same period measured in case pump is added, but colors indicate that, in both cases, the result is below 200 days per year.

Period 5-30 days (Dew.3)

From an ecological point of view, it is also relevant to know if there some areas, within a regulated reservoir, that become frequently wet and dry. If this condition verifies more than once per year, maybe during the spawning period, the implicated area could be problematic for fishes to lay their eggs, because small fishes would not have time enough to become adult and go their own way. As an example,*Figure 5.19* and *Figure 5.20* highlight with a red circle all pixels in the regulation area that are wet for a period 5-30 days more than once a year. In this case, contrasts are evident also for Roskreppfjorden, especially for the areas with low elevation. Water level variations in pumping mode are much more frequent, and for years with generally low water level these areas would be much more frequently subjected to short wet and dry period.

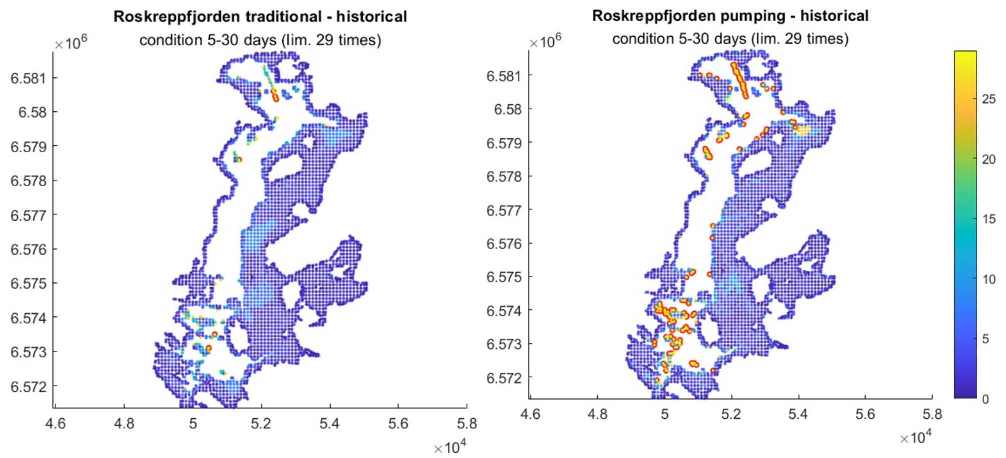


Figure 5.19: Roskreppfjorden, condition 5-30 days(lim. 29 years).

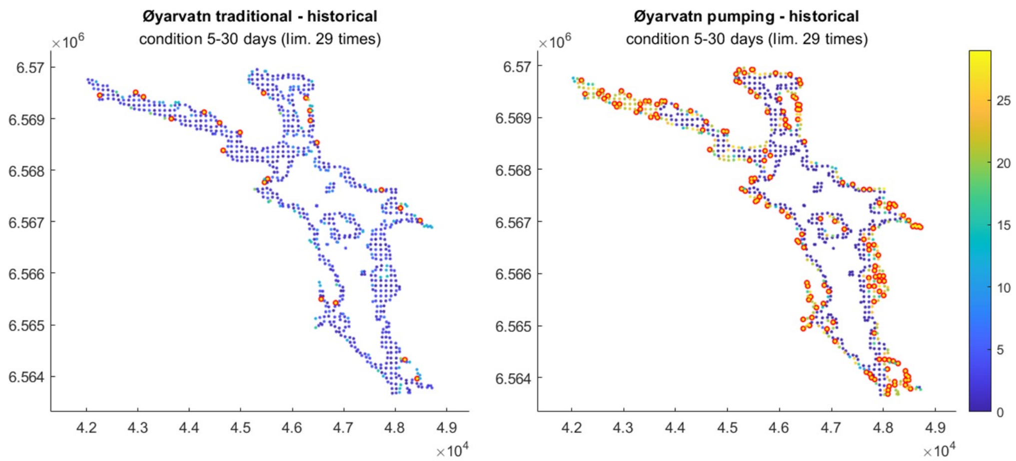


Figure 5.20: Øyarvatn, condition 5-30 days(lim. 29 years).

Comparison between minimum water level in October and water level in the following period November-March, during each year (Dew.4)

Going deeper in detail, a possible spawning season has been considered. Supposing the spawning period for fishes to be around October [25], the number of days between November and March for water level being lower than minimum water level reached in October have been counted. The last 29th year has been excluded from computation, since data from January to March of the 30th year were missing. *Figure 5.21* and *Figure 5.22* show the result, with a color scale going from blue to dark-red for increasing number of days. The better condition verifies in Øyarvatn, supposing it operating in pumping mode. The nmber of days could be generally reduced by half switching from traditional to pumping mode for Øyarvatn, while for Roskreppfjorden this positive condition would be less frequently verified.

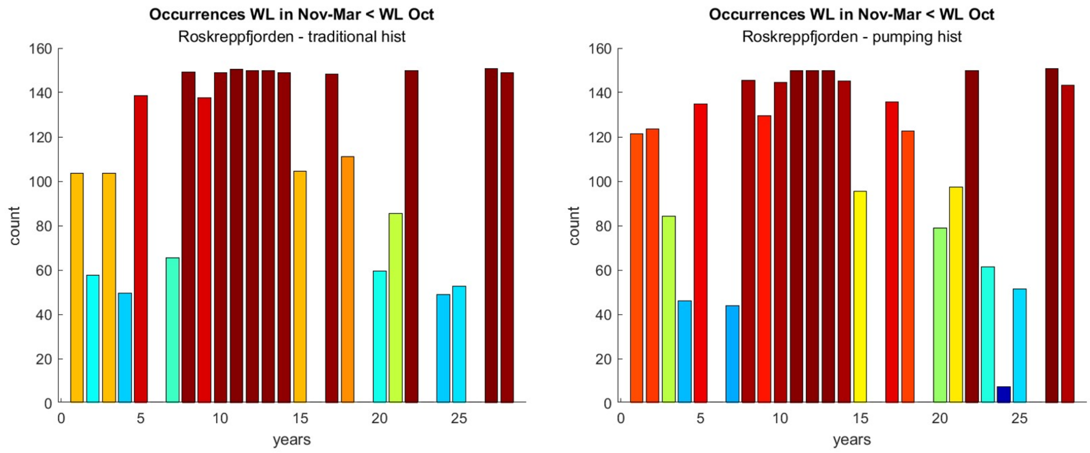


Figure 5.21: Roskreppfjorden, number of days in which WL in November-March lower than WL in October for 29 years.

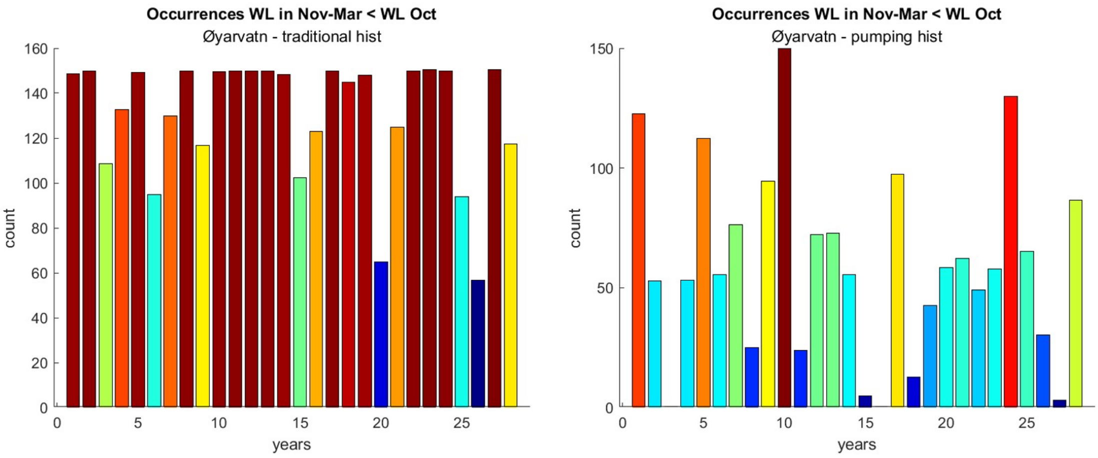


Figure 5.22: Øyarvatn, number of days in which WL in November-March lower than WL in October for 29 years.

Water level fluctuation for period March-April in each year (Dew.5)

In addition to that, it is important for alevins not to be subjected to rapid lowering of water level water level fluctuation in their first period of life [4]. For this reason, mean, median and mode water level variations in period March-April can be considered in each year. The bar plots in *Figures 5.23-5.26* represent results for median WL fluctuation in this period. The pumping mode is supposed to increase these fluctuations both for positive and negative ones. These plots can be coupled with the ones represented in *Section 5.3.3*, e.g. the mean rate of change or duration between rapid increase and decrease, to have a complete overview regarding the catchment.

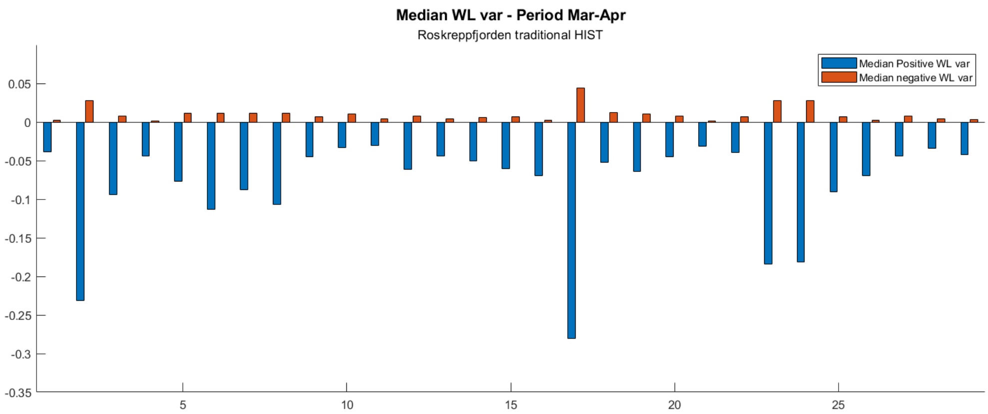


Figure 5.23: Roskreppfjorden traditional, median WL variations in meters in period March-April for 29 years.

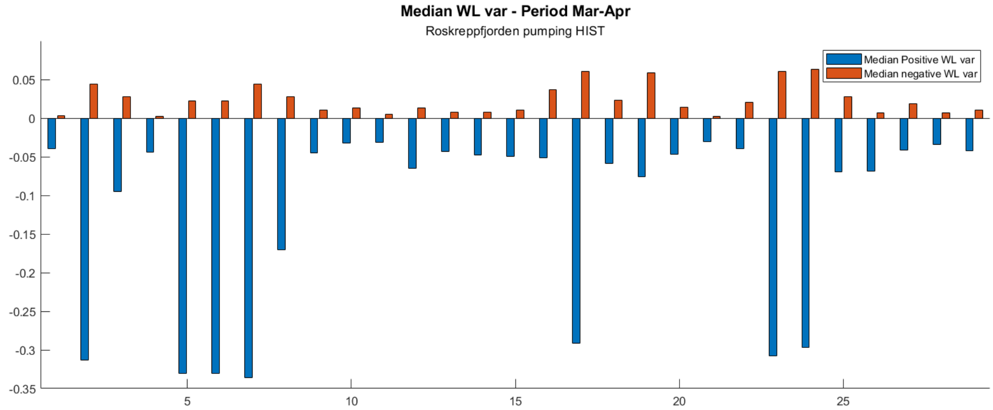


Figure 5.24: Roskreppfjorden pumping, Øyarvatn, median WL variation in period March-April for 29 years.

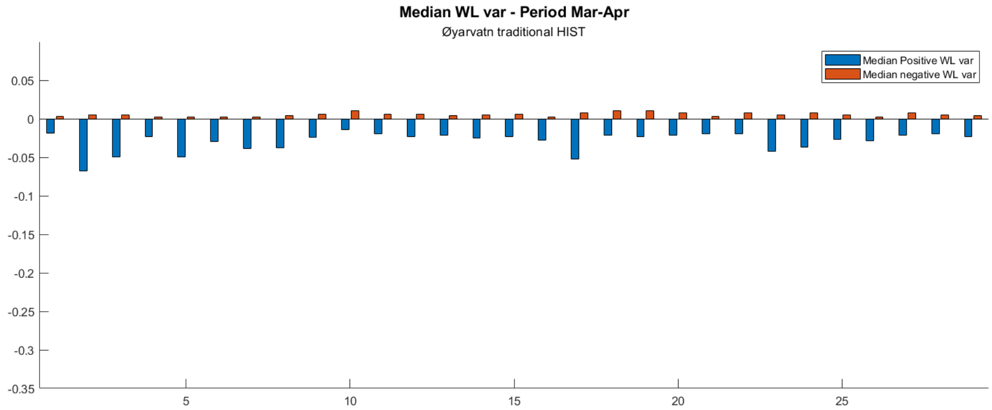


Figure 5.25: Øyarvatn traditional, median WL variation in period March-April for 29 years

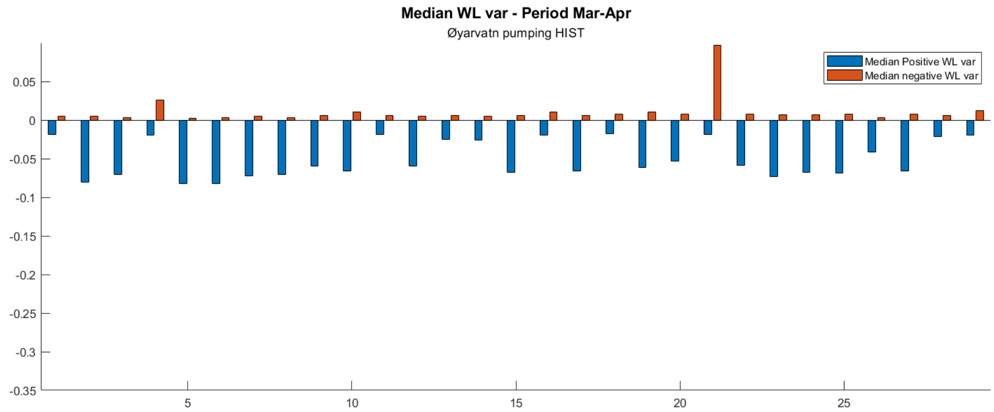


Figure 5.26: Øyarvatn pumping, median WL variation in period March-April for 29 years

5.4 Analysis for selected years

The same indices can be applied for specific periods, shorter than the entire 29-years series, in order to investigate for example years with a particularly water level pattern. As previously mentioned, selected years have been selected choosing high and low inflows respectively, to see how this aspect would have influenced the outputs.

At first, water level plots for the two selected years (1989-1990) and (2003-2004) are shown (*Figure 5.27* and *5.28).*

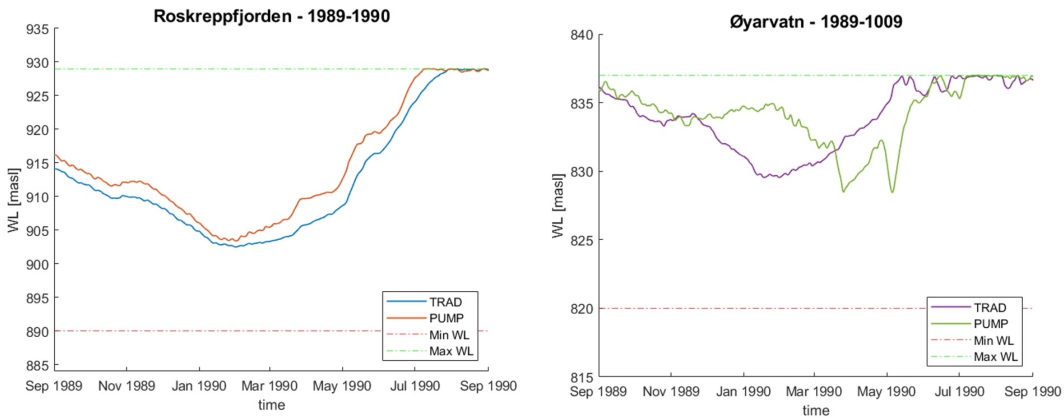


Figure 5.27: Water level for period 1989-1990, Roskreppfjorden and Øyarvatn.

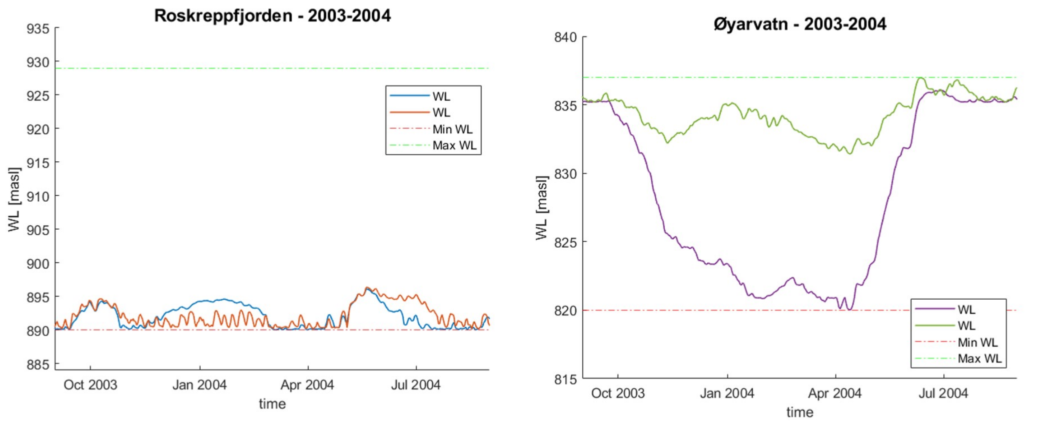


Figure 5.28: Water level for period 2003-2004, Roskreppfjorden and Øyarvatn.

The comparison is here presented for the percentage of dewatered littoral zone in the two different years and for some of the dewatering indices. All the indices can be compared, but the following have been considered the more relevant ones:

- Percentage dewatered littoral zone;
- Percentage T_{wet};
- Comparison between minimum water level in October and water level in the following period November-March;
- Water level fluctuation for period March-April.

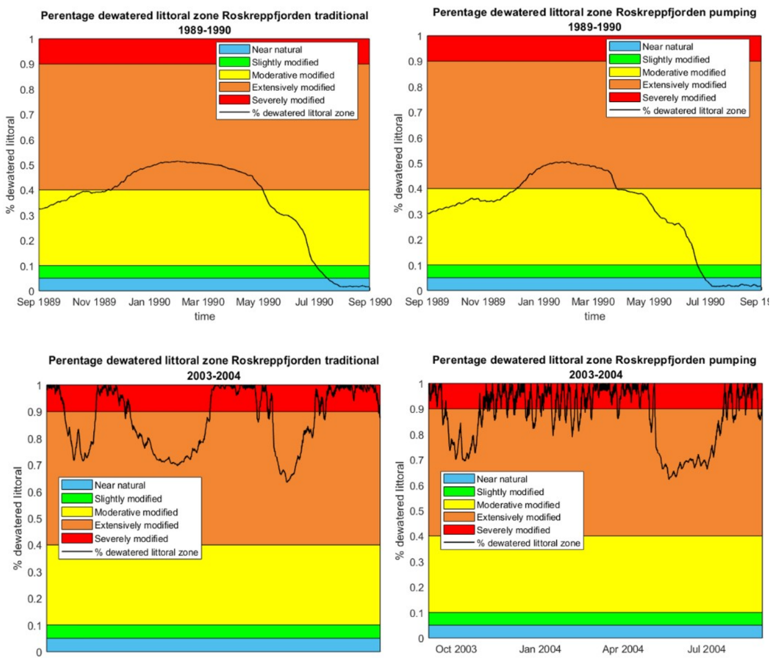


Figure 5.29: Percentage dewatered littoral zone for 1989-1990 and 2003-2004, Roskreppfjorden.

Starting from the percentage of dewatered littoral zone **(P.212)**, it is always true that switching from traditional to pumping mode, fluctuations in water level tend to increase, and so also fluctuations in dewatered littoral zone. Nevertheless large differences also between scenarios are evident for both reservoirs. The most critical situation is Roskrepp pumping for period 2003-04 (*Figure 5.29*, bottom right), because it results severely modified for almost all the time during the year, while the best scenario is identified by Øyarvatn with the pump added to the system (*Figure 5.30*, bottom right) for which extensively-modified condition (orange color) is barely reached.

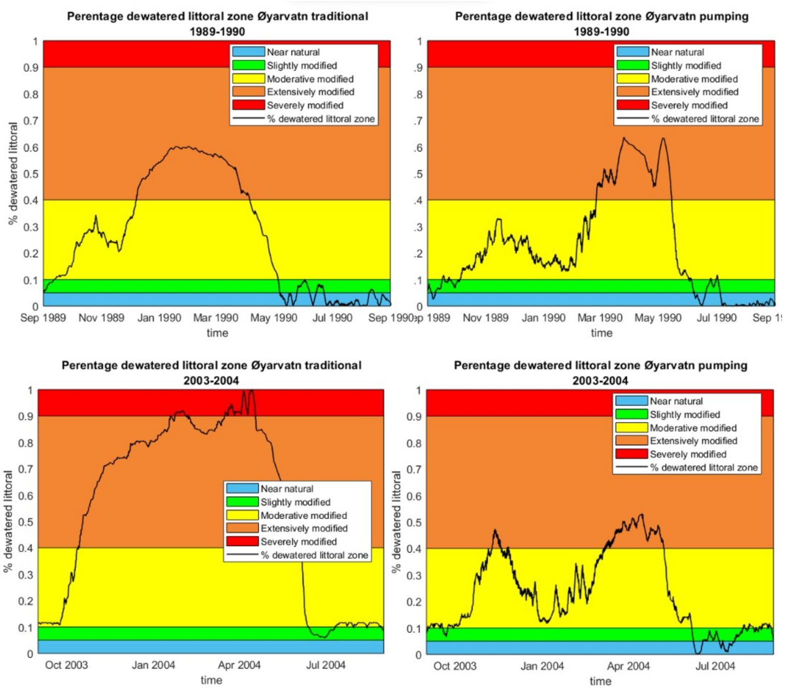


Figure 5.30: Percentage dewatered littoral zone for 1989-1990 and 2003-2004, Øyarvatn.

The same classification can be deduced by analyzing the maps for percentage T_{wet} compared with the entire selected year, index **Dew.1** (*Figure 5.31* and *5.32*). Another aspect is evident here: even if a situation with very low inflow can occur, Øyarvatn in pumping conditions would not be damaged from it. On the contrary, for Roskreppfjorden the situation for dry years would be much more critical in any case.

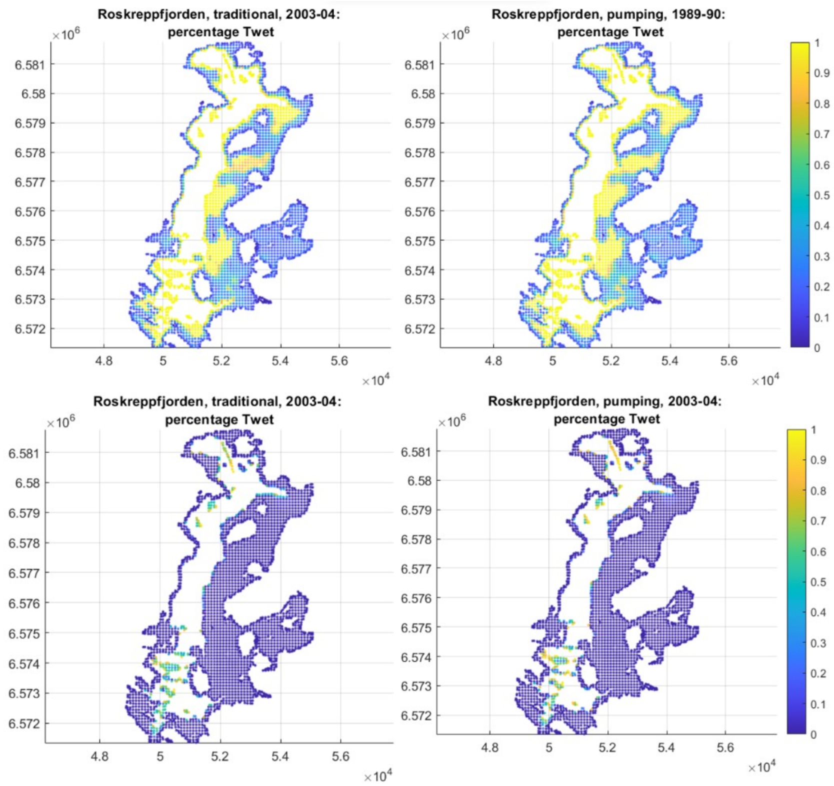


Figure 5.31: Percentage T_{wet} for 1989-1990 and 2003-2004, Roskreppfjorden

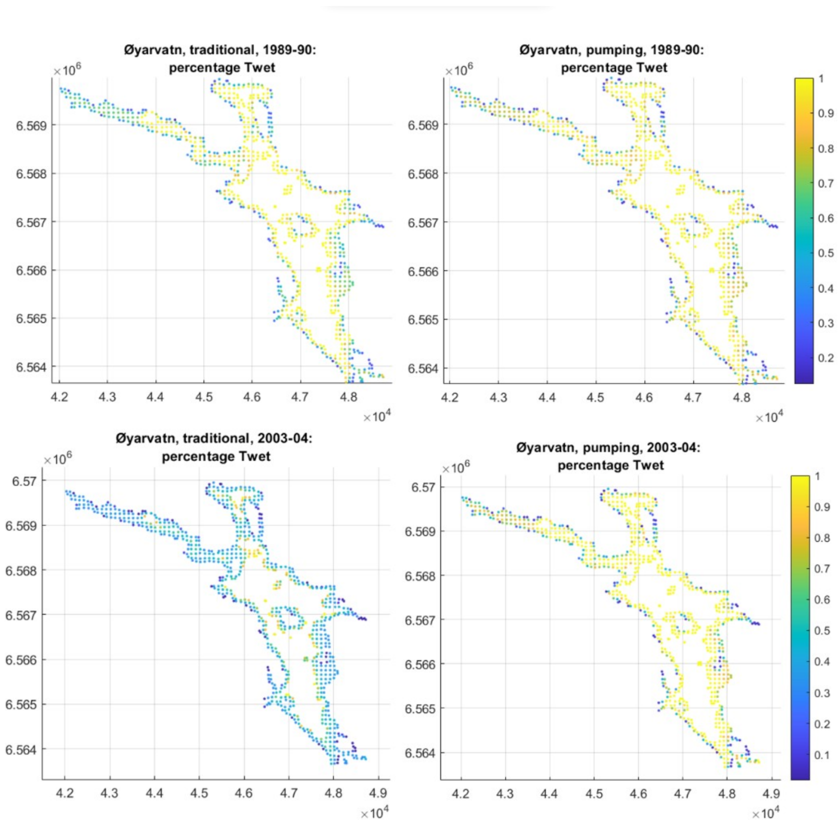


Figure 5.32: Percentage T_{wet} for 1989-1990 and 2003-2004, Øyarvatn

The third analyzed index is the one comparing water level in October with water level for the following period November-March (**Dew.4**). Both for 1989 and 2003, the number of days during November-March in which water level falls under the minimum water level recorded in October switching from traditional to pumping mode, except from Roskreppfjorden, 2003-2004. This is because the minimum water level in October 2003 corresponds to the LRV for the catchment in traditional mode, while this is not true for pumping mode. For this reason, due to the high variability of water level in this year, switching to pumping mode water level can drop below the minimum recorded value in October (*Figure 5.33*).

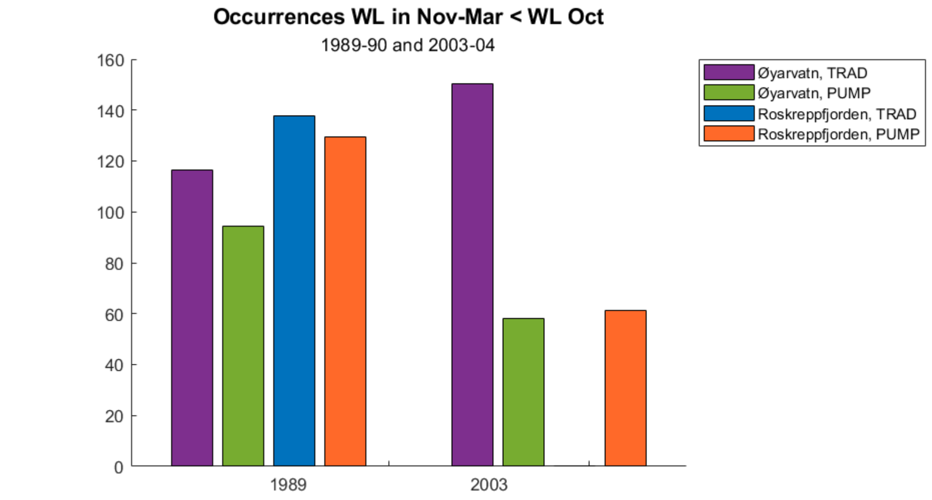


Figure 5.33: Number of days WL in November-march lower than WL in October, Roskreppfjorden and Øyarvatn.

The last index is related to water level fluctuations in March-April (**Dew.5**). From Figure 5.34, representing median positive and negative water level fluctuations for the inferred period, we can deduce that switching from traditional to pumping does not necessarily mean a reduction in water level variations, and that ramping constraints could help in control these variations.

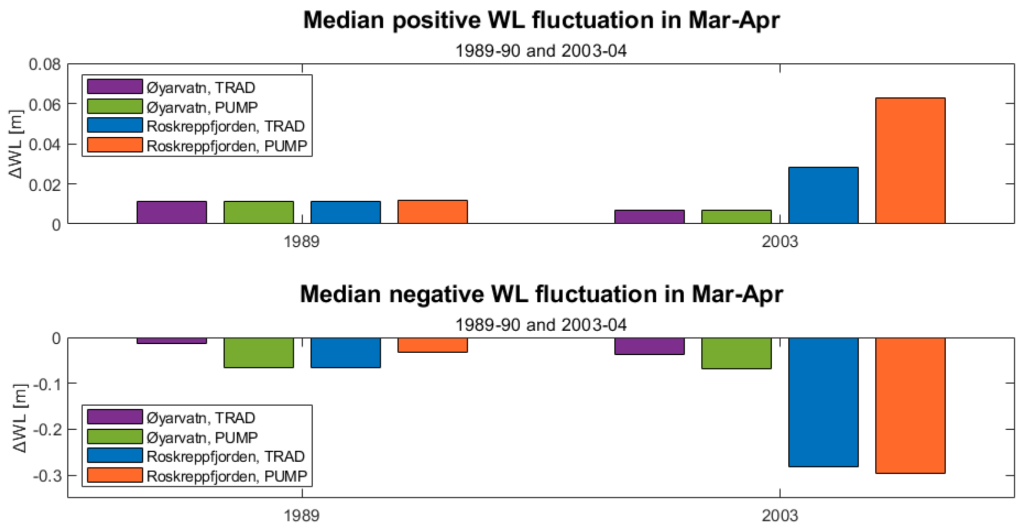


Figure 5.34: Median positive and negative WL variations, period Mach-April, Roskreppfjorden and Øyarvatn.

Using QGIS as specified in *Chapter 4.3* it is also possible to visualize interactively differences between scenarios in terms of wet and dry areas changing in time. This can help for example to identify critical areas within regulation zone for biological activity, when coupled e.g. with mapped biological data about fish spawning areas [9]. These maps are easy to produce and can be an alternative instrument to the previous plots. The added value in this case is that it is possible to do operations between different maps, overlay them and highlight different interesting aspects.

As an example, *Figure 5.35* and *Figure 5.36* represent some relevant moments for Roskreppfjorden and Øyarvatn in 1989-90 for traditional mode, while *5.37* and *5.38* are referred to pumping mode. The central light-blue area has an elevation lower than LRV, so it is always wet and pixels within regulation zone switch on and off depending on the corresponding water level.

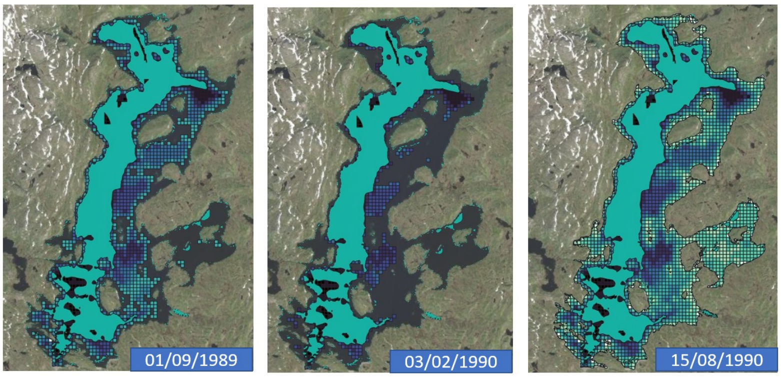


Figure 5.35: Roskreppfjorden, spatial representation of wet areas, period 1989-1990, traditional mode.

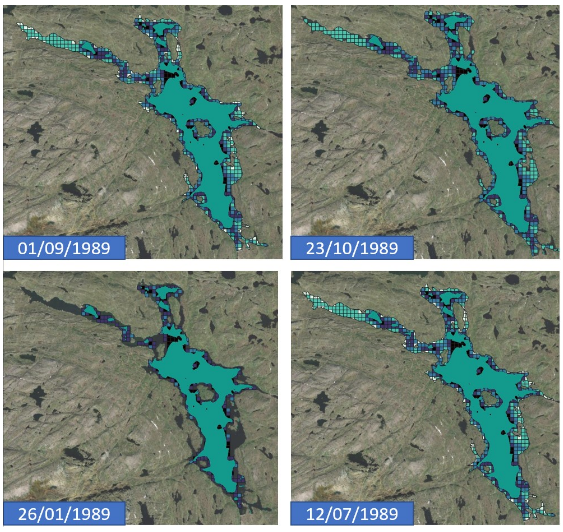


Figure 5.36: Øyarvatn, spatial representation of wet areas, period 1989-1990, traditional mode.

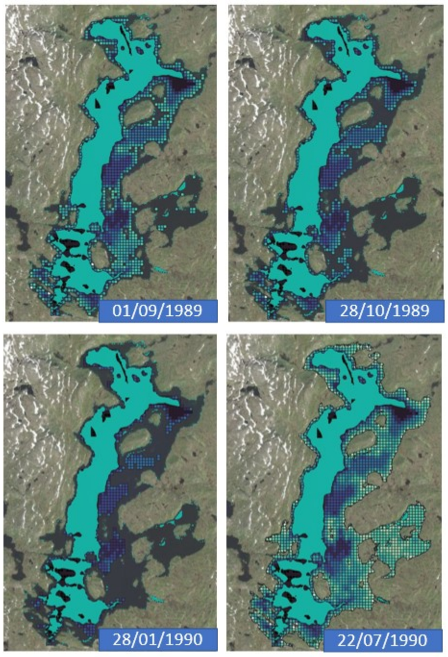


Figure 5.37: Roskreppfjorden, spatial representation of wet areas, period 1989-1990, pumping mode.

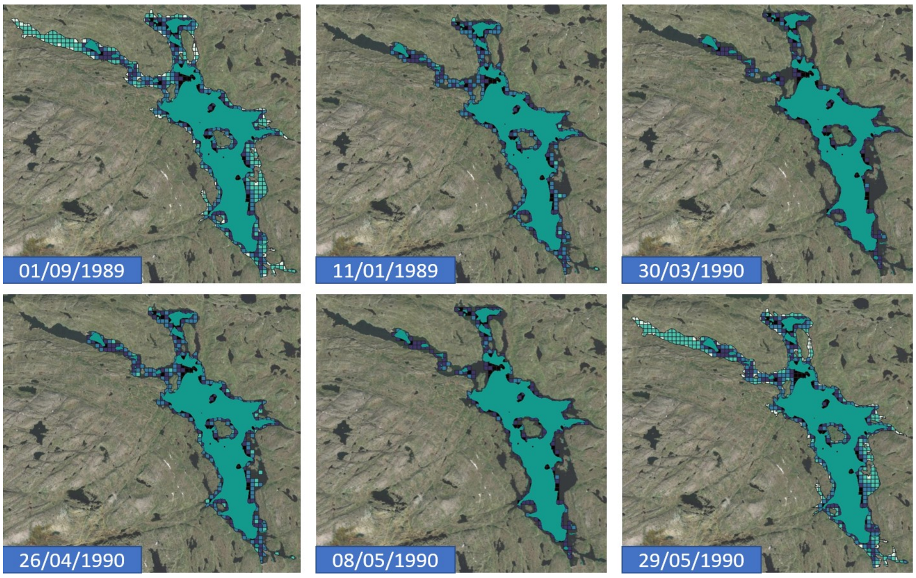


Figure 5.38: Øyarvatn, spatial representation of wet areas, period 1989-1990, pumping mode.

5.5 Comparison between historical reference period and future climate scenarios

Figures *5.39* and *5.40* show the duration curves of T_{wet} for different operating mode and climate scenarios for the two catchment, compared with the reference period.

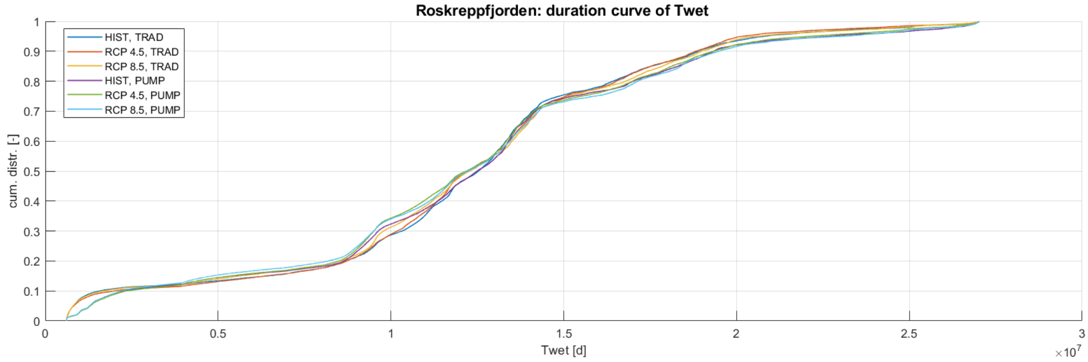


Figure 5.39: Roskreppfjorden, duration curve of T_{wet}, traditional and pumping, historical and future climate scenarios.

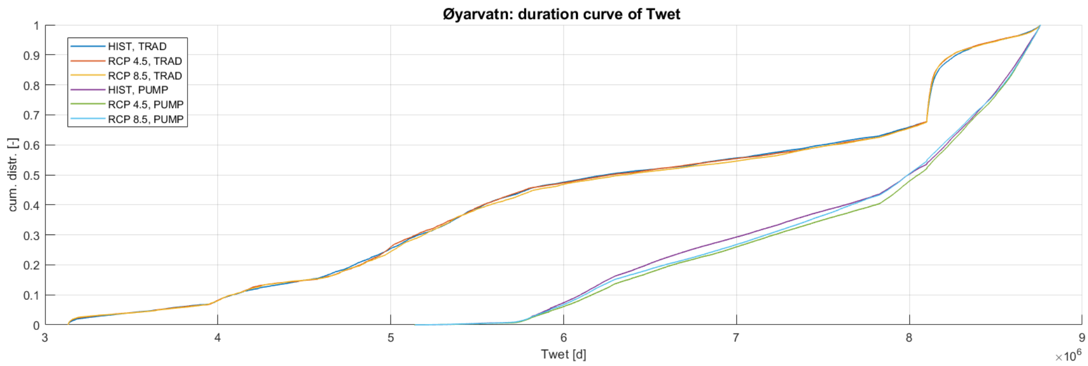


Figure 5.40: Øyarvatn, duration curve of T_{wet}, traditional and pumping, historical and future climate scenarios.

It is evident, as previously highlighted, that differences in hydropower scheme are more visible for Øyarvatn rather than for Roskreppfjorden. Another relevant aspect is that different curves are very similar considering historical reference period and future one, both for RCP 4.5 and RCP 8.5. This means that results previously obtained for different indices would probably be not so different in case of future climate scenarios, but shifted forward or backward in time with respect to the reference ones.

Reasons for results to be so similar to the ones obtained for reference period could be several. First, in this case only one combination of global and regional climate model has been used.

Taking into account all the available climate models and averaging the result, could result in a different patterns for duration curves. Additionally, future climate scenarios proposed from KSS could be downloaded till 2100, while the present future climate scenarios stop at 2050. This can influence the result, since the present analysis stops to the near future.

Apart from this, price pattern used from the three possible scenarios are the same, given by the hydropower optimization scheduling model. This is probably the main reason for future pattern being very similar to the historical reference one. Changing price patterns is supposed to produce quite different results. This will also be more evident when modelling other reservoirs in the system as well as including price variability that account for the effect of climate change at the national level (considering variability in runoff, differences in energy consumption and other changes in renewable energy sources).

Same indices previously illustrated have been produced for future climate scenarios, for the full 29 years timeseries. Doing the calculation for the whole timeseries, differences within historical reference period and future climate scenarios are not evident. As an example, Figure 5.41 shows median T_{wet} for future RCP 8.5 scenario in Øyarvatn lake.

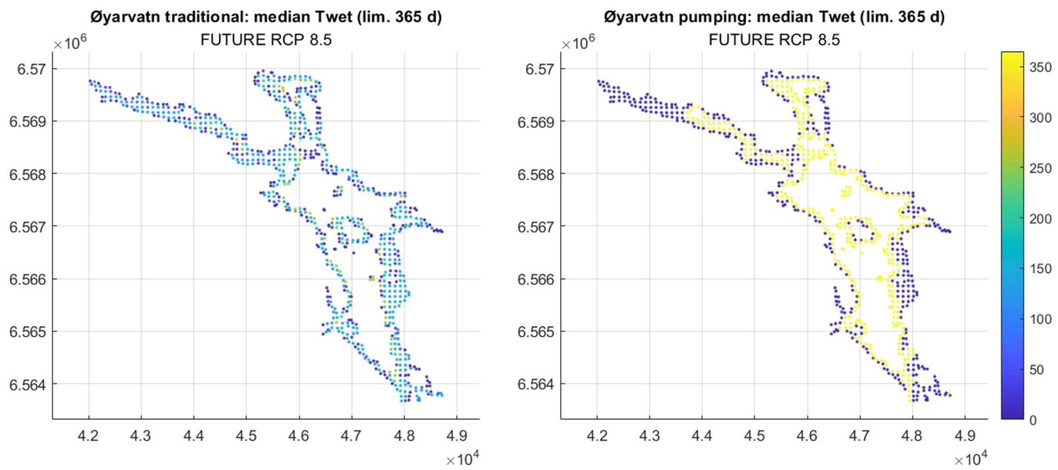


Figure 5.41: Øyarvatn, median T_{wet}, period 2022-2050, RCP 4.5.

Effects of climate in shifting forward or backward in time peaks and local minimum are more visible looking shorter period. For example, *Figure 5.42 - 5.43* show mean peaks and local minimum obtained smoothing plots for water level in year 2030-2031 for Roskreppfjorden and Øyarvatn when supposed to work in pumped-storage mode. From here it is clear that local maxima and minima differ not in intensity so much as in timing.

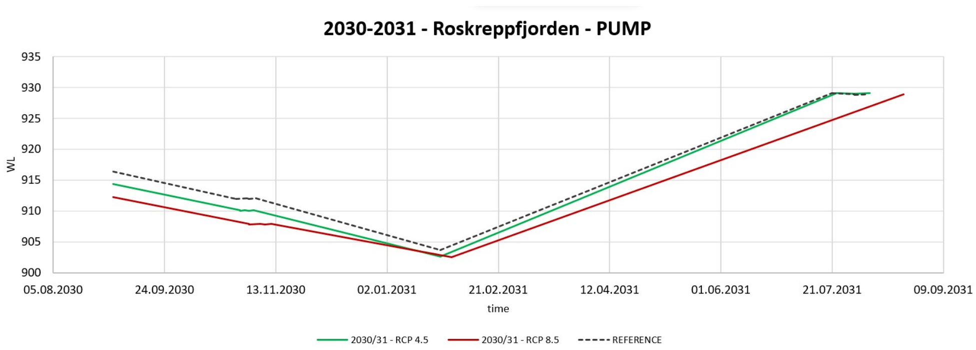


Figure 5.42: Roskreppfjorden, water level for two future climate scenarios, PERIOD 2030-2031, compared with water level in corresponding reference period, 1989-1990.

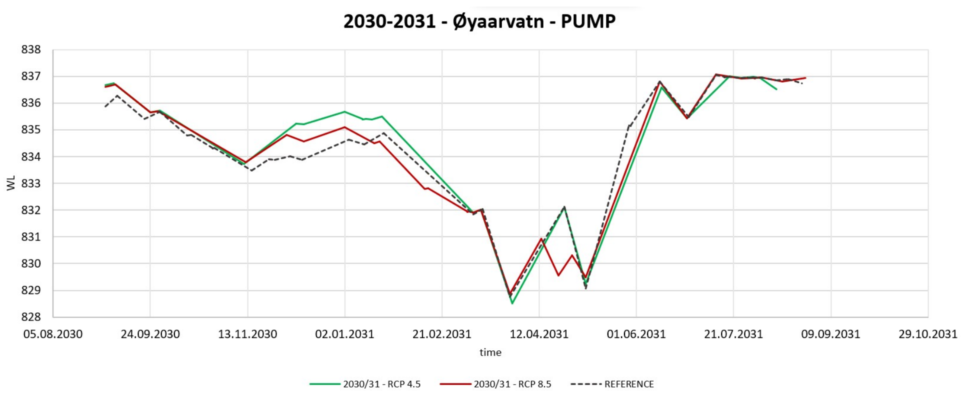


Figure 5.43: Øyarvatn, water level for two future climate scenarios, PERIOD 2030-2031, compared with water level in corresponding reference period, 1989-1990

5.6 Effects of ramping constraints

From the previous results, it is clear that critical situations in term of water level variations are present, both for Roskreppfjorden and Øyarvatn, especially in the traditional operation scheme. Introducing pumping operations could increase the fluctuations, with an intensity that can be as strong as intra-weekly prices variation, in order to get the maximum revenue from hydropower operations. However, the pumping mode can also mitigate some of the negative effects from traditional operation with a higher regulation range, especially if managed with the correct strategy.

In this respect, the medium term scheduling model offers the opportunity to insert ramping constraints on water level variations. Their aim is to reduce the rapid water level variations during hydropower operations. They can be applied along the whole year or just in specific periods, and they establish a threshold in water volume changes within an interval. Since there is few information regarding ecological impacts that would originate upgrading a traditional hydropower plant to a pumped-storage hydropower plant, it is difficult to know what could be the best solution. It is also true that ramping constraints limit the revenue of the hydropower plant itself, reducing operational flexibility [10].

For this reason, a test has been carried on, adding different constraints for the two reservoirs, for the full timeseries. For Roskreppfjorden, which is bigger, water level variations have been limited to 50 cm/day, while for Øyarvatn the limitation has been set to 10 cm/day. Limitations have been imposed both on traditional and pumping scheme. These particular ramping restrictions have been chosen based on results obtained on indices without ramping constraints. The reference point was the HYMO parameter **P.207**, that is, short term water level variations. As *Figure 5.9* and *5.10* have highlighted, there were a not negligible percentage of water level fluctuations in the range 0.5-1 m and also some portion in range 1-2 m per day, which means for the reservoir to be Moderately or Extensively Modified. To reduce them, chosen ramping constraints could be an effective solution also taking in account the different volume of the two lakes.

$$\textbf{Roskreppfjorden} \rightarrow R_{RAMP} = 50\ cm/day$$
$$\textbf{Øyarvatn} \rightarrow Ø_{RAMP} = 10\ cm/day$$

Using the same weekly inflow and prices for the scheduling model, but including the new ramping constraints, the new water level patterns for Roskreppfjorden and Øyarvatn are obtained (*Figure 5.44* and *Figure 5.45*).

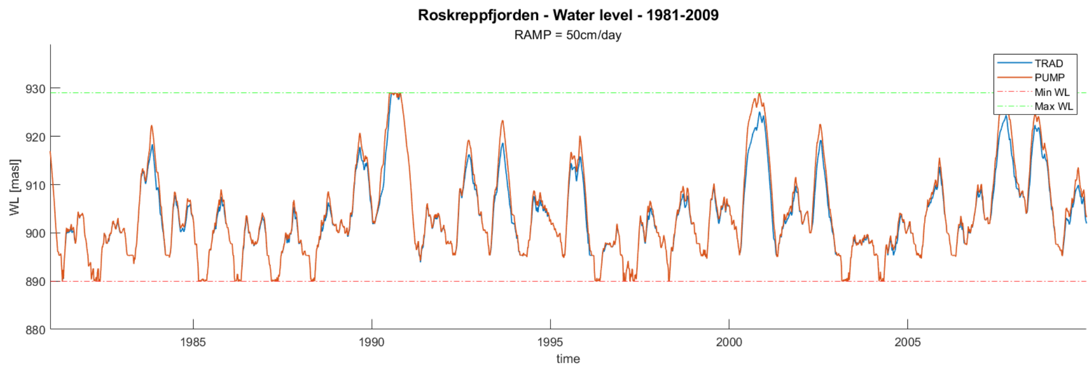


Figure 5.44: Roskreppfjporden: water level for period 1981-2009, ramping 50 cm/day.

The effect of the chosen ramping constraints on the two reservoir is clear. Comparing the new and the original pattern (*Figure 5.1* and *5.2*), this kind of constraint avoid continuously rapid water level changes, resulting in more gradual water level fluctuations.

The effect of imposing ramping constraints has been evaluated in terms of indices, considering both HYMO ones previously analyzed and some of the new proposed dewatered indices.

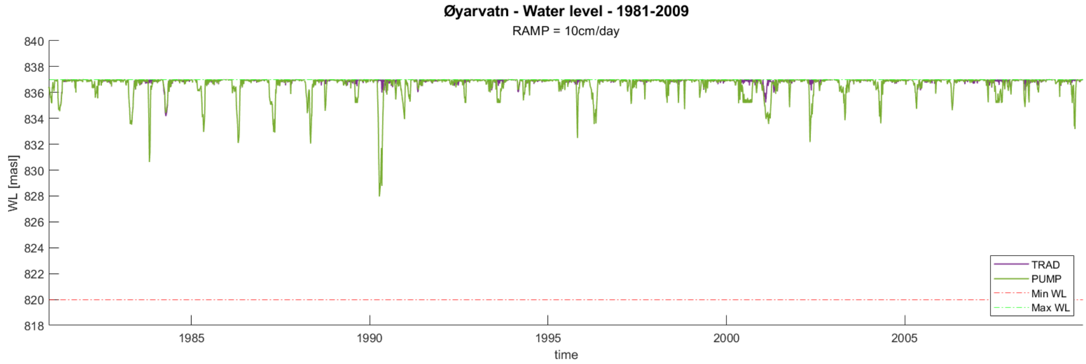


Figure 5.45: Øyarvatn: water level for period 1981-2009, ramping 10 cm/day.

First, a reduction in terms of daily water level variations (P.207) is measured, as show in *Figure 5.46* and *5.45*. This is in line with the ramping constraints. Results for positive and negative water level variations are similar to each other considering the two lakes. Especially for Øyarvatn, variations are almost all below 0.1 m/day both for traditional and pumping scheme, which means, the reservoir is classified as Near natural. For Roskreppfjorden, variations in range 1-2 m/day are no more present.

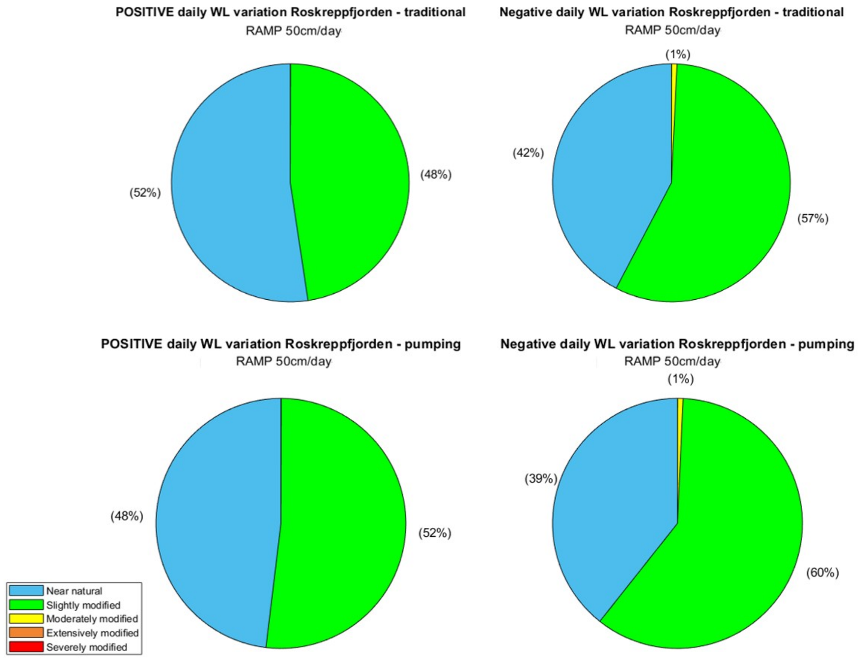


Figure 5.46: Roskreppfjorden: daily water level fluctuations period 1981-2009, ramping 50 cm/-day.

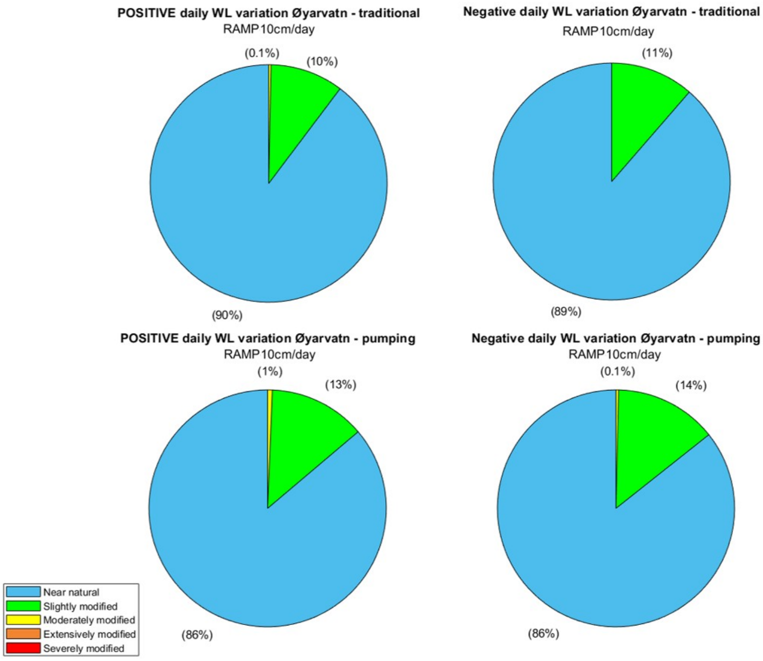


Figure 5.47: Øyarvatn: daily water level fluctuations period 1981-2009, ramping 10 cm/day.

Secondly, dewatered littoral zone versus total littoral zone **(P.212)** is evaluated. In this case, the effect of the ramping constraint is clearly. For Roskreppfjorden (*Figure 5.48*) the condition of an entirely dry littoral zone is barely reached during the whole timeseries. Moreover, conditions are much better for Øyarvatn (*Figure 5.49*). Since water level is near to HRV for almost all the time, dewatered littoral zone is, in this case, under 5% compared with the total.

The percentage of wet period compared with the entire analysed period **(Dew.1)** (*Figure 5.50*) and Median wet period for the entire series **(Dew.2)** (*Figure 5.51*) have been also considered. Since the two pattern for water level are very similar, there is no more evident difference switching from traditional to pumping mode. Even for median T_{wet}, the high contrast previously visible, especially for Øyarvatn, is now smoothed, even if some pixels with high elevation are a bit different coloured in the two cases. for Roskreppfjorden instead, looking at *Figure 5.51* where median T_{wet} is reported, some of the lowest areas in the regulation zone are wet almost all the year, condition that was not previously respected without any ramping constraint.

Interesting results are obtained considering pixels in the regulation area that are wet for a period 5-30 days more than once a year **(Dew.3)** (*Figure 5.54*). Roskreppfjorden, in this case, does not have pixels that behave like this, and for Øyarvatn there are only few examples in the entire regulation zone of pixels for which this condition is verified. These pixels are in the external part of the lake, around the HRV.

Counting the number of days for which water level in period November-March drops below minimum water level reached during October **(Dew.4)**, results for Roskreppfjorden are not so different from the condition without any ramping constraints. There is, on the other end, an improvement for Øyarvatn: both for traditional and pumping power plant, it is rare for water level in winter-spring going below water level in the autumn period more than 40-50 days. It is worth to notice that an improvement for Roskreppfjorden could be probably seen changing the type of restriction. In fact, even with a maximum water level variations of 50 cm/day, there are many situations during the full timeseries for which LRV is reached after the end of October. It is probable that a restriction on the minimum water level that could be reached would be more effective.

Plots in *Figures 5.55* and *5.56* show the median water level variations in the period March-April for 29 years. Even in this case, negative water level fluctuations are greater than positive ones. Moreover, they are lower than the ones simulated without any ramping constraints, which would be positive for the biological aspect mentioned before.

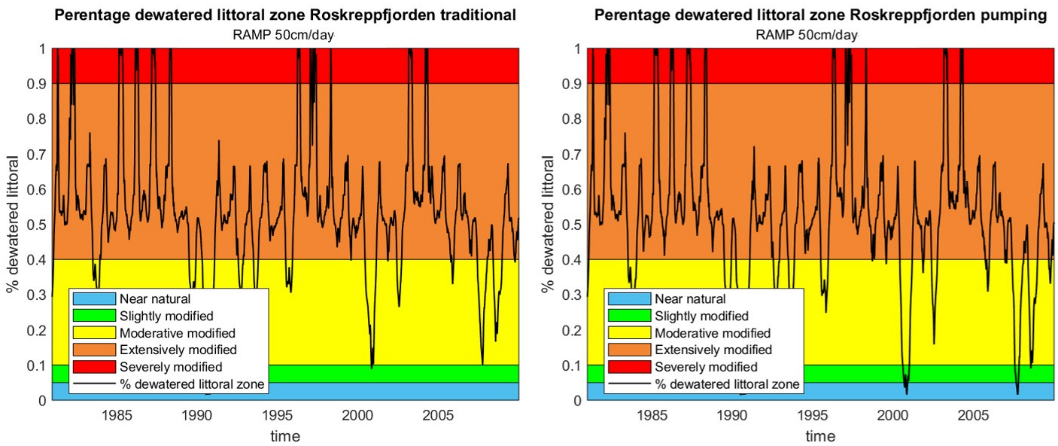


Figure 5.48: Roskreppfjorden, percentage dewatered littoral zone compared to the total littoral zone, period 1981-2009, ramping 50 cm/day.

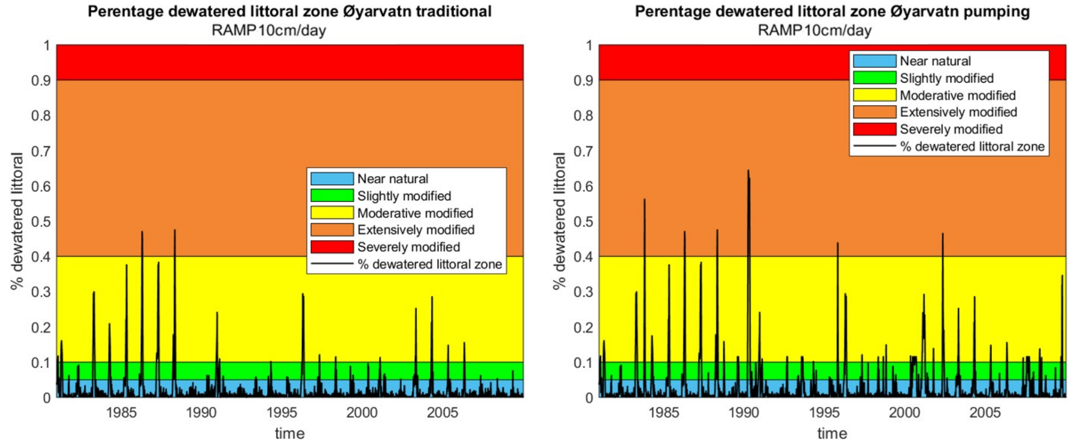


Figure 5.49: Øyarvatn, percentage dewatered littoral zone compared to the total littoral zone, period 1981-2009, ramping 10 cm/day.

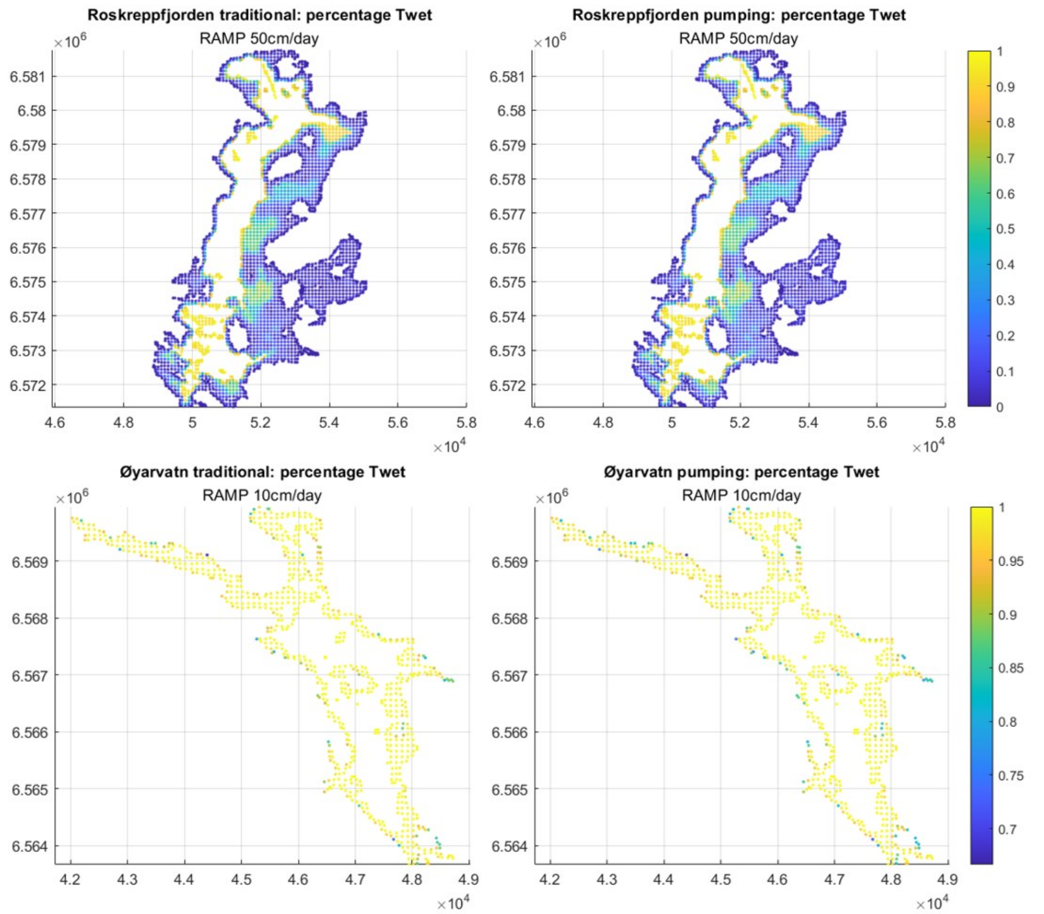


Figure 5.50: Percentage of wet period compared with the entire timeseries, period 1981-2009, ramping 50 - 10 cm/day.

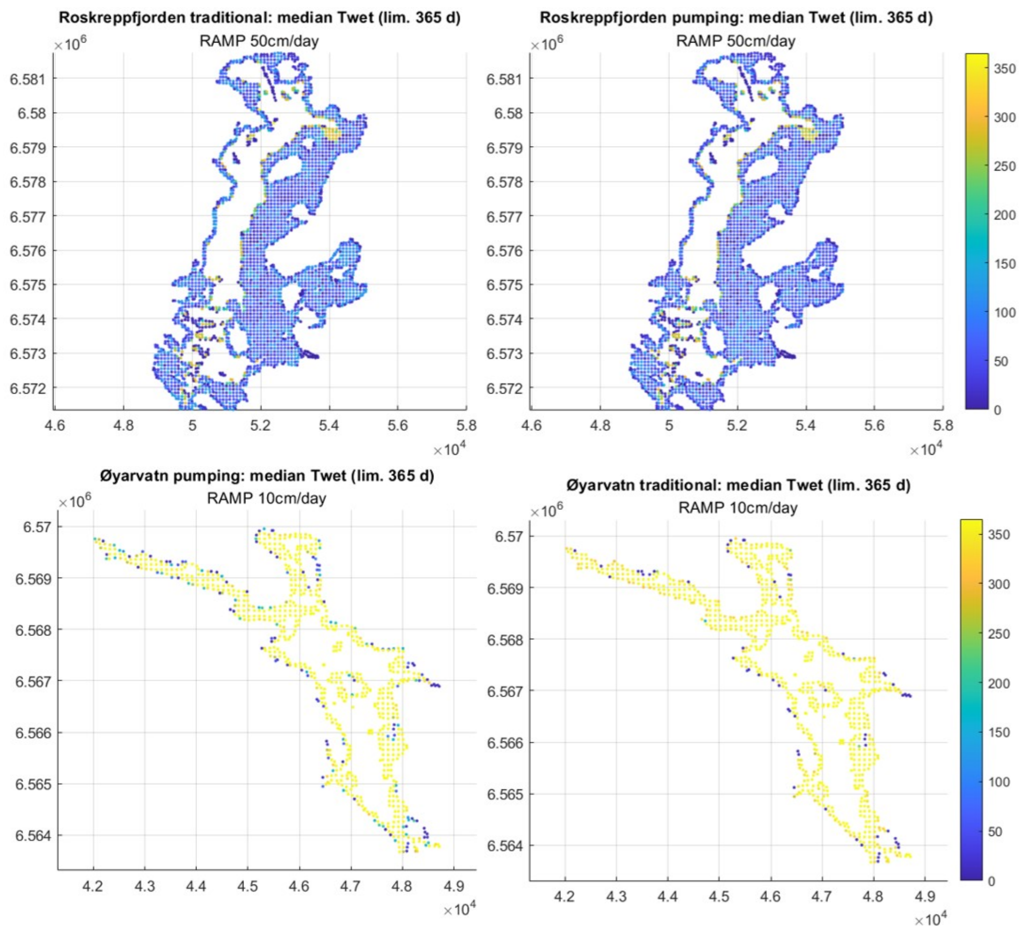


Figure 5.51: Median Twet (limit 365 days), period 1981-2009, ramping 50 - 10 cm/day.

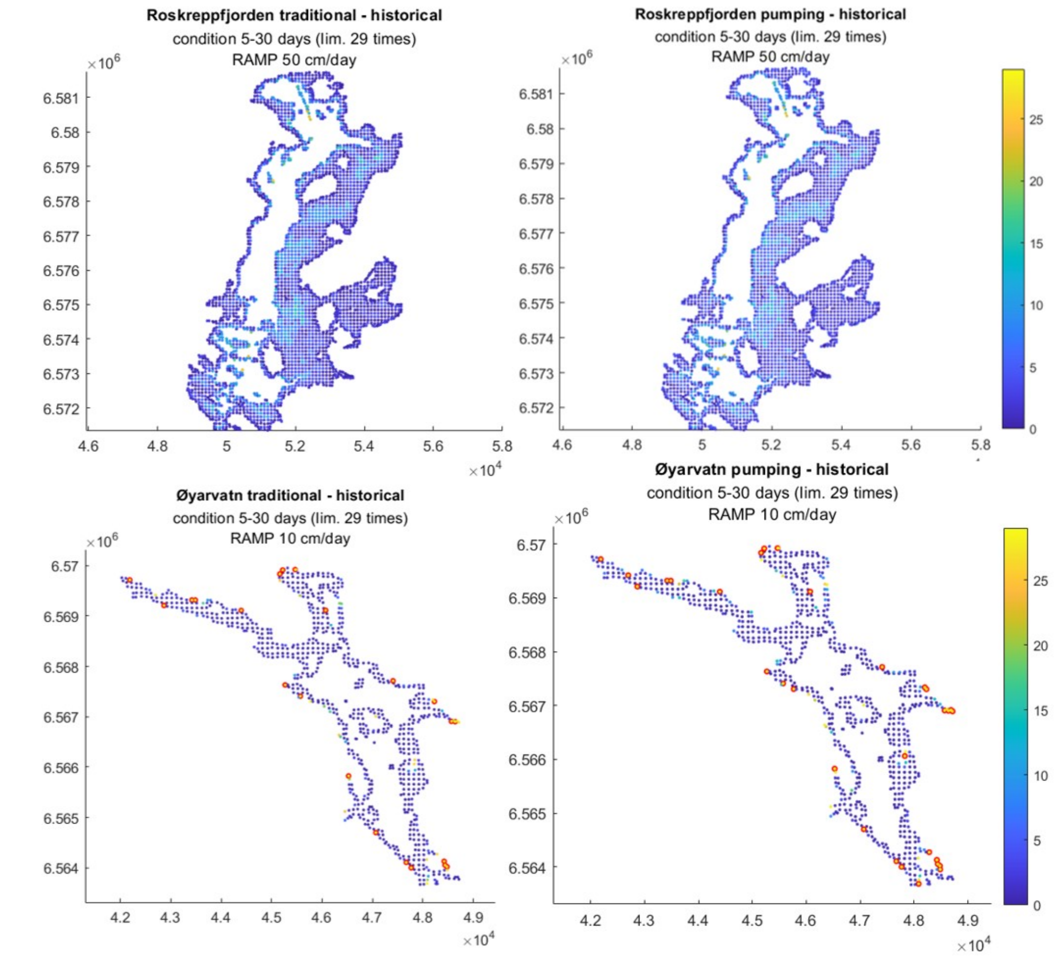


Figure 5.52: Condition 5-30 days (lim. 29 years), period 1981-2009, ramping 50 - 10 cm/day.

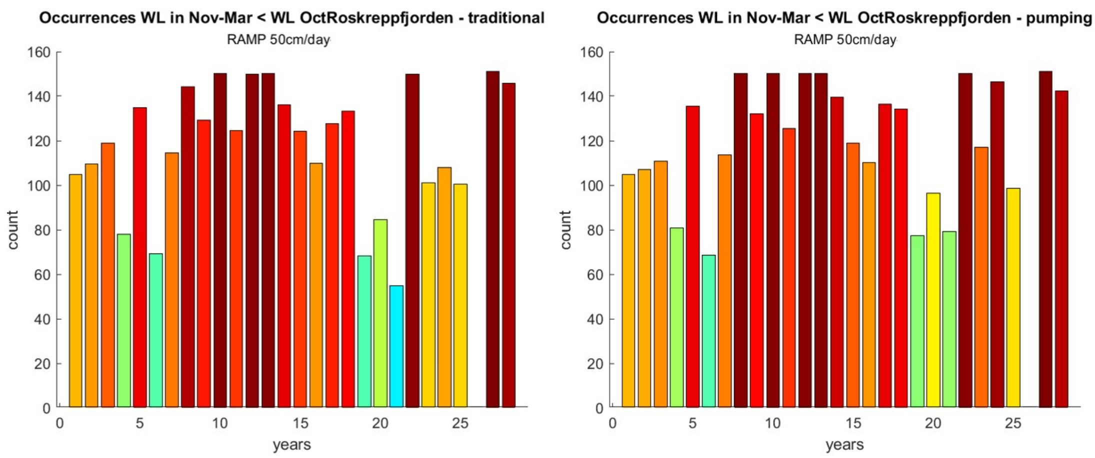


Figure 5.53: Condition 5-30 days (lim. 29 years), period 1981-2009, ramping 50 - 10 cm/day.

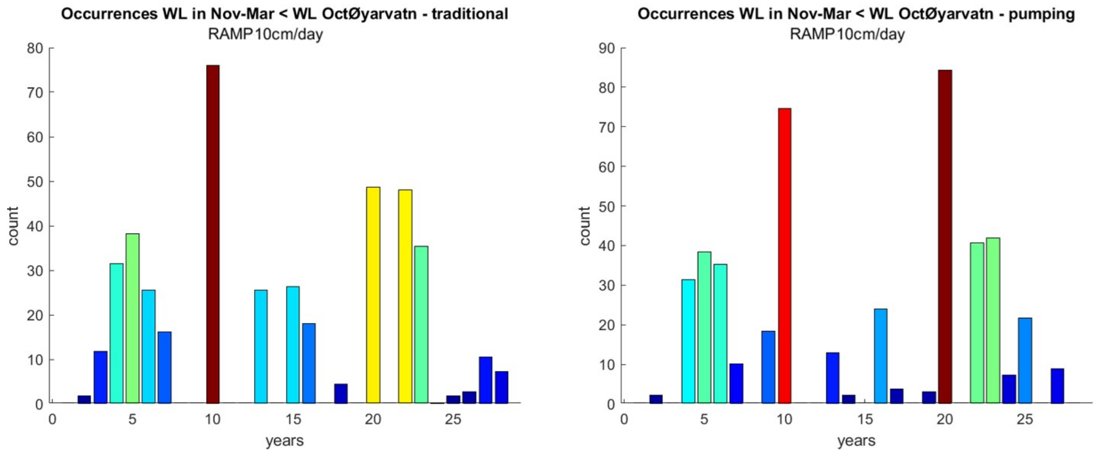


Figure 5.54: Condition 5-30 days (lim. 29 years), period 1981-2009, ramping 50 - 10 cm/day.

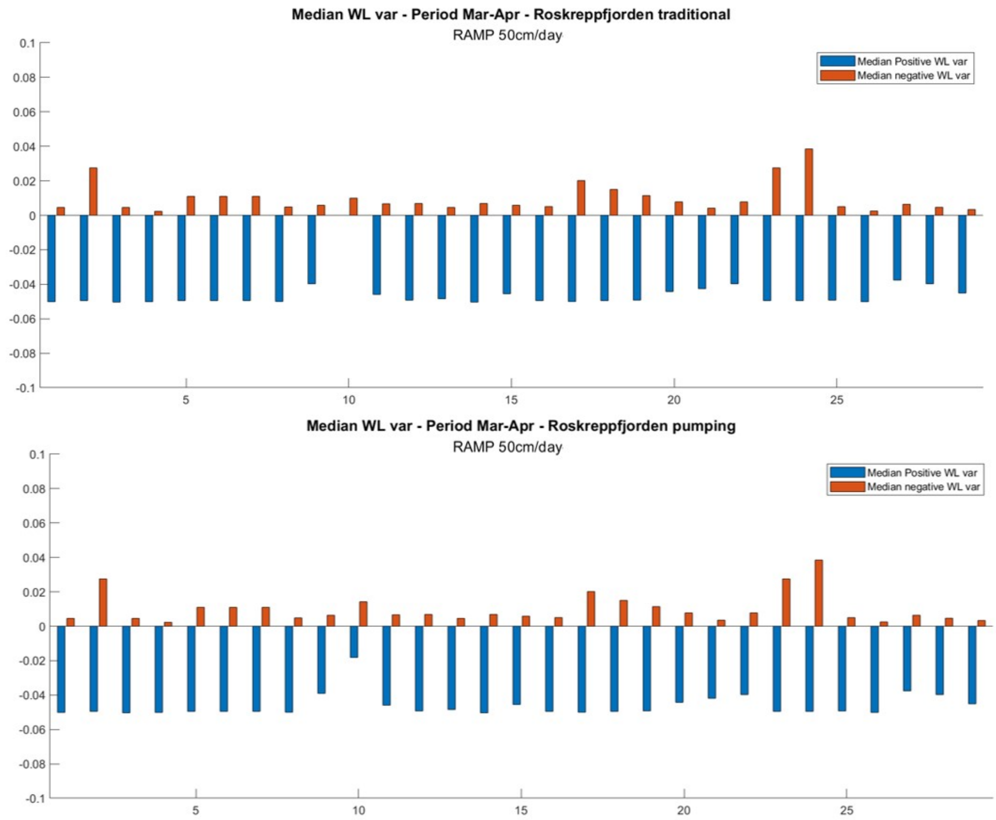


Figure 5.55: Condition 5-30 days (lim. 29 years), period 1981-2009, ramping 50 - 10 cm/day.

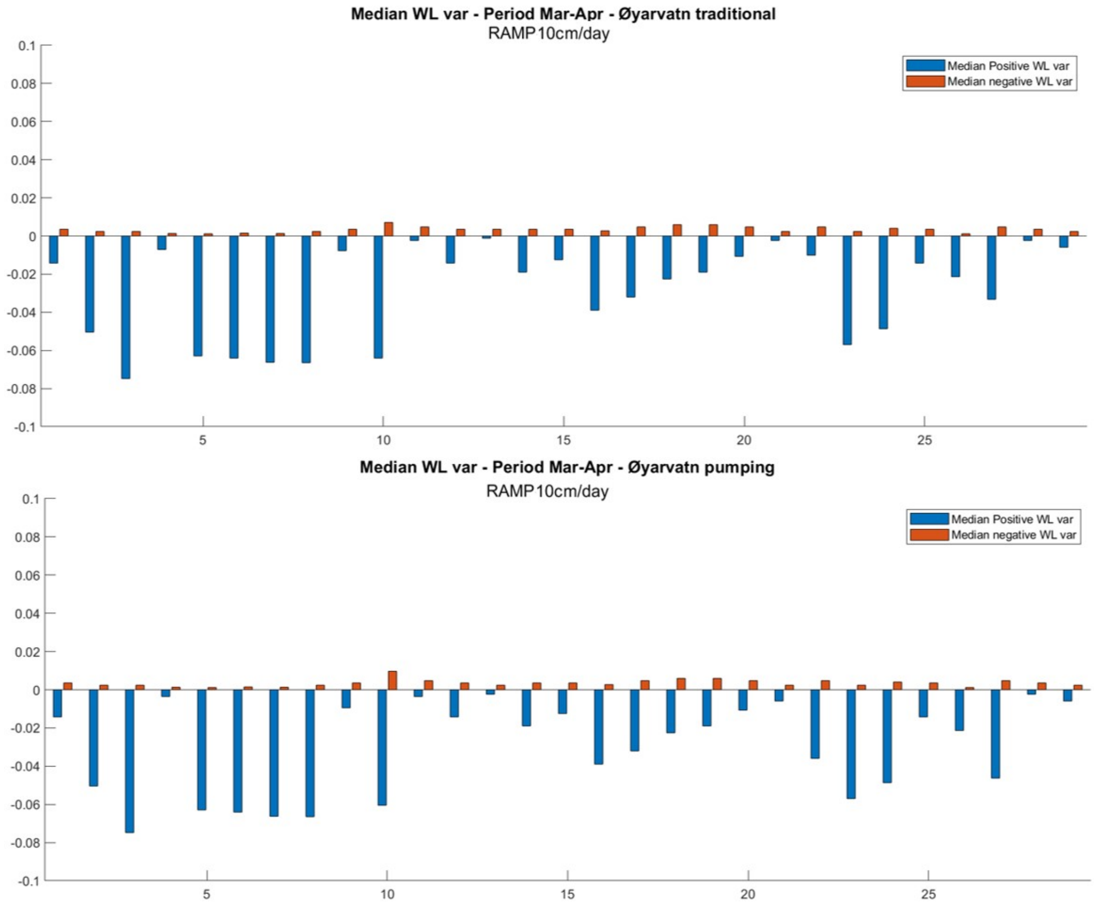


Figure 5.56: Condition 5-30 days (lim. 29 years), period 1981-2009, ramping 50 - 10 cm/day.

Chapter 6

CONCLUSION AND FURTHER WORK

Results of this research have shown how short-term water level fluctuations can have an impact on reservoirs in a hydropower plant, supposing it to work in traditional mode and pumping one and considering a specific case-study in Norway. The main evidence is that, without any kind of ramping constraints, the entire reservoir would be subjected to abrupt water level variations, whose intensity depends on its volume and morphology. It is also evident that energy prices are the main drivers of water level changes, determining the amount of water exchanged between the two reservoirs.

Another important evidence is that the smaller the reservoir is, the more impacted it results in terms of water level fluctuations. Combining this aspect with morphological data about the lake itself, e.g. with its bathymetry, and a timeseries of water level, it is possible to identify which areas within the regulation zone are more or less impacted. The environmental impacts can be evaluated in different ways, and here a classification currently in use in Norway (HYMO) has been proposed and applied. Further analyses have been carried out trying to set up new indices that could highlight differences in the two operational setups (traditional and pumping) regarding dewatered areas and water level variations. The aim is to provide a simple method to evaluate and compare environmental impacts for different scenarios. Results show that pumping operation in the smaller reservoir will reduce the area of the regulation zone impacted. In addition, using adequate ramping restrictions could help to increase renewable energy production. It is worth noticing that the proposed indices do not consider the production of the hydropower plant itself, which is an important aspect of the analysis. So a future improvement of the method, in this respect, could be to set up indices that also take into account the production factors and revenue that can come from the hydropower operations and the reduction in the use of fossil fuels, for instance, together with environmental impacts on the reservoirs.

Another important aspect that has been highlighted is that short-term water level fluctuations can cause large variations in the wet area of the reservoir over time, and examples regarding this aspect have been shown. This information can be precious when coupled with data related to the biological activity in the reservoir. Very often, the range of the hydropower regulation overlaps with biologically important littoral areas, even if the amplitude of the littoral zone can vary a lot depending on the degree of regulation from the reservoir and the reservoir itself. Knowing, for example, potential areas where fish lay their eggs in spawning period, when the spawning period is and how long it takes for eggs to hatch, it is possible to cross hydromorphological data with water level timeseries and a 'spawning map' to identify areas that need to be protected or mitigated. These areas can be targeted and restrictions for example during this critical period could be implemented. Not only for fish, but also for plants and invertebrates that can be an important component of the complex ecosystem within the reservoir. For example, even if spawning habitats have been previously studied for the two most common fish species in Norwegian reservoirs, brown trout (*Salmo trutta*) and Artic char (*Salvelinus alpinus*) [11], still, it is not well understood what are the most critical factors that define a potential spawning area. The proposed indices in combination with a better understanding of the characteristics and identification of spawning and juvenile fish areas can help in establishing necessary mitigation measures to protect habitat and species where needed.

Indeed, the present work has highlighted that inserting ramping constraints on water level variation for the operations between the two reservoirs could help reducing impacts on shoreline areas. Positive effects of ramping constraints have been evaluated with the same parameters proposed for the previous analysis. It is important to remember that limitations on water level fluctuations have been chosen to improve ecological status of the reservoirs, without considering their effects on power production. For further research, this aspect also should been taken in account, in order to choose appropriate constraints based on the specific case study.

Thank to future climate projections and with the help of an hydrological model, scenarios of changes in inflows have been defined for the future, generated from modifications in precipitation and temperature patterns. This can influence hydropower production, since inflows are connected with the water volume available for hydropower operations. In this work, a combination of global and regional climate model has been chosen to define scenarios up to2050. When looking at average values, results are not that different between the historical and future scenarios. However, results are more evident when looking at the shorter time resolution data. It will also be interesting to analyse climate scenarios' effect on hydropower production in the future. This following-up task will be carried out under the HydroConnect project, where inflows under climate scenarios for the different reservoirs in the Sira-Kvina system will be considered. Furthermore, impacts on price variability from climate change will also be considered at the national level and taken into account. This will enable to investigate how the power plants could optimize their future production strategies, taking into account climate change and environmental restrictions. Further analysis could also include all the available climate models.

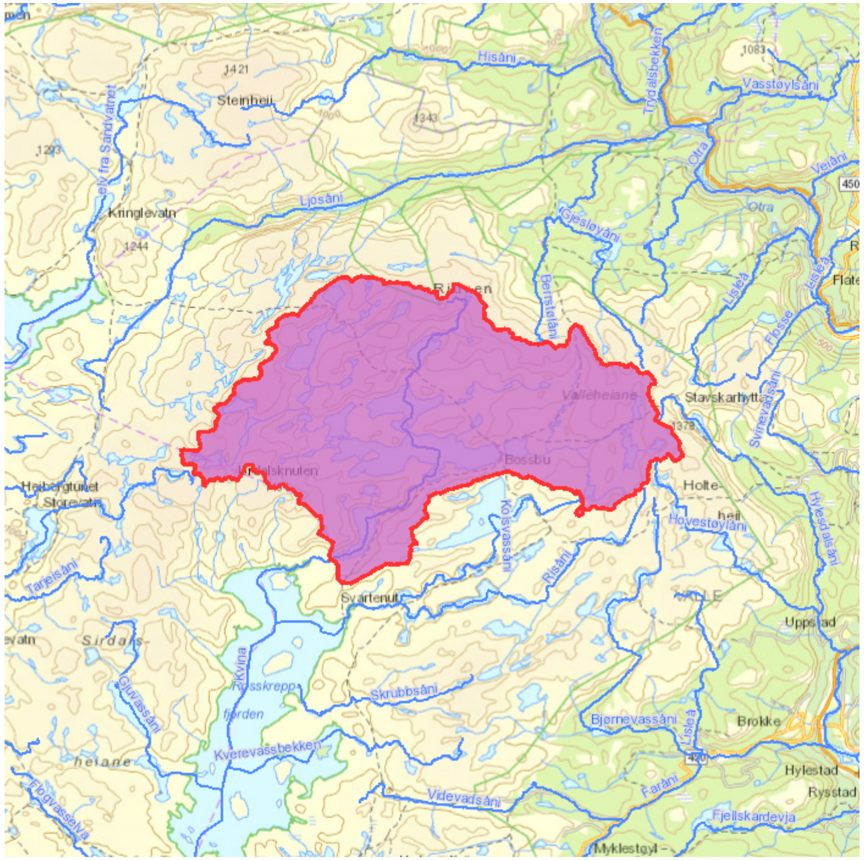
In summary, this research has shown how combining different modelling approaches (hydrological and hydropower optimization models), using various tools such as GIS and already implemented and new indices, can support environmental analyses for hydropower reservoirs. Results following the approach presented in this study will provide valuable information about the potential impacts under different hydropower operational types and evaluate potential environmental restrictions such as ramping rates.

Appendix A

Chatchments: field parameters

A.1 Morphological characteristics of catchments

- NEVINA pdf page for Gjuvvatn catchment
- NEVINA pdf page for Roskreppfjorden cathment



Norges vassdrags- og energidirektorat

NVE

Kartbakgrunn:	Statens Kartverk
Kartdatum:	EUREF89 WGS84
Projeksjon:	UTM 33N
Beregn.punkt:	54536 E 6581979 N

Nedbørfeltgrenser og feltparametere er automatisk generert og kan inneholde feil. Resultatene må kvalitetssikres.

Nedbørfeltparametere

Vassdragsnr.:	025.M2
Kommune.:	Sirdal
Fylke.:	Agder
Vassdrag.:	Kvina

Feltparametere

Areal (A)	97.0	km²
Effektiv sjø (A_{SE})	7.06	%
Elvleengde (E_L)	15.3	km
Elvegradient (E_G)	28.6	m/km
Elvegradent $_{1085}$ ($E_{G,1085}$)	12.5	m/km
Helning	11.5	°
Dreneringstetthet (D_T)	3.6	km^{-1}
Feltlengde (F_L)	12.8	km

Arealklasse

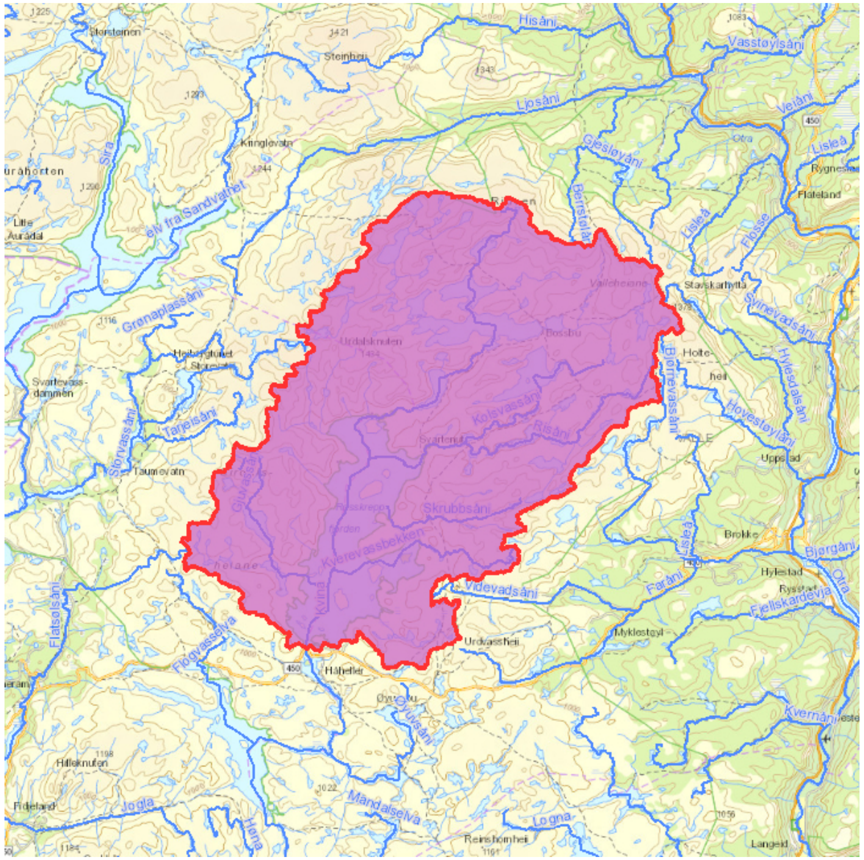
Bre (A_{BRE})	0	%
Dyrket mark (A_{JORD})	0	%
Myr (A_{MYR})	0.9	%
Leire (A_{LEIRE})	0	%
Skog (A_{SKOG})	0	%
Sjø (A_{SJO})	17.1	%
Snaufjell (A_{SF})	82.1	%
Urban (A_U)	0	%
Uklassifisert areal (A_{REST})	0	%

Hypsografisk kurve

Høyde $_{MIN}$	950	m
Høyde $_{10}$	1020	m
Høyde $_{20}$	1040	m
Høyde $_{30}$	1074	m
Høyde $_{40}$	1105	m
Høyde $_{50}$	1138	m
Høyde $_{60}$	1175	m
Høyde $_{70}$	1218	m
Høyde $_{80}$	1271	m
Høyde $_{90}$	1313	m
Høyde $_{MAX}$	1430	m

Klima- /hydrologiske parametere

Avrenning 1961-90 (Q_N)	65.3	l/s*km²
Sommernedbør	500	mm
Vinternedbør	827	mm
Årstemperatur	-0.1	°C
Sommertemperatur	5.1	°C
Vintertemperatur	-3.7	°C



Norges
vassdrags- og
energidirektorat

Kartbakgrunn:	Statens Kartverk
Kartdatum:	EUREF89 WGS84
Projeksjon:	UTM 33N
Beregn.punkt:	49733 E 6571278 N

Nedbørfeltgrenser og feltparametere er automatisk generert og kan inneholde feil. Resultatene må kvalitetssikres.

Nedbørfeltparametere

Vassdragsnr.:	025.K22
Kommune.:	Sirdal
Fylke.:	Agder
Vassdrag.:	Kvina

Feltparametere

Areal (A)	271	km²
Effektiv sjø (A_{SE})	4.84	%
Elvleengde (E_L)	29.8	km
Elvegradient (E_G)	16.6	m/km
Elvegradent $_{1085}$ ($E_{G,1085}$)	6.4	m/km
Helning	10.2	°
Dreneringstetthet (D_T)	3.3	km^{-1}
Feltlengde (F_L)	23.3	km

Arealklasse

Bre (A_{BRE})	0	%
Dyrket mark (A_{JORD})	0	%
Myr (A_{MYR})	3.6	%
Leire (A_{LEIRE})	0	%
Skog (A_{SKOG})	0.1	%
Sjø (A_{SJO})	21.9	%
Snaufjell (A_{SF})	74.4	%
Urban (A_U)	0	%
Uklassifisert areal (A_{REST})	0	%

Hypsografisk kurve

$Høyde_{MIN}$	879	m
$Høyde_{10}$	932	m
$Høyde_{20}$	977	m
$Høyde_{30}$	1020	m
$Høyde_{40}$	1041	m
$Høyde_{50}$	1074	m
$Høyde_{60}$	1108	m
$Høyde_{70}$	1146	m
$Høyde_{80}$	1193	m
$Høyde_{90}$	1263	m
$Høyde_{MAX}$	1430	m

Klima- /hydrologiske parametere

Avrenning 1961-90 (Q_N)	66.7	l/s*km²
Sommernedbør	511	mm
Vinternedbør	865	mm
Årstemperatur	0.1	°C
Sommertemperatur	5.6	°C
Vintertemperatur	-3.8	°C

Appendix B

Optimization scheduling model: results

B.1 Optimization model

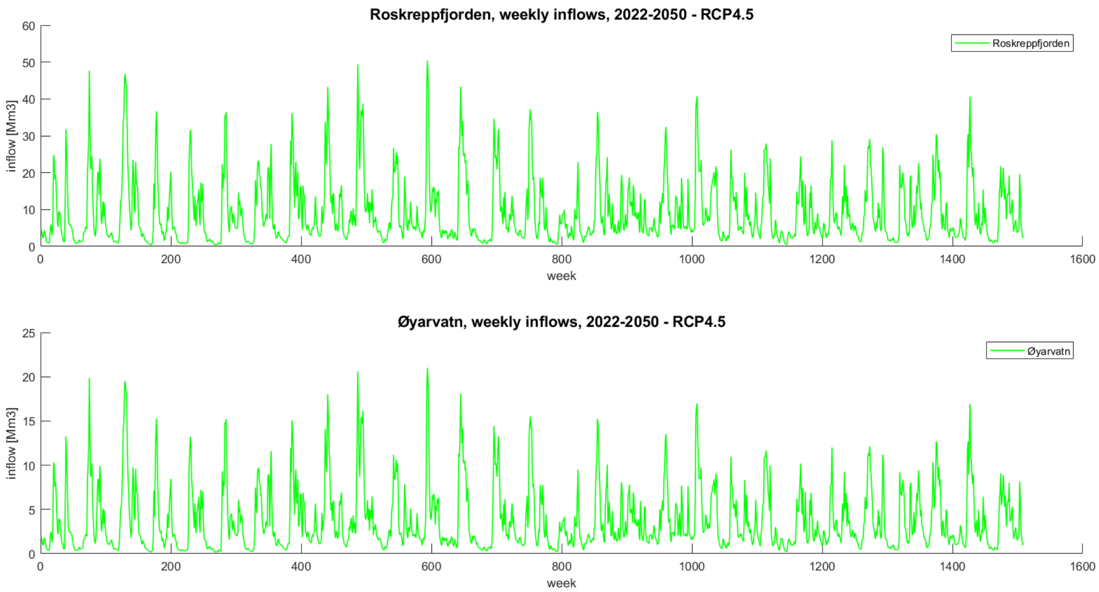


Figure B.1: Weekly inflows - years 2022-2050 - RCP 4.5

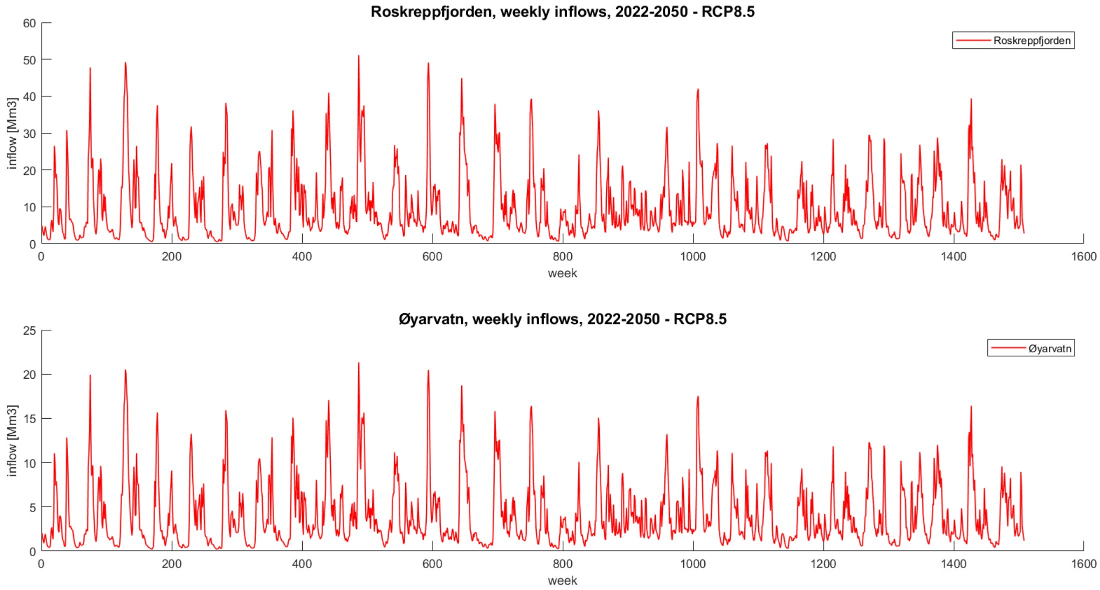


Figure B.2: Weekly inflows - years 2022-2050 - RCP 8.5

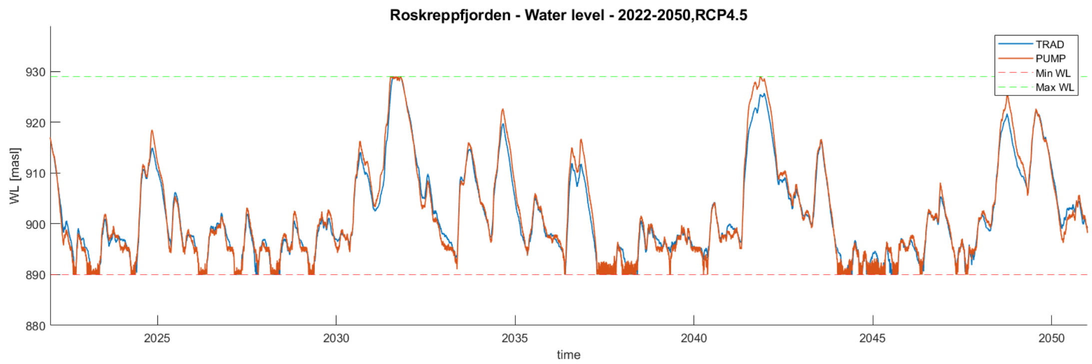


Figure B.3: Weekly inflows - years 2022-2050 - RCP 4.5

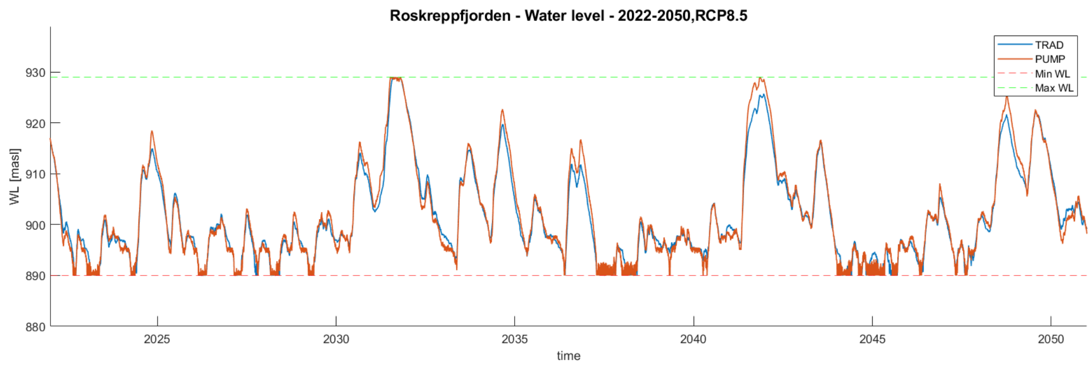


Figure B.4: Roskreppfjorden - Water level, 2022-2050, RCP 8.5

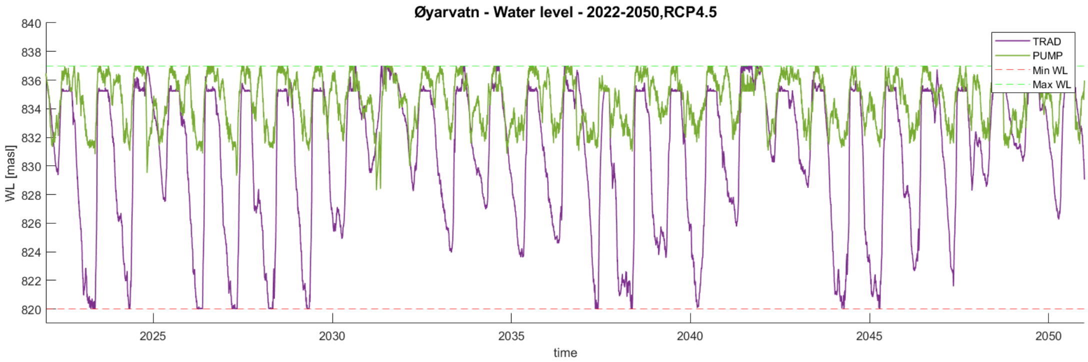


Figure B.5: Øyarvatn - Water level, 2022-2050, RCP 4.5

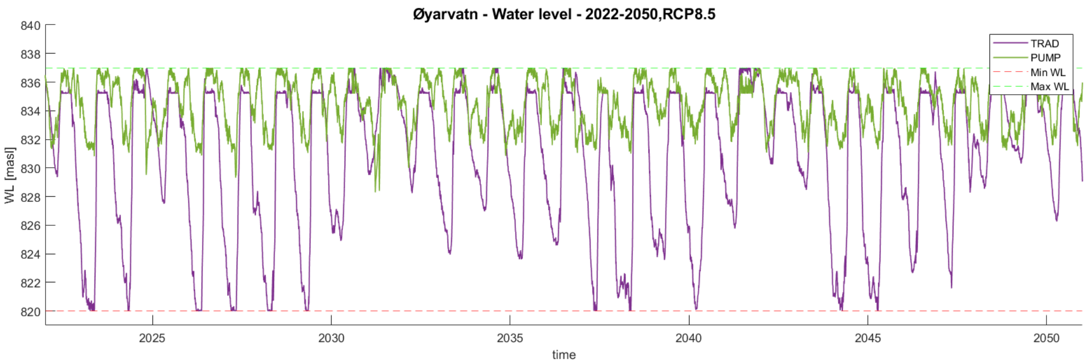


Figure B.6: Øyarvatn - Water level, 2022-2050, RCP 8.5

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