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Environmental Impacts of Pumped Storage Hydro Power Plants

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Hydropower Development
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BACKGROUND

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Norway has a large number of high head power plants with large reservoir capacity. With an increasing focus on non-storable renewable energy, pumped hydro power is gaining interest as a possible mechanism for load balancing in the future energy system. By producing from stored water in periods with low input from other renewable sources and then pumping water back up during periods with surplus power, the Norwegian hydropower system could provide an important volume of the necessary balancing power in the future system. Frequent pumping may influence the environment in the reservoirs and there are a number of issues that is not well researched in the Norwegian system. The purpose of this thesis is to do a review on available literature of environmental impacts of pumping hydro and investigate these for a Norwegian case.

OBJECTIVES

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1. Carry out a literature review of environmental impacts due to fluctuating reservoir levels. The review should be on two levels, a broad scope review of all potential impacts, and a more narrow review focussing on ice conditions.

2. Evaluate Totak as a possible site for the study. The evaluation should be based on data availability, potential for pumping and the potential for environmental impacts as assessed in task 1.

3. Model pumping behaviour at the study site to establish the physical effects of the pumping operation (range, duration and frequency). This task will provide the water level and withdrawal rates required for task 5.

4. Make an initial assessment of potential lake models for assessing ice regime. If no existing model fully meets the requirements, the potential for implementing code for this physical phenomena should be further evaluated.

5. Study the effects of pumping on ice formation, ice cover stability and possible break-up and refreeze at the study site.

Supervisor: Knut Alfredsen, with co supervisor Ånund Killingtveit on modelling peaking.

ACKNOWLEDGEMENT

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Filip Patocka Trondheim, June 2014

ABSTRACT

Massive development of new renewable energy sources is taking place all over the world in 21st century and Europe is not an exception. Wind turbine parks are being planned and built on shore, in coastal zones and in the seas of European countries.

With such a development of renewable sources comes a challenge of stable and continuous supply of electrical power which meets the demand. Renewable energy sources often have power output which cannot be easily regulated according to demand, but are rather fully dependent on forces in nature, such as a wind speed for wind power turbines, or solar radiation for photovoltaic solar modules. This problem has to be handled in order to ensure the safe and reliable operation of electricity grid in the future, which is capable of connecting the renewable energy input.

This thesis is a continuation of suitability exploration of a current Norwegian hydropower system as so called the Green battery of Europe. This balancing system could secure the planned European wind power projects during situations when the production is larger than the demand by storing energy in upper reservoirs using pumping storage hydropower. During conditions when the demand is larger than generated energy the extra input can be produced by Norwegian hydropower system as well.

The specific focus of this thesis is on evaluating the potential environmental impacts on Totak reservoir in Telemark county in Norway, caused by development of pumping storage hydropower. This hydropower plant is considered as a part of the system balancing the power output from TradeWind project, which is a wind power capacity scenario project for year 2030 consisting of 94,6GW of installed capacity in the North Sea in Belgium, Denmark, Germany, UK, Netherlands and Norway.

During the work in this thesis, model of pumping storage hydropower plant between Totak and Songavatnet reservoirs was used to calculate characteristics of operation as water level fluctuation characteristics, transferred water volumes and other characteristics for two variants of installed power output within period of 2000-2006.

Results of the pumping model were used to model the changes in temperature regime and ice formation of Totak reservoir. This was done by MyLake model developed by Norwegian Institute for Water Research in Oslo and further modified at

NTNU for usage in reservoirs. With this so called MyLakeR model I modelled the temperature regime and ice cover in period of 2000-2006 for both current situation and situation after developing the pumping storage hydropower.

This thesis provides the required complete hydrological forcing from pumping storage hydropower plant to the environment. Actual evaluation of impacts is often dependent on particular data which has to be collected on site, therefore only evaluation of potential impacts was done when the relevant data were available.

Pumping model has proven to be a powerful and reliable tool. MyLakeR model showed that the modification done on a lake model allows successful modelling on more complex sites such as Totak reservoir. It also showed that for an ice routine of the model there is a need for further adjustments in order to model the ice cover regime affected by pumping storage hydropower.

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LIST OF ABBREVIATIONS

CEDREN	Centre for Environmental Design of Renewable Energy
EU	European Union
HPP	Hydropower plant
HRWL	Highest Regulated Water Level
LRWL	Lowest Regulated Water Level
NVE	Norwegian Water resources and Energy directorate
PSH	Pumped Storage Hydropower plant
UK	United Kingdom
WL	Water Level

1. Introduction

Norway is a country where most of electrical energy is obtained from hydropower plants. A usual Norwegian hydropower system consists of high head power plants with large reservoir capacity.

Norway's large potential for hydropower generation is an asset, as European electricity markets are integrating and variable renewable energy generation is set to increase. More cross-border interconnections are needed to realise the full potential of hydropower for balancing variations in demand and supply in the regional market. Increased interconnections would also improve electricity security in Norway in times of low hydropower availability.(1)

There are currently a lot of initiatives headed into promotion and development of more renewable energy sources in all countries of European Union in order to fulfil climate and energy targets known as "20-20-20", which has three key objectives:

- A 20% reduction in EU greenhouse gas emissions from 1990 levels;
- Raising the share of EU energy consumption produced from renewable resources to 20%;
- A 20% improvement in the EU's energy efficiency. (2)

To fulfil these goals, there is a need for installing new renewable energy sources. *Wind power will make up much of Europe's future power generation. Several major projects are already being constructed and planned on the Continent, in the North Sea and along the UK coast line.*(3) The important fact worth mentioning is that renewable energy sources are a challenge in delivering the goal of stable and reliable energy supply.

The problem with wind power generation is that the generation is not connected with current needs which are decided by consumption, but rather by variations in wind intensity which are of course not controllable based on human needs. This variation results in the demand for balancing the power:

- There is a need for energy sources which can start fast within a short period of time when the demand is higher than output of energy sources in the system. For instance, when the wind is not blowing or is less intense, the output from wind powered farms will be smaller than required or predicted.

- On the other hand when the wind is blowing strongly, which is equivalent to high power generation from wind farms and at the same time with no actual use for this excess energy, due to variation in demand – there is a need for storage capacity for this so called surplus power.

There are many possible solutions in order to deal with this problem. One important, but only a partial solution is better and stronger connection of electricity grid between European countries. The effect of geographically dispersed renewable energy sources is a feasible way for reaching more stable energy output.

Due to the wide regional distribution of wind plants, short-term and local wind fluctuations are not correlated and therefore largely balance each other out. As a result, the maximum amplitudes of wind power fluctuations experienced in the power system are reduced. This phenomenon has been extensively studied throughout Europe. (4)

Spatial distribution and trade between different countries due to improved energy grid is helpful, but it is not enough. There is a need for technical solutions which can generate the lacking energy and/or store the surplus energy.

One possible solution is a pumping storage hydropower plant.

2. Norwegian hydropower system

Hydropower is an environment-friendly and renewable energy source. In Norway, 99 percent of all power generation is hydropower. Worldwide, hydropower contributes around one sixth of the total electricity supply.(5)

The advantages of hydro are many – it is renewable, it is clean, it is reliable, it is flexible and can serve many generations with low-cost electricity from a local resource.(6)

Norwegian hydropower system is capable of fast generation of energy on demand. Furthermore, there is a big opportunity of not just generation of energy when needed, but also relieving the network of surplus power due to high generation or low demand. This opportunity is exploited by using pumping storage hydropower plants, which doesn't have to be constructed on new sites; hence Norway already has an extensive system of high head hydropower plants with regulated reservoirs. Reservoir capacity in Norway is actually half the capacity of whole Europe. (3) Pumping storage systems can be developed on these already regulated reservoirs and in this way create the so called "Green battery" of Europe.

2.1. Norwegian hydropower plants

The classical hydropower plant in Norway is characterized by a high head hydropower, where energy is gained from flow of water being processed over the big elevation difference between the water level of the reservoir at the intake site and the water level of the water body at its outflow. This elevation is often in range of hundreds to thousands of meters. Energy is gained using gravitational force from drop in height of the flowing water. This water is usually stored in a reservoir created by constructing a dam at a feasible location or by using or expansion of a natural lake. From the reservoir, the tapped water is transported via a water way – penstock, shaft or usually a tunnel system to a power house, where the water creates an impact on a turbine and thus causing physical movement which is then converted to electrical energy using a generator.

It is also common that such hydropower plants are positioned in a cascade, so that they benefit from several reservoirs as shown in Figure 1. This way the energy is harvested multiple times before the river finally joins a sea.

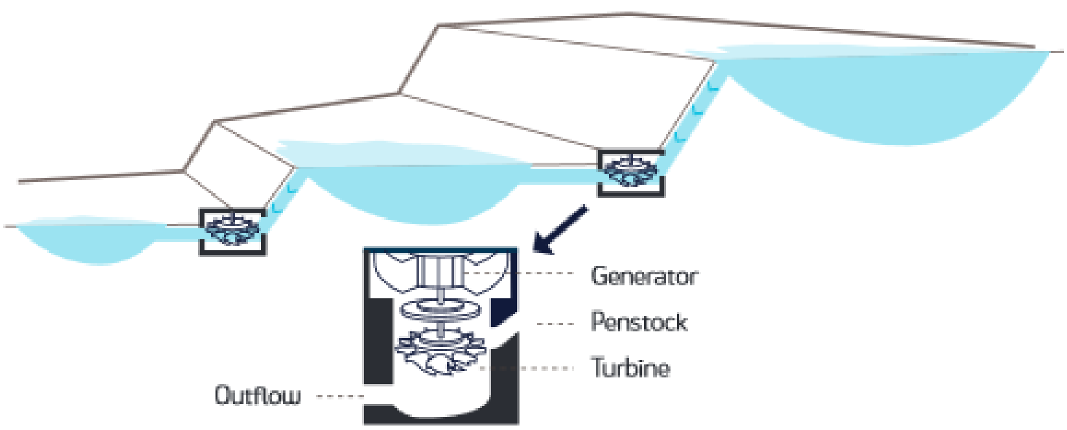


Figure 1 – Several storage schemes with hydropower positioned in a cascade (6)

A typical Norwegian hydropower system consist of a reservoir built using a dam over a natural lake, and the water being tapped by an unlined tunnel system leading to the underground power house cavern, thus creating a large height difference. Hence, by making use of the height difference rather than big water flow, the water is then passed on to Pelton or Francis turbines and subsequently sent to the receiving water body by a tailrace tunnel.

2.2. Norwegian reservoirs

As mentioned earlier, almost 50% of the capacity of European reservoirs is located in Norway. Reservoirs used for production of energy using hydro power plants are operated between both high and low operation water level. In some cases this span can be within the range of tens of meters.

This regulation span depends on the size of the reservoir, reservoir purpose, climate, weather conditions, water availability in the region and also operation plan for the reservoir to meet the required demands.

With the high head hydro power plants and its reservoirs used for water storage, fluctuation of a reservoir level in Norway is mainly seasonal – water level is low in the beginning of spring when waiting for water from the melted snow. On the other hand water level is high during or after autumn, when there are no chances of greater inflow due to the falling temperature and the change of precipitation from rain to snow. Thus the water in a catchment area becomes snow. Then the reservoir is usually full and ready to meet the demand during the winter season.

3. Pumping storage hydropower

Pumping storage hydropower is a regular hydropower plant with the capability of producing electricity using the downward water flow caused by gravity. The difference from conventional hydropower plant is that this water can be also pumped the other way too, i.e. consume the energy which is in surplus in a distribution network and store it as water allocated in an upper level reservoir. Schematic representation of such a pumped storage hydropower is shown in Figure 2.

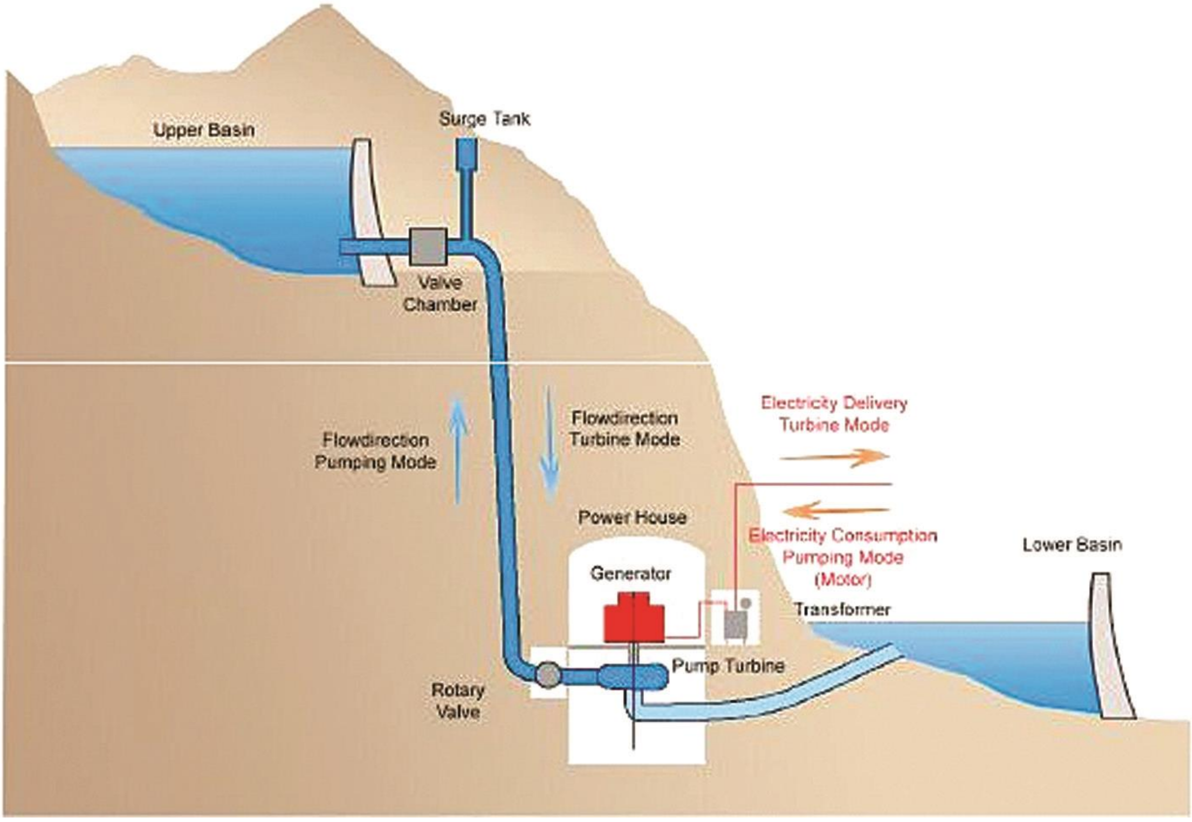


Figure 2 – Pumped storage hydropower scheme (7)

As mentioned before, Norway with its reservoir capacity and developed hydropower system qualifies as a great candidate for installing large capacity of pumping storage systems without the need for creating new reservoirs and new hydropower schemes.

First pumped storage hydropower projects were introduced in the end of 19th century in Alpine region – Switzerland, Austria and Italy. (8)

The earliest designs use separate pump impellers and turbine generators. Since the 1950s, a single reversible pump-turbine has become the dominant design for PSH. The development of PSH remained relatively slow until the 1960s when utilities in many countries began to envision a dominant role for nuclear power. Many PSH facilities were intended to complement to nuclear power for providing peaking power.(8)

In the 1990s, the development of PSH significantly declined in many countries. Many factors may have contributed to the decline. Low natural gas prices during this period made gas turbines more competitive in providing peaking power than PSH.

Environmental concerns caused the cancellation of several PSH projects and significantly prolonged the permitting process. (8)

Despite the above mentioned factors against PSH, there are still a lot of plants being operated all over the world and they are gaining interest again with new renewable energy sources and new promising approaches of using or developing PSH.

In Europe there is a number of pumped storage hydropower. Their function is usually focused on balancing the variations in daily electricity consumption as shown in Figure 3. The green colour symbolizes the surplus power in a distribution grid which is used for pumping operation. The red colour on the other hand shows the energy produced by peaking energy operation. This distribution during the day is also reflected in the prices of electrical energy, which is cheapest at night and most expensive in peak hours during morning and evening.

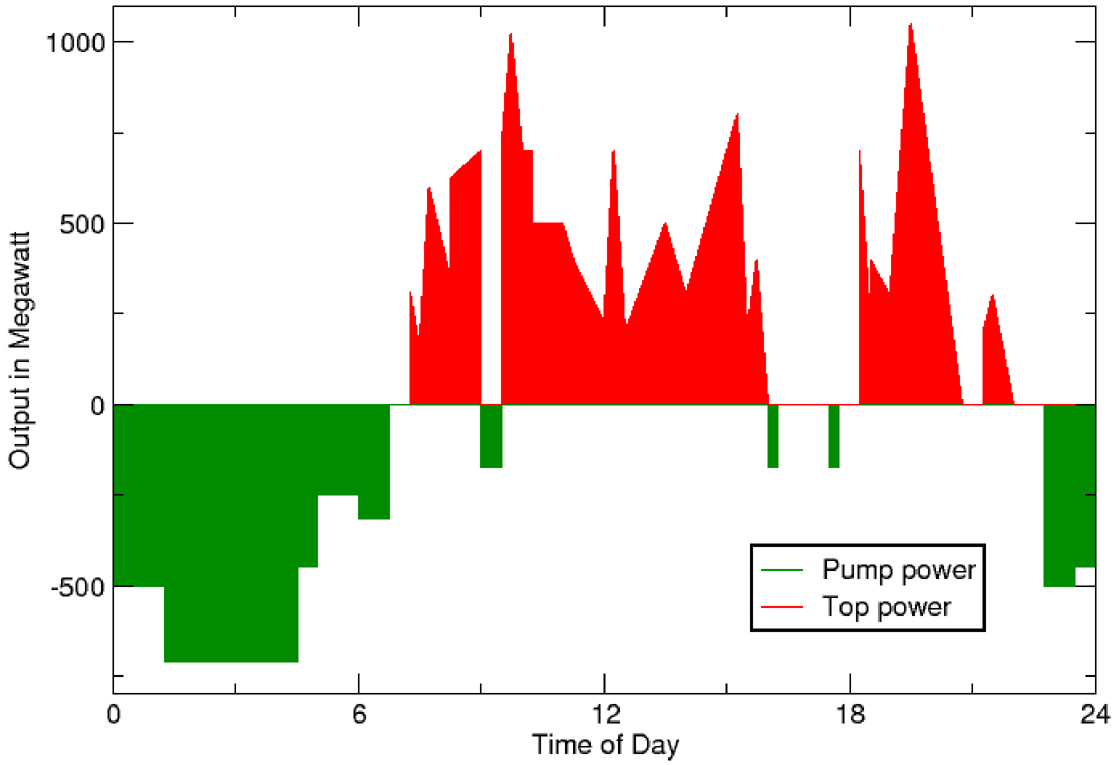


Figure 3 – Variation in a daily demand resulting in common PSH operation (9)

In Norway, there is no need for this operation because the Norwegian hydropower system can be easily regulated and the power output can therefore be adjusted according to demand. However there are some PSH operated in Norway, but they are used for covering seasonal lack of energy because there is no need for daily operation.

Indications suggest that this situation is going to change by producing more energy from non-regulated energy sources like wind power or solar power, which are both being installed extensively in Europe since the past few years.

There has been studies to see how the wind power generation, which is being built rapidly, will affect the stability of the network (for example in year 2008 the new installed wind energy was the most installed power generation technology in Europe, reaching the total of 64GW of installed power).(10)

The TradeWind project is the first EU-level study to explore the benefits a European grid with better interconnections and an improved power market design can have on the integration of large amounts of wind power.(10)

TradeWind's medium wind power capacity scenario for year 2030 consist of offshore wind power generation of 94.6 GW (94,600 MW) installed capacity in the North Sea, consisting of Belgium (3.0 GW), Denmark (5.6 GW), Germany (25.4 MW), UK (43.3 MW), Netherlands (12.0 GW) and Norway (5.4 MW). (11)

Such an installed power output of unregulated energy source will have to be connected to technologies capable of balancing this output, in order to meet the demand of the market. There is clearly a need for technology capable of producing peak power and storing of surplus power.

As visible from the Figure 4, there is a good match between consumption, estimated wind power generation and inflow to Norwegian reservoirs which is being redistributed only by storage in reservoirs and few pumping storage hydropower.

Pumping storage hydropower plants are capable of both energy generation and storing. Building is very feasible in Norway because there is no need for creating new hydropower schemes. It is feasible to achieve a new installed power reaching 20 000 MW by the year 2030, half of which can be made by pumping operation just by utilising the current concessions that exist, extending the possible use of the upper and lower reservoirs conditionally if the robustness of the existing systems allows it. (11)

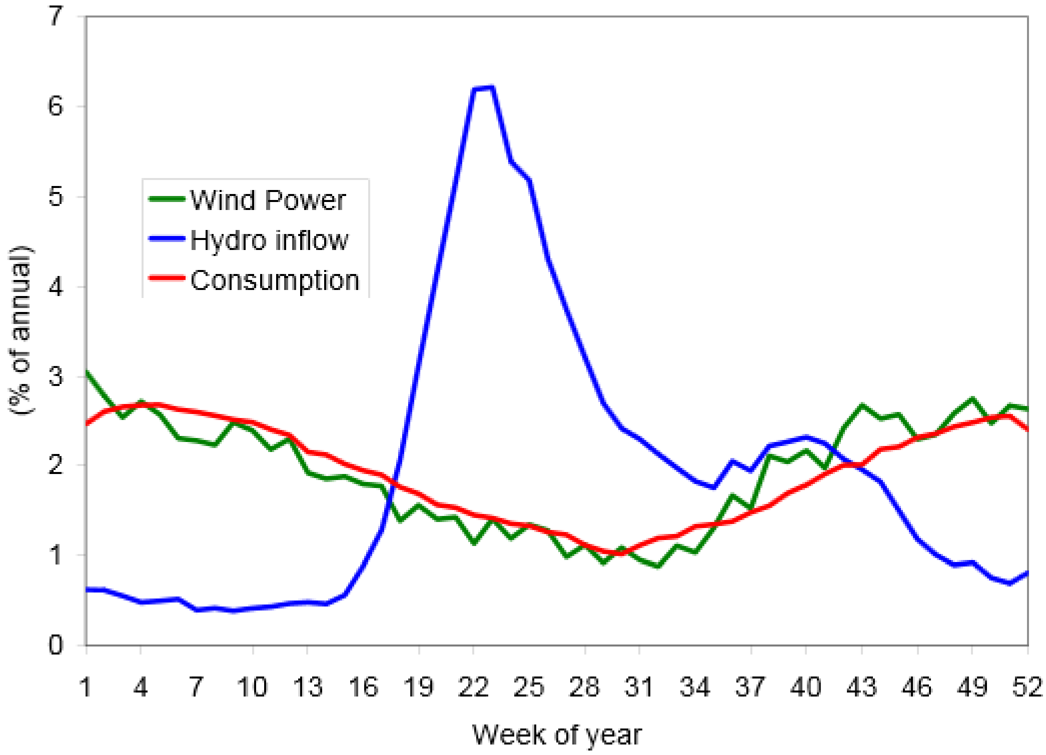


Figure 4 - Expected week by week variation in wind power production, compared with consumption and hydro inflow (12)

4. Possible environmental impacts caused by fluctuating reservoir levels

When we change the function of reservoir from a seasonal, yearly or multiple year storage into a reservoir used for a pumping storage hydropower plant, as is a potential case for many Norwegian hydropower plants, we will face smaller but more frequent fluctuations in the reservoir level within a shorter period of time. Rates of withdrawal or addition of water in reservoirs for a pumped hydro will vary mainly due to operation with relation to energy market and situation in the electricity grid, and it could also vary according to variation of water inflow, water demands and water availability in the region.

Fluctuation of reservoir water level is affecting reservoir and its surroundings in different ways. The topic of this thesis narrows the impacts to just the environmental ones.

Environmental impacts in general covers a broad area of possible impacts, which may or may not arise when dealing with water level fluctuations in reservoir.

The question is not whether the environment is impacted, as much as to what is the degree of positive and negative impacts. While hydropower projects have been proven to cause substantial impact to various sectors of the environment, it is also known to have created substantial benefits to other sectors. Hydropower projects are often multi-purpose in nature, meeting multiple needs of society in areas such as flood control, assurance of a firm water supply, recreational benefits, as well as energy production. If the costs of acquiring those benefits include some changes in the natural environment, then the decision to move forward, or not, is a societal one based on a population's value system. (13)

Consequences of environmental impacts occur when specific sites are vulnerable to those impacts. In other words, we first need to find out which environmental impacts can arise in our study site, and then evaluate if they can cause any harm. If yes, we should find out the possible ways to eliminate or at least reduce those impacts to some reasonable level.

Environmental impacts caused due to introducing pumped storage scheme instead of conventional high head hydro power plants depend on the frequency and range of water level changes.

Possible environmental impacts of fluctuating reservoir levels can be categorized into more groups as following.

4.1. Physical impacts

Physical impacts are impacts to a physical part of environment due to human activity or natural phenomenon.

The construction of a reservoir at the location of a natural lake or along a river necessitates a complex environmental assessment. In the case study mentioned below reservoirs are already built, impacts were mitigated and we now focus on what will happen when we change a function of the reservoir by introducing a pumping regime. The reservoir could then face changes as described in the following subchapters.

4.1.1. More rapid and frequent water level changes

Big reservoirs built for conventional high head hydro power plants behave as long term storage – seasonal, yearly or even multiple year storages. Fluctuations of water levels then mainly have a seasonal pattern, which means low levels during spring with the capacity of storing more water from melted snow within a catchment, and high levels during autumn for fulfilling a power demand during the coming winter season.

On the other hand reservoir for pumped storage hydropower will deal with short term fluctuations on weekly, daily or even hourly basis. The driving force behind those fluctuations is the demand for pumping operation (for storing of energy) or production of energy in the electric grid. As a result there will be more rapid and more frequent change of water level going up and down within shorter periods of time compared to gradual and quite slow water level changes in the absence of pumping operation (except for non-regular events like strong rain – fast and significant increase of water level, same happens when there is a sudden big increase in temperature during winter causing the snow to melt).

4.1.2. Changes in reservoir filling over the year

Usual reservoir filling for normal hydropower system, which means high head hydropower system, is represented in Figure 5. In this figure is visible that over the last three years (from long term point of view the pattern is same as for those 3 years) the filling of reservoirs used for hydro power production follow a strong seasonal pattern. Reservoirs are full in the end of autumn. They are being filled by melting snow starting usually in the end of April and by rain events during the summer. From the end of autumn, the level of water in the reservoir gradually decreases owing to energy production without having a big inflow to replenish the storage. During winter, all or almost all precipitation is stored as a snow within the catchment and inflow to reservoirs is therefore minimal.

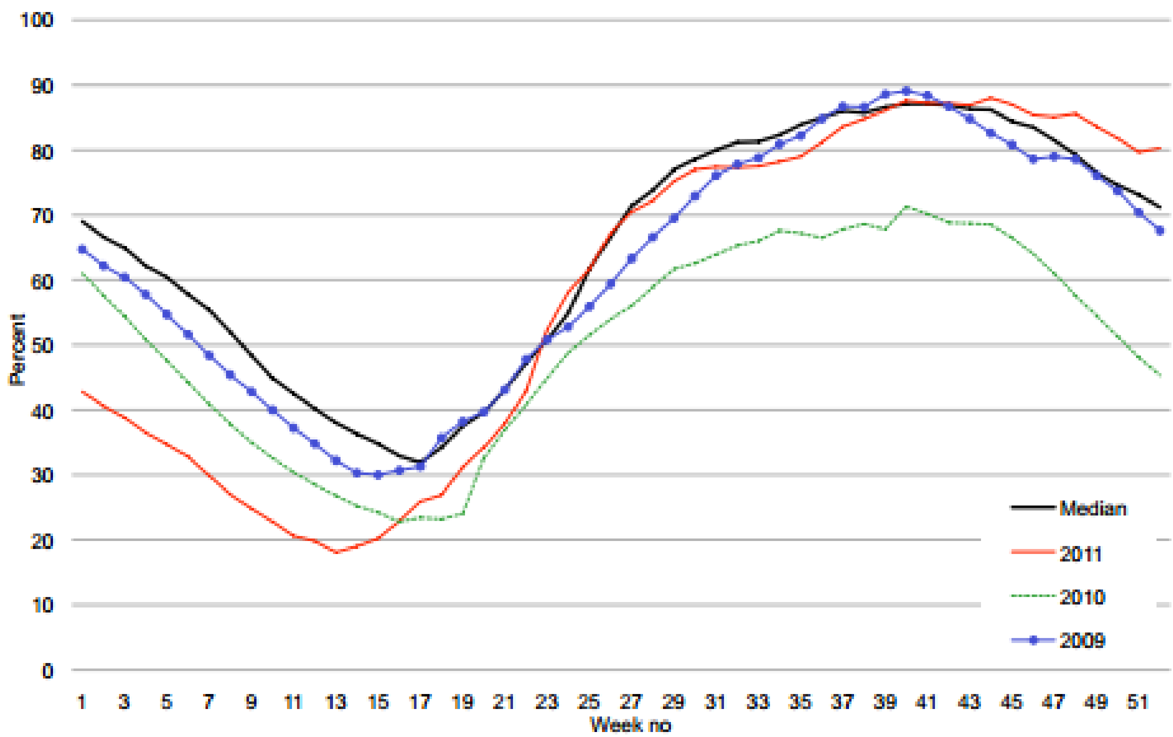


Figure 5 -*Reservoir filling for Norwegian hydropower reservoirs*. (14)

When introducing the pumping function instead of the current situation of production where water is flowing through hydro power only one way – downwards, we will face more water level changes as we have already discussed. When pumping, we need to have enough water in both reservoirs – both for pumping and energy production. Then it is very likely that, during a summer season when water level in reservoirs is usually low, with help of pumping we can return some water to upper reservoir after the usual energy generation, so both the reservoirs – upper and lower one – will have higher water level in the end, which would be an improvement over the current situation.

4.1.3. Reduction in permanent wetted littoral zone on short term basis

During the pumping operation and normal generation of energy, there is a big volume of water being transferred from one reservoir to another which leads to an increase or decrease of water level. Because demands for operation can differ within a short period of time, change of operation from pumping regime to producing one can happen quickly and even multiple times within a day. This behaviour leads to short term reductions of permanently wetted littoral zone when the water level is going down.

Littoral zone as shown in Figure 6 is defined as "*an area on the edge of reservoirs inside and outside of water, which is usually distributed to 4 zones – wooded wetland, wet meadow, marsh and aquatic vegetation*."(15)

Part of littoral zone which is permanently wetted in current situation (or wetted for a long term by seasonal filling of reservoir), will be reduced due to the fact that fluctuation of water will be greater.

What is very important in this case is morphology of the reservoir. Reservoirs with very steep banks will have small reduction of area of littoral zone; on the other hand reservoirs with mild slopes of banks will have this effect over a much bigger area.

Figure 6 – Littoral zone, Totak reservoir (16)

4.1.4. Changes in circulation patterns

In normal reservoirs there are circulation patterns which change when the surrounding conditions change. They are dependent on temperature of water in the reservoir and inlet, water temperature distribution over the depth, also flow conditions at inlet – speed and volume.

Because of pumping, flow and temperature conditions will change compared to the standard regime. To evaluate the changes it is important to determine flow patterns and velocities. Knowledge of inflow and outflow rates, their frequencies and durations for natural inflow to the reservoir and also operation – both pumping and regular production – are equally important. Thus together with morphology of the reservoir we can then for example model original circulation patterns and afterwards their changes from pumping operation. Similar approach was used for 2-dimensional hydrodynamic-temperature model at Cherokee reservoir, Tennessee. (17)

4.1.5. Changes in water temperature and ice formation

Thermal and density stratification is a phenomenon that occurs in almost all lakes and reservoir impoundments in cold regions. (18)

The thermodynamics and ice cover dynamics of a freshwater lake or reservoir are governed by meteorological forcing that determine the surface heat flux and the inflows and outflows of water.(19)

A reservoir is essentially different from a natural lake due to complexity associated with dynamic outflows.(20)

Reservoirs which will have not just regular hydropower operation, but also pumping operation, have even higher amount of dynamic outflows and inflows. That means that the water temperature and ice formation are going to change by introducing pumping operation.

The water temperature and ice formation changes in Totak are analysed in chapter 7; consequences of pumping operation to water temperature and ice formation are discussed in chapter 8.1.5 of this thesis.

4.1.6. Stability of reservoir banks

In reservoirs for hydropower use, man-made impoundments are characterized by filling-drawdown operations. These operations are determining cyclic pore water pressure variations and, as a consequence, influence stability conditions of the reservoir banks over time.(21)

Stability of reservoir banks may not be endangered just by water pressure variations, which leads the conditions out of equilibrium, but what is also important is the erosion due to wave exposure.

As the water level variations will be more rapid and frequent by introduction of PSH, the water pressure variations will also be much faster and bigger, which can lead to instability of the reservoir banks.

Studies show that fast withdrawal rates causing approximately 60% of landslides is not the only problem, but also the increase of water level which accounted for the rest 40% of the landslides.(22)

There were a number of methods developed for evaluation of slope safety, which can be used or adjusted for evaluation of reservoir bank stability due to water level fluctuations.

Strength reduction method as a development of finite element method was used for analysing the influence of water level fluctuation on slope safety. (22) Upper bound method of limit analysis method was also used for analysing the influence of decrease in water level to slope safety. (22) Other method was created by deriving "*an analytical solution of the phreatic line in the slope full of water and the simplified calculation formula of the slope phreatic line when the water level decreases. These outcomes could determine seepage pressure, and slope safety could then be calculated.(22)*

The following conclusions were arrived at:

- *The slope safety factor decreases first and then increase as the water level increases. Minimum value is reached when the water level increases to 40% - 50% of the HRWL in the slope range.*

- *When the soil condition follows a drained behaviour and as the reservoir water level decreases, the slope safety factor decreases first and then increases. Based on initial estimates the minimum value is around 50% of the HRWL.*

- *With the decrease in water level, the slope safety factor in an un-drained behaviour would be 10% less than in a drained because excess pore water pressure exists when the soil condition follows an un-drained behaviour.*

- *If the excess pore water pressure in the soil is considered, the water level decreases faster and the smaller the slope safety factor becomes, which can negatively affect the slope the most. Thus, to maintain the stability of slope, the fluctuation in water level should be kept to a minimum when draining the water off.*

- *During similar conditions, the smaller the permeability coefficient, the worse the slope stability would be as water level decreases. (22)*

The important characteristics for slope stability are created by geological conditions in the area which creates a need for geological survey.

Stability of reservoir banks is important for limitation of erosion and therefore sedimentation of reservoir, protecting of surroundings, countryside and reservoir structures.

Landslides in the catchment area of reservoir has proven to be very dangerous in history, for example a massive landslide in 1963 into the reservoir during the filling stage caused the flood wave to overtop the Vajont Dam in Italy and resulted in the death of 2000 people. (23)

4.1.7. Changes in landscape

Reservoirs used for hydropower purposes, both natural and artificial, are important part of the nature. When developing reservoirs, it is usually quite a challenge to mitigate the changes in landscape in order to be acceptable to all affected organizations, communities and authorities.

Since the reservoirs are already developed and hydropower plants are operating, all impacts were by smaller or larger scale mitigated in study case in this thesis.

The question is – what will happen to landscape when introducing pumping system instead of conventional hydropower?

Operation will not allow changing the water level beyond the boundaries of regulation, so there are not many changes in means of danger for landscape and objects located above the highest regulated water level. During special situations like floods, the danger can be decrease or increase with respect to the change of water level compared to the previous operation regime.

Landscape can be changed by shoreline erosion or accumulation of floating material caused by water level changes.

Short term exposure of littoral zone due to drawdown of water level can cause unwanted aesthetical impacts.

Needed increase of capacity of the transmission lines can lead to installation of new transmission lines or rehabilitation and increased capacity of current ones.

4.2. Biological Impacts

Biological impacts of hydropower are complex, but also is quite an explored topic. Impacts are different for each case and have to be studied thoroughly. Even after such a study, there is sometimes an impact which was not expected and has to be handled during implementation of the project.

Although reservoirs are generally planned to solve one or more primary problems such as a need for hydro-electric power, their construction generates innumerable secondary problems, many of which have proved serious.(24)

Organisms are physiologically, anatomically, morphologically and behaviourally adapted for survival in a specific habitat. Thus the destruction or creation of such habitats can either lead to the elimination or multiplication of relevant species, often with chain –reactions on other dependent or competing species. (25)

In already developed hydropower system, biological impacts are supposed to be handled through mitigating measures. This has to be studied for each single reservoir before going into possible impacts caused by changing a regime into pumping hydro.

The clear results of this change were already discussed in this thesis – namely, more frequent and rapid water level changes and much higher volumes of water travelling in and out of reservoir.

Volumes of water are not just bigger, but there is also a change in orientation of the water flow. Conventional hydropower like Norwegian high head systems have one flow direction – water is coming down to reservoir by natural way or from an outlet of a hydropower station. After that, it continues further down through outlets of a dam, other tunnel system or in flood occasions by spillway.

By introduction of pumping operation in those reservoirs we will force big masses of water to go from lower reservoir to upper one using reversible pumps. This can lead to several biological impacts.

The importance should not be just put to lower and higher reservoir, but change in operation can cause impacts also in natural water way between these reservoirs, and downstream of a dam of lower reservoir.

4.2.1. Higher risk for spreading of species

When large volume of water is going to travel upwards from a lower reservoir to the upper one, we face increased risk for spreading of species – also exotic once, which can have huge consequences.

Because water is travelling through reversible turbines under high pressure from the column of water above it, conditions for organic species are quite tough. Larger species like fish or water animals cannot survive passing through turbines (mentioned below), but those ones which are small enough, for example small aquatic macrophytes, phytoplankton like algae, zooplankton and even small macro-invertebrates like crayfishes, shrimps or snails can be transferred from lower reservoir to upper one. This way they reach new ecosystem, which they wouldn't be able to reach without pumping operation. In some cases if conditions for them are good enough to develop or reproduce, they can spread over upper reservoir and even continue against the natural river flow. This can lead to significant reduction or even extinction of current flora or fauna in ecosystem of upper reservoir and its surroundings.

There are some cases where this has happened:” *Experience from Norway (Sandsfjorden)suggests (but does not prove) that the poisonous planktonic alga Prymnesiumparvum (which has caused the death of a large number of fish in marine fish farms) has increased due to the altered water regime arising from hydropower development.”(25)*

Due to the cold climate in Norwegian mountains during winter, the risk of fast spreading of algae, which is a big problem in lakes located in warmer climate, is significantly reduced.

4.2.2. Impacts on biological production in littoral zone

Due to more frequent and rapid drawdown of water level within the regulated boundaries there will be reduction in permanent wetted littoral zone on short term basis as discussed in chapter 4.1.3 of this thesis.

The importance of morphology of the reservoir was also discussed, as that is a factor which influences the size of the littoral zone.

Relevant areas of 4 zones discussed also in chapter 4.1.3 – wooded wetland, wet meadow, marsh and aquatic vegetation does not depend just on the profile of a shoreline, but also upon past water levels as (26) says.

In general, the area of wet meadows along lakes and rivers increases with natural water level fluctuations. Many of the animals in lakes and rivers are dependent upon the wetlands of littoral zones, since the rooted plants provide habitat and food. Hence, a large and productive littoral zone is considered an important characteristic of a healthy lake or river.(26)

When creating a reservoir from natural lake by constructing a dam at the outlet, we stabilize the water level and decrease the amount and scale of natural water level fluctuations.

By introducing pumping operation, these fluctuations of water level will be more frequent, which can probably lead to extension of littoral zone – from a narrow brand of vegetation which took place after stabilization of water level back to broader littoral zone which was around the lake before development.

Because of frequent changes of water level there can be a change in population of different organisms and plants according to their preferences – littoral zone is going to be exposed to air or flooded by water from time to time, so there will be a change of habitat from more stable boundary between the areas above or below the water level.

4.2.3. Lower visibility in water

The movement of water in reservoirs for hydropower use is causing decreased visibility due to the rising and moving particles from the reservoir bed, and also by inflow of sediment from natural water way and by tunnel system from the hydropower station.

During pumping operation large volume of water is going to be transferred from lower reservoir to upper one, during production the other way, and this volume is going to be much higher than the current operation – also by probable increase of installed power. That can cause creation of stronger currents in reservoirs, at least close to the intakes and outlets of hydropower system, which will lead to increased speed of water and higher amount of small particles of sediment staying in water column rather than sedimentation to the bottom of the reservoir.

4.2.4. Impact by change of ice cover dynamics

Reservoirs in Norway are located in cold climate, so they are exposed to sub-zero temperatures for a long part of the year.

The physical impact of cold air acting on the surface of a reservoir is the formation of ice which is increases or decreases with respect to the temperature conditions around reservoir.

During the ice season, higher discharges during winter for power generation can inhibit/delay freeze-up, or can breakup an ice cover that has already formed.(27)

Impacts like breakup of already formed ice cover, or inhibition/delay of freeze-up are dependent upon the hydropower operation, in other words on change of water level. By change of hydropower from traditional high head to pumping hydro, water level will change more rapidly and more often. The impact of pumping operation would be the delay in formation of the ice cover completely, or a smaller a layer of ice over the reservoirs during winter.

From biological point of view, the ice cover is going to appear as a stable one later in the reservoir. Thickness of ice is going to be smaller which will allow more light to enter the lower lying layers of water in reservoir, thus resulting in better conditions for photosynthesis. Ice cover is will disappear soon in spring so the reservoir is will warm up subsequently. Thus the active season for organisms is to start sooner and last longer until the next freeze-up, resulting in the stimulation of primary production.

4.2.5. Increased mortality for higher species

Mortality of higher and larger species is an often discussed topic when talking about hydropower development. There has been large amount of studies regarding turbine passage mortality of fish, especially types of fish which migrates and has a high degree of importance – for example salmon in Norway.

In already developed reservoir (if there is no bypass structure) migration possibilities are already avoided. Thus when introducing pumping hydropower system, focus should be put on species which are living in both upper and lower reservoir. This is because they are going to be endangered by large volumes of water passing through reversible turbines both ways.

So the suggestion is to emphasize on the study of type, occurrence and number of possibly endangered higher species as for example trout, which is a very common type of fish living in Norwegian reservoirs.

4.3. Socio-economic impacts

4.3.1. Impacts on reservoir fishing

If the reservoir is used for any type of fish production from recreational fishing to commercial production of any kind of fish, pumping operation can have strong impacts through previously mentioned turbine passage mortality, change of habitat etc. So future reservoir fishing should be reconsidered when assessing these impacts and introducing them to concerned groups.

4.3.2. Impacts to recreational and aesthetical values

Reservoirs used for hydropower purposes, both natural and artificial, are important part of a nature. One of the multiple purposes of these reservoirs is very often the recreational usage. There are plenty of people with various interests like cabin owners, cyclists, fishers, hikers, kayakers and many more who want to use the area of reservoir and its surroundings for their needs.

In our case, reservoir is already in operation and those impacts were handled more or less during construction and implementation of the operational regime.

When introducing pumping, there will be changes which can influence recreational and aesthetical values.
Changes due to pumping could lead to:

- Changes in water quality due to increased volumes of water travelling from one reservoir to another.
- Visible changes in a shoreline zone due to bigger and more often changes of water level of reservoir.
- Possibly significant areas of short term exposed littoral zone can cause unpleasant odours

4.4. Process of evaluation of impacts

The important part of the evaluation of all mentioned impacts is to realize what was previously done within hydropower reservoir and its surroundings for mitigation of impacts by hydropower development. The next stage is to assess what will happen when introducing pumping operation instead of traditional high head hydropower, which has already been in operation for a significant period of time.

5. Site of the study

The reservoir chosen for evaluation of impacts due to the development of a pumping storage hydropower is a Totak reservoir in Telemark, Norway.

Telemark is a county located in south eastern Norway. Telemark has a very heterogeneous landscape containing many hills and valleys.

There is a complex hydropower system located in two municipalities of Telemark county, Vinje and Tokke. In total 7 hydropower stations are using water stored in 17 reservoirs created by 32 dams. Water is transferred from reservoirs by about 108 kilometres of transmission tunnels. Total elevation difference of hydropower system is around 900 meters, the water is in the end released to the lake Bandak. Total average production over the year is about 4,32 TWh which is equivalent to the electricity consumption of 200 000 Norwegian households. (29)

Figure 7 – Telemark county (28)

The Norwegian Parliament decided to develop this hydropower system in the year 1956, licences for hydropower plants were granted within years 1957 to 1964. (29) The intention was not to just build this system to generate energy, but the important factor was also to reduce the damage caused by regular floods.

Hydropower stations were built in several stages between years 1957 and 1979 as visible in a Figure 8 together with main characteristics of each station.

Hydropower station	Start of operation	Average yearly production (GWh)	Installed power (MW)	Number and type of turbine	Water level difference	Absorption capacity (m^3/s)
Haukeli	1957	33	4,4	2 pelton	267 m	2,2
Tokke	1961	2140	430	4 francis	377 m	128
Vinje	1964	1017	300	3 francis	225 m	165
Songa	1964	575	120	1 francis	294 m	48
Kjela	1979	218	60	1 francis	189 m	40
Byrte	1969	112	20	1 francis	286 m	9
Lio	1969	225	40	1 francis	332 m	14
Sum		4320		13		

Figure 8 – Overview of hydropower stations in Tokke-Vinje system (30)

Figure 9 is showing the complex Tokke-Vinje regulated system in a basic scheme.

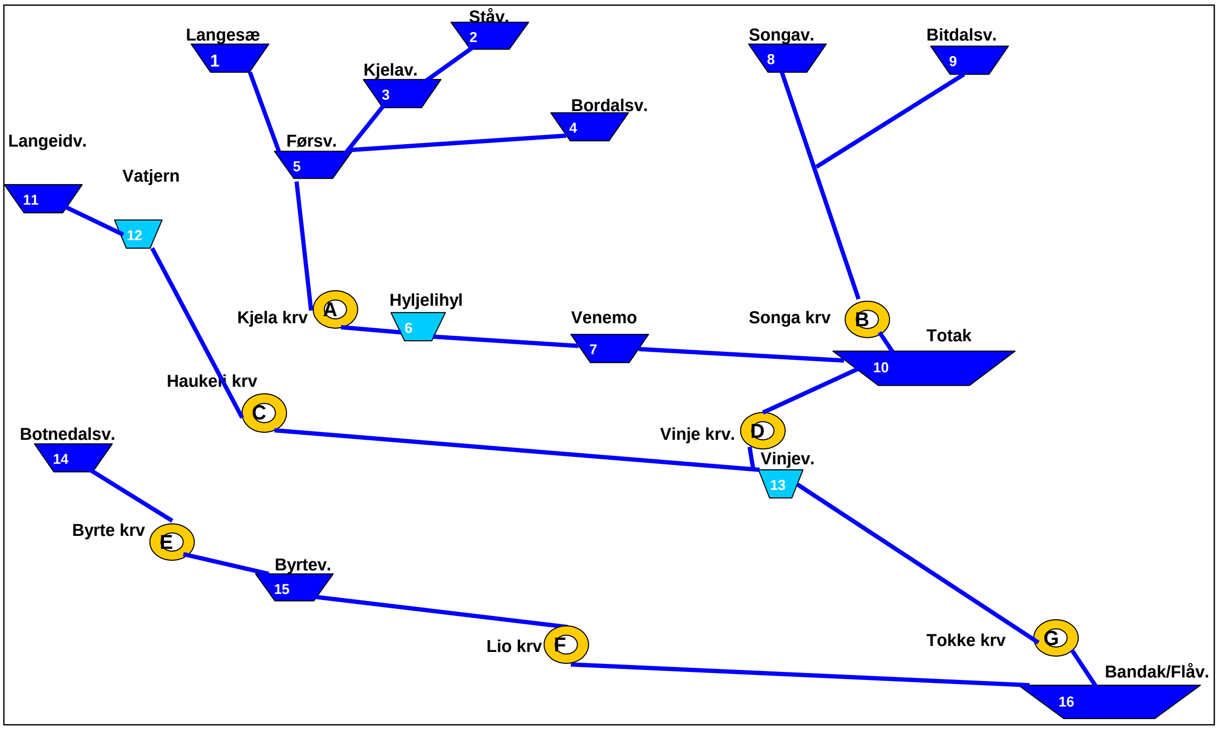


Figure 9 – Basic scheme representing Tokke-Vinje regulated system (30)

Figure 10 – Tokke – Vinje hydropower system.(30)

The detailed map in Figure 10 shows the whole catchment area of the regulated system with all its hydropower stations, reservoirs and transmission tunnels. There are also a large number of natural lakes located in the area.

This Master's thesis is not focusing on the whole system, but just on a part of it, particularly Totak reservoir and its surroundings. As visible on a scheme in the Figure 9 and on the map in Figure 11 there are two inflows to Totak by tunnel:

- First inflow is by the tunnel system from Førsvatn through Kjela hydropower plant (60MW) to Hyljelihyl reservoir, from where it continues by tunnel to Venemo reservoir, which finally releases water by another tunnel to Totak.
- Second inflow is coming by a tunnel system collecting water from Songavatnet, Bitdalsvatn, Kvikkevatn reservoirs and some side intakes from rivers along the tunnel system to Songa hydropower plant (120MW), after which the water is released to Totak.

Catalina Cortines Garcia did a Master's thesis in the year 2013 which tested a GIS-based methodology for optimal location of Pumped Storage power plants in Norway. (31) In this study during the testing of ArcGIS tool developed by Sintef Energy Research, the proposal of a pumping storage scheme between Songavatnet and Totak reservoirs was put forward. The author makes use of that study in this Master's thesis to explore reasonable range of installed power and see which possible environmental impacts this pumping storage hydropower can have.

The proposed pumped storage hydropower from the study (31) should be constructed along the tunnel system created for current Songa hydropower plant in a secure distance. Main reason for this is that the current hydropower plant can still operate during the construction phase. Reconstruction of Songa would take a long time because installed power of proposed pumped storage requires much bigger cross section of tunnel system. Thus financial loss incurred by stopping the production would probably not be covered by savings due to reconstruction when compared to a new hydropower system.

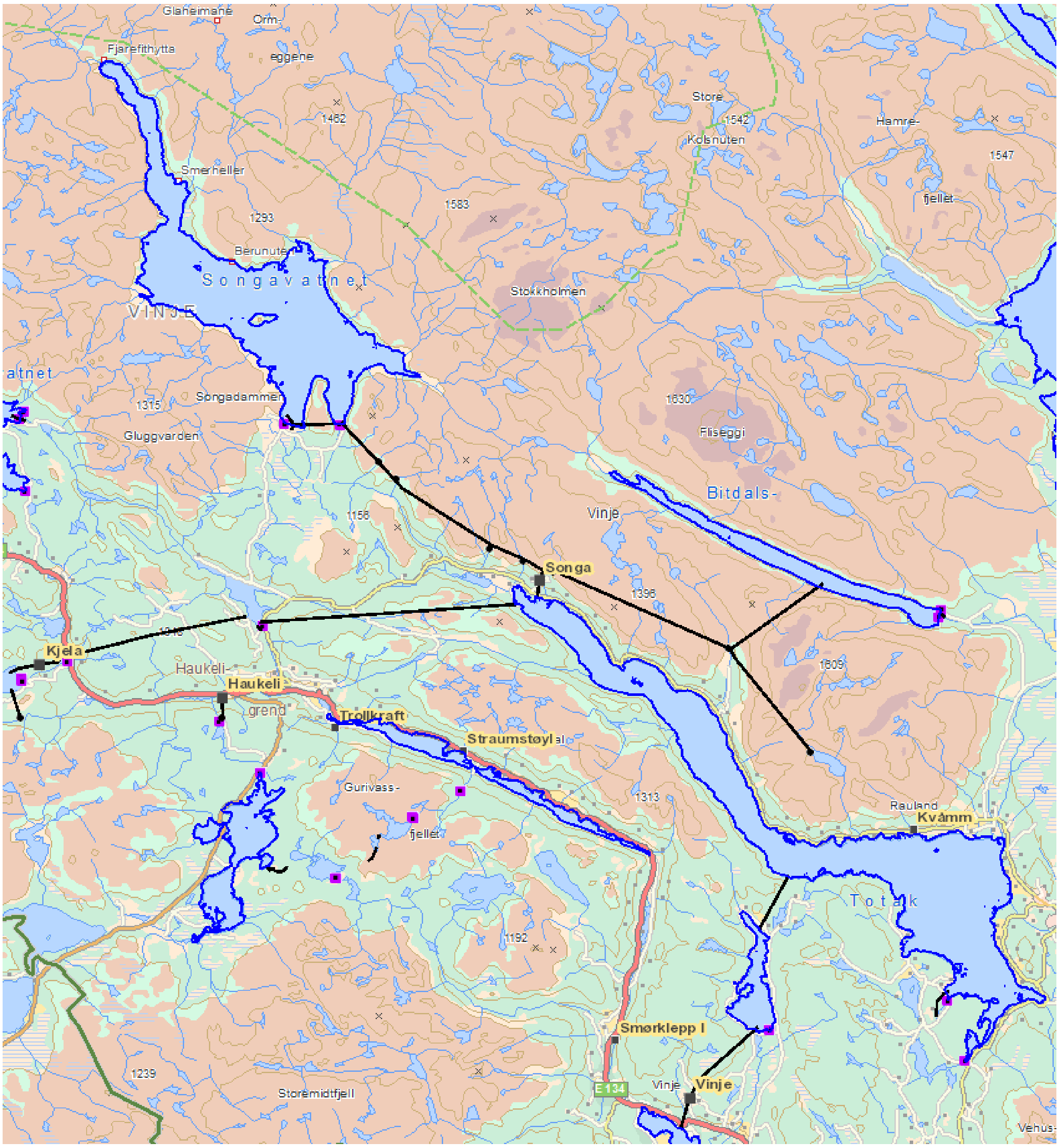


Figure 11 – Totak and its surroundings (32)

5.1. Totak reservoir

Totak reservoir is one of the deepest reservoirs in Norway. The deepest measured point is 306 metres below the water level. It was a large natural lake storing big volume of water. Because of this, feasible natural storage reservoir was constructed just by two small dams constructed at the location of natural lake outflows, one provided by sector gate for flood discharge and the other with needle-type stop logs which can be used for an emergency flood release. (33)

Main characteristics of reservoirs within **Songa** hydropower plant system				
		Songavatnet	**Bitdalsvatnet**	**Totak**
Total volume	mill m^3			2360
Regulated volume (life storage)	mill m^3	640	110	258
HRWL	m.a.s.l.	974	974	687.3
LRWL	m.a.s.l.	939	939	680
Max. WL difference	m	35	35	7.3
Area (HRWL)	km^2	30.01	5.53	37.32

Figure 12 – Main characteristics of reservoirs within Songa HPP system (33), (32)

As visible in the Figure 12 Totak reservoir doesn't have large span between lowest regulated water level and highest regulated water level, it is just 7.3 metres which is creating the regulated volume or so called life storage of 258 millions of cubic metres, i.e. around 10% of total volume of whole reservoir. During studies of normal lake levels, it was discovered that the natural summer high water level of the lake level is 686.1 m.a.s.l.; and it was proposed to increase this level just by 1.2 metres to HRWL of 687.3 m.a.s.l. which was limited by the settlements around the lake. At an earlier stage it was proposed to lower Totak by means of LRWL by much more than 6.1 metres to 680 m.a.s.l. In that way the large storage capacity would be provided at low investment costs, however due to scenic considerations the extent of lowering was limited to 680 m.a.s.l.

A Large proportion of population in Rauland is concentrated around Totak, and no doubt this beautiful district would have suffered by Totak lying empty during the summer. This would also affect the tourist traffic. Furthermore, such a drastic lowering as had been envisaged would have laid bare considerable stretches of sand and would have caused landslides at other points. Even the present lowering has resulted in some slides in the road alongside the lake in certain particularly vulnerable spots, although the damage sustained was not very extensive and was easily repaired. (33)

Only outflow from Totak during normal conditions is by supply tunnel to Våmarvatn reservoir which is impounded to same level as Totak by means of a rockfill dam. From Våmarvatn the water is transported through the tunnel to Vinje hydropower plant. Fluctuation of water level of Totak reservoir during the year in period of 1985 - 2009 is shown in Figure 13.

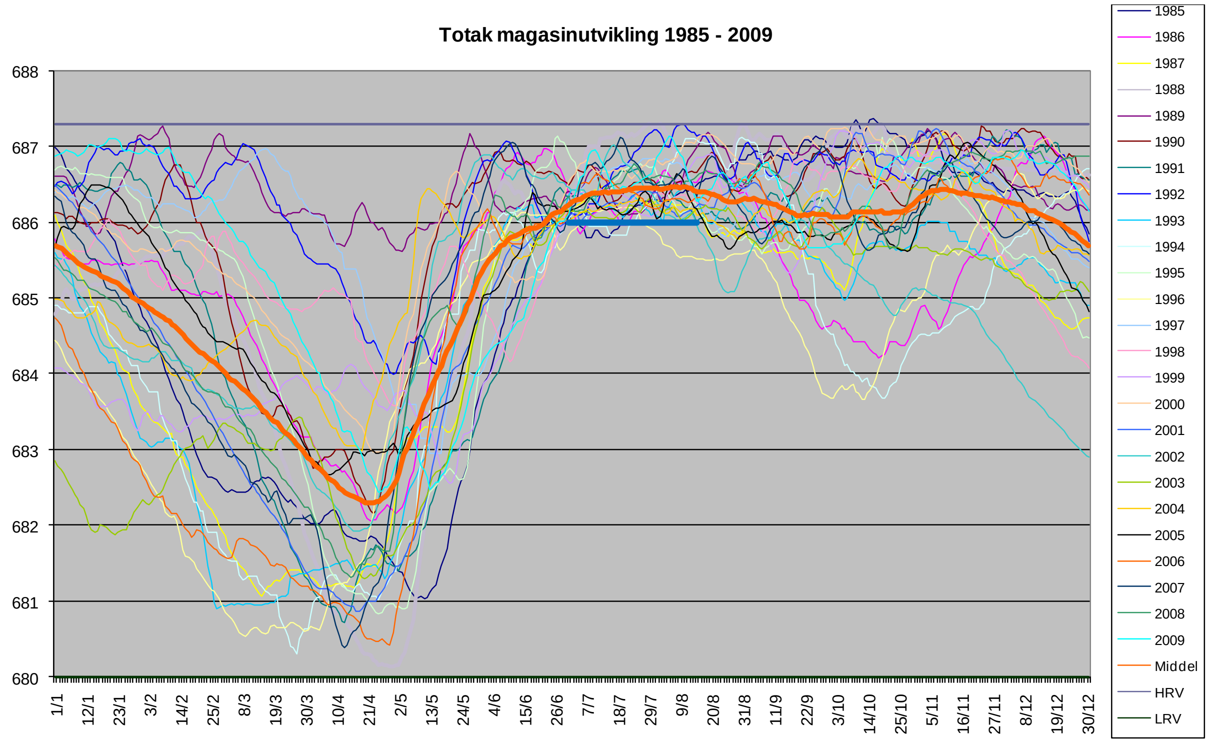


Figure 13 – Totak water level fluctuations in period 1985 – 2009 (30)

5.2. Songavatnet and Bitdalsvatnet reservoirs

The Songavatnet reservoir was constructed larger than proposed at an earlier stage with the intention to compensate the loss of life storage in Totak due to aforementioned limitations. This compensation was approved and life storage of Songavatnet was increased, although at considerable additional costs. (33)

Songa River which is flowing to Songavatnet derives from a chain of fishing lakes which are not visited often due to their remoteness. This area was inhibited in pre-historical times which were shown by archaeological investigations, but before development of the reservoir there was just one abandoned farm. The regulation was therefore concerned only about the fishing facilities and submergence of fishing cottages. Originally, there were a number of smaller lakes located in the valley which were connected together to one large reservoir by the construction of a 1200 metres long rockfill dam sealed by compacted moraine core. There was need for one additional smaller side dam of same construction and material.

Water surface area of Songavatnet is almost the same as Totak as visible in Figure 12, but life storage is almost equal to total volume of the reservoir as the Songavatnet is in area of shallow lakes. The change of the water surface area of the reservoir can be observed in Figure 15 and Figure 16, where the red colour represents the exposed area of reservoir bed without water. As visible in the progress from Figure 15 at WL 968 m.a.s.l. to Figure 16 at WL 956 m.a.s.l. when water is released from Songavatnet, the reservoir is splitting into smaller lakes as in the original state.

The supply tunnel from Songavatnet has a cross section of 39 m^2 and there is a sill elevation of 944 m.a.s.l., so the tunnel is usable when the water level in reservoir is above this elevation. For emptying the reservoir to LRWL there is an extension of supply tunnel with auxiliary intake, which has a sill elevation of 936 m.a.s.l. (33) Water level fluctuations around the year in Songavatnet in period of 1985-2009 are shown in the Figure 14.

Bitdalsvatnet is a smaller reservoir than Songavatnet, its HRWL and LRWL is same as that of Songavatnet, because it is drained by the same tunnel system, so reservoirs behave like communicating vessels. The reason for this is that tunnel system is connected in a surge chamber. Reservoir is created also by the rockfill dam with moraine core.

Tunnel system is also connected to the lake Kvikkevatn and a number of rivers collected by side intakes along the tunnel system.

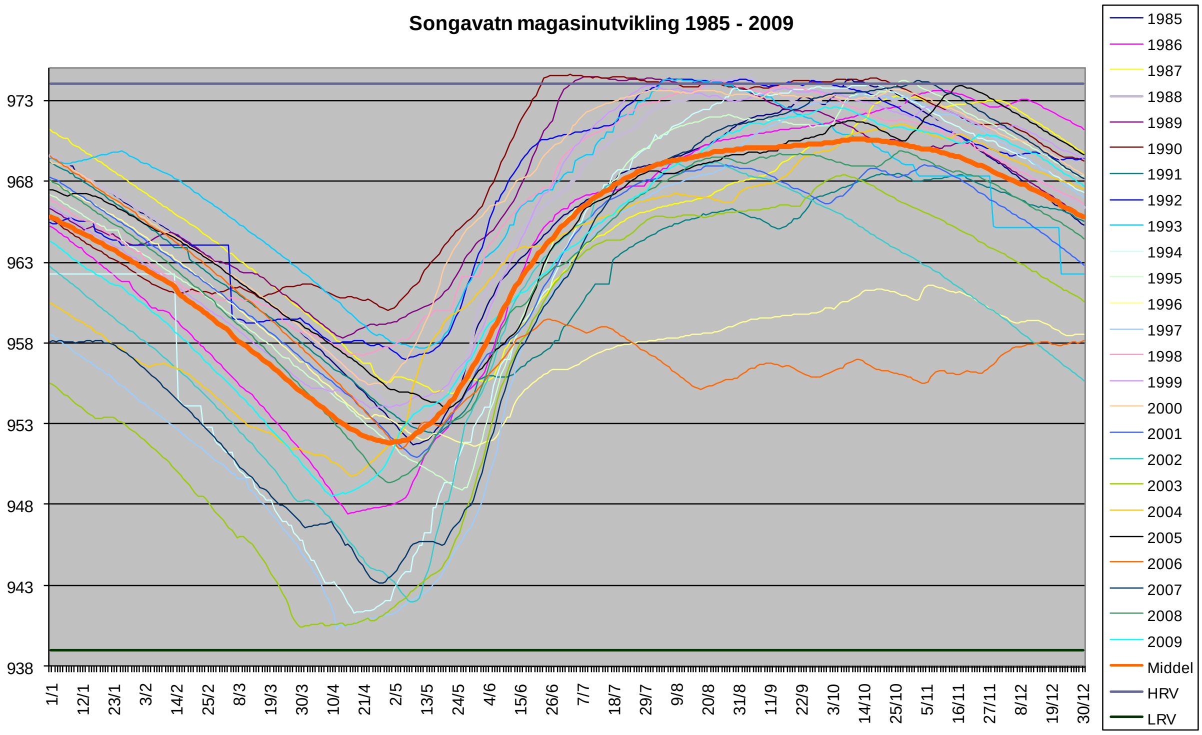


Figure 14 – Songavatnet water level fluctuations in period 1985 – 2009 (30)

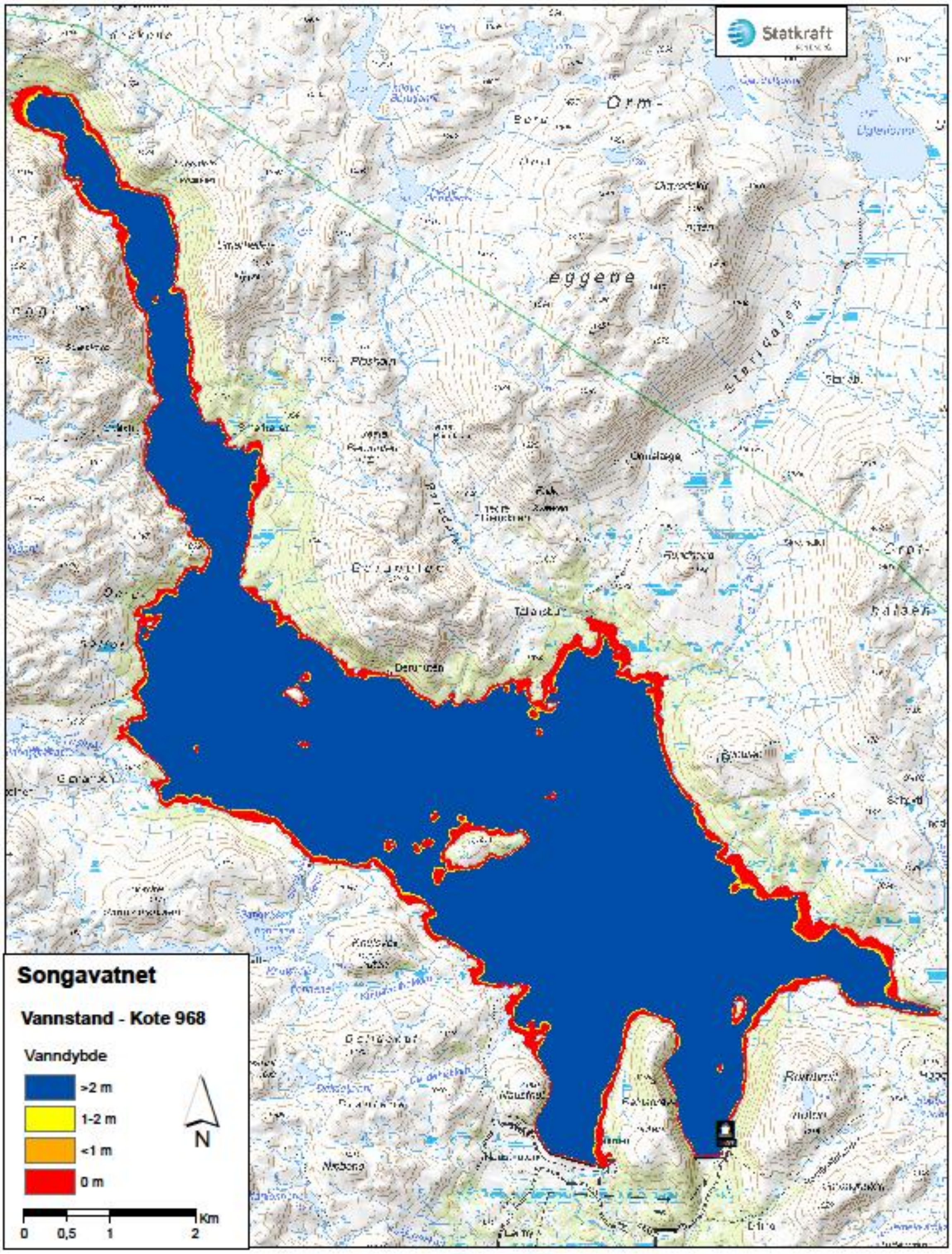


Figure 15 – Songavatnet at water level 968 m.a.s.l.(34)

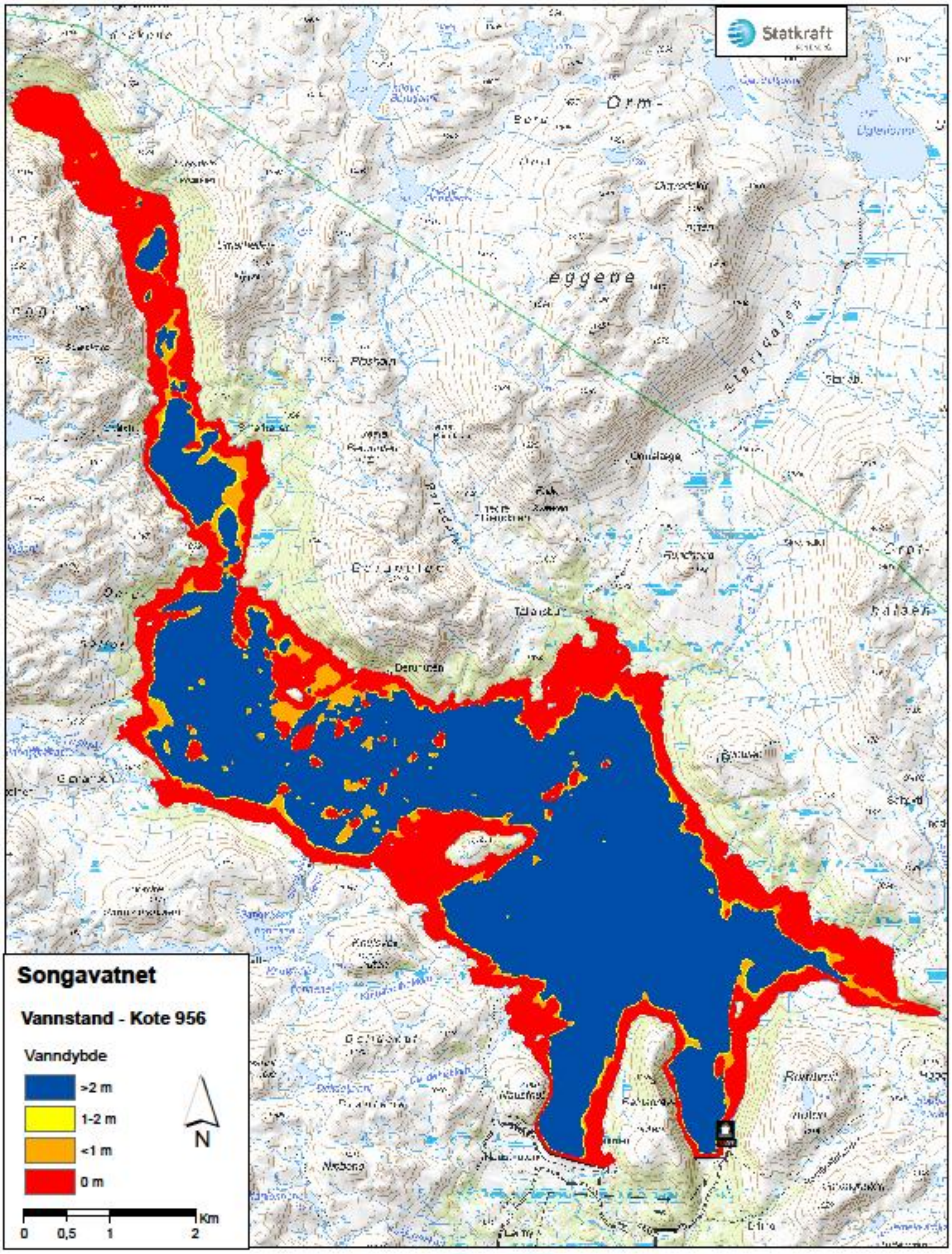


Figure 16 – Songavatnet at water level 956 m.a.s.l.(34)

5.3. Regulations and restrictions

As the system is quite complex and heavily regulated, there are restrictions which have to be followed in order to reach some required goals, particularly about tourism or fishing, as the area is popular for those interests.

Because of commercial fishing and tourism Totak is required to be filled up to the water level of 686 m.a.s.l. between 1st of July and 15th of August. (30)

From 15th of August to 1st of November there is a self –imposed restriction to hold the water level of Totak above 685.50 m.a.s.l. which creates better conditions for commercial fishing and tourism, better conditions for fish in the rivers Bitu and Tansåi and also improves energy generation for Vinje hydropower plant located downstream of Totak. (30)

6. Pumping storage hydropower model

We know how behaviour of water level (stage), water volume and other important characteristics look like by assessment of records, which are done within hydropower reservoir area.

To evaluate impacts and propose reasonable mitigation actions, we have to know how a development of other hydropower plant or reconstruction of current one with system capable of pumping operation will change water behaviour in all affected hydropower reservoirs. These physical effects of pumping operation are characterized by range, duration and frequency of operation.

The value which is most important for this assessment is how big volume of water is going to be used for operation in specified period of time. This value is linked to a change of water level, which is a figure we are going to use most for evaluation of impacts (as a figure of water level change – withdrawal rate in centimetres per hour).

The limitation used in studies by SINTEF Energy Research (35), (11) was limited to withdrawal rate of 13 centimetres per hour as it is a value discovered in a study of "*Rapid water level variations - Impact on fish, benthic fauna and aquatic vegetation*" (36). This value has however been studied as one which reduces the risk of stranding of juvenile Salmonidae species of fish in a river. Therefore usage of this value which is based on flowing water, for the study steady water in lakes or reservoirs is questionable. According to SINTEF Energy Research, the research for stranding in reservoirs is going to be done in summer 2014 as part of current Hydrobalance projects. So, more suitable boundaries are going to be explored soon in this field. In this thesis I am going to use this 13 centimetres per hour of withdrawal rate as a non-limiting guide to see how big is the reasonable installed power of pumping hydropower storage between Totak and Songavatnet in connection with the withdrawal rates.

6.1. Need for pumping operation

The driving force for pumping operation in this Master's thesis is the TradeWind project. This project consist of 94.6 GW (94,600 MW) installed capacity in the North Sea in Belgium (3.0 GW), Denmark (5.6 GW), Germany (25.4 MW), UK (43.3 MW), Netherlands (12.0 GW) and Norway (5.4 MW). (11)

Variation in production is expressed in Figure 17 by the minimum and maximum hourly production of TradeWind project between the years 2000 – 2006, this is based on wind measurement data.

This installed power can't be balanced by one pumping hydropower storage. As the designed future power output 20 000 MW is the output for new hydropower in the whole Norway in 2030 (35), in pumping model for this Master's thesis a proportional figure is used for balancing needs according to installed power of new proposed hydropower system between higher and lower reservoir.

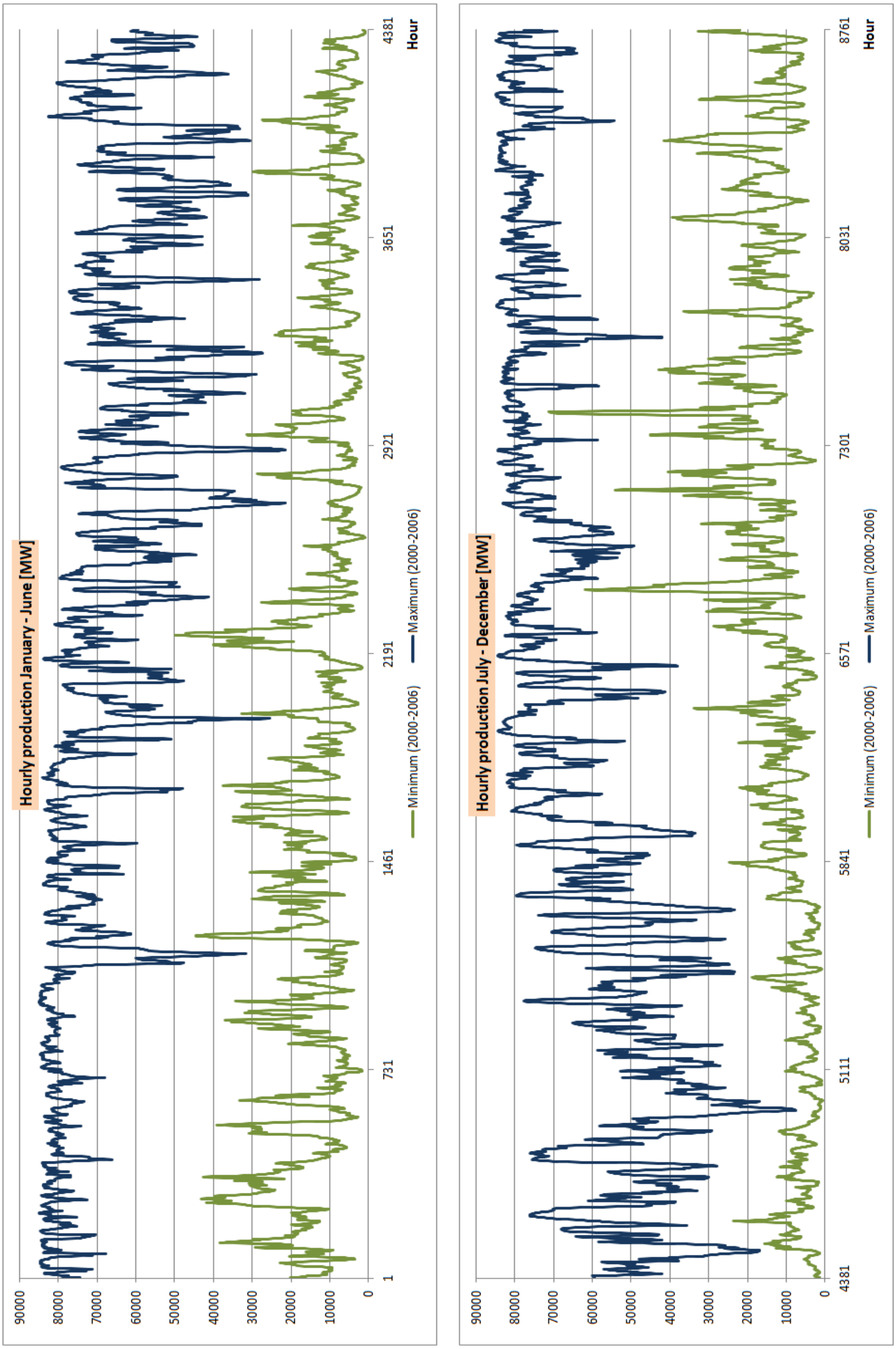


Figure 17 – Minimum and maximum hourly production of TradeWind project in years 2000 – 2006 (11)

6.2. Model description

Simulations of pumped storage operation was done on the basis of previous studies conducted by HydroPeak project of CEDREN, a study on Increasing balance power capacity in Norwegian hydroelectric power stations – a preliminary study of specific cases in Southern Norway(35) and project work conducted by SINTEF Energy Research called Norwegian hydropower for large-scale electricity balancing needs.(11)

The previously mentioned project (35) discussed that: "*There is definitely a need to balance generation and consumption on time scales ranging from minutes to weeks. An increased proportion of wind and solar power generation will probably create new demands and new market potential for Norwegian hydroelectricity*."

The same project concluded "*that it will be probably technically feasible to increase the design power output of Norwegian hydroelectric power stations by 20,000 MW without using new regulated reservoirs or exceeding the current stipulations with regard to highest and lowest regulated water levels".(35)*

For this Master thesis I used a model developed by Ånund Killingtveit and further used and improved by SINTEF Energy Research in a project work called "*Norwegian hydropower for large-scale electricity balancing needs"*.

Regarding the project work by SINTEF (11) the model is used to:

- *Simulate the water level fluctuations in the reservoirs and compare them to the current ones*
- *To determine the limiting factors for provision of balancing power*
- *To provide a basis for an assessment of environmental impacts of pumped storage*(11)

The points mentioned above for usage of the model shows that the model is highly appropriate for the purpose of this Master's thesis.

The model was built in Microsoft Excel in order to simulate operation of pumped storage hydropower plant between lower and higher reservoir. Hydropower plant can either:

- pump water from lower reservoir to upper one, which is consumption of electricity from a grid and it’s conservation in the form of potential energy
- release water from upper reservoir through turbines to lower reservoir and create electricity, so generate energy

SINTEF Energy Research describes the working procedure of the model as:

“*The model calculates in intervals of one day the water volumes which are transferred between the reservoirs. The corresponding reservoir stages are calculated from the volumes by use of reservoir-specific rating curves. The current operation is implemented using observed records of water volume and stage. In addition to these water volumes, the volumes transferred due to balancing power operation are accounted for by calculating the volumes corresponding to the required balancing power, i.e. amounts of water pumped up into the upper reservoir during electricity uptake and water volumes released into the lower reservoir during electricity generation. By combing the water volumes of the current operation and balancing power operation the future operational scheme is obtained.* “(11)

Scheme of the model is shown in Figure 18. Current operation (orange colour) is combined with balancing power operation (green colour) which is resulting into pumped storage operation. Purple colour is representing future operation based on water volumes transferred between reservoirs.

Part of the model representing current operation is based on rating curves which are available from NVE Hydra II database. Polynomial curve which is fitting these data is constructed and provides a mathematical relationship between volume of reservoir and water level. There is also a need for an inverse polynomial curve expressing relationship between water level and volume. These polynomial curves also express the reservoir bathymetry. By dividing change of volume by change of stage, we get a change of the water surface of reservoir. Because the model has time step of 1 day, daily rate of change of water level and water surface is then computed by deduction between previous day and day of computation.

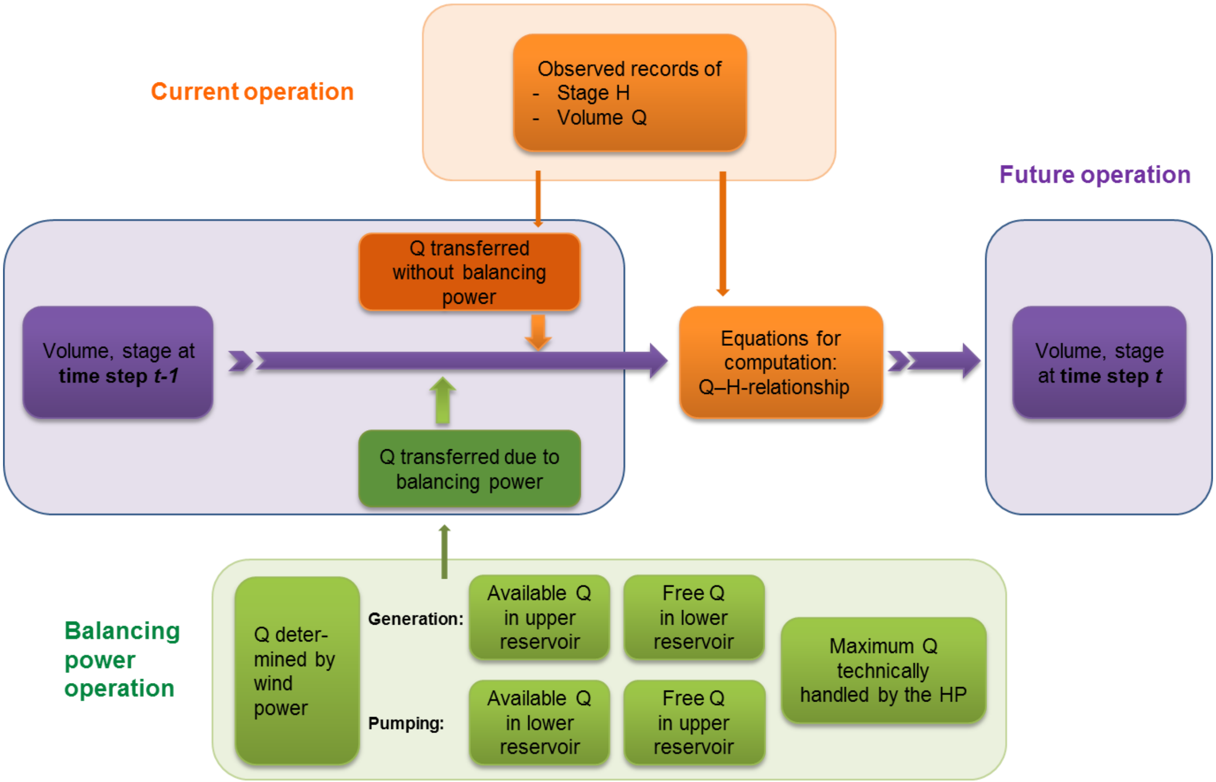


Figure 18 – Scheme of the model (11)

The model was developed for two balancing scenarios. **7 days average scenario** is done with an assumption of compensating short term fluctuations of wind power production up to 1 week. This assumption is based on the proposal that long term fluctuations could be covered by other sources of energy and hydropower will only compensate the short term fluctuations. Therefore the demand for balancing in the model is created by moving the average for 7 days of wind power production (weekly fluctuations) deducted by daily production (daily fluctuations). (11) This is also expressed and explained in Figure 19.

Second balancing scenario called **Dev-Avg** scenario (Figure 20) is for compensation of long term fluctuations of wind power production with the idea that short term fluctuation can be compensated by current energy system. High and low thresholds were defined in this scenario as average daily wind production plus minus 25%. If the production is smaller or higher than this threshold, there is a need for balancing operation in form of energy generation or energy storing.(11)

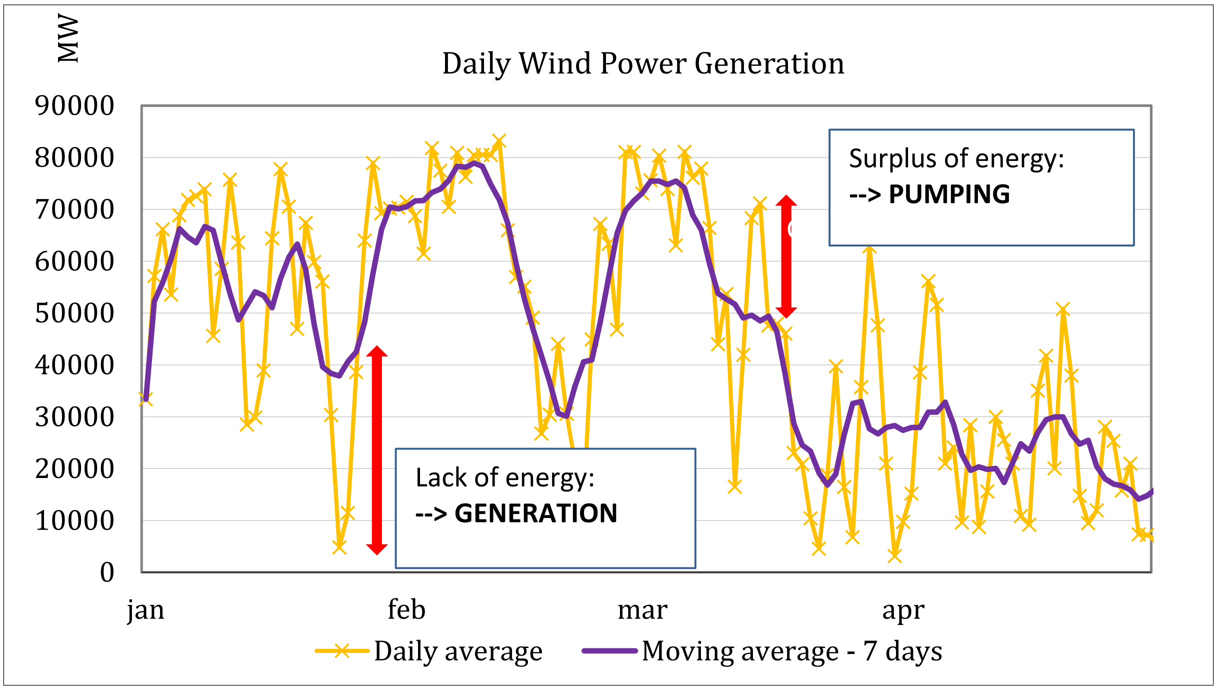


Figure 19 – 7 days average balancing scenario (11)

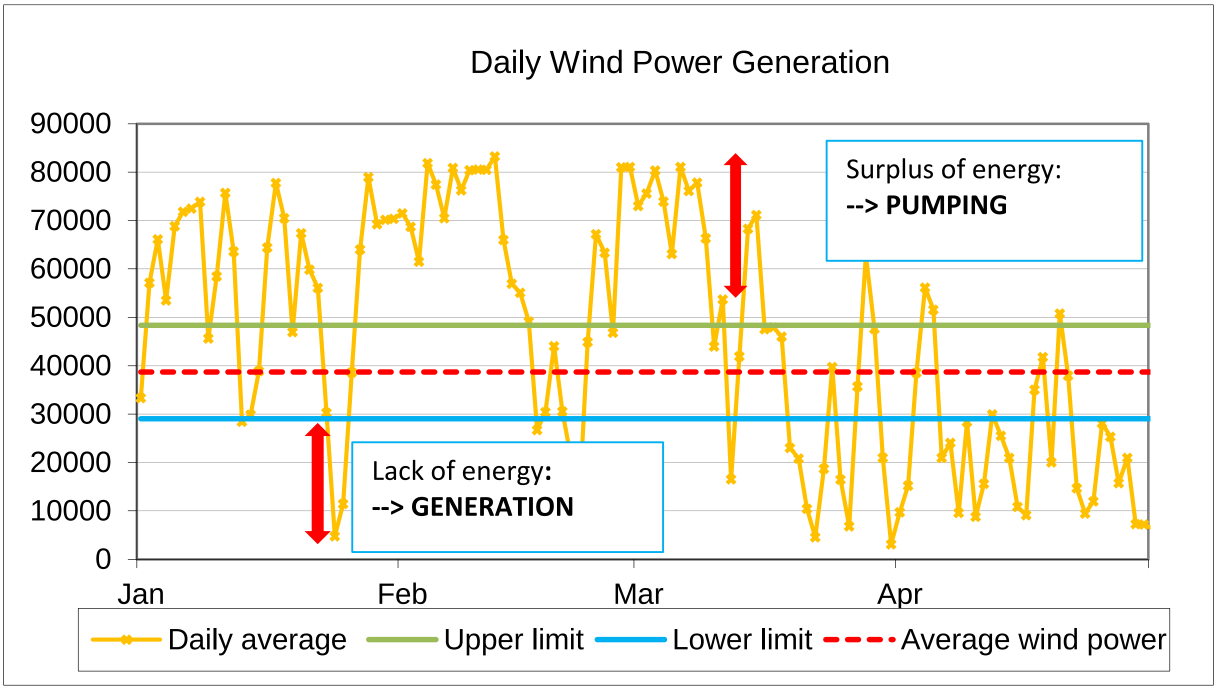


Figure 20 – Dev – Avg scenario (11)

In this thesis I used 7 days average scenario for calculation of pumping hydropower storage between Totak and Songavatn as the study by SINTEF (11) discovered that almost in all studies Dev-Avg scenario has a reduction of volumes transferred between reservoirs in comparison with 7 days average by almost 50%. Hence the worst case for the environment with more fluctuations is 7 days average scenario.

Scheme of the proposed model of pumped storage hydropower plant between reservoirs Totak and Songavatnet with all inputs and outputs is visible in Figure 21.

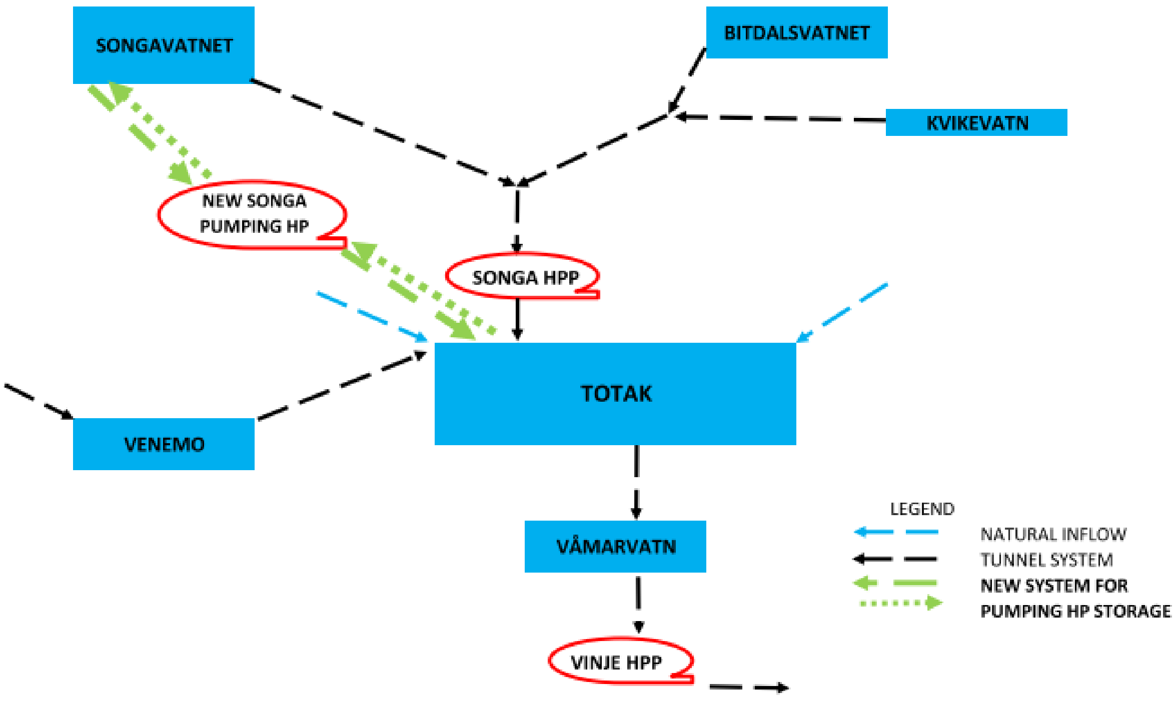


Figure 21 - Scheme of proposed pumped storage hydropower system

6.3. Data collection and preparation

As explained in chapter 6.2 the current operation is based on rating curves. Rating curves for both Songavatnet and Totak were available at NVE Hydra II database. I graphically expressed this relationship of water stage in metres above sea level (resolution in millimetres) and volume of water (life storage) in millions of m^3 and calculated mathematical expression by regression analysis.

Totak is a large reservoir with much greater volume than is the life storage as seen in Figure 12. The mathematical relationship of water stage – volume of life storage is not far away from linear relationship (see Figure 22), therefore it was not difficult to establish such a relation with good fit for measured data.

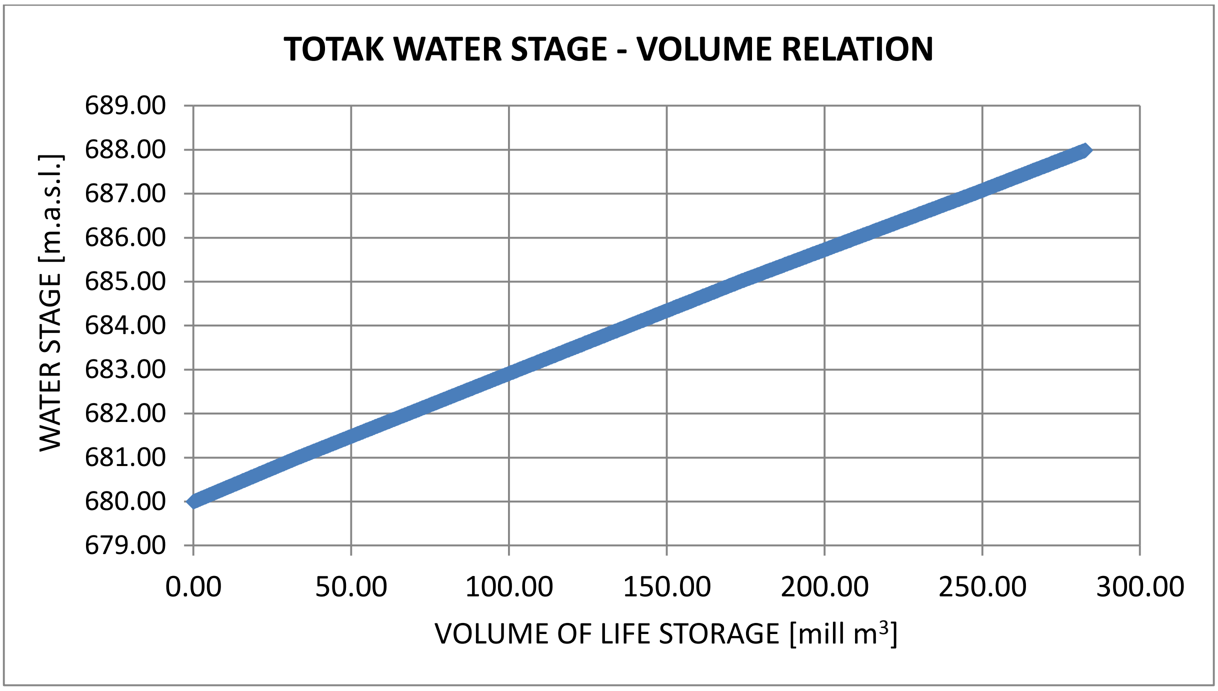


Figure 22 – Water stage – volume graphical relationship, Totak

Volume of life storage (Y) in mill m^3 in Totak calculated from water level (X) in m.a.s.l.:

$$Y= 0.231023 X^2 + 280.528 X + 83933.48, R^2=0.9999$$

Inverse function representing water level (X) inm.a.s.l.Totak calculated from volume of life storage (Y) in mill m^3:

$$X= -5.16116 \times 10^{-6} Y^2 + 0.029606 Y + 680.0135, R^2=0.9999$$

These polynomical curves are precise as coefficient of determination (R^2) shows as R^2=1 is a perfect fit.

For Songavatn the estimation of such mathematical relationship was much more difficult even though data of same quality were available at NVE Hydra II database. As visible in Figure 16 and mentioned in the text, Songavatnet is not a big reservoir as Totak. Volume of life storage is not much smaller than total volume of the whole reservoir. When the water level is drops the reservoir area starts to fill with islands and smaller lakes. Because of such a broken terrain of reservoir bed, I had to split the stage – volume relationship into multiple sections fitted with polynomial equation of the 3rd or 4th power to get reasonable accuracy. Equations are presented in Figure 23.

Volume of life storage (Y) in mill m^3 in Totak calculated from water level (X) in m.a.s.l.:												
Y_1=			-6.29E-08 X^3	+	1.77E-04 X^2	+	0 X	+	-104.290	for	X<	940.505 m.a.s.l.
Y_2=			-0.05513 X^3	+	156.618 X^2		-148299.4 X	+	4.68E+07	for	X<	947.995 m.a.s.l.
Y_3=			-7.29E-05 X^3	+	0.2076 X^2		-183.220 X	+	49271	for	X<	951.735 m.a.s.l.
Y_4=	-3.26E-05 X^4	+	0.08285 X^3		-59.288 X^2	+	0 X	+	8.99E+06	for	X<	956.235 m.a.s.l.
Y_5=	0.08609 X^4		-330.24 X^3	+	4.75E+05 X^2		-3.04E+08 X	+	7.28E+10	for	X<	960.735 m.a.s.l.
Y_6=	0.03072 X^4		-118.52 X^3	+	171490 X^2		-1.10E+08 X	+	2.66E+10	for	X<	967.735 m.a.s.l.
Y_7=	-0.01005 X^4	+	39.09 X^3		-56992 X^2	+	36928545 X		-8.97E+09			
total $Y= \Sigma Y_1^n$												

Inverse function representing water level (X) in m.a.s.l. in Songavatnet calculated from volume of life storage (Y) in mill m3:												
X_1=	-5.88E-09 Y^4	+	0.04473 Y^3		-0.0168 Y^2	+	6.0017974 Y	+	939.000	for	Y<	0.26 mill m^3
X_2=	3.01E-04 Y^4		-0.00232 Y^3		-0.0139 Y^2	+	0.3587257 Y	+	940.014	for	Y<	6.90 mill m^3
X_3=	-2.23E-05 Y^4	+	0.00137 Y^3		-0.0307 Y^2	+	0.4441034 Y	+	939.755	for	Y<	21.70 mill m^3
X_4=	1.38E-10 Y^4		-1.97E-08 Y^3	+	1.03E-06 Y^2	+	0.1047983 Y	+	941.721	for	Y<	59.85 mill m^3
X_5=	-6.24E-10 Y^4	+	2.22E-07 Y^3		-2.92E-05 Y^2	+	0.0736167 Y	+	943.655	for	Y<	111.85 mill m^3
X_6=	-1.66E-08 Y^4	+	1.05E-05 Y^3		-0.0025 Y^2	+	0.3085526 Y	+	935.932	for	Y<	193.00 mill m^3
X_7=	-2.15E-08 Y^4	+	2.15E-05 Y^3		-0.0080 Y^2	+	1.3710588 Y	+	865.703	for	Y<	289.00 mill m^3
X_8=	-3.64E-09 Y^4	+	5.57E-06 Y^3		-0.0032 Y^2	+	0.8445689 Y	+	873.365	for	Y<	463.10 mill m^3
X_9=	5.47E-10 Y^4		-1.27E-06 Y^3	+	0.0011 Y^2		-0.3761 Y	+	1008.717			
total $X= \Sigma X_1^n$												

Figure 23 – Mathematical relationship for function of water stage – volume and inverse function, Songavatnet reservoir

Broken terrain is not so visible in graphical representation in Figure 24 due to large span of regulated stage which is equal to 35 metres, but it is clear in a closer look at the data from NVE Hydra II database.

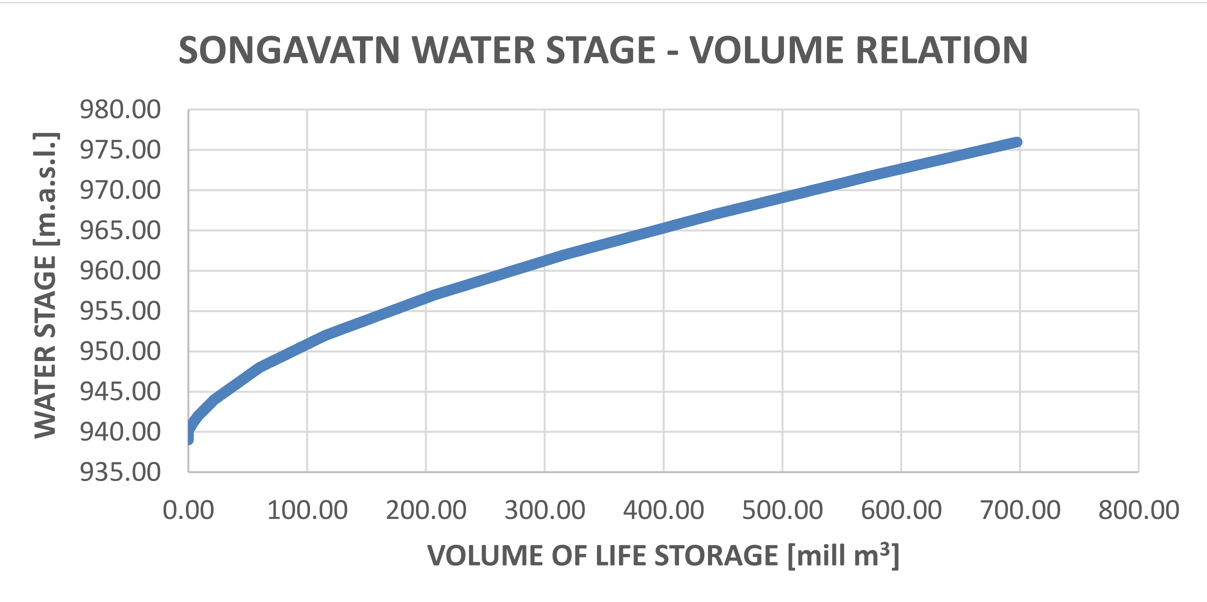


Figure 24 – Water stage – volume relationship, Songavatnet

Simulation period for pumping operation is 7 years between 2000 and 2006 as I have the data of wind measurements in this period, which are then transferred by TradeWind project characteristics as described in chapter 6.2. Because of that I used data for current use of Songavatnet and Totak reservoirs in this period and plotted them as a chart. Water stage and volume of life storage of Totak reservoir in years 2000-2006 is shown in Figure 25, and for Songavatnet in Figure 26.

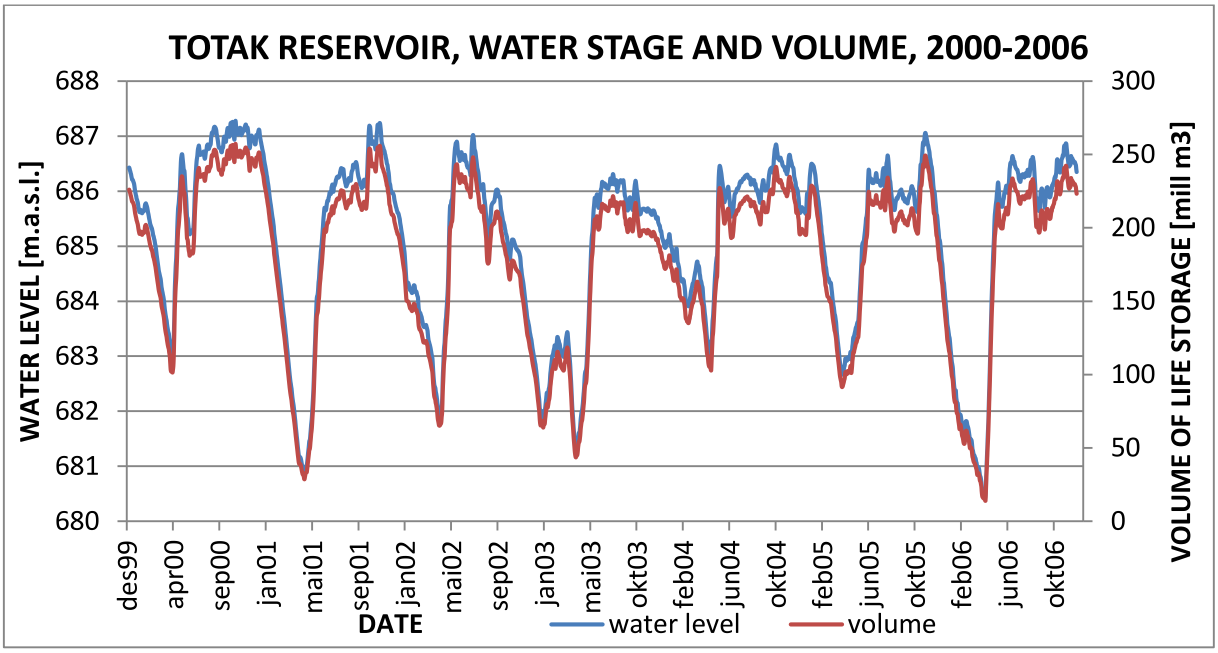


Figure 25 – Water stage and volume of life storage, Totak, 2000-2006

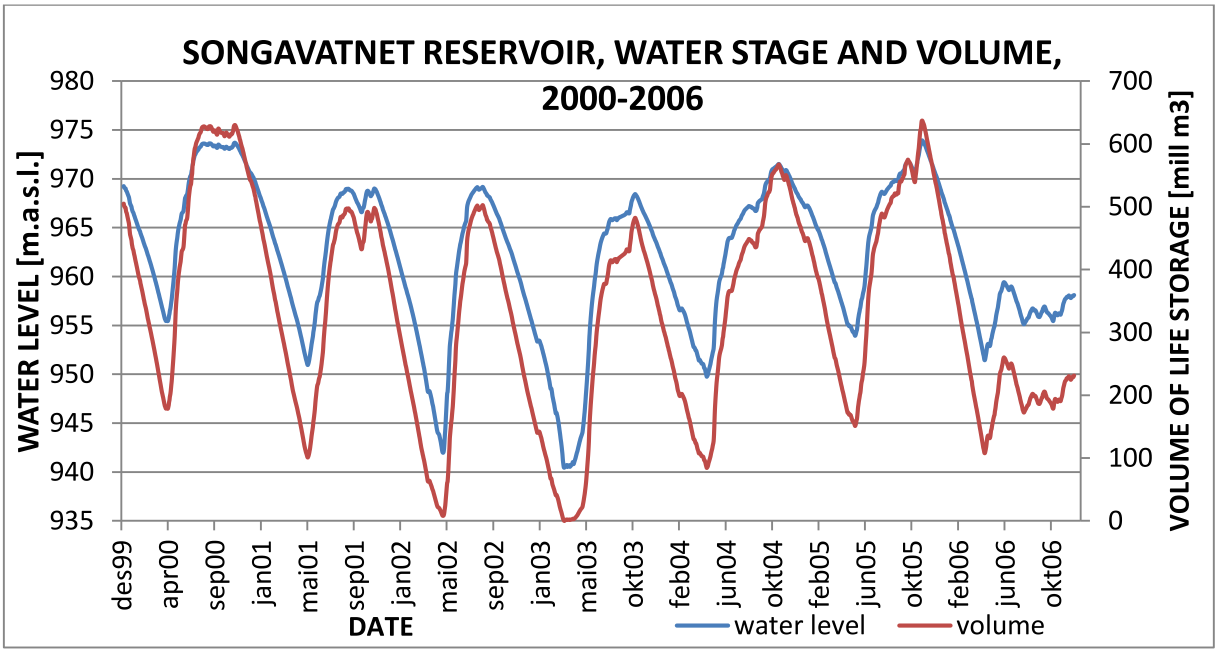


Figure 26 - Water stage and volume of life storage, Songavatnet, 2000-2006

In these charts it is visible that the fluctuation of water stage, i.e. change in reservoir volume has a strong seasonal pattern which is usual in Norwegian reservoirs as discussed in chapter 4.1.2. During spring – March, April or May the Totak and Songavatnet reservoirs are at their lowest points. In the months that follow, they are filled by water coming from melting of snow which was stored in the catchment throughout the winter. Smaller fluctuations are caused by changes in production which is not constant and rain events which happens randomly in the catchment area and supply reservoirs with water.

6.4. New Songa pumped storage hydropower plant, P = 1200 MW

C.C. Garcia (31) proposed a pumping hydropower station with installed power of 1200MW based on a broad calculation of water level change in Totak and Songavatnet reservoir. She was assuming the area of reservoirs as an area of the surface of the water when reservoirs are full. Based on preliminary calculation of costs of construction and installation she proposed a layout as in Figure 27 which can be further discussed. The proposal contains a tunnel with cross section of 265 m^2. In the power house 6 reversible Francis turbines should be installed, 4 of them with power output of 250 MW at discharge of 110 m^3s^{-1} and 2 smaller turbines designed for power output 100 MW at discharge of 44 $m^3\ s^{-1}$. (31)

The result of water level change of this study was 8 centimetres per hour for Songavatnet and 4.2 centimetres per hour for Totak.

I computed the withdrawal rates for Totak precisely by using described model and methodology (chapter 6.2) as a balancing power plant for part of the TradeWind project output. Following assumptions were made:

- Installed power of 1200 MW + 120 MW for electricity production, new pumping storage hydropower plant + current Songa HPP
- Installed power of 1200 MW for pumping operation
- Efficiency 0.91
- Head loss assumption of 6.5 metres as a constant

- Energy equivalent 0.64 kWh/m^3 for energy generation (32), -0.8 kWh/m^3 as energy needed for pumping operation when assuming 20% of losses for pumping operation
- Amount of energy to be balanced is equal to ratio of 1200 MW as installed power of pumping storage and 20 000 MW as total energy to balance. This is referred to as share of capacity (=0.06).

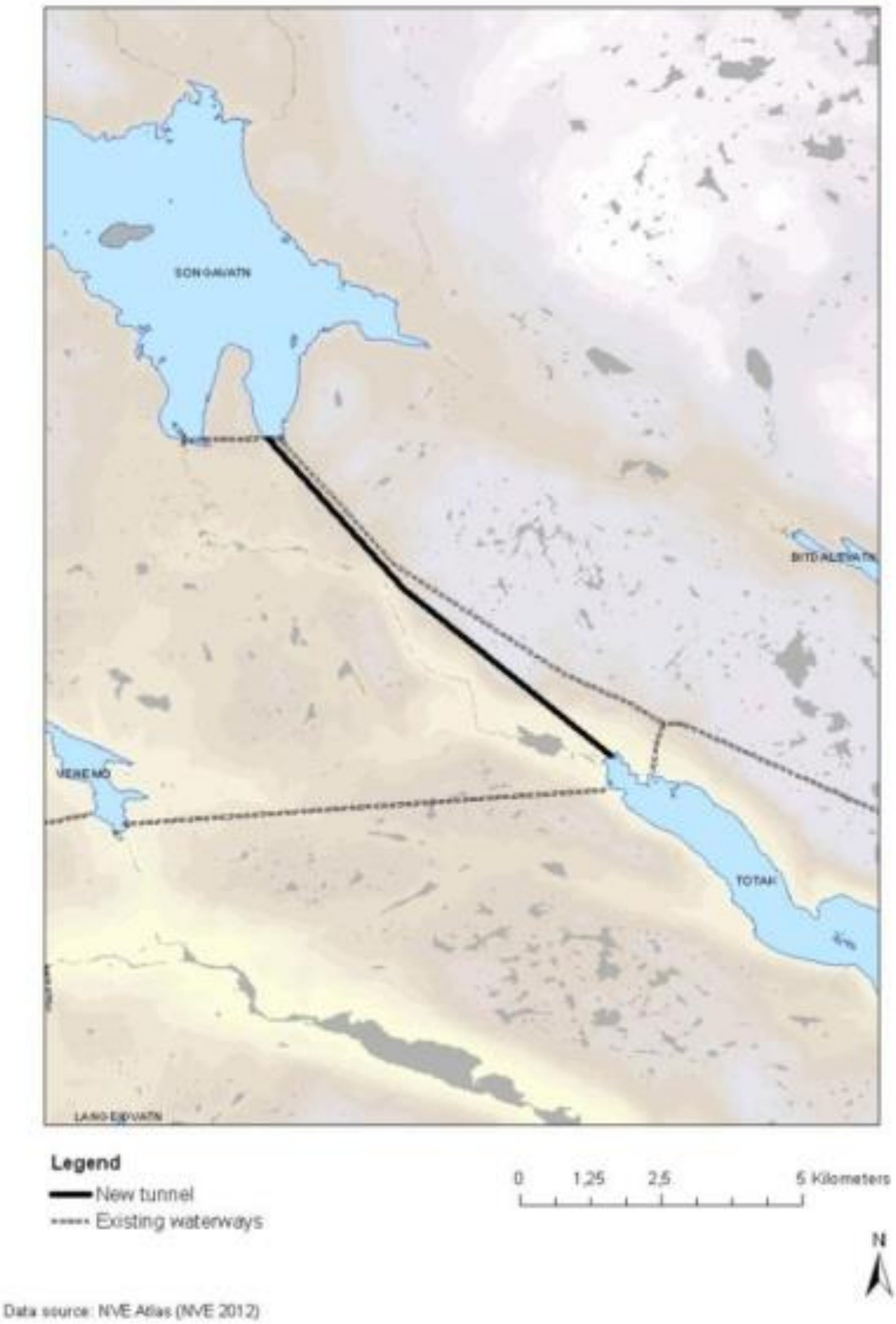


Figure 27 – Layout of proposed tunnel location for Songa pumped storage hydropower plant (31)

C. C. Garcia (31) assumed volume of upper reservoir as a volume combined by Songavatnet and Bitdalsvatnet. I used only Songavatnet reservoir. Reason for this is that the tunnel connecting Songavatnet and Bitdalsvatnet has a cross section of 39 m^2 (33) from Songavatnet to surge chamber of Songa HPP, and 7m^2 from Bitdalsvatnet to surge chamber of Songa HPP. In comparison with new tunnel system with a cross section of 265 m^2 required for pumping storage HPP, it is a very small tunnel. This tunnel will act as a connection of these 2 reservoirs and fill or drain Bitdalsvatnet according to the change of water level in Songavatnet, but this change will be so small considering the pumping or energy generation that the calculation is on a safe side when assuming only Songavatnet reservoir for balancing.

With those assumptions I simulated the operation of future pumped storage hydropower plant for past period of 2000 – 2006 with further published results.

Current operation is by calculation of model resulting in water level fluctuations in Totak as a lower reservoir and Songavatnet as an upper reservoir between the years 2000-2006:

- Totak
    - Maximum withdrawal rate 0.67cm/hour (0.16m/day)
    - Maximum increase of water level 1.79cm/hour (0.43m/day)
- Songavatnet
    - Maximum withdrawal rate 2.12cm/hour (0.51m/day)
    - Maximum increase of water level 4cm/hour (0.96m/day)

When the pumping operation takes place instead of just normal hydropower generation with Songa HPP during the same period of time, water level fluctuations change within these boundaries:

- Totak
    - Maximum withdrawal rate 5.3cm/hour (1.27m/day)
    - Maximum increase of water level 6.3cm/hour (1.5m/day)
- Songavatnet
    - Maximum withdrawal rate 32.7cm/hour (7.85m/day)
    - Maximum increase of water level 29.1cm/hour (6.98m/day)

From these figures it is clearly visible that pumping hydropower storage scheme between Totak and Songavatnet reservoirs with installed power of 1200MW has a large impact on current variations of water stage. Modifying of temporal current variations in the reservoirs volume, water stage and water surface area affected seasonal pattern of reservoir, short term fluctuations on daily basis and reservoirs filling and emptying.

6.4.1. Seasonal trend

Seasonal trend for Norwegian reservoirs is described in chapter 4.1.2 and presented in Figure 5.

Water stage at Songavatnet and Totak in period 2000-2006 is visible in Figure 28 and Figure 29. Current water stage behaviour is represented by orange colour, and simulated water stage behaviour with Songa PSH in operation by blue colour.

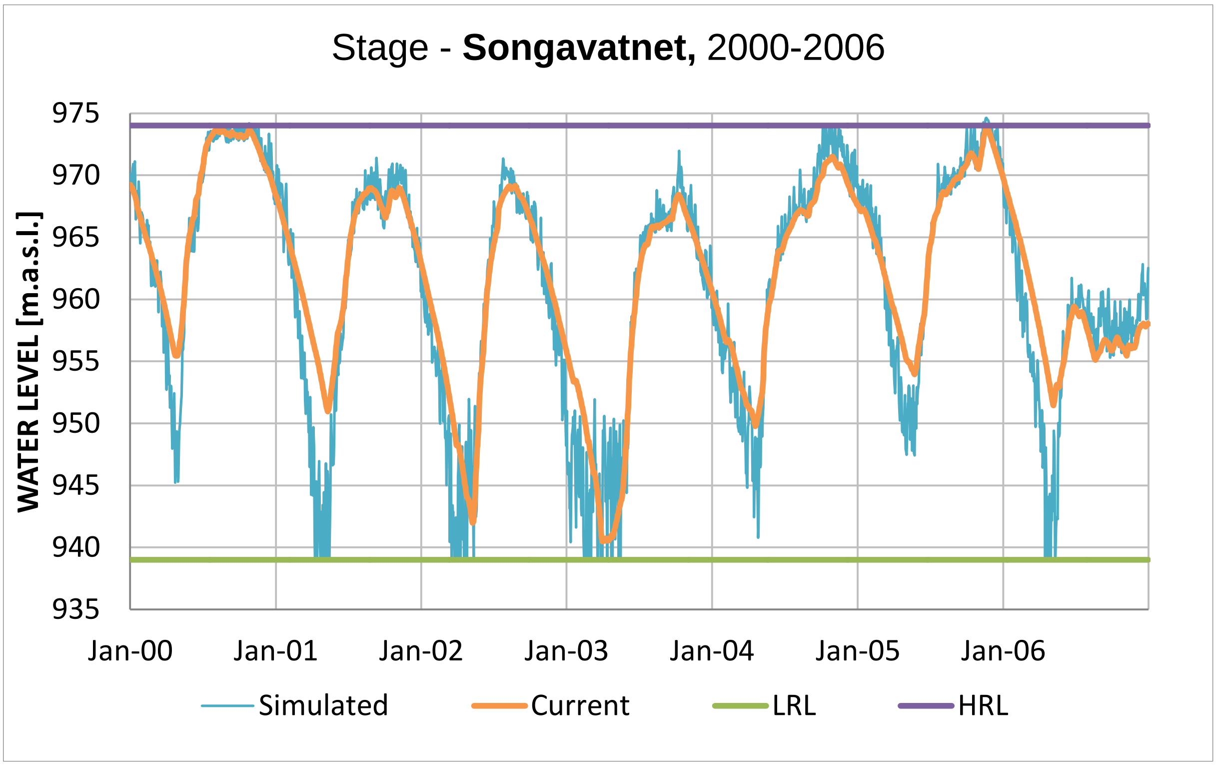


Figure 28 – Water stage, Songavatnet, 2000-2006

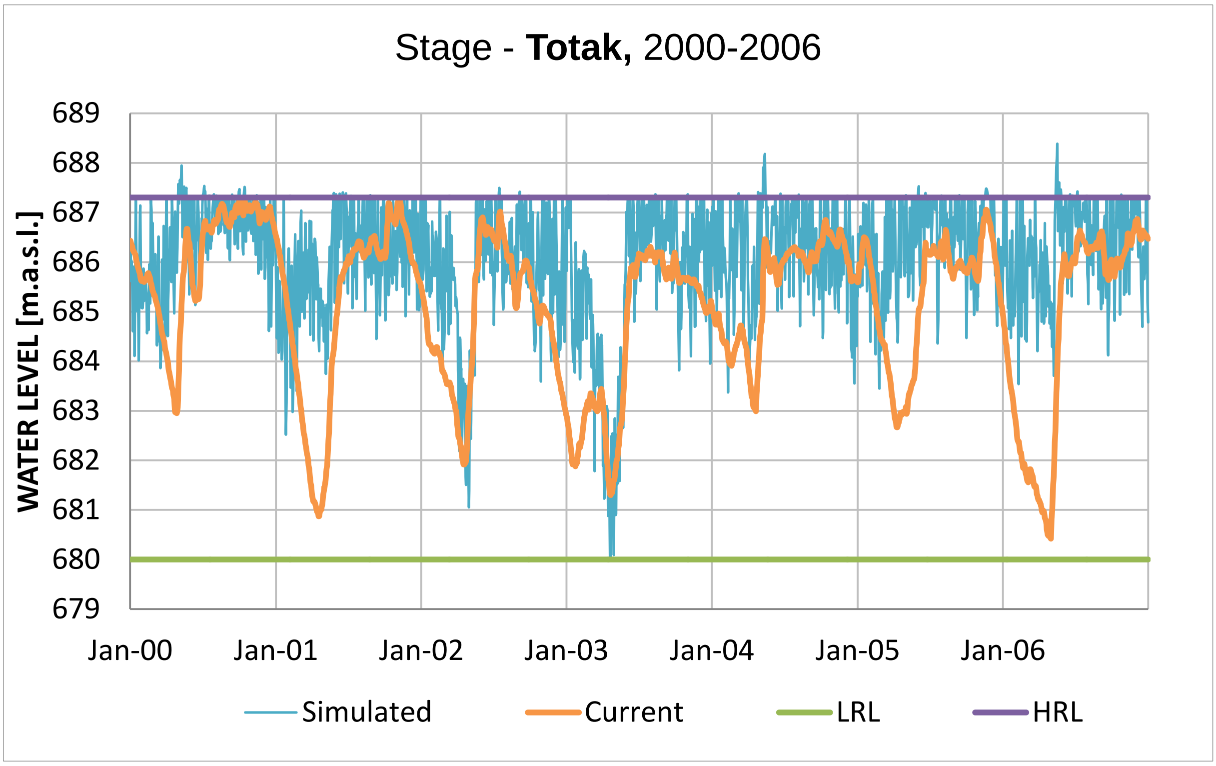


Figure 29 – Water stage, Totak, 2000-2006

As visible in Figure 28, the seasonal cycle in Songavatnet reservoir is still the same even after introducing the pumping operation. The difference is when the reservoir is normally low during spring, it is even lower with PSH. Actually 4 times out of 7 years it got totally emptied down to LRWL. During high levels before winter, reservoir is fuller but there is not such a significant difference.

Totak reservoir (Figure 29) as a lower reservoir of PSH is losing the clearly visible seasonal pattern by pumping operation as the volume of life storage is not as big as in Songavatnet due to regulation. Water in reservoir is almost all the time above the current water stage, often at HRWL.

6.4.2. Short term fluctuations

Short term fluctuations vary by balancing needs and reservoir characteristics. They are coming directly from the operation of pumping hydropower storage which is releasing significant volume of water within short period of time, hours or days, from the lower reservoir to the higher one.

The frequency of changes increased significantly as visible in Figure 30, where the changes are shown in percentage of days when there was a change in water stage. At Songavatnet the water level is changed during 6% of the days, which is altered by pumping operation to over 40% of days. Totak has a similar increase, from 17.4% to over 40% of days with water level change.

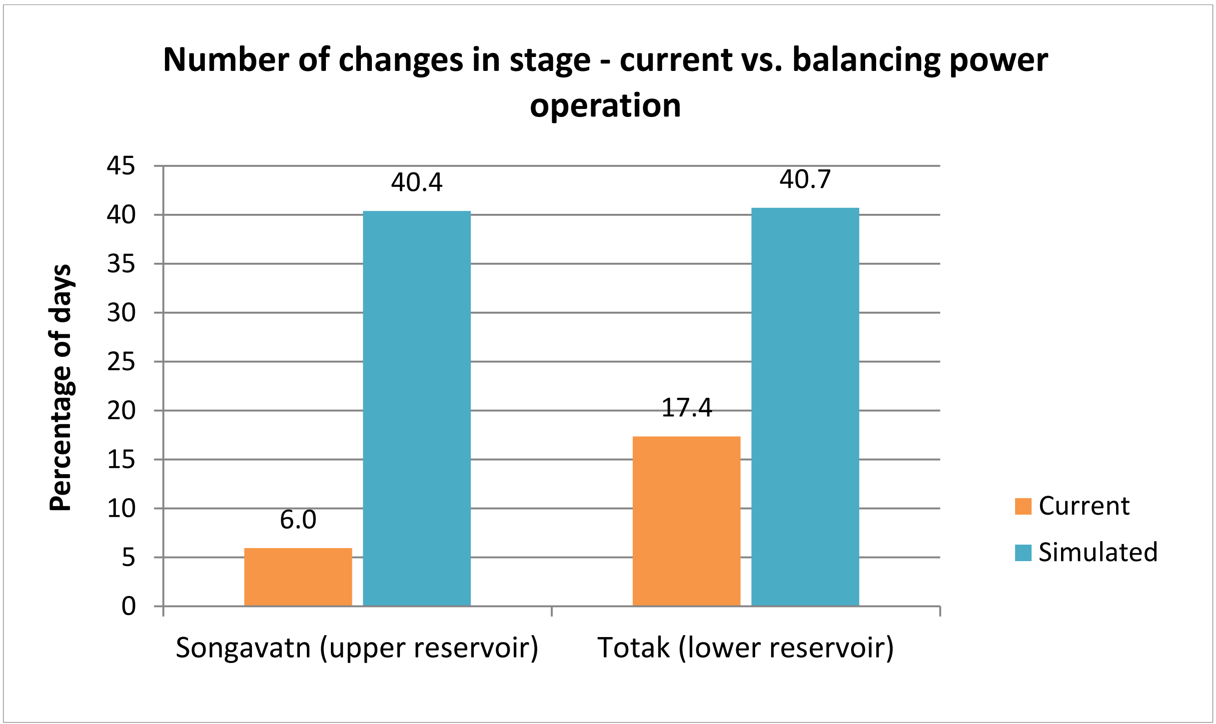


Figure 30–Change in short term fluctuations, Totak, Songavatnet, 2000-2006

The magnitude of water level fluctuation differs a lot according to reservoir properties. The big difference in relation to change of volume with change of water level is also related to current water stage in reservoir – for example Songavatnet reservoir has the LRWL close to the stage where total volume of reservoir is emptied. Therefore change in water level is big for small amount of volume. From rating curve of reservoir provided by NVE it is visible that first 1.5 metre between water level 939 and 940.5 is filled just by 0.25 mill m^3.

Average daily water level change (absolute value) is changed:

- From 0.127m/day (0.5 cm/h) to 1.01m/day (4.2 cm/h) at Songavatnet
- From 0.05m/day (0.2 cm/h) to 0.5m/day (2.1 cm/h) at Totak.

This change of daily behaviour of water level from more stable and constant changes to more often bigger oscillating changes is clearly visible in Figure 31 and Figure 32.

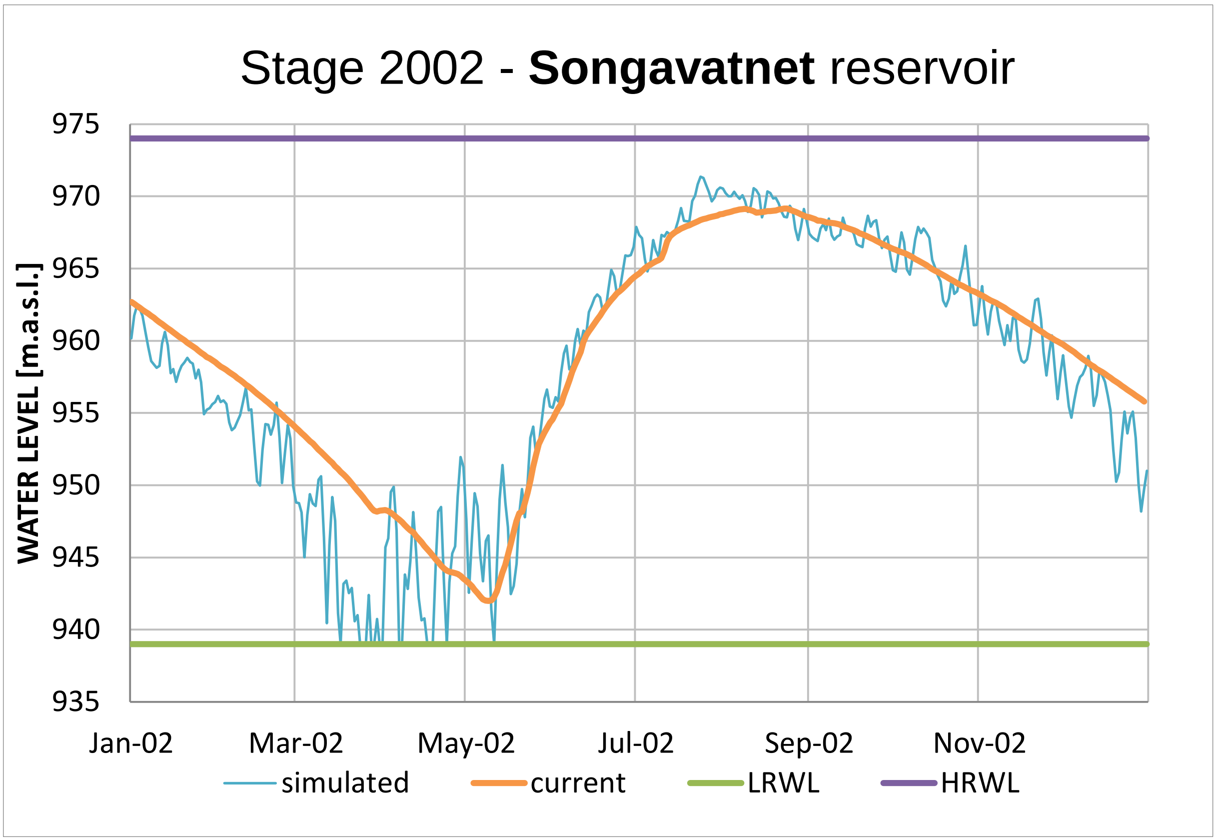


Figure 31 – Water stage, Songavatnet, 2002

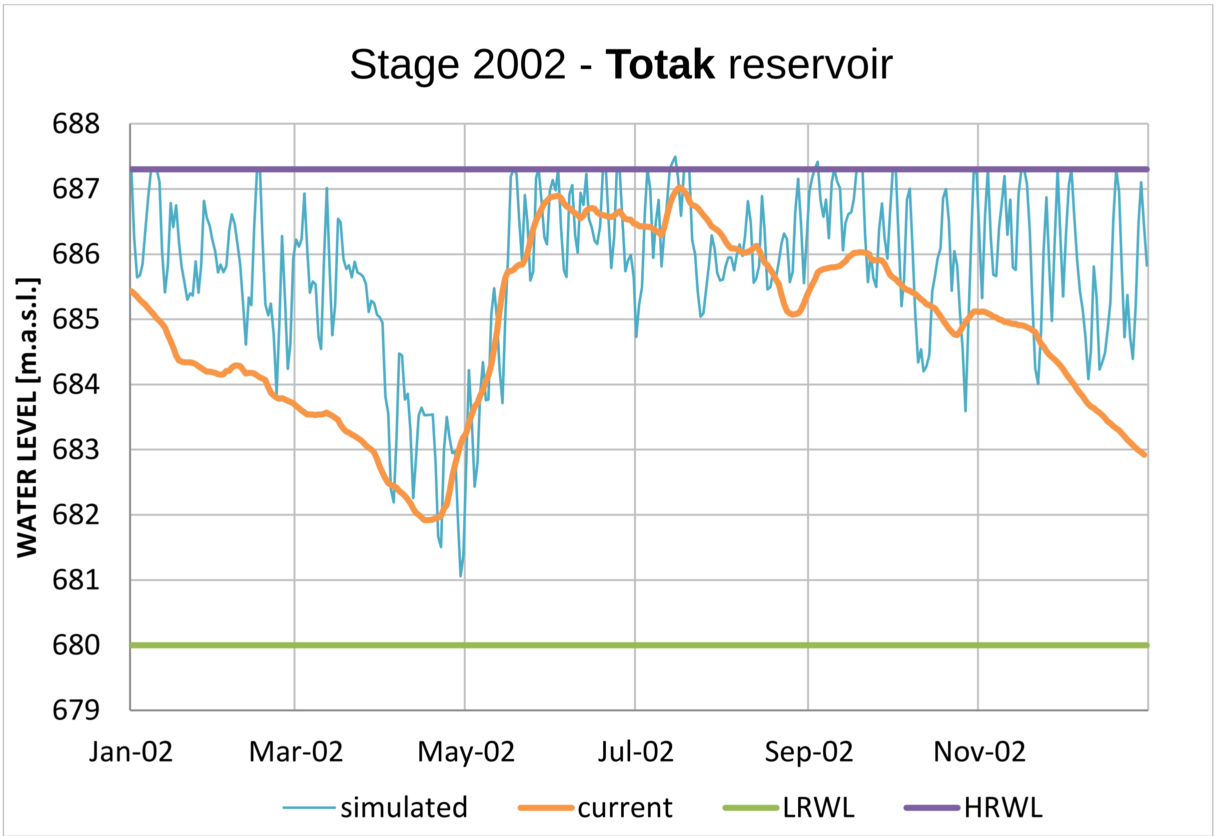


Figure 32 – Water stage, Totak, 2002

6.4.3. Seasonality pattern

Seasonality pattern of short term fluctuations is shown in Figure 33 for Songavatnet and Figure 34 for Totak, where the difference of current operation (blue colour) and simulation of PHS (orange colour) can be viewed.

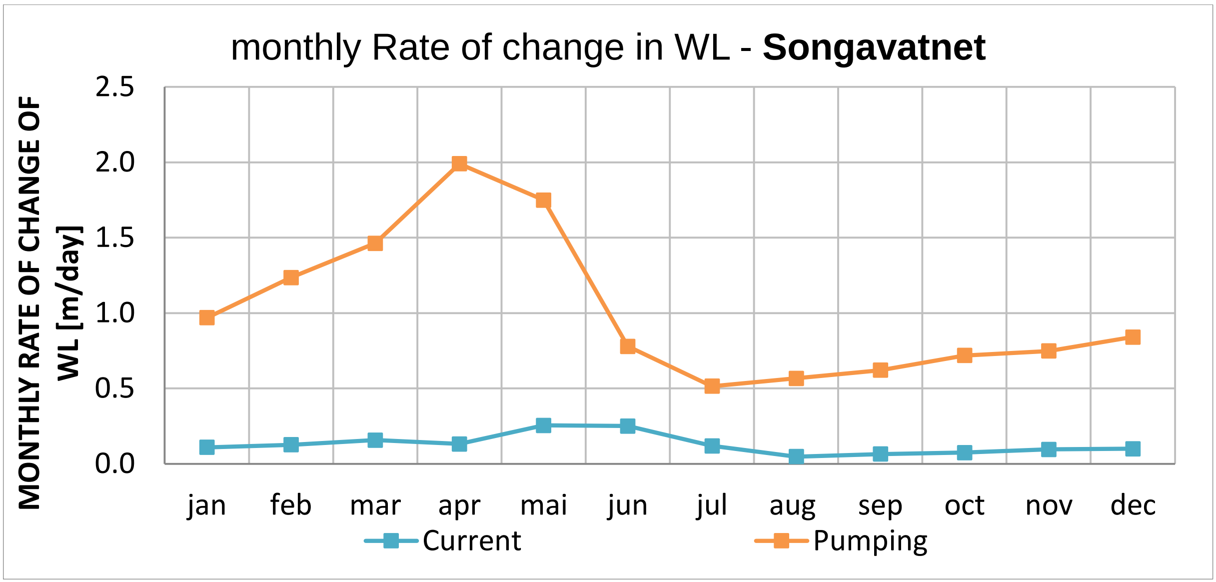


Figure 33 – Monthly rate of change in WL, Songavatnet

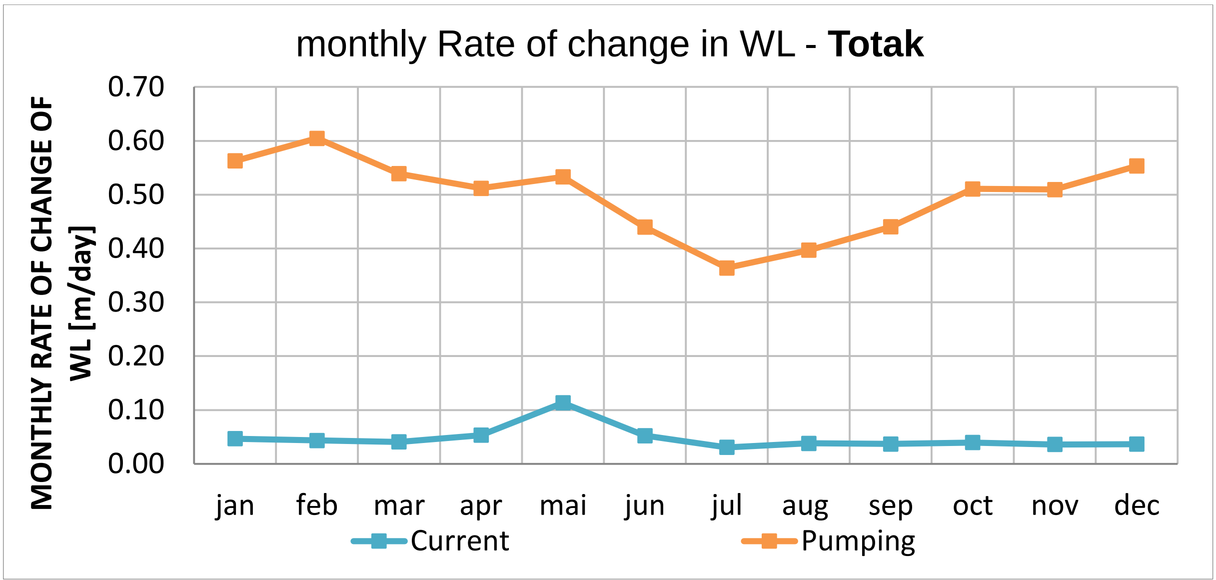


Figure 34 – Monthly rate of change in WL, Totak

Songavatnet reservoir has bigger values of rate of change in water level for pumping operation scenario, especially during spring when reservoir is getting empty. That is caused by characteristics of Songavatnet, where small volume is causing big change of water level when the reservoir is at a low stage.

6.4.4. Emptying and filling of reservoirs

Reservoir emptying or filling in current operation by reaching LRWL or HRWL is presented in Figure 35 for Songavatnet and Figure 36 for Totak.

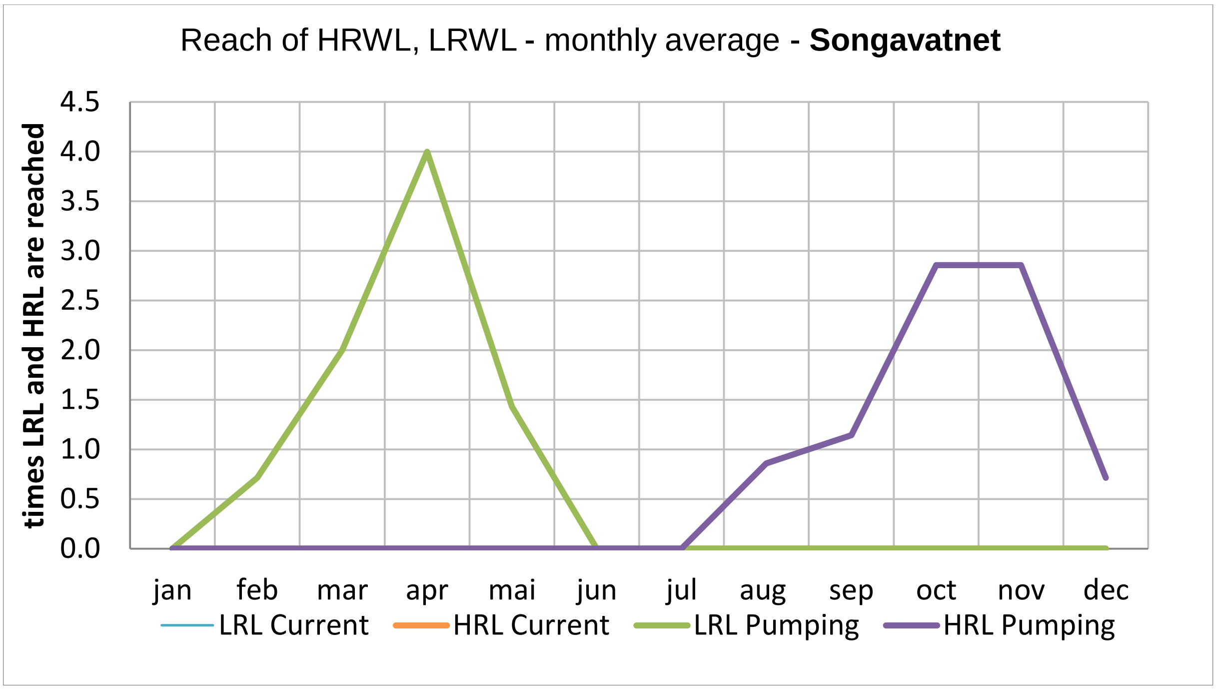


Figure 35 – Emptying and filling of Songavatnet, monthly average

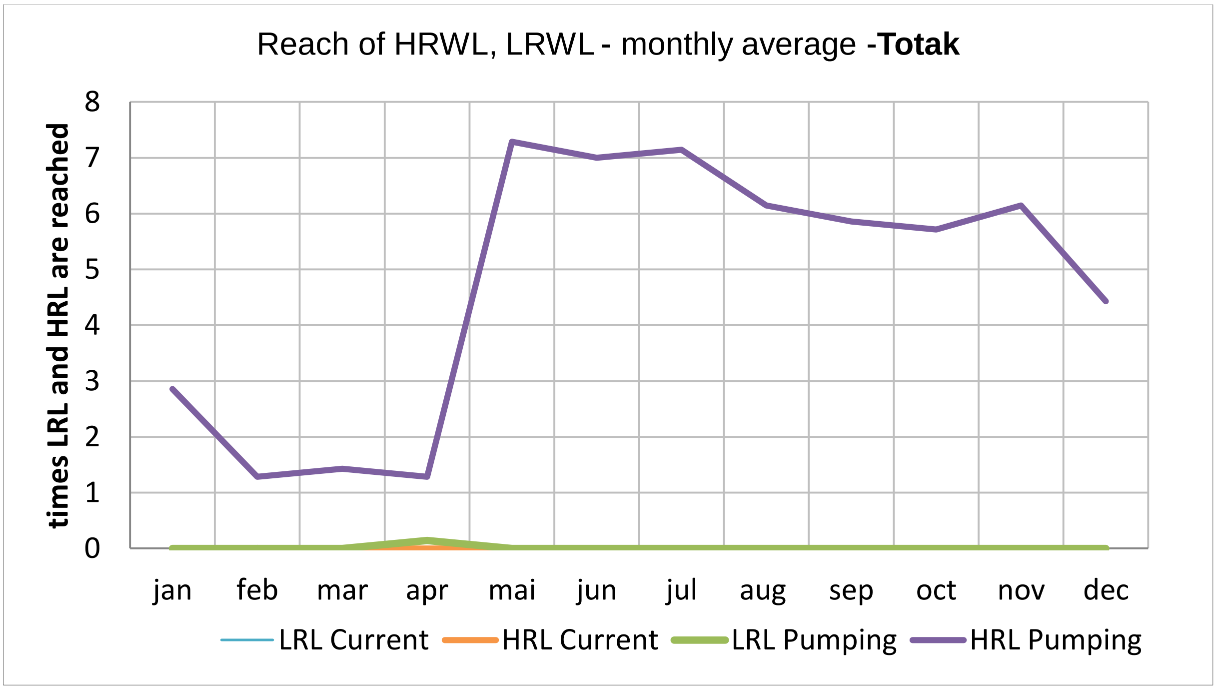


Figure 36 – Emptying and filling of Totak, monthly average

With pumping operation in Songavatnet, LRWL is reached during spring, mostly in April at an average of 4 times a month. HRWL is reached during autumn 3 times a month in October and November. Attainment of HRWL and LRWL in this reservoir is clearly followed by seasonal fluctuation. Current operation is within boundaries of HRWL and LRWL, which are not reached.

Totak is held also within the boundaries of HRWL and LRWL in current operation, but the difference from Songavatn is that LRWL except for one instance was also never reached. HRWL on the other hand is reached quite often, 5-7 times on an average from May to December.

Figure 28 and Figure 29 are showing that the water level is getting close to both limits in current operation scenario, but due to strong regulation of the whole system of hydropower plants in the area, it never touches them as that would be against intentions for hydropower production. Water level below LRWL means that hydropower plant using water from this reservoir is not able to operate. Water level above HRWL means that there will be spill of volume exceeding this water level, which means financial loss from water which could have been stored and used for production. Both situations should be avoided by correct water management, planning and operation.

6.4.5. Limitations

Operation of pumping hydropower storage plant has some limitations which decide how big the energy production or pumping operation is:

- Balancing power created by share of capacity of TradeWind project
- Turbine capacity
- Reservoir volume

The power plant's maximum power yield (electricity generation) or consumption (pumping) is limited to the power that corresponds to the water discharge the turbine is designed for. If the balancing power demand exceeds this power the turbine capacity becomes the limiting factor for the provision of balancing power. Further, the amount of available balancing power may be limited by the water volumes which are available/free in the reservoirs.(11)

Factors determining the amount of balancing power operation of Songa PSH between Songavatnet and Totak during the period 2000-2006 is shown in Figure 37 for pumping or production, or both together. Most limiting factor for 1200 MW of installed power is the energy that needed to be balanced (81% for pumping, 66% for production), and then turbine capacity (for pumping, 16%) or free volume in lower reservoir (for production, 23%). Number of days where each limit was reached is shown in relevant columns. In period of 2000-2006 total amount of days for pumping operation was 1207 and for production it was 1211 days.

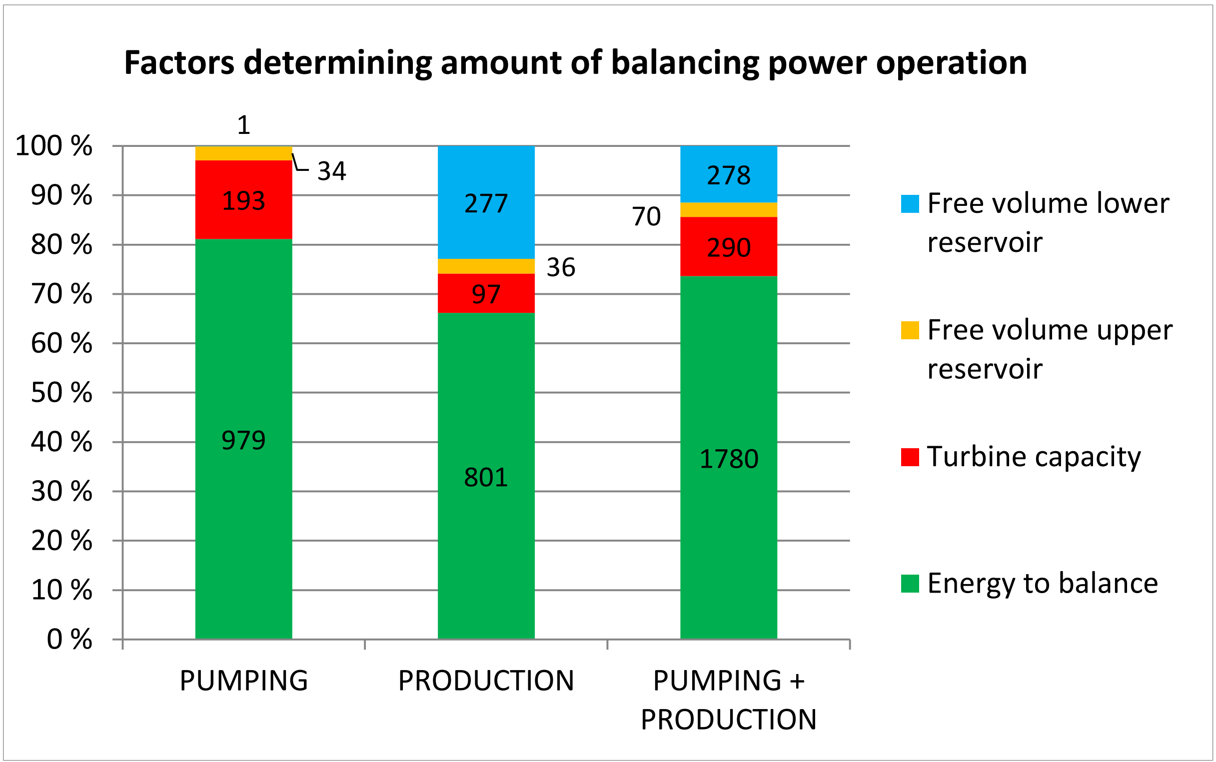


Figure 37 – Factors determining amount of balancing power operation, Songa PSH

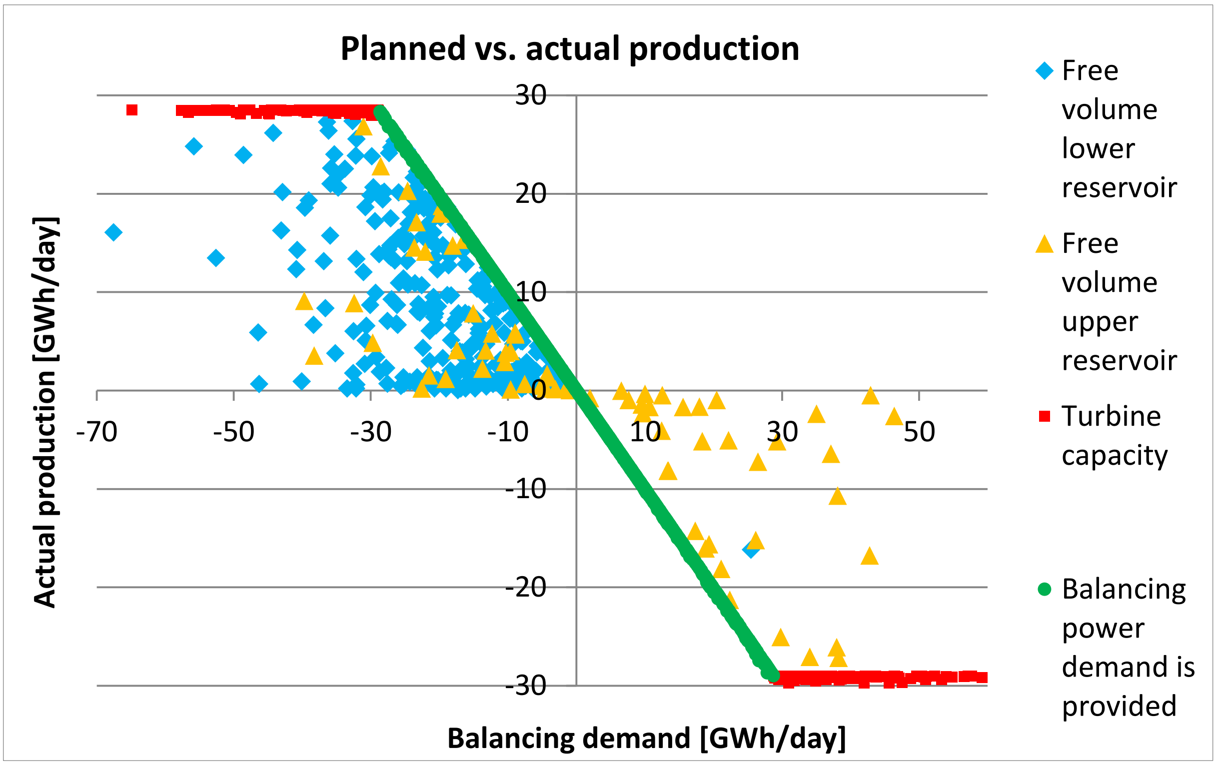


Figure 38 – Planned versus actual production, Songa PSH

Figure 38 represents a plot of planned production versus actual production with limiting factors. Red dots creating lines are representing the maximal production limited by turbine capacity for production or pumping. Green line is representing the values where demand for operation or pumping can be met without limitations. Blue and yellow marks are representing situations where demand is not met due to lack of free volume in upper or lower reservoir. Second quadrant is representing production, fourth quadrant the pumping operation.

6.4.6. Overview of 1200MW PSH variant

In this case, the 1200MW of installed power of PSH is suggested by C. C. Garcia (31). This PSH is used for balancing of 6% of capacity needed by TradeWind project which is fulfilling in:

- 81.1% of this share of capacity at pumping operation mode, where the most limiting factor is turbine capacity (16%)
- 66.1% of this share of capacity at production mode, where the most limiting factor is free volume in lower reservoir, in other words Totak is filled to HRWL and there is no place for extra volume of water which should be used for production of energy

From environmental point of view, studies by SINTEF(35) and (11)suggested that withdrawal rate should not exceed 13 centimetres per hour. In this case the maximal withdrawal rate in Totak is 5.3 cm/hour which is well below target. In Songavatnet this limit is exceeded with maximal withdrawal rate of 32.7 cm/hour, which is caused by reservoir characteristics. When the results are filtered to show only withdrawal rates when the reservoir life storage is filled by more than 90 million of m^3 (84% of days in period 2000-2006, Figure 39) the maximal withdrawal rate is only 11.7 centimetres per hour. In Totak there is enough water in life storage (average life storage of Totak when Songavatnet is below 90 mill m^3 is 182 mill m^3) which could be used to fill Songavatnet by pumping.

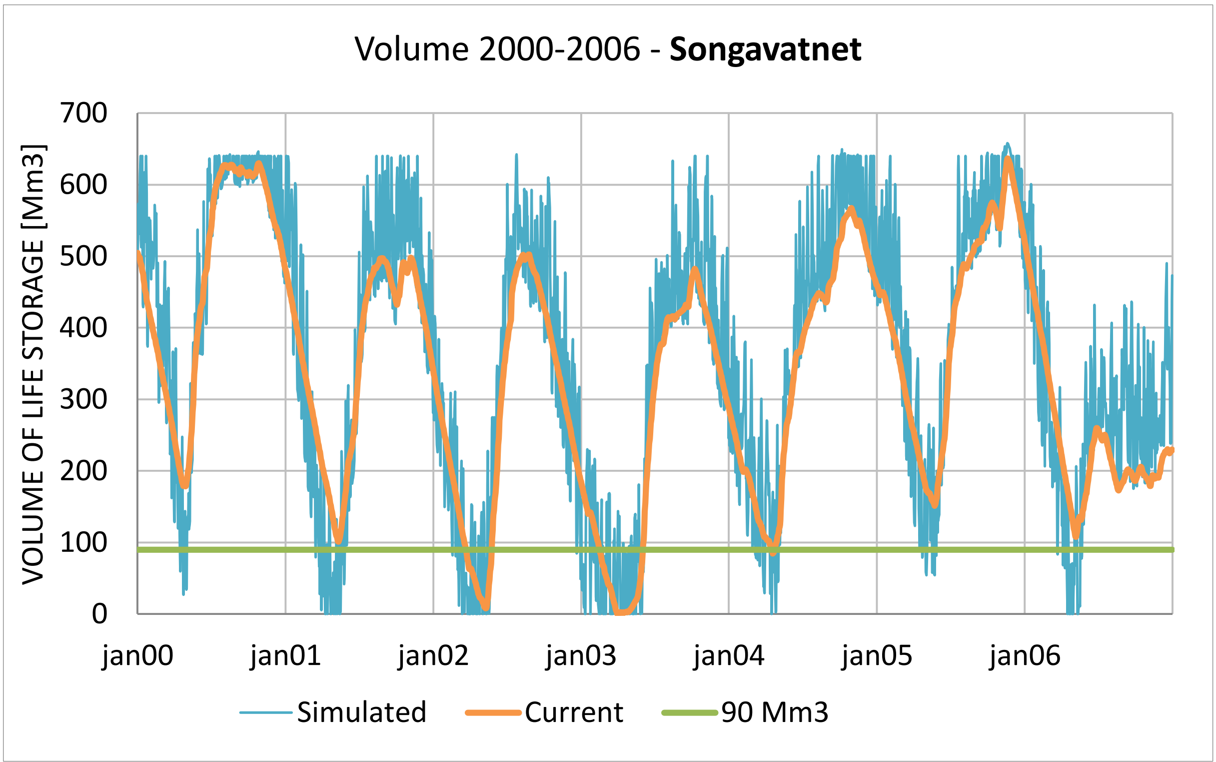


Figure 39 – Volume of life storage in Songavatnet, 2000-2006

6.5. New Songa pumped storage hydropower plant, P = 3150 MW

As an alternative to 1200 MW, a variant with bigger installed power of 3150 MW was explored. Bigger installed output is causing bigger fluctuations in both reservoirs as larger volumes of water have to be transferred. Share of energy for balancing of TradeWind project by Songa pumping storage hydropower is established at 15.8% (3150 MW /20 000 MW).

6.5.1. Seasonal trend

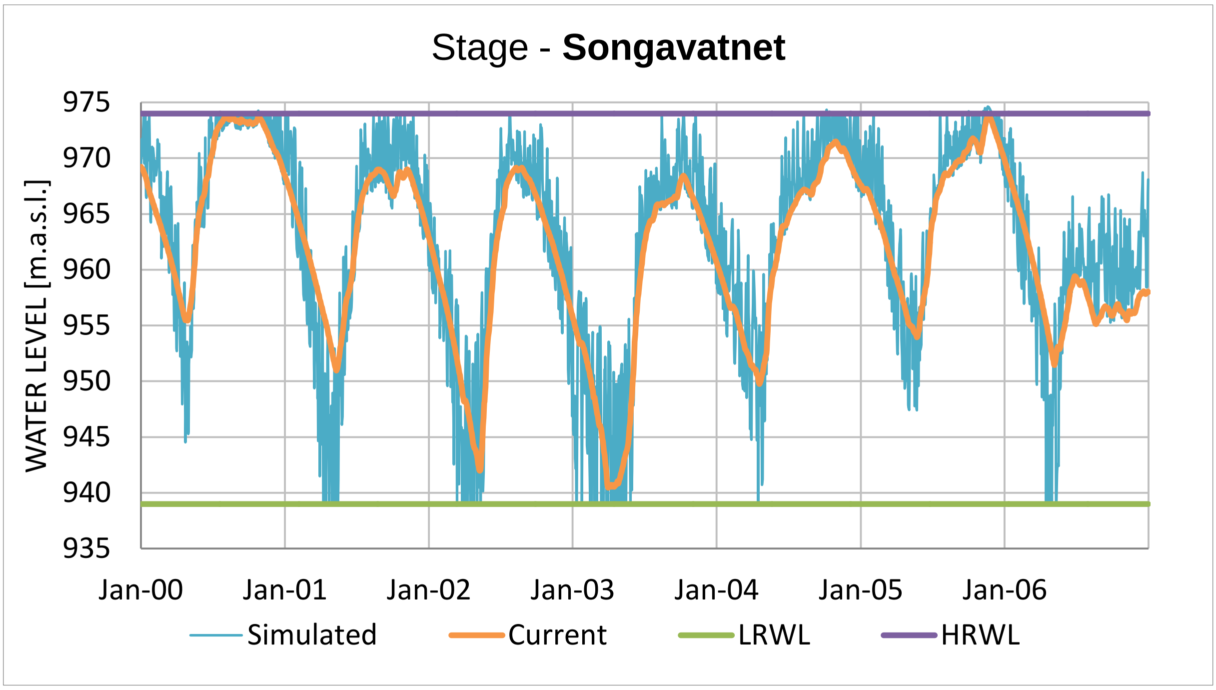


Figure 40 – Water stage, Songavatnet, 2000-2006

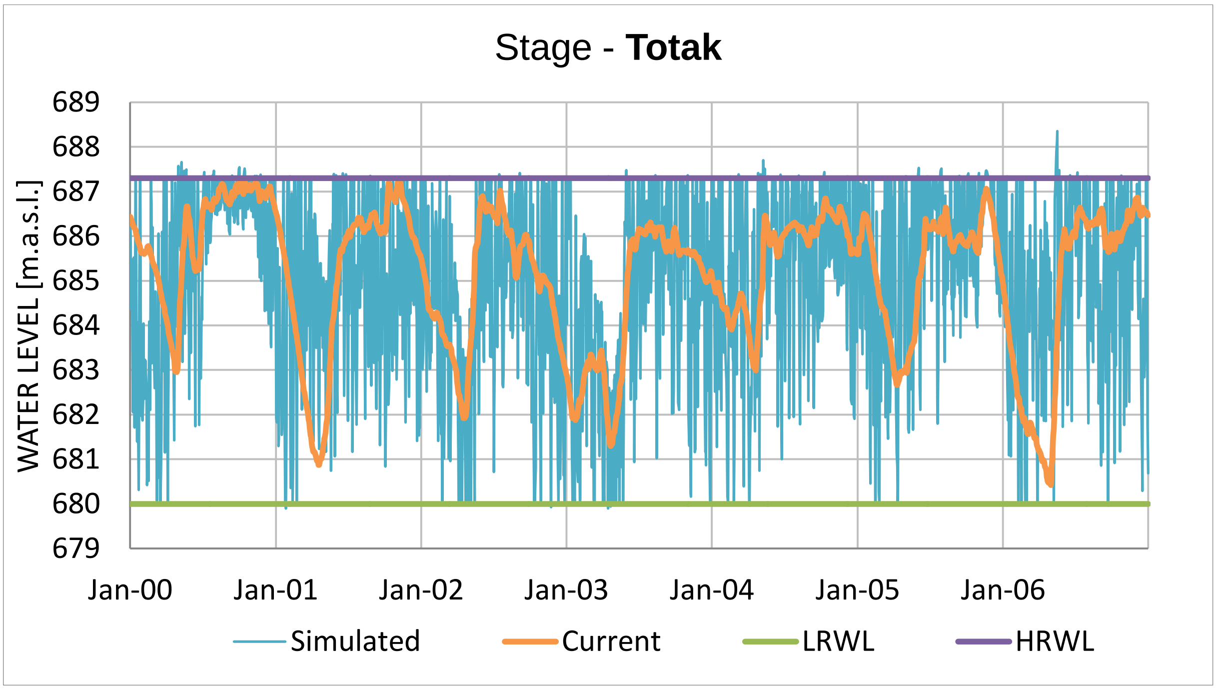


Figure 41 – Water stage, Totak, 2000-2006

Songavatnet reservoir is still following the strong seasonal trend even with pumping regime. Totak is on the other hand is losing the seasonal pattern in some years and it is strongly supressed during other years owing to short term fluctuations caused by operation of Songa PSH. Water stage development in period of 2000-2006 is visible in Figure 40 for Songavatnet and Figure 41 for Totak. The change from 1200MW variant is visible by bigger influence of pumping which is overcoming the current seasonal pattern especially in lower reservoir – Totak.

6.5.2. Short term fluctuations

Short term fluctuations have almost the same characteristics as in previous variant. Presented in Figure 42 is:

- 41% of days with stage change in Songavatnet (1200MW variant 40.4%)
- 41.4% of days with stage change in Totak (1200MW variant 40.7%)

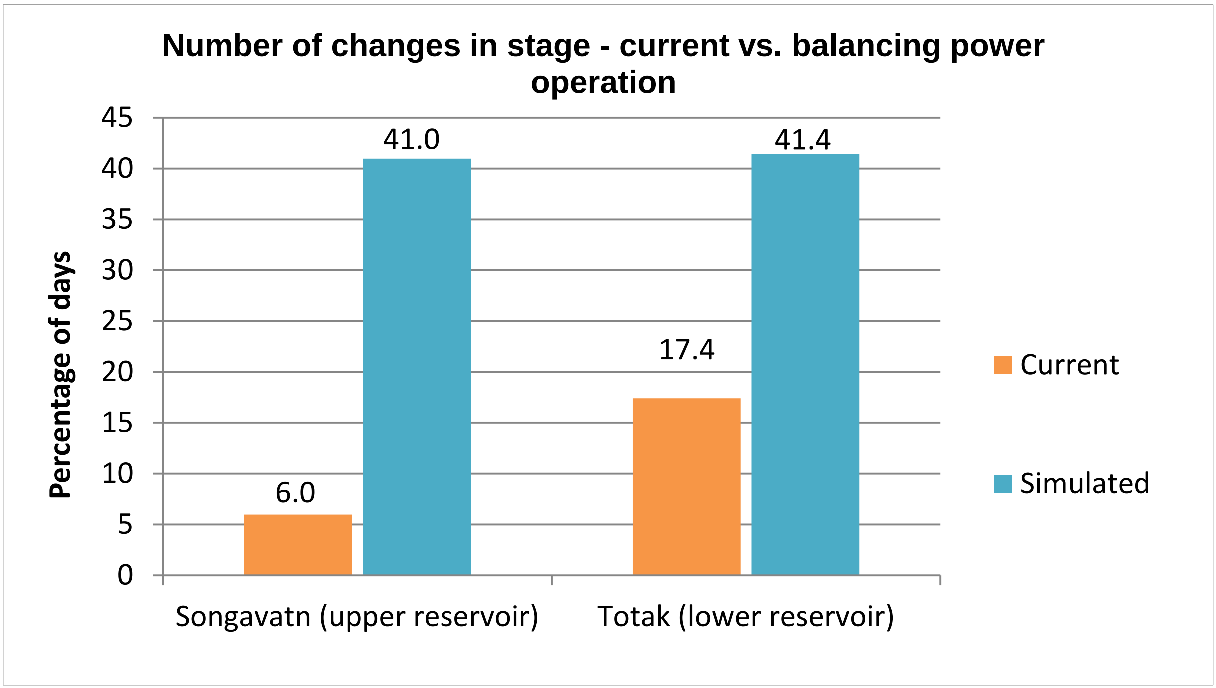


Figure 42 – Number of changes in stage, Songavatnet and Totak, 2000-2006

Average water level change in this scenario (absolute value) is one time bigger than in previous variant with installed power 1200MW:

- 2.09 m/day (8.7 cm/h) at Songavatnet (1.01m/day at 1200MW variant)
- 1.18 m/day (4.9 cm/h) at Totak (0.5 m/day for 1200MW variant).

Fluctuations of stage for both reservoirs are visible from Figure 43 and Figure 44.

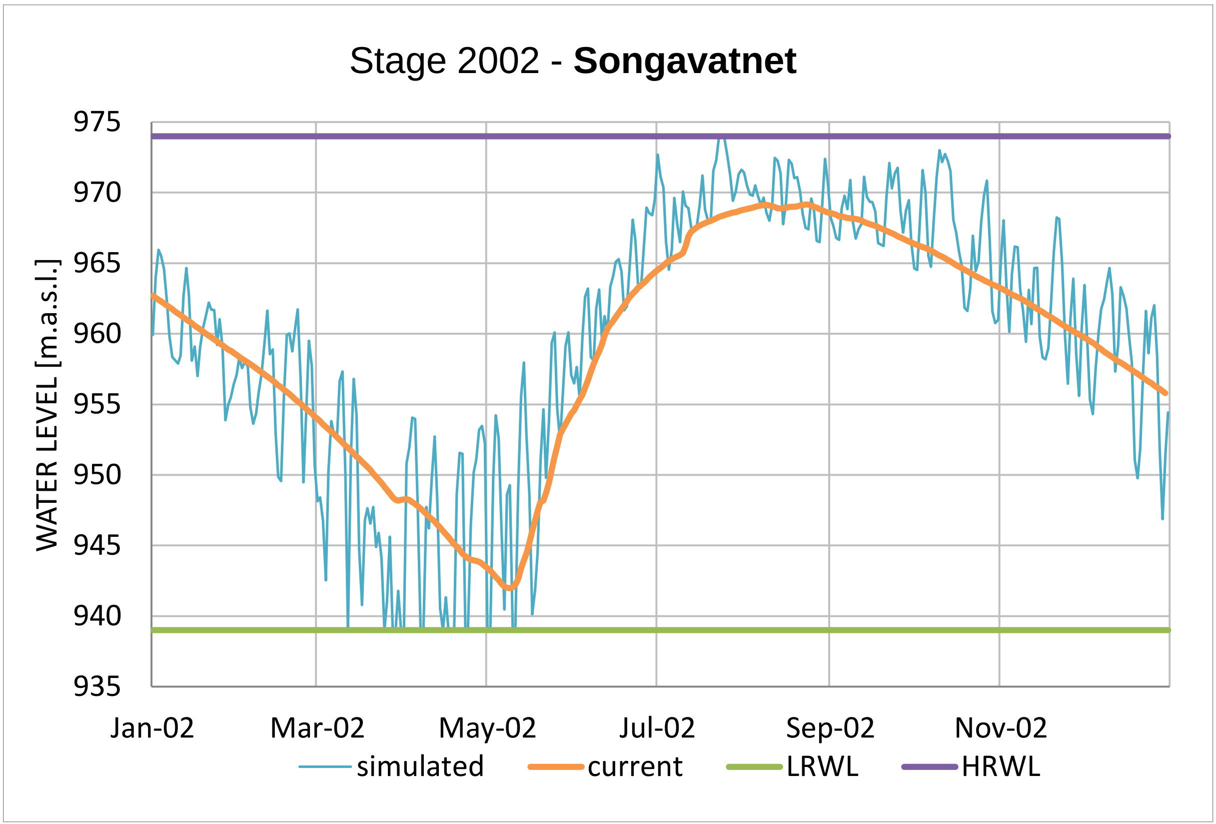


Figure 43 – Water stage, Songavatnet, 2002

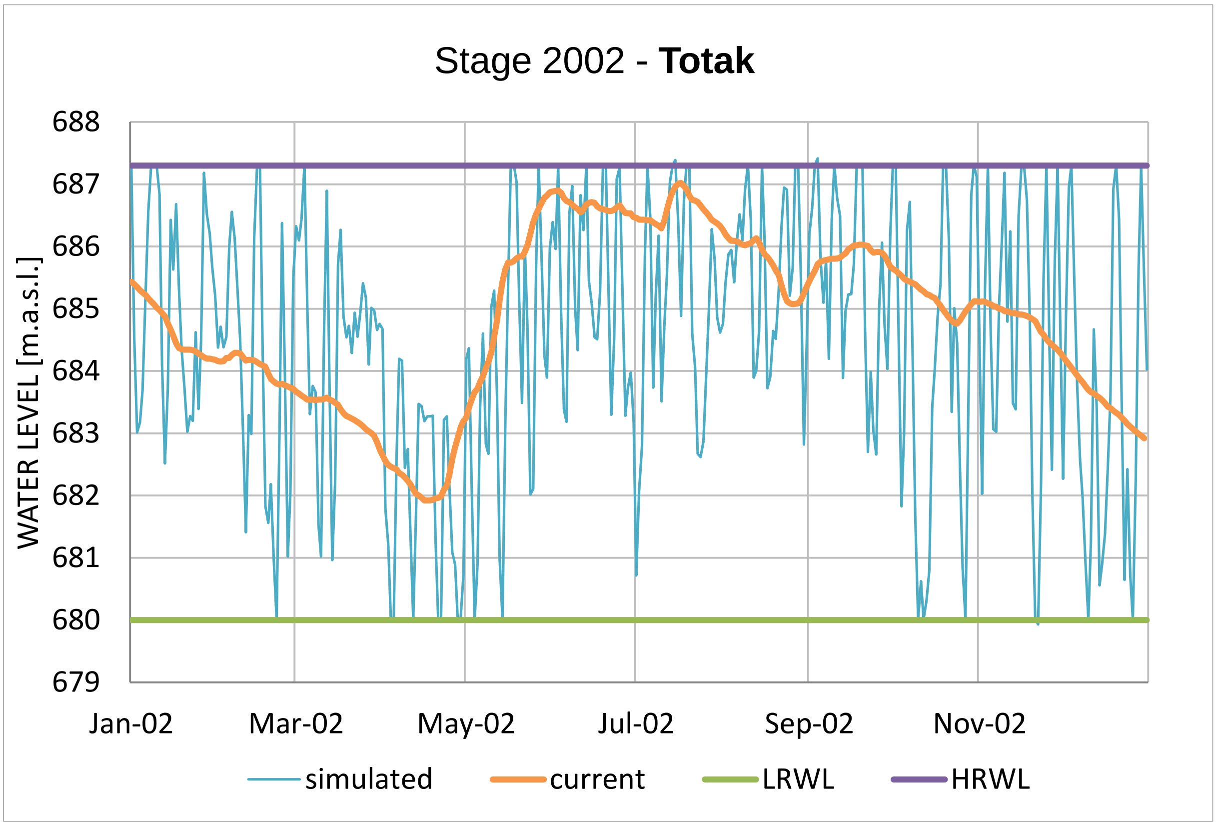


Figure 44 – Water stage, Totak, 2002

6.5.3. Seasonality pattern

Seasonality pattern of rate of change in WL can be seen in Figure 45 and Figure 46, where blue colour is representing current operation, orange colour operation with PSH with 3150MW of installed power, and green colour is for previous case of PSH with 1200MW of installed power. As visible from figures pattern of rate of change is the same in both scenarios, but the extent is doubled.

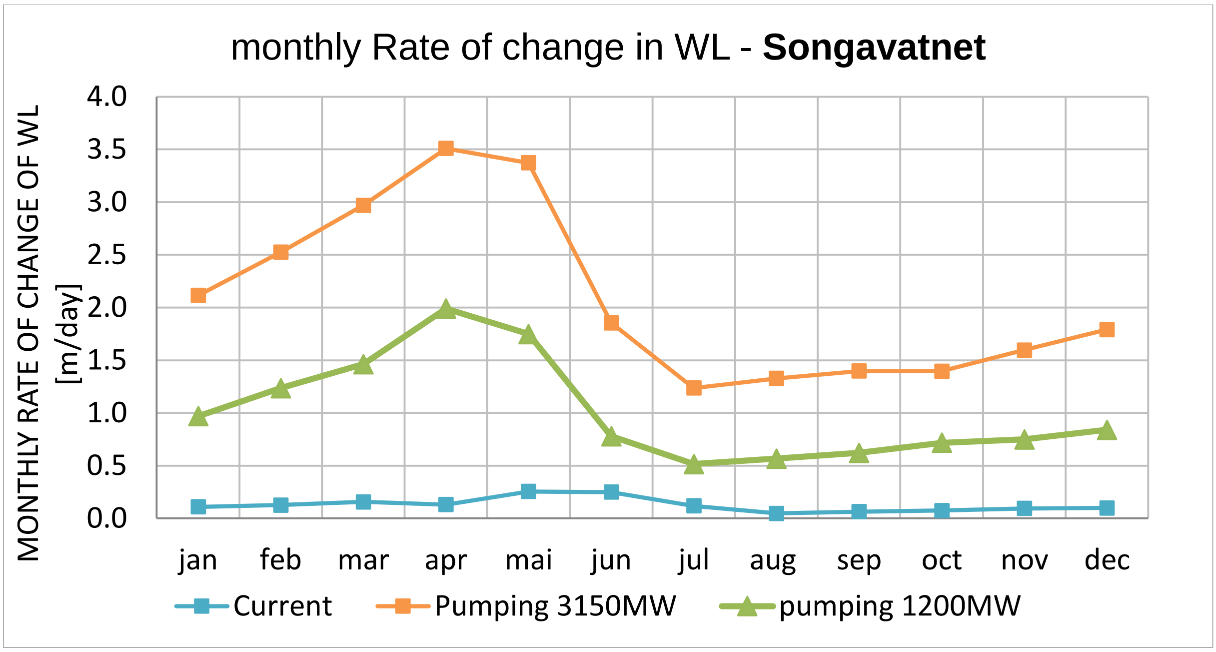


Figure 45 – Monthly rate of change in WL, Songavatnet

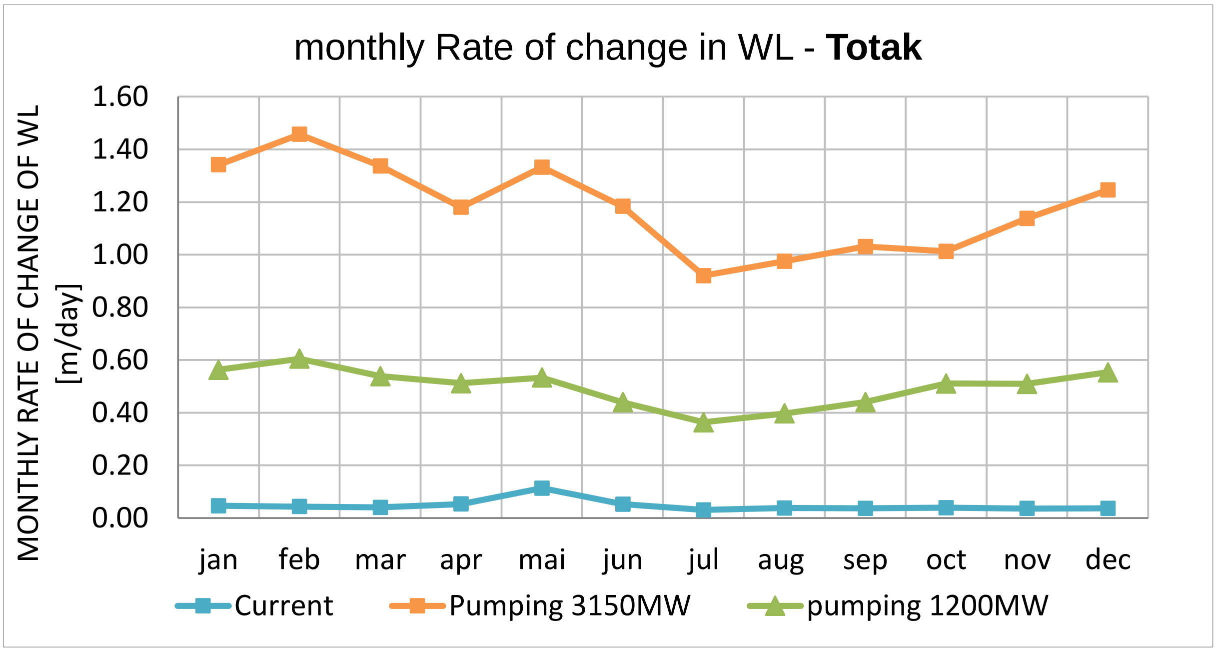


Figure 46 – Monthly rate of change in water level, Totak

6.5.4. Emptying and filling of reservoirs

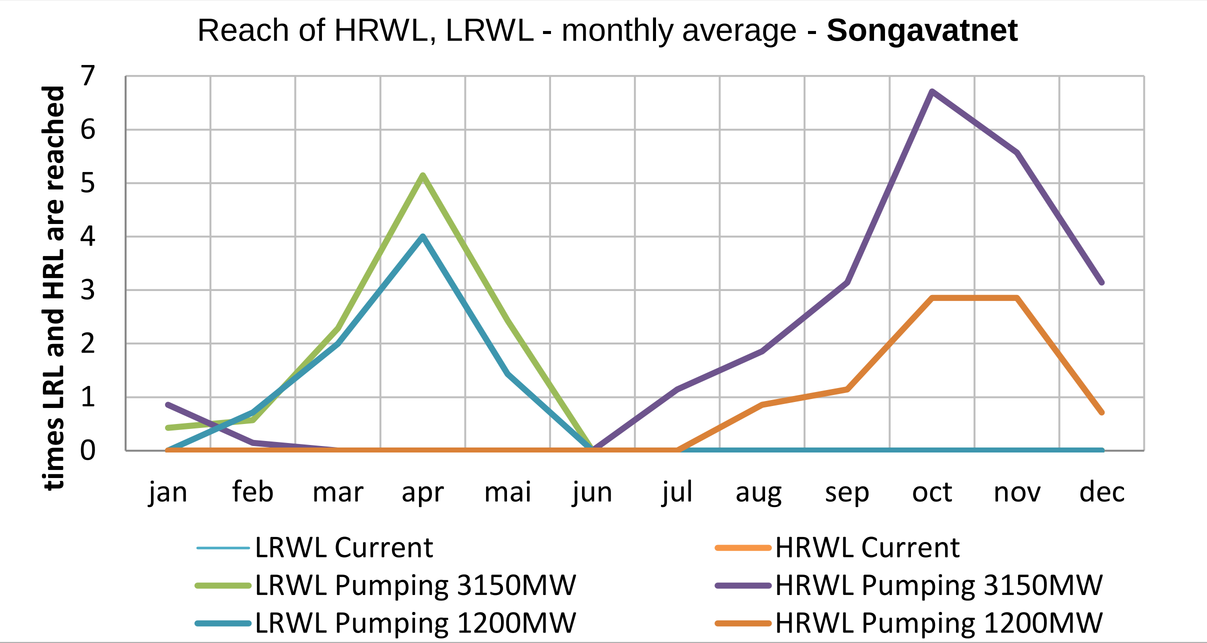


Figure 47 – Emptying and filling of Songavatnet, monthly average, 2000-2006

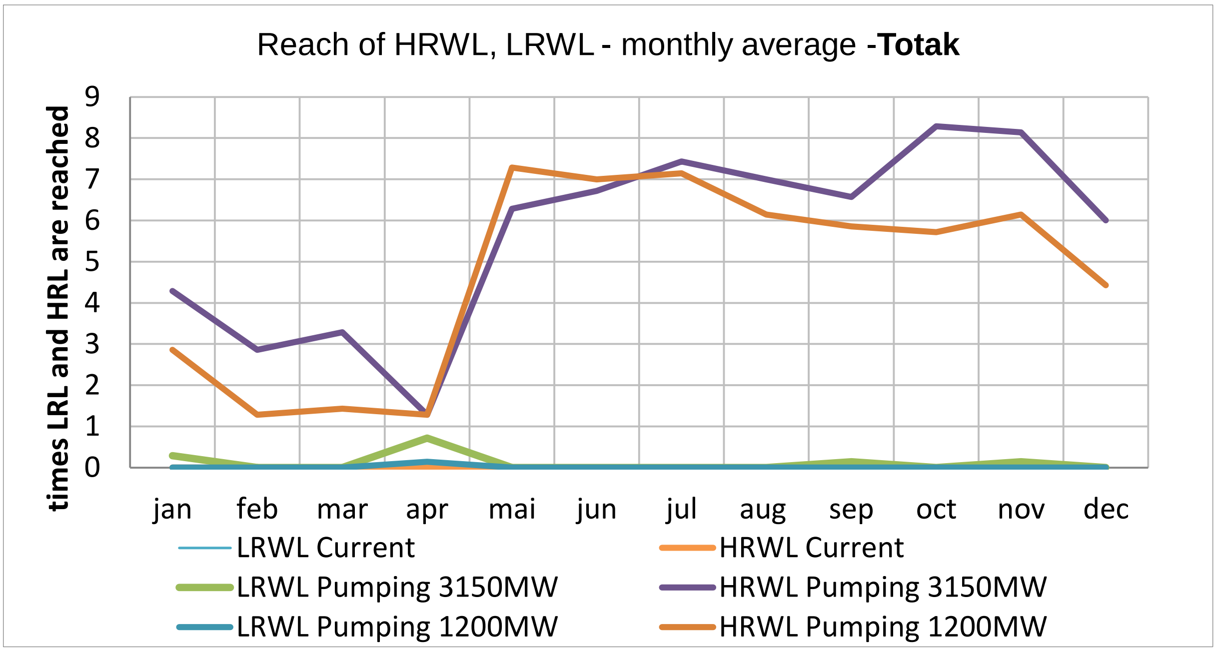


Figure 48 – Emptying and filling of Totak, monthly average, 2000-2006

In Figure 47 it is visible that LRWL in Songavatnet is reached 5 times on an average during April instead of 4 times in 1200MW variant. HRWL is reached significantly more times during the autumn. In Totak (Figure 48) the LRWL is reached almost the same in both variants, HRWL is reached few times more during the end of the year.

6.5.5. Limitations

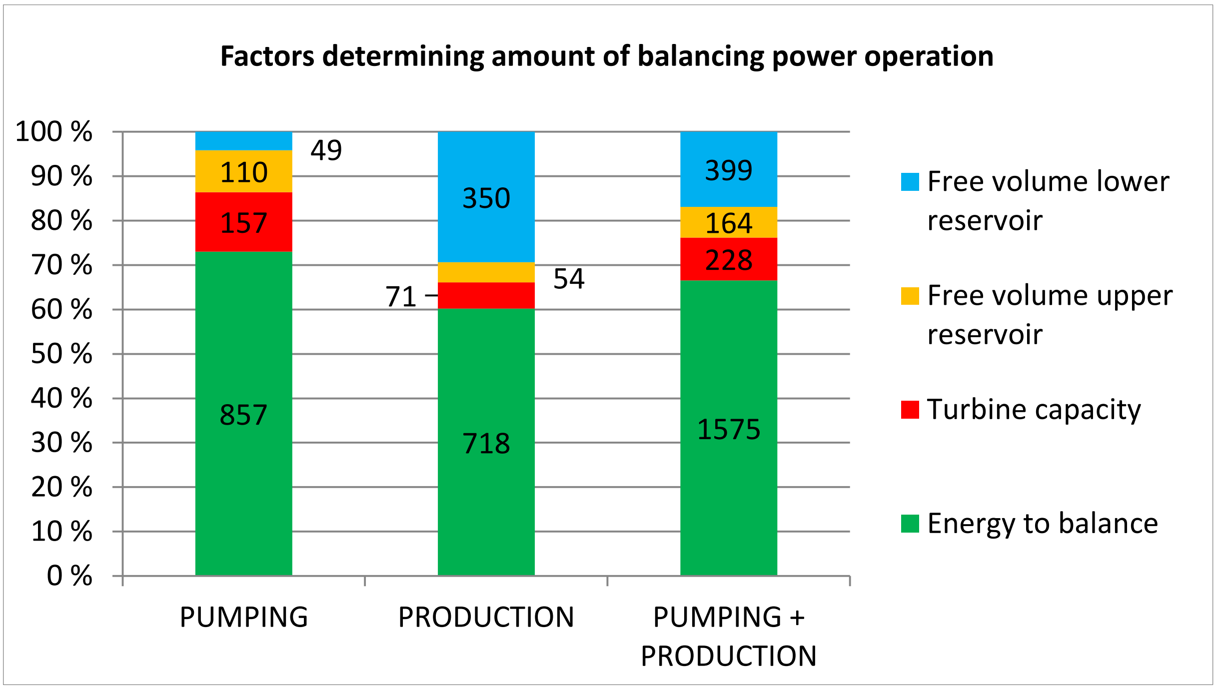


Figure 49 - Factors determining amount of balancing power operation, Songa PSH

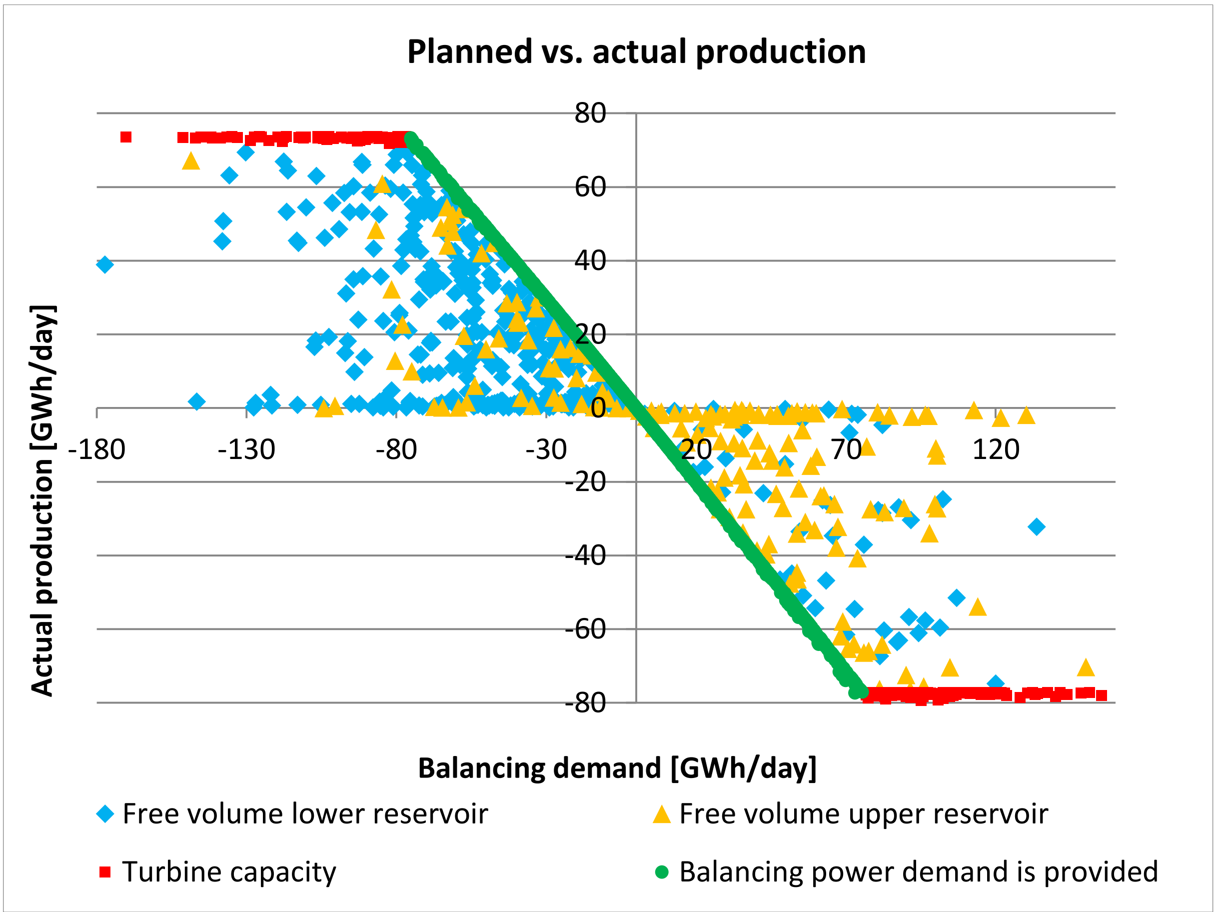


Figure 50 - Planned versus actual production, Songa PSH

Factors determining the amount of balancing power operation of Songa PSH with installed power of 3150MW between Songavatnet and Totak between 2000 and 2006 are shown in Figure 49 for pumping or production, or both together. Most limiting factor for 3150 MW of installed power is still the energy to balance – 73% for pumping, 60% for production (80% for pumping and 65% for production for 1200MW variant). Turbine capacity is the next limiting factor for pumping operation – 13% and free volume in lower reservoir for production – 29%. Number of days where each limit was reached is shown in relevant columns. In period 2000-2006 total amount of days for pumping operation was 1173 (1207 for previous 1200MW variant) and for production 1193 days (1211 days for previous 1200MW variant).

6.5.6. Overview of 3150MW variant

In this case the 3150MW is used for balancing 15.8% of capacity needed by TradeWind. Project is fulfilling

- 73.1% of this share of capacity at pumping operation mode, where the most limiting factor is turbine capacity (13.4%) followed by free volume in upper reservoir (9.4%)
- 60.2% of this share of capacity at production mode, where the most limiting factor is free volume in lower reservoir (29.3%), in other words Totak is filled to HRWL and there is no place for extra volume of water which should be used for production of energy

Water level changes were in studies by SINTEF Energy Research (35), (11) factors representing the forcing causing environmental impacts of pumping storage hydropower plant operation.

Totak in this scenario with PSH of installed power 3150MW is still within the limit of 13cm/hour of withdrawal of water stage. Maximal withdrawal rate is 13 cm/hour which is 3.12 metres per day, mean water stage withdrawal in this case is about 5.2 cm/hour as shown in Figure 51.

Songavatnet as a smaller reservoir has very large withdrawal rates when it is almost empty. Maximal withdrawal rate observed is 55 cm/day which is 4.2times more than suggested limit value. On the other hand mean value of withdrawal rate is just 9.3 cm/hour which fulfils the criteria. Results are presented in Figure 51.

SONGA VATNET m/day	Current		Simulated 3150MW	
	Rate of stage INCREASE	Rate of stage DECREASE	Rate of stage INCREASE	Rate of stage DECREASE
Median	0.10	0.11	1.52	1.61
P90	0.33	0.17	4.45	4.93
Maximum	0.96	0.51	12.34	13.22
Mean	0.15	0.11	2.12	2.19

TOTAK m/day	Current		Simulated 3150MW	
	Rate of stage INCREASE	Rate of stage DECREASE	Rate of stage INCREASE	Rate of stage DECREASE
Median	0.04	0.04	1.00	1.04
P90	0.15	0.08	2.87	2.72
Maximum	0.43	0.16	3.71	3.13
Mean	0.06	0.04	1.24	1.24

SONGA VATNET cm/h	Current		Simulated 3150MW	
	Rate of stage INCREASE	Rate of stage DECREASE	Rate of stage INCREASE	Rate of stage DECREASE
Median	0.42	0.46	6.32	6.72
P90	1.38	0.71	18.54	20.53
Maximum	4.00	2.12	51.43	55.07
Mean	0.63	0.46	8.85	9.13

TOTAK cm/h	Current		Simulated 3150MW	
	Rate of stage INCREASE	Rate of stage DECREASE	Rate of stage INCREASE	Rate of stage DECREASE
Median	0.17	0.17	4.18	4.34
P90	0.62	0.33	11.96	11.32
Maximum	1.79	0.67	15.45	13.03
Mean	0.26	0.18	5.15	5.19

Figure 51 – Water stage changes, current situation and 3150MW PSH, Songavatnet and Totak

The results of withdrawal rate changes in Songavatnet according to the actual volume of water in the reservoir are presented in Figure 52 from which it is visible that without any limitations the withdrawal rate greater than 13cm/h is reached in 1 out of 4 days in average, if the volume is kept above 300 million of m^3 which is less than half of the volume, the limit is exceeded only in 1 out of 10 cases. Volume development in Songavatet during period of 2000-2006 is represented in Figure 53.

Volume of life storage	Songavatnet - rate of stage				nb. of days when decrease >13cm/h
	increase		decrease		
	m/day	cm/hour	m/day	cm/hour	
any	12.34	51.4	-13.22	-55.1	658 (25.8%)
>100Mm^3	12.34	51.4	-6.88	-28.6	491 (19.2%)
>200Mm^3	5.72	23.8	-5.49	-22.9	376 (14.7%)
>300Mm^3	4.96	20.7	-4.94	-20.6	272 (10.7%)
>400Mm^3	4.27	17.8	-4.54	-18.9	175 (6.9%)
>500Mm^3	3.83	16	-4.24	-17.7	90 (3.5%)

Figure 52 – Change of rate of stage according to volume, Songavatnet

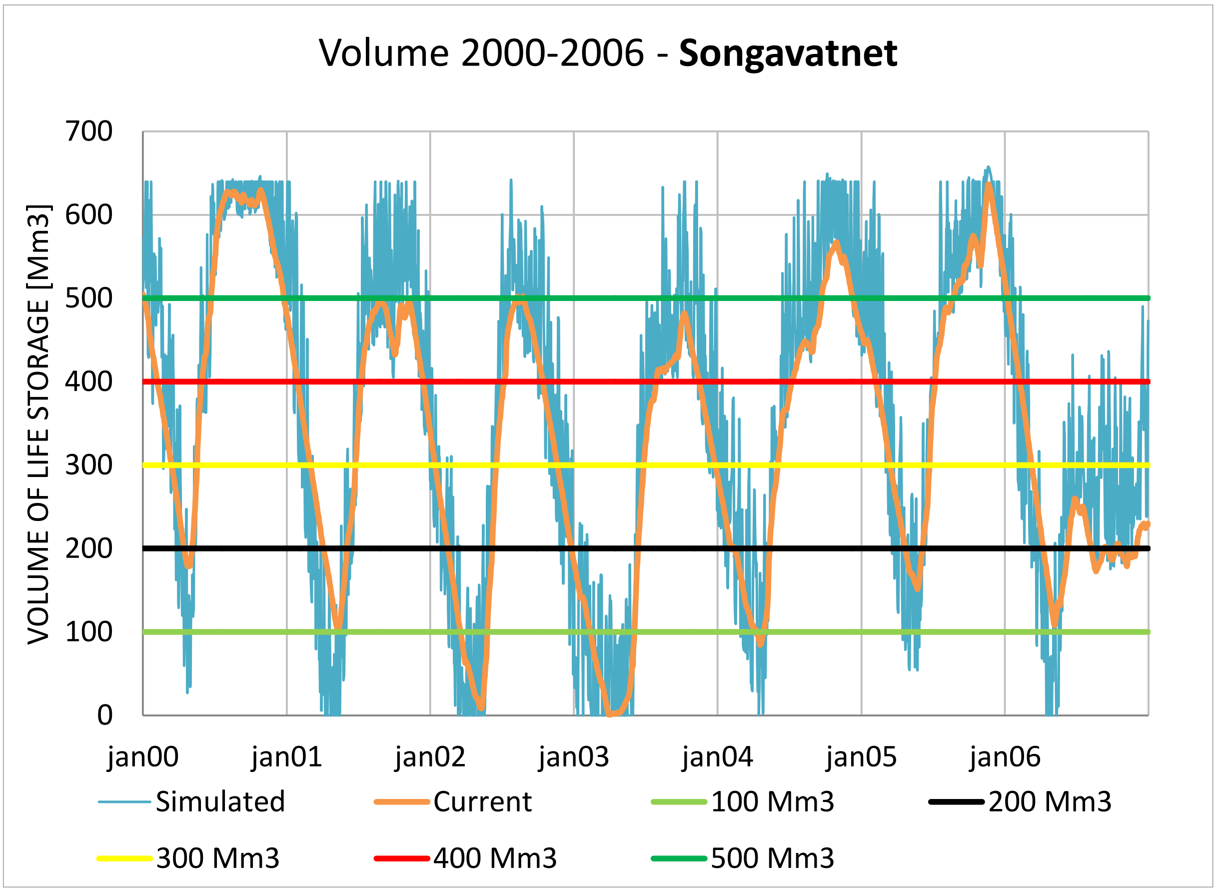


Figure 53 – Volume variation in Songavatnet, 2000-2006

6.6. Comparison of variants

Process of choosing of right and reasonable installed power of PSH is a balancing process with multiple aspects; where, economic feasibility is the most relevant parameter for actually considering if the project is worth developing. The project has to be at the same time also technically viable and environmentally acceptable.

Both variants presented in this project are just preliminary suggestions trying to see the reasonable boundaries for PSH between Songavatnet and Totak reservoirs in Telemark.

Both variants were explored as installed and working for balancing a part of the needs of TradeWind project during period of 2000-2006. Songa hydropower plant with its installed power of 120MW was working for the whole explored period, so designed PSH did not interfere with its operation. This fact is making a difference between decrease and increase of rates of change in water level of reservoirs.

The smaller, cheaper version with installed power of 1200MW is covering a smaller percentage of balancing demand but with bigger probability of full cover of this demand (74% against 62.3%). The bigger variant would be of course more expensive, but it would cover bigger demand when the volume of free water in both reservoirs would allow it. The important fact to mention is that the volume of water travelling between both reservoirs is significantly increased. That is causing bigger fluctuation of water level resulting in a larger driving force which could cause environmental impacts.

7. Change in water temperature and ice formation

Basic introduction of water temperatures and ice formation dynamic has been discussed in chapter 4.1.5.

The studied Totak reservoir is a much more complex study site compared to natural lake due to the presence of dynamic inflows and outflows.

Generally, because of vertical mixing due to water withdrawal, the temperature in the summer season in the deep layer of the reservoir becomes higher than that of natural lake in the same depth. The reverse of this can happen in winter as the colder upper layers are mixed with the warmer bottom layers. (27)

The complexities of the hydrodynamic and thermal processes in a reservoir require the use of numerical models to provide an accurate description of the thermal and density stratification, as well as ice cover evolution. (27)

There is a number of water quality models from fully mixed zero dimensional to complex three-dimensional models.

I used one-dimensional model for simulation of temperature and ice cover as the main driving force for temperature distribution of water in reservoir is different density of water for different temperature, which leads to distribution according to vertical direction. Another reason is that "*higher order dimensional models (2D and 3D) require, in increasing order of complexity, detailed information on reservoir bathymetry and hydrological regimes including inflows and outflows, and boundary conditions."*(27)

An important aspect of interest in cold regions is the evolution of the thermal regime during winter and its impact on the ice regime in the reservoirs… To model these aspects, a reservoir hydrothermal model should also include in its formulation the formation, development and ablation of ice covers, so that the annual thermal cycle as well as the ice cover dynamics can be simulated.(27)

Ice cover plays an important role in the thermal regime of reservoirs. Shorter ice cover season on reservoirs due to earlier break-up, for example, will advance summer stratification and lead to higher surface temperatures and delay in autumn turnover. (27) Other ice cover effects are load on dam according to ice thickness, and immobilization of part of the volume as ice decreases the life storage of the reservoir.

The studies on reservoirs are often focussing on the impacts of reservoir releases, because regulation of reservoirs leads to colder releases during warmer period and warmer releases during colder period in comparison with pre-regulation period. Totak reservoir is an already regulated reservoir in our study, and the regulation is actually so strong that only ordinary outflow is through the tunnel to Våmarvatn for further production of energy in Vinje hydropower plant. This study is therefore focused on temperature regime of Totak as it is right now, and probable temperature regime which is likely to change by pumping hydropower plant.

7.1. Description of MyLake model

One-dimensional model used for calculation of thermal regime and ice cover of Totak reservoir is called MyLake, which is a process based lake thermal and ice cover model developed by Norwegian Institute for Water Research in Oslo, Norway. This model was then modified by S. Gebre, T. Boissy and K. Alfredsenat NTNU to "*take into account the effect of reservoir outflows on the hydrodynamic and thermal regime of the reservoirs*". (27) The modified model is called MyLakeR (where R denotes a reservoir).

7.2. Data for model computation

Model computation is based on time step of one day. Model needs these inputs:

- Meteorological forcing for computation of energy balance of a time step
- Hydrological forcing
- Reservoir geometry.

I collected all necessary data of meteorological forcing from an application by Norwegian Meteorological Institute named eKlima (37). Data come from stations in the vicinity of Totak–Møsstrand II, Øyfjell, Tveitsund, Øyfjell i Telemark, Skafså and Rauland. Data are needed for periods of 1984 – 1993 which was established as a calibration period, and 1999 – 2007 as a modelling period for pumping operation. Meteorological data used in MyLakeR model are:

- Mean air temperature (TAM, °C)
- Precipitation (RR, mm)
- Mean relative humidity (UUM, %)
- Average wind speed (FFM, m/s)
- Average cloud cover (NNM, octas)
- Average air pressure (POM, hPa)
- Global radiation (no available data)

As global radiation data were not available, they were estimated using Matlab Air-Sea Toolbox. (27)

Hydrological forcing input is created by data of daily inflow and outflow. As Figure 21 shows the catchment of Totak reservoir has a quite complex system of regulation. Data known from NVE database are daily changes in reservoir volume, data for production of Songa hydropower plant during most of the period, sometimes even with water temperature measurements; and production of Vinje hydropower plant. Total inflow and outflow for Totak is then reconstructed from these known inflow (Songa HPP) and outflow (Vinje HPP) and corrected to realistic values containing all inflow and outflow from change of volume between time steps in Totak reservoir from recorded water stage.

Temperature of inflow to Totak reservoir is coming from measurements of temperature of water passing through turbines of Songa HPP. The main inflow to Totak is coming from reservoirs, and the main inflow to Totak from Songa PSH will come from Songavatnet as well. There were some measurements of this temperature in period 1970-1978 (Figure 54) and during part of the year 1997 (Figure 55), from which the water temperature of inflow was reconstructed.

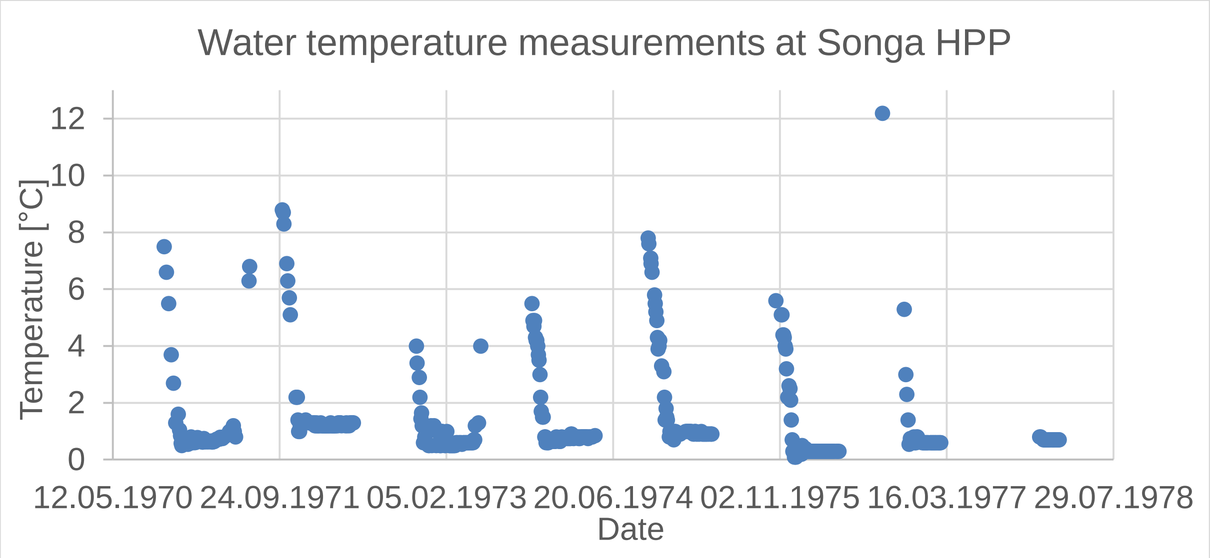


Figure 54 – Water temperature measurements at Songa HPP, 1970-1978

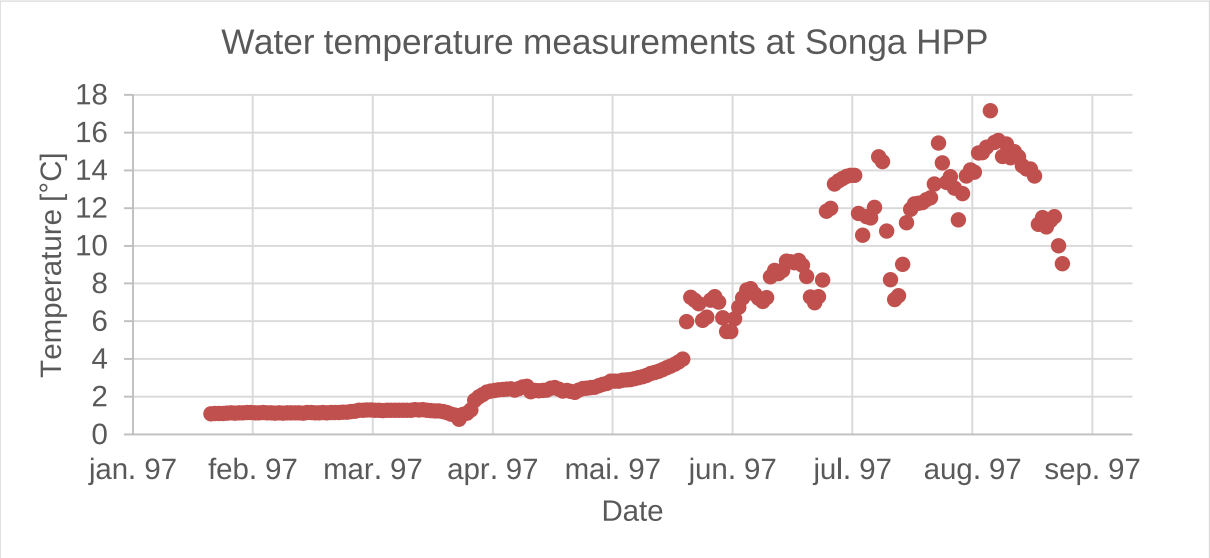


Figure 55 – Water temperature measurements at Songa HPP, 1997

For calibration and validation of model there is a need of vertical temperature profile measurements. NVE database provided measurements which took place one or two times a year in period of 1980-1993 at a depth of 0 – 100 metres with variable depth step, smaller near the surface and usually 10 metres in larger depths. Temperature profiles (without depth information) are plotted in Figure 56.

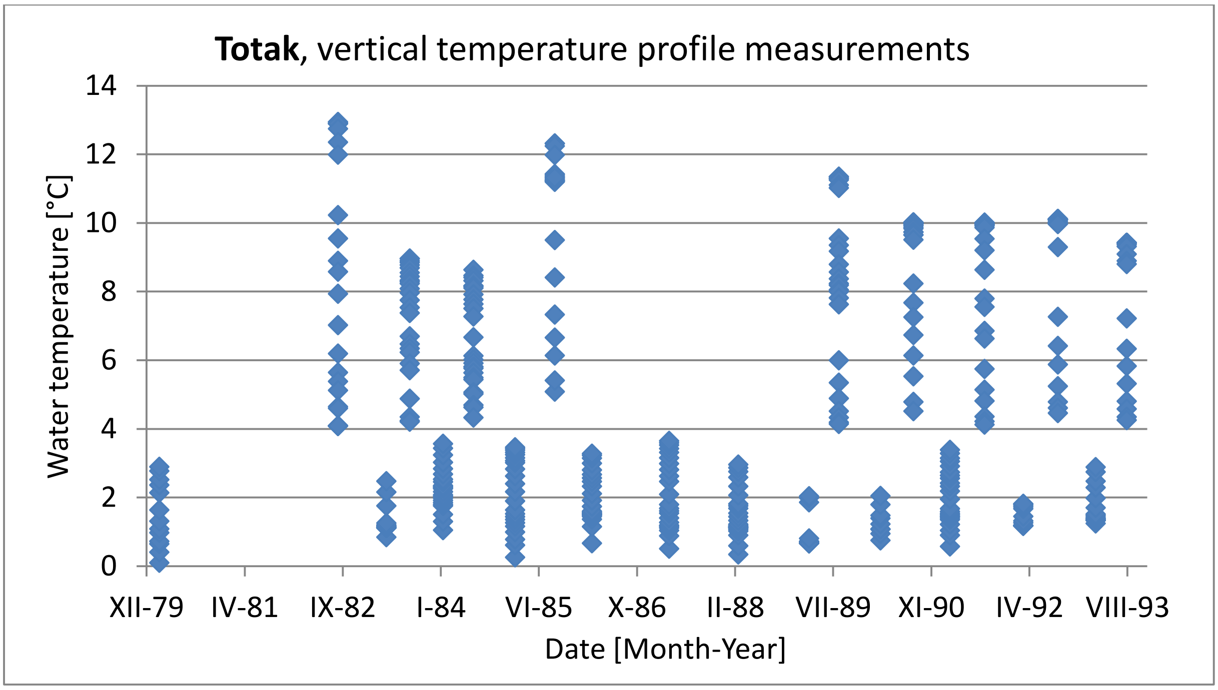


Figure 56 – Vertical temperature profile measurements, Totak (data from NVE)

Reservoir geometry data were established from NVE Atlas (32), where I found a file containing the depth map of Totak reservoir and graphical curve representing depth – area relationship. I mathematically represented this relationship and used it in MyLakeR.

7.3. Model process

MyLakeR model distributes the volume of reservoir into horizontal layers of thickness Δz which are considered as fully mixed. The model numerically solves the distribution of thermal energy, ice cover formation and ablation using the conservation of thermal energy for each vertical layer.(27)

The process of placing the inflow is based on the density of water which is dependent on its temperature. If the density of inflow is higher, the inflowing water sinks until the correct layer with higher density is found. Then the inflow layer is put on top of this found layer. Outflow elevation is a fixed value in this case, as water leaving reservoir is collected by a tunnel. Water layer located in this level is then withdrawn out of the reservoir as outflow and the layers of water from above with smaller density replace the lost volume.

Mixing of water in reservoir is caused by gravity and turbulence. Molecular diffusion is not significant by scale and therefore not considered with one exception of diffusing mixing in surface layer caused by wind.

The model triggers ice formation when water layer temperature drops below the freezing point and the temperature of the super-cooled layers is set to the water freezing point. Before the formation of an ice-cover, ice-crystals are suspended in the water column and grow until they float to the surface and form a slushy layer which freezes to form the initial ice-cover. (27)

The model considers solid ice-cover from thickness of 3 centimetres of accumulated frazil ice. (27) The growth or decay of ice cover can then happen from both sides of ice as freezing of reservoir water, or freezing of precipitation which falls onto the ice cover in form of water or snow. Snow is also functioning as the thermal insulation for his much smaller thermal conductivity than ice has. (38)

For validation of ice cover generation in the model, it is required to have measurements of ice depth which are unfortunately not available for Totak reservoir.

Before actual computation there was need for model calibration. Model was calibrated for data from period 1984 – 1993 as there were sufficient data available in regards of meteorological forcing, hydrological forcing and vertical temperature profile measurements for comparison of modelled results with reality.

I used a process of optimization routine where the objective function is to minimize the root mean squared error between computed and observed vertical temperature profiles. Optimization process was finished after 600 iteration with function value of 1.17.

7.4. Model results

Modelled period was from summer 1999 to summer 2007 as there was a need for modelling of temperature and ice cover from 1.1.2000 – 31.12.2006 where the data for wind generation, thus hydrological forcing changed by operation of pumping storage hydropower from pumping model is available.

This period was modelled first with data relevant for current operation with Songa HPP. Than the same period was modelled for additional inflow and outflow which is being created by operation of Songa PSH and then compared.

Water temperature profile with average daily values is visible in Figure 58 for current operation, and Figure 59 for operation with Songa PSH.

From graphical results in Figure 58 and Figure 59 is visible that with pumping storage hydropower the water in Totak reservoir is colder during winter because of supply of cold water from Songavatnet, on the other hand reservoir is warmer during summer because of supply of warm water from Songavatnet. Maximal reached temperature is 1.5°C higher with operating PSH, but in general the average value of water temperature with PSH is smaller by 0.24°C, median value is smaller by 0.54°C (see Figure 57).

Characteristics of water temperature, Totak reservoir		
	Songa HPP = current operation	Songa HPP + Songa PSH = future operation
Maximum	10.57 °C	12.09 °C
Minimum	0.13 °C	0.06 °C
Median	3.09 °C	2.55 °C
Average	3.99 °C	3.75 °C

Figure 57 – Characteristics of modelled water temperature, Totak reservoir

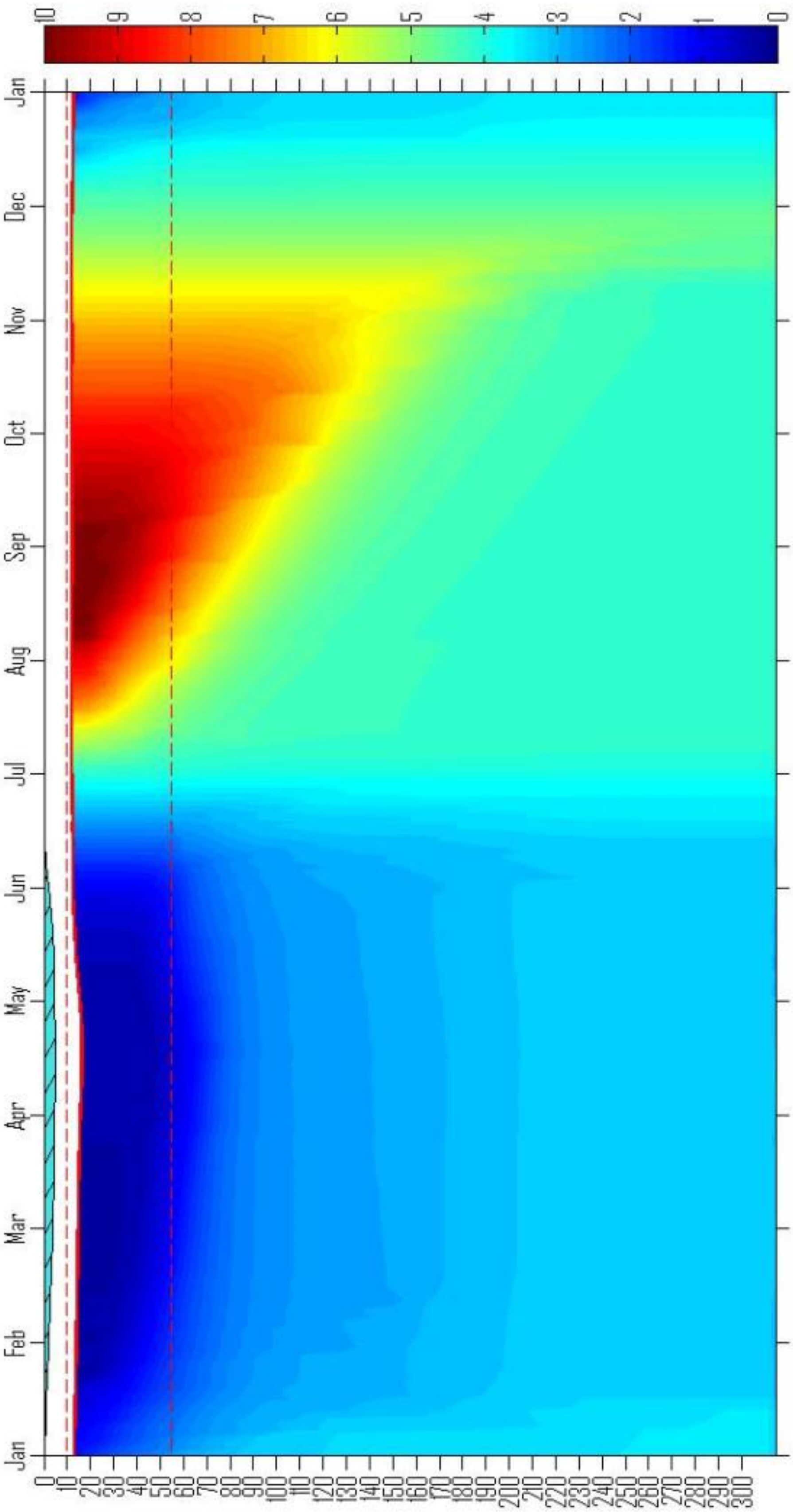


Figure 58 – Daily average values of water temperature throughout the year, Totak reservoir, current operation

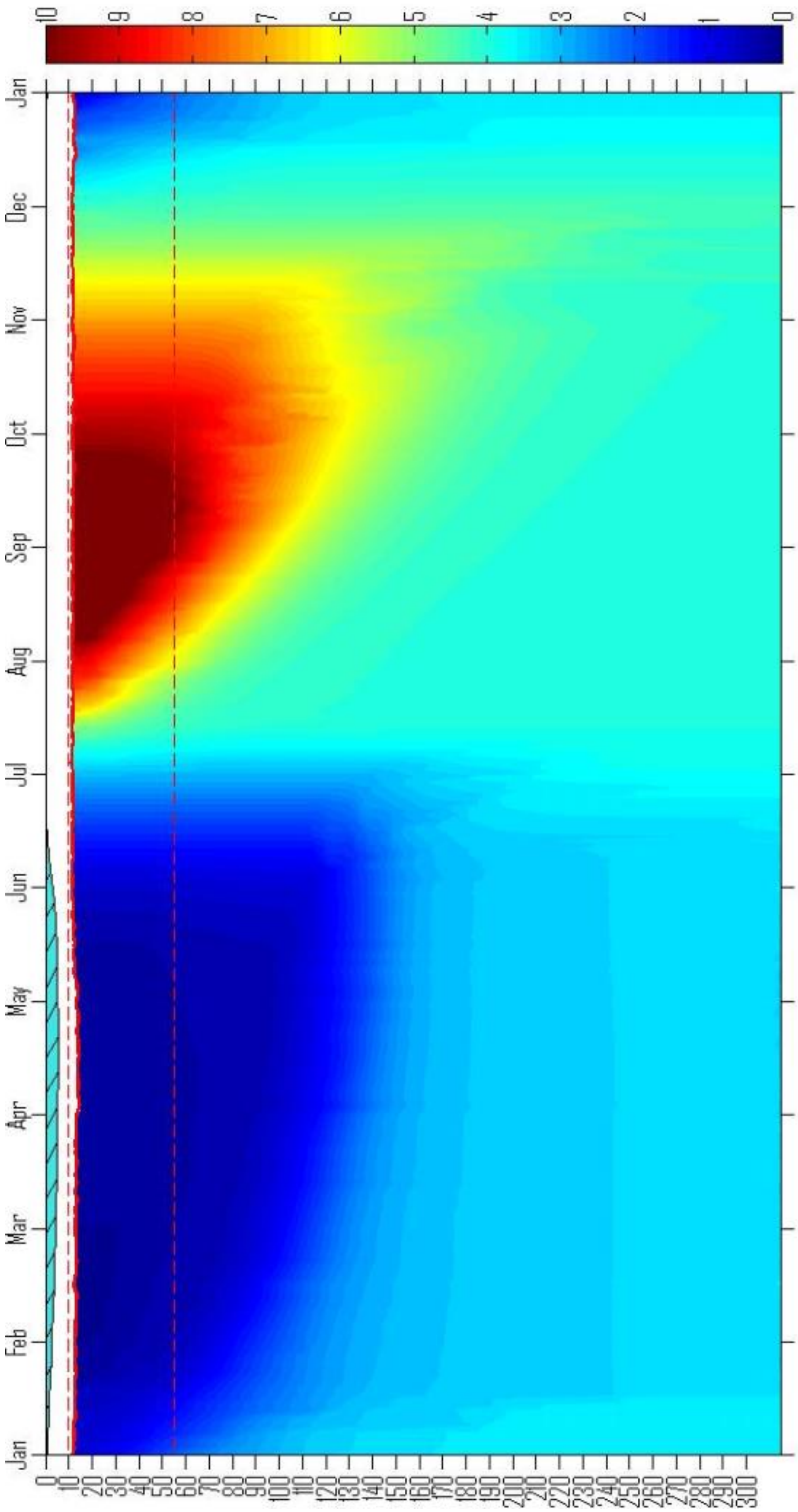


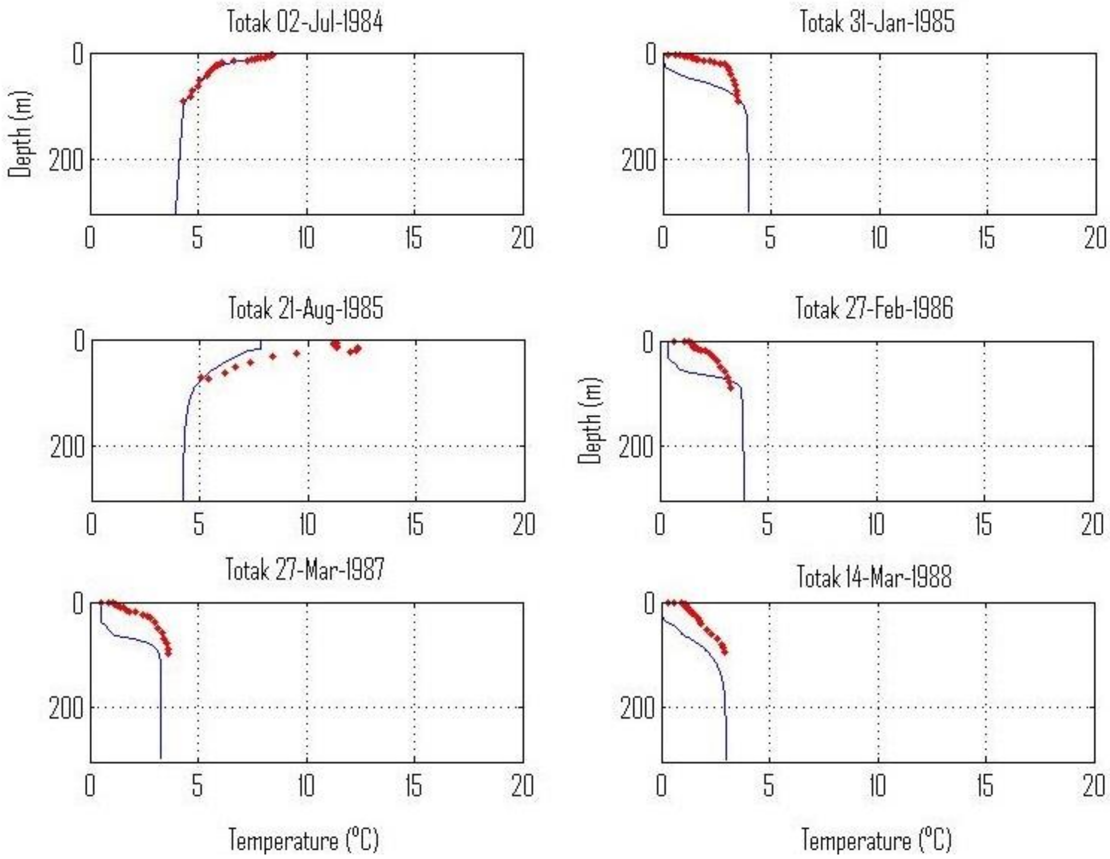
Figure 59 – Daily average values of water temperature throughout the year,

Totak reservoir, pumping operation

The temperature of water coming from Songavatnet reservoir depends a lot on a vertical placement of the intake in reservoir. During this study was this value not designed, therefore temperatures of inflow from Songavatnet are considered the same as the measured values of temperatures of water flow through Songa HPP.

The temperature values for depths larger than 100 metres are calculated with bigger uncertainty because the water temperature profile measurements were done in Totak just to depths of less than 100 metres, thus there are no values for comparison of modelled temperatures and actual temperatures. I assumed the temperature on the bottom of Totak reservoir as a stable value of 3.95°C, which is a value when water has the biggest density. Values between last measured depths and the bottom of Totak were interpolated.

The model behaviour can be checked by observing a fit of measured and modelled water temperature profiles over the depth, as visible in Figure 60. The modelled temperature is following the measurements quite well, the difference is estimated as maximally 1°C.



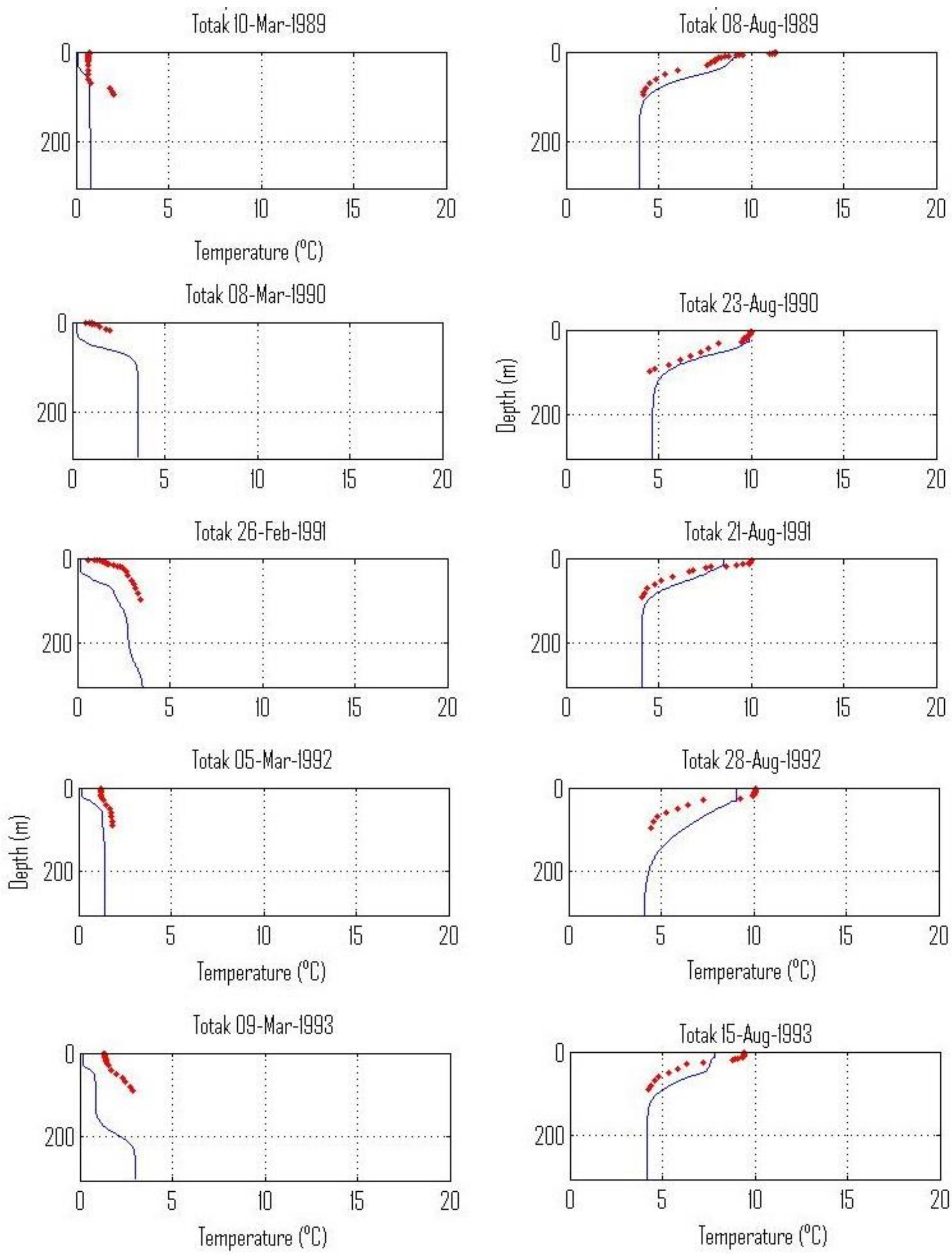


Figure 60 - Observed(red) and modelled(blue) temperature profiles in Totak reservoir

Results of modelling of ice cover are presented in next figures. Figure 61 is showing starting date and break up date of ice cover in 2 different scenarios – current operation with Songa HPP as first alternative, Songa PSH together with Songa HPP as second alternative. First and last year of these results are not representative as Songa PSH is operating just within period of 1.1.2000-

31.12.2006 due to wind generation data series. In results of other 6 winter seasons where PSH is operating is visible, that the ice cover is starting sooner and is breaking up later.

Ice cover at Totak reservoir, 8/1999- 6/2007					
Songa HPP - current operation		Songa HPP + Songa PSH = future operation		START SOONER (+)	BREAK UP LATER (+)
START	BREAK UP	START	BREAK UP		
16.02.2000	30.05.2000	02.02.2000	01.06.2000	14	2
18.01.2001	18.06.2001	09.01.2001	24.06.2001	9	6
28.12.2001	06.06.2002	23.12.2001	14.06.2002	5	8
23.12.2002	13.06.2003	12.12.2002	23.06.2003	11	10
15.01.2004	31.05.2004	31.12.2003	04.06.2004	15	4
25.01.2005	09.06.2005	22.01.2005	16.06.2005	3	7
07.01.2006	20.06.2006	05.01.2006	24.06.2006	2	4
24.01.2007	08.06.2007	23.01.2007	09.06.2007	1	1

Figure 61 – Ice cover timing at Totak reservoir, summer 1999 – summer 2007

Maximal thickness of ice cover during current operation is calculated as 0.66 metres with snow cover with thickness of 0.16 metres on top. Maximal thickness of ice cover with inflow and outflow generated by Songa PSH is increased to 0.74 metres with snow cover with thickness of 0.17 metres on top of the ice. Ice generation during simulated period is shown in Figure 62 by blue line, red line on the top is simulating snow cover.

My expectation from results of ice cover routine was the total opposite of how results actually look like. I considered an ice cover less stable during larger fluctuations which would end up with smaller ice thickness and shorter period when reservoir has an ice cover. Reason for the opposite result is because MyLakeR doesn't have a routine for physical break up of ice as a result of rapid and frequent water level fluctuations, ice cover routine is computed only from temperature forcing.

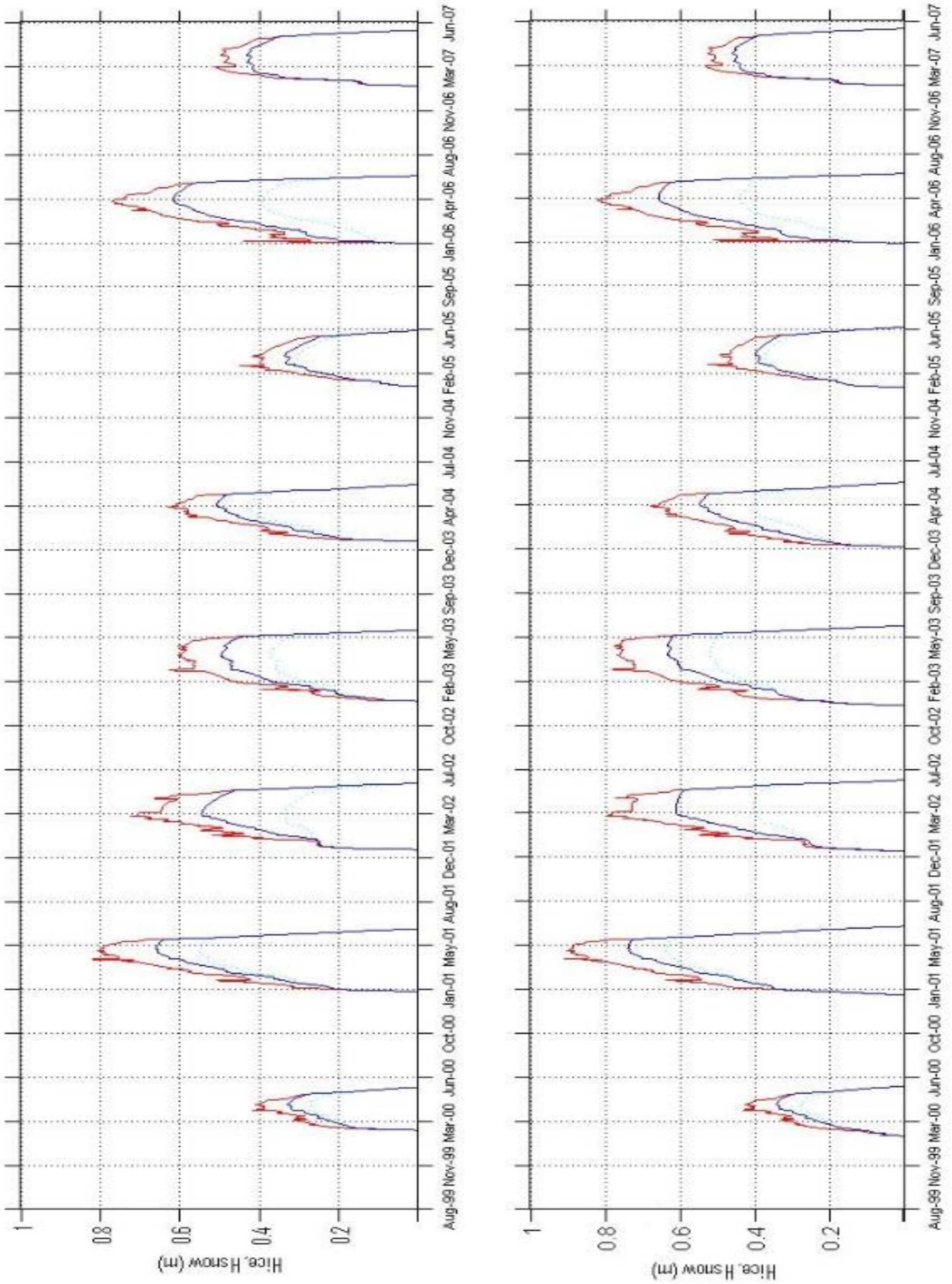


Figure 62 – Ice (blue) and snow (red) development in period of 2000-2006, Totak reservoir, current operation (left) and pumping operation (right)

7.5. Physical break up of ice

MyLakeR model is modelling ice phenology, ice thickness and snow depth on the surface of ice based on meteorological forcing, hydrological forcing and reservoir geometry. There is one more problem related to ice formation – dynamic outflows or inflows in Totak reservoir can cause a physical break up of already developed ice layer.

Ice cover season can be distributed to 3 time periods:

- Formation period
- Midwinter period
- Breakup period (39)

During the formation period, thermal processes cause generation of frazil ice and then first solid ice cover as calculated by MyLakeR model. Frazil ice, ice slush and first weak ice cover follow the changes in water level. Because of the lesser density of ice compared to that of water, such ice forms are kept on the surface due to buoyancy. Internal stability of such new ice cover was explored in some studies, where the buoyancy of accumulated ice and the resistance of the banks are the stabilizing forces. Destabilizing force is represented by the sum of "*hydrodynamic shearing of the flow under the cover, shearing stress of wind on the cover and weight of ice along the slope of the ice/water interface, as well as hydrodynamic trust on the leading edge of the cover"*.(39)

The strength of the cover increases greatly after the cover begins to consolidate and then a much thinner cover is required for stability. A floating, fragmented ice cover can respond to changes in discharge, attaining the required thickness and level for stability. A solid cover has greater strength but does not have the same degree of flexibility to adapt to changes in water level. Large and rapid water level variations caused by hydroelectric peaking or spring runoff can break up the solid cover. (39)

Examples from climatic areas where the ice cover is created on reservoir shows that operation of hydropower plant is usually modified to conform to the stability criteria required for stable cover formation. After the ice cover has solidified, normal operation is resumed. (39)

As there will be very dynamic regime in Totak throughout whole winter season, such operation criteria is most probably useless. At reservoirs, i.e. water bodies with no flow or very limited flow velocities; it was observed that the ice freezes on the banks when there is a withdrawal in water level. When the water level is rising, in some cases new cover freezes above this cover which is still frozen in the reservoir bank, however most part of the ice re-floats and assumes its original position in the ice cover at higher water levels (39). Ice cover which was not in contact with reservoir banks does not develop fractures (hinges) as the ice cover on shores, and is falling or raising as a floating solid ice cover. Example of such behaviour of a river is shown in Figure 63 and Figure 64.

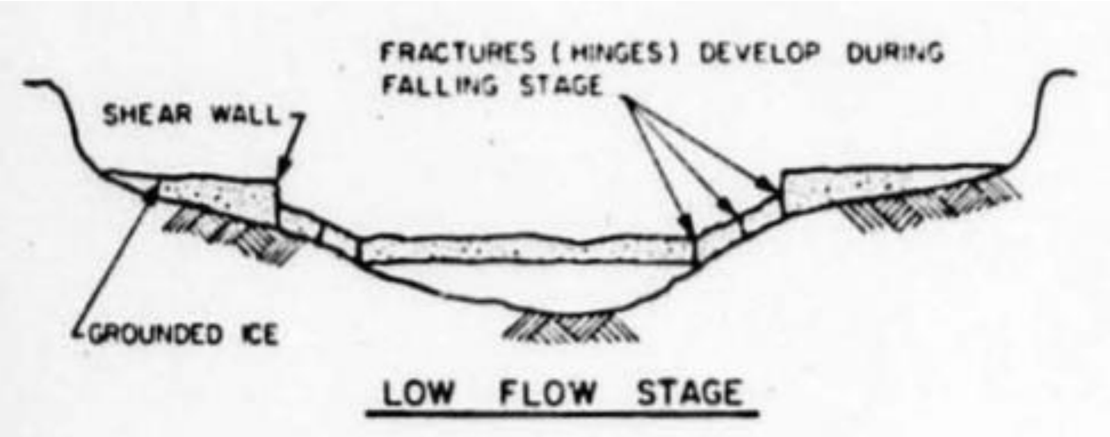


Figure 63 – Development of fractures and grounded ice during withdrawal of water level in a river (39)

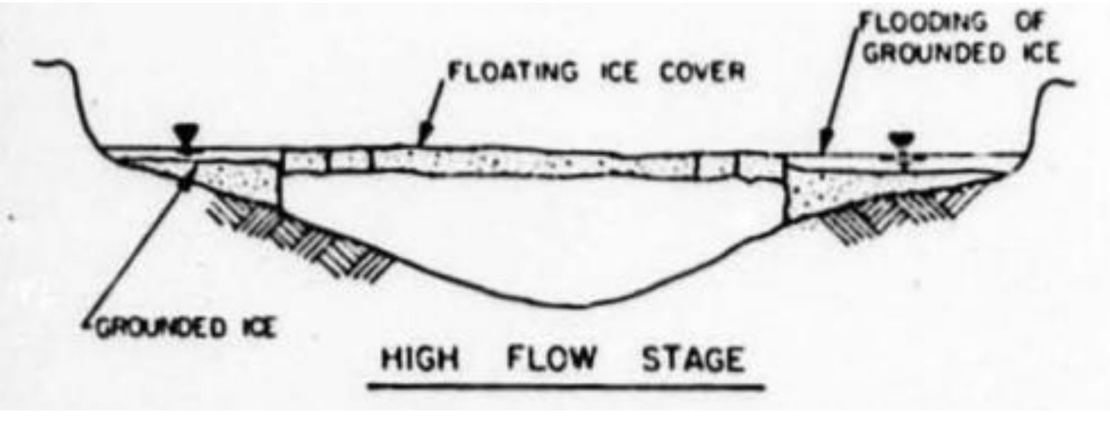


Figure 64 – Behavior of ice cover after increase of water level after low stage in a river (39)

The breaks up processes in the end of winter or during spring are a result of thermal processes when the heat is being supplied from atmosphere to an ice cover. This process is calculated by MyLakeR model.

8. Impacts on Totak reservoir by pumping storage hydropower

In this chapter the potential impacts from chapter 4 analysed for Totak reservoir are presented.

8.1. Physical impacts

8.1.1. More rapid and frequent water level changes

Frequency, speed and size of water level changes is extensively discussed in evaluation of outputs from pumping model in chapter 6.4 for PSH with 1200MW of installed power, and chapter 6.5 for PSH with 3150MW of installed power. Example of water level fluctuation in Totak during the year 2002 for bigger PSH is shown in Figure 65, where orange colour represents current water stage and blue colour water stage during operation of PSH.

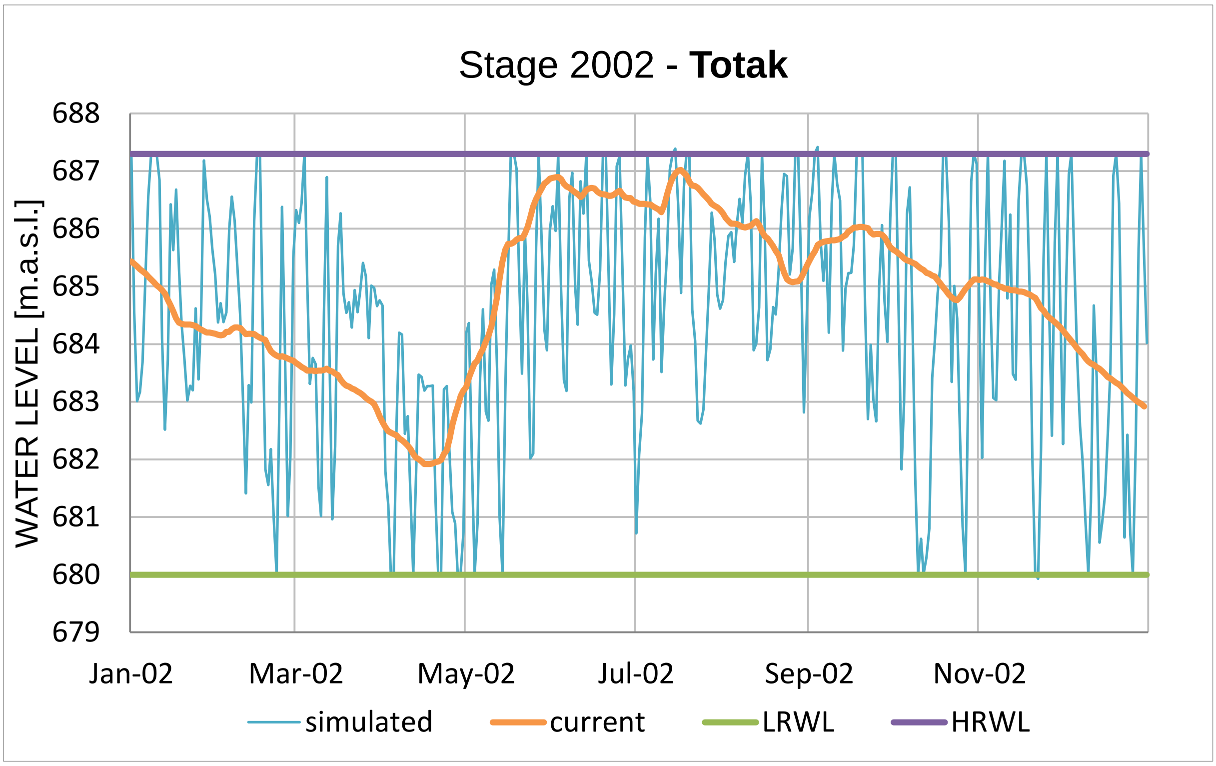


Figure 65 – Water stage, Totak, 2002. PSH with 3150MW of instaled power

Days with water level change are increased from 17% to 41% with PSH.

Average daily water level change (absolute value) is changed from 0.05m/day (0.2cm/h) to 0.5m/day (2.1cm/h) with 1200MW PSH, or 1.18m/day (4.9cm/h) with 3150MW PSH.

8.1.2. Changes in reservoir filling over the year

Usual reservoir filling pattern for Norwegian reservoir was presented in Figure 5. As seen in Figure 29 the seasonal pattern of Totak reservoir is partly supressed by fluctuation from pumping in case of 1200MW PSH. Almost no seasonal pattern is observed when PSH has an installed power of 3150MW (Figure 41). This behaviour is due to fact that volume of water being transferred from and into Totak by operation of PSH is much greater than seasonal fluctuations. In general, especially in case of 1200MW PSH (Figure 66), the Totak reservoir has a higher water level compared to present operation over the whole year.

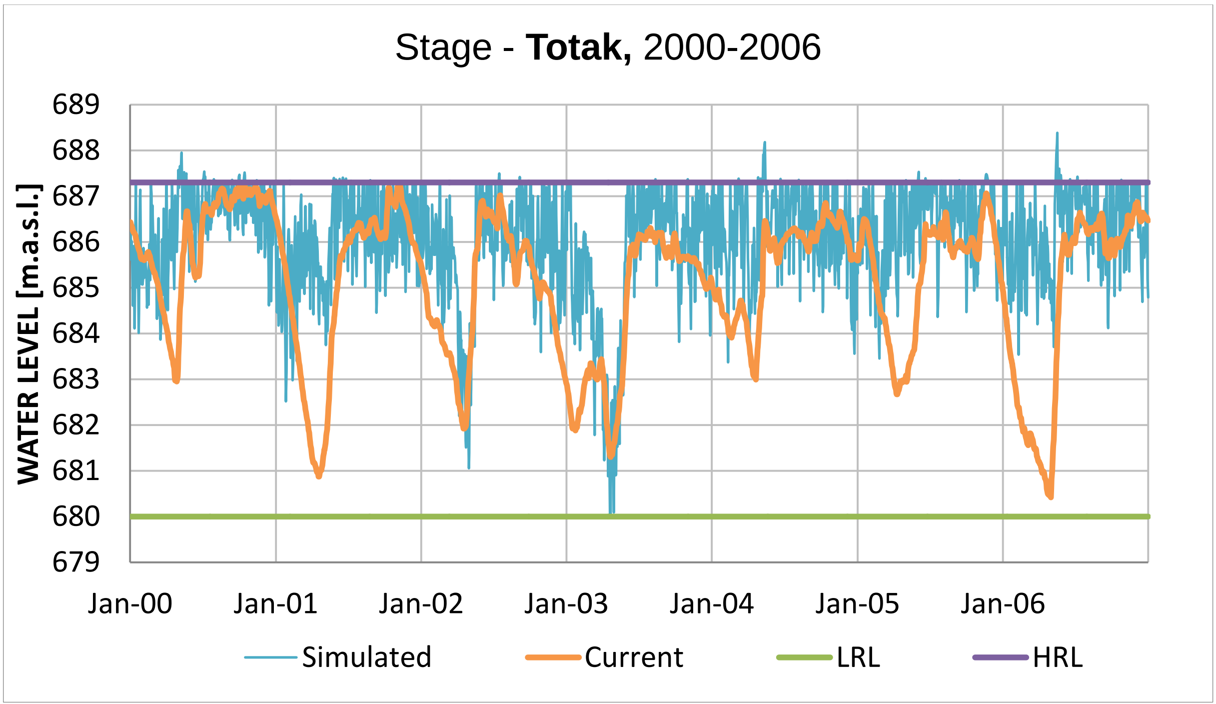


Figure 66 -Water stage, Totak, 2000-2006. PSH with 1200MW of installed power

8.1.3. Reduction in permanent wetted littoral zone on short term basis

Large volumes of water transferred by PSH during pumping operation from Totak reservoir to Songavatnet are causing decrease of water level and exposure of area on the edge of Totak reservoir which is called littoral zone. Opposite situation with flooding of this littoral zone is happening during energy generation.

PSH between Totak and Songavatnet is not functioning for balancing the network, i.e. with multiple cycles of pumping or energy production during the day. Purpose of this PSH is to balance the TradeWind project of wind power plants, which makes the need of pumping operation stable, often for multiple days. Average pumping or production in period of 2000-2006 was 2 days long, with maximal period of 9 days of continuous pumping or 8 days of continuous production.

Rate of change of water surface area in Totak was calculated by the pumping model to see how large areas are exposed or flooded during PSH operation. Estimated flooded or exposed areas during the period of 2000-2006 are shown in Figure 67.

Rate of change in area	current operation	PSH	
		1200MW	3150MW
Maximal flooded area per day [km^2]	0.17	0.6	1.48
Maximal exposed area per day [km^2]	0.06	0.5	1.25
Average flooded area per day [km^2]	0.03	0.2	0.5
Average exposed area per day [km^2]	0.02	0.21	0.5
Max. flood. area - Estimated shoreline width - [m]	2.4	8.5	21
Max. exp. area - Estimated shoreline width - [m]	0.85	7.2	17.8
Avg. flood. area - Estimated shoreline width - [m]	0.36	2.9	7
Avg. exp. area - Estimated shoreline width - [m]	0.25	3	7

Figure 67 – Changes in area, Totak, 2000-2006

In the same figure shoreline widths calculated along the shore length of 70.5km are also estimated (32). So for example from exposed shoreline width of 0.25m which is a current day average there is an average change of 7 metres of exposed shoreline width by pumping operation of PSH with installed power of 3150MW.

As the water level fluctuations are often and with large span of water stage compared to current situation, the shoreline is very unstable and littoral zone has much greater area during the operation of PSH. A part of the littoral zone, which is wetted by slowly changing water level during current operation, can be few metres under water level after development of PSH.

Described changes will most probably lead to redistribution of 4 zones of littoral zone described in chapter 4.1.3 as the edge of reservoir inside and outside of the water will have more dynamic boundary.

8.1.4. Changes in circulation patterns

The conditions in Totak are changed by introducing pumping operation due to large inflow of water with specific temperature and speed during energy generation, and large outflow of water during pumping.

For detail and precise evaluation there is a need for 2-dimensional or 3-dimensional modelling approach. MyLake model used for evaluation of temperature regime is only one dimensional model with vertical dimension which is not enough for evaluation of circulation patterns. There is also a need for spatial distribution of water temperature for the evaluation of circulation.

Pumping model calculation is presents every day volumes of water transferred from Songavatnet to Totak or the other way. This is a valuable input needed for set up of 2D or 3D model for circulation patterns, together with location of inflow and outflow, their elevation, and speed of inflowing or outflowing water with regard to design of tunnel between Songavatnet and Totak.

The circulation pattern of Totak reservoir will be changed by pumping operation. Total volume of Totak reservoir is 2360 mill m^3, where the volume of life storage is equal to 258 mill m^3. Pumping model shows that the average annual volume of water processed by PSH in period of 2000-2006 is:

- 6550 mill m^3, divided almost to equal parts for pumping or energy generation in case of 1200MW of installed power of PSH, which is 2.8 times the whole volume of Totak reservoir
- 15340 mill m^3 together for pumping and energy generation in case of 3150MW of installed power of PSH, which is 6.5 times the whole volume of Totak reservoir.

As observed, volumes of water transferred through turbines of PSH are large even in comparison with total volume of Totak reservoir. Therefore their influence on circulation patterns is obvious and should be studied in case of interest in Songa PSH development. Model for circulation pattern was not developed in this thesis.

8.1.5. Changes in water temperature and ice formation

Changes in water temperature and ice formation in Totak reservoir by introducing pumping operation are extensively discussed in chapter 7.

Results of modelling by MyLakeR are presented and discussed in chapter 7 of this thesis. Results show that the water temperature is higher during summer and lower in winter during pumping operation. This is very dependent on a temperature of the water in the reservoir which is a source, and that is dependent on a design of water works, especially vertical placement of the intake structure.

Ice cover is an important parameter reflected in biological conditions in reservoir (see chapter 8.2.4), it also generates forces on structures such as the reservoir dams, which should be able to withstand these forces. Spillways has to be designed for safe passage of excessive water in case of spring flood.

Concern for understanding of ice generation processes in Totak reservoir is also created by elimination of frazil ice entrainment to the intake tunnel of Songa PSH. This situation is known to be problematic as the built up frazil ice at the intake results in limiting or even blocking the intake, thus causing limitations in energy production. Limitation of velocity, stable ice cover and placement of intake in deep water is preventing this problem from occurring. (40)

Ice formation results are not covering the topic of physical break up of ice due to rapid and frequent water level changes caused by Songa PSH. Therefore ice cover in reality should be thinner then presented, the ice cover period during the winter should be also shorter than presented.

As the ice cover can be unstable during winter due to large fluctuations by operation of PSH, any type of transport over the reservoir during winter for example by snow scooters should be prohibited as it is deemed dangerous.

8.1.6. Stability of reservoir banks

Studies showed (see chapter 4.1.6) that the most problematic water level for stability of reservoir banks is around the middle between LRWL and HRWL, when the potential landslide can take a place both during withdrawal and increase of water level.

Geological survey of Totak and its surrounding should be done in order to know rock and soil conditions in the area, especially permeability coefficient which is an important characteristics considering slope stability during water level fluctuations.

There has been some instability problems after development of Totak reservoir, when some slides in the road alongside the reservoir were observed. Damage was not extensive and was easily repaired.(33)

As the water level fluctuations are going to be more rapid and frequent, danger of slides is increased. Periodic observation of shores and area surrounding Totak reservoir should take place in order to take mitigating actions when necessary.

Shores of Totak reservoir are already stable against erosion due to wave exposure and as there won't be any change in HRWL and LRWL in the reservoir, thus there is no danger from pumping operation concerning this source of erosion.

8.1.7. Changes in landscape

Songa PSH has a large installed power output, therefore construction of additional transmission lines is unavoidable. Connection with TradeWind power project has to be made, which cannot be handled by current network. This will lead to visual impacts on landscape.

Often fluctuation can cause shore erosion, exposed areas of shores of Totak can lead to unwanted aesthetical impacts in landscape where people visiting the area, owning cabins for recreation and similar are used to have more or less stable water level of reservoir as it is right now, influenced only by seasonal fluctuation.

8.2. Biological impacts

8.2.1. Higher risk for spreading of species

Volumes of water travelling through reversible turbines upwards from lower reservoir to upper one is huge, 3280 mill m^3 annually in case of PSH with installed power 1200MW, 7690 mill m^3 annually in case of the larger alternative.

The physical meaning of this is that organisms, which couldn't naturally reach the higher reservoir as they can't travel against the flow or there are physical barriers avoiding this movement.

Reversible turbines will allow this transfer, so the organisms which are living in the water, or raised by flow from the bottom can be transferred. There is almost 300 metres of head difference between Totak and Songavatnet, so organisms has to be able to withstand this pressure to survive the passage. Blades of reversible turbine and friction of tunnel connecting reservoir are also limiting factors, see chapter 8.2.5. Nevertheless, plants or their parts as well as small organisms like aquatic macrophytes, algae, zooplankton and macro-invertebrates like crayfishes, shrimps or snails can be transferred. This can lead to change in biodiversity of Songavatnet and Bitdalsvatnet. Study of species of plants and living organisms which are found in Totak, but are not registered in Songavatnet and Bitdalsvatnet should be done, along with evaluation of their possible impact on biodiversity of these upper reservoirs.

8.2.2. Impacts on biological production in littoral zone

These impacts are related to changes in permanently wetted littoral zone as discussed in chapter 8.1.3. Rooted plants in littoral zone are providing important habitat and food for a lot of organisms. As the frequency, speed and magnitude of water level fluctuation increases by implementation of PSH, the littoral zone area will be much bigger with more dynamic boundary between types of littoral zone – wooded wetland, wet meadow, marsh and aquatic vegetation.

The littoral zone will be extended to broader zone as mentioned in chapter 4.2.2. Because of the changes between dry and wet conditions there will be change in occurrence and representation of current organisms and plants based on their favourable habitat. Biological production connected with this vegetation will be based on those changes.

Sudden decreases of water level, which is a case of withdrawal rates of water level presented by operation of PSH, can have negative impacts on biological production in littoral zone.

Due to exposed stream bed, destroyed algae, invertebrates and some stranded fish were observed after unnatural low water levels and sudden decrease of water level in Snake River, Wyoming. (41)

Algae and invertebrates along with other organisms can also suffer from such changes in Totak reservoir. Thus focus should be put to study the survival ability of these species living in affected areas, especially associated with their length of survival in their unfavourable conditions compared to length of operation cycles of PSH. Average cycle of operation, i.e. change between decrease and increase of water level, is estimated as 2 days in Totak, with maximal length of continuous decrease of increase of water level 8 days.

8.2.3. Lower visibility in water

Lower visibility in Totak reservoir is closely dependent on multiple factors, which are transported volume of water, velocity of inflow (energy generation) or outflow (pumping operation) from the tailrace tunnel of PSH. Design is also very important – cross section area of the tunnel in relevance with water velocity, placement and orientation of the tunnel portal. Location of tunnel system of Songa PSH as suggested by C.C. Garcia (31) is shown in Figure 27. Tailrace tunnel from Songa PSH is located in north-eastern part of Totak, where both the depth of reservoir and the volume of this part of reservoir is small, less than 20 metres as shown in Figure 68.

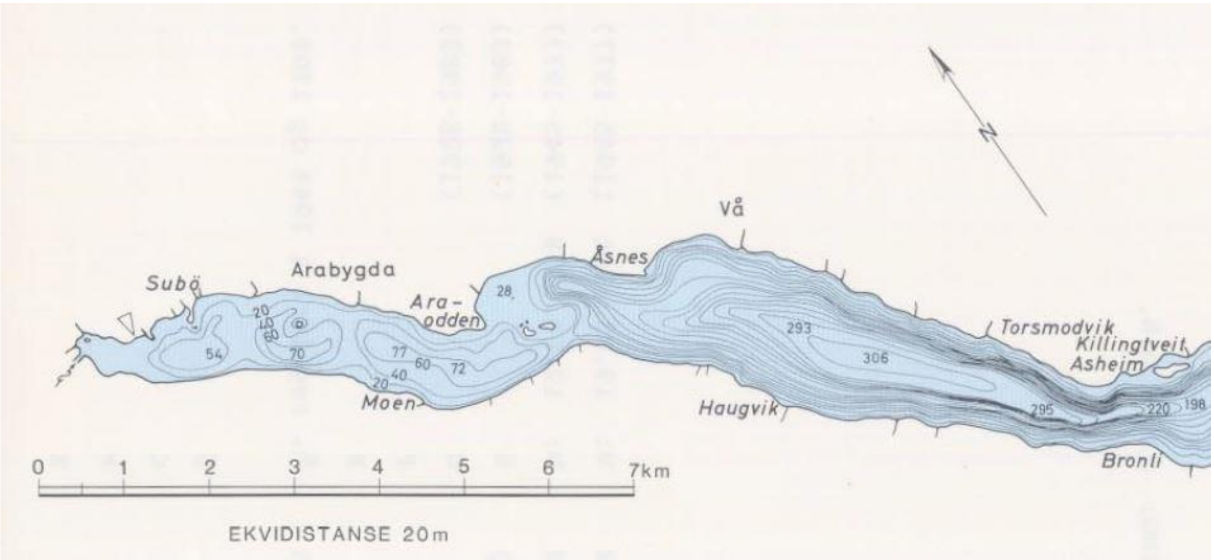


Figure 68 – Depth map of eastern part of Totak reservoir (32)

As Figure 27 also shows, this part of Totak already has two tunnel outflows releasing water to reservoir, one from Songa HPP releasing water from Songavatnet and Bitdalsvatnet, and other one from Venemo reservoir downstream of Kjela HPP. The placement of tunnel outflow of Songa PSH should therefore be considered in regards with reservoir bed stability, with optional extension from suggested layout to location with greater depth. Particles raised from reservoir bed by water outflow from tunnel will decrease the visibility in water in Totak reservoir. In reverse mode during pumping, raised particles in volume of water passing through reversible turbines will cause increased wear of turbine blades and transport the sediment to Songavatnet.

As more and more particles travel with water currents without settling down after inflow caused by operation of PSH could then mean not only aesthetical impacts leading to decrease in attractiveness for recreation, but also limitation in light entrainment to water body. That could lead to decreased photosynthesis ability of water plants.

8.2.4. Impacts by change of ice cover dynamics

Change in ice cover dynamics due to pumping storage hydropower is expected due to changes in water temperature regime and due to sooner breakup of ice cover caused by more frequent and rapid water level fluctuations.

When the ice cover is thinner, formed later or broken up sooner, primary biological production in reservoir is stimulated. This is resulting for example in better conditions for fisheries.

Ice cover dynamics computed by MyLakeR showed that ice cover will be thicker and it will last longer during pumping storage operation. This is a questionable result as MyLakeR is not computing a physical break up of ice cover due to water level fluctuations.

8.2.5. Increased mortality of higher species

There is a good population of char and trout in Totak reservoir. Maximal values of withdrawal rate shows that according to current studies (35) and (11) there will be no danger for stranding of juvenile fish of *Salmonidae* species in Totak reservoir in both variants of PSH.

The problem arises in volume of water transferred from one reservoir to other. Volume of water pumped from Totak to Songavatnet is shown in Figure 69. Total volume of full Totak reservoir is 2360 mill m^3. That means that in case of 3150MW of installed power daily transferred volume can be almost equal to 5% of total reservoir volume.

Pumping operation	PSH	
	1200MW	3150MW
Annual average volume [mill m^3]	3 280	7 685
Daily average volume [mill m^3]	9.0	21.1
Daily maximal volume [mill m^3]	40.9	107.5

Figure 69 – Volumes of water transferred by pumping operation, Songa PSH

There are 3 general types of stress arising from pumping operation which could be harmful to fish in Totak:

- Pressure and cavitation
- Contact with the turbine blades
- Shear forces and the turbulence. (42)

"*Turbine passage mortality has been studied extensively for juveniles and adults of migratory fish species, but few studies have directly quantified mortality of fish eggs and larvae." (43)* Usual studies are done for low head projects located on rivers used by migrating type of fish like salmon, which can be greatly impacted by such hydropower projects, but these studies are also applicable for pumping storage hydropower.

There are some studies done for PSH plants with different results. "*Some studies have suggested that entrainment of larvae and eggs at hydropower facilities can be very high and can affect the abundance of some species. Similar results have been obtained at pumped-storage facilities. However, at least one study found no direct link between entrainment of larvae and population size." (44)*

In regards with mentioned pressure stress Figure 70 is showing "*the pressure regimes resulting in little or no mortality of early life stages of fish in laboratory studies"*. (42) "*Study of Lampert (1976) exposed fry of whitefish Coregonus and common carp Cyprinuscarpio, as well as larger individuals of other species, to the simulated pressure regime of a pumped-storage hydroelectric station. Rapid increases from atmospheric pressure to over 5000 kPa followed by a 10-min depressurization caused no mortality. In a similar experiment, Rowley (1955) mimicked the pressure effects of penstock and turbine passage by subjecting rainbow trout Oncorhynchusmykiss to pressure increases of 244-1277 kPa in less than 1 min, followed by a virtually instantaneous release of pressure. Although the fish were immobilized while under pressure, normal activity resumed immediately after depressurization, and no deaths could be attributed to the test conditions." (42)*

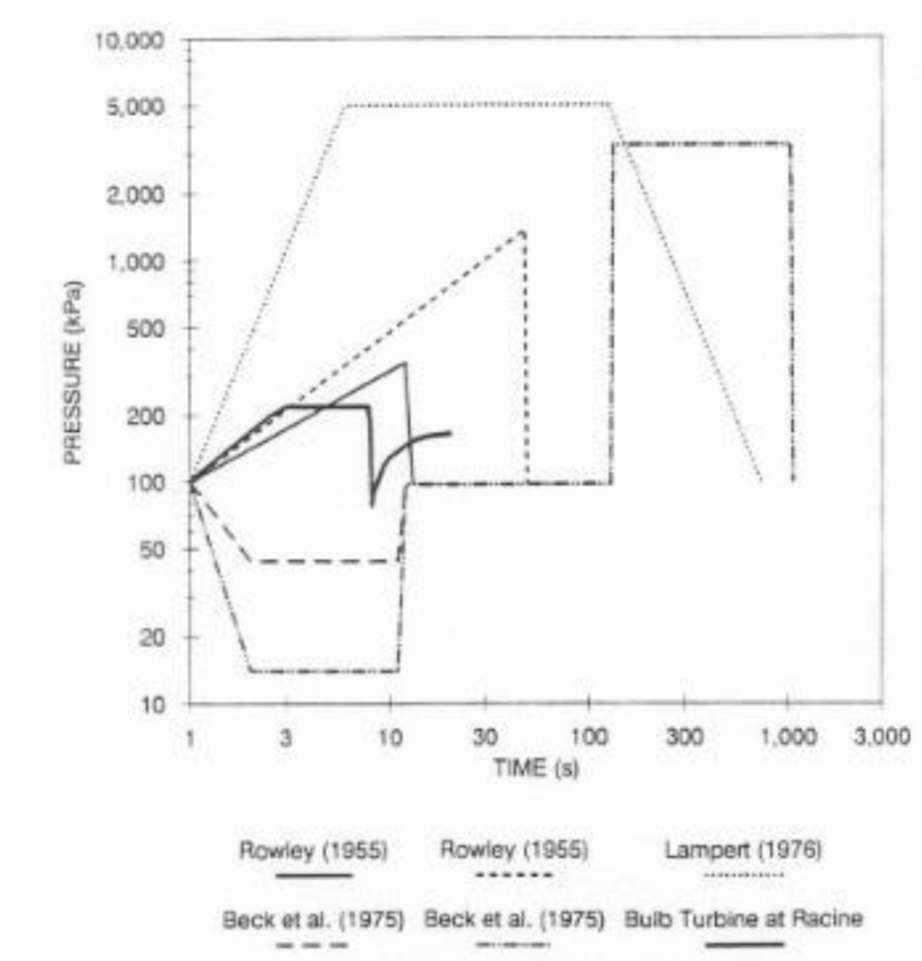


Figure 70 – Pressure regimes resulting in little or no mortality of early life stages of fish in laboratory studies (42)

Fish or their other stages of life as egg, larvae or fry would, in case of getting trapped in the water being transported from Totak to Songavatnet, experience the decrease of pressure with regards to the collected water depth and depth of intake. This means that they would be subject to an instant increase of pressure to about 3000 kPa, which is equal to 300 metres of water column. Gradual decrease of pressure would follow ending at the pressure equivalent to the depth of the outlet when reaching the Songavatnet reservoir.

From mentioned laboratory studies (42) it is visible that there will be no harm to fish population at any stage of life due to pressure regimes created by PSH. Also no or only little mortality was observed due to sub-atmospheric pressure, turbulence or shear forces acting on the fish.(42) Cavitation on the other hand is lethal, but that is a process avoided by correct design as every unwanted state would cause wear and tear of the turbine.

Mortality of fish in Totak would occur due to the contact of fish with turbine blades. This situation was studied before and formulas according to the type of turbine, their characteristics and size of fish were developed. Example of such formula cited in (42) by Von Raben, 1957:

$$P = \frac{l \cdot n \cdot R \cdot a \cdot cos\alpha}{f}$$

Where *P = the probability of blade contact;*

l = fish length (%);

n = number of runner blades;

R = revolutions per second;

a = cross-section area (m^2) of water passage;

α = blade angle

f = discharge (m^3/s).

Graphical relationship can be established for such a formula as on Figure 71.

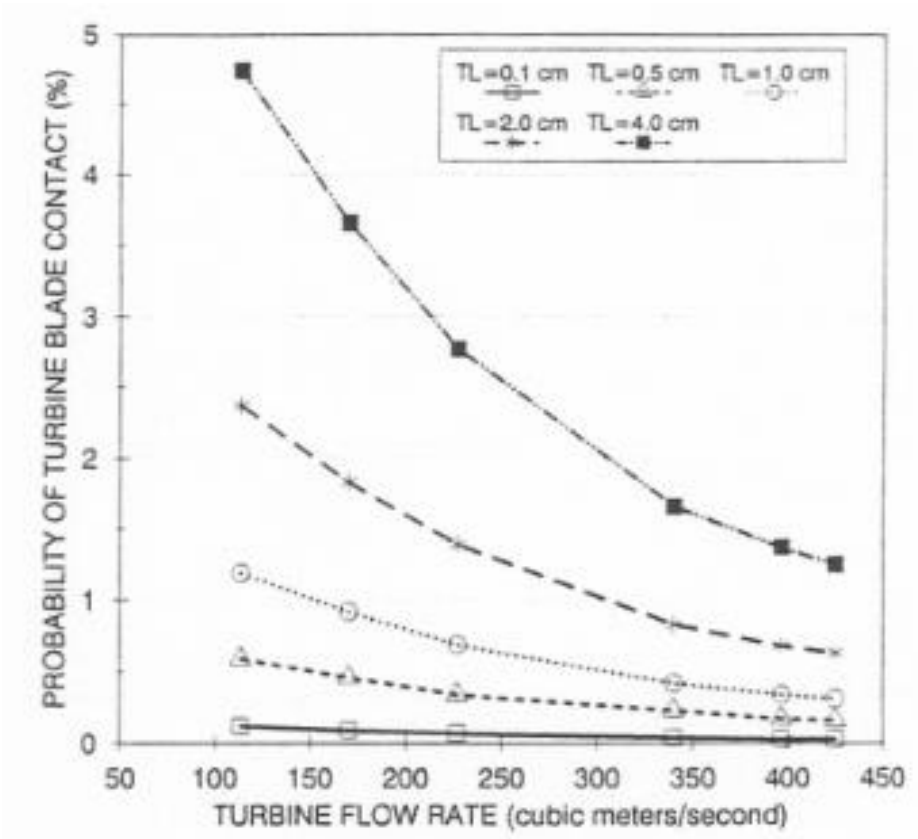


Figure 71 – Probability of blade contact during turbine passage for various sizes of fish early life stages.(42)

There are a number of mitigation measures which could be done in order to limit the mortality of higher species related to operation of PSH. “*Barrier nets of nylon mesh can provide fish protection at various types of water intake, including hydropower facilities and pumped storage projects. Nets generally provide protection at a tenth the cost of most alternatives, however, they are not suitable for many sites.” (44)* Nets have problems with ice; therefore there would be a need for removing those before winter and re-installing them during spring in Totak reservoir, which would cover a period of time of life of early life stages of fish. Adults of trout and char which are the most common and valuable species of fish in Totak, are considered as good swimmers and therefore are able to swim out of the volume of water travelling to the tunnel inlet, if they consider it as a danger. Ultrasonic and light systems have been tested for pumping storage hydropower systems with the intention to keep the fish at a distance from inlets with encouraging results. (44) Electrical barriers have been successfully used to prevent the upstream passage of fish. (44)

8.3. Socio-economic impacts

8.3.1. Impacts on reservoir fishing

Recreational fishing is an important activity in Totak. Studies were made in connection with this activity, for example effects of eventual lowering of LRWL from current 680 m.a.s.l. on benthic fauna and fish. Statkraft is currently testing some strategies which would help with attractiveness of fishing in this reservoir.

Totak is one of many reservoirs where reproduction of fish is greater than extraction. Because of that there are a lot of small fish and young adults. The most common species are char and trout (røye and ørret in Norwegian). (45)

Statkraft as the owner of the hydropower system is aware of the importance of fishing activities. They started a project with the intention of increasing the population of large trout and promoting the interest in fishing this way. The first stage of the project was releasing of 3-year old fish eating trout which can help in keeping down the number of small fish. The next stage of project is annual release of up to 600 marked trout over a 4-year period. This trout is hatched in Telemark and it is originally a native trout from Totak. This measure should strengthen the trout strain.(45)

The regulation for improvement of fish habitat is taken care by restrictions followed by Statkraft hydropower plants in the area, periods when Totak has to be filled to required water level are discussed in chapter 5.3.

Pumping operation should not interfere with presented regulations and restrictions. The regulations are presented for the example year of 2002 in Figure 72 as red colour line where first part at 686 m.a.s.l. is the requirement, and a second part at 685.5 m.a.s.l. is a self-imposed restriction. For variant with 3150 MW of installed power see Figure 73.

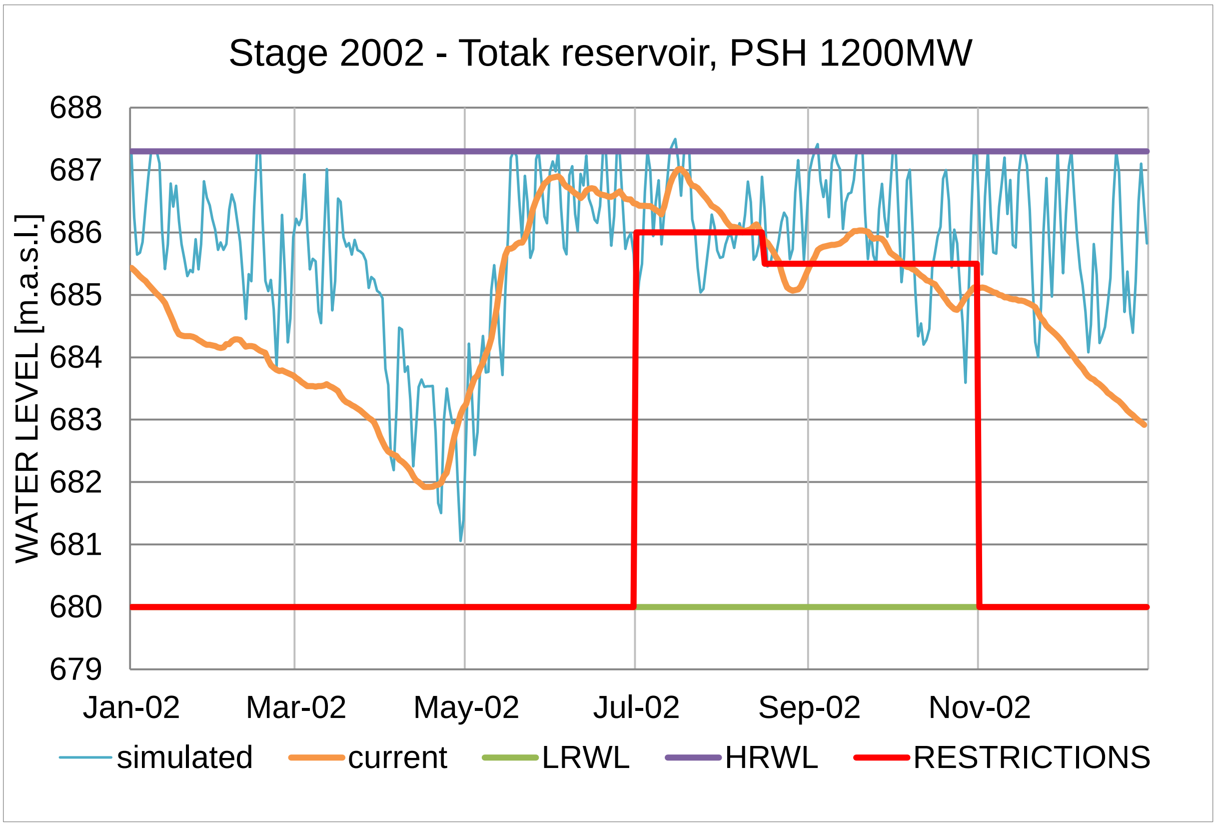


Figure 72 – Water stage, Totak 2002. PSH with installed power of 1200MW

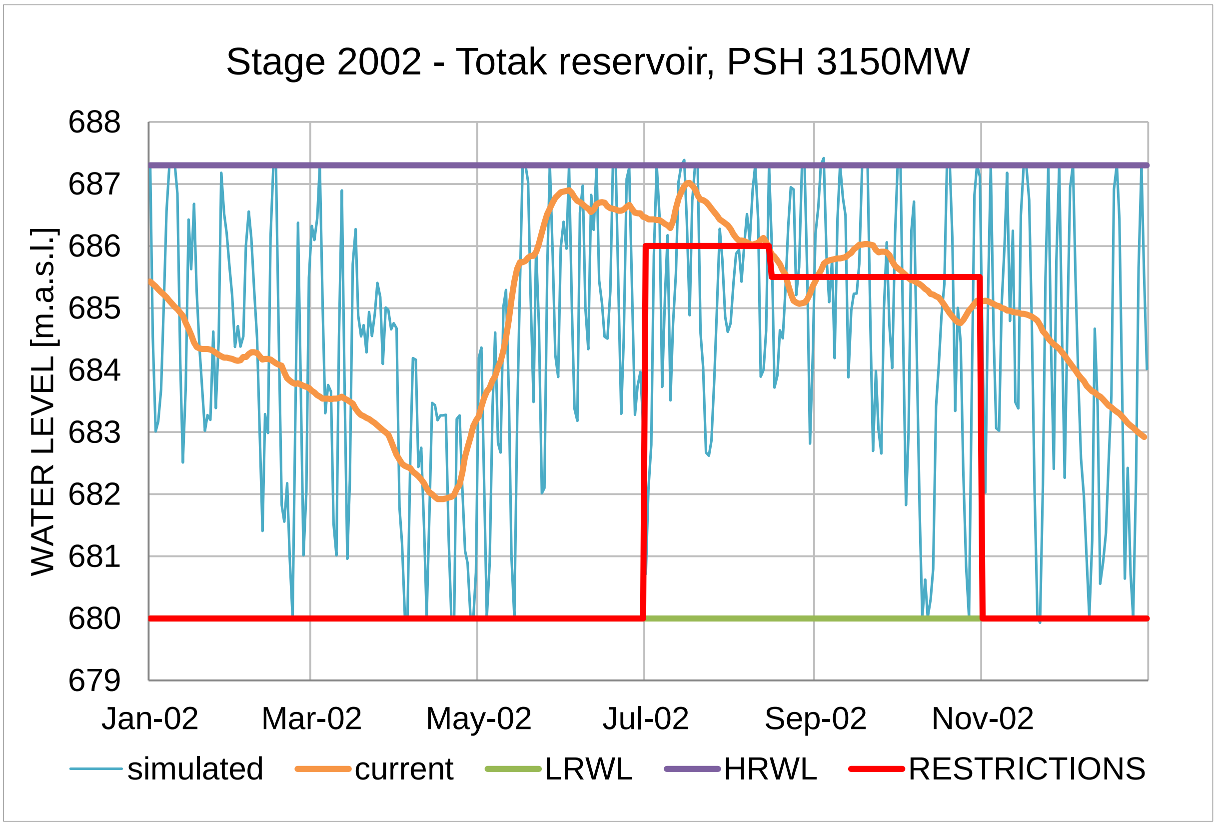


Figure 73 – Water stage, Totak, 2002. PSH with installed power of 3150MW

The sample year 2002 shows on both figures that pumping operation interferes with these restrictions, especially in case of bigger installed power of PSH. These restrictions should be conserved as they are right now, or eventually reconsidered, if commercial fishing in Totak is going to be maintained.

Solution could be made by regulation criteria for operation of PSH, which would only allow usage of free volume of water above the restricted water level. This will lead to reduction of energy storage and production of energy.

As discussed before the water level in Totak is going to be in general higher than it is right now, especially in case of smaller installed power of PSH. This situation would actually improve conditions for fish survival in the reservoir throughout the year.

Possible problems might arise not from water level fluctuation which can lead to stranding of juvenile fish, but by volume of water travelling between reservoirs. Mortality of fish introduced by pumping operation is discussed in chapter 8.2.5 and should be explored in detail and mitigated.

8.3.2. Impacts on recreational and aesthetical values

These impacts are closely linked with other impacts mentioned in previous chapters.

Recreational and aesthetical values can be affected by change in water quality due to pumping as is for example lower visibility of water, see chapter 8.2.3. Large areas of the reservoir bed exposed by significant withdrawal rates from one day to another would feel unattractive, could cause unpleasant odours from mud and organic material rotting in littoral zone. Another problem is harder access to the water for example with boats used by owners of cabins in the area for recreation and fishing. In case of negative impacts of PSH on fisheries the attractiveness for fisherman would be also decreased. Visible changes in landscape for example by wrong placement of new distribution network would lead to loss of attractiveness as a tourist destination.

9. Conclusion and recommendation

Massive development of new renewable energy sources is taking place all over the world in 21st century and Europe is not an exception. This thesis is a continuation of suitability exploration of a current Norwegian hydropower system as so called the Green battery of Europe. This balancing system could secure the planned European wind power projects during situations when the production is larger than the demand by storing energy in upper reservoirs using pumping storage hydropower. During conditions when the demand is larger than generated energy the extra input can be produced by Norwegian hydropower system as well.

Totak reservoir in Telemark county in Norway was explored as a lower reservoir for pumping storage hydropower plant which would cover the part of balancing capacity of TradeWind project, which is a wind power capacity scenario project for year 2030 consisting of 94,6GW of installed capacity in the North Sea in Belgium, Denmark, Germany, UK, Netherlands and Norway.

Pumping storage operation using Songavatnet reservoir as upper reservoir and Totak as a lower reservoir was modelled. Characteristics of operation of PSH as water level fluctuations, transferred water volumes and other were calculated for two variants of installed power output, 1200MW and 3150MW, within period of 2000-2006. Results together with process of modelling showed that pumping model is a powerful and reliable tool.

Literature review on possible environmental impacts which could be caused by this operation was conducted, which lead to evaluation of these possible impacts based on forcing resulting from a pumping model.

Water temperature in Totak reservoir together with ice cover regime was modelled for both current situation and situation changed by introducing pumping storage hydropower in period of 2000-2006. Presented results showed that transformation of MyLake to MyLakeR, i.e. from model designed for natural lakes into model able of complicated system with dynamic inflows and outflows, was successful. On the other hand expectation of ice cover regime was not fulfilled as a more dynamic regime should have ended up in smaller ice thickness and shorter period of time when there is an ice cover during the winter season. The reason for this is that MyLakeR model is not computing a physical break up of ice cover due to water level fluctuations. This could be further improved in future work.

Except of water temperature and ice cover, potential for other environmental impacts caused by pumping storage operation was evaluated for Totak reservoir. There is need for further evaluation supported by field measurements and exploration. Special caution should be putted to danger of bank erosion and potential slides by more rapid and frequent water level changes.

Evaluation of impacts on upper reservoir – Songavatnet, and also Bitdalsvatnet should be done. As they are smaller reservoirs than Totak, potential damage is much higher as water level fluctuations will be bigger and faster as pumping model showed. Possible decrease of impacts could be done by regulation criteria which wouldn't allow to empty Songavatnet under certain water level.

The pumping storage operation was considered as not interfering with current hydropower projects. There is a need for complex economical assessment to balance the pumping operation with system of current hydropower plants in a way of achieving best results.

Suggestion for future work:

- Creation of routine for a physical break up of ice within MyLakeR model in order to reflect dynamic changes caused by pumping storage hydropower
- Evaluate the possibility of interaction between two MyLakeR models between lower and upper reservoir, where the water being moved from one reservoir to other would have the temperature characteristics not as an input file from measurements from past, but actual temperatures resulting from modelling according to a vertical placement of inflow structure
- Evaluate environmental impacts for upper reservoir

This Master's thesis outlined the possible environmental impacts for pumping storage hydropower plant in general as well as for a specific case located in Telemark county, Norway.

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