NTNU
Norwegian University of
Science and Technology

Flood dampening in hydropower systems

Bendik Kristoffer Torp Hansen

Hydropower Development
Submission date: July 2018
Supervisor: Knut Alfredsen, IBM
Co-supervisor: Tor Haakon Bakken, SINTEF Energi

Norwegian University of Science and Technology
Department of Civil and Environmental Engineering

Flood dampening in hydropower systems

Bendik Hansen

Master's thesis in Hydropower Development

Submission date: July 2018

Supervisors: Tor Haakon Bakken, SINTEF Energi

Knut Alfredsen, NTNU

Norwegian University of Science and Technology

Department of Civil and Environmental Engineering

NTNU
Norwegian University of
Science and Technology

Faculty of Engineering
Science and Technology
Department of Hydraulic and
Environmental Engineering

M.Sc. THESIS IN
HYDROPOWER DEVELOPMENT

Candidate: Bendik Kristoffer Torp Hansen

Title: Flood dampening in hydropower systems

1 BACKGROUND

The Norwegian hydropower system has a large storage capacity and a potential for dampening floods by taking advantage of empty capacity in periods of high runoff. Different factors influence the ability to store runoff in a flood situation, where both available capacity and potential for reservoir drawdown prior to the flood are important. For situations with drawdown, the flood prognoses are also important for planning purposes. In multi-purpose reservoirs the balance between drawdown and water storage for other uses also has to be taken into consideration. Flood dampening has recently been used as an argument for hydropower regulation in rivers, and this thesis will evaluate the experience with flood dampening in regulated rivers (both multi-purpose and pure flood dampening reservoirs) through a literature study and through the use of models for a selected river in Norway.

2 MAIN TASKS

The main tasks of the thesis are the following:

1. Perform a literature study to evaluate the status of flood dampening nationally and internationally. This could be in regard to both pure flood dampening reservoirs and reservoirs where flood dampening is one of several purposes. In the latter case it is important to look into how flood dampening is prioritized compared to other reservoir uses. Furthermore, previous studies about flood dampening in Norway should be reviewed for comparison or use in sub-task 3.

2. The model WEAP is a system to evaluate multi-purpose uses of water through prioritizing the releases from a reservoir. An evaluation of the flood dampening in Orkla shall be made based on this model and simulated runoff from a rainfall-runoff model. The results shall be compared to those of an existing model of Orkla made in nMag. Historical floods from before regulation in 1983 shall be the

basis for the model. The impact of initial reservoir filling, season, reservoir location, and drawdown capacity shall also be evaluated.

3. Based on catchment areas and regulation capacities of the evaluated rivers, the potential for finding a simple factor to describe the flood dampening potential of reservoirs shall be investigated, as well as how such a factor would work in a multi-reservoir system.

3 GUIDANCE, DATA, AND INFORMATION

The academic supervisor (faglærer) is Knut Alfredsen at the Institute of Civil and Environmental Engineering, NTNU. The main supervisor is Tor Haakon Bakken from SINTEF Energi. The candidate is otherwise personally responsible for collecting, controlling, and using data. Help from the supervisors mentioned above or others must be clearly referenced in the report.

4 REPORT

Structure and style of the report is important. Assume the target audience consists of technical personnel on a senior level. The report should contain a summary that gives the reader information and background, methodology, and main results. The report should contain an index and a reference list. The reference list shall be formatted according to an existing standard.

This text shall be included in the report.

Collected data shall be documented and delivered in a digital format.

The format of the report shall follow the NTNU standard. All figures, maps, and pictures that are included in the report shall be of high quality and have clear legible text on axes and legends.

The candidate shall include a signed disclaimed stating the presented work is his/her own, and that all contributions from other sources are identified through references or other means.

The thesis shall be submitted no later than the 9th of June 2018.

Trondheim 06th of February 2018

____

Knut Alfredsen
Professor

Summary

The influence of the hydropower system on floods in the river Orkla was investigated by simulating flood events in regulated and unregulated conditions. A discharge time series was simulated using an HBV model with temperature and precipitation data inputs from the gridded dataset called seNorge2. The model was semi-distributed and simulated 7 separate catchments at the same time. A WEAP model was set up for the Orkla catchment draining to Bjørset, including all relevant rivers, reservoirs and transfers. Selected events from the HBV discharge timeseries were then simulated with and without regulation reservoirs in the system. The floods were simulated with three different initial water levels: empty, realistic, and full, where "full" is identical to no reservoir at all in this model. The effect of drawdown from full reservoirs prior to a flood event was investigated by defining the reservoirs as full and giving the system a set number of days to release water before the flood event. This was done for several different release capacities.

The results showed that the reservoirs were more than large enough to fully absorb all their flood inflows under the assumed realistic reservoir filling, and that the constraint on how much the flood was reduced by was controlled by the fraction of water flowing into the regulated areas versus the unregulated areas. The discharge capacities of the transfer intakes were shown to be a limiting factor in how much of the discharge was regulated, as the transfers suffered large spills at the highest floods. Different release capacities influenced the dampening potential significantly if the reservoir was full prior to a flood.

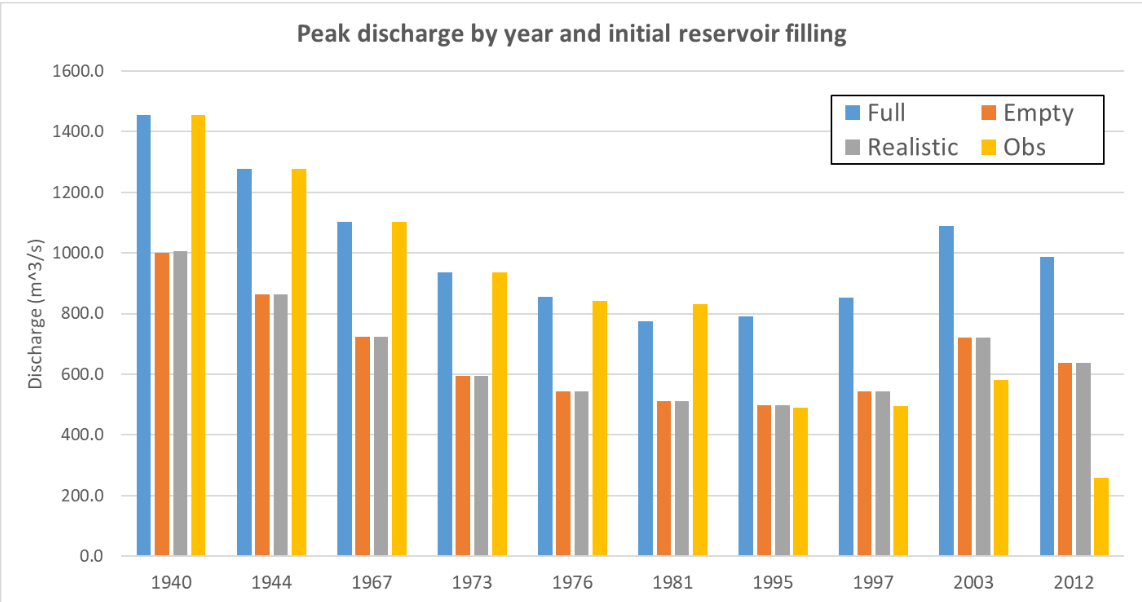


Figure A: Orkla flood dampening main results. The figure shows floods in selected years. Up to and including 1981, the "full" and "observed" peaks should ideally be equal. After 1981, the "realistic" and "observed" should be equal.

In addition to evaluating the flood dampening potential in Orkla, an attempt was done at finding a relationship between the regulation capacity and the flood dampening in reservoir systems in general. Due to a lack of real data to do an analysis on, a theoretical catchment with randomizable characteristics was created. The system had up to 10 reservoirs with random storage volumes and yearly inflows, and this enabled a variance in how much storage there was and where the storage was located compared to the inflows. Floods based on the Orkla flood hydrographs were simulated in the system, and the regulation capacity and flood dampening for hundreds of random configurations were generated. Curves were then fitted to the data.

The data from the hypothetical catchment showed that flood dampening varied greatly between catchments, even when they had the same regulation capacity. Furthermore, dampening could vary a lot between individual floods in one catchment, while in another the dampening could be the same for all the different floods. The curves were tested on data obtained from the literature study and performed relatively well considering the large spread in the synthesized data.

The development of a factor called "flood regulation capacity" was proposed to reduce the inaccuracies in the curves. This would remove storage that is not relevant for flood dampening purposes from the regulation capacity, such as filled or excessively large storage.

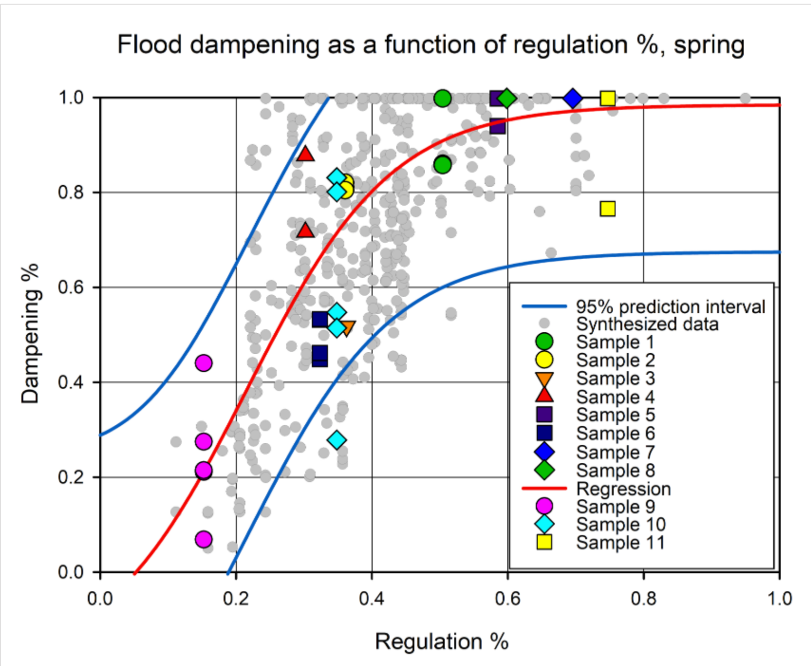
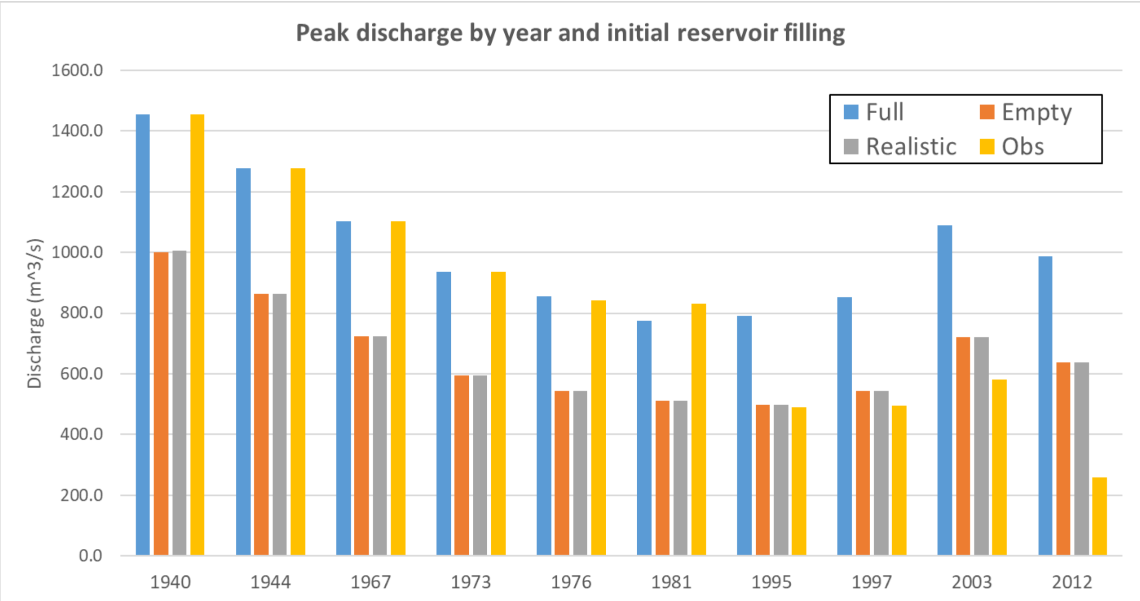


Figure B: Regulation capacity vs. flood dampening relationship for spring snowmelt floods for the theoretical catchments. Each "Sample" represents one specific hypothetical system configuration, and each point within a sample represents one of the floods.

Sammendrag

Påvirkningen fra vannkraftsystem på flom i elva Orkla ble undersøkt ved å simulere flomhendelser i regulerte og uregulerte tilstander. En vannføringsserie ble simulert med en HBV modell med temperatur- og nedbørsdata seNorge2 rutenett-datasettet. Modellen var delvis distribuert og ble simulert med 7 forskjellige nedbørfelt samtidig. En WEAP modell ble satt opp for delen av Orkla nedbørfelt som drenerer til Bjørset. Modellen inkluderte alle relevante elver, magasin, og overføringer. Utvalgte hendelser fra HBV tidsserien ble så simulert med og uten reguleringsmagasin i systemet. Flommene ble simulert med tre forskjellige initialvannstander: tomme magasin, realistisk fylte magasin, og fulle magasin, hvor «fulle magasin» er identiske med tilstanden uten magasin i hele tatt i denne modellen. Effekten av forhåndstapping før en flom ble undersøkt ved å definere magasinene som fulle og gi dem et visst antall dager til å tappe for flommen kom. Dette ble gjort for flere forskjellige tappekapasiteter.

Resultatene viste at magasinene var mer enn store nok til å sluke alt tilsiget deres under den antatte realistiske fyllingsgraden, og at begrensningen på hvor mye flommen ble dempet var styrt av prosenten av vannet som kom inn i den regulerte delen av feltet i forhold til den uregulerte. Slukeevnen til overføringene i felte ble vist å være en begrensende faktor i hvor stor andel av vannet som ble regulert, ettersom overføringene spilte store mengder vann i de største flommene. Forskjellige tappekapasiteter hadde betydelig påvirkning på flomdempningspotensialet dersom magasinene var fulle før flom.

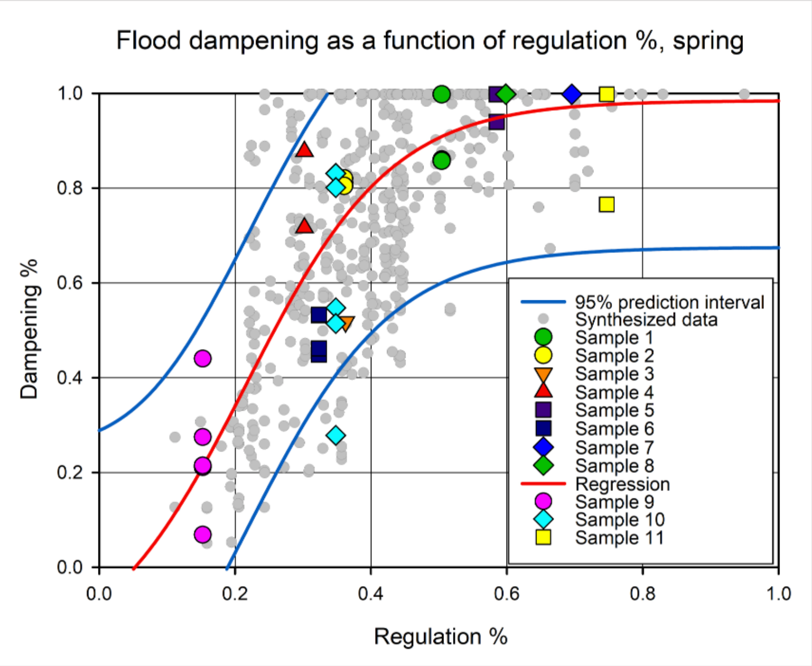


Figur C: Hovedresultater fra flomdempningsstudiet I Orkla. Figuren viser flommer fra utvalgte år. "Full" og "Obs" vannføring skal ideelt sett være like opp til og med 1981. Etter 1981 skal "realistic" og "Obs" være like.

I tillegg til å undersøke flomdempningspotensialet i Orkla ble det gjort et forsøk på å finne en sammenheng mellom reguleringsgrad og flomdempning i et magasinsystem. Grunnet mangel på ekte data å gjøre en analyse på ble et syntetisk nedbørfelt med tilfeldige parametere satt opp. Systemet hadde opptil 10 magasin med tilfeldige lagringsvolum og årlige tilsig, og dette tillatte variasjon i hvor mye magasinvolum det var i feltet i tillegg til hvor volumet var plassert. Flommer basert på hydrogrammene fra Orkla ble simulert i systemet, og reguleringsgraden og flomdempningen fra hundrevis av forskjellige system ble generert. Kurver ble så tilpasset dataen.

Resultatene fra det hypotetiske nedbørfeltet viste at floddempning varierte i stor grad mellom feltene, selv når de hadde den samme reguleringsgraden. I tillegg kunne dempningen variere kraftig mellom forskjellige flommer i ett felt, mens et annet felt hadde samme dempning for alle flommene. Kurvene ble testet på data fra litteraturstudiet og presterte relativt bra med tanke på den store spredningen i den syntetiske dataen.

Utviklingen av en faktor kalt flomreguleringsgrad ble foreslått for å redusere unøyaktigheten i kurvene. Dette ville fjerne lagrinsvolum som ikke er relevant for flomdempningsformål, slik som allerede fylt volum eller overflødig stor lagringskapasitet.



Figur D: Forhold mellom reguleringsgrad og flomdempning for vårflommer i de teoretiske nedbørfeltene. Hver "sample" representer ett spesifikt oppsett av systemet, og hvert punkt i en "sample" representer en av flommene.

Preface

The intended audience of this thesis is technical personnel on a senior level, and therefore it was assumed that the reader has a good understanding of hydrological processes and modeling, as well as about hydropower systems. As such, many terms that are not common knowledge to the general public were not defined or explained, as this would be tedious both for the advanced reader and the writer. Explanations for such terms can readily be found online or in introductory hydrology and hydropower books.

An attempt was made to keep explanations and consequences of the results in the thesis to the discussion section. Therefore, the results section presents only this, results. If there is confusion about what is presented there, it is hopefully either explained in the methodology section or in the discussion.

Acknowledgements

First and foremost, I would like to thank my academic supervisor, Knut Alfredsen, for his dedication to the field of hydrology and teaching. His enthusiasm, integrity and expertise have been highly inspiring during this 2-year master. He has also provided valuable feedback and responded quickly to requests and questions during the writing of the thesis.

I would also like to thank my main supervisor, Tor Haakon Bakken, for his repeated encouragement and trust in my abilities. He has been more than willing to help, and has provided a hoard of relevant information, in addition to utilizing the resources in his scientific network for my assistance.

There have been many others who have assisted me in this thesis. Inge Grut and Frode Vassenden from TrønderEnergi and Kristine Lilleeng from MultiConsult supplied required data, Abebe Adera at NTNU helped me acquire climate data quickly (and repeatedly), and the ubiquitous “Jack” on the WEAP forums helped solve technical issues.

Last, but not least, I would like to thank my classmates Menno Kemp, Rodrigo Suarez, and Ana Juarez. Menno helped me set up macros in Excel which saved me uncounted hours of work; Rodrigo answered all my questions about hydropower development, not only during the thesis but for the whole 2-year period; and Ana assisted with insightful feedback and was excellent company during what would otherwise have been many lonely weeks at the office.

Disclaimer

I hereby verify that all work presented in this report is my own unless it is attributed to another source. All contributions from other sources are identified through citations or by other means.

…………………………………

Bendik Hansen

Date: 9/July/2018

Table on contents

List of figures

List of tables

1 Introduction

1.1 Floods

Floods are a major threat to human life and property on a worldwide basis, posing a challenge for developing and developed nations alike. This has been the situation for thousands of years, and it is not likely to end soon, considering the fact that climate change prognoses estimate a global increase in short intense rainfall events and an increasing intensity and frequency for extreme precipitation events in mid-latitude regions (Collins, Knutti et al.). Intense or prolonged precipitation is not the only cause for floods, however. Other drivers can be snow melt, storm surges from cyclones, or even man-made factors such as dam or levee failure, often in combination with high precipitation events. Among natural disasters[1], floods are both the most frequent and the leading cause of death, having killed 6.8 million people in the 20th century (Doocy, Daniels et al. 2013). Flash floods, characterized by intense precipitation, high flood velocities and short warning times, have the highest mortality rate (death per flood event) (Doocy, Daniels et al. 2013), but some of the highest death tolls in the 20th century were caused by flood surges from cyclones and typhoons; 300 000-500 000 and 138 000 people were killed from cyclone flood surges in Bangladesh in 1970 and 1991 respectively. In the Bengali floods, the main cause of death was drowning; but the implications of a flood disaster can go far beyond the immediate effects. In 1931, some estimate that up to 3.7 million people died as a result of disease and starvation from an extreme flood in the Yangtze river in China (NOAA). 7 years later, the Chinese military command breached a dyke in the same river in an attempt to stop Japanese invaders, killing at least 500 000 people (Lary 2001).

In addition to the appalling loss of life from flooding, it can also incur extreme economic losses by damaging buildings, infrastructure, croplands, etc. Furthermore, it can put a halt to industrial activity in the area for prolonged periods. In 2011, Bangkok was struck by what is called the most economically damaging flood in history, with an estimated cost of USD 45.6B (although the mortality was relatively low with approximately 900 deaths) (World Bank 2011). Other economically devastating floods include the 1998 flood in Yangtze, China, with a cost of USD 30B and 1598 deaths (Hayashi, Murakami et al. 2008), and the “Great flood of 1993” in Mississippi, USA, with a cost of USD 15-20B and 50 deaths (Larson 1996). These floods all occurred in historically flood-prone rivers, and flood prevention measures were already in effect in the areas that were damaged by the floods.

[1] Pandemics and famines not included.

Norway is no exception to the dangers and damages of flooding, although the sparse population density means the floods will never reach such disastrous death tolls as described above. In fact, floods in Norway rarely inflict casualties; only approximately 100 people have died from flood disasters[2] in the country in the last 300 years (Tollan 2018). The majority of those deaths were in the flood named "Storofsen" (1789), which is the largest known flood in Glomma - the longest river in Norway. It was caused by a combination of high snowmelt and sustained high precipitation, killing 68 people and inflicting severe damage on farmland, buildings, and livestock along the river reach (Eikenæs, Njøs et al. 2000). Around 200 years later (1995), a flood event with a return period of 100-200 years dubbed "Vesleofsen" hit the Glomma catchment, taking one life and inflicting economic damages of approximately NOK 1.8 billion (USD 0.22 billion) (NVE 2016). High economic tolls have also been inflicted on a national scale in the last ten years, with damages exceeding NOK 1 billion every year except one since 2011 (Glover, Sælthun et al. 2018). Figure 1 shows the compensation paid by Norsk Naturskadepool (Norwegian Natural Perils Pool), which covers damages to insured private property. While this does not cover all the damages from floods, it shows the high cost of floods in Norway in the previous decade, and highlights the 1995 flood in Glomma.

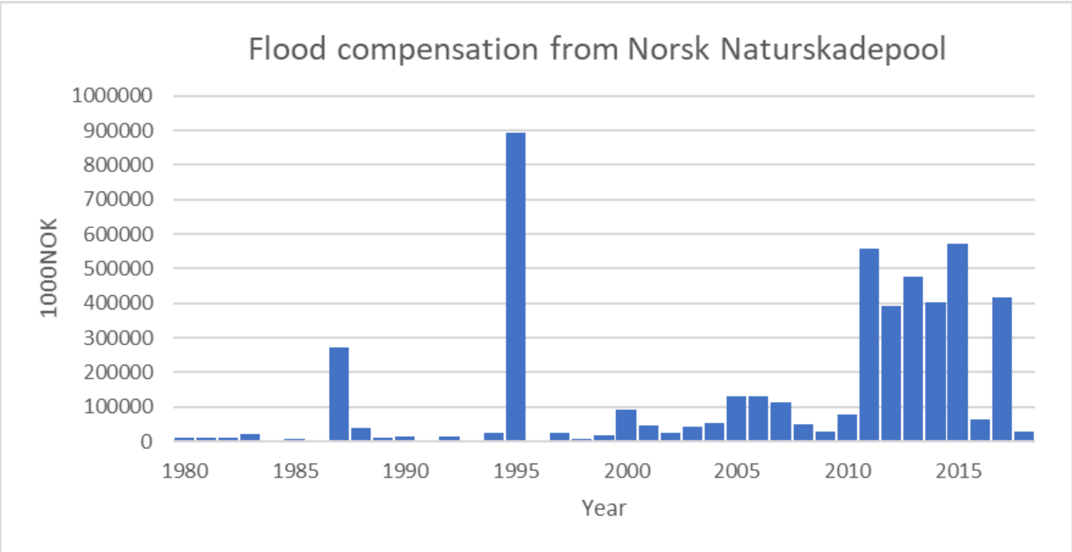


Figure 1: Compensation paid by Norsk Naturskadepool. (Norsk Naturskadepool 2018).

Another reason to turn one's attention towards flood dampening is the fact that the Norwegian Water Resources and Energy Directorate (NVE) estimates that, in Norway, the yearly annual flood will increase due to climate change in the coastal regions of Norway in the coming decades. In inland regions (such as Orkla and Glomma, mentioned in this report), the mean

[2] Flood waves from landslides are not included.

flood will tend to decrease. This is largely due to the type of annual maximum flood that occurs in those regions; inland areas are characterized by spring snowmelt floods, and increasing temperatures will reduce the amount of precipitation that falls as snow and the amount of snow that is stored over the winter. However, the report also points out that catchments like Orkla might suffer increased autumn floods. The increase in coastal regions is for the most part directly related to an estimated increase in precipitation. (Lawrence and Hisdal 2011).

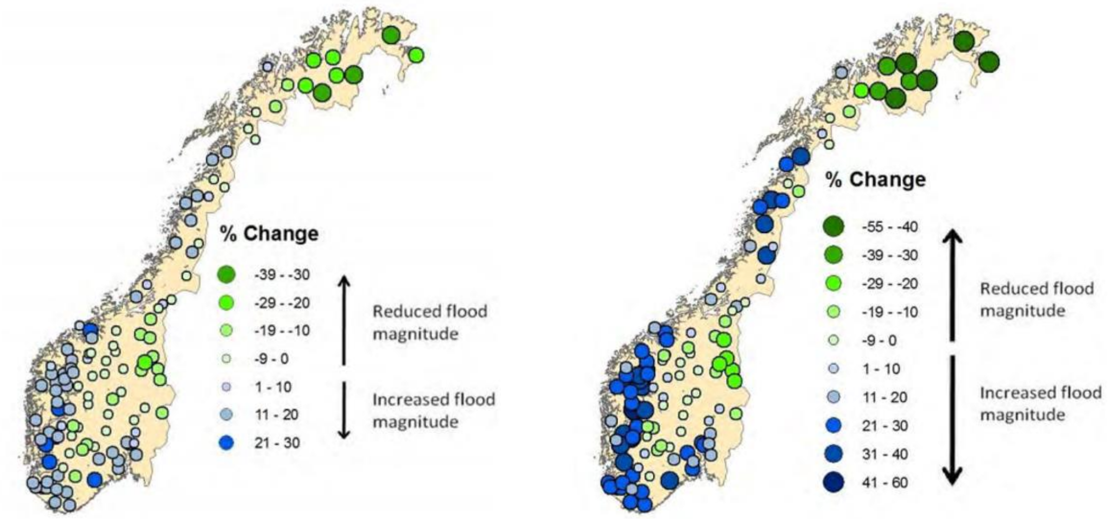


Figure 2: Estimated change in mean annual flood by region in Norway. The changes are compared to the period 1961-1990. The map on the left shows the period 2021-2050, and the map on the right shows the period 2071-2100. (Lawrence and Hisdal 2011).

1.2 Flood protection

Flood protection measures can consist of efforts to reduce a flood by diverting or intercepting parts of it with channels/tunnels or reservoirs, or making sensitive areas able to withstand floods by use of levees and dikes. These are all widely used worldwide, and notable examples include dikes in the Mississippi river valley in the United States, the Aswan High Dam in the river Nile in Egypt, the Linhuaigang project in the Huaihe River in China, and the Red River Floodway in Canada. The objective of flood protection from reservoirs often goes hand in hand with purposes like water supply, irrigation, and hydropower generation, since a typical reservoir is designed to store water from the wet (flood) season and distribute it in the dry season. However, a conflict of interest between flood protection and other purposes might arise if the reservoirs are already filled when a flood is predicted; there is a risk that the flood will not be as high as estimated, so if the reservoir is tapped to make room for it there could be a lack of water to meet other demands later. Nonetheless, approximately half of the multipurpose dams listed in the

International Commission on Large Dams' (ICOLD) database "The World Register of Dams" (WRD) have flood control listed as one of their functions, while a minority of the reservoirs with flood control as one of their functions are for that purpose alone (Figure 4) (Bakken 2018).

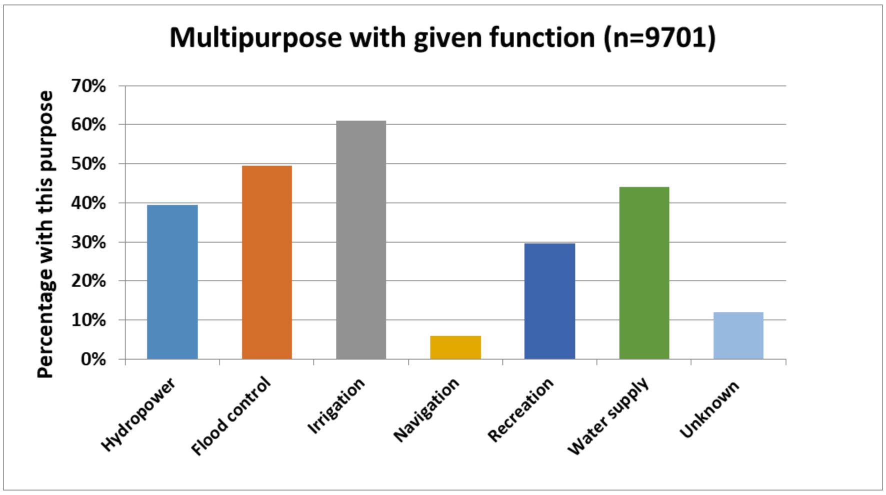


Figure 3: Multipurpose reservoir distribution. The figure shows the percentage of reservoirs that have a given function listed as one of its purposes (Bakken 2018).

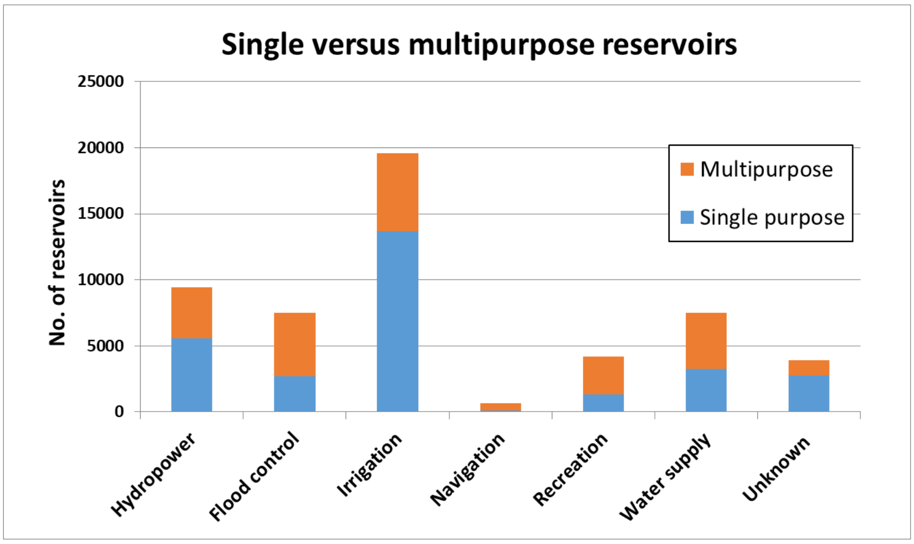


Figure 4: Number of single purpose and multipurpose reservoir in each category. (Bakken 2018).

With the global reservoir storage capacity decreasing due to sedimentation (Wisser, Frolking et al. 2015), it becomes increasingly important to assess the benefits of all the different uses of water storage reservoirs. The economic value that society gains from flood control reservoirs, however, can be difficult to ascertain. The basic approach might seem straightforward; estimate the damage caused by the flood with and without the flood control reservoirs in place, but according to Glover, Sælthun et al. (2018), little conclusive work has been done internationally to put a lifetime monetary value on the flood dampening caused by reservoirs. They proposed a procedure that would help put a monetary appreciation on flood control from reservoirs, which will be discussed in further detail in the Literature Review section.

In Norway, designated flood protection works mainly consists of dikes and lowered riverbeds to protect local areas. Of the 335 Norwegian dams in the WRD database, not one is listed as having flood control as either a single or multi-purpose (Bakken 2018). Regardless of their official designation, however, the Norwegian reservoirs do play a substantial role in flood dampening, despite a lack of financial compensation or reimbursement for potential losses. In fact, they are expected to; the Norwegian Water Resource Law states that reservoirs should be managed within their operational regime to limit damages to the public and private interests, as far as this is possible without prohibitive costs or disadvantages (Vannressursloven §5). In many cases, as previously stated, the flood dampening coincides well with the interests of the reservoir operator, such as to fill the reservoir during the spring floods. Drawdown of the reservoir prior to a flood event might also serve the operator’s interest, as excessive flooding can damage the dam and spillways, but they still provide a highly valuable service to society. The report from Glover, Sælthun et al. (2018) indicates that the prevented lifetime economic damages due to regulated reservoirs in Skienvassdraget, an area covering 3% of Norway, amount to a present value of approximately NOK 2-3 billion (100 million per year). This is almost twice the amount NVE is asking the Norwegian government for in order to implement necessary flood prevention measures such as dikes and reinforcements in all of Norway (NVE 2017). Their request does not recommend any flood prevention measures in Telemark county, where Skienvassdraget is located.

The first step in evaluating the value from flood control from reservoirs is to estimate their flood dampening effect. The purpose of this thesis is to perform a study of existing literature to get an overview of the state of and experience from flood control in reservoirs on a global and national scale, and then further to evaluate the flood dampening of a specific system in Norway by simulating it with and without reservoirs. The effect of different factors such as initial filling and drawdown prior to the flood events will be examined. Lastly, the possibility for finding a simple way to describe the flood dampening potential of a single- or multi-reservoir system based on catchment/system characteristics will be investigated.

2 Literature Review

A seemingly common and relatively straightforward method of flood dampening estimation is to compare the inflow/outflow of a reservoir during one or several flood evens. Lopez-Moreno, Begueria et al. (2002) investigated the influence of the Yesa reservoir (Spain) on flooding by comparing the observed inflow and outflow hydrographs for a 41-year period after its construction. By applying a number of statistical analysis tools on the data, they found that both the frequency and magnitude of outflow floods were decreased, but with a reduced dampening effect on floods with a higher return period (similar to the findings of Higgs and Petts (1988) as shown in Figure 5: , but contrary to modelling done by Lee, Chang et al. (2001), although the conclusions of the latter are questionable). Furthermore, the relationship between reservoir filling and flood dampening was investigated based on reservoir stage data. Interestingly, despite the decreased dampening effect for larger floods, the coefficient of determination (R^2) for the relationship between reservoir filling and flood dampening was significantly higher for floods greater than 10 times the mean flow (R^2=0.78) than for floods equal to 3 and 5 times the mean flow (R^2=0.36 and 0.40 respectively), indicating that the reservoir operation for very frequent floods depend not only on available storage, but also on other demands (such as season and expected snow melt) to balance the needs of water availability and flood protection.

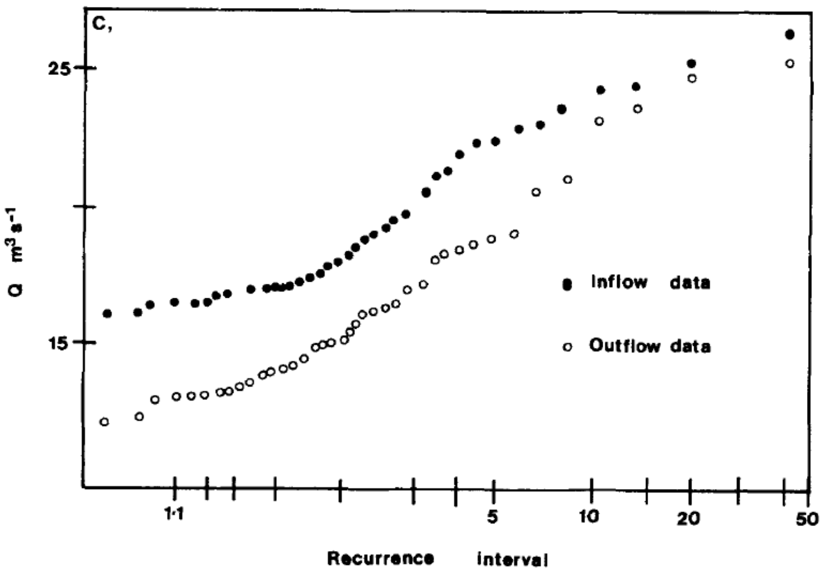


Figure 5: Magnitude of n-year floods above and below Stocks Reservoir on the River Hodder (UK). (Higgs and Petts 1988).

Zsuffa (1999) used a similar method to investigate the effect of reduced floodplain storage due to channelization associated with hydropower and flood protection levees in the Danube river, although this time the observed water levels from before and after alteration were compared. Zsuffa argued that, despite quickened runoff response and unchanged annual maximum water levels in the river-section in question, the flood protection had increased. This was due to the fact that the Danube is heavily protected by high levees in sensitive areas, so the flood threat comes from levee ruptures, rather than levee overtopping, and such ruptures are caused by the combination of high flood levels and long flood durations (also mentioned by Ngo, Madsen et al. (2008)). By channelizing rivers and raising levees to prevent storage in floodplains, the superposition of flood waves from different upstream areas is avoided, and each flood wave can travel through the river quickly without aggregating in large flood plain storages and causing sustained high flood levels. Zsuffa showed that the "Flood Load" value (consecutive days with a water level over a certain threshold [meter-days]) was reduced by up to 85% for the 10-year flood at the gauging station closest to the Austrian barrage system. Although this study does not deal directly with flood control from dams, it was included to demonstrate the importance of tailoring the flood protection design to the system in question (flood peak dampening efforts could have a negative impact in the heavily leveed Danube river).

In the above-mentioned studies, flood dampening analysis was based on observed data. However, this type of data is often incomplete or entirely lacking (Higgs and Petts 1988, Fitzhugh and Vogel 2010). Furthermore, when comparing data from before and after reservoir construction, it can be difficult to isolate the impacts of reservoirs from the impacts of other developments such as land use and land cover changes, long-term climatic trends, etc. on the river flow (Higgs and Petts 1988, Lopez-Moreno, Begueria et al. 2002, Fitzhugh and Vogel 2010). The importance of isolating the acting factor is demonstrated in Higgs and Petts (1988), where what appears to be a significant drop in flood frequency and magnitude over several decades after flood reservoir construction is shown to be connected to a large extent to an absence of extreme precipitation in the same period. These issues can be circumvented by using modelling tools to estimate flood dampening. Additionally, modelling tools allow the user to simulate events such as the probable maximum flood (PMF), as well as to simulate the dampening caused by a proposed or ungauged system.

Fitzhugh and Vogel (2010) looked at data from 4859 different streamflow gauges in the continental United States in an attempt to assess the actual impacts dams have had on flood flows, and to investigate the relationship between dam storage volume and flood alteration. The authors used multivariate regional regression methods on more than 200 “hydrological units” (HUs) covering the bulk of the continental United States, with variables calculated on a decadal basis to account for changes over time. The mean annual flood (MAF) was also calculated on a decadal basis from the daily streamflow data. Among the variables were catchment characteristics like drainage area, slope, soil characteristics, etc.; as well as median annual precipitation (per decade), population density (as a proxy for urbanization and impermeable surfaces), and storage ratio (total storage capacity in all upstream dams divided by the decadal mean annual runoff). See Fitzhugh and Vogel (2010) for a full list of included regression variables. By including climate, population, and storage ratio data as independent variables, the authors aimed to capture each variable’s influence on flood flows over time, in order to isolate the impact caused by dams. Of the HUs where acceptable regressions were found (HUs covering 78% of the area of the continental United States), 84% indicated a statistically significant relationship between storage ratio and flood flow reduction. By running the regression for the MAF with the actual storage ratios and with the storage ratio set to zero, the dampening caused by the storage capacity in each HU was determined.

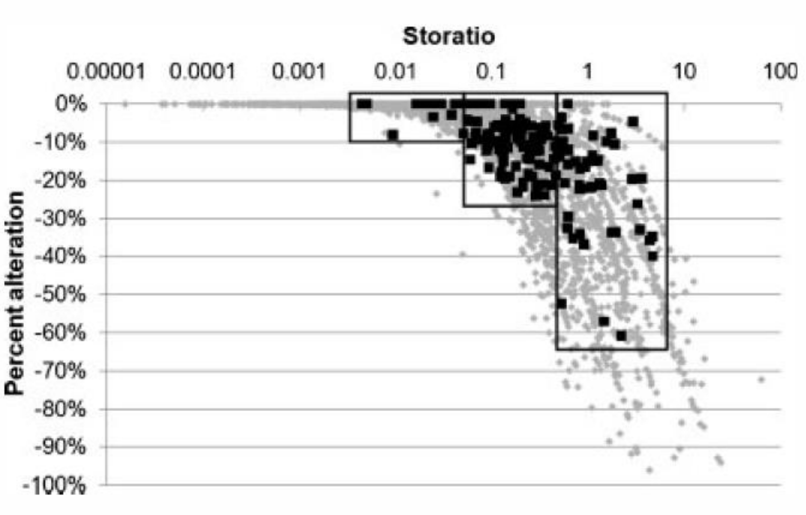


Figure 6: Storage ratio vs. estimated alteration of the medium annual flood (MAF).The black points are the averages for each hydrological unit (HU). The three boxes indicate “none to low”, “none to moderate”, and “none to very high” levels of alteration from left to right respectively. The boxes meet at 0.05 and 0.5 (Fitzhugh and Vogel 2010).

As seen in Figure 6, the dampening effect varies greatly for the same storage ratio, ranging from less than 10% to more than 70% for similar values (e.g. where the storage ratio is approximately 3). This is because the results are based purely on the observed impact of the storage ratio, regardless of the characteristics (such as spillway capacity), purpose, or operation of the reservoirs. The authors point out that the results can be useful for indicating the range of possible alterations to the MAF caused by dams. It is important to point out that the results shown in Figure 6 are only for the mean annual flood, and would likely vary greatly for floods of other return periods. In fact, a number of papers included in this review pointed out a reservoir's different dampening response to different magnitude floods (Higgs and Petts 1988, Zsuffa 1999, Lee, Chang et al. 2001, Lopez-Moreno, Begueria et al. 2002, Miotto, Claps et al. 2007, Wan, Hua et al. 2017). Furthermore, Miotto, Claps et al. (2007) indicated that the dampening response is highly sensitive to the hydrograph shape (e.g. early peak, late peak, etc.), even with hydrographs of the same magnitude peak and volume, as shown in Figure 7. Notice that at ηm (peak outflow/peak inflow) of approximately 0.5, the efficiency ranges from 0.2 (80% reduction) to 0.8 (20% reduction) for the same reservoir. Wan, Hua et al. (2017) further demonstrated the variable efficiency of individual reservoirs for different floods by looking at the impacts of single reservoirs in a multi-reservoir system in Huai River in China. By comparing the flood peak and volume estimated for a "no-reservoir" scenario to the values obtained by successively adding reservoirs one at a time to the calculations, the contribution of each reservoir to the total flood dampening could be determined. This procedure was carried out for 10 large historical floods, and the results show an enormous spread in the relative contribution from each dam; many dams had a peak contribution more than three times its average (minimums were not listed). The dam with the highest effect for any given flood had a maximum of 71.5%, while the average contribution from the same reservoir was 22.6%. The authors state that this is due to the unique characteristics of each flood, such as location, magnitude, and timing; as well as the reservoirs having varying storage and release capacities, operating rules, and locations. The combined effect of the entire multi-reservoir system also varied greatly with each flood, with peak discharge reductions ranging from 7.6% to 33.9%, with an average of 18.7%.

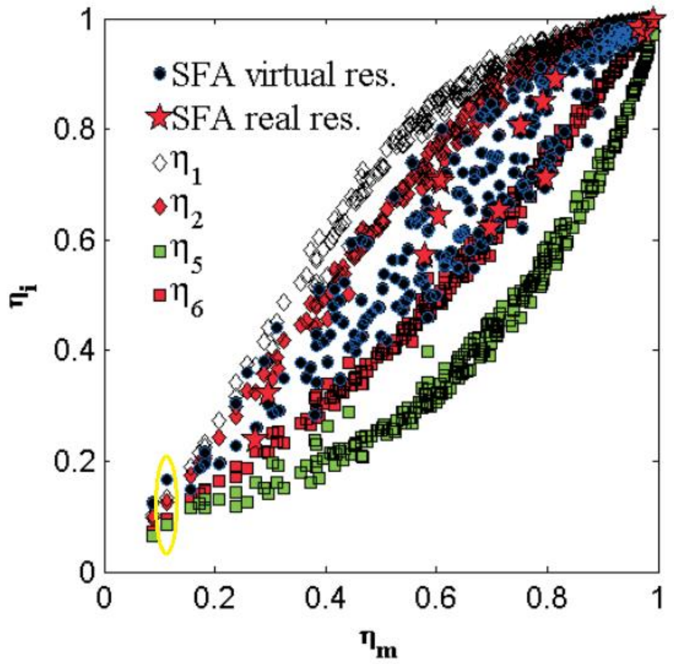


Figure 7: Simulated reservoir dampening with different inflow hydrograph shapes. η1-6 indicate different hydrograph shapes. SFA is the results obtained from the authors' Synthetic Flood Attenuation index. ηm is the average efficiency (peak outflow/peak inflow: 1 = no dampening) for a given reservoir, while ηi is that reservoir's efficiency at hydrograph i (or SFA). The yellow circle indicates the results from one single reservoir, to help understand the graph. (Miotto, Claps et al. 2007).

Mateo, Hanasaki et al. (2014) investigated the impact of two large reservoirs on the devastating 2011 Chao Phraya flood in Thailand which was mentioned in the introduction. The purpose of the two reservoirs, with a combined storage volume of 23 billion m^3, is flood protection during the wet season and water supply during the dry season, and the authors simulated the flood dampening from the reservoirs with different operational strategies. Historical operation was simulated utilizing observed inflows/outflows and water levels, and was implemented by setting a fixed discharge rate in the wet and dry season (based on bias corrected mean annual inflow), as well as water storage levels to reach by certain dates (with contingencies for releases during abnormal inflows). By altering the storage limit target level and date, the authors could simulate the effect changes in drawdown magnitude and timing would have on flood dampening. The results showed that the reservoir had dampened the flood peak by approximately 22% and that their alternative reservoir operation could dampen the peak by another 6.25% of the unregulated peak, but the authors argued that this was not a good indicator of the potential for flood mitigation. The simulation used a model with an integrated floodplain inundation calculation (H08 combined with CaMa-flood), and the results indicated that, on average, the flooded area was reduced by an additional 20% for the best scenario. The actual flood plain inundation reduction for the 2011 flood was 40% on average (depending on flood depth) (Mateo, Hanasaki et al. 2014). Another study estimates the flood peak reduction to have been 15% (Wichakul, Tachikawa et al. 2013). It is worth pointing out that the increased flood dampening in Mateo, Hanasaki et al. (2014) would lead to decreased water supply safety. This is because the new strategies involved keeping the reservoirs at a lower water level than current operation dictates. The study estimated that the proposed operational strategies would lead to 0 months with empty reservoirs and claimed that this indicated there would be no problems with dry season water supply. However, this claim is absurd as the proposed operation involved scaling the releases from the dam based on how much water was left (lower reservoir filling would lead to lower releases), which in practice prevents the reservoirs from emptying, but also implies that the water demand is somehow proportional to the reservoir filling, when it fact an inverse relationship seems more likely.

It is obvious that there are strong conflicting interests between the uses of a multi-purpose reservoir. In the Three Gorges Project, for example, the water level is maintained at a low level during the wet season to increase its flood protection capacity, which means there is a lower head and less water (water in excess of the turbine capacity is spilled) for hydropower production, as well as reduced navigation conditions. The reservoir will only retain water if the inflow exceeds the dam's safety discharge, and the retained water will be released as quickly as possible (Hayashi, Murakami et al. 2008). However, the problem of conflicting objectives can occur even within the scope of one single purpose. The operational strategy for the Hoa Binh reservoir (primary purpose: flood protection) in Vietnam dictates a number of criteria for water release, based on both the water level in the Red River at Hanoi far downstream and the water level in the reservoir itself. If the water level at Hanoi reaches a certain threshold, the Hoa Binh reservoir will retain water to reduce the flood, but only until a certain water level is reached in the reservoir, at which point the threshold water level at Hanoi for retaining additional water in the reservoir is increased. This is because high water levels in the reservoirs can be damaging and/or dangerous, so they must be justified by avoiding extreme conditions at Hanoi. Furthermore, the rate of release increase is limited to protect the ecosystem and society in the downstream section of the reservoir (Ngo, Madsen et al. 2008). When multireservoir systems are considered, Karbowski (1993) showed that there can be many different operational strategies to achieve the same minimum flood discharge downstream of the system, which means maintaining water levels below thresholds in certain reservoirs can be prioritized at the expense of others, without compromising downstream water levels.

As a result of devastating floods in the United States, Europe, and Asia during the 1990s, researchers at the Norwegian Water Resources and Energy Directorate (NVE) proposed a study (HYDRA) investigating if human interventions such as land-use/land-cover changes, hydropower regulation, roads/railroads, flood protection works, etc., could lead to increased flood risks (Tollan and Ljøgodt 1995). The massive flood (Vesleofsen) in the River Glomma later the same year helped kick-start the project, and it was initiated in 1996. As part of the HYDRA study, Knut Alfredsen at SINTEF/NTNU developed a model of the River Gudbrandsdalslågen to determine the flood dampening caused by the hydropower regulation in the system. The model incorporated components of the system, such as lakes, river reaches, channels/pipes, catchment areas, hydropower stations, and spillways. The system consisted of many natural lakes that had been altered by hydropower regulation, and the natural state was simulated by approximating the natural release of the lake using broad-crested weirs, with parameters estimated from historical data and maps. The difference between the simulated regulated and simulated natural results indicated that the peak discharge out of the catchment was reduced by approximately 11% (Wathne and Alfredsen 1998). The model is general, not specific to Gudbrandsdalslågen, and it was later adapted to the entire Glomma catchment, and was used for discharge and water level calculations in the HYDRA project.

In the end, the HYDRA project concluded that flood protection works such as dikes and lowered riverbeds had a negligible effect on the total flood dampening in the catchment. Similarly, the impact of land use change from urban development contributed very little to the total flow (Eikenæs, Njøs et al. 2000). Locally, however, flood protection works and land use changes can have enormous impacts. Dikes, while protecting the local area, can have negative impacts both upstream and downstream. Upstream, they can create a backwater effect that raises the water level significantly. Downstream, the removal of flood plains can increase the flood peak and also make the peak appear more quickly, which reduces the available response time. The HYDRA study estimated that the flood peak appeared up to 20 hours earlier in certain areas due to flood protection works upstream. The study also indicated that the annual runoff in urban areas had increased significantly due to land use changes (such as adding impervious surfaces), in several cities by more than 50%. As urban areas only make up 1.5% of the Glomma catchment, this did not have a large impact on the total flow (Eikenæs, Njøs et al. 2000).

Several other examples of Norwegian flood dampening studies are compiled in Glover, Sælthun et al. (2018). They examined case studies of floods in various catchments as part of a project to develop a procedure for calculating the economic value of regulation reservoirs with respect to flood dampening. NVE has developed a tool (Sælthun 2017) that estimates the economic cost of a T-year flood based on detailed information about land use and development such as buildings in the area (Figure 8). By doing this calculation with and without flood protection works such as dikes (not reservoirs) in place the tool can estimate the yearly avoided costs by calculating the difference in area under the curve for 1 year (where the recurrence interval is replaced by the probability of occurrence, 1/T). The report points out, however, that reservoir flood control does not reduce the damages of a flood with a given return period (unlike dikes), but rather reduces the chance of that flood happening. Thus, the T-year flood will be different in a catchment with flood control reservoirs. By running the program twice with the different recurrence intervals, one can calculate the difference in damage costs to find the economic value of the flood control from the reservoirs.

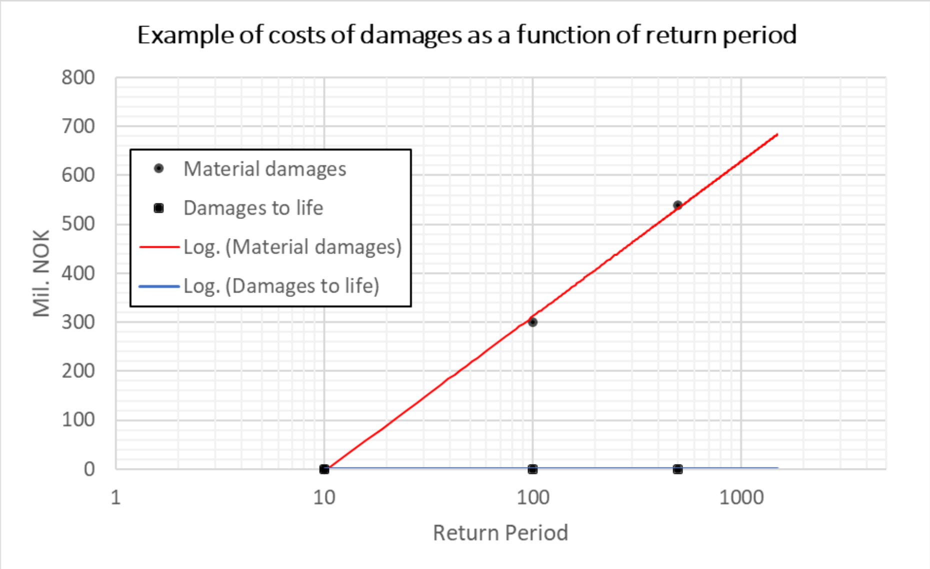


Figure 8: Illustrative example of return period vs. cost curve. In Norway, there is very rarely loss of life from flooding. The figure is translated with permission from figure 4-2 in Glover, Sælthun et al. (2018).

A brief summary of the main takeaways, methods, and results from some of the papers in the literature study is presented below. This is to illustrate the many different methods being used to estimate the flood dampening caused by reservoirs, as well as the numerous different indicators for flood severity, such as peak discharge, peak water level, inundated area, and flood load.

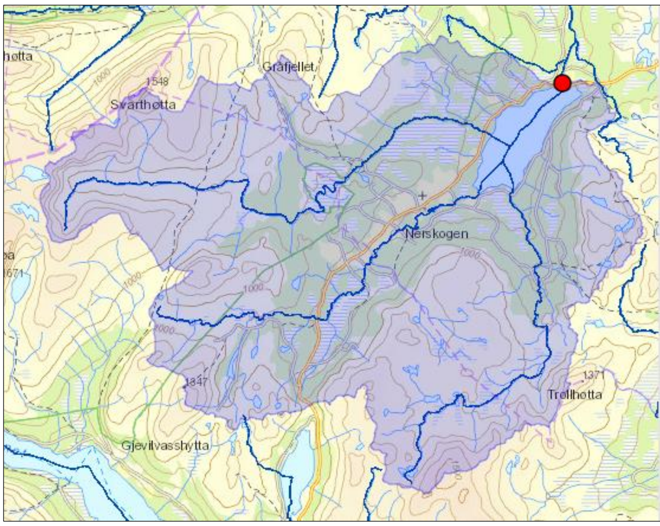
Table 1: Summary of literature review.

Author	Method	Aspect of flood investigated	Main takeaway	Results
Lopez-Moreno, Begueria et al. (2002)	Compare observed inflow and outflow timeseries from reservoir.	Flood peak reduction with different return period floods and different reservoir fillings.	Stronger correlation between reduction and res. filling for higher return period floods. Lower % reduction for higher return period. Dampening sensitive to initial res. filling.	Reduction in peak flood flow of 0-80%. No reduction when reservoir was 90%+ full before flood.
Zsuffa (1999)	Compare observed time series of flow and water levels from before and after regulation.	Flood Load (sustained high river levels), peak water level, peak discharge.	Dikes vulnerable to sustained high water levels, more important to route flood quickly and avoid flood superimposition than reduce peak.	Unchanged flood discharge peaks, increased number of floods, but significantly reduced flood loads. Increased flood protection.
Higgs and Petts (1988)	Compare observed discharge time series before and after regulation.	Peak summer and winter flood per year and number of floods above statistical threshold.	Reduction of floods caused by a lack of heavy rainfall in regulated period. Benefit of reservoir flood control lower the further downstream from it one gets. Lower reduction for higher return period floods.	Inconclusive. Lower magnitude floods after regulation, but likely caused by lack of precipitation.
Fitzhugh and Vogel (2010)	Compare time series of both discharge and regulation volume in an area, no "before and after" period, only regulation capacity.	Reduction in mean annual flood as a function of regulation capacity.	Mean annual flood important for ecosystem. Wide range of dampening from same regulation capacity.	Regulation capacity vs. dampening curve for mean annual flood. >25% reduction of mean annual flood 55%+ of large rivers in U.S.
Miotto, Claps et al. (2007)	Synthesize hydrographs of varying shapes and run through hypothetical reservoir. Compare to value from analytical index.	Flood peak reduction with different reservoir parameters and hydrograph shapes.	Flood dampening highly sensitive to hydrograph shape, despite hydrograph having same peak and volume.	Dampening within a single reservoir ranged with up to 60 percentage points for different hydrographs.
Mateo, Hanasaki et al. (2014)	Compare simulated (H08-CaMa) flow with and without reservoir. Discharge from rainfall runoff model.	Flooded area and depth of flooding, flood volume, peak.	Flood peak reduction not always accurate measure of extent. Flooded area reduced significantly more than flood peak.	Flood peak reduced by 15-22%, flooded area by 40%. Alternate operation could reduce flood another 6.25% and flooded area by 20%.
Ngo, Madsen et al. (2008)	Simulate flows, water levels and hydropower production (Mike 11) for different operational strategies.	Water level in reservoir, water level in river, high flow duration in river.	Must balance need between reservoir safety and downstream river safety. Can increase safety and hydropower income at the same time. Dikes cannot take sustained high floods.	Reservoir reduces flood water level and flood duration downstream compared to unregulated conditions. Can improve HP and protection, or one further at the expense of the other.
Glover, Sælthun et al. (2018)	Various. Used case studies from other projects.	Return period of peak and its implied flooded area damage.	Flood protection from reservoirs provide huge economic benefits in Norway.	Various. Ex: Full dampening in regulated Tyssedal while neighboring unregulated catchment had extreme flood.

3 Data acquisition:

3.1 Catchment characteristics

Catchment areas, specific runoff, flood frequencies, land use, elevation distribution, and a number of other characteristics are available for download at NVE's website www.nevina.nve.no. This tool automatically delineates a catchment based on a user-defined point and calculates all the corresponding characteristics from its databases. The outputs can be exported as a shapefile for easy import into GIS software. Using this procedure, catchments and characteristics were generated for 15 separate points (dam sites, gauging stations, and transfer locations).



Parameternavn	Generert verdi
ObjectId	40,248
Vassdragsnummer	121.BB12
Klimaregion	Midt
Region	Midt
Areal (km²)	214.18
Avrenning (mm/år)	941.42
Minimum høyde (m)	614
Maksimum høyde (m)	1,575
Sjø (%)	4.14
Bre (%)	0
Skog (%)	25.86
Dyrket mark (%)	2.38
Myr (%)	11.05
Snaufjell (%)	45.68

Figure 9: Example of NEVINA catchment delineation and characteristics output (not all characteristics are included).

Additional elevation data (a 50m resolution digital terrain model) was obtained from www.geonorge.no, a website for the distribution of maps and other spatial data, administered by the Norwegian Mapping Authority.

3.2 Precipitation and temperature

Spatially interpolated precipitation and temperature data for all of Norway with a resolution of 1 square kilometer is available from the Norwegian Meteorological Institute (dataset seNorge2). The data is available from 1957 to the present and has a daily time resolution. A description of how the dataset was generated and how to acquire it can be found in Lussana, Saloranta et al. (2018) and Lussana, Uboldi et al. (2016). Abebe Adera at the Norwegian Institute of Science and Technology (NTNU) has developed a program in R that allows the user to extract the desired data for specific catchments based on GIS shapefiles (Figure 10), and to calculate the average value in the catchment. With his help, temperature and precipitation data were extracted for the sub-catchments of interest in the greater Orkla catchment for the period 1957-2015.

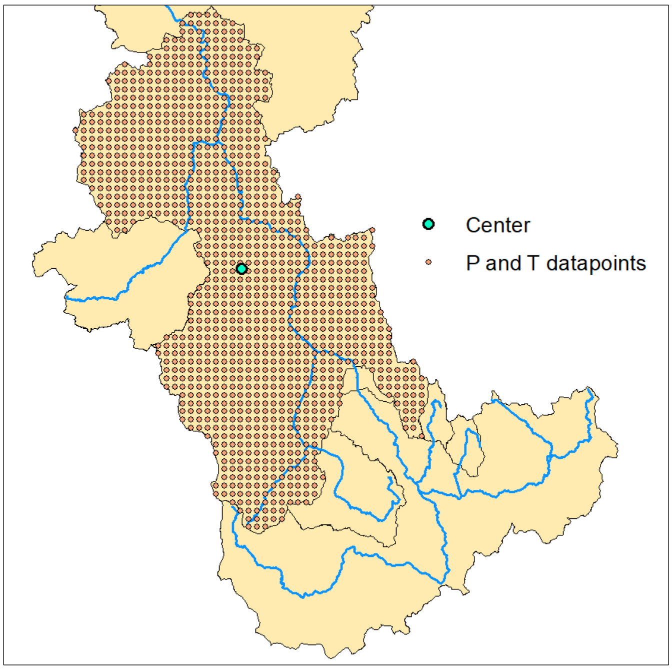


Figure 10: Example of extracted seNorge2 temperature and precipitation data grid for Bjørset local catchment.

3.3 Hydropower system characteristics

Information on reservoir size, volume-elevation curves, and the topology of the hydropower system was supplied by Knut Alfredsen at NTNU in the shape of a model setup from a previous study of the catchment. Information on transfer capacities and release gates were supplied by Frode Vassenden and Inge Grut at TrønderEnergi. Additional specification and details were also obtained from NVE's website www.atlas.nve.no, which contains a hoard of information about hydrology and hydropower in Norway that can be selected from an interactive map and exported as a georeferenced shapefile.

3.4 Hydrological data

Potential evaporation for the region and gauged flows for the runoff stations at Bjørset and Næverdal were supplied by Knut Alfredsen at NTNU. Additional observed data for the river Gaula and reservoir storage levels for Aursunden in Glomma was obtained from NVE's databases with access through NTNU (HYDRA). The river and lake network shapefiles for Gaula were downloaded from www.atlas.nve.no.

4 Study area

The river Orkla is located in the counties Oppdal, Hedmark, and Trøndelag in central Norway. The river stretches across 172km and has a catchment area of 3053km^2 at its outlet in Orkdalsfjorden. Due to the lack of natural lakes in its main river, Orkla has a limited potential to dampen floods, of which both spring snowmelt floods and autumn rain floods are common. The autumn floods are, according to Drageset (2002), the most critical, as they occur when the reservoirs are typically full. The catchment was developed for hydropower during the 1970s and early 80s, despite substantial public resistance to the construction of the large reservoirs in the rivers Grana and Inna. There are 5 large hydropower stations in the system: Ulset (35MW), Litjfossen (75MW), Brattset (80MW), Grana (75MW), and Svorkmo (55MW) with an average annual production of 1371GWh (Toldnæs and Heggstad 2017). These powerplants are supplied by 4 regulated reservoirs: Falningsjøen in Falninga, Stor Sverjesjøen in Sverja, Granasjøen in Grana, and Innerdalsvatnet in Inna. Falningsjøen and Stor Sverjesjøen are natural lakes that have been regulated, while Granasjøen and Innerdalsvatnet are artificial reservoirs. The lowest powerplant, Svorkmo, utilizes the releases through all the upstream powerplants; Brattset utilizes the releases through Litjfossen and Ulset; and the remaining three powerplants operate on independent inflows. The hydropower system is Orkla is operated by Kraftverkene i Orkla, KVO ("The Powerplants in Orkla"). For the remainder of this study, the focus will be on the catchment area draining to the streamflow gauge at Bjørset Dam (see Figure 14), just upstream of the first intake to Svorkmo powerplant. The reasoning for this is that all the reservoir regulation happens upstream of that point, and Bjørset gauge has a long timeseries both before and after regulation. Investigating the flow at Orkanger, where Orkla flows into the fjord, would only mean including a larger unregulated area which makes it harder to see the effect of the reservoirs. An overview of the entire Orkla catchment is shown in Figure 11 below.

The Bjørset Dam catchment area is 2317km^2 with an elevation ranging from 130masl. to 1640masl. With the exception of Svorkmo, it contains all the reservoirs and power plants listed above, and has a total reservoir storage capacity of 426 million m^3. The average gauged flow since 1912 is 48.4m^3/s (1526Mm^3) (according to NEVINA the annual runoff is 679mm, 49,9m^3/s), but the specific runoff varies greatly within the catchment; the average annual runoff to Innerdalsvatnet is 538mm, while for Granasjøen it is 941mm. The storage regulation capacity at Bjørset is thus 0.28 (or 0.27, using NEVINA's runoff).

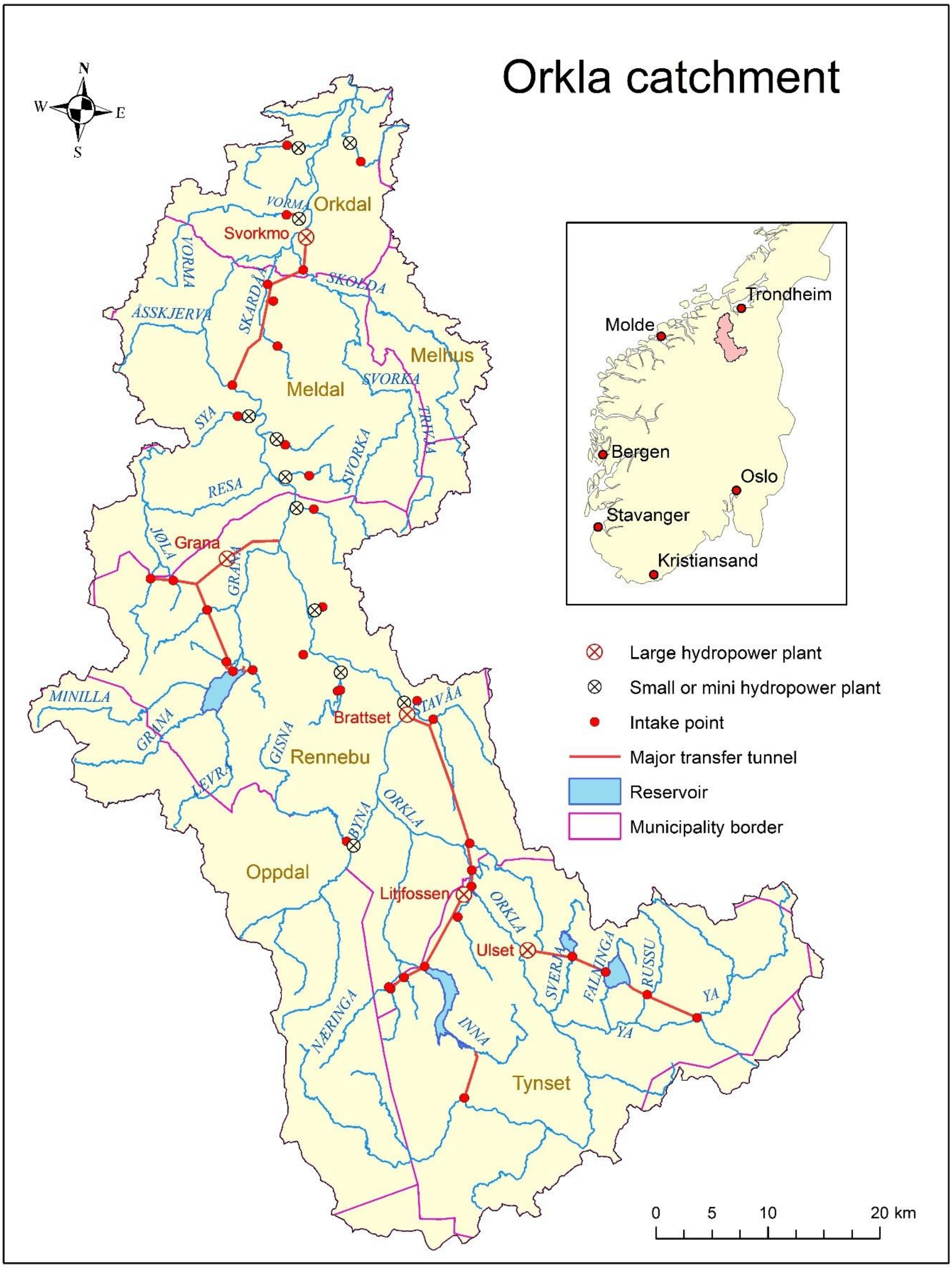


Figure 11: Overview of the Orkla catchment area and its hydropower system.

There are many transfer tunnels in the catchment: the tunnels from Øvre Dølvad in upper Orkla to Innerdalsvatnet and from Ya to Falningsjøen both divert large areas into the two lakes. Power plants and their intakes were not included in the study other than for reservoir drawdown, as their impact was not pertinent to the flood at Bjørset. The Bjørset catchment was divided into 14 separate sub-catchments to estimate flows at appropriate places, consisting of transfer intakes, gauging stations, and reservoir outlets. A brief summary of their characteristics can be found in Table 3 below, and a map showing their position and size can be found in Figure 14.

Table 2: Reservoir data.

Reservoir	Active storage at HRWL (Mm^3)	HRWL (masl)	LRWL (masl)
Sverjesjøen	7	873	868
Falningsjøen	125	873	825
Granasjøen	144	650	610
Innerdalsvatnet	150	813	778

Table 3: Summary of characteristics for each sub-catchment. The transfers significantly change the regulation % in the catchments they lead to. It is assumed that the transfers divert 100% of their respective yearly discharges, which is not quite accurate – a more detailed analysis will be carried out with model simulations.

Sub-catchment name	Local catchment area (km^2)	Total catchment area (km^2)	Annual runoff (mm)	Local reservoir capacity	Total reservoir capacity	Reg. % (unregulated)	Reg. % (regulated)
Bjørset	1151	2317	679	0	426	27%	27%
Falningsjøen	22	22	692	125	125	810%	80%
Granasjøen	214	214	941	144	144	71%	70%
Innerdalsvatnet	106	106	538	150	150	262%	62%
Kviknebekken	11	11	633	0	0	0%	0%
Larshussætra	5	5	959	0	0	0%	0%
Næringa	32	32	662	0	0	0%	0%
Næverdal	13	793	627	0	132	27%	N/A
Orkanger	735	3052	695	0	426	20%	20%
Øvre Dølvad	216	216	707	0	0	0%	0%
Russu	28	28	874	0	0	0%	0%
Storbekken	4	4	628	0	0	0%	0%
Storfossen	338	780	628	0	132	27%	N/A
Sverjesjøen	20	20	743	7	7	47%	47%
Ya	156	156	740	0	0	0%	0%

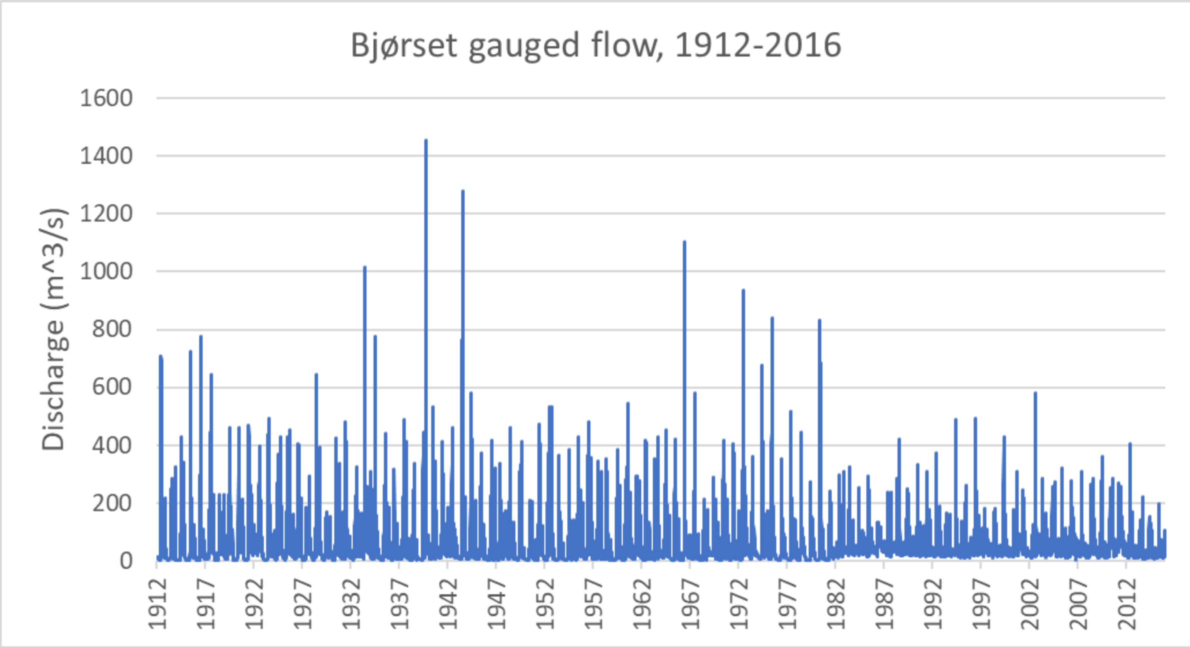


Figure 12: Bjørset gauged flow timeseries for the period 1912-2016. Note that there are two very large floods in the 1940s, outside of the period with temperature and precipitation data for simulation.

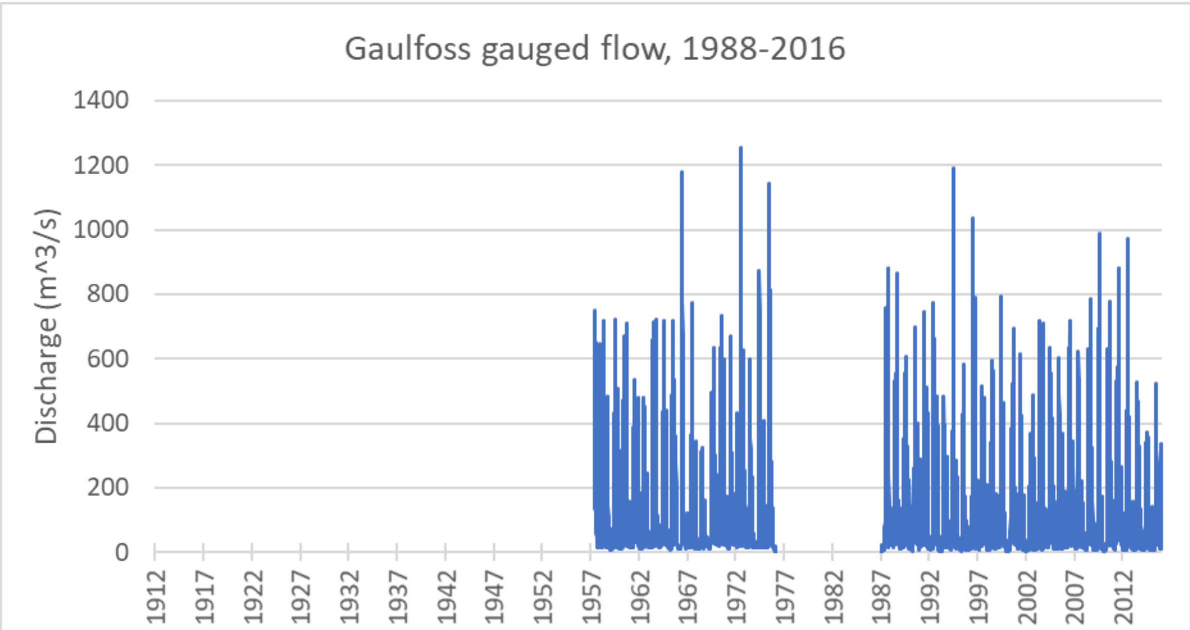


Figure 13: Gaulfoss gauged flow timeseries for the period 1957-2016.

Gaulfoss is a gauging station in the river Gaula, which is an unregulated catchment adjacent to Orkla. This timeseries (despite being only partial) was included as a means of verifying the floods in Orkla in the regulated period where there were no representative observations. Notice that the Gaulfoss timeseries captures the floods in Orkla in 1967, 1973, and 1976. These were all snowmelt floods, and it is reasonable to expect other snowmelt floods, such as 1995, 1997, 2010 and 2013, to be present in both catchments as well.

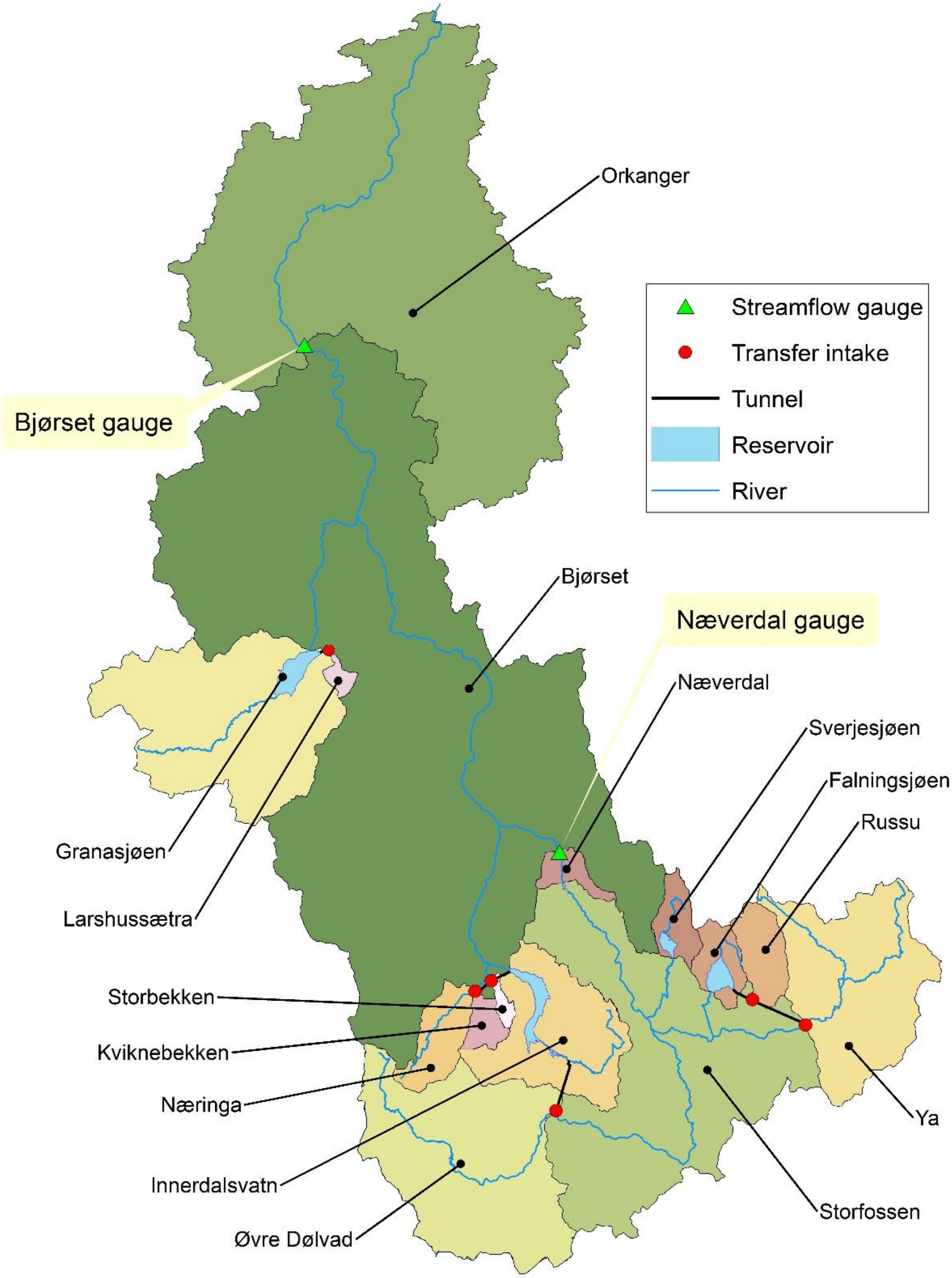


Figure 14: Map of relevant components of the Orkla catchment. The map labels indicate the name given to the various sub-catchment in this study.

5 Methodology

5.1 Reservoir release capacities and transfer capacities

The potential releases (Table 4) were estimated using release gate dimensions and elevations supplied by TrønderEnergi and a basic orifice flow equation:

$$Q = B * h * C_d * \sqrt{2 * g * H} \quad (1)$$

where Q is the maximum potential release through the opening, B is the width of the gate in meters, h is the height of the gate in meters, Cd is the discharge coefficient, g is the force of gravity, and H is the head of water above the center of the gate in meters. Cd was assumed to be 0.61 due to lack of data on the gates.

The maximum allowed releases were subjectively determined based on map data such as roads and settlement and flood return periods in the reservoir outlet rivers, as attempts to retrieve actual numbers from TrønderEnergi were unsuccessful. The effect of hydropower releases was also investigated, and therefore two separate simulations were done: one using only the allowable river releases to draw down the reservoir, and one using the total allowed capacity, which includes hydropower releases through tunnels.

Table 4: Reservoir release capacities and limits. The potential release already includes hydropower capacity.

Reservoir	Potential release at HRWL (m^3/s)	Max. allowed river release (m^3/s)	Hydropower Capacity (m^3/s)	Total allowed release capacity (m^3/s)
Sverjesjøen	10	10	4.5	10
Falningsjøen	75	15	13	28
Granasjøen	370	100	18	118
Innerdalsvatnet	107	40	30	70

The transfer capacities for the catchments of Ya, Russu, and Dølvadsætra were given by TrønderEnergi and confirmed using the Manning equation with available data on head differences and length/area of transfer tunnels:

$$Q = A * M * S_0^{\frac{1}{2}} * R^{\frac{2}{3}} \quad (2)$$

where Q is the maximum flow in the tunnel, M is the manning number, S_0 is the slope of the tunnel, and R is the hydraulic radius (wetted perimeter/area) of the tunnel. All tunnels were assumed to be drill and blast with M=40. except the Ya transfer which was known to be a TBM tunnel, which was given M=80.

As only the areas of the tunnels were given, they were all assumed to be circular. Calculations with more realistic horseshoe-shaped tunnels yielded similar results, so this was deemed acceptable for an approximation.

The calculated value for Dølvadsætra, 80m^3/s, was much larger than the given value of 42m^3/s. As no reason could be found for this low value, and supplementary data from TrønderEnergi suggested that a higher value was correct, this calculated value was chosen instead. The values that were supplied by TrønderEnergi were used for Ya and Russu. The remaining transfers did not have sufficient data to be calculated using Manning's equation and were therefore assumed to be able to transfer 100% of their inflows. Spills from these transfers would in any case have been quite small compared to the total flow due to their small catchment areas.

Table 5: Transfer discharge capacities. 100% indicates that they were assumed able to transfer all the flow in their respective rivers.

Transfer name	Transfer capacity (m^3/s)
Dølvadsætra	80.3
Larshussætra	100%
Russu	53
Ya	59
Storbekken	100%
Kviknebekken	100%
Næringa	100%

5.2 WEAP

Water Evaluation and Planning System (WEAP) (www.weap21.org) is a water resources planning tool that lets the user assess the effects of both supply characteristics (streamflow, groundwater, etc.) and demand characteristics (water use pattern, efficiency, allocation priority, etc.). The system integrates the simulation of both natural processes (e.g. rainfall runoff models) and engineered components (e.g. reservoirs and powerplants). It also has integrated GIS functionality, and utilizes a graphical user interface where components can be added and arranged in a user-friendly manner (Figure 15). WEAP is particularly useful for simulating areas with multiple water uses, such as irrigation, hydropower and drinking water, as it lets the user define demand priorities. It is also very useful for simulating "what if" scenarios, such as climate change, population increase, or land use developments.

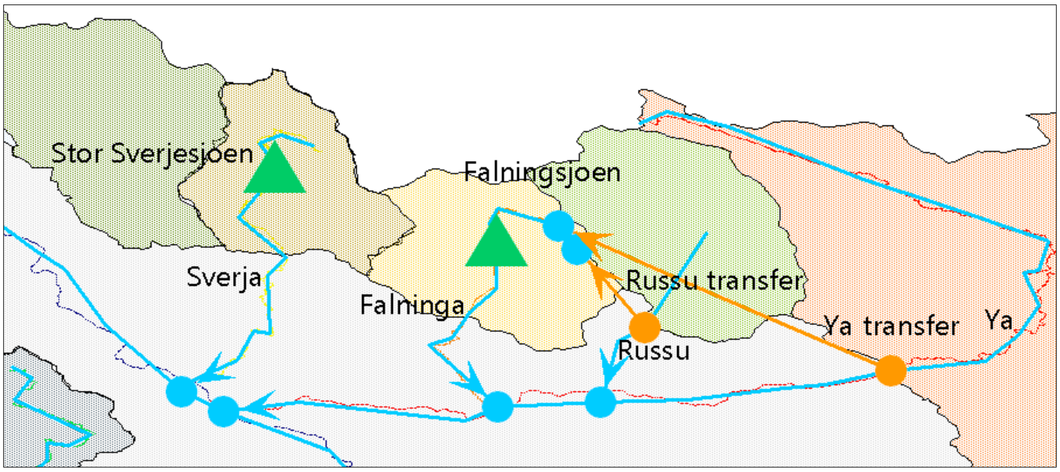


Figure 15: Example of WEAP layout. The catchments in the background are imported shapefiles and not part of any WEAP calculations.

The Orkla system in its unregulated and unregulated condition was set up in WEAP and each catchment was defined with individual inputs for area, temperature, and precipitation. The program's built-in soil-moisture rainfall-runoff model utilizes an energy balance procedure, which means it uses many different climate parameters such as temperature, precipitation, latitude, wind, cloud cover, and snow albedo in order to simulate snow accumulation/melt and evaporation. For runoff generation it uses a linear tank similar to the one in the HBV model described below. WEAP also allows other runoff input methods, including series with inflows to each river (headflows). The catchment setup in its regulated conditions is illustrated below.

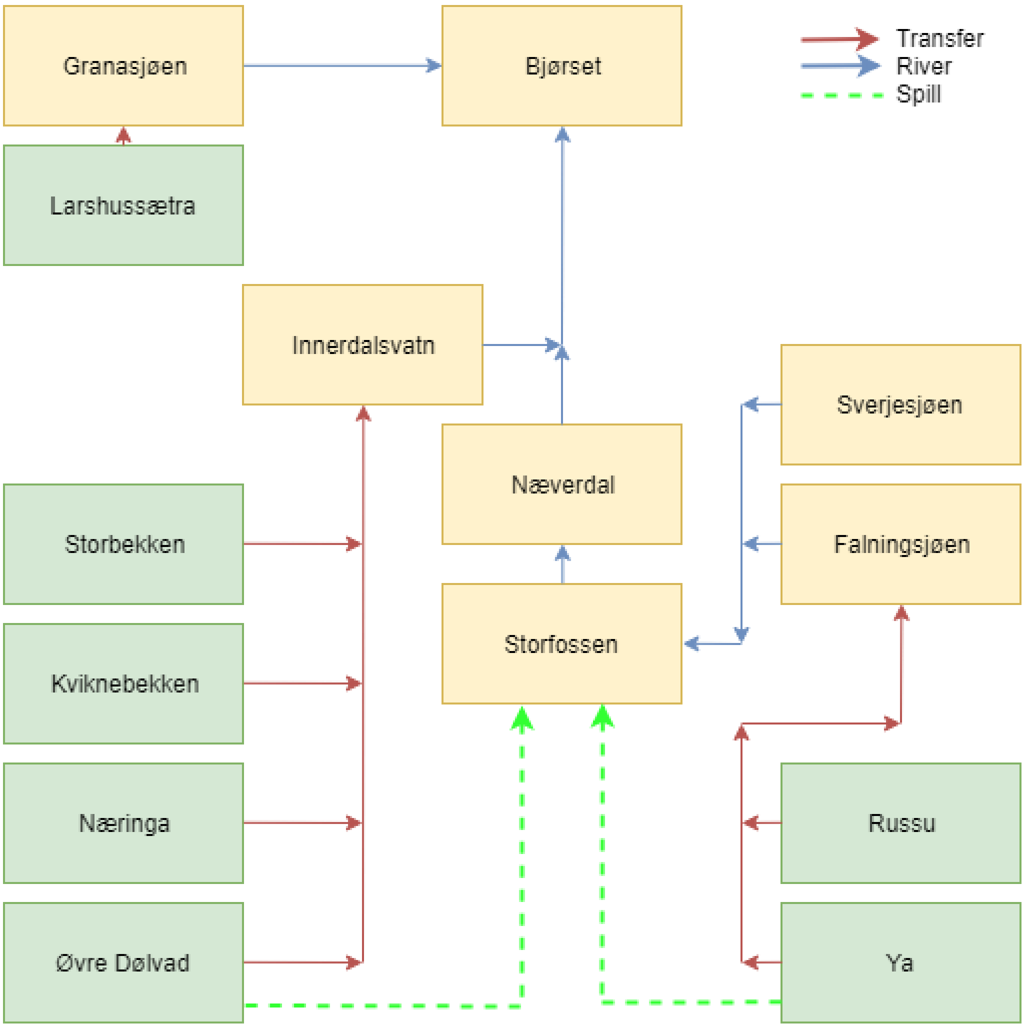


Figure 16: Schematic overview of the Orkla/Bjørset catchment area in regulated conditions. Green modules indicate transfer catchments. Only Ya and Øvre Dølvad had a limited transfer capacity and were therefore the only transfer catchments that could spill.

5.2.1 Reasoning for change of runoff model

Ideally, the climate input parameters should be from observed or realistically estimated values. In the present study, the required climate data (other than temperature and precipitation) was not readily available, and attempts were made at calibrating the model by using what were assumed to be reasonable values. However, satisfactory results were not obtained for the calibration despite great efforts, and it performed particularly poorly at reproducing the highest peaks of snowmelt floods, tending to produce floods with long durations and low magnitudes instead. The model was found to be highly sensitive to the maximum and minimum limits on snow albedo, as well as cloud cover (which was the main source of error in energy balance snow melt calculations in Tvedalen (2015)). WEAP received a major update in April 2018. One of the changes that was listed was improved mass balance calculation for the soil-moisture method, but the updated version was not tested in this study.

Rather than trying to acquire the detailed climate data and calibrate the runoff model in WEAP, a decision was made to change to a runoff model that could simulate the runoff acceptably using the data already at hand and then use that output as headflows input in WEAP. The HBV model developed at the Swedish Meteorological and Hydrological Institute (Bergström 1967) was ideal for this purpose as it only requires temperature and precipitation as time-series inputs and was developed for Scandinavian conditions.

5.3 HBV rainfall-runoff simulation

The standard HBV-model is divided into 4 routines: the snow routine, the soil routine, the upper zone, and the lower zone. The snow routine is divided into 10 elevation zones for the catchment in question, to more accurately simulate differences in snow processes due to elevation changes. It uses a degree-day model to simulate snow-melt. The soil routine uses a non-linear soil-moisture equation to generate surface flow, and the upper and lower zone use linear tanks with varying numbers of outlets which shape the hydrograph.

5.4 PINE HBV

The benefit of the HBV model is the relative ease with which it can be set up and calibrated for a catchment with limited data. Inputs consist of fixed catchment characteristics, such as area and elevation zones; regional parameters, typically only potential evapotranspiration; and temperature and precipitation time series. All the remaining parameters, such as snowmelt temperature and linear tank outlet coefficients, are calibrated based on observed flow timeseries. It is very helpful to have an autocalibrator for this process, as doing it manually can be challenging. An already developed HBV model called PINE HBV with an integrated PEST autocalibrator was initially used.

Note: During HBV calibration, the transfer catchments were not simulated as separate entities. Rather, the area was simulated with Bjørset and Storfossen catchments correspondingly larger, and discharges were afterwards scaled to each transfer catchment based on equation 3. The discharges in Bjørset and Storfossen were reduced based on the fraction of area "lost" to transfer catchments. Additionally, lake percentages were assumed to be 0, as their impact on the HBV simulation was observed to be negligible in this case.

Two separate PINE HBV calibrations were performed: One for Bjørset total catchment and one for Næverdal total catchment (the two gauging stations used in this study). Both calibration periods were 10 years, from September 1st, 1960 to September 1st, 1970 (hydrological years in Norway), and the calibration was verified on the following 10 hydrological years. The autocalibrator was instructed to prioritize the fit for flood peaks rather than water balance and low flows. When the parameters were calibrated, the unregulated time series was simulated for the two options and scaled to the sub-catchments using three different methods: All scaled from Bjørset, all scaled from Næverdal, and some scaled from Bjørset and some from Næverdal, depending on whether they were located in Næverdal catchment or not. The scaling was done based on both area and annual runoff (in mm) compared to the catchment the flow was calibrated for by using equation 3.

$$q_{local} = q_{total} * \frac{A_{local} * Q_{local}}{A_{total} * Q_{total}} \quad (3)$$

where q is the flow on a given day, A is the area, and Q is the annual runoff to the catchment.

A different option was also attempted: to first find the parameter set for Bjørset and Næverdal through autocalibration, and then run the PINE HBV simulation for each sub-catchment using their individual area, elevation distribution, precipitation and temperature, but with the parameters from Bjørset or Næverdal, depending on their location. This method would utilize the semi-distributed data more thoroughly, but the initial autocalibrated parameter sets gave a poor fit when the simulated flows were accumulated at Bjørset and Næverdal. It was believed that parameter sets could be found which give an acceptable fit but it proved to be prohibitively cumbersome and time-consuming to do in PINE HBV, as it required manual editing of each catchment's parameter file and new simulations (which needed to be exported and accumulated) for each catchment each time a variable was changed.

5.5 Multi-catchment HBV model

The benefit of utilizing the distributed data for each catchment was deemed to warrant the creation of a separate HBV model (henceforth referred to as EXCEL HBV) that could simulate all catchments simultaneously and automatically combine the results for comparison with observed flows. The model output on Bjørset total catchment was checked against the PINE HBV output as a benchmark during development; ideally the outputs should be identical for the same parameter-set on the same catchment. The setup was the same as the standard HBV model, with the exception that each elevation zone was divided into 4 snow packs to illustrate spatial variation in snow cover depth and that the inflow to the upper zone in each timestep is divided in two, with half entering at the beginning and half at the end of the timestep (both of these are also in use in PINE HBV). Overall it is a semi-distributed model (Table 6). All flood simulations were done using the EXCEL HBV output, as it was found to give approximately the same fit as the best simulation from PINE HBV but with the added benefit of presumably representing local phenomena more accurately. The simulation was done using a single parameter set for all catchments, which was obtained by starting with the parameter set for Bjørset from PINE HBV and tweaking parameters manually.

Table 6: Distribution of cells in EXCEL HBV.

Cell type	Number of elements	Factors that vary between cells
Catchment	7 (arbitrary)	Area, gauged temp. and precip., lake area, number of forested zones, temp. and precip. gauge elevation, elevation distribution.
Elevation zone	70 (10 * catchments)	Actual temperature and precipitation, type of precipitation, forest cover.
Snow pack	280 (4 * elev. zones)	Amount of snowfall as fraction of total (e.g. 2, 0.5).

5.6 Scaled observed runoff

There were certain observed floods which were not captured by any of the HBV simulation. Furthermore, the HBV simulations only extend back to 1957 due to the availability of climate data. Therefore, the poorly simulated floods and the floods that occurred in the period before climate data is available were replaced with runoff scaled from the observed values. For those floods, all catchment runoff were scaled from the runoff at Bjørset since the Næverdal timeseries does not extend far enough back in time to cover all the floods, and the scaling was done based on area and annual runoff using equation 3.

5.7 Flood simulations

5.7.1 Floods with and without reservoirs

Floods with a simulated (using EXCEL HBV) unregulated peak greater than 800m^3/s were selected for investigation and run through the WEAP model setup (Figure 16), as an appropriate number of floods were available above that threshold. The initial reservoir level was set before each flood simulation depending on the time of year, with values for realistic filling obtained from NVE's observed reservoir filling curves for the region (Figure 17). The median filling was used to represent a realistic value.

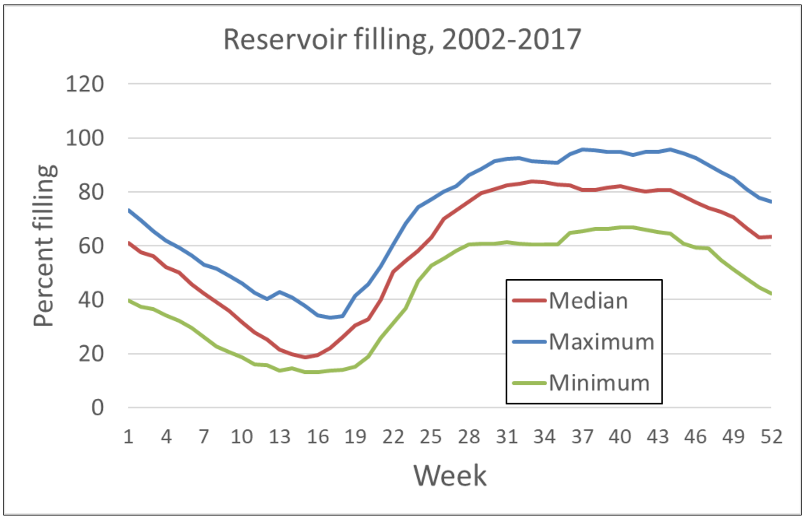


Figure 17: NVE reservoir filling for Norwegian elspot-region III.Data retrieved from http://vannmagasinfylling.nve.no/

Each flood was simulated three times: with full reservoirs, with empty reservoirs, and with reservoir at a realistic level. Due to the lack of lake routing and hydraulic constraints on outflow, the full reservoirs scenario is identical to a scenario with no reservoirs at all, and this represents unregulated conditions. For these simulations there was no outflow from the reservoirs unless they were full and spilled. The results were compared to the results from an existing model setup in nMag, a hydropower and reservoir operation simulation program (see Killingtveit (2004) for more detail on nMag). The nMag model was not made for flood simulation, but it was run with and without reservoirs for comparison of the runoff generation and flood peak reduction.

5.7.2 Effect of drawdown

To see what the effect of releasing water from the reservoirs prior to a flood event would be, simulations for the two autumn floods on record were done in WEAP with initially full storage. The snowmelt floods were not considered since the reservoir levels are typically very low when they arrive. A number of days ranging from 1 to 7 were then given for reservoir drawdown in the system to create flood control storage prior to the event. Transfer intakes were assumed to be uncontrolled, so the intakes would still supply water to the reservoirs even if the reservoirs were being drawn down.

5.7.3 Drawdown release rules

Rudimentary reservoir release rules were implemented to avoid increasing the total flood discharge at Bjørset due to reservoir releases. Releases were constrained so that the total flow at Bjørset would not exceed the 5-year flood, which is 659m^3/s according to NVE's NEVINA tool. This meant that if the total inflow to the system was 700m^3/s and 300m^3/s of this was flowing into the reservoirs, the reservoirs were allowed release up to a total of 259m^3/s (659-(700-300)). The allocation to each reservoir was done based on that reservoir's average fraction of the total regulated flow. If a reservoir received 40% of the total regulated flow on average, it was allowed to release 40% of the total allowable reservoir release, 103.6m^3/s in this case (0.4*259). The minimum of this value and the potential/allowed release capacity listed in Table 4 was then used. This was deemed a reasonable way to make sure each reservoir was drawn down proportionally to their expected flood inflow without exceeding allowable flow levels at Bjørset.

Since the headflows were deterministic, the release from each reservoir was calculated in excel and used as a timeseries for Maximum Hydraulic Outflow (MHO) in WEAP. MHO defines how much water is released from the reservoir while its filling is lower than HRWL. An additional procedure was added in WEAP which constrained reservoir releases to the minimum of the value in the timeseries and the value the reservoir could actually release based on its current water level above the release gate, which is a variable dependent on reservoir filling.

5.8 Flood dampening

The flood dampening of a system was defined as the percentage that the daily peak flow was reduced by. This was done by finding the peak flow during the flood period with and without reservoirs in the system and then calculated using equation 4:

$$\%\ dampening = 100 * \frac{(Q_{peak_{unreg.}} - Q_{peak_{reg.}})}{(Q_{peak_{unreg.}}} \tag{4}$$

where Q_{peak_unreg} is the simulated unregulated peak, and Q_{peak_reg} is the simulated regulated peak with "realistic" initial reservoir filling.

5.9 Regression curves

Initially, the intention was to create a relationship between regulation capacity and flood dampening based on the cases that were studied thus far. However, as the literature review yielded few cases where the required data could be extracted, a different approach was selected, which involved synthesizing data to generate a regression curve between regulation capacity and flood dampening.

5.9.1 Theoretical catchment

A theoretical catchment with randomized parameters, shown in Figure 18, was set up to simulate its flood dampening response with different characteristics. The input hydrographs were based on the Orkla floods, and the annual total inflow was defined as 1500 million m^3, approximately the same as at Bjørset. Each reservoir in the system received a random reservoir storage capacity and a random annual inflow, where the storage capacity was constrained to be less than or equal to the annual inflow to that reservoir to prevent unrealistically large local regulation capacities. The local inflow to each reservoir was obtained by giving each reservoir a random fraction of the total inflow in the hydrograph (so that the total fraction equaled 1). There was a 33% chance that a reservoir would have 0 capacity in order to randomize the topology of the system to some extent, although reservoir 7 was exempt from this rule to make sure 100% of the discharge entered a regulated catchment.

The floods in Orkla were divided into autumn (only one autumn flood was used, as they had very similar hydrographs) and spring floods. Each flood was simulated 200 times. The range of possible reservoir storages was different for the two sites; for spring floods it could vary between 0 and 200 million m^3 and for autumn floods it could vary between 0 and 50 million m^3. This was because the autumn floods were observed to reach 100% dampening at much lower reservoir volumes than spring floods, due to their short and intense peak. Additionally, as it was expected that there would be a clear relationship between the dampening of a short intense autumn flood and its recurrence interval, the autumn floods were simulated for 4 different scenarios; 20, 50, 100, and 200 years recurrence intervals. Since the catchment's annual runoff and hydrographs were based on Orkla, the flood peak values at various recurrence interval floods were also taken from the corresponding values at Bjørset. No such division was done for spring floods, and this will be addressed in the discussion section. To convert the flood to a given recurrence interval T, the input discharge series was multiplied by the appropriate factor so that the peak was equal to the T year flood.

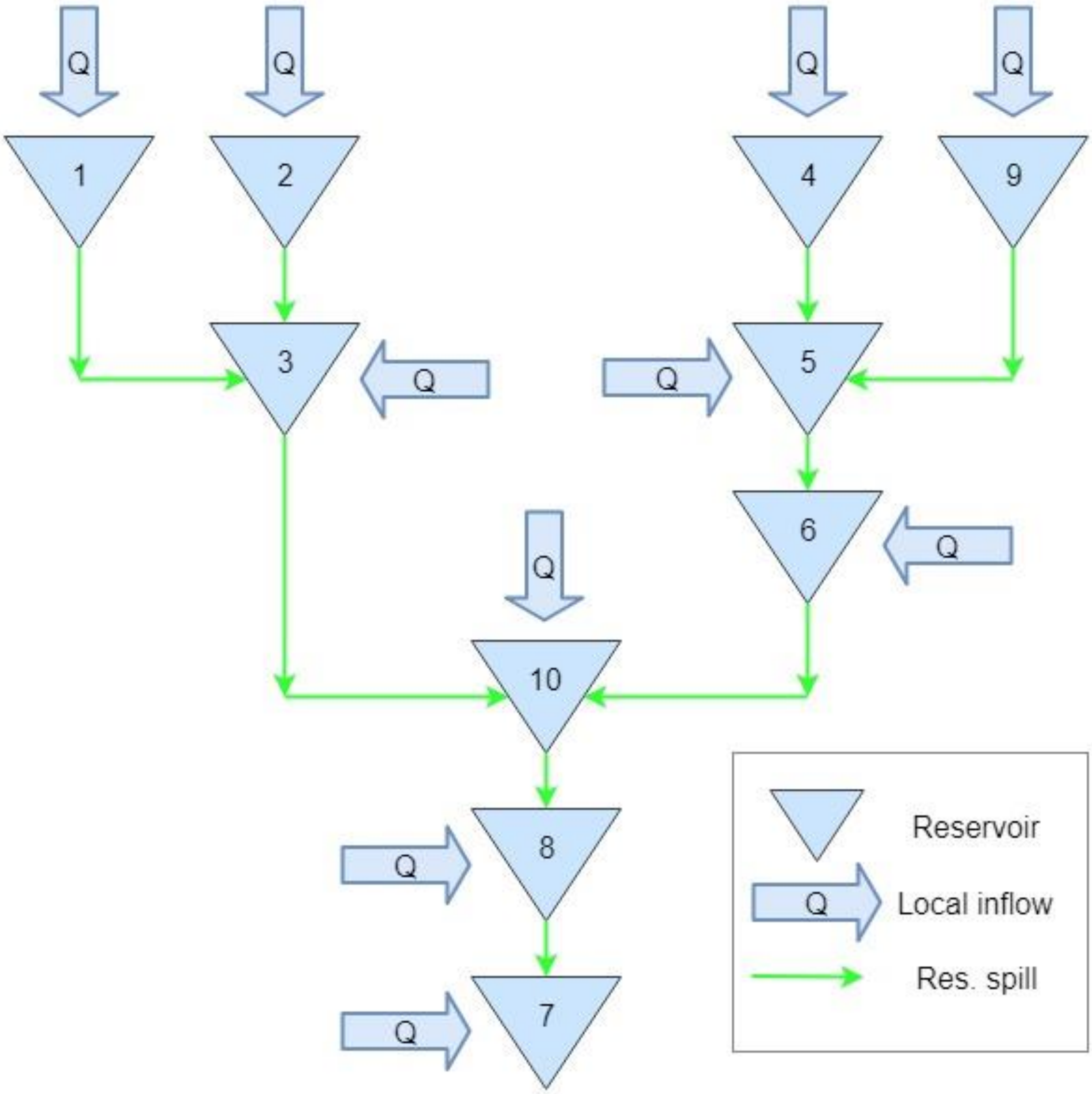


Figure 18: Setup if theoretical randomizable catchment.

5.9.2 Dampening curves

Once the synthesized data on flood dampening with varying regulation capacity was obtained, regressions were found for each type that was simulated: spring floods and 4 different recurrence interval autumn floods. The fitted lines were found by using the regression tool in SigmaPlot Version 14.0.

Dampening curve verification

The fitted curves obtained from the regression were tested by comparing their results to the results obtained in other flood dampening studies. Sufficient data on regulation capacity, flood dampening, and catchment areas was found in 5 other cases (

Table 7).

Table 7: Studies used for verification of regression curves.

Area	Author	Event	Comments
Glomma/Lågen, Norway (HYDRA)	Eikenæs, Njøs et al. (2000)	Vesleofsen spring flood, 1995	
Yesa, Spain	Lopez-Moreno, Begueria et al. (2002)	Based on recurrence interval vs. dampening curves, non-specific	Unknown hydrograph shapes
Brandywine Creek, USA	Slutzman and Smith (2008)	Hurricane Floyd, 1999	Yearly runoff estimated from coarse runoff map
Alvdal (Glomma), Norway (GLB)	Glover, Sælthun et al. (2018), Walløe (2018)	Various spring floods 1966 to 1995	
Orkla, Norway	Work from this thesis	Various spring and autumn floods 1940 to 2012	

6 Results

6.1 Rainfall-runoff model calibration

The simulated runoff using PINE HBV calibrated for Bjørset yielded a slightly higher Nash-Sutcliffe model efficiency coefficient (NSE) than EXCEL HBV for both Bjørset and Næverdal. The flood peaks in Bjørset were similar in both simulations, but the flood peaks at Næverdal were slightly more exaggerated in EXCEL HBV than in PINE HBV. The NSE at Næverdal for the scaled obs. discharge was significantly higher, although it did not perform better on floods, except in 1973.

Figure 19 and Figure 20 show the results from the EXCEL HBV model. Since the runoff was simulated for each catchment, the runoff had to be accumulated at Bjørset before the fit of the model could be evaluated. This function was integrated into the model. The fit at Næverdal was evaluated after calibration at Bjørset was complete and was not part of the calibration process.

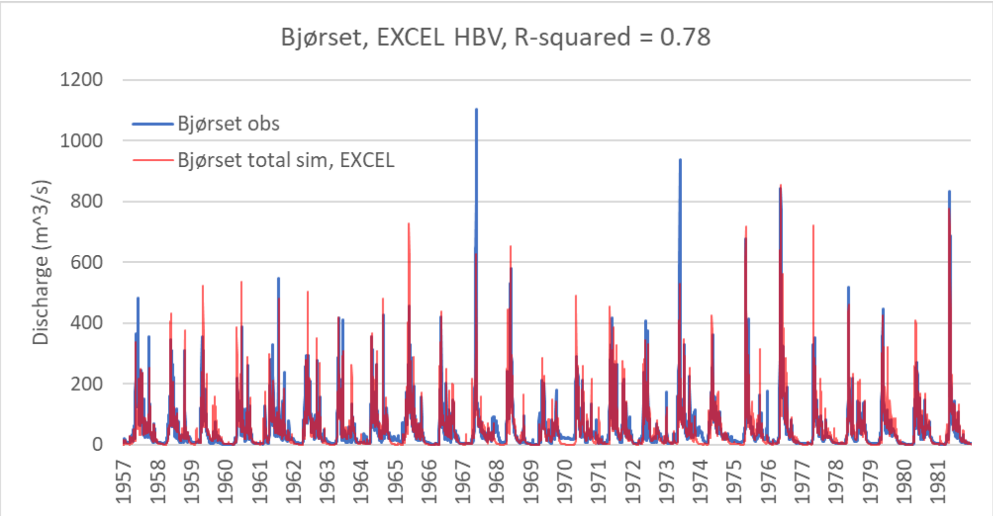


Figure 19: Model calibration for Bjørset gauge using EXCEL HBV.

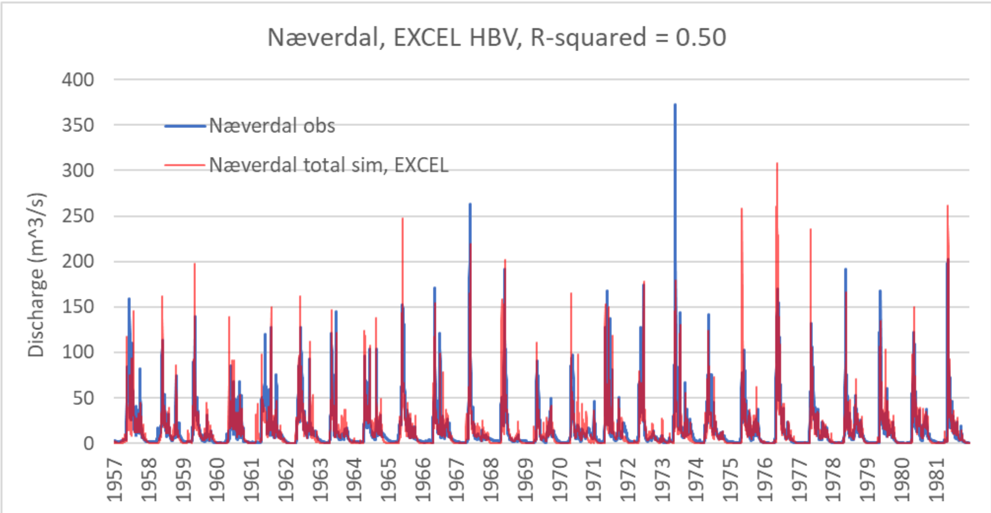


Figure 20: Model simulation fit at Næverdal using EXCEL HBV. All catchments used the Bjørset parameter set.

Figure 21 and Figure 22 show the results from PINE HBV when the model was calibrated for the total flow at Bjørset. The graph for Bjørset is the PINE HBV output, while the graph for Næverdal is the cumulative flow from the Næverdal catchments after scaling the simulated flow at Bjørset to each of the sub-catchments.

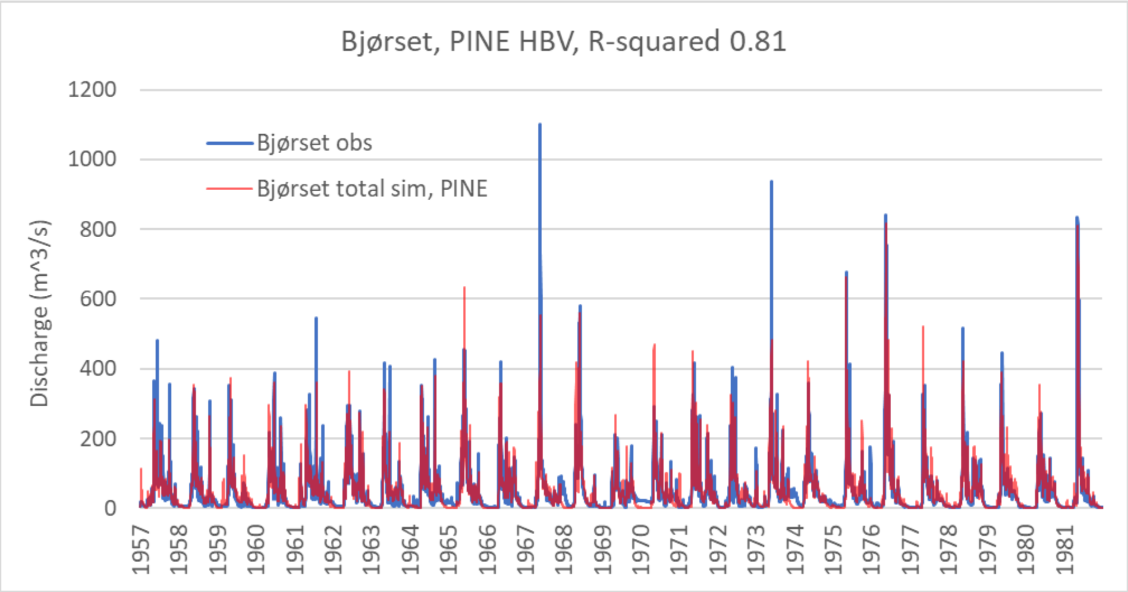


Figure 21: Model calibration for Bjørset gauge using PINE HBV.

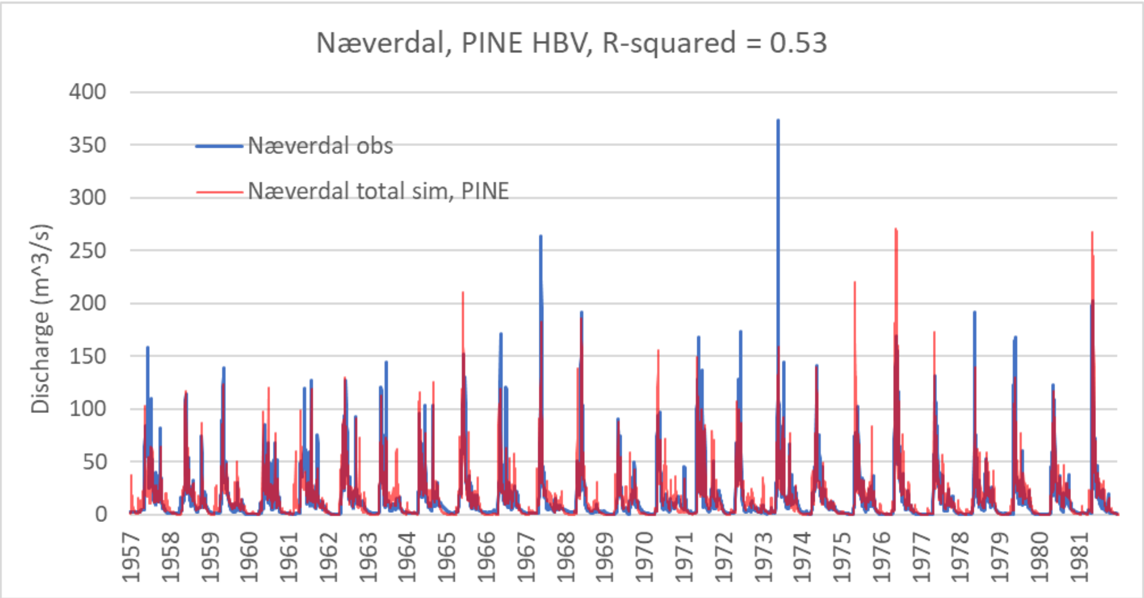


Figure 22: Model simulation fit at Næverdal using PINE HBV. All catchments used the Bjørset parameter set.

Figure 23 shows the fit at Næverdal for the discharge that was scaled from the observed flow at Bjørset.

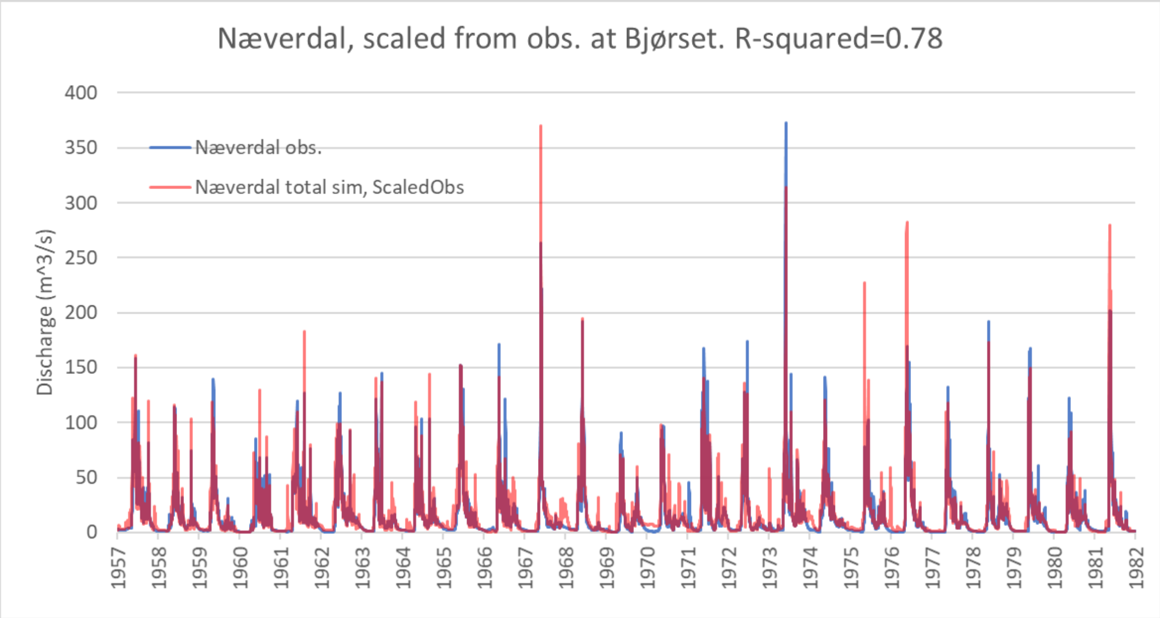


Figure 23: Scaled observed flow accumulated at Næverdal.

The model simulation for two typical years is shown in Figure 24. The fit for the low flows appears good, despite low flows not being prioritized in the calibration.

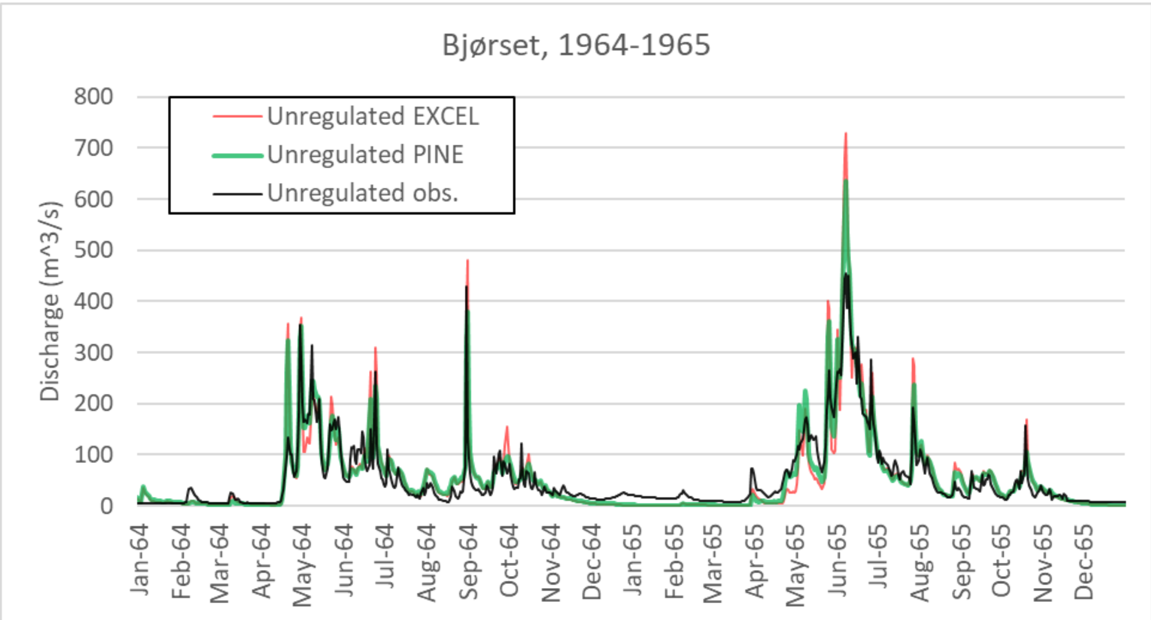


Figure 24: Model simulation fits for typical years (1965-1965).

The simulated runoff for unregulated conditions after 1983 is shown in Figure 25. Peaks in the observed regulated runoff at the same time as in the simulated floods is a good indicator that the simulation is correct. In 2012 there was no proportional peak in the observed runoff.

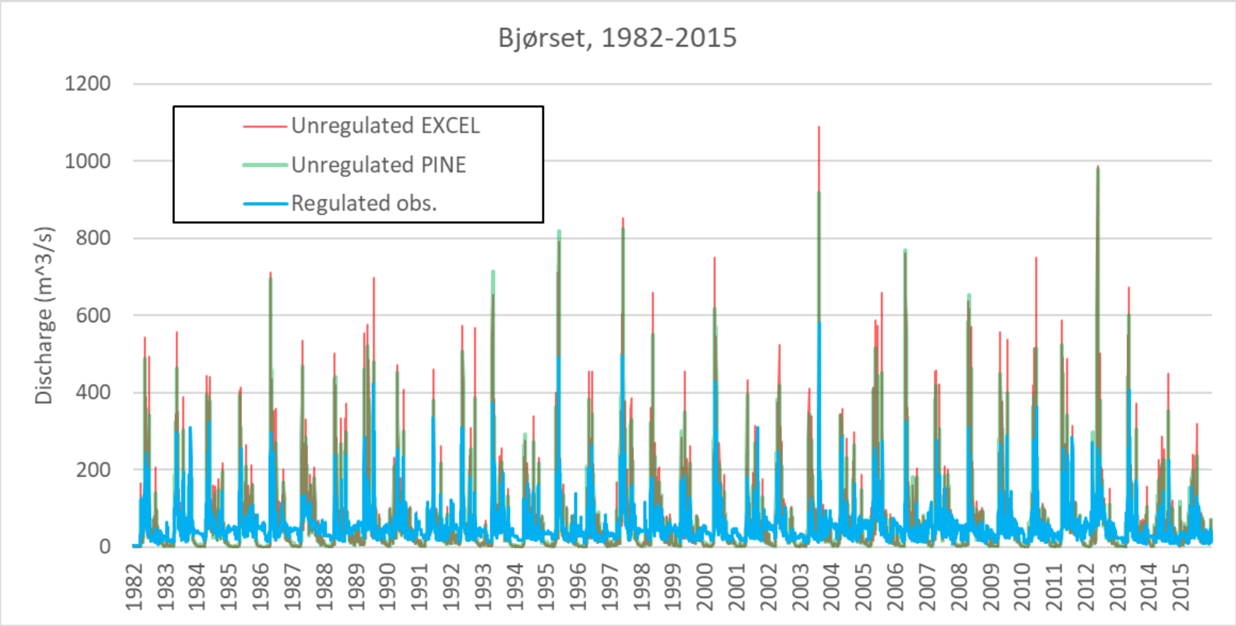


Figure 25: Simulated unregulated runoff at Bjørset for the period 1982-2015.

The simulated average annual total inflow and average annual inflow to each regulated area for the entire timeseries is given in Table 8. This includes transfers with limits on maximum discharge capacity. The percentage of the average annual flow to Bjørset that entered a reservoir was 33% for EXCEL HBV simulations and 38% for simulations based on scaled observed discharge.

Table 8: Average total annual inflow and regulation capacity in relevant areas.

	Simulation method	Sverjesjøen	Falningsjøen	Granasjøen	Innerdalsvatnet	Total in regulated area	Bjørset
Annual Q (Mm^3)	EXCEL HBV	15	129	177	226	547	1662
	Scaled from Observed	14	145	193	225	577	1527
Reg %	EXCEL HBV	48.1%	96.5%	81.5%	66.3%	77.9%	25.6%
	Scaled from Observed	50.0%	86.2%	74.7%	66.7%	73.8%	27.9%

6.2 WEAP flood simulations

The comparison between observed and simulated floods with realistic reservoir levels in the regulated period (Figure 26) indicates that the model performed reasonably well for those years, with the exception of 2012. The 2012 flood is associated with a strong increase in temperature from one day to the next with no precipitation, and was similar in both EXCEL and PINE HBV. The time series for the downstream gauge at Storsteinhølen and the adjacent catchment of Gaula at Gaulfoss did not show floods in this period. The flow was still included in further evaluations as it did not stand out as unreasonable or unrealistic, despite potentially having not occurred.

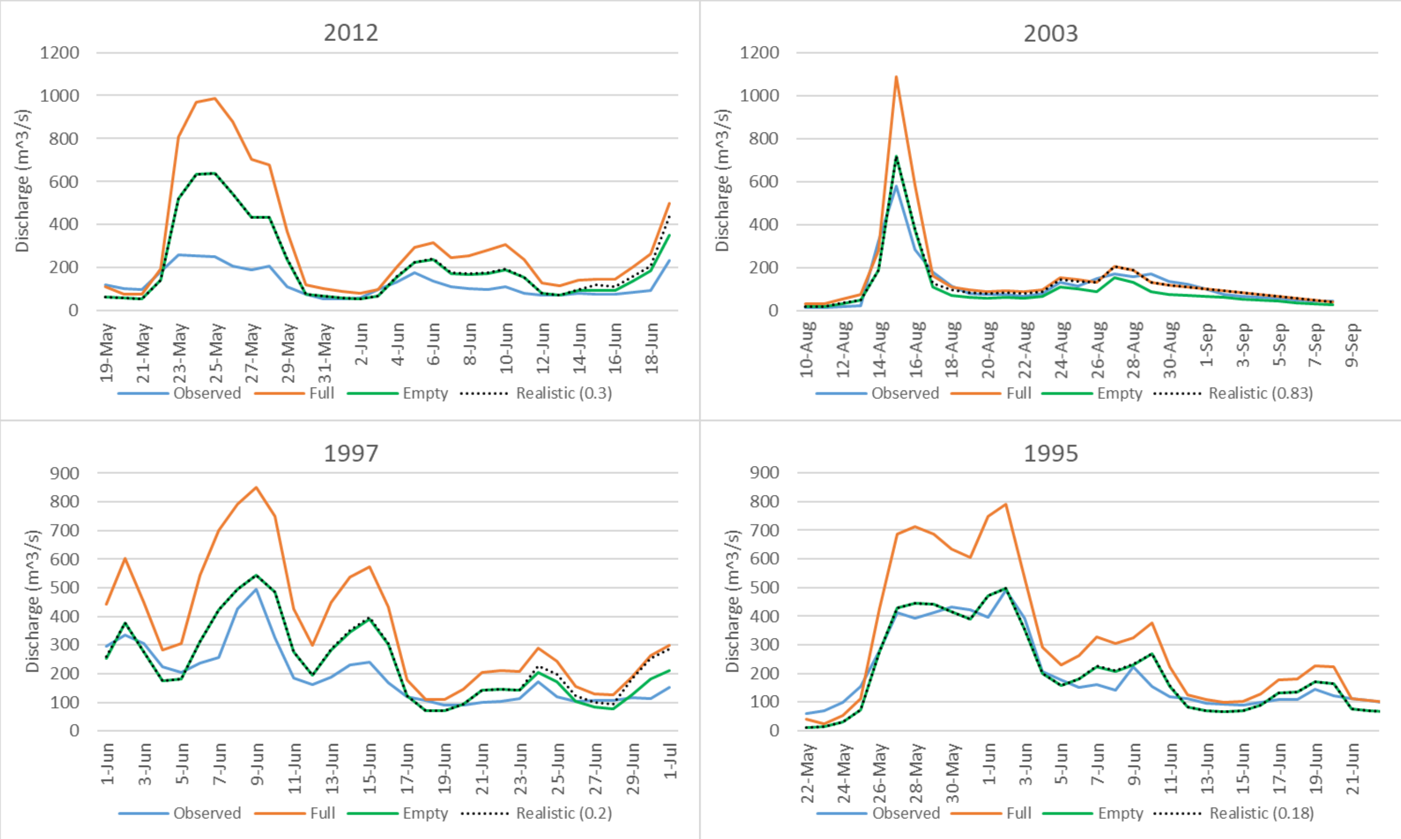


Figure 26: Flood simulation for the regulated period with various initial water levels. A full initial water level is identical to no reservoir at all, due to the lack of lake routing. The observed and realistic reservoir filling scenarios should ideally be equal.

The model performed well for 2 out of 4 floods in the unregulated period (Figure 27). The hydrographs for the floods in 1967 and 1973 (and also 1944, but that was not simulated in HBV) have distinctively different shapes than the other spring floods, and it was suspected that the strong peaks in those years were associated with heavy rainfall creating additional runoff and increasing snowmelt rates (increased snowmelt due to rain is not accounted for in HBV). However, an investigation of the precipitation during the various floods did not show any such patterns. The 2 unregulated floods with poor fits plus the 2 floods before data became available on precipitation and temperature were simulated using scaled observed runoff and therefore give a perfect fit compared to the observed.

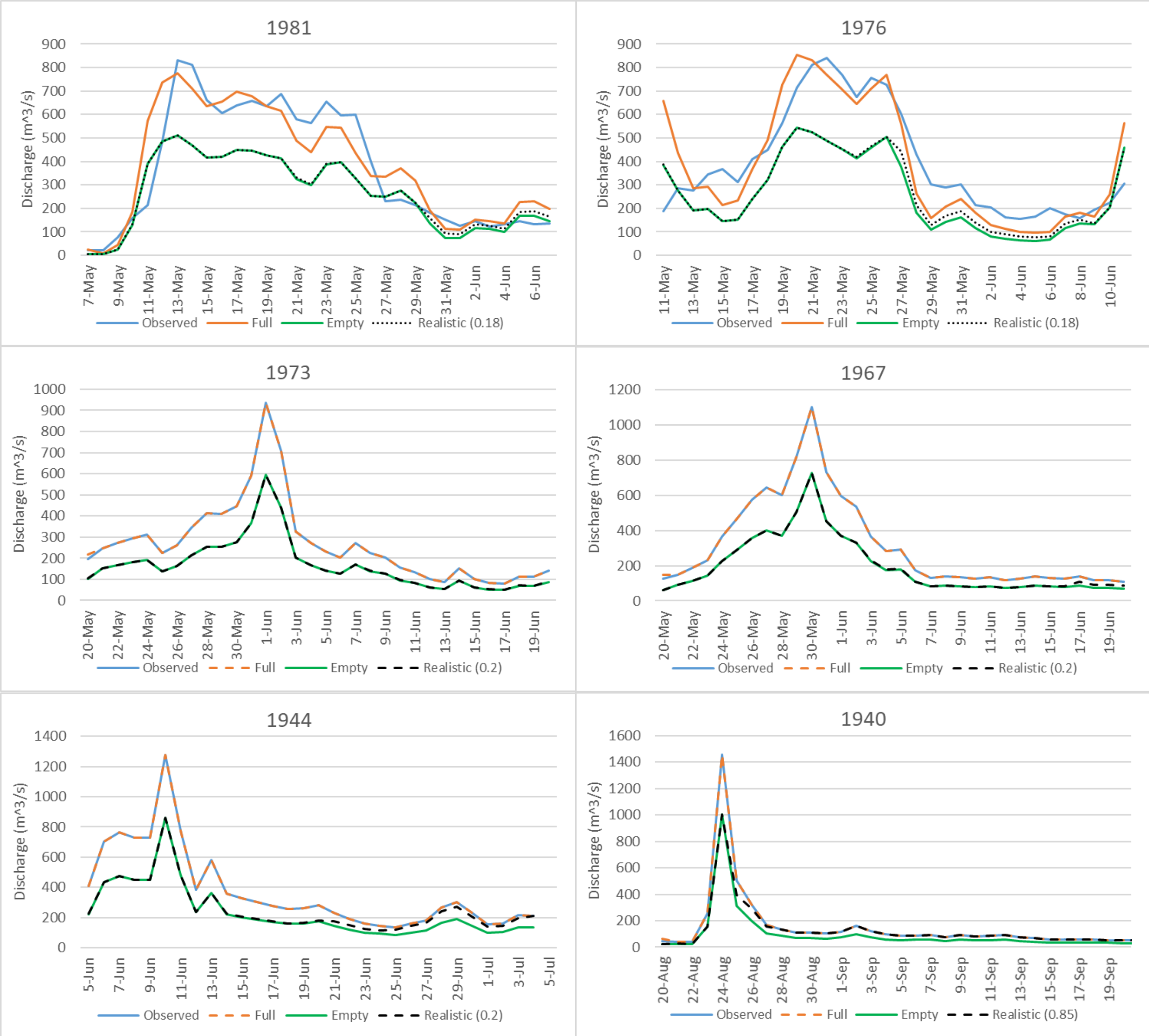


Figure 27: Flood simulation for the unregulated period with various initial water levels. A full initial water level is identical to no reservoir at all, due to the lack of lake routing. The observed and full reservoir scenarios should ideally be equal. The earliest four floods were simulated using scaled observed runoff, and thus are identical to the observed flow in the full reservoir condition.

6.2.1 Flood dampening main results

The average flood dampening for the realistic scenario was 35%, with a maximum of 37% and a minimum of 31%. The nMag simulation yielded slightly higher flood dampening percentages.

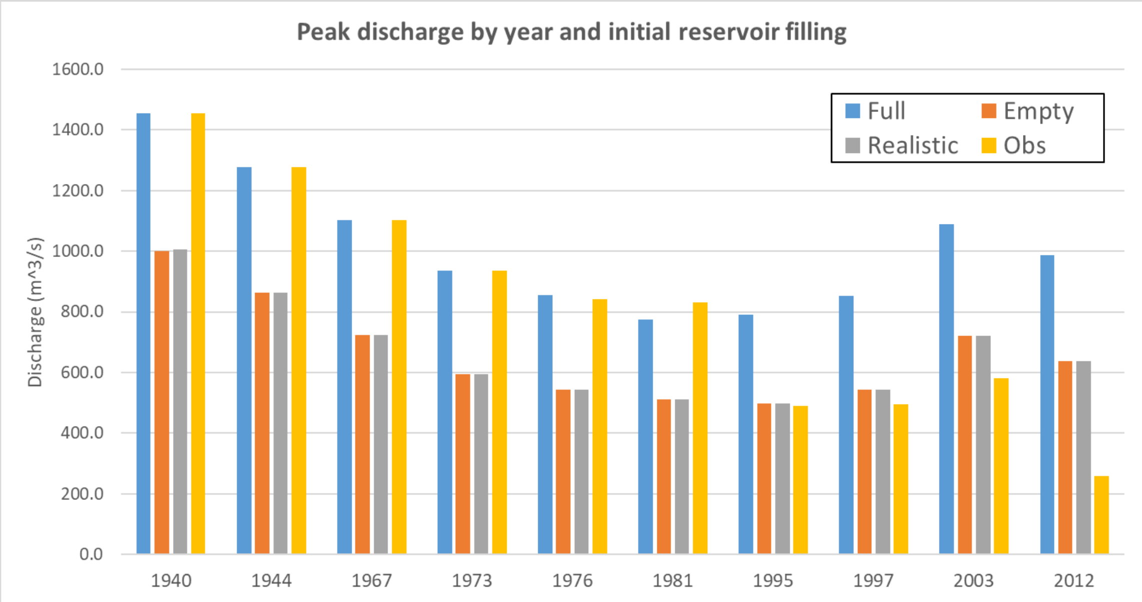


Figure 28: Peak observed discharge and peak simulated discharge for each initial filling scenario. Up to and including 1981, the "full" and "observed" peaks should ideally be equal. After 1981, the "realistic" and "observed" should be equal.

Table 9: Main results from flood dampening in Orkla. Results are compared to the ones obtained from nMag.

Year	Initial realistic Filling	Peak Full	Peak Empty	Peak Realis-tic	Peak Obs.	Peak nMag reg.	Peak nMag unreg.	Percent reduc-tion WEAP/ EXCEL HBV	Percent reduction nMag
1940	0.85	1455	1002	1006	1455			31%	
1944	0.30	1278	863	863	1278	685	1128	32%	39%
1967	0.20	1102	725	725	1102	584	964	34%	39%
1973	0.20	936	595	595	936	619	1071	36%	42%
1976	0.18	855	544	544	841	392	617	36%	36%
1981	0.18	775	511	511	833	450	732	34%	38%
1995	0.18	792	497	497	490			37%	
1997	0.20	852	544	544	495			36%	
2003	0.83	1089	720	720	581			34%	
2012	0.30	988	638	638	258			35%	

There was a strong relationship between the flood dampening percentage and the peak magnitude of the floods, with dampening decreasing as peaks increased (Figure 29).

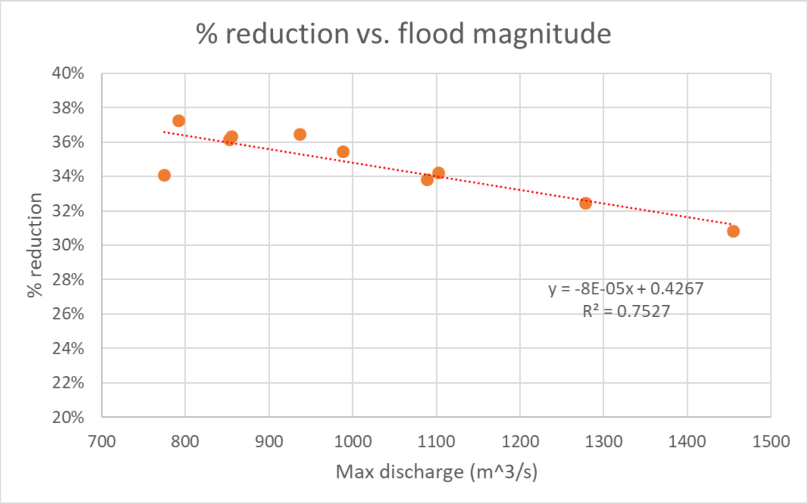


Figure 29: Percent reduction as a function of flood magnitude.

6.2.2 Impacts from drawdown

With potential reservoir releases, the maximum flood dampening potential was reached after 1 day of releases in both floods. With allowed releases including hydropower, it took 3 and 4 days for 2003 and 1940 respectively (Table 10). When hydropower was not included, the reservoir dampening effect dropped sharply, and did not reach its full dampening potential in 7 days of releases (Table 11).

Table 10: Flood peaks and flood dampening with varying days of release (including hydropower) prior to flood event. A darker color indicates a lower dampening effect.

Year	2003		1940		2003		1940	
	Peak (m^3/s)		Peak (m^3/s)		% dampening		% dampening	
Days warning	Potential	Allowed	Potential	Allowed	Potential	Allowed	Potential	Allowed
7	720	720	1002	1002	34%	34%	31%	31%
6	720	720	1002	1002	34%	34%	31%	31%
5	720	720	1002	1002	34%	34%	31%	31%
4	720	720	1002	1021	34%	34%	31%	30%
3	720	746	1002	1045	34%	31%	31%	28%
2	720	827	1002	1132	34%	24%	31%	22%
1	818	961	1146	1326	25%	12%	21%	9%
0	1089	1089	1455	1455	0%	0%	0%	0%

Table 11: Flood peaks and flood dampening with varying days of release (excluding hydropower) prior to flood event. A darker color indicates a lower dampening effect. Only allowed flows are shown, as the potential are identical to those in Table 10.

	Year			
	2003	1940	2003	1940
Days warning	Peak (m^3/s)		% dampening	
7	728	1042	33%	28%
6	741	1051	32%	28%
5	755	1084	31%	25%
4	804	1129	26%	22%
3	854	1173	22%	19%
2	899	1241	17%	15%
1	1015	1378	7%	5%
0	1089	1455	0%	0%

6.3 Theoretical catchment results

The randomized catchment showed a highly varying reaction to spring floods. In some configurations, every flood was dampened by the same percentage, while in others there was a spread over 50 percentage points. Even when the regulation capacity was approximately the same, the catchment could react entirely different to the floods in two different configurations, as shown in Figure 30. This figure shows the dampening percentage for each spring flood in each configuration, and the "Samples" highlight the performance of individual theoretical catchment setups. The results show that not only does the dampening percentage vary greatly between each setup even with the same regulation capacity, it can also vary greatly within one single setup based on the flood hydrograph. Sample 10, for example, ranges from 25% to over 80% dampening for different floods, while Sample 3 with the same regulation capacity has the same dampening for all the different floods. 197 configurations were simulated, so only a few of the results are showed with unique categories, otherwise the graph would not be legible.

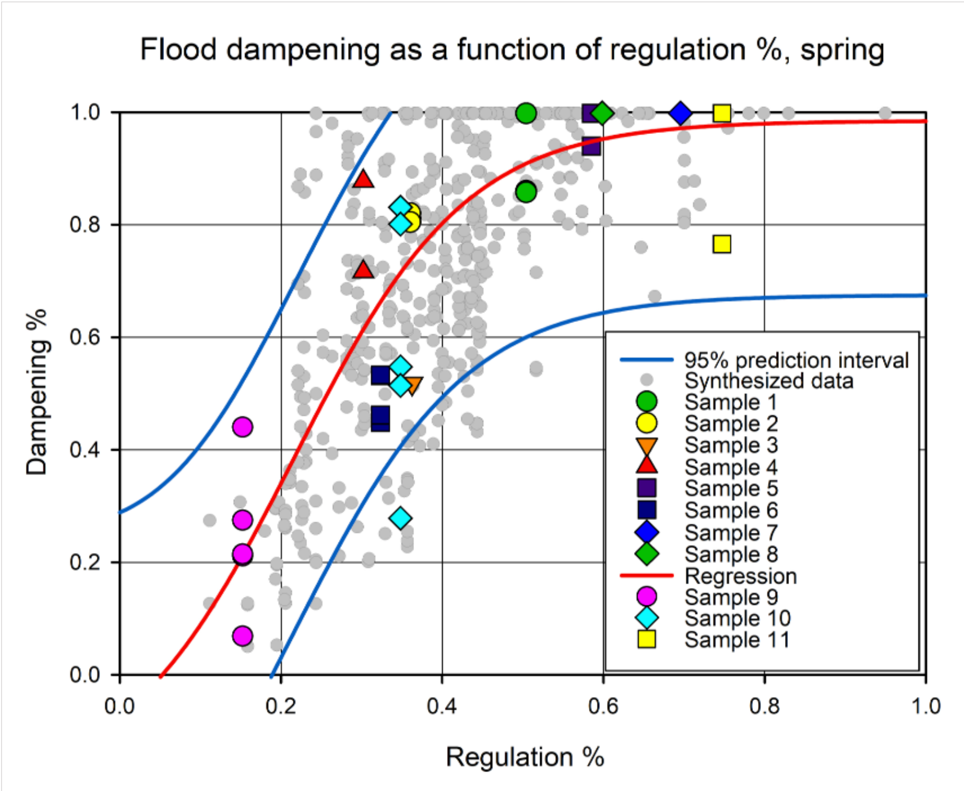


Figure 30: Regulation capacity vs. flood dampening relationship for spring snowmelt floods for the theoretical catchments. Each "Sample" represents one specific system configuration, and each point within a sample represents one of the floods. 7 spring floods were modeled in each random configuration (n=197), but most configurations are not shown with unique values as the graph would be illegible. The points within a sample often lie on top of one another, which is why it's not possible to see 7 different points for each sample.

The equation for the regression curve for spring floods is given below (Table 12). It utilized a 4-parameter sigmoid equation.

Table 12: Spring coefficient of determination (R^2) and trendline equation coefficients for the regulation capacity vs. flood dampening curve. The equation for the curve is: Y = d+a/(1+exp(-(X-c)/b)), where X is the regulation capacity and Y is the dampening percentage. The output should be constrained to be the minimum of 100% and the equation result, as the curve extends beyond 100% dampening.

R-squared	a	b	c	d
0.595	1.1958	0.1069	0.2163	-0.2089

Only one flood hydrograph was simulated for the autumn cases, but with varying magnitudes. The different system configurations still showed great variance in their ability to dampen flood, even with the same regulation capacity (Figure 31). The relationship between regulation capacity and flood dampening was stronger with higher return period floods (Table 13). The simulations were done in batches based on return period, therefore no comparison could be done for the different response to different floods (return periods, in this case) within individual configurations as was done for the spring flood investigation.

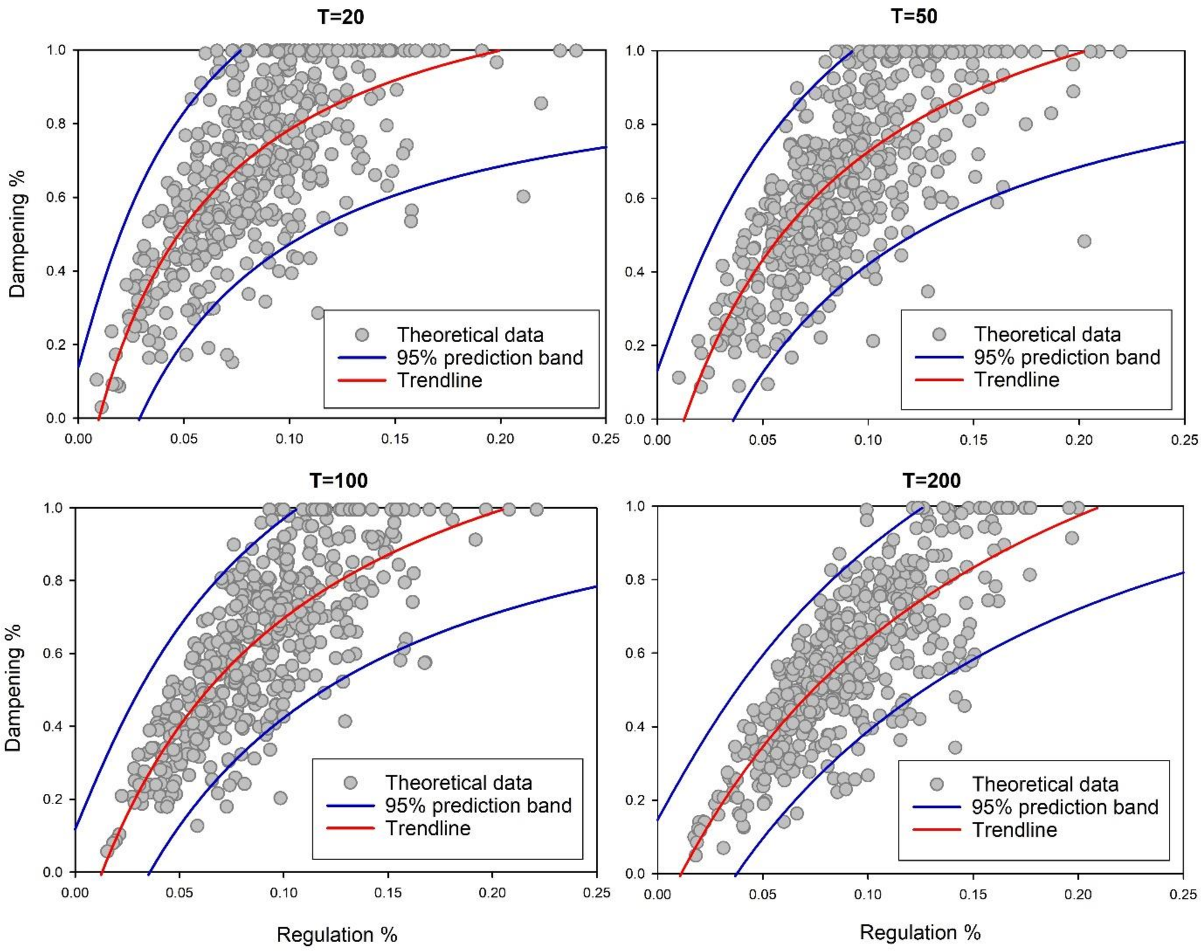


Figure 31: Regulation capacity vs. flood dampening relationship for autumn rain-floods for the theoretical catchmenst. The figure shows the synthesized data and the regression lines for 20, 50, 100, and 200-year floods.

The equations for the various autumn regression curves are given below (Table 13). They utilized a 3-parameter rational equation

*Table 13: Autumn coefficient of determination (R^2) and trendline equation coefficients for the regulation capacity vs. flood dampening curves. The equation for the curve is: Y = (1+a*X)/(b+c*X), where X is the regulation capacity and Y is the dampening percentage. The output should be constrained to be the minimum of 100% and the equation result, as the curve extends beyond 100% dampening*

Return period	R-squared	a	b	c
T=200	0.645	-93.8846	-7.9781	-50.9614
T=100	0.604	-80.5685	-4.843	-52.0642
T=50	0.541	-79.4198	-4.1045	-54.1871
T=20	0.547	-105.41	-4.1999	-79.312

The verification of the dampening curves indicates a good correlation to values from other sources.

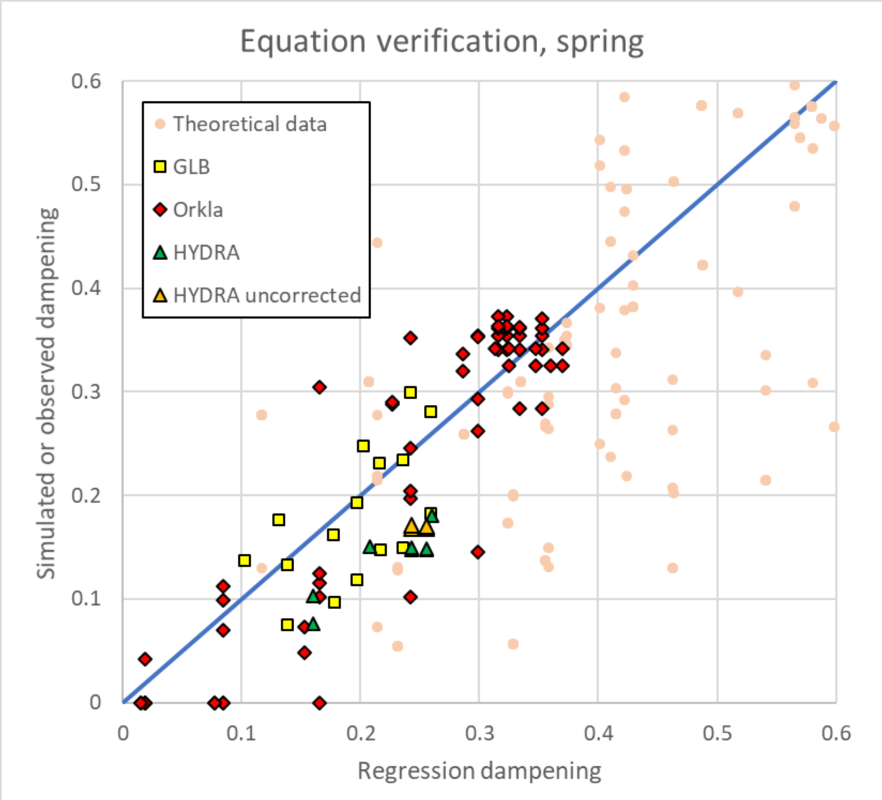


Figure 32: Verification of regulation capacity - flood dampening regression for spring snow-melt floods. There are many more "Theoretical data" points in the higher dampening region, but the axes were cut to show the most relevant results in more detail. The "HYDRA uncorrected" points indicate the flood dampening in Øyeren in 1995 without subtracting the effect of non-reservoir flood control measures.

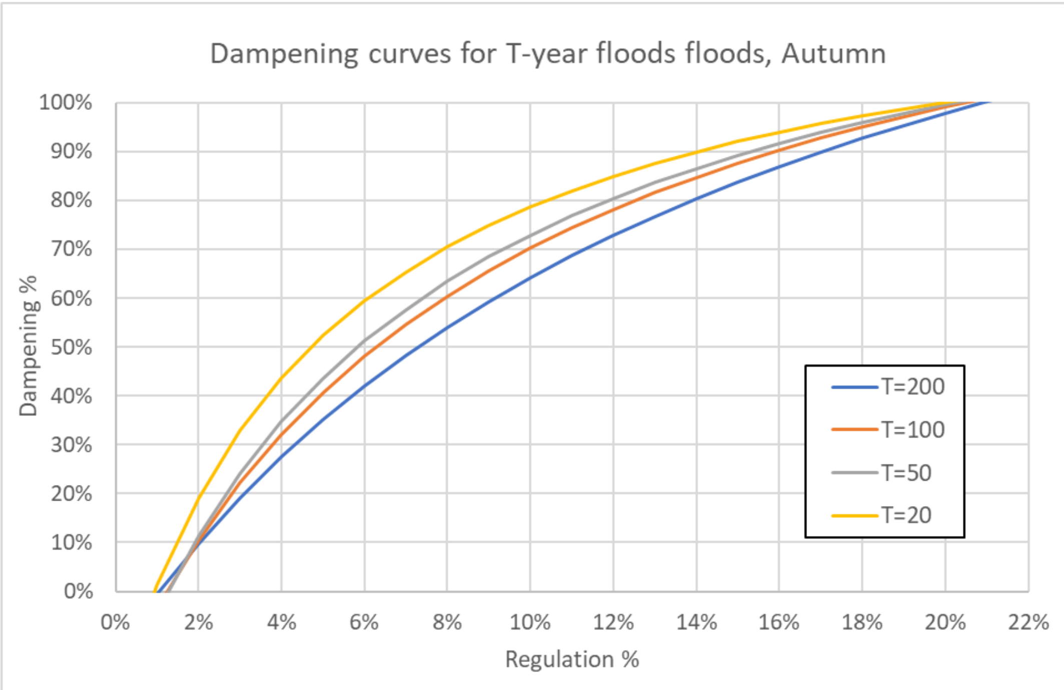


Figure 33: Dampening curves for 20. 50, 100, and 200-year autumn floods.

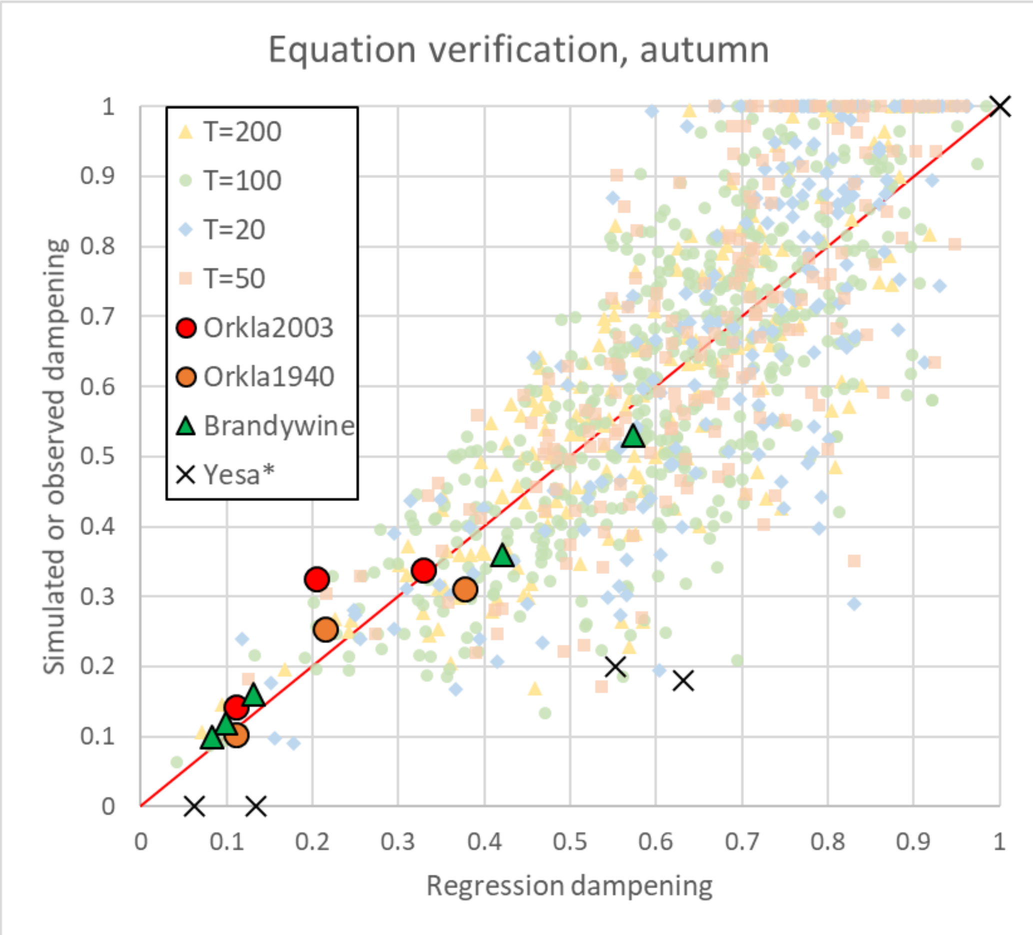


Figure 34: Verification of regulation capacity - flood dampening regression for autumn rain-floods. The T-year floods are from the theoretical catchments. The Yesa case will be addressed in the discussion.

7 Discussion

As there are many tasks involved in this project, a discussion will be made on each topic.

7.1 Rainfall-runoff simulation

The EXCEL HBV model did not yield better results than the PINE HBV model, despite utilizing more spatially distributed data. However, the EXCEL HBV model was calibrated manually by an inexperienced modeler. With an autocalibrator or more experience, it is possible that the EXCEL HBV calibration could be improved. The comparison of the two simulations should not be made purely based on the NSE, as the low flow accuracy is not pertinent to this study. Rather, a consideration of how well the models simulated the flood peaks should be done. The EXCEL HBV model output was chosen for the flood simulations despite its slightly poorer performance compared to the observed values. This was because it included more spatial variation inputs, which would produce individually shaped hydrographs in each catchment, as opposed to the PINE HBV model which would produce the exact same hydrograph for each catchment but with differing magnitudes. It is somewhat troubling that both models missed half of the flood peaks in the unregulated period, as it puts the accuracy of simulated floods for the regulated period into question. The only way to determine the accuracy of the regulated simulation is to run the floods through the model and compare the observed and simulated regulated flows, and thus is cannot be directly evaluated during calibration – this is the main point of the simulation, to generate a reliable timeseries for the unknown period. The poor fit for flood peaks at Næverdal (Figure 20 and Figure 22) is another cause for concern, as it indicates that the models did not simulate the runoff to the individual catchments as accurately as desired. In 1976, for example, the Næverdal simulation was approximately 150m^3/s too high (Figure 20). At Bjørset, however, it was very accurate (Figure 19). This implies that the catchments not draining to Næverdal compensated for the error by having too little runoff, and this can be a big issue since the proportion of runoff going to the reservoirs is a key component of the flood dampening.

Therefore, it is questionable whether the results in this study can be said to be accurate representations of real events, with conclusions that an actual flood in a certain year could have been reduced by a certain amount, or that without reservoirs a certain year would have suffered a certain flood. What can be concluded, however, is that if the simulated floods were to occur, the simulated results would apply. As long as the simulated regulated and unregulated values are compared, and the simulated floods do not appear unrealistic, the results will remain relevant.

It would likely be possible to improve the fit for the simulated runoff to each catchment by using two parameter sets in the EXCEL HBV model: one for Næverdal catchments and one for Bjørset catchments (excluding those draining to Næverdal). First, the Næverdal parameters could be adjusted until a good fit was found for that calibration, and then the Bjørset parameters could be adjusted until the total flow at Bjørset was also accurate. However, this thesis was not intended to be an exercise in HBV calibration, so other tasks had to be prioritized.

It is also likely that errors were induced by the input data. The temperature and precipitation values are spatially interpolated, and therefore some peaks in precipitation might have been smoothed over and lost.

In retrospect it seems clear that the catchments of the Ya and Øvre Dølvad transfers should have been simulated in HBV as well, as they are large and contribute greatly to the total runoff. However, the hardware in the available computers was becoming a limitation as additional catchments were included, since the model was made in excel and used a lot of memory. This should be remedied by making the formulas more efficient and implementing macros. Even without changing the code, it would have been better to refrain from simulating the three small catchments of Næverdal, Sverjesjøen, and Falningsjøen in HBV, but rather make room for the large catchments of Ya and Øvre Dølvad. The size of the catchment was irrelevant for the resources the model used.

7.2 Flood simulation

The simulations reproduced the observed flow with reasonable accuracy. The “empty” and “realistic” scenario flow at Bjørset was identical in all cases except in 1940 (Figure 27, Table 9), where the “realistic” was marginally higher. This was since the reservoirs never spilled during the floods, not even with the “realistic” filling[3]. It is worth pointing out that the floods that were scaled from the observed flow are not necessarily more accurate than the ones from EXCEL HBV, despite having, by definition, perfect fits with the flow at Bjørset. This can be demonstrated by looking at the flow at Næverdal, as shown in Figure 35 below. The scaled observed runoff overestimates the peak by approximately the same value as the EXCEL HBV runoff underestimates it by. The significantly higher NSE value likely comes from the good fits for lower flows, and therefore is not indicative of the fit that concerns this study.

[3] Only Sverjesjøen filled up and spilled in 1940, the other reservoirs could still absorb more.

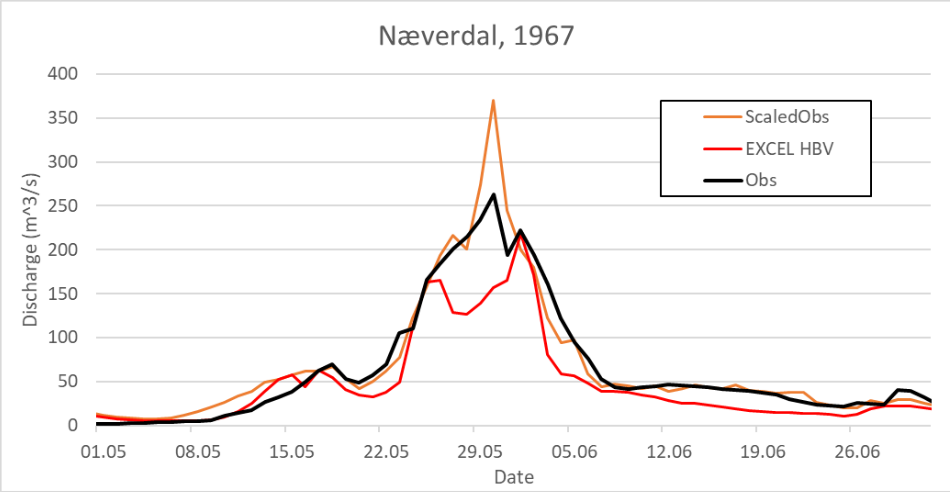


Figure 35: Total flow at Næverdal using EXCEL HBV and scaled observed discharge.

It was perhaps unnecessary to involve WEAP in the flood simulation process. The program's potential was not fully utilized as the reservoir filling and spilling was quite rudimentary. The fact that a new simulation had to be done for each flood also made it somewhat cumbersome to use when changing parameters such as release rates. WEAP has an excellent "scenario" function, but it does not allow these scenarios to start until a year after the simulation start, and thus becomes unusable when simulations are started immediately before the event. It would be very difficult to control the initial reservoir storage when one year of operation passes before the date of interest. Since the flood modelling is quite simple, it seems in hindsight that it could have been set up in Excel for easier parameter changes and data export. This would also enable the simulation of all floods at once, and such a model was made for the theoretical catchments spring floods.

The WEAP program appears better suited for long duration simulations, where short events such as floods are not as relevant, but monthly or yearly water balance becomes a bigger concern.

7.3 Flood dampening

7.3.1 General

The fact that the reservoirs never filled up during floods means that the flood dampening relied solely on how much of the total water flowed into the reservoirs – none of the reservoirs reached their full potential except for the 1940 flood. The dampening varied somewhat with each flood due partially to spatial variation in climate inputs leading to varying fractions of the total inflow in the unregulated part of the catchment. The dampening was in the range 31-37%, which is uncoincidentally similar to the percent of average annual inflow that flowed into reservoirs (33-

37%) which was described in the flood dampening results section. The reduced flood dampening with increased flood peaks in Figure 29 is similar to what several other studies have found (Higgs and Petts 1988, Lopez-Moreno, Begueria et al. 2002), but due to very unexpected reasons. Higgs stated that lake routing and reservoir storage became less effective at dampening the larger the flood return period, but this study did not utilize lake routing, and the reservoirs were not filled.

7.3.2 Effect of transfer capacities

The main reason for variations in flood dampening, apart from the effect of spatial differences in snow, rain and temperature inputs, was the transfer capacity limitations in Ya and Dølvadsætra. In the highest floods, the peak flows in the transfer catchments became significantly higher than their capacity, and this lead to large spills into the unregulated areas (Figure 16). The spill was naturally very strongly related to the peak flow of the flood, and thus the floods with the highest peak had the lowest fraction of its volume going into the reservoirs, leading to reduced dampening (Table 14).

Table 14: Effect of peak flow on intake spill and the dampening percentage.

Year	Peak flow (m^3/s)	Spill past intakes (m^3/s)	% reduction	Spill as % of peak	Sum of % spill and % reduction
1940	1455	102	31%	7%	38%
1944	1278	72	32%	6%	38%
1967	1102	43	34%	4%	38%
2012	1089	28	34%	3%	37%
1995	775	0	34%	0%	34%
2013	988	14	35%	1%	36%
2003	852	29	36%	3%	39%
1973	936	16	36%	2%	38%
1976	855	4	36%	0%	36%
1997	792	0	37%	0%	37%

Whether or not the flood dampening would actually be greater with unlimited transfer capacity, is another question. The answer relies on how full the reservoirs are. As a test, the flood in 1940 was simulated again with unlimited transfer capacities, and the results show that it would have been dampened by an additional 85m^3/s, which would be an extra 6 percentage points of dampening. The reduction is slightly lower than it could potentially have been since two of the reservoirs, Innerdalsvatnet and Sverjesjøen, filled up and spilled some of the inflow.

Despite the potential inaccuracies in the simulation of floods in Orkla, there can be little doubt that the reservoirs have had a major flood dampening effect, and that this dampening is very strongly related to the fraction of water that is regulated. This is evident not only from the flood simulations, but also from the lack of flood peaks after regulation in the 1980s. It is true that there was a long period between 1944 and 1967 where there was a similar lack of flood peaks, but the simulated flood peaks with accurate "regulated" simulated values after 1982 is a strong indication that there were floods that got dampened. Several of the simulated floods in the regulated period floods were also observed in the neighboring catchment of the river Gaula. The Gaula spring floods in 2010 and 2013 were both present in the Orkla simulations, but they did not reach the threshold of $800m^3/s$ to be included in the analysis.

It is likely that the climate input did not capture strong local dofferences in precipitation, so if those existed they were not properly considered in the modeling.

7.3.3 Comparison to nMag

The nMag flood dampening values were slightly higher as the model setup assumed larger values for the transfer capacities of Ya and Øvre Dølvad. The high flood dampening from nMag in 1973 is caused by the fact that Næverdal had a much larger percentage of the total flood volume in that year (Figure 19, Figure 20). The inflows in nMag were scaled from both Bjørset and Næverdal observed flows, with almost all the regulated flows being scaled from Næverdal. Therefore, a larger fraction of the total flow went into the reservoirs. Overall the comparison confirms the result that it was the regulated inflow that limited the flood dampening, not the reservoir volume.

7.4 Drawdown

7.4.1 Potential versus allowed release

Table 10 shows that restricting the reservoir releases for local concerns will have a negative impact on the total flood dampening at Bjørset. The decision on how much water to release from the reservoirs should be based on many factors. The primary concern in all reservoir operations is dam safety, and this must never be compromised as it can have catastrophic consequences. However, even within the operational regime that is safe for the dam there are many things to take into account when considering the operational strategy for a reservoir, such as the available time before a flood, the certainty of the forecast, and the weighing of local damages versus avoided damages downstream. If an extreme flood is forecasted with high certainty and with short warning, it might be acceptable to create large floods in the local rivers as a consequence of heavy releases if this provides significant dampening later in the downstream areas. If the warning time is longer the water could be released more gradually, but the certainty of the forecast will likely be lower and the reservoir operators could be hesitant to draw down the reservoirs since there is a risk that the flood will not happen and they will have lost water that could have been used for production. It must be pointed out that the "allowed" values for releases are not necessarily realistic at all, but merely used as a demonstration of what could happen if releases were constrained to that level.

7.4.2 Effect of hydropower capacity

It is interesting to see how significant the hydropower capacity was for the effect of drawdown on flood dampening. Table 11 shows that without hydropower releases, the allowed reservoir releases would not be large enough to fully dampen the flood, even with 7 days warning. This could be an important aspect of the effect of hydropower tunnels (not just reservoirs) on flood dampening that is often not given due credit. This effect will be larger the higher the hydropower discharge capacity is compared to the allowed or possible river releases. It should be noted that the hydropower and allowable river releases could not be treated separately as they were in this study if the powerplant discharged back into the small local river. In such cases the hydropower tunnels would not necessarily serve a flood dampening function as they could not be used to increase the allowable discharge of the reservoir. However, if the potential release capacity of a reservoir is the limiting factor (e.g. the gates are not large enough), hydropower intakes can serve drawdown purposes even if released into their own rivers. In the 1995 flood in Glomma, the hydropower stations in the river were run at full capacity to reduce reservoir levels prior to the expected flood, and the operators even had to pay to deliver the electricity in some cases (Tingvold 1999). The hydropower plants in the tributaries to Orkla release into the main river (Figure 11).

7.5 Theoretical catchment

The regression curves in Figure 30 and Figure 31 show a huge variation in percent dampening for the same regulation capacity. In all the graphs the dampening can range from 20-30% to 100% for one single regulation capacity which is similar to the results for the mean annual flood dampening in Fitzhugh and Vogel (2010). In this case it is caused partially by the topology of the system; two cases with the same regulation capacity might look entirely different. One factor is the location of the reservoirs; one case could have few but large reservoirs located far upstream in the catchment, while another could have the same reservoirs located far downstream. The downstream reservoirs would have a much higher potential to dampen floods, assuming their storage capacity was large enough, while the upstream ones could have a large excess of capacity. Another case could be having a few large reservoirs in a few tributaries or far upstream areas versus having many smaller reservoirs in many areas. The small reservoirs might have sufficient capacity to dampen their respective inflows, and thus a much larger percentage of the inflow would actually be reduced. The positioning and dimensioning of the reservoirs will therefore have a very large impact on the system's ability to dampen floods, and it is possible to have a large regulation capacity and still a very small flood dampening potential, even with realistically-sized reservoirs (not greater than 100% regulation capacity). It should be noted that the regulation capacity in the theoretical catchments represents the available capacity when the floods came (the reservoirs were always empty until the flood arrived), as the potential volume of a reservoir is irrelevant if the reservoir is partially filled prior to an event. It is imperative to keep this in mind if using the curves, otherwise one can get entirely unrealistic flood dampening percentages for an actual case. This will be discussed in more detail in section 7.5.3.

In addition to the topology, the hydrograph of the flood will significantly impact the dampening percentage, which was also shown in Miotto, Claps et al. (2007). For the spring floods, 7 different hydrographs were used, and the exact same topology often showed a different response to each. Figure 30 shows this by presenting samples of the theoretical catchments. It is interesting to note that the hydrograph influence varies from catchment to catchment even if they have the same regulation capacity, with some showing the same dampening potential in all floods and others having a spread of more than 50 percentage points from one flood to another. This difference could be due to one system having smaller reservoirs that fill up at different rates, so for some floods they can dampen fully, others partially, and others not at all. Another system could have only large reservoirs that never fill up fully no matter the flood, which would yield the same dampening for all events. This phenomenon was not investigated in further detail, but it highlights the difficulty of making a general flood dampening equation due to the unique character of each reservoir system.

The impact of spatial variances in runoff magnitudes is not taken into account in these theoretical catchments, as the inflow to a model is scaled based on its mean annual inflow.

To accurately assess the flood dampening of a given flood, additional parameters should be included in the regression. The dampening of floods would likely depend on flood volume, flood peak, and the shape of the hydrograph. The volume and peak for spring floods did not show any relationship to each other, as the volume depends largely on how much snow has accumulated through the winter and is available for melt, while the peak depends on current climatic inputs, such as temperature and precipitation. These additional parameters were not included for spring floods in this project, but it is recommended that they be considered if future studies try to improve the accuracy of the dampening prediction. For the autumn floods only one hydrograph was used, and for such floods there is a direct relationship between peak, volume, and flood dampening. This was because it was an intense flood that only lasted for one day, and therefore the results obtained can only be used for similar events (i.e. not prolonged rain floods).

It would also be advisable to curtail (in the calculations) the maximum regulation capacity assigned to a reservoir (e.g. at 60%). For example, if a reservoir has a storage capacity of $100Mm^3$ and a yearly inflow of $100Mm^3$, there will likely never be a flood that actually fills up this entire capacity, or even close to it, at least not in Norway. The regulation capacity it adds to the calculation of flood dampening is therefore unnaturally high if all the capacity in the system is accumulated and viewed against all the inflow to the system. Furthermore, it is only the available storage when the flood comes that is relevant for flood dampening. Therefore, a term called flood regulation capacity is proposed.

7.5.1 Flood regulation capacity

The flood regulation capacity is here defined as the sum of relevant available storage in the system when the flood arrives, divided by the yearly annual inflow to the system. The available storage, if measurements are not available, can be estimated based on average values for that time of year, for example by using reservoir filling curves as was done in parts of this study. Additionally, the maximum probable volume (MPV) of a flood as a fraction of the annual average inflow could likely be estimated on a regional basis. This should be incorporated as a constraint in the flood regulation capacity, but on the scale of individual reservoirs: **A reservoir should be assigned a relevant available storage equal to the minimum of the MPV (scaled to that reservoir's inflow) and the available storage when the flood arrives.** This is because an available storage greater than the MPV is not relevant for dampening, but an available storage lower than MPV means the volume becomes a constraint. The flood regulation capacity of the entire system would then be the sum of the relevant available storage for each reservoir divided by the average annual inflow to the system. This proposition is speculative and has not yet been tested, but it would be a small task to implement into the hypothetical randomizable catchment model used in this study. It is believed that this could reduce the large spread in the simulation and thus increase the accuracy of the dampening curves. However, it would also increase the data requirements for using the curves, as they would necessarily have to be used with flood regulation capacities as inputs instead of regular regulation capacities. It would likely work best in a system where all reservoirs are independent (i.e. not draining into each other), but it would hopefully still provide some benefit in more complex systems. Its main purpose would be to eliminate irrelevant storage from the calculations.

Note that variations within a single configuration would not be reduced. A factor that describes the individual flood would be required to reduce that uncertainty. It might be possible to create curves for different values of MPV, similar to how it was done for recurrence intervals for the spring floods in this study.

Two examples of flood regulation capacity calculations are given below.

Table 15: Flood regulation capacity calculation example 1. For reservoir A, the relevant available storage is only 60Mm^3 despite the reservoir having an available capacity of 70 Mm^3. This is due to the capacity exceeding the MPV.

Reservoir	A	B
Storage capacity (Mm^3)	100	50
% filling	30%	25%
Annual inflow (Mm^3)	150	100
PMV (% of annual)	40%	40%
PMV (Mm^3)	60	40
Available storage (Mm^3)	70	37.5
Relevant available storage (Mm^3)	60	37.5
Regulation capacity (total)	**60.0%**	
Flood regulation capacity (total)	**39.0%**	

Table 16: Flood regulation capacity calculation example 2. The initial reservoir fillings have been increased compared to ex. 1.

Reservoir	A	B
Storage capacity (Mm^3)	100	50
% filling	70%	80%
Annual inflow (Mm^3)	150	100
PMV (% of annual)	40%	40%
PMV (Mm^3)	60	40
Available storage (Mm^3)	30	10
Relevant available storage (Mm^3)	30	10
Regulation capacity (total)	**60.0%**	
Flood regulation capacity (total)	**16.0%**	

Note that the lower value for flood regulation capacity compared to regulation capacity does not necessarily imply a reduced flood dampening potential. It just assigns the number in a different way, and must be compared to curves that were developed using the same method for proper results. However, the two methods might yield different estimated dampening percentages, and the lower number for flood regulation capacity in example 2 *does* indicate a reduced flood dampening potential compared to the value in example 1. The flood dampening percentage would be found by looking up the flood regulation capacity on the appropriate flood dampening curve.

7.5.2 Dampening curves

The curves that were fitted to the generated data points yielded relatively low R-squared values (coefficient of determination, not Nash-Sutcliffe). This is expected, as the data points were spread widely for each regulation capacity. The fact that the regression fit for autumn floods improved with higher return periods was similar to the results of Lopez-Moreno, Begueria et al. (2002). In that study, they attributed this pattern to different operational strategies and priorities during more frequent floods – it might not be worth drawing down the reservoir to dampen a harmless 5-year flood, for example. That cannot be the case in this study, since all floods were modelled with the same operation. It is not clear what caused this, and it could also have been a coincidence.

There were many different types of curves that yielded similar R-squared value when fitted to the data. These could often look significantly different. The decision for which regression to use for the autumn floods was based both on the R-squared value and the relationship between the curves for the different T-year floods. The curve set in Figure 33 shows the dampening decreasing with increasing return period, which is reasonable. Another curve set with the same R-squared value showed the same relationship up until a certain regulation capacity, at which point the lower return period lines reduced their slopes and crossed the lines of the higher return period lines (Figure 36). Graphs sets which indicated such unrealistic phenomena were rejected. The regression line for the spring floods was based purely on the R-squared value.

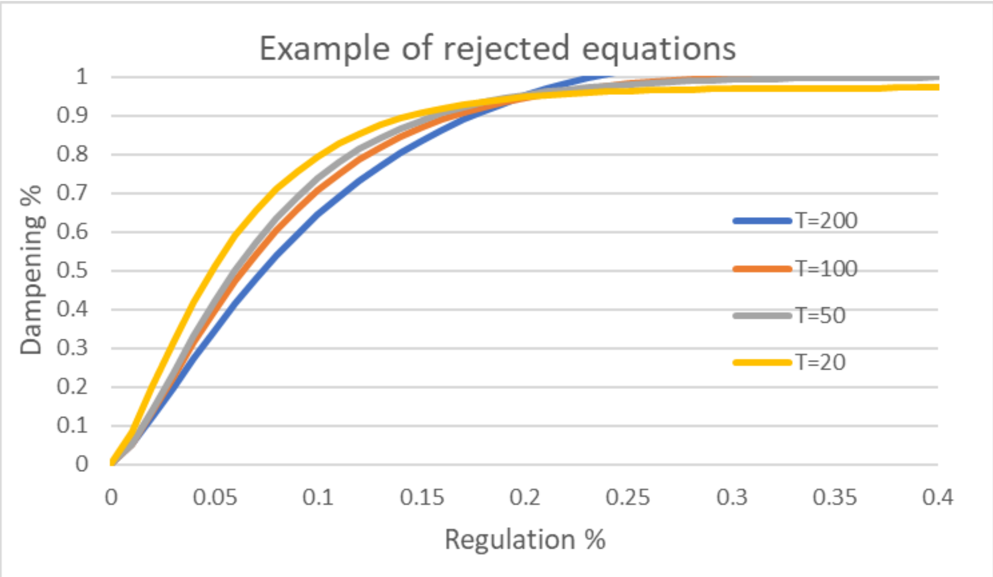


Figure 36: Example of rejected equations. The curves indicate that the dampening of higher return period floods will reach 100% at lower regulation capacities than for lower return period floods, which is unrealistic.

7.5.3 Dampening curve verification

The results from the studies listed in

Table 7 were used to check how well the flood dampening curves performed. As the reservoirs in the hypothetical catchment were defined as empty when the flood came, the available storage capacity was equal to the total storage capacity. As previously stated, it is the available capacity that is relevant for flood dampening, and therefore it was not the regulation capacity from the studies that was used on the graphs, but the percentage of yearly inflow that was available in the reservoirs when the floods came (similar to the flood dampening capacity described above, but not as advanced). Furthermore, the flood dampening was typically given for an area far downstream of an unregulated area. The curves were developed for an area in the flood was measured at the outlet of a reservoir (module 7 in the catchment never had 0 volume). To make sure this was accounted for, the regulation capacity for each event was calculated for the regulated areas only, and the flood dampening was determined for that area alone. This dampening was then scaled to the total area based on the fraction of the area that was regulated. A procedure and example is given below.

1) Determine total storage volume in the catchment.
2) Determine total inflow to the regulated (i.e. where water runs into a reservoir) area of the catchment.
3) Determine regulation capacity in the regulated area, then reduce to account for reservoir filling.
4) Find the flood dampening in the regulated area using the appropriate dampening curve and the reduced regulation capacity. This is all the flood dampening that will happen from reservoirs in the catchment.
5) Scale the flood dampening based on the percentage of the yearly inflow (if not available, use area as an estimation) that is regulated.

Example of how to apply the dampening curves:

Table 17: Dampening curve application example.

Catchment: Orkla		Comments
Type of flood	Autumn, T=200	Determines which curve to use
Total storage vol.	426	Data
Regulated inflow	577	Data
Regulation capacity in regulated area	74% [4]	Data
Reservoir filling	85%	Data
Reduced regulation capacity	11%	0.74*(1-0.85)
Flood dampening in regulated area	68%	From curve
Regulated inflow as % of total	38%	Data
Flood dampening in total area	26%	0.68*0.38

[4] Since the dampening curves are not linear, the same results will not be obtained if one uses the regulation capacity for the total area directly instead of scaling to the total area at the end.

The curve for spring floods (Figure 32) had the highest number of points to verify on, and it performed reasonably well. As expected there was some deviation from the line, which can be caused not only by the uncertainty of the curve, but also by potential uncertainties in how the simulated/observed data was obtained. The points for Orkla were from simulations with varying initial reservoir fillings using the model developed in this project. It is interesting to note that the curve did not appear to perform better in Orkla than the other catchments, despite being made using floods from that river. The performance was also different for the GLB and HYDRA data, which were both from areas in Glomma, some of the points are even for the same floods. This highlights that the methods used in the flood dampening studies can vary greatly and influence how well the curve results match the data.

The curve output for the autumn floods (Figure 34) seems to fit very well, but the results give a deceiving sense of accuracy. For all the Brandywine points the reservoirs in the system had a very large regulation capacity (>40%), and as this was an intense, short rain-flood associated with a hurricane the volume of water was not nearly enough to fill the reservoirs. The dampening depended solely on the fraction of the area that was regulated. The same results would have been obtained from the curve for any regulation capacity greater than 20%, and thus the curve was not challenged with this data set. For Orkla, the case was the same for the two points with the highest dampening – only the four remaining data points for Orkla challenged the model, and it would not be reasonable to draw a conclusion that the curve fits well based on only those four points. The points from Yesa Reservoir were included despite a lack of knowledge about the type of floods the results referred to. They do not fit the results from the curve at all, and this could be due to a hydrograph that is entirely different from the intended use (which is a 1-day intense rain-flood). Additional data points that fall within the variable section of the curve should be acquired to see how well it performs.

If the dampening curves presented in this study are improved to the point where they can be applied with some sense of certainty in the real world, they could have a number of useful applications, both during planning and during operation of reservoirs. This could include using them to estimate what regulation capacity one would need to install to protect against a certain type or magnitude of flood, or to estimate how much reservoir storage would need to be available when a flood comes to achieve a desired dampening.

8 Conclusions

8.1 Flood dampening in Orkla

The hydropower regulation in Orkla has a large flood dampening effect, with more than 30% dampening for all simulated floods. The potential flood dampening in the system is not typically constrained by reservoir capacity, but by inflow to regulated area and transfer capacity. The reservoirs in the system has the potential to be drawn down quickly prior to a flood, and therefore the system has a high flood dampening potential even if reservoirs are filled a few days prior to an autumn flood. The hydropower tunnels in the system contribute greatly to this drawdown capacity if constraints are put on how much water is allowed to be released in the local rivers.

8.2 Regulation capacity vs. flood dampening

The flood dampening potential of a reservoir system varies greatly even for systems with the same regulation capacity. This is due to the unique topology of each system, where reservoir storage capacity location is a key factor. Furthermore, one reservoir system can have a large spread in dampening potential based on the flood hydrograph, and the magnitude of this spread varies from catchment to catchment. Therefore, flood dampening curves developed solely based on flood dampening and regulation capacity will necessarily have a high uncertainty. It is recommended to include additional parameters that describe the flood and the system in more detail in the regression. Examples of attempts at describing such parameters can be found in Souza, Studart et al. (2017) (system characteristics) and Miotto, Claps et al. (2007) (flood hydrograph). Another such parameter is suggested in this thesis.

8.3 Dampening curves

Dampening curves based on synthesized data showed a reasonable prediction accuracy for most of the floods they were tested on, despite being developed with only one independent variable: regulation capacity. It seems likely that their accuracy could be significantly improved by further work.

8.4 Flood regulation capacity

The investigation of a factor called flood regulation capacity is recommended. This would constrain the regulation capacity to only include storage that is relevant for flood dampening, which might reduce the inaccuracy of the dampening curves.

References

Bakken, T. H. (2018). Personal communication: ICOLD-database and processed data figures. B. Hansen.

Bergström, S. (1967). Development and Application of a Conceptual Runoff Model for Scandinavian Catchments. SMHI Rapporter, Hydrologi och Oceanografi.

Collins, M., et al. Long-term Climate Change: Projections, Commitments and Irreversibility. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, US**:** 1032.

Doocy, S., et al. (2013). "The Human Impact of Floods: a Historical Review of Events 1980-2009 and systematic Literature Review." PLOS Currents: Disasters.

Drageset, T.-A. (2002). Flomberegning for Orkla ved Meldal og Orkanger. Flomsonekartprojektet, The Norwegian Water Resources and Energy Directorate.

Eikenæs, O., et al. (2000). Flommen kommer... Sluttrapport fra HYDRA - et forskningsprogram om flom. HYDRA, NVE and 16 others.

Fitzhugh, T. W. and R. M. Vogel (2010). "The impact of dams on flood flows in the United States." River Research and Applications **27**(10): 1192-1215.

Glover, B., et al. (2018). Verdien av vassdragsreguleringer for reduksjon av flomskade, MultiConsult.

Hayashi, S., et al. (2008). "Effect of the Three Gorges Dam Project on flood control in the Dongting Lake area, China, in a 1998-type flood." Journal of Hydro-environment Research **2**: 148-163.

Higgs, G. and G. Petts (1988). "Hydrological changes and river regulation in the UK." Regulated Rivers: Research and Management **2**: 349-368.

Karbowski, A. (1993). "Optimal flood control in multireservoir cascade systems with deterministic inflow forecasts." Water Resources Management **7**: 207-223.

Killingtveit, Å. (2004). nMag2004: A computer program for hydropower and reservoir operation simulation, Norwegian University of Science and Technology (NTNU).

Larson, L. W. (1996). The Great USA Flood of 1993. IAHS Conference: Destructive Water: Water-Caused Natural Disasters - Their Abatement and Control. Anaheim, California, USA.

Lary, D. (2001). "Drowned Earth: The Strategic Breaching of the Yellow River Dyke, 1938." War in History **8**(2).

Lawrence, D. and H. Hisdal (2011). Hydrological projections for floods in Norway under future climate. 2011:5, Norwegian Water Resources and Energy Directorate.

Lee, K. T., et al. (2001). "Reservoir attenuation of floods from ungauged basins." Hydrological Sciences Journal **46**(3): 349-362.

Lopez-Moreno, J. I., et al. (2002). "Influence of the Yesa reservoir on floods of the Aragón River, central Spanish Pyrenees " Hydrology and Earth System Sciences **6**(4): 733-762.

Lussana, C., et al. (2018). "seNorge2 daily precipitation gridden dataset over Norway from 1957 to the present day." Earth System Science Data **10**: 235-249.

Lussana, C., et al. (2016). seNorge2: An observational gridded dataset of temperature for Norway, Norwegian Meteorological Institute.

Mateo, C. M., et al. (2014). "Assessing the impacts of reservoir operation to floodplain inundation by combining hydrological, reservoir management, and hydrodynamic models." Water Resources Research **50**(9): 7245-7266.

Miotto, F., et al. (2007). An analytical index for flood attenuation due to reservoirs.

Ngo, L. L., et al. (2008). "Implementation and Comparison of Reservoir Operation Strategies for the Hoa Binh Reservoir, Vietnam using the Mike 11 Model." Water Resources Management **22**: 457-472.

NOAA. NOAA's Top Global Weather, Water and Climate Events of the 20th Century. National Oceanic and Atmospheric Administration.

Norsk Naturskadepool (2018). "NASK - Naturskadestatistikk." from https://www.naturskade.no/statistikk/.

NVE (2016). "1995: Vesleofsen, stor flom på Østlandet." Retrieved 26.06, 2018, from https://www.nve.no/om-nve/vassdrags-og-energihistorie/nves-historie/1995-vesleofsen-stor-flom-pa-ostlandet/.

NVE (2017). "Oversikt over behov for flom- og skredsikringstiltak, sortert på fylker og kommuner." Retrieved 26.06, 2018, from https://www.nve.no/flaum-og-skred/sikrings-og-miljotiltak/oversikt-over-behov-for-flom-og-skredsikringstiltak-sortert-pa-fylker-og-kommuner/.

Sælthun, N. R. (2017). Brukerveiledning NKA. Nytte/kost-verktøy NKA-2016 v 1.10, NVE.

Slutzman, J. E. and J. A. Smith (2008). "Effects of Flood COntrol STructures on Flood REsponse for Hurricane Floyd in Brandywine Creek Watershed, Pennsylvania." Journal of Hydrologic Engineering **11**(5): 432-441.

Souza, D. N. d., et al. (2017). "Flood dampenng by reservoirs: proposition of a graphical parametric method." Brazilian Journal of Water Resources **22**(39).

Tingvold, J. K. (1999). Effekt av vassdragsreguleringer i Glomma og Lågen på stor flom. HYDRA, NVE.

Toldnæs, J. P. and R. Heggstad (2017). "Orkla." Retrieved 30.06, 2018, from https://snl.no/Orkla.

Tollan, A. (2018). "Flom." Retrieved 26.06, 2018, from https://snl.no/flom.

Tollan, A. and T. Ljøgodt (1995). Prosjekt HYDRA - mot ekstremflommer [Project HYDRA - against extreme floods]. Vann og Energi [Water and Energy], NVE. **2**.

Tvedalen, A. K. (2015). Snow melt: Evaluation of an energy balance model. Department of Geosciences. www.duo.no, University of Oslo. **Master of Science**.

Walløe, K. L. (2018). Personal communication: Vedlegg til rapport "Verdien av vassdragsreguleringer for reduksjon av flomskader". B. Hansen.

Wan, X., et al. (2017). "Evaluating the impacts of a large-scale multi-reservoir system on flooding: case of the Huai River in China." Water Resources Management **32**: 1013-1033.

Wathne, M. and K. Alfredsen (1998). Effekten av regulering på flomdemping i Gudbrandsdalslågen [The effect of regulation on flood-dampening in Gudbrandsdalslågen]. HYDRA, SINTEF Bygg of miljøteknikk.

Wichakul, S., et al. (2013). "Developing a regional distributed hydrological model for water resources assessment and its application to the Chao Phraya River basin." Journal of Japan Sociecty of Civil Engineers, Ser. B1 (Hydraulic Engineering) **69**(4): I_43-I_48.

Wisser, D., et al. (2015). "Beyod peak reservoir storage? A global estimate of declining water storage capacity in large reservoirs." Water Resources Research **49**: 5732-5739.

World Bank (2011). Rapid assessment for resilient recovery and reconstruction planning. Thai Flood 2011. Bangkok, Joint Publ. of World bank and Global Facility for Disaster Reduction and recovery.

Zsuffa, I. (1999). "Impact of Austrian hydropower plants on the flood control safety of the Hungarian Danube reach." Hydrological Sciences Journal **44**(3): 363-371.

APPENDIX A: OBSERVED AND SIMULATED FLOOD FLOWS AT BJØRSET

2012					2003					1997				
Date	Observed	Full	Empty	Realistic (0.3)	Date	Observed	Full	Empty	Realistic (0.83)	Date	Observed	Full	Empty	Realistic (0.2)
19.05.2012	121.6	112.6	63.7	63.7	10.08.2003	12.8	32.7	19.8	19.8	01.06.1997	296.1	444.2	255.1	259.0
20.05.2012	103.7	78.8	58.5	59.3	11.08.2003	13.0	29.3	17.6	20.0	02.06.1997	335.6	603.6	376.9	376.9
21.05.2012	100.0	78.0	56.5	56.5	12.08.2003	19.1	53.4	31.9	36.6	03.06.1997	307.3	448.9	275.8	275.8
22.05.2012	179.7	194.1	141.7	141.7	13.08.2003	20.3	72.7	50.0	50.0	04.06.1997	225.1	281.6	176.0	176.0
23.05.2012	257.9	806.4	519.1	519.1	14.08.2003	324.0	280.0	189.1	189.1	05.06.1997	204.0	304.3	180.9	180.9
24.05.2012	255.9	971.2	633.8	633.8	15.08.2003	581.2	1088.6	720.5	720.5	06.06.1997	236.1	543.0	313.3	313.3
25.05.2012	249.9	988.0	637.9	637.9	16.08.2003	282.7	585.2	376.3	378.0	07.06.1997	258.2	701.7	423.8	423.8
26.05.2012	205.9	876.8	543.5	543.5	17.08.2003	177.0	163.1	107.6	127.0	08.06.1997	427.5	793.4	496.4	496.4
27.05.2012	190.7	701.8	433.7	433.7	18.08.2003	111.8	109.8	70.1	94.4	09.06.1997	494.9	851.9	543.8	543.8
28.05.2012	205.7	678.5	432.8	432.8	19.08.2003	77.5	94.3	60.3	85.0	10.06.1997	326.1	749.9	485.0	485.0
29.05.2012	112.1	368.6	240.0	242.7	20.08.2003	74.4	88.4	57.3	79.9	11.06.1997	184.1	425.2	277.3	277.3
30.05.2012	78.9	118.9	76.4	77.4	21.08.2003	75.4	91.5	60.8	83.1	12.06.1997	162.6	300.0	195.5	195.5
31.05.2012	57.3	103.2	66.4	67.3	22.08.2003	66.1	87.7	58.7	79.8	13.06.1997	187.1	449.5	283.1	285.3
01.06.2012	55.6	90.9	58.9	59.8	23.08.2003	78.7	98.2	64.7	89.0	14.06.1997	230.4	537.2	345.8	351.1
02.06.2012	60.5	81.1	53.5	54.2	24.08.2003	132.5	153.7	110.1	142.2	15.06.1997	239.7	572.1	392.1	397.3
03.06.2012	100.6	100.4	67.4	68.2	25.08.2003	115.6	143.9	100.5	136.8	16.06.1997	167.3	432.6	303.3	306.8
04.06.2012	133.7	204.6	156.5	157.8	26.08.2003	148.3	132.3	89.5	132.3	17.06.1997	119.9	178.5	124.2	124.2
05.06.2012	175.5	292.7	225.0	226.8	27.08.2003	171.8	205.4	152.3	205.4	18.06.1997	106.0	110.9	72.1	72.1
06.06.2012	136.1	315.8	240.1	242.0	28.08.2003	155.9	185.8	132.7	185.8	19.06.1997	88.8	109.7	71.2	71.2
07.06.2012	113.9	247.8	174.7	177.2	29.08.2003	168.6	131.8	86.4	131.8	20.06.1997	90.4	146.1	95.2	95.2
08.06.2012	105.3	256.5	168.5	171.5	30.08.2003	134.1	118.9	75.5	118.9	21.06.1997	98.5	205.9	143.3	143.3
09.06.2012	98.8	279.8	172.0	175.6	31.08.2003	122.8	109.4	69.9	109.4	22.06.1997	104.6	212.0	145.7	145.7
10.06.2012	109.8	306.2	192.1	195.3	01.09.2003	102.4	102.3	65.7	102.3	23.06.1997	114.1	207.6	141.8	141.8
11.06.2012	81.0	236.5	157.2	157.2	02.09.2003	75.8	93.3	59.8	93.3	24.06.1997	170.9	289.9	203.6	226.1
12.06.2012	71.4	129.4	79.5	79.5	03.09.2003	65.4	81.8	52.2	81.8	25.06.1997	118.1	244.1	172.4	198.1
13.06.2012	71.3	116.7	73.5	73.5	04.09.2003	60.8	73.4	47.0	73.4	26.06.1997	104.9	155.3	103.7	123.2
14.06.2012	79.5	140.3	92.7	99.3	05.09.2003	56.1	64.9	42.2	64.9	27.06.1997	107.0	128.5	82.4	100.6
15.06.2012	75.2	146.8	94.0	119.2	06.09.2003	49.3	56.0	36.7	56.0	28.06.1997	106.3	124.9	77.9	94.8
16.06.2012	77.4	145.3	92.8	111.9	07.09.2003	43.7	47.7	31.2	47.7	29.06.1997	114.8	189.5	126.5	181.0
17.06.2012	85.7	205.5	139.8	159.7	08.09.2003	42.3	40.6	26.6	40.6	30.06.1997	114.3	262.9	182.2	253.7

APPENDIX A: OBSERVED AND SIMULATED FLOOD FLOWS AT BJØRSET

1995					1981					1976				
Date	Observed	Full	Empty	Realistic (0.18)	Date	Observed	Full	Empty	Realistic (0.18)	Date	Observed	Full	Empty	Realistic (0.18)
22.05.1995	61.3	39.5	11.9	11.9	07.05.1981	21.9	25.0	3.7	3.7	11.05.1976	188.8	657.4	383.9	387.5
23.05.1995	70.1	23.6	14.5	14.5	08.05.1981	22.6	7.7	5.0	5.0	12.05.1976	285.9	437.5	275.1	275.1
24.05.1995	98.5	54.4	31.0	32.2	09.05.1981	75.9	45.6	25.0	25.0	13.05.1976	276.4	285.1	192.3	192.3
25.05.1995	155.9	111.6	73.5	73.5	10.05.1981	157.5	185.4	129.6	132.8	14.05.1976	343.8	291.7	199.1	199.1
26.05.1995	277.4	425.1	275.1	275.1	11.05.1981	212.6	572.0	388.8	388.8	15.05.1976	368.0	214.9	146.0	146.0
27.05.1995	413.7	685.5	430.3	430.3	12.05.1981	486.7	737.4	483.9	483.9	16.05.1976	312.9	231.9	151.7	151.7
28.05.1995	392.2	711.8	446.6	446.6	13.05.1981	832.6	774.7	510.7	510.7	17.05.1976	411.2	367.9	241.6	241.6
29.05.1995	413.7	687.6	442.1	442.1	14.05.1981	810.8	711.9	470.0	470.0	18.05.1976	448.1	490.6	321.9	321.9
30.05.1995	432.9	633.9	415.7	415.7	15.05.1981	662.5	635.9	416.0	416.0	19.05.1976	562.0	727.8	462.2	462.2
31.05.1995	421.9	604.4	390.6	390.6	16.05.1981	605.6	656.1	420.5	420.5	20.05.1976	714.2	854.8	544.4	544.4
01.06.1995	397.5	749.4	470.2	470.2	17.05.1981	639.4	698.2	447.9	447.9	21.05.1976	810.8	829.8	524.3	524.3
02.06.1995	490.3	791.8	496.8	496.8	18.05.1981	658.7	678.3	445.1	445.1	22.05.1976	841.5	767.3	488.5	488.5
03.06.1995	392.2	534.3	353.1	353.1	19.05.1981	635.6	636.9	424.8	424.8	23.05.1976	768.0	707.6	451.7	451.7
04.06.1995	208.5	292.9	201.9	201.9	20.05.1981	686.1	616.8	412.6	412.6	24.05.1976	674.3	645.8	413.5	418.1
05.06.1995	178.6	230.0	157.9	157.9	21.05.1981	579.9	488.2	325.6	330.7	25.05.1976	755.4	709.7	458.5	465.8
06.06.1995	150.9	263.4	182.0	182.0	22.05.1981	562.0	440.8	298.2	303.4	26.05.1976	726.4	767.6	503.3	506.0
07.06.1995	162.7	327.0	223.7	225.4	23.05.1981	654.8	547.8	385.9	390.2	27.05.1976	601.9	559.3	376.9	443.8
08.06.1995	141.2	305.1	208.3	211.2	24.05.1981	594.5	545.2	398.1	398.1	28.05.1976	429.4	262.1	180.6	212.6
09.06.1995	222.3	325.8	230.7	233.1	25.05.1981	598.2	436.2	327.5	327.5	29.05.1976	300.5	158.9	107.9	127.9
10.06.1995	155.9	375.2	267.4	270.0	26.05.1981	399.3	339.8	252.8	252.8	30.05.1976	288.3	208.9	142.9	167.1
11.06.1995	119.6	222.0	156.3	158.1	27.05.1981	229.4	336.1	250.2	250.2	31.05.1976	300.5	239.2	160.2	188.5
12.06.1995	113.8	125.5	82.6	83.6	28.05.1981	235.8	370.4	276.8	276.8	01.06.1976	214.7	180.6	117.2	140.5
13.06.1995	95.8	108.1	70.5	71.4	29.05.1981	212.6	317.5	224.2	224.2	02.06.1976	204.5	128.5	81.4	100.0
14.06.1995	91.9	99.2	65.5	66.4	30.05.1981	182.9	192.1	134.2	158.5	03.06.1976	162.1	111.7	71.7	88.8
15.06.1995	90.6	101.9	68.4	68.9	31.05.1981	152.9	114.1	75.1	93.0	04.06.1976	154.4	99.9	65.1	80.5
16.06.1995	98.5	128.9	90.9	90.9	01.06.1981	125.4	108.4	73.4	89.1	05.06.1976	163.7	94.8	62.1	76.5
17.06.1995	109.5	177.7	131.4	131.4	02.06.1981	144.0	152.3	117.0	132.8	06.06.1976	200.5	100.4	66.9	81.3
18.06.1995	108.1	179.6	134.3	134.3	03.06.1981	124.1	147.0	112.2	126.5	07.06.1976	176.4	164.0	117.6	134.8
19.06.1995	146.0	228.0	171.4	171.4	04.06.1981	131.0	134.9	100.0	112.7	08.06.1976	157.5	181.6	134.0	152.1
20.06.1995	121.1	222.0	165.0	165.0	05.06.1981	145.5	226.0	168.8	186.4	09.06.1976	194.6	166.4	133.1	135.5

APPENDIX A: OBSERVED AND SIMULATED FLOOD FLOWS AT BJØRSET

1973					1967					1944				
Date	Observed	Full	Empty	Realistic (	Date	Observed	Full	Empty	Realistic (	Date	Observed	Full	Empty	Realistic (
20.05.1973	196.6	216.3	102.0	105.9	20.05.1967	126.4	146.1	61.6	62.5	05.06.1944	406.4	406.4	219.6	225.5
21.05.1973	245.4	245.4	151.8	151.8	21.05.1967	149.6	149.6	92.6	92.6	06.06.1944	703.8	703.8	435.4	435.4
22.05.1973	270.5	270.5	167.4	167.4	22.05.1967	185.3	185.3	114.7	114.7	07.06.1944	763.9	763.9	472.6	472.6
23.05.1973	294.2	294.2	182.0	182.0	23.05.1967	230.9	230.9	142.9	142.9	08.06.1944	729.3	729.3	451.2	451.2
24.05.1973	313.3	313.3	193.8	193.8	24.05.1967	365.4	365.4	226.0	226.0	09.06.1944	729.3	729.3	451.2	451.2
25.05.1973	223.9	223.8	138.5	138.5	25.05.1967	468.0	468.0	289.5	289.5	10.06.1944	1277.8	1277.8	862.9	862.9
26.05.1973	262.9	262.8	162.6	162.6	26.05.1967	576.0	576.0	356.3	356.3	11.06.1944	772.7	772.7	478.0	478.0
27.05.1973	344.7	344.6	213.2	213.2	27.05.1967	646.3	646.3	399.8	399.8	12.06.1944	383.6	383.6	237.3	237.3
28.05.1973	411.9	411.8	254.8	254.8	28.05.1967	599.0	598.9	370.5	370.5	13.06.1944	583.6	583.6	361.0	362.8
29.05.1973	408.7	408.7	252.8	252.8	29.05.1967	817.4	817.4	505.7	505.7	14.06.1944	359.4	359.4	222.3	225.7
30.05.1973	447.7	447.7	277.0	277.0	30.05.1967	1102.1	1102.1	725.1	725.1	15.06.1944	327.4	327.4	202.5	205.6
31.05.1973	591.2	591.2	365.8	365.8	31.05.1967	729.3	729.3	451.2	451.2	16.06.1944	299.6	299.6	185.4	188.1
01.06.1973	936.2	936.1	594.9	594.9	01.06.1967	595.1	595.1	368.1	368.1	17.06.1944	278.3	278.3	172.2	174.7
02.06.1973	708.0	708.0	438.0	438.0	02.06.1967	535.0	535.0	331.0	332.1	18.06.1944	255.3	255.3	157.9	160.3
03.06.1973	327.4	327.4	202.5	202.5	03.06.1967	365.4	365.4	226.0	229.4	19.06.1944	260.3	260.3	161.0	163.5
04.06.1973	270.5	270.5	167.4	167.4	04.06.1967	280.9	280.9	173.8	176.4	20.06.1944	283.6	283.6	175.4	178.0
05.06.1973	230.9	230.9	142.9	142.9	05.06.1967	291.5	291.5	180.4	183.0	21.06.1944	233.3	233.3	144.3	174.3
06.06.1973	203.3	203.3	125.8	125.8	06.06.1967	176.1	176.1	109.0	110.6	22.06.1944	192.8	192.8	119.8	149.8
07.06.1973	273.1	273.1	169.0	169.0	07.06.1967	131.3	131.3	81.2	82.4	23.06.1944	158.3	158.3	99.4	122.9
08.06.1973	223.9	223.8	138.5	140.1	08.06.1967	139.5	139.5	86.3	87.6	24.06.1944	146.2	146.2	91.8	113.6
09.06.1973	203.3	203.3	125.8	127.7	09.06.1967	132.9	132.9	82.2	83.4	25.06.1944	136.2	136.2	85.5	119.4
10.06.1973	154.8	154.8	95.8	97.2	10.06.1967	124.8	124.8	77.3	78.4	26.06.1944	158.3	158.3	99.4	143.1
11.06.1973	132.9	132.9	82.2	83.4	11.06.1967	132.9	132.9	83.4	83.4	27.06.1944	181.6	181.6	114.0	164.2
12.06.1973	100.3	100.3	62.1	63.0	12.06.1967	115.4	115.4	72.5	72.5	28.06.1944	265.4	265.4	166.6	239.9
13.06.1973	86.1	86.1	53.3	54.1	13.06.1967	126.4	126.4	79.4	79.4	29.06.1944	302.3	302.3	189.8	273.3
14.06.1973	151.3	151.3	93.6	95.0	14.06.1967	137.8	137.8	86.5	86.5	30.06.1944	228.5	228.5	143.5	206.6
15.06.1973	100.3	100.3	62.1	63.0	15.06.1967	129.6	129.6	81.4	81.4	01.07.1944	156.5	156.5	98.3	141.5
16.06.1973	84.7	84.7	52.4	53.2	16.06.1967	124.8	124.8	78.4	84.1	02.07.1944	161.8	161.8	101.6	146.3
17.06.1973	80.7	80.6	49.9	50.6	17.06.1967	137.8	137.8	86.5	107.0	03.07.1944	214.6	214.6	134.7	197.7
18.06.1973	113.9	113.8	70.4	71.5	18.06.1967	118.5	118.5	74.4	92.0	04.07.1944	212.3	212.3	133.3	212.3

1940				
Date	Observed	Full	Empty	Realistic (0.85)
20.08.1940	45.5	65.2	22.2	25.2
21.08.1940	43.3	43.3	21.3	26.8
22.08.1940	38.1	38.1	23.6	23.6
23.08.1940	255.7	255.7	158.2	158.2
24.08.1940	1454.6	1454.6	1001.6	1006.4
25.08.1940	502.7	502.7	311.0	394.5
26.08.1940	318.9	318.9	197.3	288.3
27.08.1940	165.3	165.3	102.3	158.7
28.08.1940	136.2	136.2	84.2	136.2
29.08.1940	112.3	112.3	69.5	112.3
30.08.1940	107.8	107.8	66.7	107.8
31.08.1940	101.8	101.8	63.0	101.8
01.09.1940	118.5	118.5	73.3	118.5
02.09.1940	160.0	160.0	99.0	160.0
03.09.1940	120.1	120.1	74.3	120.1
04.09.1940	96.0	96.0	59.4	96.0
05.09.1940	84.7	84.7	52.4	84.7
06.09.1940	88.9	88.9	55.0	88.9
07.09.1940	90.3	90.3	55.9	90.3
08.09.1940	78.0	78.0	48.2	78.0
09.09.1940	90.3	90.3	55.9	90.3
10.09.1940	83.4	83.4	51.6	83.4
11.09.1940	86.1	86.1	53.3	86.1
12.09.1940	90.3	90.3	55.9	90.3
13.09.1940	76.7	76.6	47.4	76.6
14.09.1940	68.9	68.9	42.6	68.9
15.09.1940	60.3	60.3	37.3	60.3
16.09.1940	57.9	57.9	35.8	57.9
17.09.1940	56.7	56.7	35.1	56.7
18.09.1940	56.7	56.7	35.1	56.7