Master's thesis

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

Folakemi Ope Olabiwonnu

Assessment of the Role of Hydropower Reservoirs in Sustaining Ecologically Viable Low Flow Conditions under Present and Future Climate

Master's thesis in Hydropower Development
Supervisor: Tor Haakon Bakken
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Declaration of Authorship

I declare that I am, Olabiwonnu Folakemi Ope, the sole author of the thesis named

“Assessment of the Role of Hydropower Reservoirs in Sustaining Ecologically Viable Low Flow Conditions Under Present and Future Climate”

Which has been submitted to the examination office of Civil Engineering Department on 11th of July 2020.

I have fully referenced the ideas and work of others, whether published or unpublished.

Literal or analogous citations are clearly marked as such.

Acknowledgement

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Abstract

Usually, low flow in rivers occur as a result of an extended period of dryness which is likely attributed to drought. Due to drought being a natural occurrence as an outcome of reduction in precipitation in a region for a long time, reservoirs can be used to mitigate negative effects on the supply of water in dry periods and also supply water for other purposes besides its primary purpose, which in Norway is hydropower production. Unfortunately, due to climate change across the world such as in the mountainous regions of Norway, low flow occurs in rivers during summer. This is mainly a consequence of increased evaporation and reduced precipitation. Also, in the winter period, low flow is prevalent due to precipitation being stored as snow which irrespective of increased periods of melting, hydropower production causes reduced flow. Hence, controlling the water level using reservoirs cause direct and indirect impacts in the flow regime of rivers just as regulation releases might make flows higher than it would have been naturally. River Glomma in southern Norway was therefore chosen as a case study to examine the effect of regulation on the ecosystem and how regulation releases might make flows higher than it would have been naturally and consequently sustain low flow condition. Subsequently, two unregulated basins in the river Glomma was equally chosen to evaluate the effect of climate change on the low flow condition of the river without regulation. Thereafter, meteorological data and flow data were used to calibrate hydrological model on Water Evaluation and Planning System (WEAP) so as to observe the effect of regulation on this river. Results from this thesis provide insight on the effect of climate change on low flow conditions with and without the regulation. Additionally, findings suggest that the effect of reservoir storage on low flow during critical periods in both winter and summer should be assessed and recommendations can be made to policy makers on planning strategies into how water is released downstream so as to sustain low flow condition, thus providing recommendations to companies to determine when to increase released water during the periods of low flow.

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ABBREVIATIONS

WEAP	Water Evaluation and Planning System
NVE	Norwegian Water Resources and Energy Directorate
IPCC	Intergovernmental Panel on Climate Change
IHA	Indicators of Hydrologic Alteration
GIS	Geographical Information System
HBV	Hydrologiska Byråns Vattenbalansavdelning
DHI	Institute for water and Environment
WGS	World Geodetic System
NSE	Nash Sutcliffe Efficiency
RMSE	Root mean square error

CHAPTER 1

INTRODUCTION

1.1 Introduction

The purpose of this chapter is to introduce the research domain of hydropower reservoirs in sustaining ecologically viable low flow conditions. Accordingly, this chapter presents the background of study, problem statement, research questions, research aim, research objectives, research scope, and thesis organization.

1.2 Overview

Over several centuries, the need for water has increased for more purposes than sanitation. As time went by, it began to be seen as an economic good, as it can be used for hydropower production (Barbier, 2019). Hence, institutions for water management as well as for improvement of water policies were needed for frequent review and better conservation of the eco system (Barbier, 2019). But with the increasing need for water comes different challenges arising from day to day of which one of them is the changing climate.

Drought is seen as one of the most damaging weather-related challenges as regards economic cost (Van Loon and Laaha, 2015). Even though drought occurs naturally, due to climate change, its effect on hydrological processes has become more intense (Mukherjee et al., 2018). Drought can be categorized into meteorological, agricultural, and hydrological drought of which Meteorological drought arises as a result of climatic changes while Agricultural droughts are caused by poor planning which affects crop yield (Leng et al., 2015). However, hydrological drought occurs when the available water falls below its significant threshold (Hisdal and Tallaksen, 2000). Hence, reduction in the rate of precipitation can result in meteorological drought and agricultural drought in a specific region, which later leads to hydrological drought (Wanders and Wada, 2015). Moreover, drought is a temporary dry period (Dai, 2011), and can be termed as a disaster which occurs periodically. It has environmental, social, and economic effect in any region where it occurs (Wen et al., 2011). Thus, the damaging effect it has on the eco system cannot be over emphasized (Van Loon and Laaha, 2015) and consequently, low flow periods can be experienced in rivers (Vicente-Serrano et al., 2014).

Therefore, in a country like Norway which uses more than 70% of its largest rivers for production of electricity via hydropower as published by the Norwegian Environment Agency (environment.no, 2020), low flow can occur especially when drought is experienced.

Moreover, in southern Norway, low flows are experienced mostly during the summer as a result of the high temperature and reduced precipitation, however in the northern region of Norway, low flow occurs during the winter. However, reservoirs can be used to secure adequate flow in rivers for hydropower production and to improve the low flow conditions via increased water releases (Zufelt, 2015).

1.3 Background of Study and Problem Statement

In recent years, Norway has experienced drought which has resulted in a lot of economic losses. However, since river regulation is a common practice in Norway as hydropower accounts for most of Norway’s power supply (energifaktanorge.no, 2020), it can both affect the eco system due to the water withdrawal during low flow period, and it can also provide additional water for higher release during periods of low flow(Young et al., 2011). Hence, there is need investigate how reservoirs can sustain ecological viable low flow condition.

1.4 Research Questions

The main research questions to be explored in this thesis are:

RQ1. How do reservoirs affect low flow conditions during summer and winter in the present climate?

RQ2. How are reservoirs expected to affect low flow conditions during summer and winter in future climate?

1.5 Aim

The aim of this thesis is to assess the role of hydropower reservoirs in sustaining ecologically viable low flow conditions under present and future climate.

1.6 Research Objectives

To address the aforementioned research questions, the objective of this thesis are as follows:

- To identify a suitable regulated basin to use as a case study.

- To collect and pre-process the needed data in order to configure a hydrological model in WEAP so as to represent/simulate the regulation.
- To calibrate the model against historical observations of discharge.
- To evaluate the snow module of WEAP.
- To assess the effects of the regulation (reservoir) on low flow during critical periods by the use of hydrological indices.
- To assess the effect of climate change on the low flow indices for the situation with and without the regulation.

1.7 Research Scope

River Glomma in Southern Norway which is the largest and equally the longest river in Norway with a total length of 621 kilometers in the Southern region of Norway was chosen for this research. This river possesses extensive hydropower production and it is being maximized as there are several hydropower stations that generate electricity using the water from the river.

In addition, two unregulated basins in the river Glomma was equally chosen to evaluate the effect of climate change on the low flow condition of the river without regulation. Hence, meteorological data and flow data were retrieved from the Norwegian database from measuring gauges that were installed around the two smaller basins so as to calibrate a hydrological model on Water Evaluation and Planning System (WEAP) software against observed historical discharge. Also, the snow module of WEAP. Additionally, the Digital Elevation Model (DEM) and the shape files of the catchments were inputted in ArcMap software for catchment preparation purposes and presentation of data.

1.8 Thesis Organization

The organization of this thesis is as follows. Chapter 1 introduces the background and the description of the study. Chapter 2 presents the literature review. Chapter 3 describes the methods and approach used. Chapter 4 presents the results. Chapter 5 discusses the results of the study. Chapter 6 summarizes the conclusions, limitations, and future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a review of previous research carried out on Hydropower reservoirs and its effect on the environment. Additionally, this chapter presents a brief background of hydropower and its overview in Norway while considering mitigation approach to climate change. Besides, this chapter reviews the factors influencing low flow condition in rivers, mitigation approach of hydropower to low flow in Norway. Also, review of modelling tools, rainfall runoff models, background of WEAP, a review of ArcGIS, related works similar to the current study was discussed, and lastly, the summary of the chapter is presented.

2.2 Background of Hydropower

Increasing economic development, population, energy consumption and its effect on changing climate has motivated more exploration into renewable energy (Zarfl et al., 2015). The changing climate is unquestionably the outcome of human activities, as it has resulted in the emission of greenhouse gases which is increasingly worrying (Wanders and Wada, 2015). This has led to a lot of countries decreasing their dependence on hydrocarbon-based energy production (Koc, 2012; Benejam et al., 2016). On that account, renewable energy is a lot more acceptable and sought after for its cleaner energies and help in mitigating climate change (Fan et al., 2020).

Hydropower which is a renewable source of energy is being invested in more than before. Hydropower has come a long way since the 1500 when waterwheel became foremost in its use for power generation in Europe. The waterwheel used were improved upon with time and the generation of power using water gained popularity (Fasol, 2002). In fact, according to Intergovernmental Panel on Climate Change (IPCC), hydropower utilizes the energy captured from flowing water to generate electricity and its project ranges from dam, run-of-river, and even in-stream projects (IPCC, 2011).

Hydropower projects, however, mostly require high capital cost but in contrast with other renewable sources, hydropower has low operating and maintenance cost (Fan et al., 2020). Consequently, the developments in hydropower has produced economical, efficient, and affordable power all over the world (Fasol et al., 2002). Thus, the principal function of a river regulated for hydropower use is to increase the natural discharge that can be used when energy demand is high during the winter and can also dampen spring flood during the summer (Rokaya et al., 2019).

2.3 Overview of Hydropower in Norway

Norway, a northern country, is one of the largest hydropower producers in the world. It has a favorable environment that is endowed for generating hydroelectric power (Rørslett, 1989). Having a mountainous terrain with high elevation and steep falls, its precipitation is moderately distributed all year round (Thaulow et al., 2016). Respectively, a regular Norwegian hydropower project involves impounding natural lakes which are operated with regulation measures on several rivers, hence, interbasin transfer often occur (Rørslett, 1989).

Nevertheless, Norway recognized the importance of the use of water for generating power supply in 1312 as written by King Håkon V (Gooch et al., 2010). The first hydropower plant in Norway was built in 1877 and from then, hydropower generation became the primary use of water in Norway apart from domestic uses, agricultural uses, and industrial uses. Even though there was a setback in hydropower development during the 2nd world war, the hydropower system in Norway boomed and became fundamental in Norwegian economic development (Gooch et al., 2010).

According to a report by nve.no in 2019, 93% of the Norwegian electricity production was generated from Hydropower which is a renewable source of energy. As at the beginning of 2020, the annual production in developed hydro is approximately 136 TWh with 2.6 TWh to be generated from hydropower stations that are currently under construction. Hence, the total installed power generated from hydropower in Norway is 32 671 MW. Accordingly, Table 1 depicts the distribution of hydropower in Norway (nve.no, 2020).

Table 2.1: Distribution of hydropower in Norway (nve.no)

Group	Number	Installed capacity	Average annual production
<1 MW	574	186 MW	0.8 TWh
1-10 MW	737	2633 MW	10.3 TWh
10- 100 MW	257	9582 MW	42.3 TWh
>100 MW	83	20270 MW	82.4 TWh
Pumped storage	30	--	-0.2 TWh

Irrespective of this impressive number from Table 2.1, Hydropower is highly dependent on climate and weather, and therefore sensitive to climate change. As it is, climate change is one of the lingering problems experienced in the 21st Century (Shu et al., 2018). It has resulted in increased drought intensity due to the significant rise in temperature as well as increasing difference in precipitation patterns (Wanders and Wada, 2015). Therefore, climate change affects water cycle, hence, for a reliable and steady electricity supply, it is essential to assess the effect of climate change on both hydropower reservoirs and the eco system at large (Fan et al., 2020).

2.4 Climate Change and its Effect on Hydropower.

Climate change affects flow regime in many different ways. With global warming increasing, the balance between snow to rain is reducing. As a result, the changes in precipitation and temperature affect the volume of discharge in rivers (Rokaya et al., 2019). Therefore, increased precipitation would have significant effect on hydropower generation (Lia et al., 2015), while increase in temperature could potentially cause a higher demand for household and industrial water needs. This surely create an indirect effect on water availability for hydropower production (Shu et al., 2018).

Moreover, one of the leading component effecting climate change is global warming. Despite the fact that global warming is the gradual increase in temperature, temperature patterns are increased worldwide, and precipitation patterns are altered in response. Consequently, the alteration to precipitation patterns leads to extreme seasonal precipitation which can affect downstream areas, along with temperature pattern resulting in snowmelt occurring sooner than it should (Harrison et al., 2006; Shu et al., 2018). Thus, increase in evapotranspiration rate is adversely affecting waterbodies as it leads to more significant water loss (Lorenzo et al., 2010). Specifically, all this have an impact on hydropower generation.

2.4.1 Future projections of Climate change

Over time, according to Intergovernmental Panel on Climate Change, IPPC (2011), it has been noted that with increasing energy usage, there is a corresponding increase in Greenhouse gases. General Circulation Models (GCM) which indicate earth components, are therefore a widely accepted numerical models used in research on climate change (Fowler et al., 2007). Hence, climate scenarios are devised with the help of GCM to provide hydrologists with details and theories about greenhouse gas emission in the future (Bergström et al., 2003).

Even so, due to the spatial resolution of GCMs being between 200-300km horizontally and therefore coarse, downscaling is done so that the model can be usable for projecting future streamflow scenarios at a finer resolution(Fowler et al., 2007; Raje and Mujumdar, 2010). Therefore, GCMs can be downscaled into Regional Climate Models (RCM) or Limited-area Model (LAM) (Fowler et al., 2007).

Hence, Intergovernmental Panel on Climate Change (IPCC) created Scenario drivers in their fifth Assessment Report (AR5), thereby outlining a series of Representative Concentration Pathways (RCPs) for future climate projection. They are RCP 2.5, 4.5, 6 and 8.5 W/m^2. According to San José et al (2016), Representative Concentration Pathways (RCPs) are pathways which are determined for climate modelling and research into greenhouse gases. In addition, they incorporate land use change that are in accordance with broad climate outputs that is recognized and used in climate modeling. Hence, the pathways are generated using radiative forcing which is caused by CO_2 emissions due to social economic development and population growth (San José et al., 2016). Among all of them, RCP 8.5 simulates high greenhouse gas emissions while RCP 4.5 and 6 serve as stabilization scenarios. RCP 2.5 is however seen as an alleviation scenario (Nilawar and Waikar, 2019).

However, systematic bias has been observed over the years with the use of GCM and RCM (Wilby et al., 2000; Ehret et al., 2012). This has necessitated a method of bias correction of the raw climate model output .The bias correction of climate model is a method used in amending any systematic deflection in outputs of GCM, and then correcting it with observational data to produce a more accurate climate projection for climatic impact assessment (Ehret et al., 2012; Hempel et al., 2013; CCAFS, 2020).

2.4.1.1 Bias Correction Method

There are several bias correction methods that can be used to adjust errors in climate model outputs. Some of which are as follows:

a) **Delta Change method**

This method makes use of RCM projected future mean change in climate to correct observation data (Diaz-Nieto and Wilby, 2005; Hawkins et al., 2013). When applying it to precipitation data, a multiplicative correction is used while for temperature projection, an additive correction is carried out (Teutschbein and Seibert 2012).

b) Local intensity scaling

This approach focuses on days on which precipitation occurs (Soriano et al., 2018). It models wet day intensity and wet day frequency of precipitation time series. Hence, after incorporating three steps, the corrected precipitation will be similar to the observed data in terms of the mean and wet day intensity and frequency (Schmidli et al., 2006; Teutschbein and Seibert 2012)

c) Linear scaling

According to Teutschbein and Seibert (2012), this approach uses monthly correction values that are derived from the difference between observation data and simulated data. Hence, linear scaling adjusts the climate projections using monthly errors (Soriano et al., 2018). However, linear scaling method cannot correct biases in wet day intensity and wet day frequency (Teutschbein and Seibert 2012).

d) Quantile mapping

By using gamma distribution function, quantile mapping calibrates the distribution function of any variable and improves it to make it better fit with the observed data. Most of the time, this is carried out for precipitation data (Teutschbein and Seibert 2012; Soriano et al., 2018) using the equation below:

$P_{i,j}$ corrected$= a \cdot P_{i,j} + b$………………………………………………………..Eqn(1)

Where

$P_{i,j}$ represents the raw precipitation supplied by climate model i in day j

$P_{i,j}$ corrected represents the corrected precipitation for climate model i in day j

a and b represent quantiles mapping parameters (Soriano et al., 2018)

2.4.2 Mitigation approach to Climate Change

Hydropower reservoir can be used to adjust and counterbalance the annual effect of climate change (Zhang et al., 2012). Extreme weather occurrence like drought which have a direct influence on low flow condition can be prepared for by carrying out a comprehensive risk evaluation of climatic impacts (Shu et al., 2018). Studies have applied climatic data which are solely temperature and precipitation data to assess changes in drought patterns and its effect on low surface water flow (Feyen and Dankers, 2009).

Hence, a contingency plan based on hydrological model forecast for dispensing more discharge around this period of time can be created, (Shu et al., 2018) and this can in turn sustain low flow in rivers.

Furthermore, in order to promote sustainability, renewable source of energy should be invested in more than ever. Hydroelectric power can be complemented with wind power and solar power to make a hybrid energy system which would lead to less use of hydrocarbon-based energy (Shu et al., 2018).

2.5 Overview of Low Flow in Rivers

As discussed by Rolls et al. (2012), low flow constrains the expanse of aquatic habitat by restricting the movement and interchange of matter and biota, thereby limiting carrying capacity in flowing rivers and its eco system. In critical periods such as the winter and summer, the thermal regimes and flow condition in rivers is especially important to the aquatic biota, and particularly for the fish population in the river (Isaak et al., 2012). Populations of cold water fishes such as Salmons and trout for example, are affected by unsuitably warm temperature in low flow periods and this may result in loss of habitat and even periodical disruption to the fish migration for spawning (Keefer et al. 2009; Isaak et al., 2012).

Conversely, McMahon and Finlayson (2003) stated that low flow occurrence in rivers is complicated by positions in the watercourse as the extent and intensity of the low flow reduces as the river flows further downstream. Although, it should be noted that the biodiversity around a river are subject to some hydrological attributes before any interference from hydrological extreme events (Biggs et al., 2005). Hence, the aquatic biota along a river adapts to its high and low flow events. Even so, when the low flow event is more severe than those accustomed to by the aquatic biodiversity, they may not be able to adapt, and this can affect their survival (Rolls et al., 2012).

Therefore, as concluded by Heggenes et al (1996), the effect of low flow on fish habitat suitability was more obvious with Atlantic Salmons. In Norway, for instance, where brown trout and Atlantic salmons are the prevalent fish species, it has been noted that periods of low flow stresses the fishes as it can reduce their habitat to isolated ponds and this results in increased water temperature (Lobón-Cerviá and Sans, 2017). Hayes et al., (2010) however mentioned that sustained low flow may have no unfavorable effect on the juvenile fishes.

Accordingly, some of the hydrological attributes within a riverine ecosystem (Righter et al., 1996; Rolls et al., 2012) are as follows:

a) Magnitude

Environmental flow released downstream is determined from the quantity of the river discharge. A slight change, however minute it might be can have a sizeable ecological consequence. However, the effect of changes in rate of low flow vary depending on topography amongst other factors (Rolls et al., 2012).

b) Duration

Prolonged period of low flow has more effect on aquatic biota than one with shorter duration. As the period of low flow lengthens, there are dangers of desiccation which can inherently lead to migration of the biodiversity, fishes being stranded in isolated pools, and even decrease in specie richness (Datry, 2012; Rolls et al., 2012).

c) Timing

Timing of events determine the extent of mortality or stress endured by the aquatic biota in a river. Low flow event can be particularly consequential in the summer than the winter. During the summer, low flow can result in drastically reduced growth of fishes. However, during the winter, low flow has hardly any noticeable negative effect on the aquatic life in the river McCargo and Peterson 2010; Dare et al. 2002; Rolls et al., 2012).

d) Frequency

The frequency of low flow events will ultimately influence the spawning, adaptability, and mortality rate of the aquatic biota. After a while, rivers which experience frequent periods of low flow will unlikely have species that are unable to endure this period (Righter et al., 1996; Rolls et al., 2012).

e) Rate of change

Rate of change of discharge affects how likely it would be for some organisms to be stranded in ponds. Hence, depending on the rate of low flow, mobility of organism is affected a lot of aquatic organisms are negatively affected (Righter et al., 1996; Rolls et al., 2012).

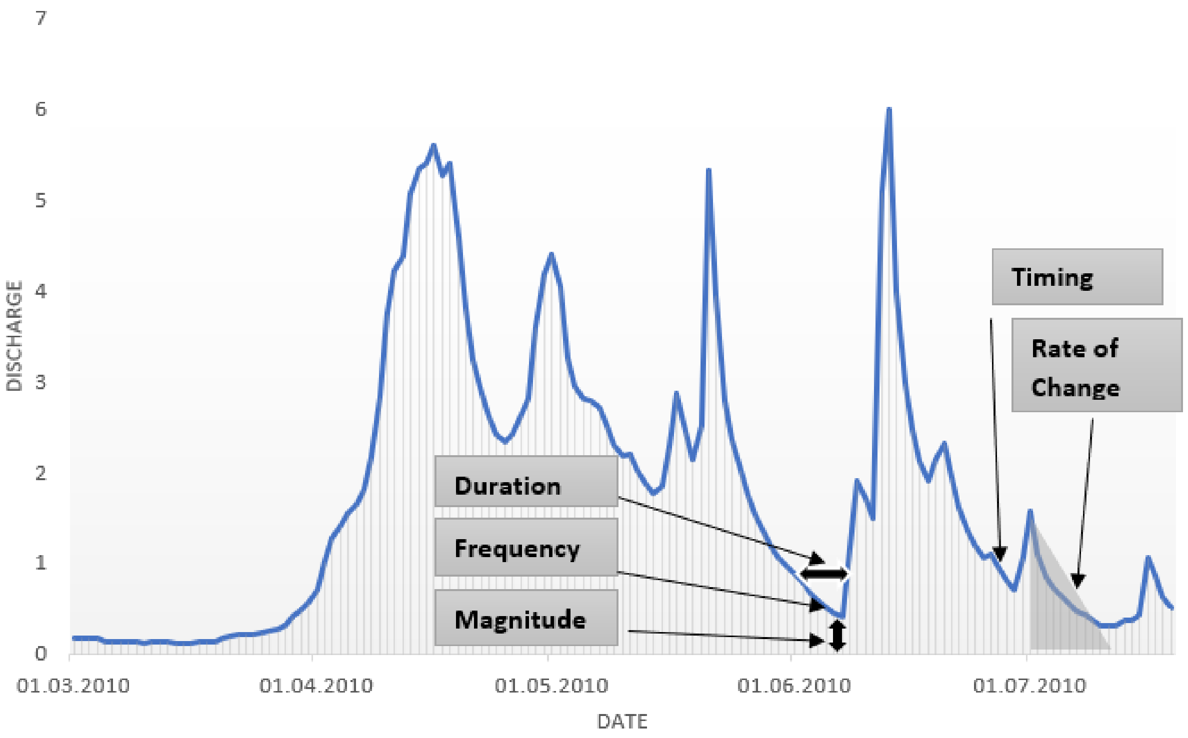


Figure 2.1: Representation of hydrological attributes of low flow in rivers (Rolls et al., 2012)

Based on the findings from (Rolls et al., 2012), Figure 2.1 depicts hydrological attributes of low flow in rivers.

2.6 Indicators of Hydrologic Alteration

Hydrological indices are increasingly applied in research for describing and assessing the different streamflow regimes (Oden and Poff, 2003) due to hydrologic alterations which causes notable changes in hydrologic attributes (Kannan et al., 2008). As any variation to runoff inevitably affects the biodiversity in the river, according to Richter et al. (1996) there are several important streamflow characteristics that can be used in assessing riverine biotic and abiotic eco system integrity. Some of the streamflow characteristics are the annual and seasonal variability, timing of extremes, seasonal pattern of flow, water temperature, dissolved oxygen level and many more (Allan, 1995; Walker et al., 1995; Richter et al., 1996; Richter et al., 1997). Therefore, in 1990, a program called Indicators of Hydrologic Alterations (IHA) (see Table 2.2) was developed by The Nature Conservancy (TNC) to further study and assess hydrologic alterations within the eco system (Richter et al., 1996, Richter et al., 1997; Mathews and Richter, 2007).

The IHA consists of 33 parameters that can be used to evaluate ecological alteration based and they were recommended due to the ecological importance of said flow parameters. This is shown in Table 2.2 **(**Richter et al., 1997; Richter et al., 1998; Mathews and Richter 2007; Guo et al., 2009).

In fact, Indicators of hydrologic alteration (IHA) has been developed as a software and its use spread in 1996 after a guide on how it operates was described by Richter et al (1996), however, the Nature Conservancy followed up on this program by defining a range to determine when a flow alteration is too much with an approach titled “Range of Variability Approach” and this was incorporated into the IHA software (Richter et al., 1997; Mathews and Richter 2007).

Table 2.2: Summary of hydrological parameters used in Indicators of Hydrologic Alteration, and their characteristics (Richter et al., 1996)

IHA statistics group	*Regime characteristics*	*Hydrologic parameters*
Group 1: Magnitude of monthly water conditions	Magnitude Timing	Mean value for each calendar month
Group 2: Magnitude and duration of annual extreme water conditions	Magnitude Duration	Annual minima 1-day means Annual maxima 1-day means Annual minima 3-day means Annual maxima 3-day means Annual minima 7-day means Annual maxima 7-day means Annual minima 30-day means Annual maxima 30-day means Annual minima 90-day means Annual maxima 90-day means
Group 3: Timing of annual extreme water conditions	Timing	Julian date of each annual 1 day maximum Julian date of each annual 1 day minimum
Group 4: Frequency and duration of high and low pulses	Magnitude Frequency Duration	No. of high pulses each year No. of low pulses each year Mean duration of high pulses within each year Mean duration of low pulses within each year
Group 5: Rate and frequency of water condition changes	Frequency Rate of change	Means of all positive differences Means of all negative differences No. of rises No. of falls

2.7 Mitigation effect of hydropower to Low flow condition

Ordinarily, the lowest flows occur due to snow storage during the winter months while low flow events which occur during the summer, are a result of precipitation deficit and high evaporation (Tallaksen, 2000). Aside from this, there are transition regions which can experience low flow anytime, be it summer or winter (Hisdal et al., 2001), hence, low flow can be experienced in any of these two seasons (Hisdal et al., 2001; Tallaksen, 2000). However, the occurrence of severe low flow considering future increasing demand for water will have a critical impact on the environment. An analysis of historical time series of data therefore provides the necessary information needed to model low flow and understand how to mitigate it (Tallaksen, 2000).

By using Norway as a case study, in Norway, precipitation is experienced as snow during the winter months, and this can go on for as between three months to five months. During this period, runoff is highly reduced and demand for electricity is at its peak (Thaulow et al., 2016). Specifically, depending on counties within Norway, seasonal streamflow fluctuates. For example, it was discovered that the western part of Norway experiences higher precipitation and has steep falls in comparison to the eastern side which has low precipitation and wider valleys (L'Abée-Lund and Villar, 2017).

Regardless, with river regulation, according to Huokuna et al. (2020), hydropower generation modifies the downstream runoff hydrograph. During the winter, the altered hydrograph shows increased flow to counter the higher demand for power. Hence, this undoubtedly increases discharge released to the downstream section and helps to maintain the downstream area and sustain low flow condition. In fact, as found by Rørslett (1989), several rivers had average discharges that were way less than before regulation. Therefore, river regulations can be used to help fish population in rivers. Timing of water releases can help decrease temperature during critical periods, and this can be advantageous for fishes like Salmons (Isaak et al., 2012). IN addition, the spring flood is contained by the reservoir.

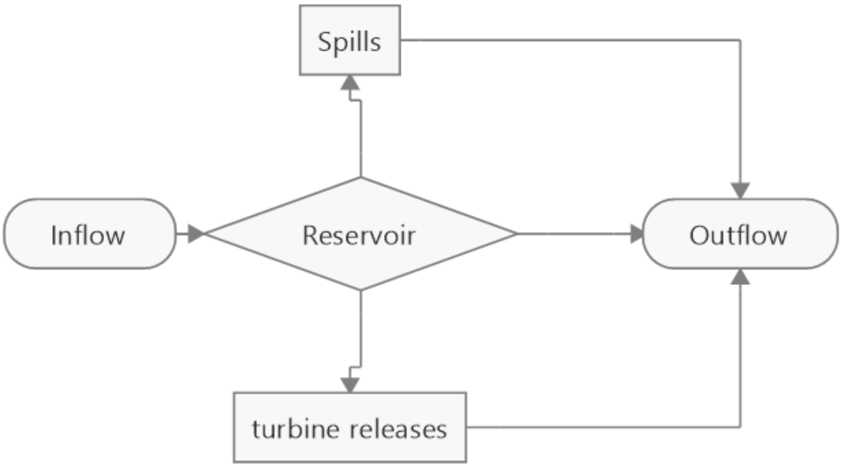


Figure 2.2: A simplified representation of the inflow and outflow in a reservoir (Hecht et al., 2020)

Figure 2.2 is a schematic of how the inflow into a reservoir can be withdrawn to be used in the turbine for hydropower generation and its outflow can ultimately increase flow in the downstream river reach. Therefore, river regulation can be used to mitigate low flows by the release of more water during periods of low flow in addition to storing water, thereby reducing the natural peak flows for later use for power production (Zufelt, 2015).

2.8 Review of modelling tools

Management of water resources is becoming more significant as climate changes and population increases (Akivaga et al., 2010). The use of models to simulate both gauged and ungauged basins is now popular. Models can be used for forecasting, simulating water resource management, evaluation of water quality, erosion and sedimentation, climate change amongst others (Devia et al., 2015).

In addition, hydrological processes are better understood, and their behavior predicted by models (Devia et al., 2015). In fact, as reported by Wheater et al. (2008), a model is a simplified representation of a real-world system and when combined with meteorological data, models can be used to forecast inflow to reservoirs. However, the model has to be calibrated to get the best results out of it.

Calibration of model setup involves optimization of the parameters that potentially have an effect on the model. This is carried out by adjusting these parameters while comparing the simulation results of the observation data inputted till the best fit parameter set is discovered (Beven, 2011). Therefore, an efficient model calibration is one which its simulation results are close to observations from the natural observed processes (Devia et al., 2015). Accurate representative input parameters are however needed for better prediction of hydrological processes which would lead to a more efficient management of water (Sivasubramaniam et al 2020).

2.8.1 Rainfall Runoff Models

Rainfall-runoff modelling is frequently used to assess climate change effects on river runoff (Beven, 2011). They are widely accepted as standard tools for assessing and simulating hydrological processes and these models can be used for flood forecasting and evaluation of water resource management among other things (Devia et al., 2015). The advantage of rainfall-runoff modelling with relation to low flow is that any low flow indices can be calculated by transferring data from gauged catchment to an ungauged one, then calibrating the meteorological inputs (Engeland et al., 2006). The disadvantage is that as the model becomes more complex, there are increasing risk of uncertainties.

However, rainfall-runoff models can be classified into different approaches with varying levels of complexity (Robinson, 2008). As described by Harrison and Whittington (2001), The fundamental approaches to modelling runoff are:

a) **Empirical**

It is necessary in this approach to initiate a connection between the climatic inputs and the corresponding hydrological output.

b) **Conceptual**

In this approach, a depiction of the physical processes is applied to imitate catchments and discharge in the catchment area. Therefore, models for each catchment needs to be calibrated using climatic and streamflow data.

c) **Deterministic**

Deterministic approach is established on complex physical theories. Hence, its examples are mostly spatially distributed in two or three dimensions (Harrison and Whittington, 2001). Accordingly, due to the sensitivity of catchments to climate change, the data considered to be important input parameters in rainfall runoff modelling are precipitation data, temperature data and catchment area (Harrison and Whittington,2001; Devia et al., 2015; Ledesma and Futter 2017).

All the same, the input data gotten from gauging station are subject to different kinds of errors. For precipitation data, the errors can be as a result of wind, evaporation, splash in some gauges or even mechanical and human error (Goodison et al., 1989). Hence, data control has to be used to fill missing data in the observations gotten. Only slight errors are experienced in relation to temperature data, but errors due to thermometer exposure can also occur (Ledesma and Futter 2017).

As a result of all these errors linked to gauges, gridded estimates of weather parameters obtained from meteorological stations can be used as alternatives for simulating rainfall-runoff modelling. As concluded by Ledesma and Futter 2017, gridded datasets fit better and produce better result than the ones measured with on-site instrumental meteorological observation.

Hence, gridded data can be taken as valid alternatives to instrumental datasets for simulating runoff processes when there is inconsistent or unavailable dataset in a region (Ledesma and Futter 2017).

2.8.2 Overview of WEAP

Water Evaluation and Planning System (WEAP) is an initiative of the Stockholm Environment Institute (WEAP.org, 2020). It is a modelling software that can be used to simulate different water demand and supply amongst other processes, and it can be used to assess water resource planning and management issues (Arranz and McCartney, 2007). In fact, according to Yates et al. (2009), WEAP21 can describe the water-related infrastructure and institutional arrangements of a region in a comprehensive, outcome-neutral, model-based planning environment that can identify strategies and help evaluate freshwater ecosystem services.

Therefore, over time, WEAP has been in use for several years for planning of water, while being improved from time to time (Yates et al., 2005). It consistently works by interpreting water supply as the amount of precipitation that drop into a basin and gradually, the supply is reduced through demand for water (Arranz and McCartney, 2007; Yates et al., 2005). WEAP is very user-friendly. Its interface allows simulation time step to be set as desired by the researcher (Arranz and McCartney, 2007; Yates et al., 2005) and it is able to simulate hydrologic processes which can be made to permit assessment and management of water in a river basin (Yates et al., 2005). Hence, it can be used to study the water processes before and after hydrologic alterations as shown in Figure 2.3.

In addition, WEAP can be used to analyze different scenarios after creating a Current Account of the basin being studied. The other scenarios created can therefore be used for assessing alternative assumptions and climate change impact, depending on the researcher (Sieber and Huber-Lee, 2005). Hence, WEAP allows the option of scenarios to answer “what if” questions.

The “what if” questions can be related to:

a. Population growth,
b. Alteration to reservoir operating rules,
c. The potential of Introducing of water conservation,
d. Introducing water recycling program,
e. Climate change alteration,

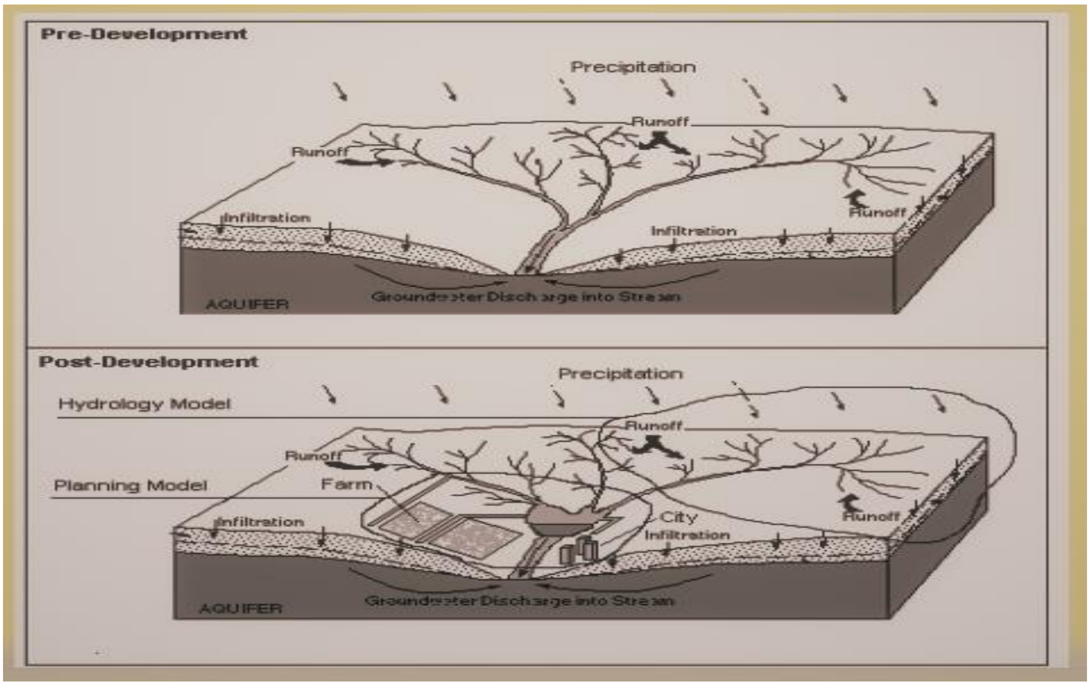


Figure 2.3: Schematic transition in hydrological processes before and after regulation (Yates et al., 2009)

As presented by Yates et al. (2009), Figure 2.3 shows the simple processes before regulation and the complex processes which takes place after regulation.

Nevertheless, it should be noted that WEAP can do a lot more by assessing Urban water management in terms of impact of changes in management of wastewater and storm water (WEAP.org, 2020). WEAP incorporates a link to Parameters Estimation Tool (PEST) which is a free software for Modlel-Independent Parameter Estimation and Uncertainty Analysis. PEST can be used to calibrate more variables in the model setup; hence it reduces calibration time and increases simulation accuracy (Sieber and Huber-Lee, 2005).

2.8.3 Review of ArcGIS

A lot of distributed data, a type of which is topographic data is becoming more accessible in the form of digital Geographical Information System (GIS). In fact, GIS has been an important tool in hydrological modelling. It is known for its functionality and consistence in catchment and stream network delineation using Digital Elevation Model (DEM) of terrains (Maidment and Morehouse, 2002). ArcGIS is a geographic information system that can be used for the creation and modification of maps and management and documentation of geographic information. With ArcGIS, different spatial data can be effectively utilized.

Thus, ArcGIS incorporates ArcMap which is one of its main branches along with ArcGlobe, ArcScene, and ArcCatalog. Their different functions are as described below:

a) ArcMap can be used for map creating, editing, analyzing, and managing two-dimensional maps
b) ArcGlobe can be used for presenting global and large three-dimensional data.
c) ArcScene can be used for editing three-dimensional data
d) ArcCatalog can manipulate and manage GIS data.

According to Khosrowpanah et al. (2007), ArcGIS are primarily used for processing data having spatial component. Spatial data which can either be vector or raster files can be analyzed within ArcCatalog or ArcMap. Hence, ArcCatalog can be used to create and edit spatial data while ArcGIS analyses and processes this data (Khosrowpanah et al., 2007). An example of a map created using ArcMap interface is shown as Figure 2.4 below.

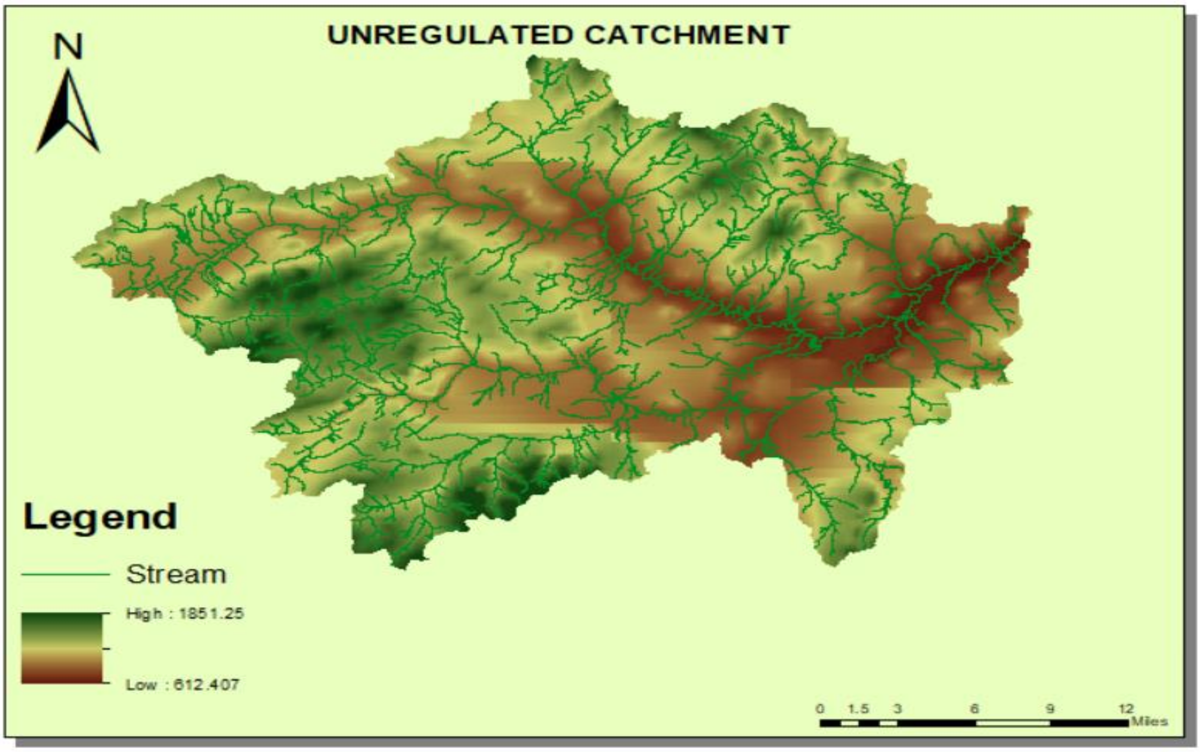


Figure 2.4: A map created using ArcMap

Figure 2.4 presents an illustration of a schematic of river catchment drawn with ArcGIS.

2.9 Related works

As noted by Rolls et al. (2012), low flow condition is known to negatively affect the ecosystem as it reduces the area and depth of aquatic habitat. Hence, literatures in which hydropower has been used to mitigate this effect are listed below:

Table 2.3: List of Reviewed Papers in Relation to Effect of Regulation on Low Flow Condition

Author	Contribution	Result (in Relation to Low Flow)	Country
Huokuna et al. (2020)	Ice in reservoirs and regulated rivers	Using a case study, it was identified that the hydrograph for regulated monthly mean discharge has modified low flow in comparison with hydrograph of unregulated flow.	Canada
Guo et al. (2012)	Effects of the Three Gorges Dam on Yangtze River flow and river interaction with Poyang Lake, China: 2003–2008	Results signifies that that due to impoundment by the Three Gorges dam in October, there was reduced flow ,hence the low flow period wasn't helped but after October , release of water due to hydropower generation helped to increase the outflow in the rivers during the low flow seasons.	China
Rolls et al. (2012)	Mechanistic effects of low-flow hydrology on riverine ecosystems: ecological principles and consequences of alteration. Freshwater Science 31: 1163–1186	Natural periods of low flow can be sustained via flow regulation.	Australia
Zhang et al. (2012)	Has the Three-Gorges Dam made the Poyang Lake wetlands wetter and drier	Irrespective of the adverse effects of the dam construction, the discharge released during the low flow periods are higher	China
McMahon and Finlayson, (2003)	In spite of the fact that the river flow regime has changed to some extent,	In a regulated river, it was noticed that the periods of low flow have higher discharges after regulation and the streamflow during the summer is reduced (Flow regulation reduces the severity of low flow).	Australia

Table 2.3 depicts findings on prior studies in relation to effect of regulation on low flow condition in relation to the author, contribution, result (for low flow) and country.

2.10 Brief Description of other Hydrological Models

2.10.1 MIKE Model

This is a modelling software that is an initiative of Institute for water and Environment (DHI). It is a physically based model which requires a lot of data to accurately model hydrological processes. It incorporates water dynamics and simulation products like MIKE FLOOD, MIKE SHE, MIKE HYDRO River, MIKE HYDRO BASIN and MIKE 21C to make modelling of water resources better (DHI-WE, 2005; Devia et al., 2015).

2.10.2 HBV Model

The Hydrologiska Byråns Vattenbalansavdelning (HBV) model is a lumped conceptual catchment model that is used for simulation of river discharge and water pollution. According to Devia et al (2015), it divides the catchment into sub catchment which are later sub divided into elevations and vegetation zones. HBV has different versions and it is very user friendly.

2.10.3 TOPMODEL

This is a topography based hydrological physical model that surface and groundwater interactions in a water shed. It can determine storage deficit at any location (Beven, 1997; Devia et al., 2015). Hence, this model makes use of Green-Ampt approach in simulating runoff and its result are represented a s hydrograph (Devia et al., 2015).

2.11 Summary

This chapter discuss the background of hydropower and its overview in Norway, mitigation approach to climate change, overview of low flow in rivers, mitigation approach of hydropower to low flow in Norway. Additionally, this chapter present the review of modelling tools, rainfall runoff models, background of WEAP, a review of ArcGIS, related works similar to the current study, and summary.

CHAPTER 3

METHODS AND APPROACH

3.1 Introduction

This chapter introduces the study area, the existing hydropower plants that make use of the river of interest, river Glomma and methods used in model calibration of Folldal, Brandval and Glomma catchments for present and future climate. In addition, this chapter covers the online resources used, the model assessment carried out on Folldal and Brandval sub catchments and the hydrological input data used.

3.2 Study Area

The study area is located in the South eastern part of Norway with its main river tributaries, Atna, Rena and Vorma going across three (3) counties. The basin being studied is a part of River Glomma vassdraget main catchment. River Glomma is well known as the longest and largest river in Norway. It is 460.7km long and historically known in Norway for being a log-floating river. Equally, it is maximized for hydropower production. Hence, it has several run-of-river power plants situated on it. The study area therefore encapsulates River Glomma is 20305km^2 and has a surface runoff of 15.2 l/s*km^2. The project area is however mostly surrounded by forest. It is made up of about 57.2% forest area, 20.5% mountain area (nve.no, 2020). About 40% of the catchment is around 500-1000masl while 30% is above 1000masl (Berge et al., 2008).

Figure 3.1 above depicts the location of the catchment within Norway that will be explored in this thesis. In addition, the catchment area has 0.2% developed land, 9.9% marshland and 3.3% cultivated land (nve.no, 2020). Hence, the annual precipitation around this region is 630mm with the summer precipitation being 343mm and winter being slightly lower at 286mm. Also, the annual temperature experienced around this region is -0.1 °C with summer being about 7.9 °C and winter average temperature being -5.8 °C (nve.no, 2020).

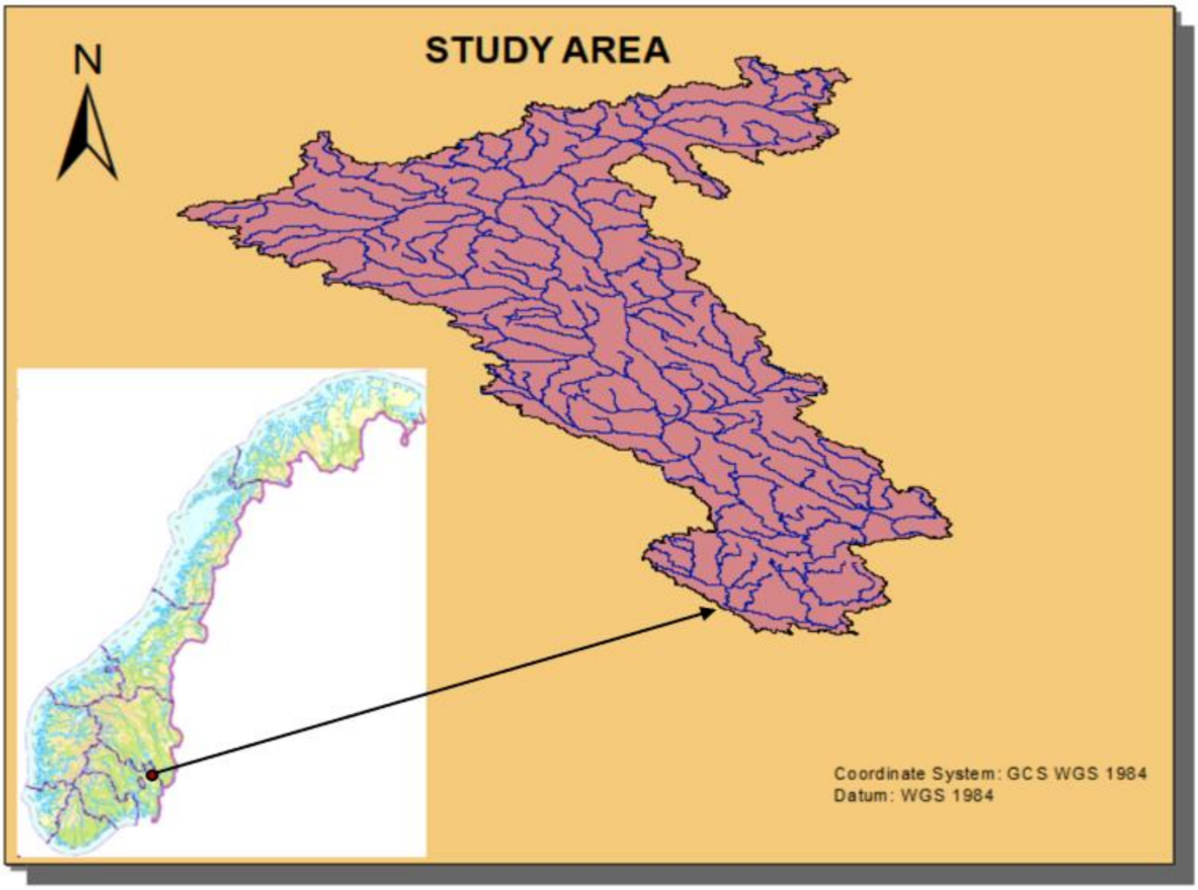


Figure 3.1: Location of study area within Norway

3.3 Existing hydropower stations using River Glomma

The Glomma river is a major source of hydroelectric power supply. It is a heavily regulated river with about 57 hydropower stations (Gooch et al., 2010), a lot of which are Run-of-river power plants. Even so, there are 26 hydropower reservoirs which were made by maximizing natural lakes for power production (Berge et al., 2008; Gooch et al.,2010). Accordingly, as at 2015, it annually generates 138 TWh from all its power stations. Some of the hydropower plants exploiting the river Glomma are listed in Table 3.1 below.

Table 3.1: Some existing power stations utilizing Glomma river (Berge et al., 2008; nve.no, 2020)

Hydropower Stations	**Commission date**	**Installed capacity**	**Annual production**	**Owner**
Skjefstadfoss 1 and 2 powerplants	1910	23.8 MW	139 GWh	E-CO Energi
Storfallet power plant	1915	2.7 MW	8.4 GWh	Kiær Mykleby
Sølna powerplant	1916	5.35 MW	15.7 GWh	Østerdalen kraftproduksjon AS
Kuråsfoss power plant	1952	10.6 MW	62 GWh	Ren Røros Strøm AS
Savalen powerplant	1971	57 MW	166 GWh	Opplandskraft DA
Rendalen powerplant	1971	92 MW	642 GWh	Opplandskraft DA
Strandfossen Powerplant	1971	22.5 MW	154 GWh	E-CO Energi
Løpet powerplant	1971	29 MW	155 GWh	E-CO Energi
Kongsvinger 1 and 2 powerplants	1975	42.7 MW	200 GWh	E-CO Energi
Braskereidfoss powerplant	1978	40 MW	170 GWh	Eidsiva Energi Vannkraft AS
Sæteråa power plant	1998	32KW	100 MWh	
Hofkvern Power Plant	2000	60 KW	275 MWh	Hofkern kraftverk
Glesåa powerplant	2009	2.1 MW	6.7 GWh	Nordre Løsset
Syversætre Foss power plant	2012	2.5 MW	10.5 GWh	Syversætre Foss kraftverk

3.4 The Fishes in River Glomma

River Glomma is extensively used for hydropower generation. Apart from this, it has a good water quality and a neutral pH level which makes it favorable for fish production (Lingsten and Holtan, 1981; Linløkken 1993). Hence, according to Linløkken (1993), river Glomma harbours about 24 fish species in its lower part, even though the fish species reduce with increasing altitude (Hesthagen and Sandlund, 2004). Some of the fishes are graylings, brown trout, whitefish, pike, burbot, perch, bullhead, minnow, ruffe, several cyprinids and smelt. However, the prevalent fishes, native to the River Glomma are known to be brown trout, graylings, minnow, and Siberian sculpin (Hesthagen and Sandlund, 2004).

Therefore, due to the regulation of river Glomma, fish passages had to be constructed so that the fishes will be able to cross from the upstream to the downstream section of the river. Even so, annually, millions of fishes need to migrate to their spawning habitat. In the case of graylings, their spawning migration is recorded by Linløkken (1993) to be between May till early July especially when the water temperature is around 4- 4 8 °C (Hesthagen and Sandlund, 2004; Nygård, 2012). Brown trout, however, migrate around late spring till autumn. But these migrations may be due to unavailability of spawning or nursery ground for the population of mature and immature fishes in the river.

Respectively, in the case of brown trout, their spawning takes place within September and October and as noted by Linløkken (1993), areas with low discharge is not suitable for their spawning and nursery grounds. In addition, when the discharge is very low, the spawning migration and migration speed of Brown trout is affected (Jensen and Aass, 1995). Generally, as stated by Berge et al (2008), In the mountainous area, fish productivity has reduced as a result of water fluctuation. However, in places with stable and increased flow, there is booming fish diversity.

3.5 Online Resources

3.5.1 Høydedata

Høydedata can be used for viewing and downloading digital elevation models in different formats. It can be used to measure distance between two elevations while equally showing the terrain in the region, hence, drawing the elevation profile (nve.no, 2020). It is made available at hoydedata.no.

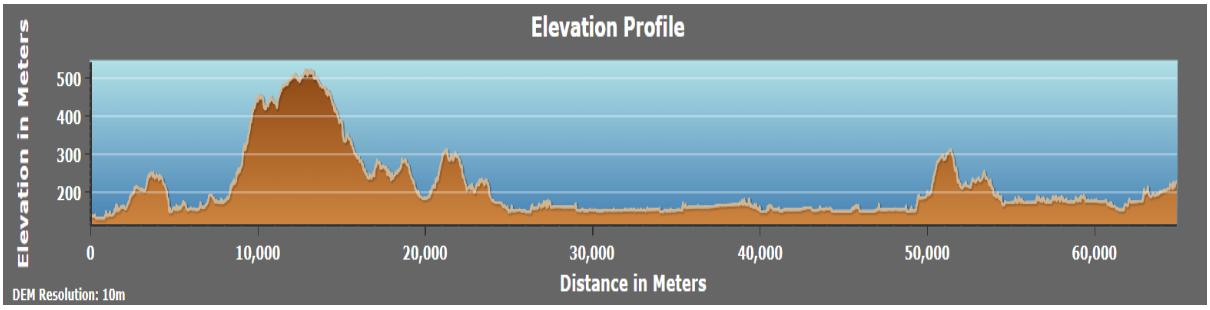
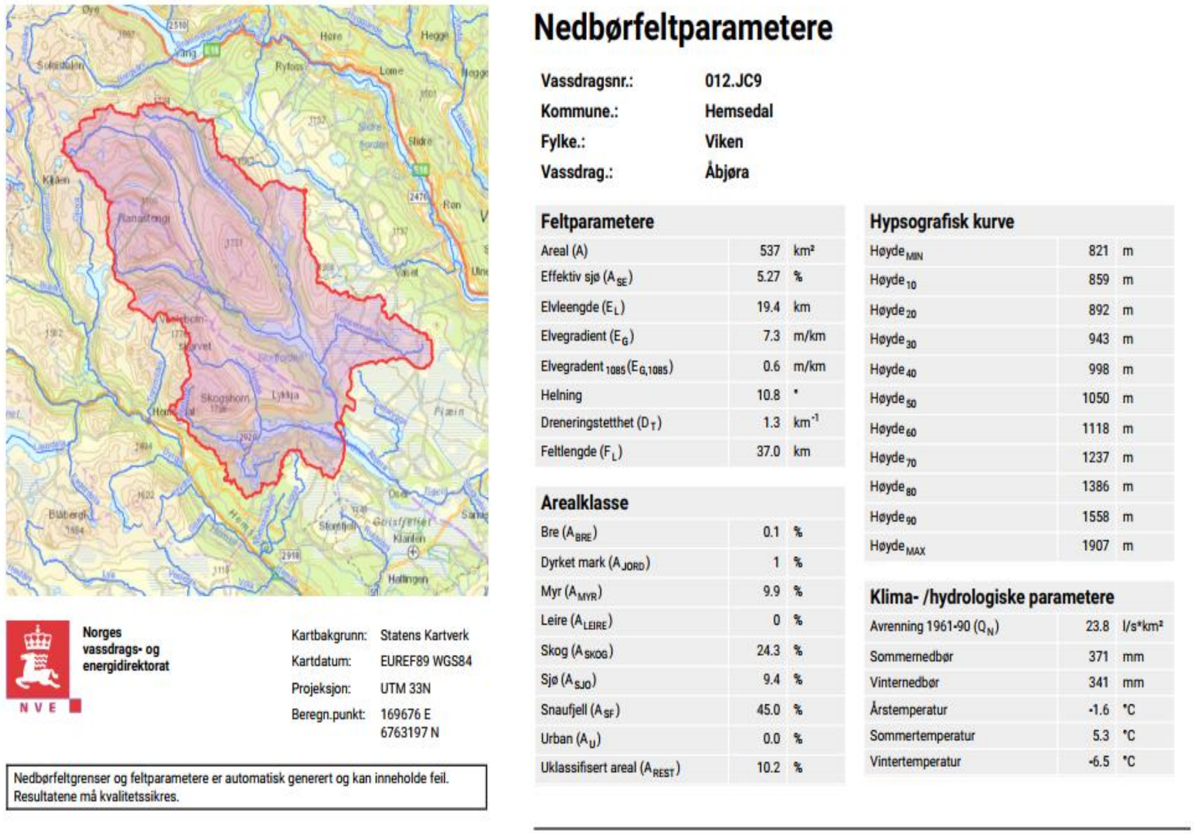


Figure 3.2: Typical example of a report generated using Høydedata

Figure 3.2 shows an example of a report generated using Høydedata showing the elevation profile of an area in southern Norway.

3.5.2 NEVINA

NEVINA is a mapping service which can be used to generate river catchments, calculate precipitation fields, and water flow indices and climate parameters. This tool is available online and its parameters can be used for hydrological calculations (nve.no, 2020). It is made available at nevina.nve.no. An example of a report generated from NEVINA is shown as Figure 3.3



Norges
vassdrags- og
energidirektorat

NVE

Kartbakgrunn:	Statens Kartverk
Kartdatum:	EUREF89 WGS84
Projeksjon:	UTM 33N
Beregn.punkt:	169676 E 6763197 N

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

Nedbørfeltparametere

Vassdragsnr.:	**012.JC9**
Kommune.:	**Hemsedal**
Fylke.:	**Viken**
Vassdrag.:	**Åbjøra**

Feltparametere		
Areal (A)	537	km²
Effektiv sjø (A_{SE})	5.27	%
Elvleengde (E_L)	19.4	km
Elvegradient (E_G)	7.3	m/km
Elvegradent $_{1085}$ ($E_{G,1085}$)	0.6	m/km
Helning	10.8	°
Dreneringstetthet (D_T)	1.3	km^{-1}
Feltlengde (F_L)	37.0	km

Arealklasse		
Bre (A_{BRE})	0.1	%
Dyrket mark (A_{JORD})	1	%
Myr (A_{MYR})	9.9	%
Leire (A_{LEIRE})	0	%
Skog (A_{SKOG})	24.3	%
Sjø (A_{SJO})	9.4	%
Snaufjell (A_{SF})	45.0	%
Urban (A_U)	0.0	%
Uklassifisert areal (A_{REST})	10.2	%

Hypsografisk kurve		
$Høyde_{MIN}$	821	m
$Høyde_{10}$	859	m
$Høyde_{20}$	892	m
$Høyde_{30}$	943	m
$Høyde_{40}$	998	m
$Høyde_{50}$	1050	m
$Høyde_{60}$	1118	m
$Høyde_{70}$	1237	m
$Høyde_{80}$	1386	m
$Høyde_{90}$	1558	m
$Høyde_{MAX}$	1907	m

Klima- /hydrologiske parametere		
Avrenning 1961-90 (Q_N)	23.8	l/s*km²
Sommernedbør	371	mm
Vinternedbør	341	mm
Årstemperatur	-1.6	°C
Sommertemperatur	5.3	°C
Vintertemperatur	-6.5	°C

Figure 3.3: Typical example of a report generated using NEVINA

Figure 3.3 illustrates a sample report of a catchment and its properties as generated by NEVINA.

3.5.3 NVE katalog

In NVE (Norwegian Water Resources and Energy Directorate) map catalog, maps related to waterbodies, data about protection and security, danger hotspots in terms of avalanche, rockslides, flood zones and Energy are made available to the general public. The formats can be selected to be in .dxf, .gbd, .shp , .geojson, .gdd, .gml, .kmz, .sos , hence, the user can choose the one needed for a project. In addition, the coordinates of choice like WGS84, EUREF89, NAD83 or ETRS89 can be chosen (nve.no,2020). This map catalog is made available at kartkatalog.nve.no.

3.5.4 NVE Atlas

NVE Atlas shows most of the thematic map data in Norway and has images gotten from Street view and aerial photograph. Information that can be found on this website include expanded or undeveloped hydropower in Norway and hydrological measuring stations amongst other. It is made available at atlas.nve.no.

3.5.5 Senorge

Senorge is a website where the daily data for snow, water, weather, and climate for Norway are stored. The data is generated based on interpolations of observations gotten from gauges around Norway. It is made available at senorge.no.

3.5.6 Norsk Klimaservicesenter

Norsk Klimaservicesenter (KSS) is a website which helps to stores climatic and hydrological data for research purposes into the impacts of climate change on the environment and the society as a whole. The website is available at Klimaservicesenter.no.

3.6 Selection of Unregulated sub catchments

Since Glomma is a heavily regulated river, two unregulated sub catchments, Brandval and Folldal, were found within it to use for its calibration so as to simulate the natural runoff of Glomma before river regulation. However, due to elevation difference, the two unregulated basins had to be found in the upstream and downstream section of the whole Glomma basin as shown in Figure 3.4. Then they were calibrated, and their parameter setup noted for use in the main Glomma catchment.

3.7 Preparation in ArcGIS

In this thesis, river networks and digital elevation models (DEM) had to be prepared and changed to WGS 84 using ArcGIS. In addition, map preparations and presentation like the one shown in Figure 3.4 was modelled in ArcMap interface of ArcGIS.

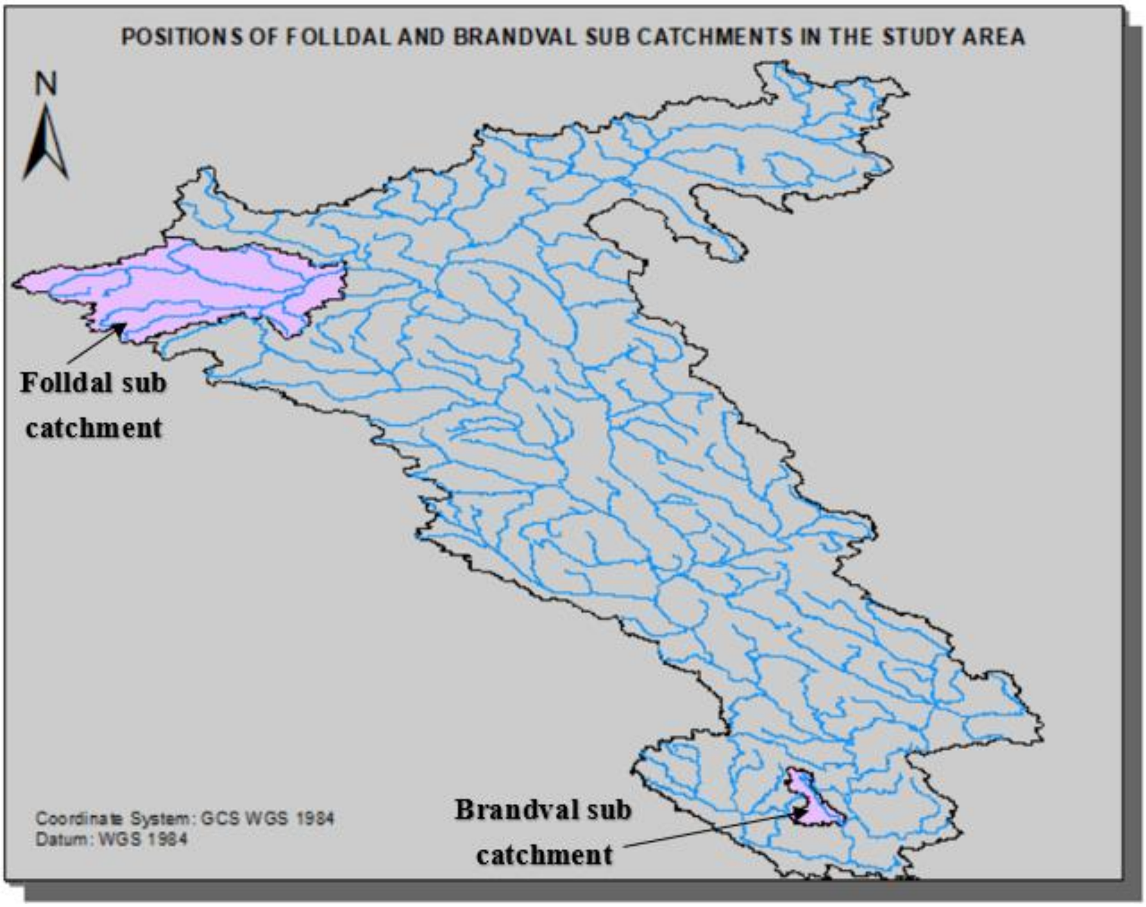


Figure 3.4: Location of the unregulated sub catchments that were used to calibrate unregulated flow in River Glomma

3.7.1 Brandval sub catchment

Brandval sub catchment is located at an elevation of 100-500masl at the downstream side of Glomma catchment. With an area of 110.6km^2 and specific runoff of 11.4 l/s*km^2, the temperature ranges between -3.1 °C in the winter and 11.2 in the summer with the annual temperature being 2.8 °C. Furthermore, the annual precipitation in this region is 665mm (NVE.no). Three major files were gotten for map preparation purposes on ArcGIS and they are:

- Digital elevation model (obtained from høydedata.no).
- Catchment boundary shapefile (obtained from nevina.no).
- River network (obtained from kartkatalog.nve.no).

These were added into ArcGIS to create a map of the catchment area.

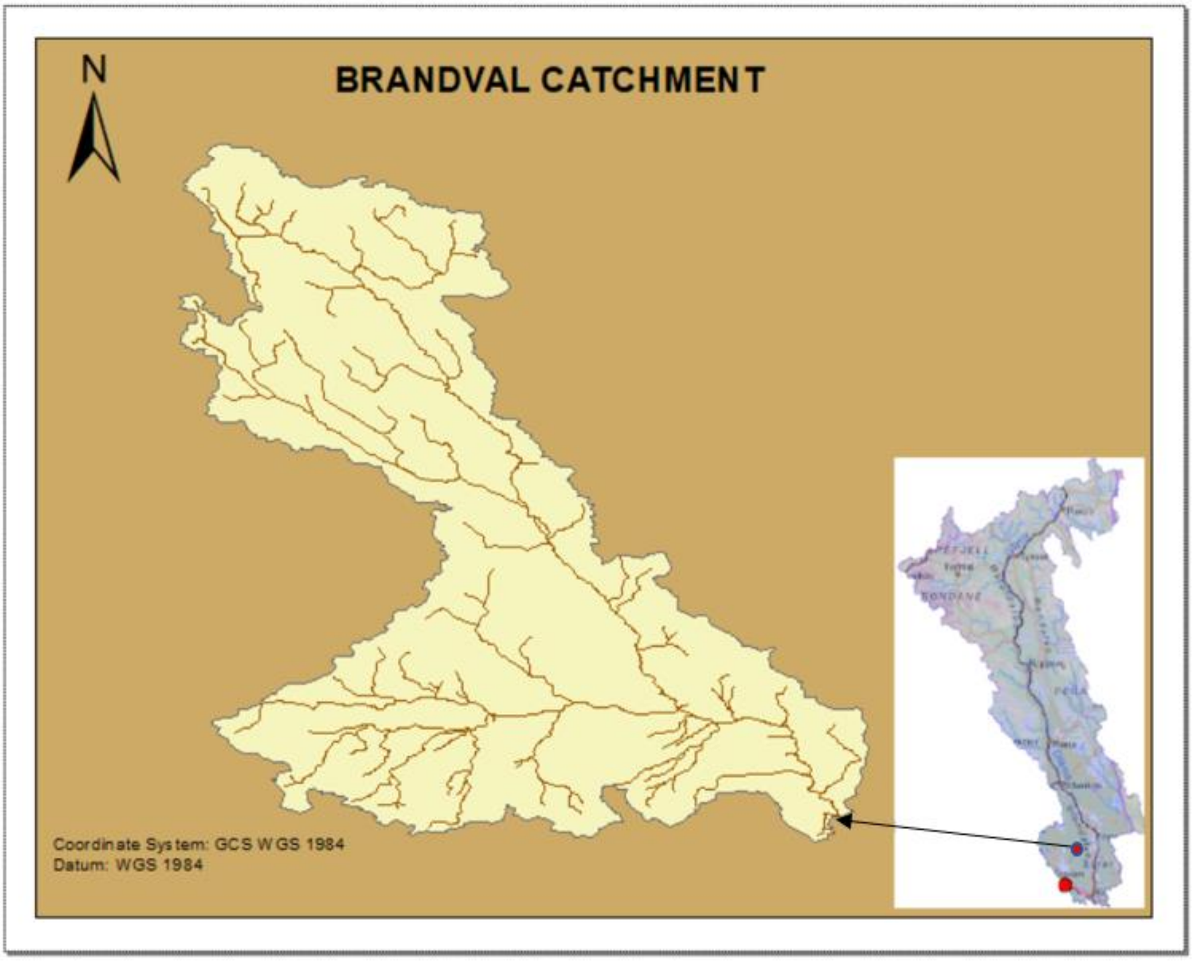


Figure 3.5: Location of Brandval sub catchment relative to River Glomma

Hence, Figure 3.5 is the map generated for Brandval sub basin using ArcGIS.

3.7.2 Folldal sub catchment

Folldal sub catchment has an area of 1367.9km^2 and specific runoff 11.4 l/s*km^2. Its elevation ranges between 617-1851masl. Around this region, the annual precipitation is 578mm with the summer and winter precipitation being 323mm and 255mm, respectively. Also, the annual temperature in this region is -1.9 °C while the summer and winter 5.1 °C and -6.9 °C, respectively. Hence, Folldal catchment is presented in Figure 3.6.

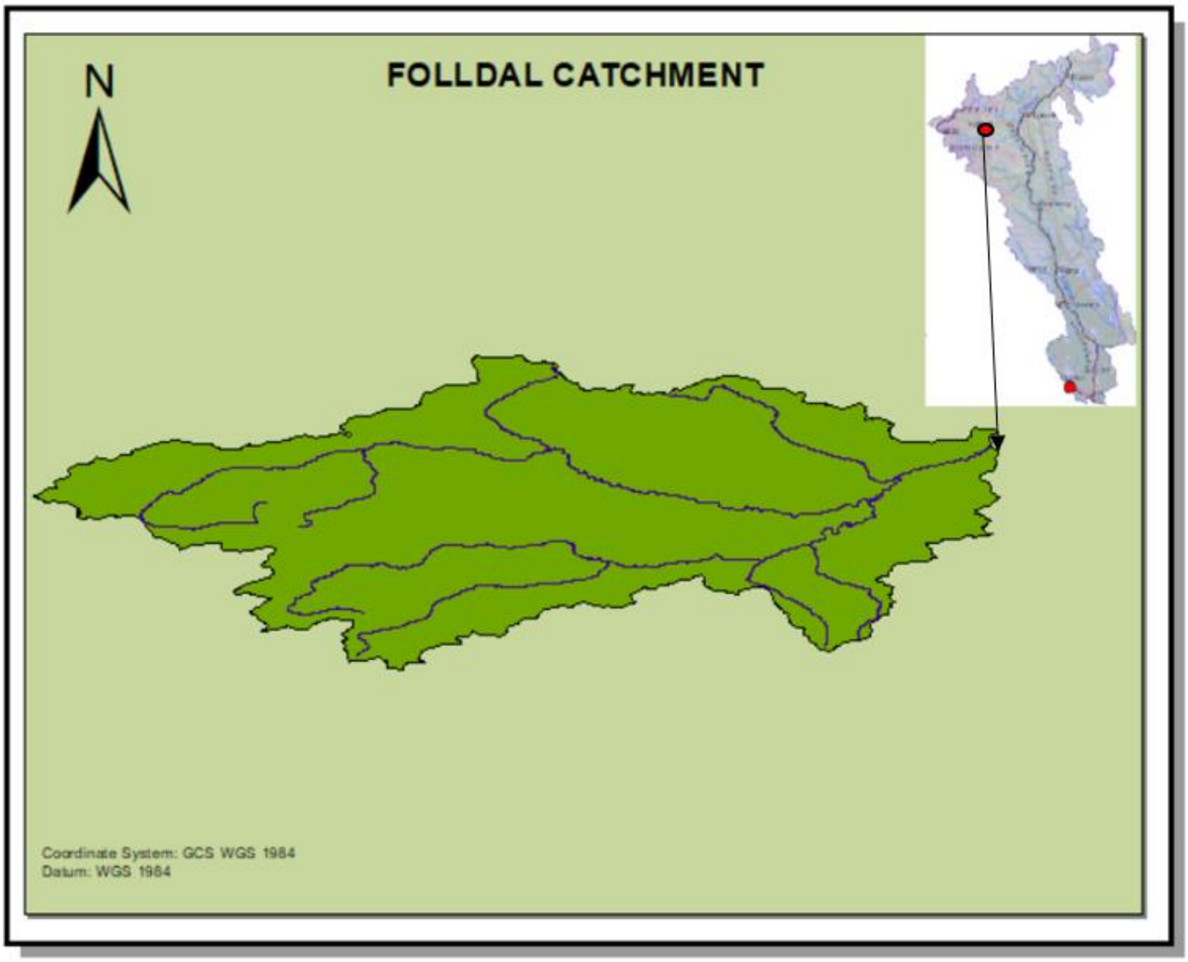


Figure 3.6: Location of Folldal sub catchment relative to River Glomma

Figure 3.6 is the map created for Folldal sub basin using ArcGIS.

3.8 Hydrological Input data

Data is important in hydrology. In this study, the role of reservoir in sustaining low flow was assessed for both present and future climate. Time series of data from 1st January 2009 till 13th February 2020 was obtained to simulate present climate condition. To work on future climate, two time periods were considered, and they are 1st January 2040 till 31st February 2051 and 1st January 2080 till 31st February 2091, respectively.

3.8.1. Precipitation data

For this study, gridded daily precipitation data from 1st January 2009 till 13th February 2020 were obtained from senorge.no to simulate present climate. However, all precipitation data were gotten for all catchments except for Brandval sub catchment which used an on-site meteorological observation data. Hence, the precipitation data was prepared as .csv files so as to be used in WEAP model. Figure 3.7 shows a typical sample of the precipitation data used in this thesis.

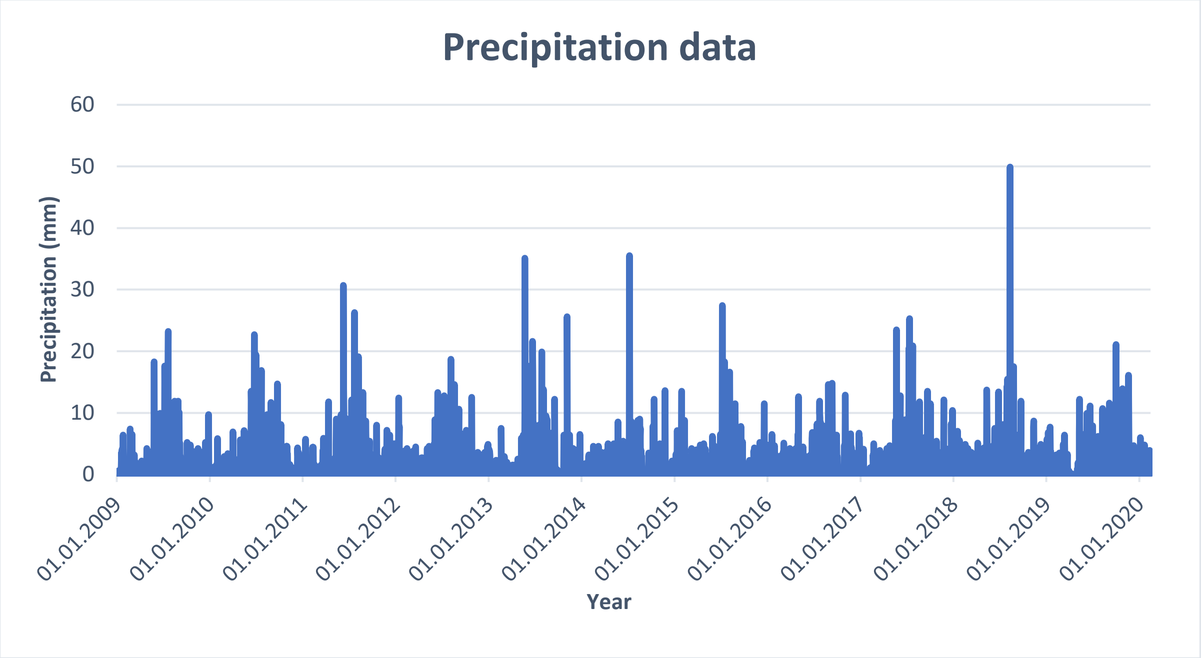


Figure 3.7: Sample of gridded precipitation data gotten from senorge.no

For the future climate, the data used in bias correction so as to be able to simulate future climate was obtained from klimaservicesenter.no (2020). Hence, for the purpose of this study, climate projections for Norway with the emission scenario RCP 8.5 was considered and data for separate seasons were retrieved for the study area. Two different time periods 2040 to 2051 and 2080 to 2091 were considered and the climate index for the precipitation is as shown in Table 3.2.

Table 3.2: RCP 8.5 climatic index obtained for climatic projection of precipitation (klimaservicesenter.no)

Seasons	**Time period**		**Unit**
	2040-2051	**2080-2091**	
Summer	1.02	1.05	Percentage
Winter	1.05	1.25	Percentage
Spring	1.2	1.3	Percentage
Autumn	1.1	1.15	Percentage

As earlier discussed in Section 2.4.1.1, **t**here are different methods that can be applied so as to correct systematic bias in raw climate model output. However, for the purpose of this thesis, delta change approach was used. The future precipitation projection was calculated using a multiplicative correction as shown in Equation 2

$$\Delta P = \frac{Pfuture - Pcurrent}{Pcurrent} + 1 \text{……………………………………………………………} \text{Eqn (2)}$$

Therefore

$$P_{future} = \Delta P * P_{current} \text{……………………………………………………………...} \text{Eqn(3)}$$

Where,

ΔP represents the climate index

P_{future} represents the future precipitation

$P_{current}$ represents the current precapitation

Accordingly, the precipitation data obtained for the 2009-2020 time period which represents the present climate was bias corrected and modified using delta change approach and the climate index in Table 3.2, to derive precipitation time series of data for 2040-2051 and 2080-2091 time period.

3.8.2. Temperature data

The temperature data used for this study was obtained from senorge.no and were based on interpolated weather observations. Brandval catchment was however an exception in this case as it used an on-site observation data. These files were equally prepared in Excel as .csv files so as to be easily used in WEAP model. Figure 3.8 shows a sample of the temperature data.

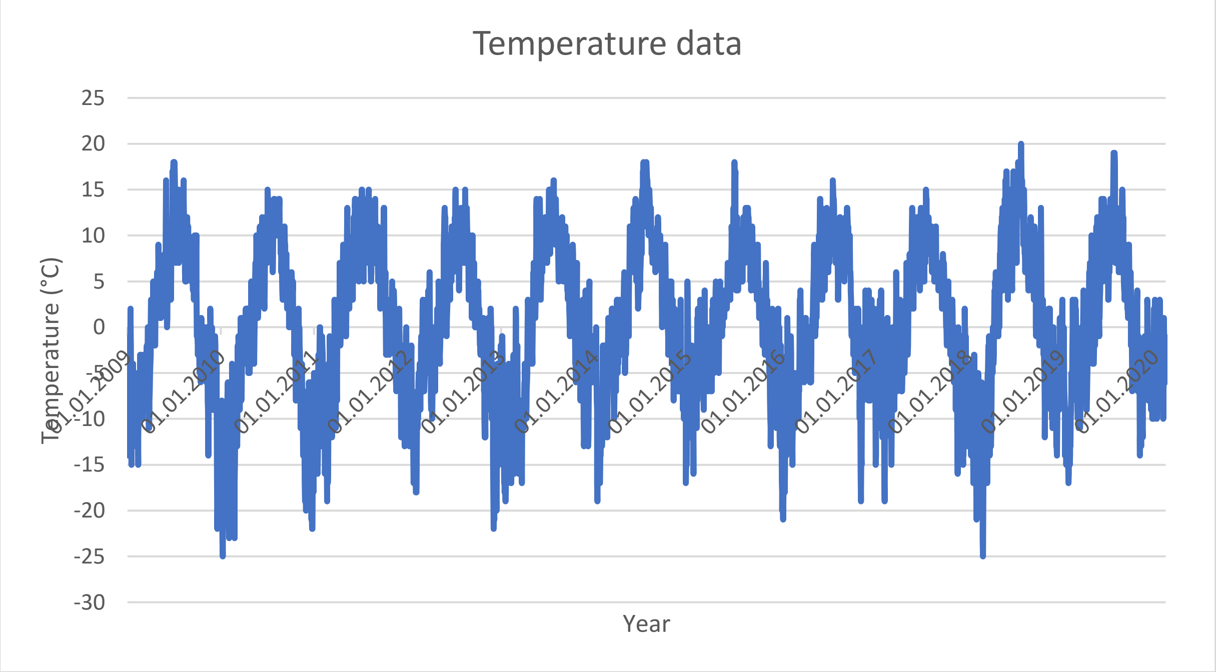


Figure 3.8: Sample of gridded precipitation data gotten from senorge.no

Temperature data to be used for climatic projection for time periods 2040-2051 and 2080-2091 as obtained from klimaservicesenter.no (2020) is as shown in Table 3.3.

Table 3.3: RCP 8.5 climatic index obtained for climatic projection of Temperature (klimaservicesenter.no)

Seasons	**Time period**		**Unit**
	2040-2051	**2080-2091**	
Summer	2	3	Degree
Winter	3	5	Degree
Spring	3	4	Degree
Autumn	3	3	Degree

Additionally, the temperature data obtained for the 2009-2020 time period which represents the present climate was bias corrected using the delta change approach of additive correction for temperature change as shown in Equation 4

$T_{future} = T_{current} + \Delta T$……………………………………………………………………Eqn(4)

Where

ΔT represents the climate index

T_{future} represents the future projected temperature

$T_{current}$ represents the current temperature

Accordingly, the current temperature data was bias corrected and modified using delta change method which incorporated the climatic index in Table 3.3 to derive time series of data for 2040-2051 and 2080-2091 time period.

3.8.3. Streamflow data.

For the streamflow data to be obtained, the names of its gauging stations were noted and sent to the hydrology department of Norwegian Water Resources and Energy Directorate (NVE). After which the obtained data was prepared in Excel as .csv files for WEAP model use. Figure 3.9 shows a sample discharge data.

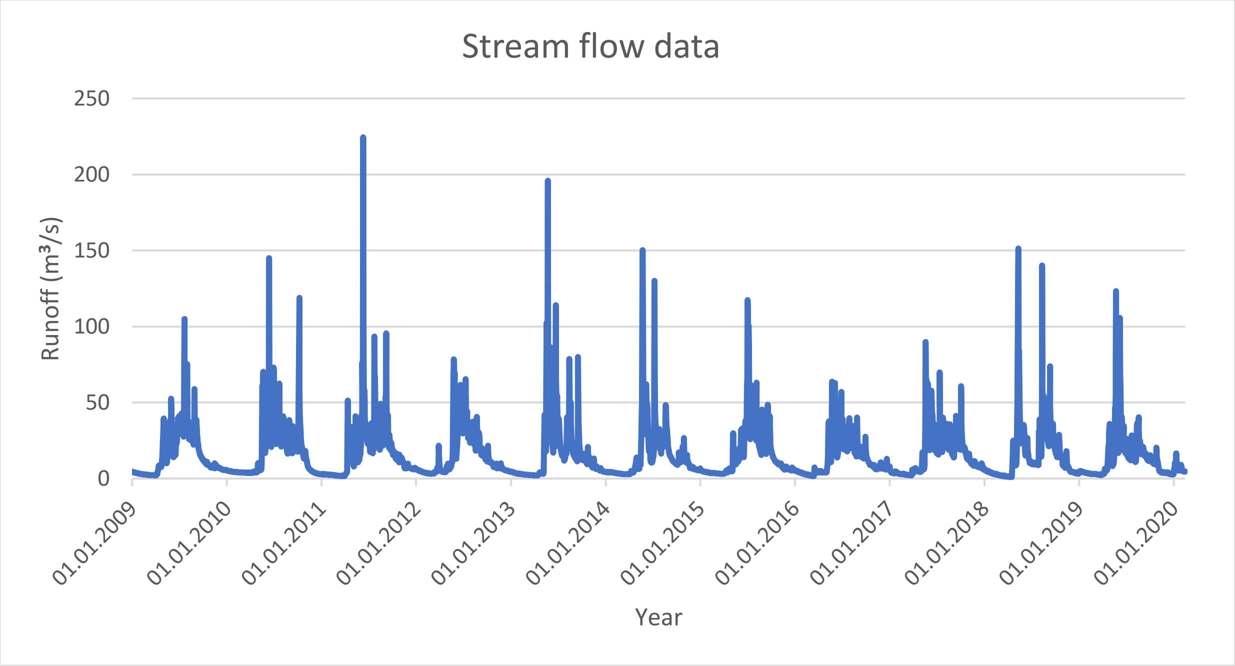


Figure 3.9: Sample of gridded precipitation data gotten from sernorge.no

3.8.3.1 Scaling

Scaling of data is used for predicting discharge in an ungauged river basin. Similarity is an important guide used for comparing ungauged with gauged catchment (Sivasubramaniam et al., 2020). Hence, the catchments can be compared using the

- area
- elevation distribution
- specific runoff
- land use type etc.

After which the formula is used to calculate the streamflow in the ungauged catchment

$$Qbrandval = \frac{Fbrandval*Abrandval}{Fk*Ak} Qk \quad \text{……………………………...………Eqn (5)}$$

Where

Qu represents unknown discharge gauge

Qk represents discharge from the known gauge in m^3/s

Fu represents the Specific runoff of brandval catchment in $l/s*km^2$

Au represents catchment area for brandval catchment

Fk represents the Specific runoff at the gauge station

Au represents catchment area of the gauge station

However, for the brandval sub catchment, there were two gauges which were close to it. The positions of the gauges relative to Brandval sub catchment is shown in Figure 3.10.

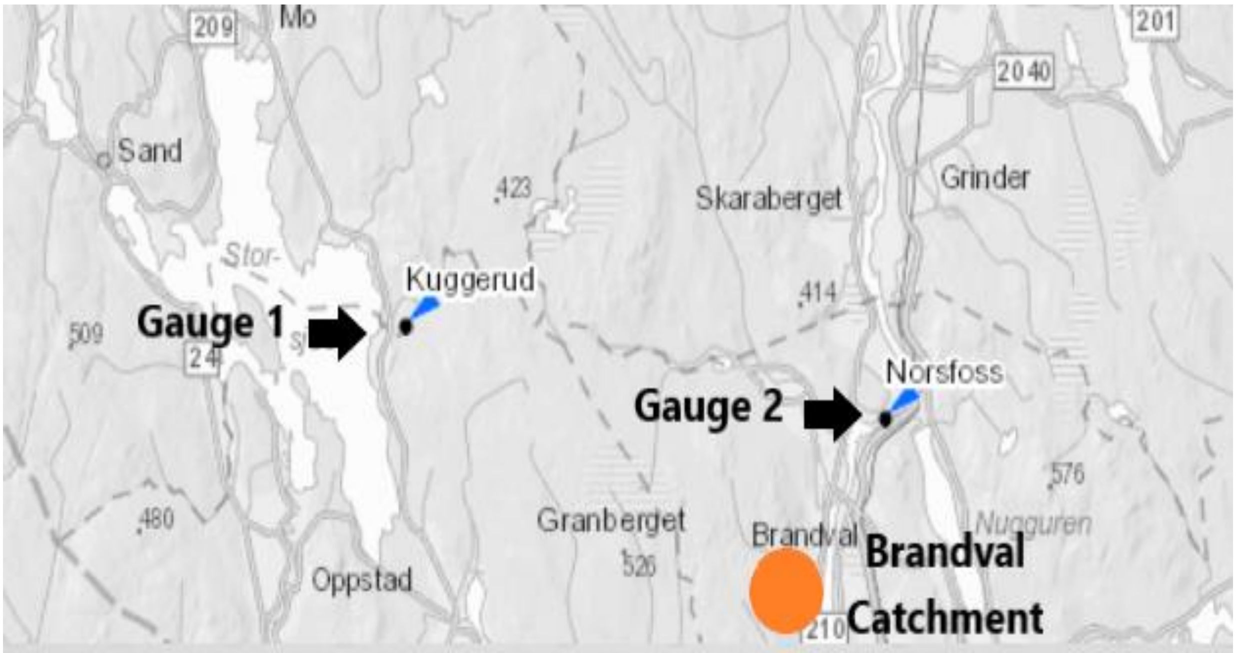


Figure 3.10: Location of the gauges around Brandval catchment

Hence, these two gauges were compared with brandval as shown in the Table 3.4.

Table 3.4: Information of the Gauging stations in relation to Brandval sub catchment

Gauging stations	**Area(km^2)**	**Specific runoff (l/s*km^2)**	**Elevation (m.a.s.l)**
Kuggerud (Gauge 1)	48.2	15	175
Norfoss (Gauge 2)	18934	15.5	220
Unknown Catchment			
Brandval	110.6	11.4	190

After comparison using the catchment area, the specific runoff, and the elevation difference, Kuggerud gauge (Gauge 1) was used to scale brandval catchment by using the formula in Equation 8.

$Qbrandval = \frac{Fbrandval*Abrandval}{Fkuggerud*Akuggerud} Qkuggerud$……………………………..………Eqn (6)

$Qbrandval = \frac{11.4*110.6}{15*48.2} Qkuggerud$ ……………………………………….....…….Eqn (7)

$Qbrandval = 1.7439 * \ Qkuggerud$……………………………………….....….... Eqn (8)

Hence, the scaling factor that was used to scale the brandval runoff is 1.7439

3.9 Model calibration

In WEAP, the calculation method to be used for simulating runoff has to be chosen. WEAP makes these methods available:

- Rainfall runoff (simplified coefficient method)
- Irrigation Demands only (simplified coefficient method)
- Rainfall runoff (Soil Moisture Method)
- MABIA method (dual KC, daily)
- Plant growth (daily; CO_2, water, and temperature stress effects)

However, for the purpose of this study, the Rainfall runoff (Soil Moisture Method) was chosen and only its land use and climate section were considered. The soil moisture method in WEAP combines equations and conceptual diagrams as described in Figure 3.11.

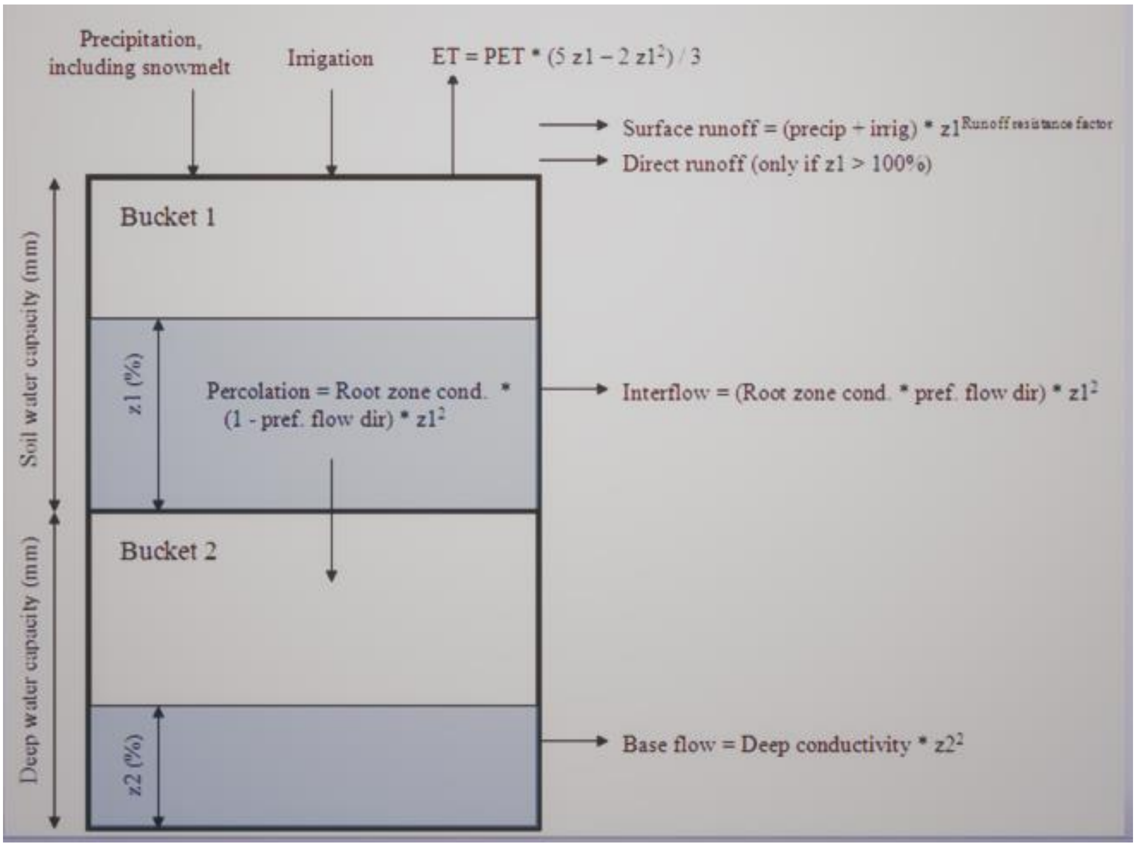


Figure 3.11: Conceptual diagram and equations in Soil moisture method in WEAP (Sieber and Purkey, 2015)

The soil moisture method incorporates snow module which can be used while simulating the effect of snow on the catchment. WEAP recommends the use of latent heat of fusion (334 kj/kg) for the snow melt. However, for this study, it was discovered that latent heat of vaporization (2260kj/kg at 100°C) simulated a better result.

Furthermore, WEAP incorporates parameter estimation tool (PEST) which makes simulation a bit less tedious while reducing time spent on manual calibration. PEST is an automatic estimation tool which compares the historical observations with simulation output while adjusting model parameters to improve its accuracy (weap21.org).

Hence, the basic parameters set for the purpose of this study is listed as:

- For the monthly demand variation, all branches within a demand site should have the same variation
- All branches within a catchment can have different climate data
- The snow melt in the soil moisture method should use latent heat of vaporization.
- The lowest allowed demand priority is 99

Therefore, to accurately model the hydrology of a river basin according to Harrison and Whittington (2001), a number of key steps is involved:

a) A river basin was chosen, and in this case, River Glomma was selected.
b) Meteorological data like Precipitation and Temperature data were given. Also, Streamflow data was gotten from specific gauges in the river catchment.
c) Then the rainfall – runoff processes were modelled and calibrated

3.9.1 Model setup in WEAP

For the purpose of this thesis, two sub basins, Folldal and Brandval had to be calibrated so as to properly represent the upstream and downstream flow condition of Glomma basin as seen in Figure 3.4. These two sub basins were used to eventually calibrate the natural flow conditions in river Glomma before hydropower regulation. Hence, it was ensured that Folldal and Brandval catchments are not being used for hydropower production. Subsequently, the two sub basins were calibrated, and the parameter sets obtained were transferred into the sub basins that Glomma was divided into.

3.9.1.1 Folldal sub catchment

The stream network and shapefiles for the Folldal basin was obtained from the Norwegian map catalog kartkatalog.nve.no in the Geographic coordinate system WGS84 so as to be readable in WEAP. This was then incorporated into WEAP with the years and timesteps set according to the years of data being used. The unit and basic parameters were also set appropriately. Since WEAP does not recognize any imported stream network, the mainstream in the Folldal basin had to be redrawn in WEAP with its runoff/infiltration line indicated as presented in Figure 3.12.

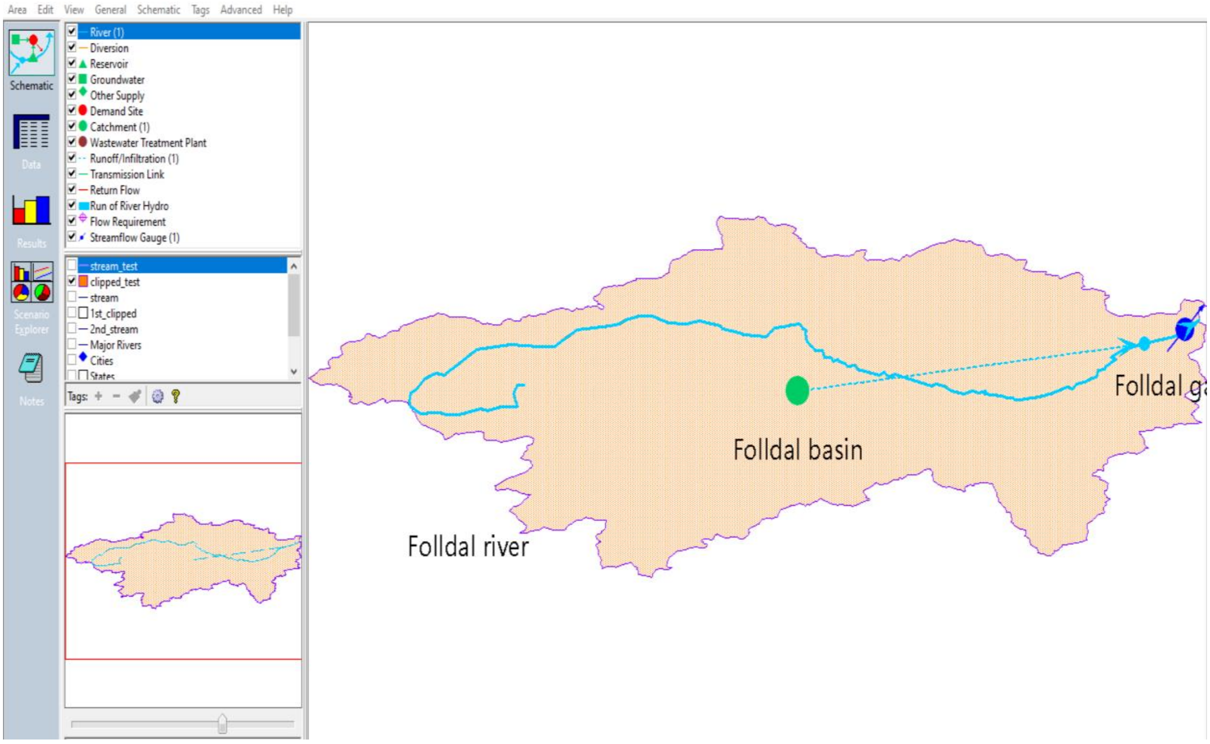


Figure 3.12: WEAP setup of Folldal unregulated catchment

In addition, after the placement of the streamflow gauge, stream flow data was keyed in appropriately to simulate the runoff in said catchment. The temperature and precipitation data were read in from a file into the Climate section of the Soil Moisture method.

The model parameters were set with PEST used to improve the accuracy of the parameters. Hence, the optimized parameters are listed in Table 3.5.

Table 3.5: Calibrated parameters in Folldal

Model parameters	Calibrated parameters	Unit
Area	1367.9	km²
Kc (crop coefficient)	0.5	-
Soil water capacity	101.6	mm
Deep water capacity	99.5	mm
Runoff resistance factor	2	-
Root zone conductivity	12	mm/day
Deep conductivity	8.4	mm/day
Melting point	1.2	°C
Freezing point	-0.7	°C
Preferred flow direction	0.4	-
Initial Z1	30	%
Initial Z2	30	%
Humidity	32.9	%
Cloud fraction	6.4E-6	-
Wind	2	m/s
Initial snow	50	mm
Latitude	62	-

3.9.1.2 Brandval sub catchment

Just like the Folldal sub catchment, brandval was set with similar unit and basic parameters. Then the precipitation, temperature and runoff data scaled from Kuggerud gauge were inputted in WEAP. In addition, the catchment shape file of Brandval basin and stream network were inputted into WEAP basin as shown in Figure 3.13

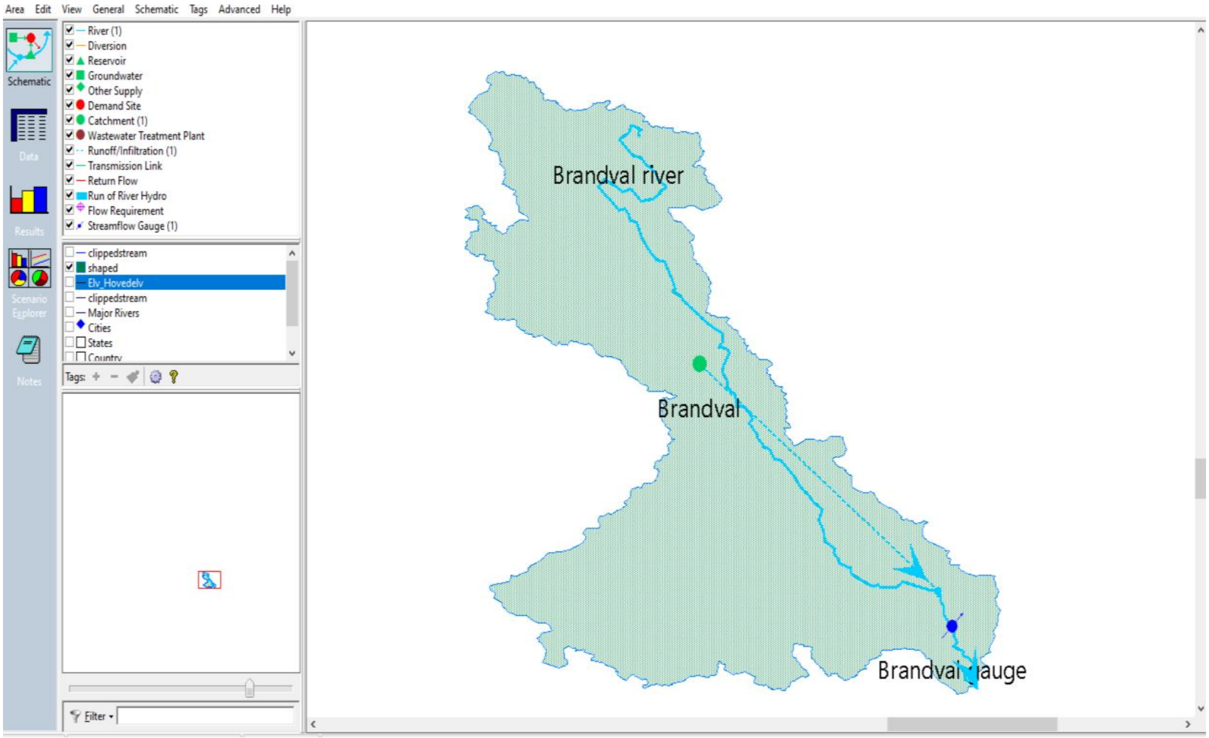
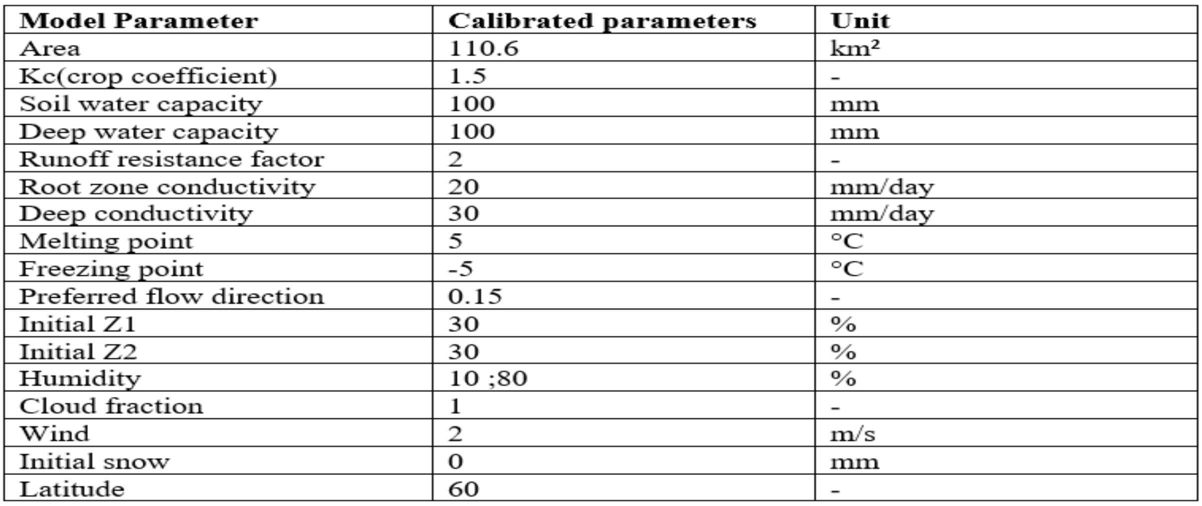


Figure 3.13: WEAP setup of Brandval catchment

Afterwards, Brandval model parameters were calibrated using the software package for Model-Independent Parameter Estimation and Uncertainty Analysis (PEST). The updated parameters are as presented in Table 3.6.

Table 3.6: Calibrated parameters in Brandval



Model Parameter	Calibrated parameters	Unit
Area	110.6	km²
Kc(crop coefficient)	1.5	-
Soil water capacity	100	mm
Deep water capacity	100	mm
Runoff resistance factor	2	-
Root zone conductivity	20	mm/day
Deep conductivity	30	mm/day
Melting point	5	°C
Freezing point	-5	°C
Preferred flow direction	0.15	-
Initial Z1	30	%
Initial Z2	30	%
Humidity	10 ;80	%
Cloud fraction	1	-
Wind	2	m/s
Initial snow	0	mm
Latitude	60	-

Some of the model parameters in Figure 3.5 and 3.6, are duly explained below.

- **Kc** refers to the crop coefficient for each land cover (Sieber, 2006).
- **Runoff resistance factor (RRF)** affects the runoff in a river. The higher RRF, the lesser the surface runoff (Sithiengtham,2019).
- **Z1 and Z2** are the estimates of the root zone saturated conductivity of the upper and lower storage (Sieber, 2006).
- **Deep percolation**: This controls the transmission of the water to a water body as baseflow or to ground water storage (Sieber, 2006; Sithiengtham,2019).
- **Deep conductivity:** According to Sithiengtham (2019), this refers to the capacity of the water to be baseflow and it remains unchanged no matter the land cover type. However, as deep conductivity increases, baseflow increases.
- **Preferred flow direction:** this regulates the path of the water from the root zone layer. Hence, it determines if the water percolates to the interflow or groundwater (Sithiengtham,2019).
- **Root zone conductivity:** This controls the transmission of the water which will be partitioned according to preferred flow direction (Sieber, 2006).

3.9.1.3 Glomma Basin

a) Simulation of pre regulation streamflow in Glomma river with respect to present climate.

To simulate the condition of low flow within the Glomma basin before hydropower regulation, the basin was separated into smaller basins as shown in the Figure 3.14 below

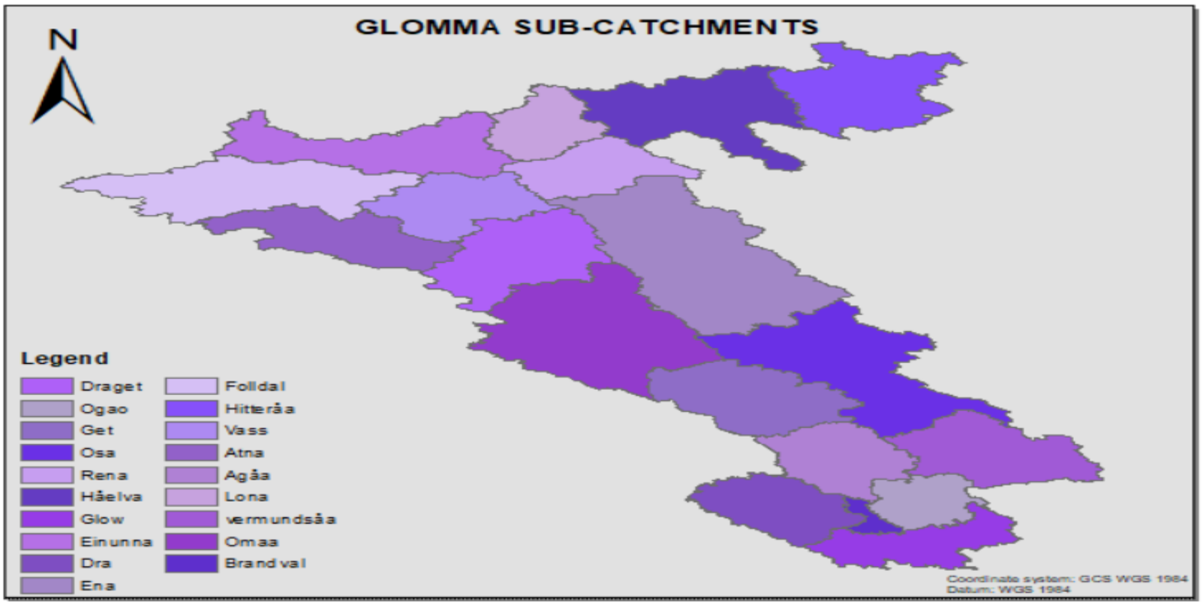


Figure 3.14: Glomma catchment showing the sub-catchments

Afterwards, the stream network and shapefiles for Glomma basin was obtained from kartkatalog.nve.no in the Geographic coordinate system WGS84 for adaptation into WEAP and the model was setup as presented in Figure 3.15.

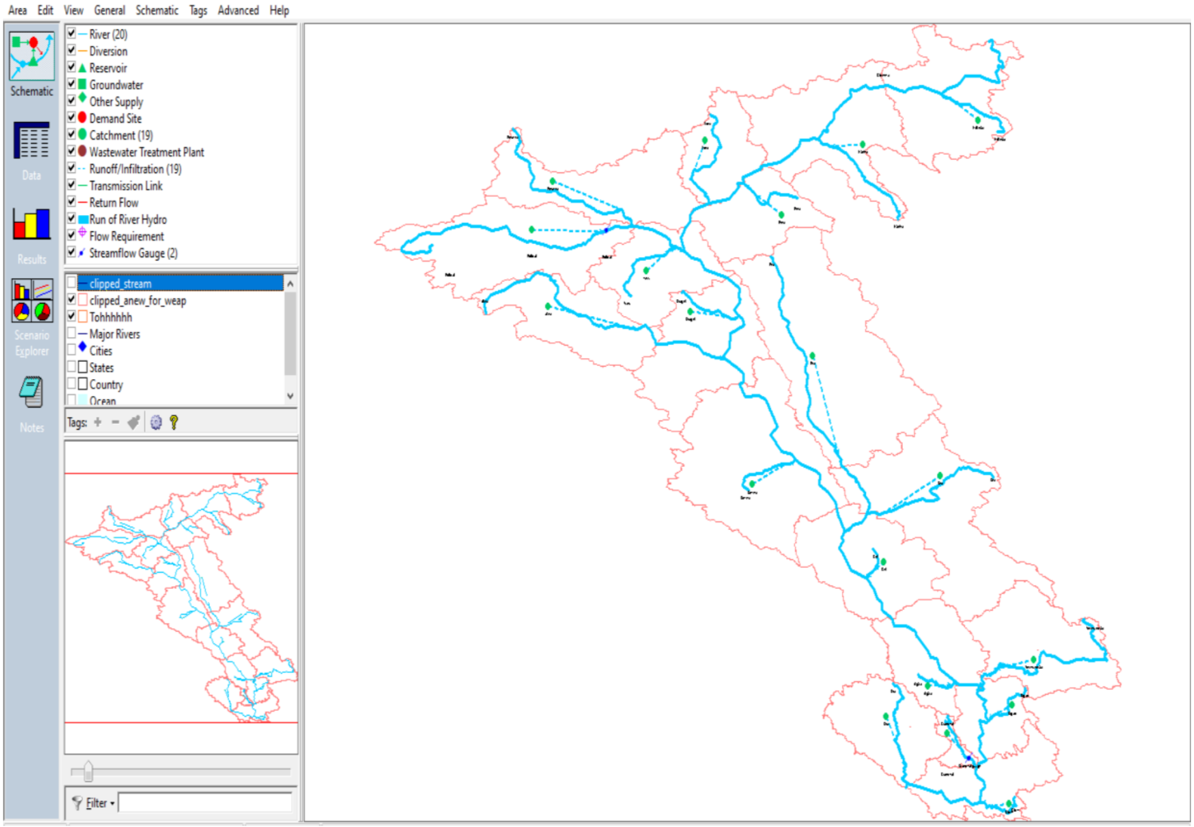


Figure 3.15: WEAP set up of Glomma catchment showing the sub-catchments for unregulated runoff simulation

Then, the calibrated parameters from both Brandval and Folldal catchments were transferred into the smaller catchments which Glomma basin was divided into as represented in Table 3.7. The observations generated from interpolated weather observations were gotten for each of the sub-catchments from senorge.no. It should be noted that only the two gauges Brandval and Folldal were used to model the unregulated discharge.

Table 3.7: Information about the sub-catchment and the choice of sub basin selected for its calibration

River basins	Area(km^2)	Elevation range (m.a.s.l)	Latitude(°)	Parameters used for calibration
Ena	2375.2	566-1071	61.8	Folldal
Osa	1071.3	498-809	61.1	Brandval
Omma	1957.0	957-1232	62.0	Folldal
Rena	686.3	1000-1300	62.2	Folldal
Einunna	1129.8	1211-1676	62.3	Folldal
Atna	913.6	1203-1608	61.8	Folldal
Vass	817.9	1193-1518	61.9	Folldal
Brandval	110.6	149-548	60.0	Brandval
Folldal	1367.9	617-1851	62.0	Folldal
Hitteråa	1115.3	900-1000	62.6	Folldal
Håelva	1301.7	1000-1543	62.5	Folldal
Lona	581.0	1000-1435	62.5	Folldal
Dra	813.6	423-642	60.4	Brandval
Glow	743.8	228-465	60.2	Brandval
Ogao	513.9	200-414	60.4	Brandval
Vermundsåa	1064.7	434-648	60.7	Brandval
Draget	1147.3	1029-1435	61.5	Folldal
Get	1099.6	374-852	60.9	Brandval
Agåa	820.9	458-633	60.6	Brandval

b) Simulation of post regulation streamflow in Glomma river with respect to present climate.

To model the regulated discharge from Glomma river, the stream flow gauges around the Glomma catchment were noted and their discharge data obtained from the hydrology department of the Norwegian Water Resources and Energy Directorate (NVE). These gauging stations were added to the WEAP model and their discharge data added appropriately. The model setup is presented as Figure 3.16.

c) Glomma basin with regulation considering Future climate

So as to assess the effect of climate change under future climate, climate change scenarios were created in WEAP for both year 2040-2051 and year 2080-2091 time span using the Scenario functionality in WEAP. Using the data from 2009-2020 as the reference, the new scenarios were titled **climate change '40** to represent the future climate projection 2040-2051 and **climate change "80** to represent the future climate projection 2080-2091 as shown in Figure 3.17.

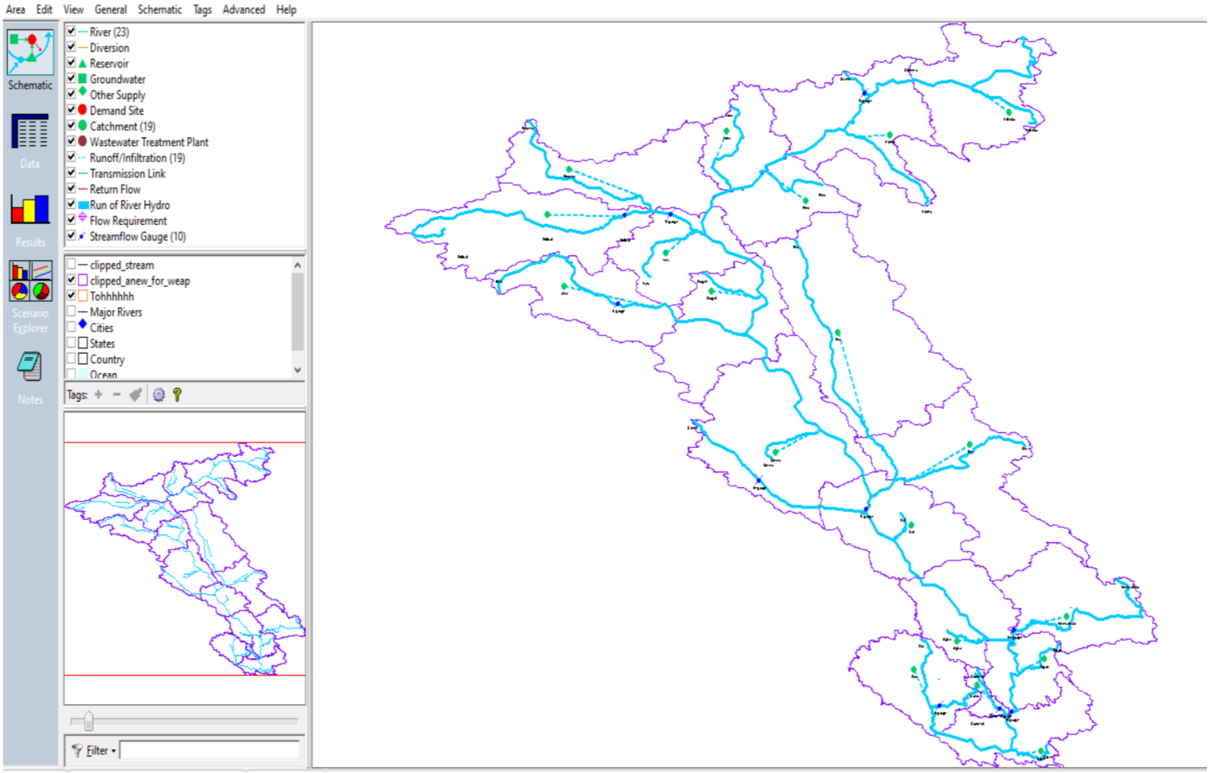


Figure 3.16: WEAP set up of Glomma catchment showing the sub-catchments for regulated runoff simulation

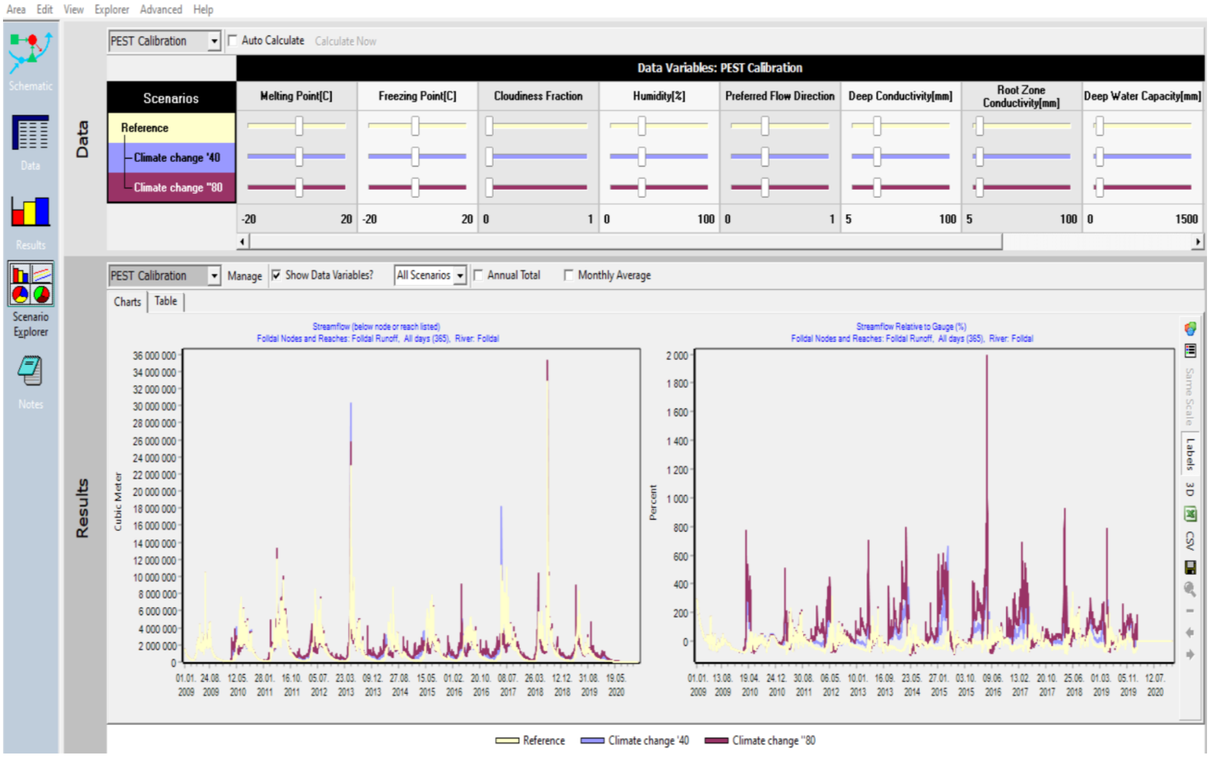


Figure 3.17: WEAP set up of Climate change scenarios

3.10 Use of Indicators of Hydrologic Alteration (IHA) for Statistical Analysis.

For the purpose of this thesis, the 1st three (3) groups are considered in the IHA Statistical group as they relate to low flow condition. For each group, few things were considered. Table 3.8 below shows the hydrologic parameters that would be calculated in this thesis.

Table 3.8: Indicators proposed by Richter et al (1996)

IHA statistics group	Regime characteristics	Hydrologic parameters
Group 1: Magnitude of monthly water conditions	Magnitude Timing	Mean value for each calendar month
Group 2: Magnitude and duration of annual extreme water conditions	Magnitude Duration	Annual minima 1-day means Annual minima 3-day means Annual minima 7-day means Annual minima 30-day means
Group 3: Timing of extreme water conditions	Timing	Julian date of each 1 day minimum

3.11 Model Performance Assessment

WEAP has incorporated the use of PEST to give a faster and easier calibration (WEAP.org, 2020). However, the quality of the simulated model has to be assessed. Hence, the goodness of fit criteria is applied. Moreover, Goodness of fit indicators refers to methods that are adopted in checking the quality of the model. Some of the popular ones are listed as follows:

3.11.1. Nash Sutcliffe Efficiency (NSE)

This is a popular method that is used in evaluating models (Nash and Sutcliffe, 1970; Harmel and Smith, 2007). NSE has a range between infinity and one (1), with 1 being the optimal value (Moriasi et al., 2007). However, as observed by Hermel and Smith (2007), NSE is highly sensitive to extreme values. Hence, the formular used for its calculation is shown below:

$$E = 1.0 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2}$$

…………………………………………………………...……....Eqn (9)

Where

O_i represents the observed data

P_i represents the modelled data

$\bar{o}$ represents the mean of observed data

$\bar{o}$

3.11.2 Root mean square error

RMSE is a well-known indicator that shows the goodness of fit between the simulated and observed data (Harmel and Smith, 2007). In RMSE, values close to zero (0) are much desired (Moriasi et al., 2007) hence, the lower the RMSE, the better. The formula used for it is shown below

$$\mathrm{RMSE} = \sqrt{N^{-1}\sum_{i=1}^{N}(O_i - P_i)^2} \quad \text{………………………………………………….……..Eqn (10)}$$

Where

O_i represents the Observed data

P_i represents the simulated data

N represents the number of data sets

3.11.3. Coefficient of determination (R^2)

R^2 shows the linear relationship between observation data and simulated data. The optimal value in this ranges between -1 and 1 (Moriasi et al., 2007). The optimal value is 1, and even though R^2 is commonly used for statistical evaluation of models, as noted by Legates and McCabe, (1999), R^2 is insensitive to additive and proportional differences in the simulated and observed data. A formula that can be applied for this is shown below:

$$R^2 = \left(\frac{\sum_{i=1}^{n}(o_i - \bar{o})(s_i - \bar{s})}{\sqrt{\sum_{i=1}^{n}(o_j - \bar{o})^2}\,\sqrt{\sum_{i=1}^{n}(s_i - \bar{s})^2}} \right)^2 \quad \text{…………………………………….……………………..Eqn (11)}$$

Where

O_i represents the Observed data

S_i represents the simulated data

$\bar{O}$ represents the mean of observed data

$\bar{S}$ represents the mean of simulated data

3.12 Summary

This chapter discussed the study area, the existing hydropower plants that make use of the river of interest and the fishes in river Glomma. In addition, the methods used in model calibration of Folldal, Brandval and Glomma catchments for present and future climate were discussed along with the online resources used.

CHAPTER 4

RESULT

4.1 Introduction

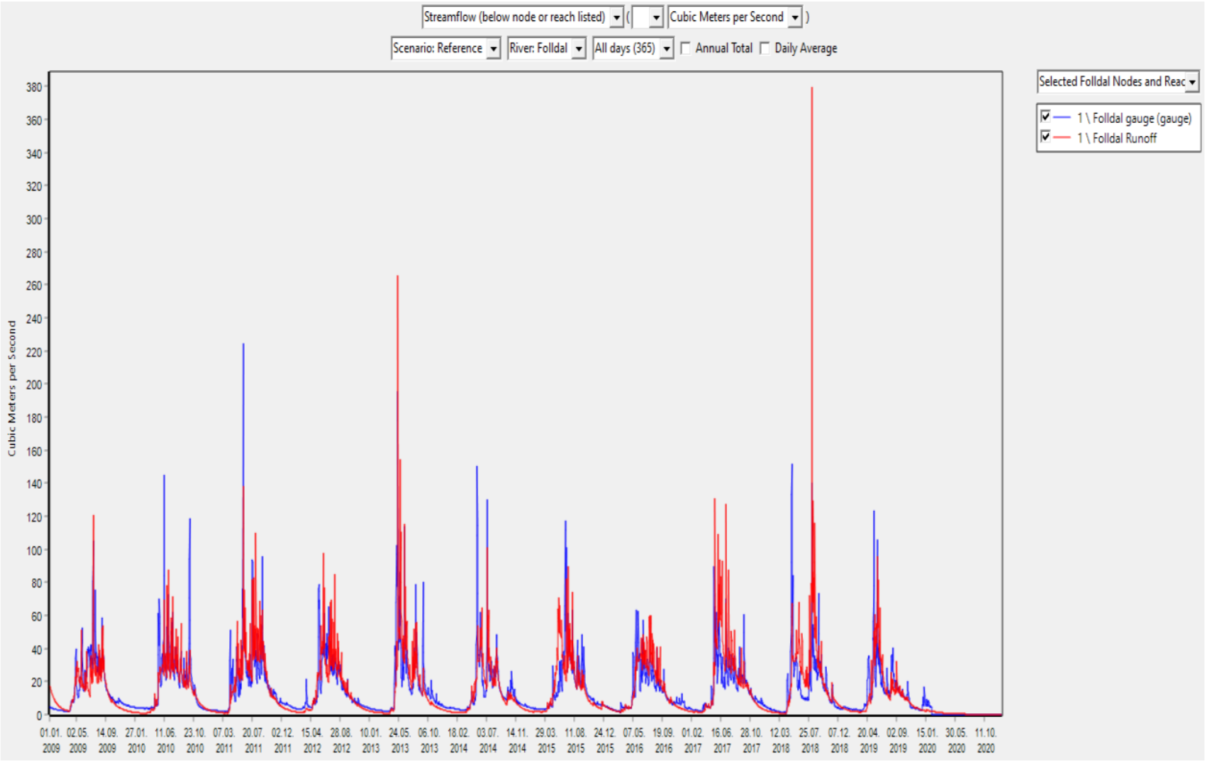
This chapter presents the results from the model simulations from WEAP. There are simulation results for Glomma catchment which is the main study area, and two other sub catchments, Folldal and Brandval which was used in calibrating Glomma catchment.

4.2 Result from Folldal basin calibration

The results presented below shows the daily average, annual total, and the actual evapotranspiration for both the Observed and simulated data in WEAP.

4.2.1 Presentation of streamflow data for Folldal sub catchment

The result presented in Figure 4.1 below shows the observed runoff inputted into the model with its simulated result.



Streamflow (below node or reach listed) (Cubic Meters per Second)

Scenario: Reference River: Folldal All days (365) ☐ Annual Total ☐ Daily Average

Selected Folldal Nodes and Reac

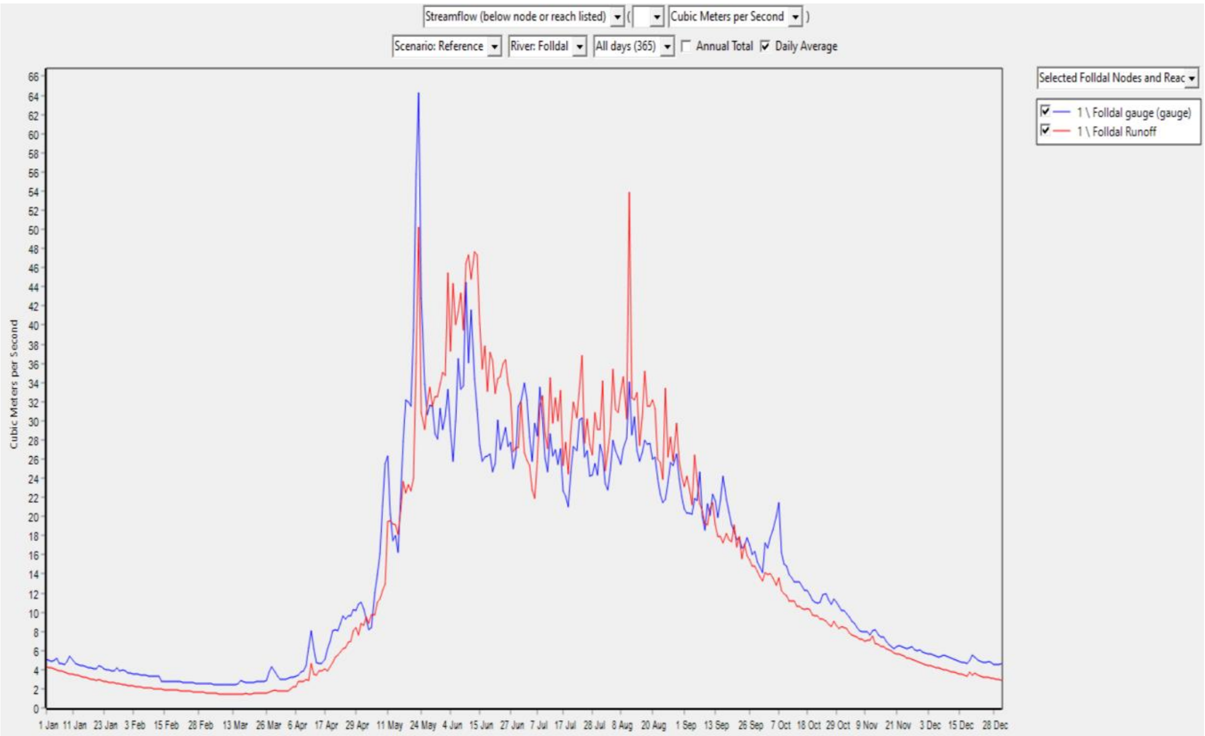
☑ 1 \ Folldal gauge (gauge)

☑ 1 \ Folldal Runoff

Figure 4.1: The simulated and observed runoff for Folldal sub catchment

4.2.2 Presentation of daily average runoff for Folldal sub catchment

The result shown in Figure 4.2 is the daily average of both simulated and observed runoff.


Streamflow (below node or reach listed) (Cubic Meters per Second)

Scenario: Reference | River: Folldal | All days (365) | ☐ Annual Total | ☑ Daily Average

Selected Folldal Nodes and Reac

☑ 1 \ Folldal gauge (gauge)

☑ 1 \ Folldal Runoff

Figure 4.2: The hydrographs for both the simulated and observed runoff for Folldal sub catchment

In Figure 4.2, the blue line shows the observed hydrograph while the red line represents the simulated hydrograph for the catchment.

4.2.3 Presentation of actual evapotranspiration rate around Folldal sub catchment

The result presented in Figure 4.3 shows the Actual evapotranspiration around Folldal area. which represents the upstream section of River Glomma.

4.3 Result from Brandval calibration

The results presented represent the daily average, annual total, and the actual evapotranspiration for both the observed and simulated data in for Brandval model in WEAP.

4.3.1 Presentation of streamflow data for Brandval sub catchment

The result shown in Figure 4.4 the observed runoff inputted into the model with its simulated result.

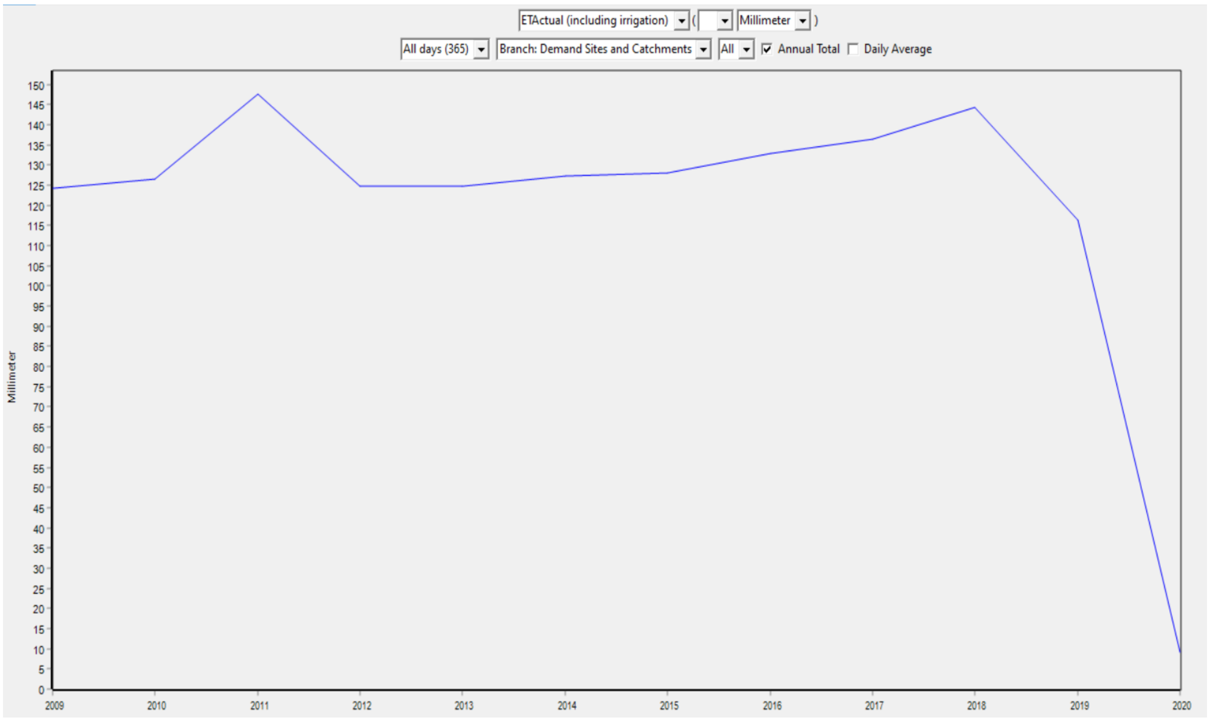


Figure 4.3: The Actual evapotranspiration around Folldal sub catchment

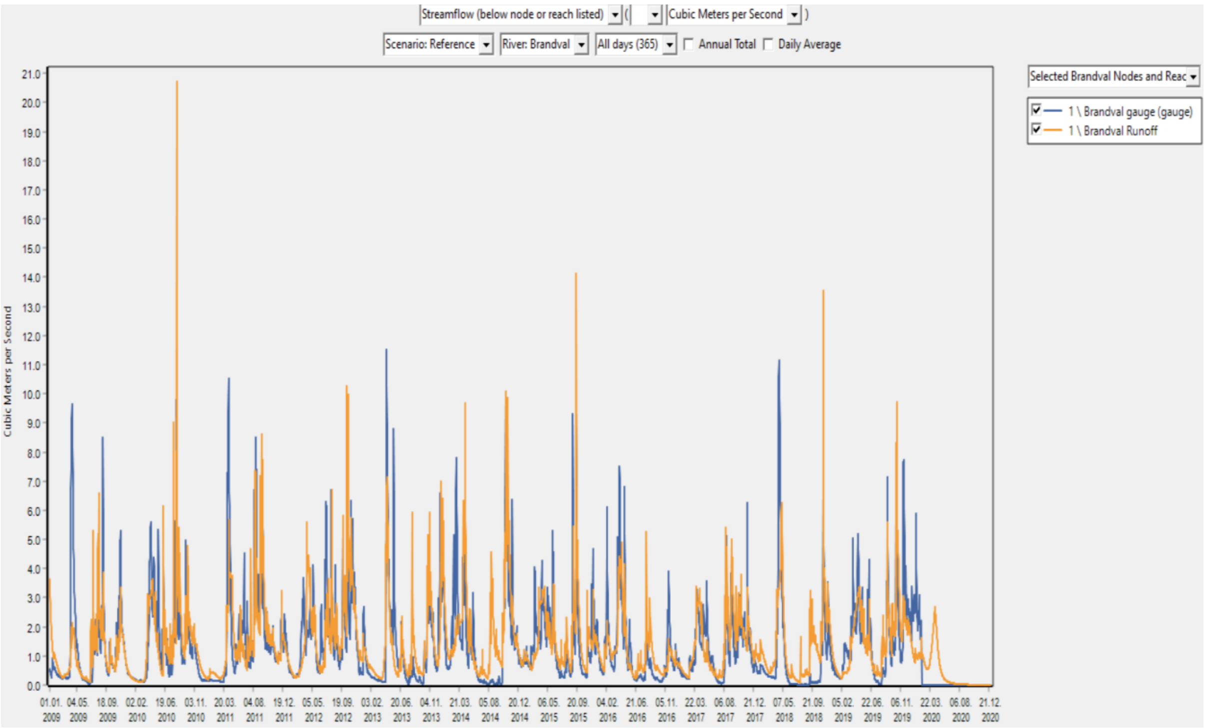
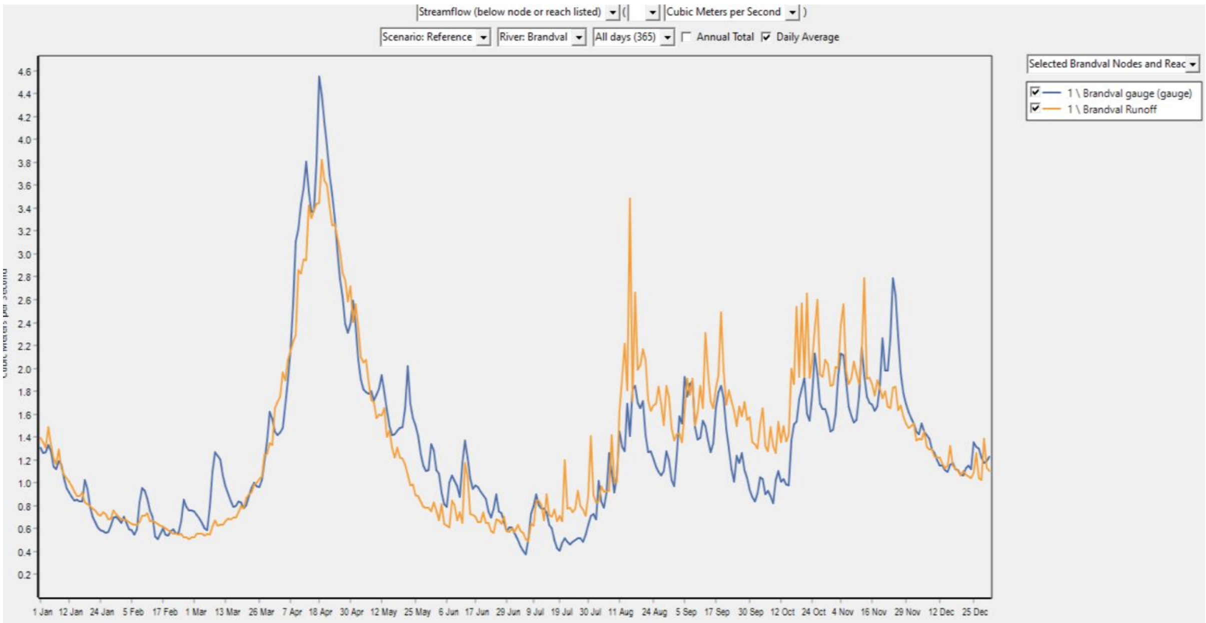


Figure 4.4: The hydrographs for both the simulated and observed runoff for Brandval sub catchment

4.3.2 Presentation of streamflow daily average of Folldal Sub basin

The result presented in Figure 4.5 shows the daily average of observed runoff inputted into the model with its simulated result.



Streamflow (below node or reach listed) ( ) Cubic Meters per Second

Scenario: Reference | River: Brandval | All days (365) | ☐ Annual Total | ☑ Daily Average

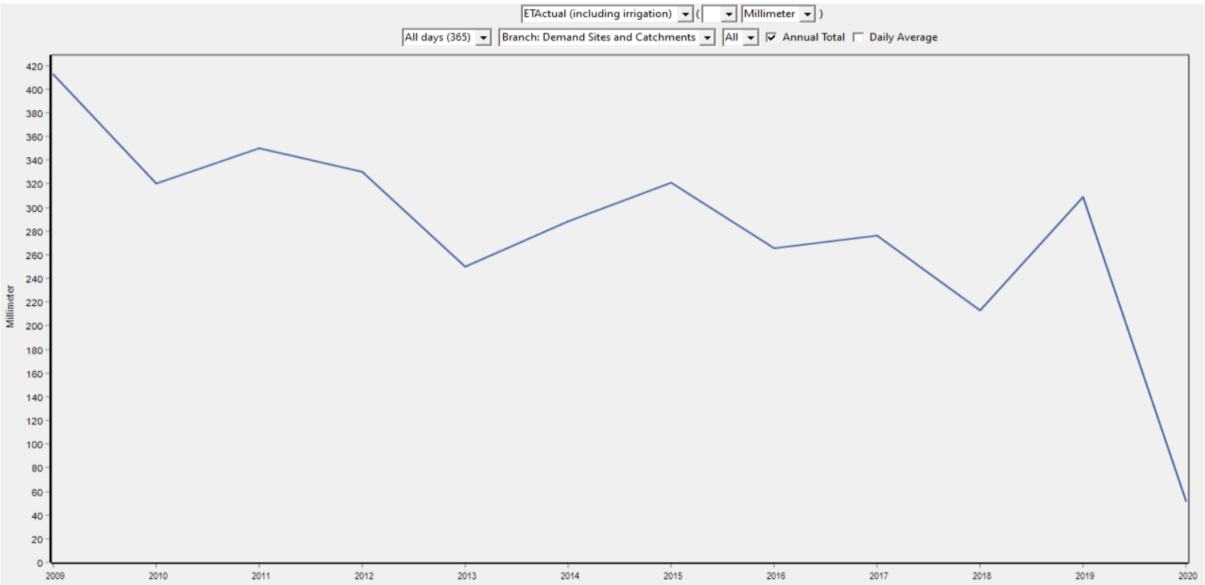
Selected Brandval Nodes and Reac

☑ 1 \ Brandval gauge (gauge)
☑ 1 \ Brandval Runoff

Figure 4.5: The hydrographs for both the simulated and observed runoff for Brandval sub catchment

4.3.3 Presentation of streamflow evapotranspiration of Brandval sub catchment

The result presented in Figure 4.6 shows the Actual evapotranspiration around Brandval which represents the downstream section of River Glomma.



ETActual (including irrigation) ( ) Millimeter

All days (365) | Branch: Demand Sites and Catchments | All | ☑ Annual Total | ☐ Daily Average

Figure 4.6: The Actual evapotranspiration around Brandval sub catchment

4.4 Model Performance Assessment

To check the quality of Folldal and Brandval sub catchments, the Coefficient of Determination (R^2) and Nash Sutcliff Coefficient of Efficiency (NSE) were calculated. The result is as listed in Table 4.1 below.

Table 4.1: Tabular presentation of the results of the quality assessment of Folldal and Brandval sub catchments

Sub-catchments	BRANDVAL	FOLLDAL
NSE	0.76	0.85
R^2	0.78	0.90

In addition, the Graphical representation of the $\mathbf{R^2}$ for Folldal and Brandval sub basins are duly presented in Figure 4.7 and 4.8

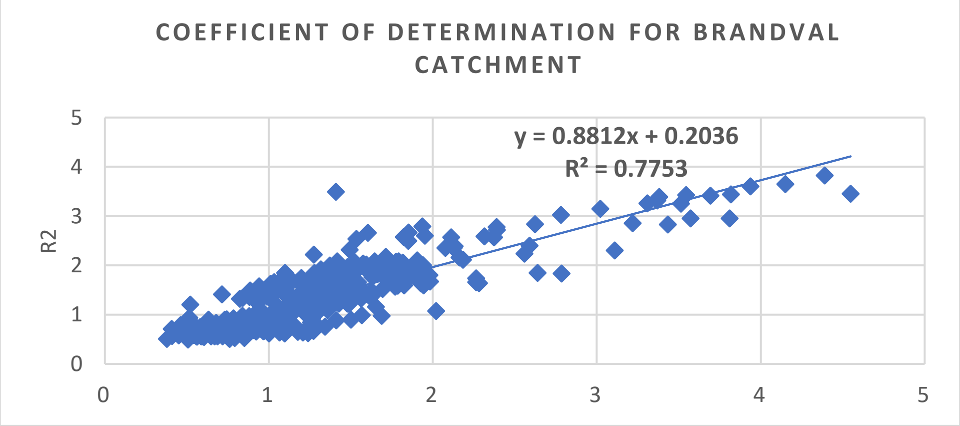


Figure 4.7: The Linear regression obtained from Brandval streamflow data

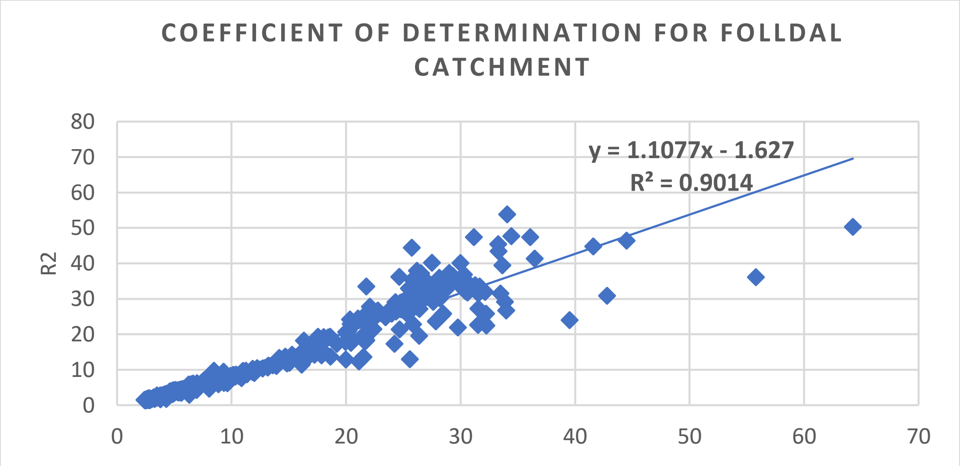


Figure 4.8: The Linear regression obtained from Folldal streamflow data

4.5 Result of Simulations carried out under Present Climate.

To assess the effect of reservoir regulation on low flow during critical periods like winter and summer, the natural runoff of Glomma basin before its regulation had to be simulated, after which its result is compared with the current hydrographs of gauges around said basin.

4.5.1 Presentation of the Result of Glomma Catchment before reservoir regulation.

The results presented in this section shows the daily average, annual total, and the actual evapotranspiration for the simulated result in WEAP.

4.5.1.1 Results showing the simulated Unregulated Flow in Glomma basin

The results presented in Figure 4.9 shows the simulated result for the Glomma river based on the sub catchments used for its calibration in WEAP.

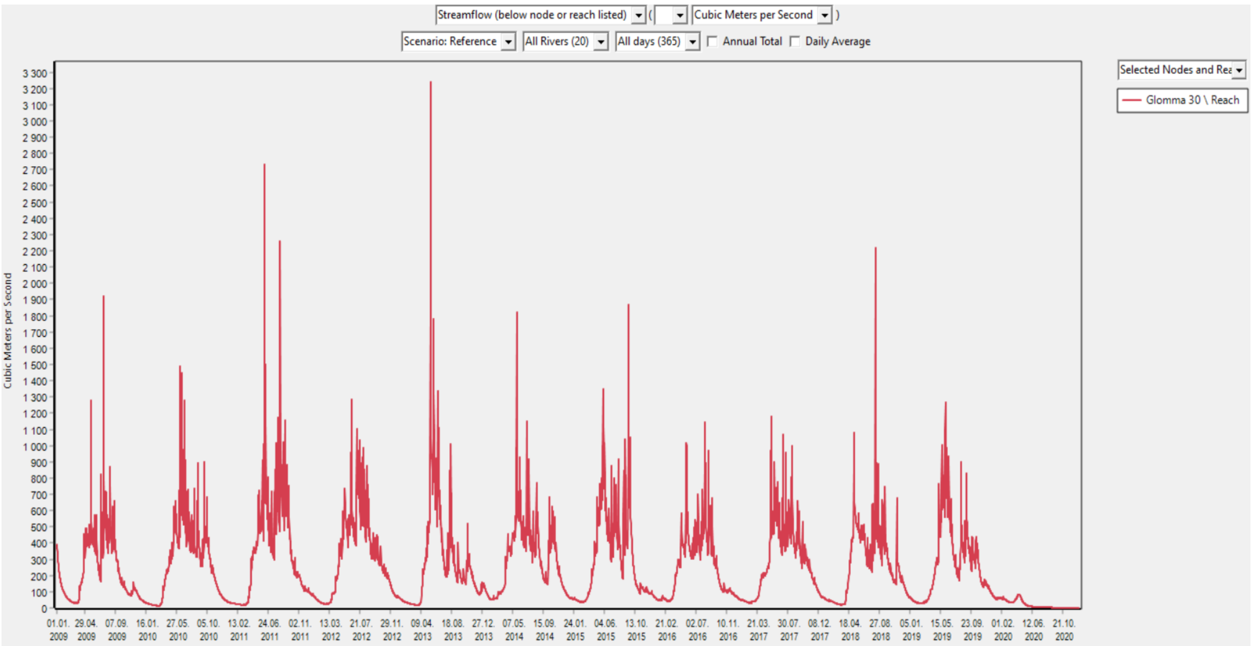


Figure 4.9: The hydrograph for Glomma simulated runoff

4.5.1.2 Presentation of simulated annual total streamflow for Glomma basin

The result shown below in Figure 4.10 is the annual total result simulated for Glomma river.

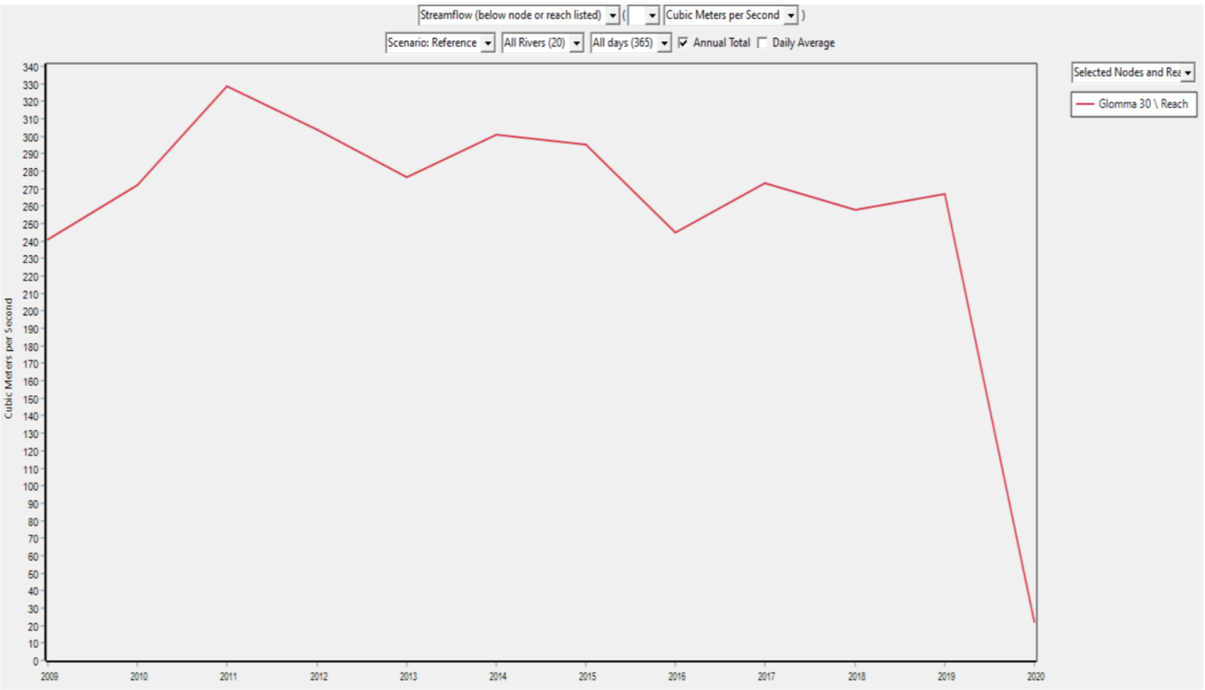


Figure 4.10: The annual total runoff for Glomma catchment

4.5.1.3 Presentation of simulated daily average streamflow for Glomma basin

The result shown below in Figure 4.11 presents the daily average of the simulated runoff for Glomma Basin.

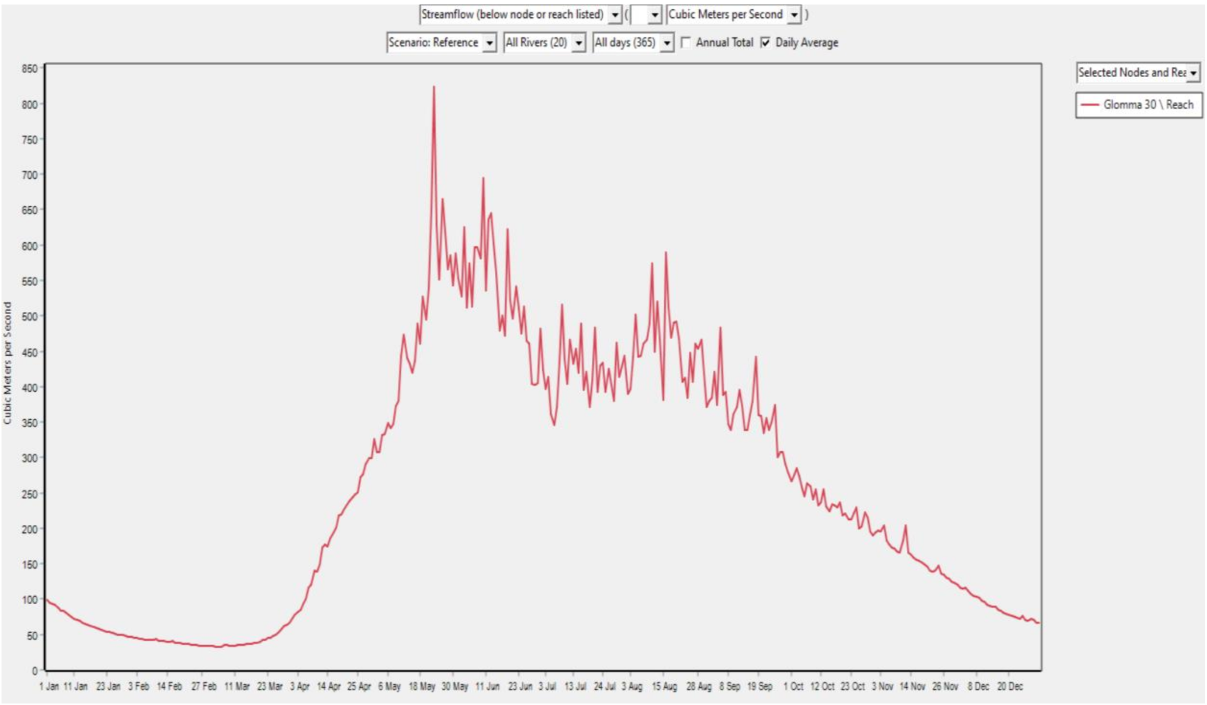
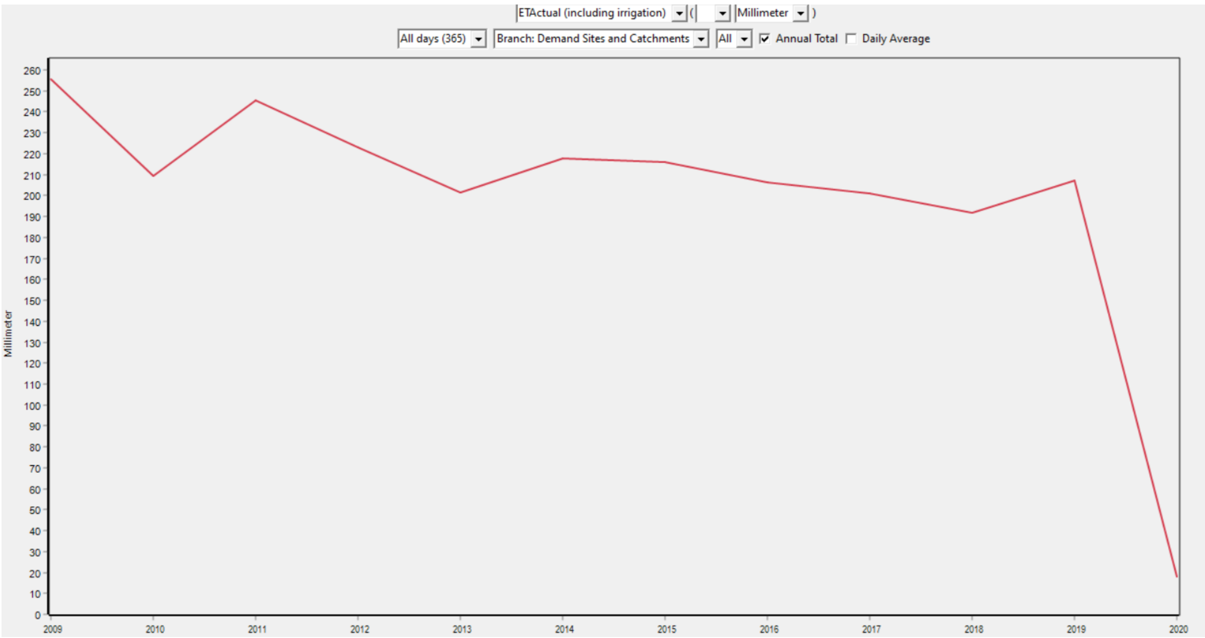


Figure 4.11: The simulated daily average flow of River Glomma

4.5.1.4 Presentation of simulated evapotranspiration rate for Glomma basin

The result in Figure 4.12 shows the result of the actual evapotranspiration rate which was simulated for Glomma Basin using WEAP.



ETActual (including irrigation) ( ) Millimeter)

All days (365) Branch: Demand Sites and Catchments All ☑ Annual Total ☐ Daily Average

Figure 4.12: The simulated evapotranspiration rate of River Glomma

4.5.2 Presentation of comparison between the results obtained from Glomma basin before and after regulation.

The results presented are the results showing the simulated runoff (which depicts the natural flow condition before flow regulation) and the corresponding observed data (which represents the flow after river regulation) for three additional gauges added to simulate the regulated river runoff in Glomma catchment. In this case, the three gauges presented are named N gauge, A gauge and G gauge. These gauges are situated at strategic points on the Glomma river as shown in Figure 4.13

4.5.2.1 Results of N gauge along Glomma catchment

The result presented shows the daily average of N gauge (Glomma 29) which is the historical observed streamflow near the outlet of Glomma basin, and its simulated runoff showing the pre-regulation river condition (Glomma 30) as shown in Figure 4.14.

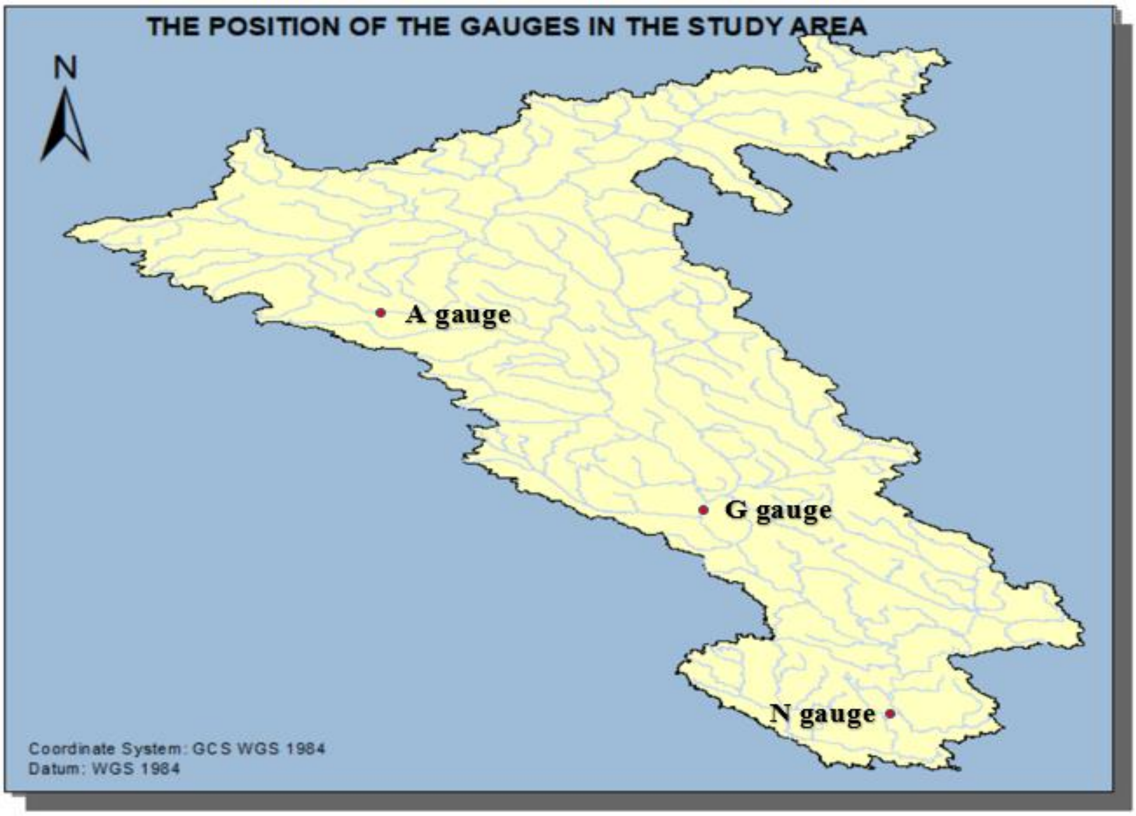


Figure 4.13: The positions of the gauges relative to each other in the study area

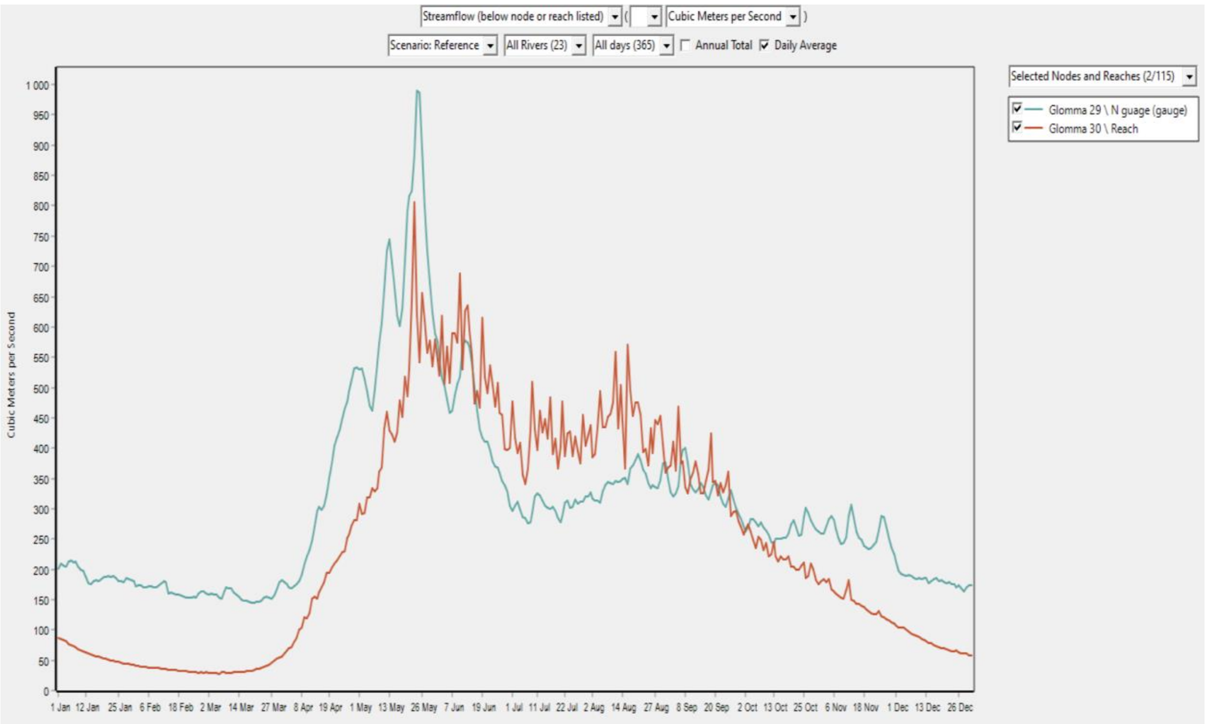


Figure 4.14: The daily average of observed runoff and the simulated runoff of River Glomma

In addition, Figure 4.15 presents the observed and simulated time series from 1st January 2009 till 13th February 2020.

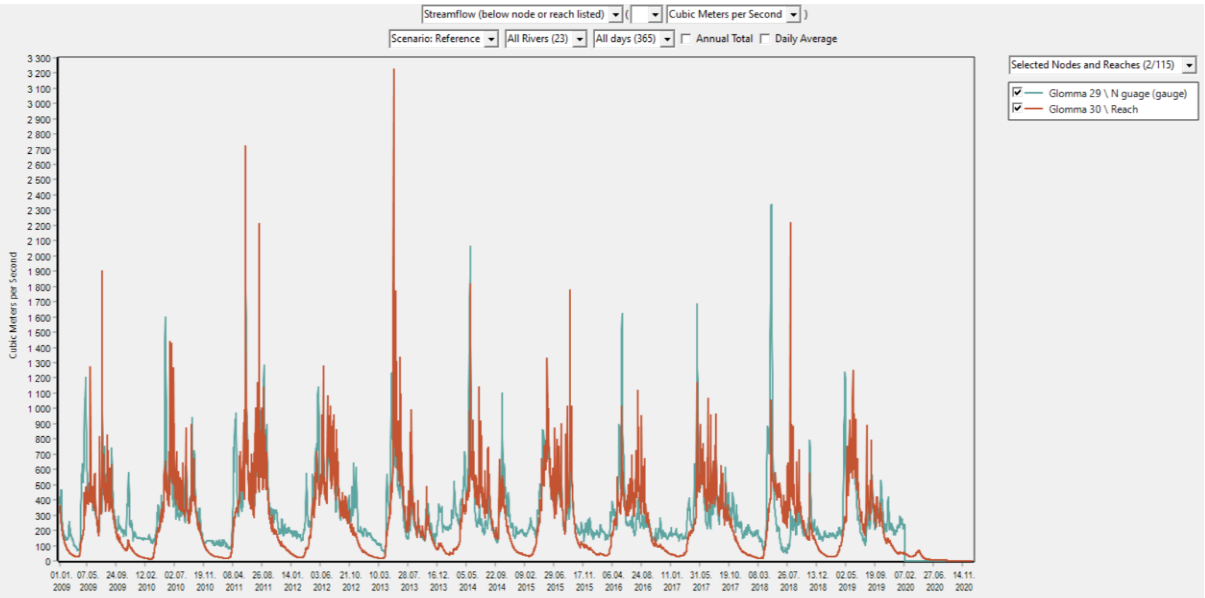


Figure 4.15: The observed runoff and the simulated runoff of River Glomma

4.5.2.2 Results of A gauge along Glomma catchment

The result shown in Figure 4.16 represents the daily average runoff at recorded with A gauge (Atna 1) which is the historical observed streamflow situated upstream of Glomma basin, and its simulated runoff showing the pre-regulation stream flow condition (Atna 2).

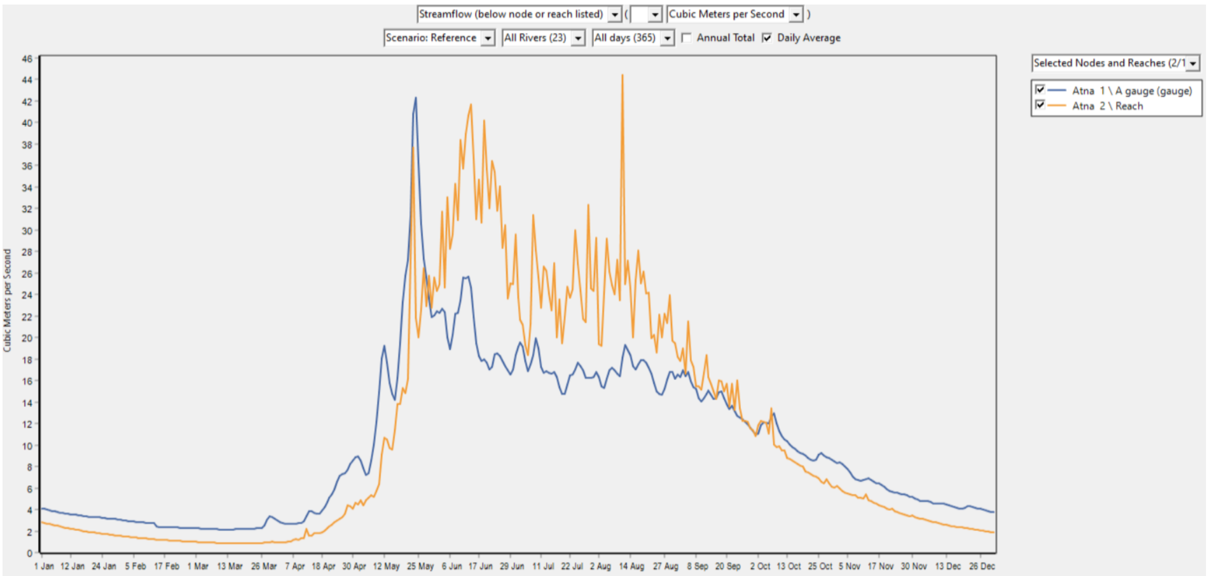


Figure 4.16: The simulated and observed daily average runoff at A gauge

In addition, its streamflow comparison is presented in Figure 4.17

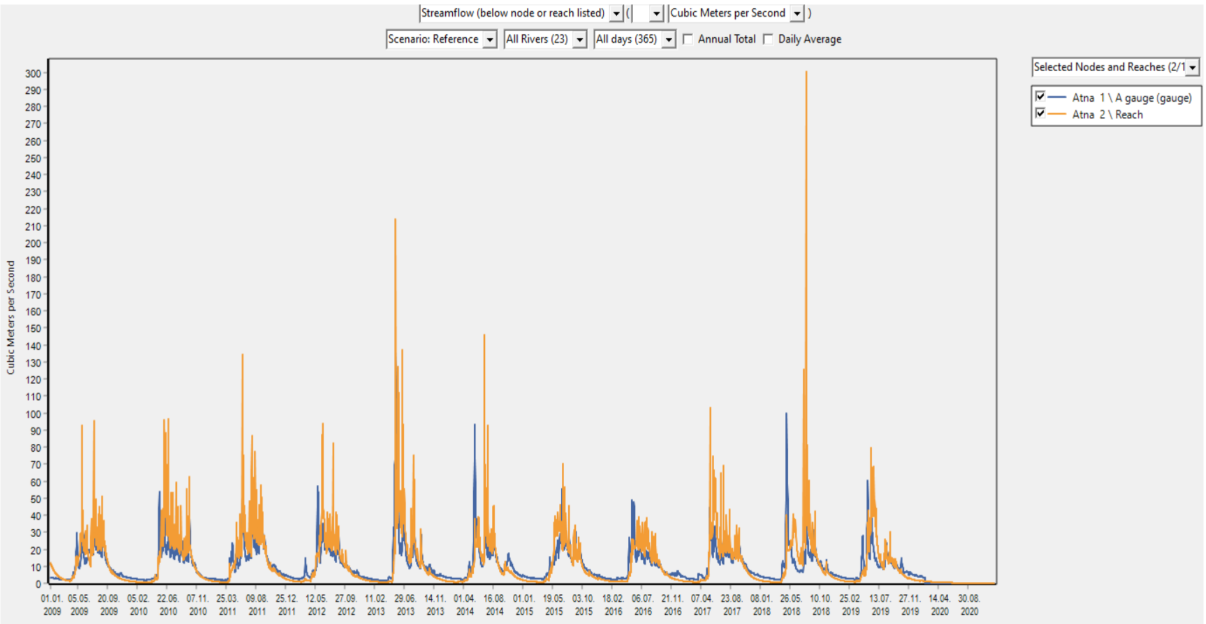


Figure 4.17: The comparison between observed and simulated runoff for A gauge

4.5.2.3 Results of G gauge along Glomma catchment

The result presented shows the daily average of G gauge (Glomma 19) which shows the historical observed streamflow of the gauge situated along Glomma river and around the center of Glomma basin. Equally, its simulated runoff showing the pre-regulation river condition (Glomma 20) is shown in Figure 4.18.

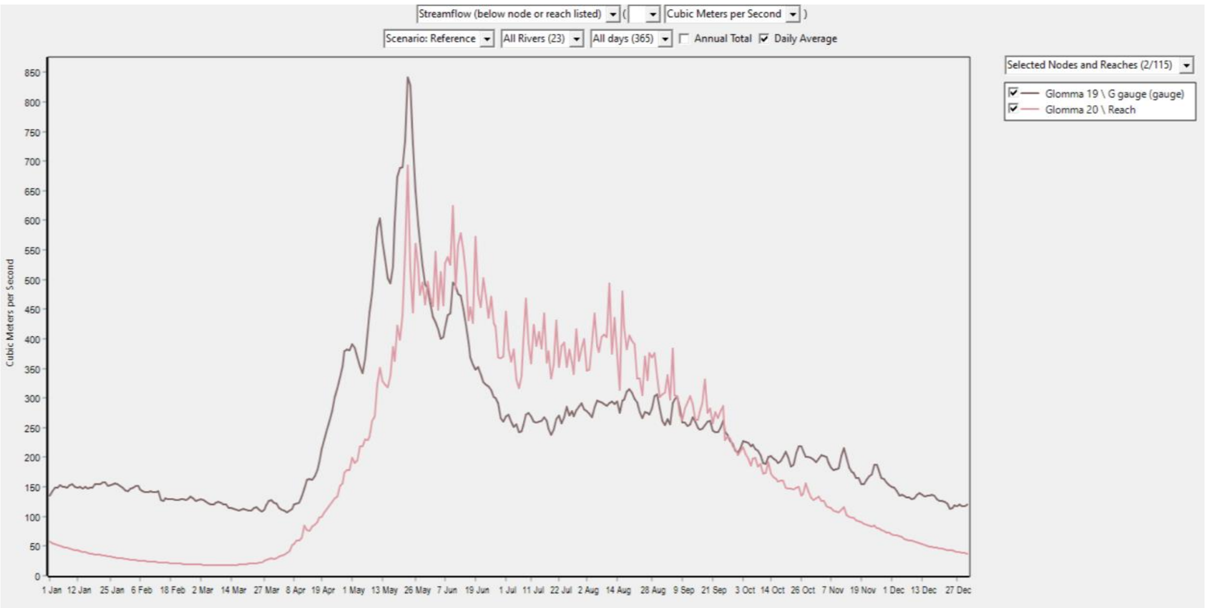
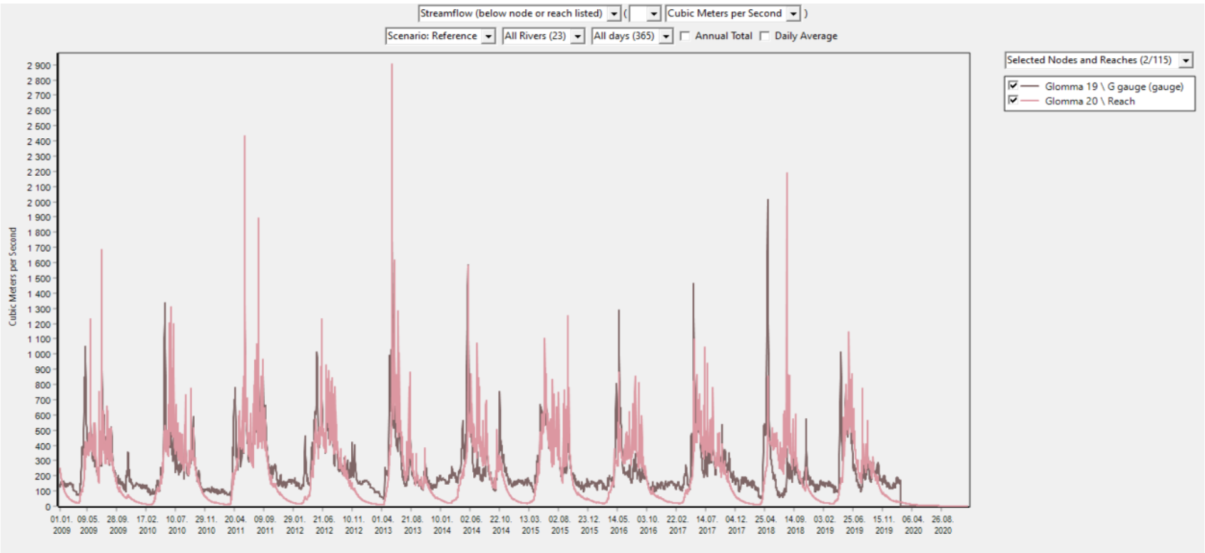


Figure 4.18: The observed runoff and the simulated daily average runoff of River Glomma

In Figure 4.19, both the observed time series of flow and simulated runoff at G gauge is duly presented for time period 1st January 2009 till 13th February 2020.



Streamflow (below node or reach listed) (Cubic Meters per Second)

Scenario: Reference | All Rivers (23) | All days (365) | ☐ Annual Total ☐ Daily Average

Selected Nodes and Reaches (2/115)

☑ Glomma 19 \ G gauge (gauge)

☑ Glomma 20 \ Reach

Figure 4.19: The observed and simulated runoff of River Glomma

4.6 Result of Simulations carried out under Future Climate

The climate projections carried out for the two Scenarios titled climate change '40 (which represents the future climate projection 2040-2051) and **climate change "80** (which represent the future climate projection 2080-2091) are compared with the reference year 2009-2020 using IHA indices. After which the results are presented in the sections below.

4.6.1 Presentation of the Result for all Climate projections using Glomma River.

Using IHA statistics, results are presented for each of the Groups, from Group 1-3 for the 3 gauges that are used to compare the pre and post regulation effect of low flow on discharge in River Glomma.

4.6.1.1 Results of N gauge using IHA indices

The results presented in this section compares simulation results of N gauge on Glomma river for all climate scenarios identified in this thesis.

a) **Group 1**

Figure 4.20 presents the compilation of the mean value for each of the months from 2009-2020.

In addition, the climatic projections from year 2040-2051 and 2080-2091 are also dully presented in graphical forms.

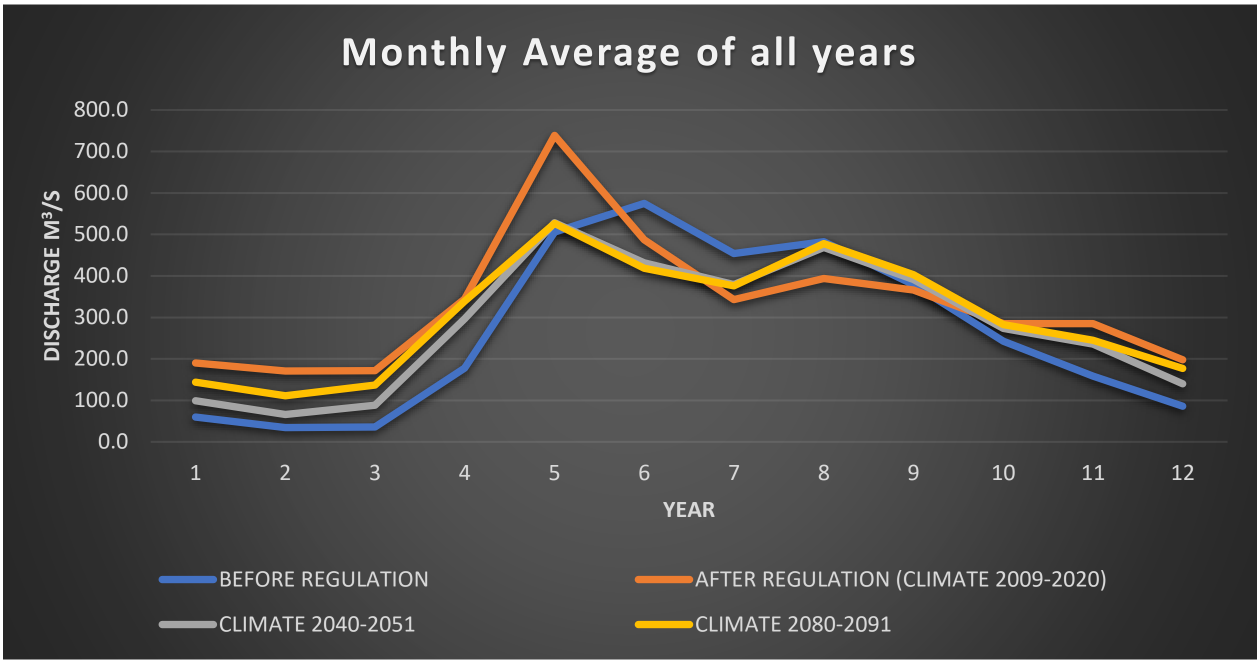


Figure 4.20: The monthly averages of all climate scenarios in River Glomma

b) Group 2

For N gauge, the results presented from Figure 4.21 to Figure 4.24 shows the 7-day minimum flow, the 30-day minimum flow and the low flow in the summer and also in the winter.

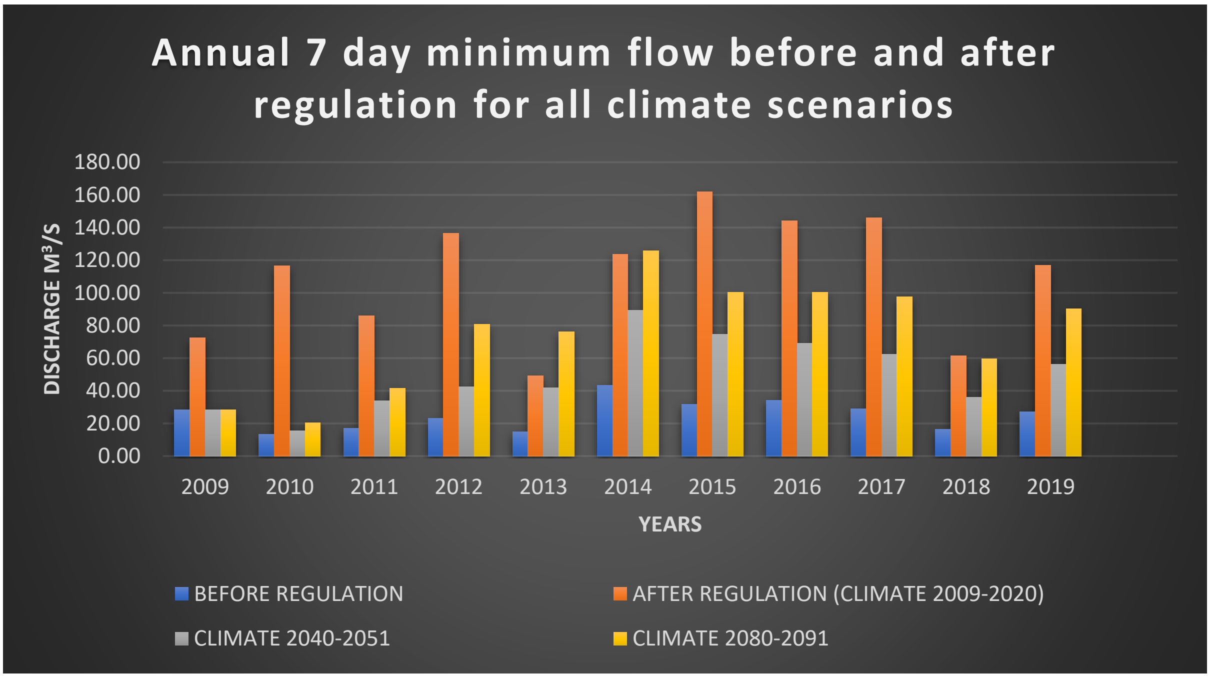


Figure 4.21: The 7-day minimum flow of all climate scenarios in River Glomma

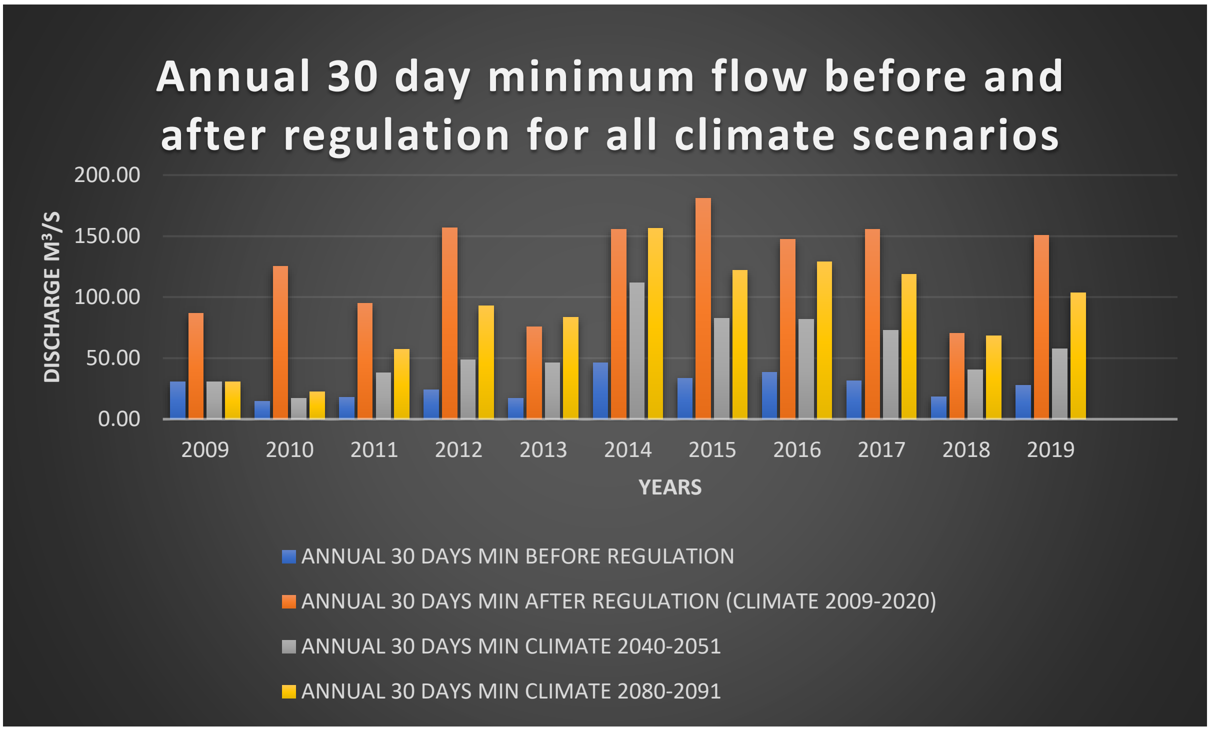


Figure 4.22: The 30-day minimum flow of all climate scenarios in River Glomma

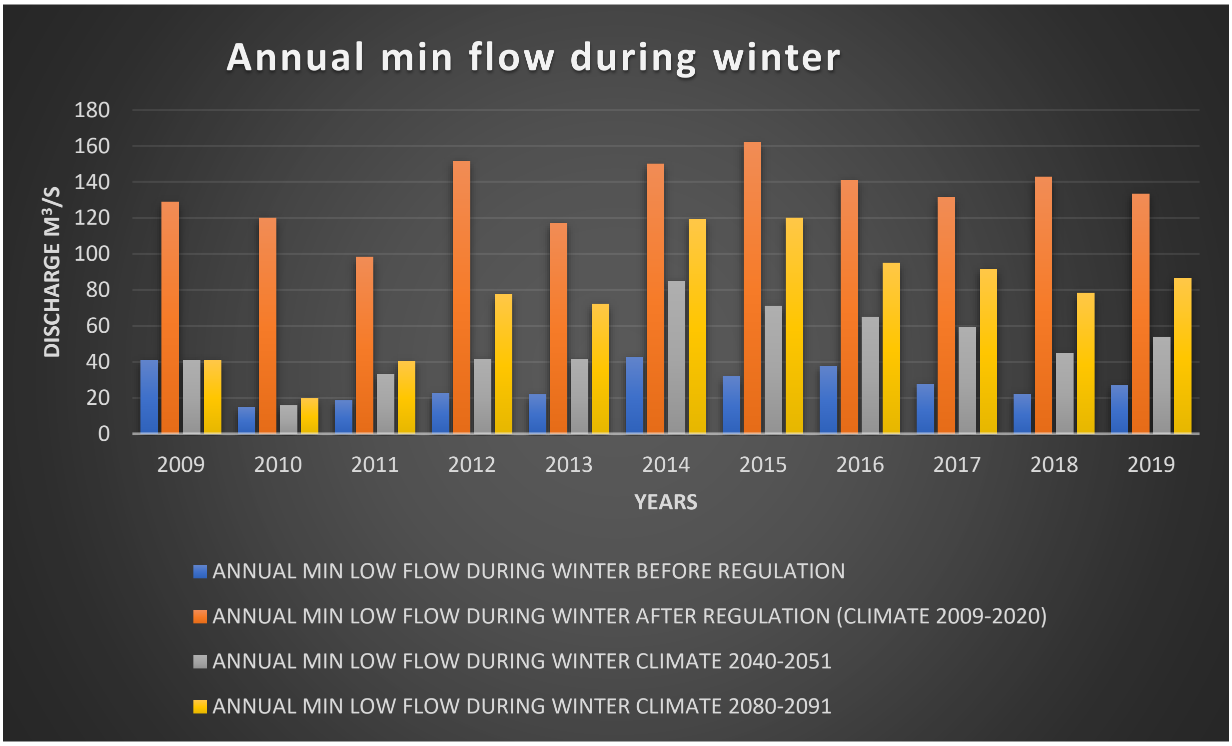


Figure 4.23: The annual minimum flow during the winter for all climate scenarios in River Glomma

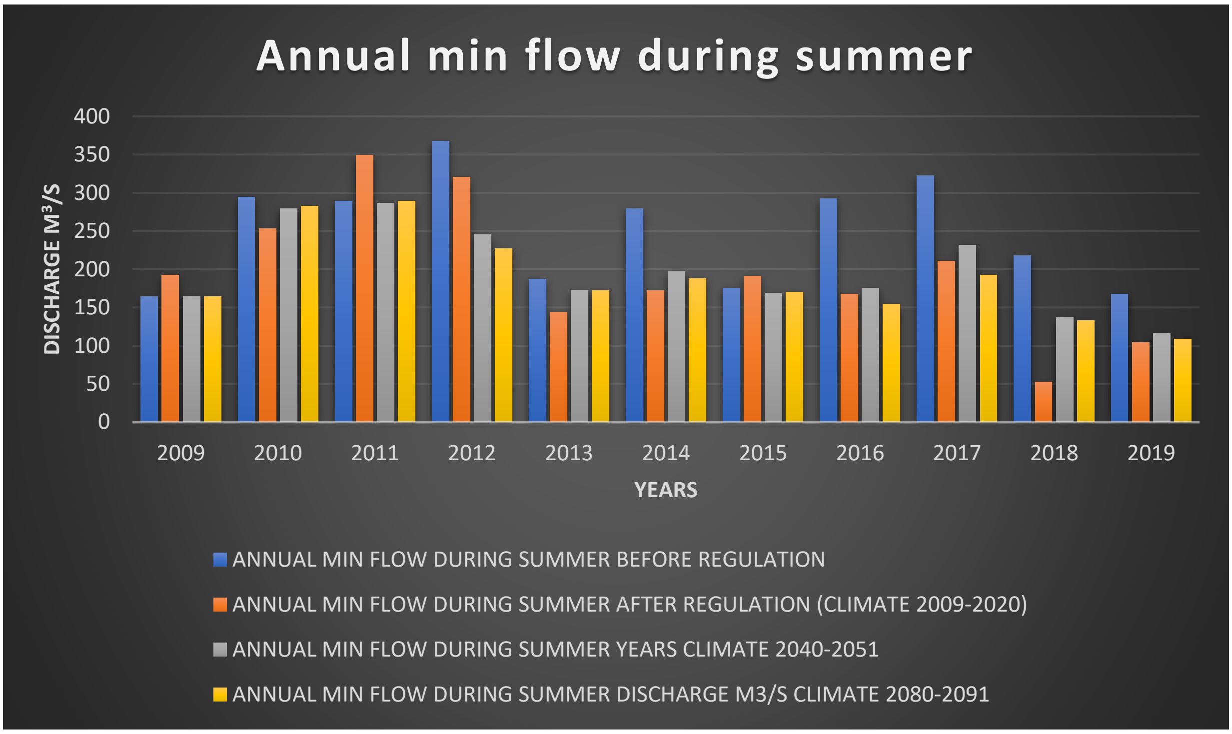


Figure 4.24: The annual minimum flow during the summer for all climate scenarios in River Glomma

c) Group 3

Group 3 represents the timing of the critical flow. Hence, the average timing of the annual low flow of N gauge is presented in Figure 4.25.

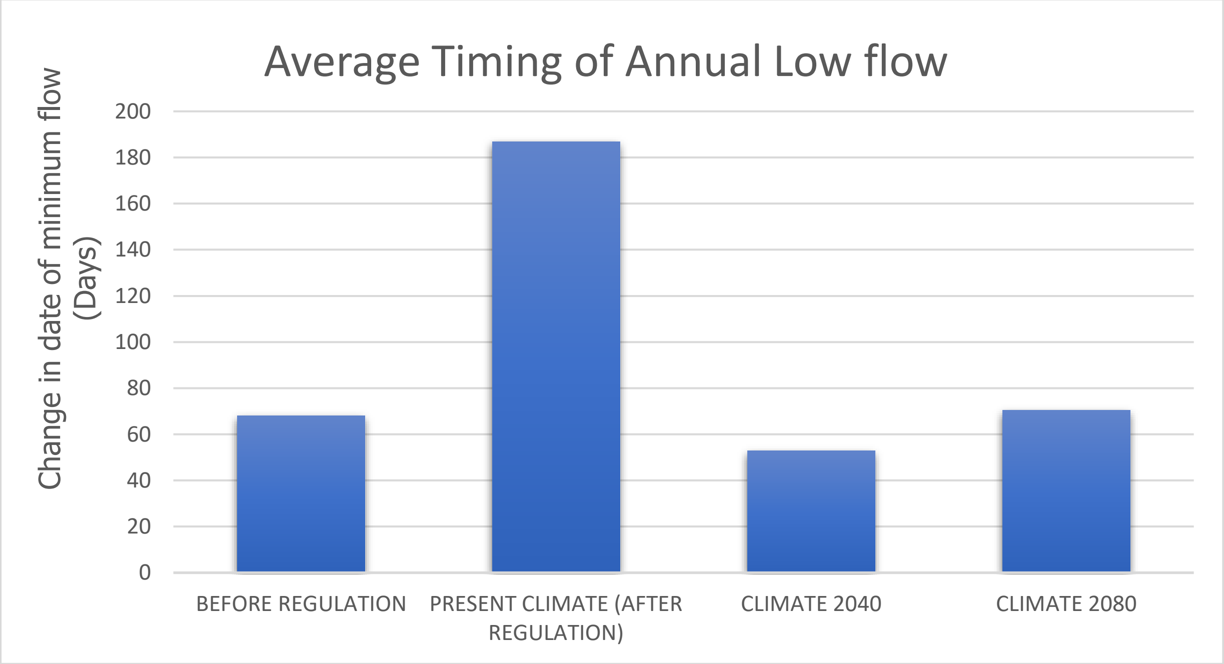


Figure 4.25: The average timing of Annual low flow for all climate scenarios in River Glomma

4.6.1.2 Results of A gauge

a) Group 1

This presents the compilation of the mean value for each of the months from 2009-2020. In addition, the climatic projections from year 2040-2051 and 2080-2091 are presented in Figure 4.26.

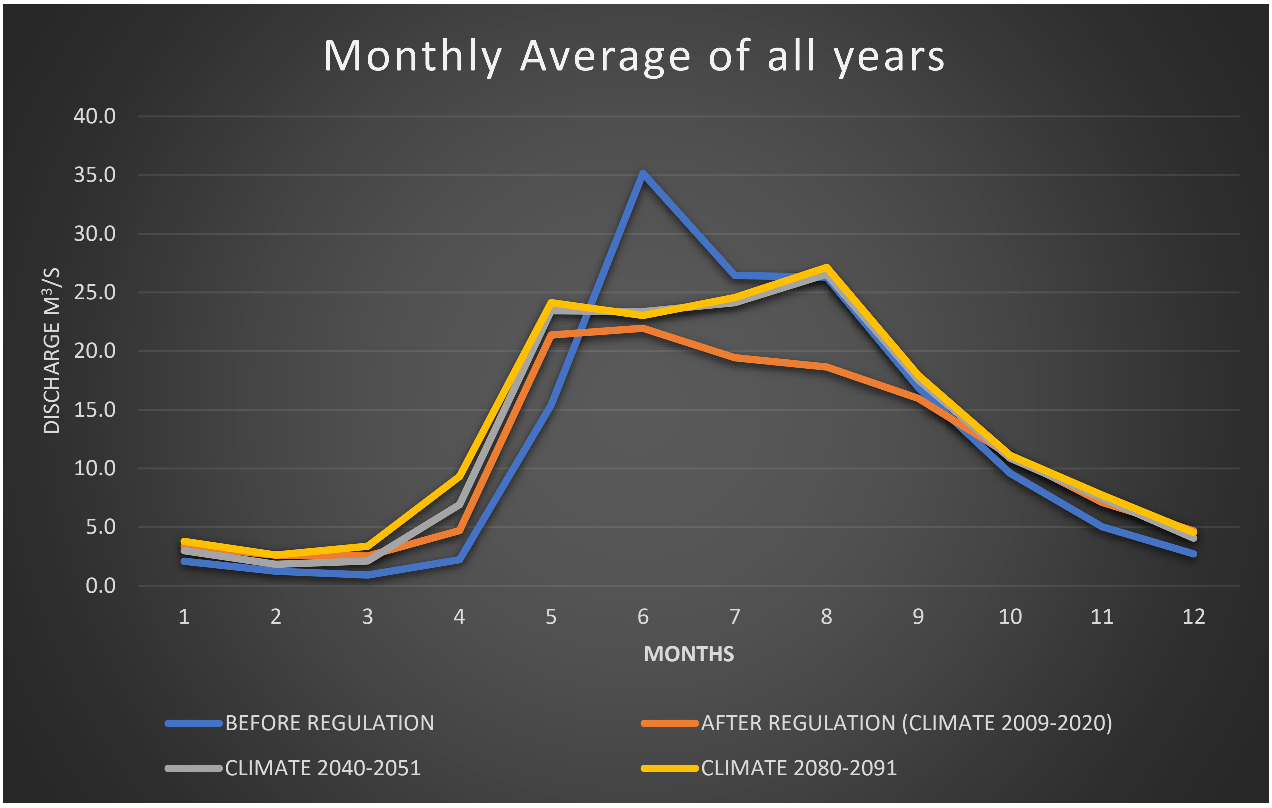


Figure 4.26: The monthly averages of all climate scenarios in River Glomma

b) Group 2

For A gauge, the results presented from Figure 4.27 to Figure 4.30 shows the 7-day minimum flow, the 30-day minimum flow and the low flow in the summer and also in the winter.

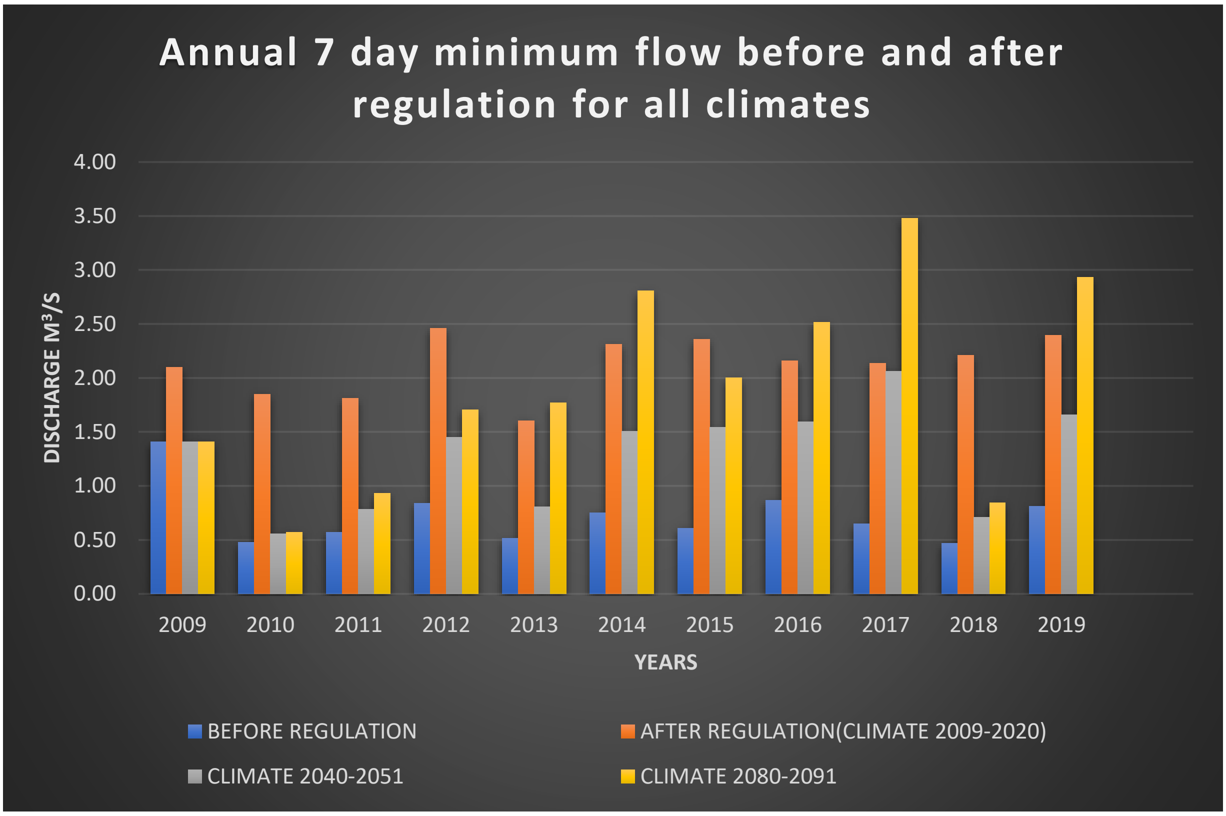


Figure 4.27: The 7-day minimum flow of all climate scenarios in River Glomma

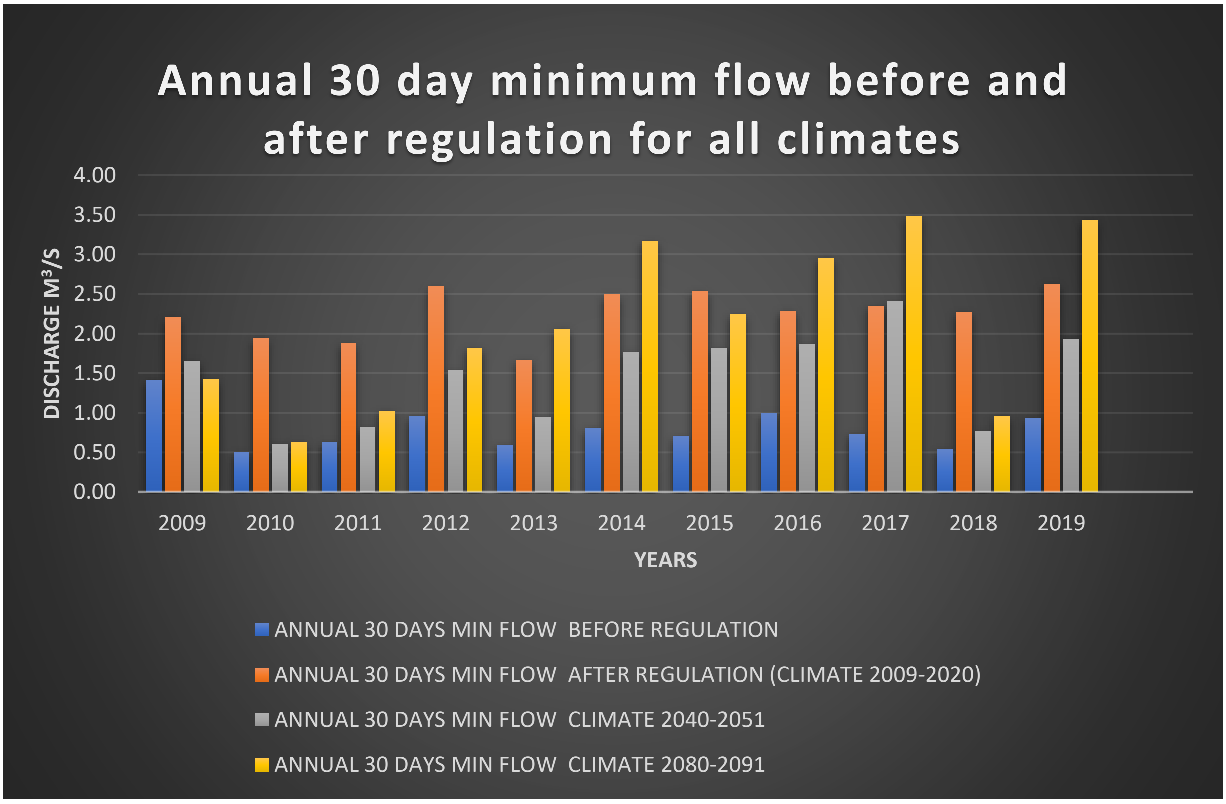


Figure 4.28: The 30-day minimum flow of all climate scenarios in River Glomma

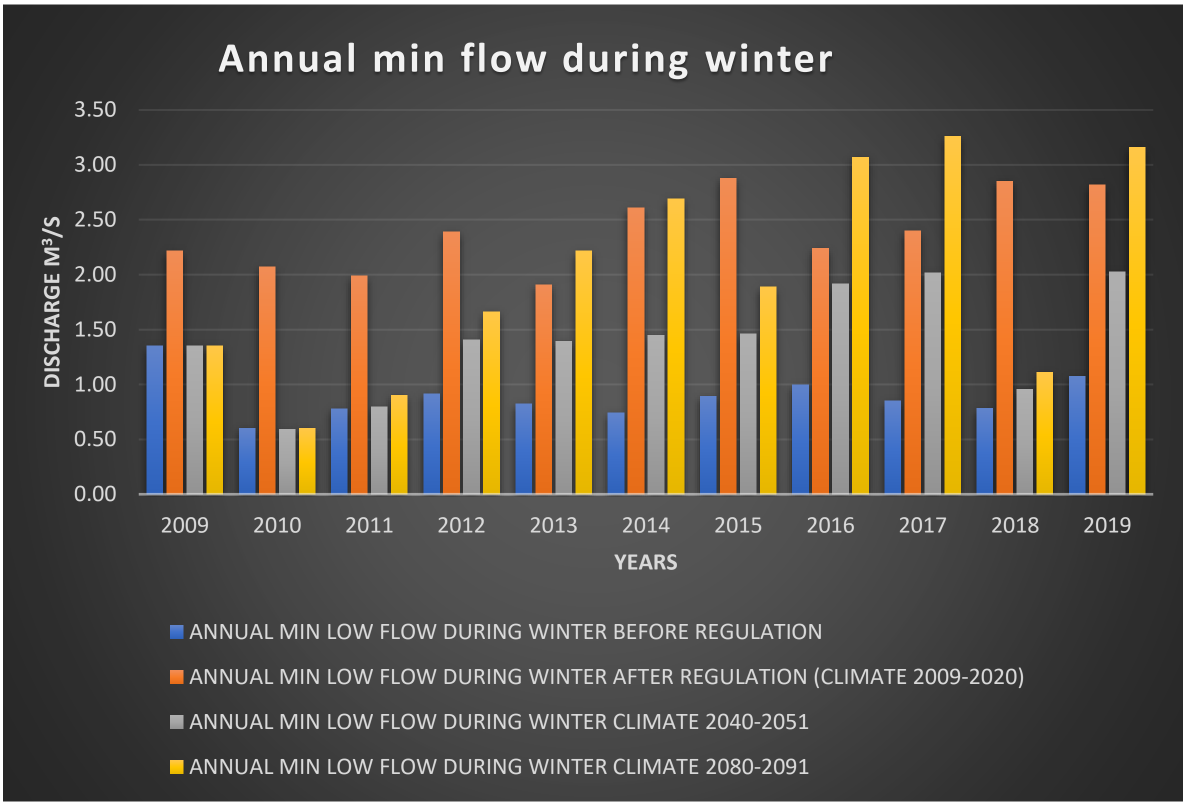


Figure 4.29: The annual minimum flow during the winter for all climate scenarios in River Glomma

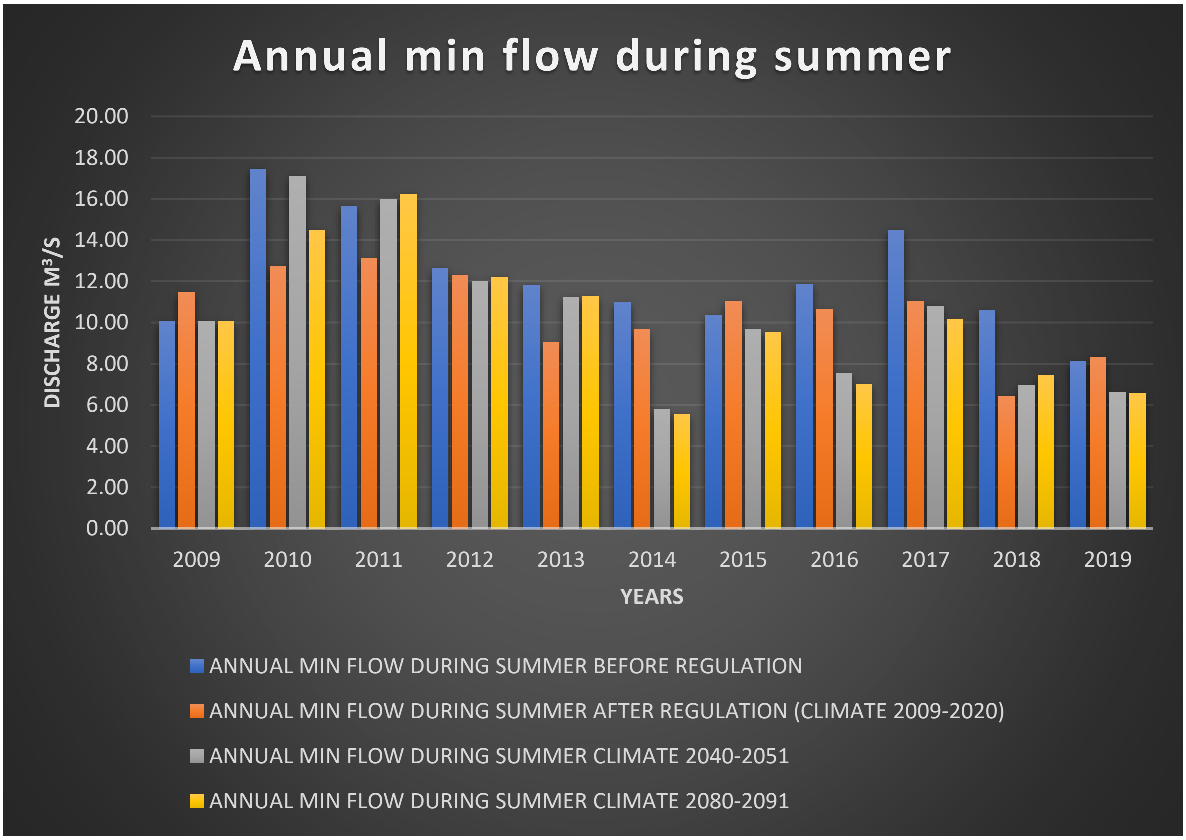


Figure 4.30: The annual minimum flow during the summer for all climate scenarios in River Glomma

d) Group 3

Group 3 represents the timing of the critical flow. Hence, the average timing of the annual low flow of A gauge is presented in Figure 4.31.

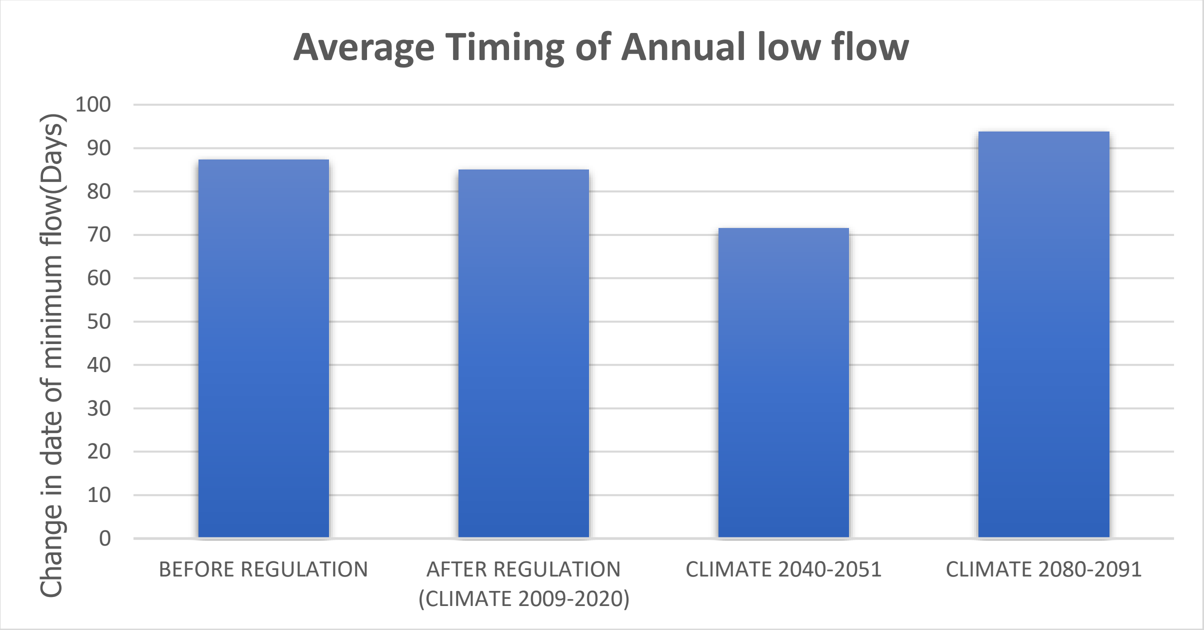


Figure 4.31: The average timing of Annual low flow for all climate scenarios in River Glomma

4.6.1.3 Results of G gauge

a) Group 1

This presents the compilation of the mean value for each of the months from 2009-2020.In addition, the climatic projections from year 2040-2051 and 2080-2091 are presented in Figure 4.32.

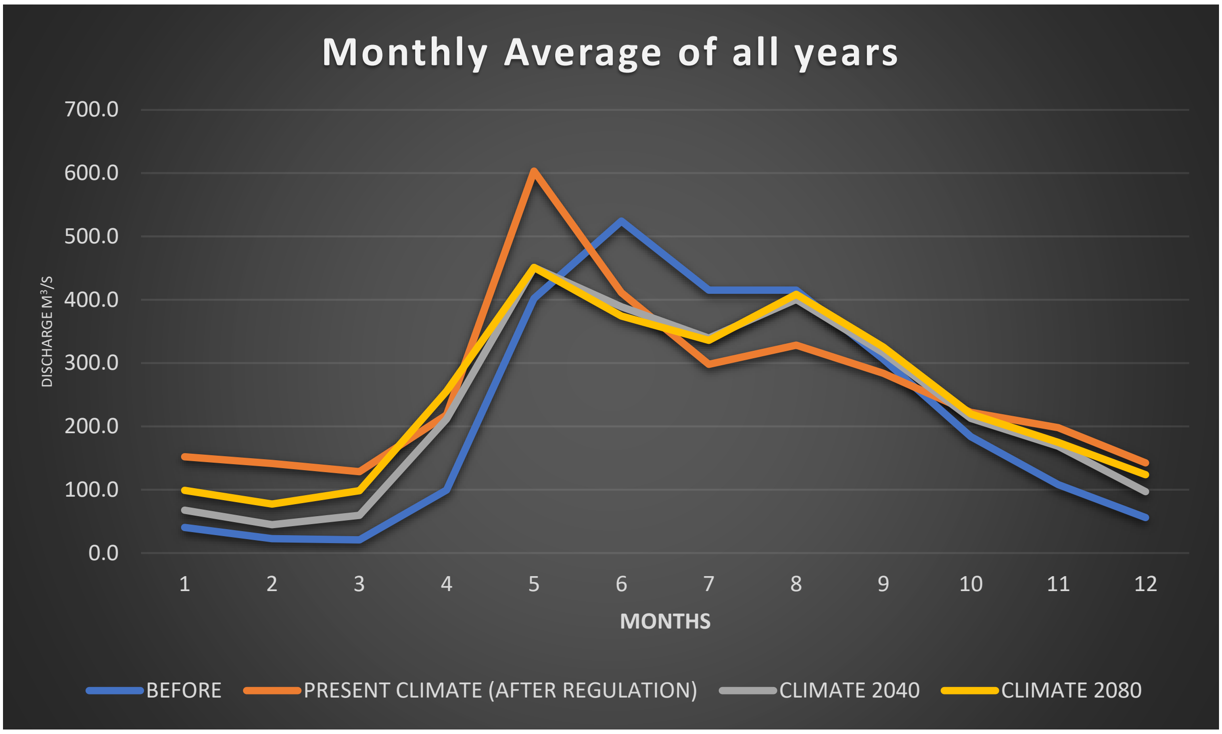


Figure 4.32: The monthly averages of all climate scenarios in River Glomma

b) Group 2

The results presented from Figure 4.33 to Figure 4.36 shows the 7-day minimum flow, the 30-day minimum flow and the low flow in the summer and also in the winter.

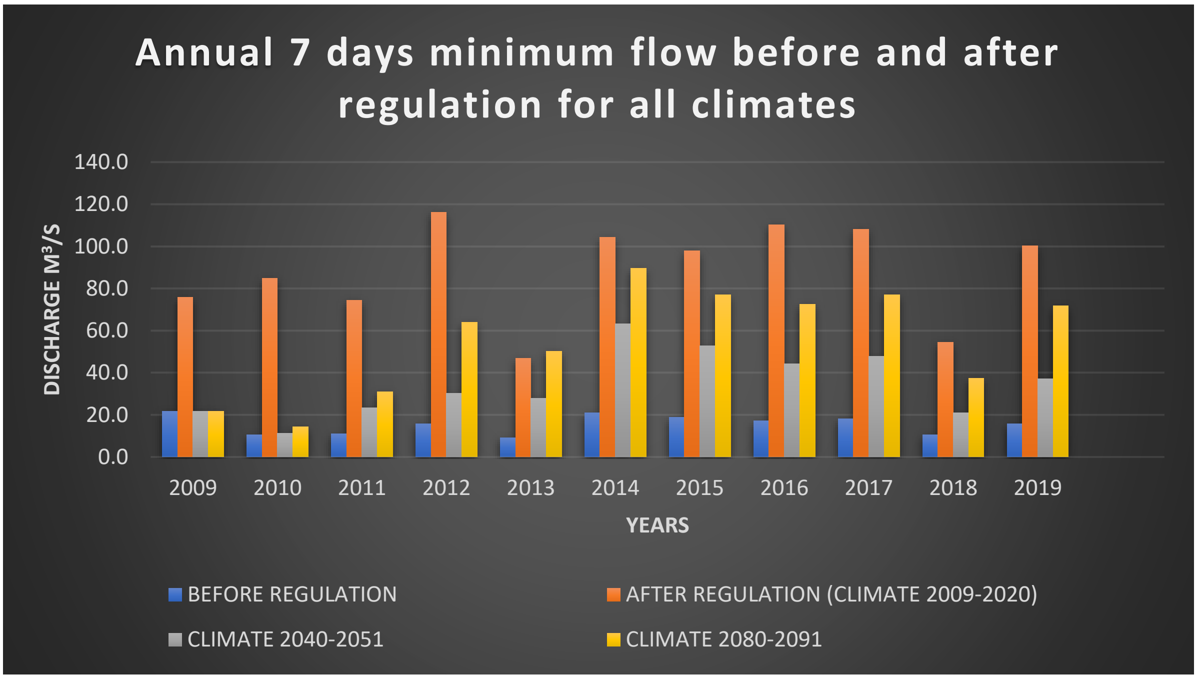


Figure 4.33: The 7-day minimum flow of all climate scenarios in River Glomma

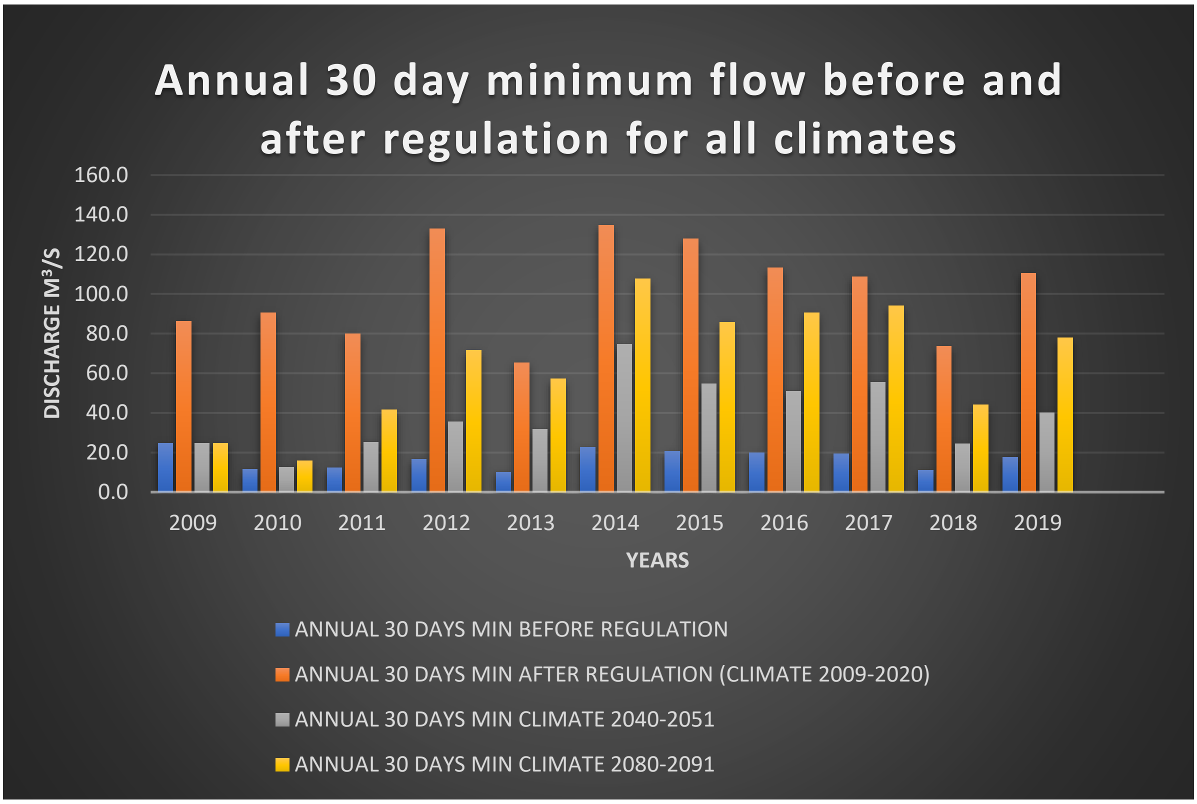


Figure 4.34: The 30-day minimum flow of all climate scenarios in River Glomma

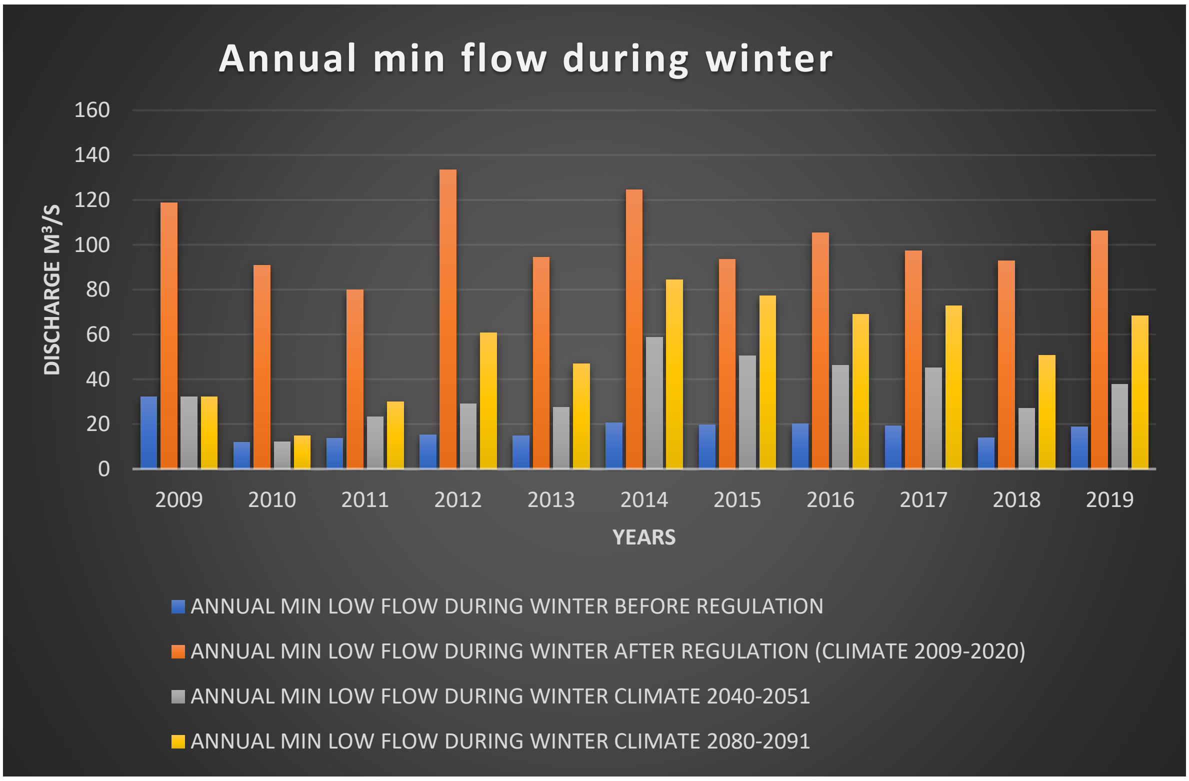


Figure 4.35: The annual minimum flow during the winter for all climate scenarios in River Glomma

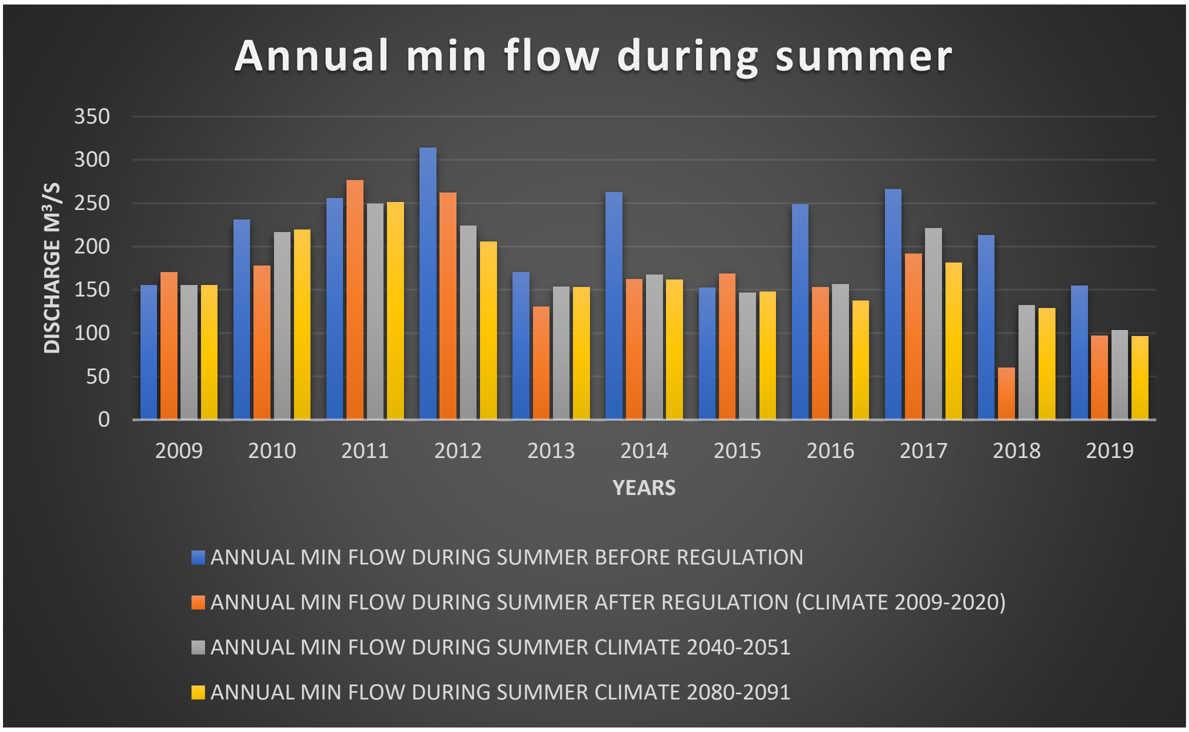


Figure 4.36: The annual minimum flow during the summer for all climate scenarios in River Glomma

c) Group 3

Group 3 represents the timing of the critical flow. Hence, the average timing of the annual low flow of A gauge is presented in Figure 4.37.

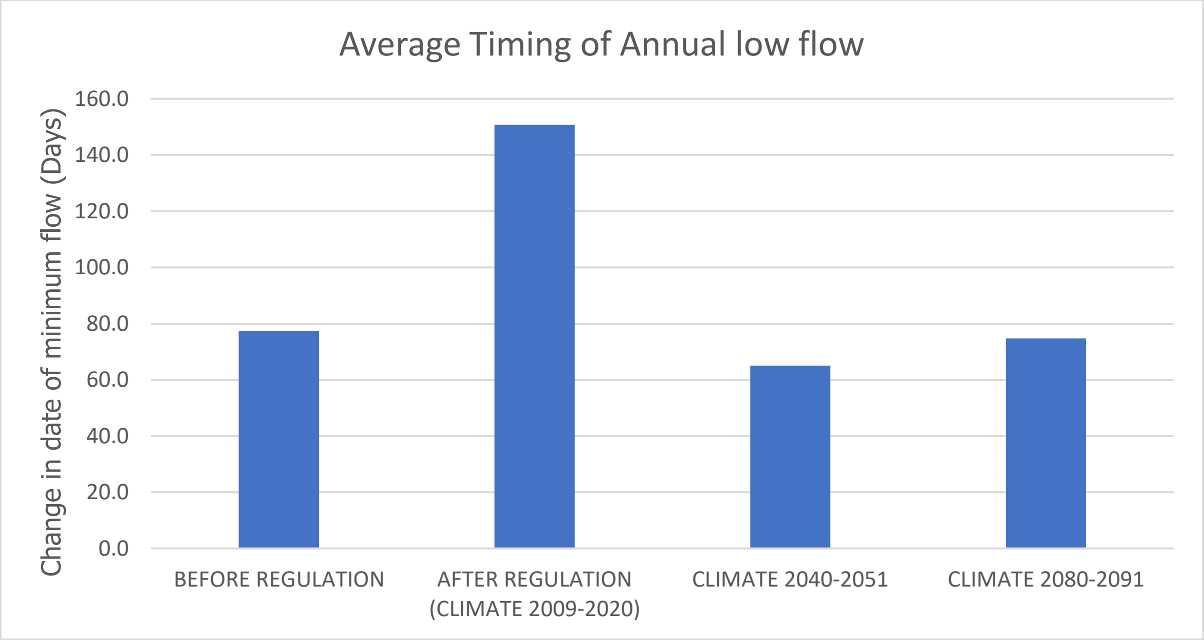


Figure 4.37: The average timing of Annual low flow for all climate scenarios in River Glomma

4.7 Evapotranspiration result of the different climate scenarios

Annual total of the actual evapotranspiration rate of all the different climate scenarios as modelled by WEAP is presented in Figure 4.38.

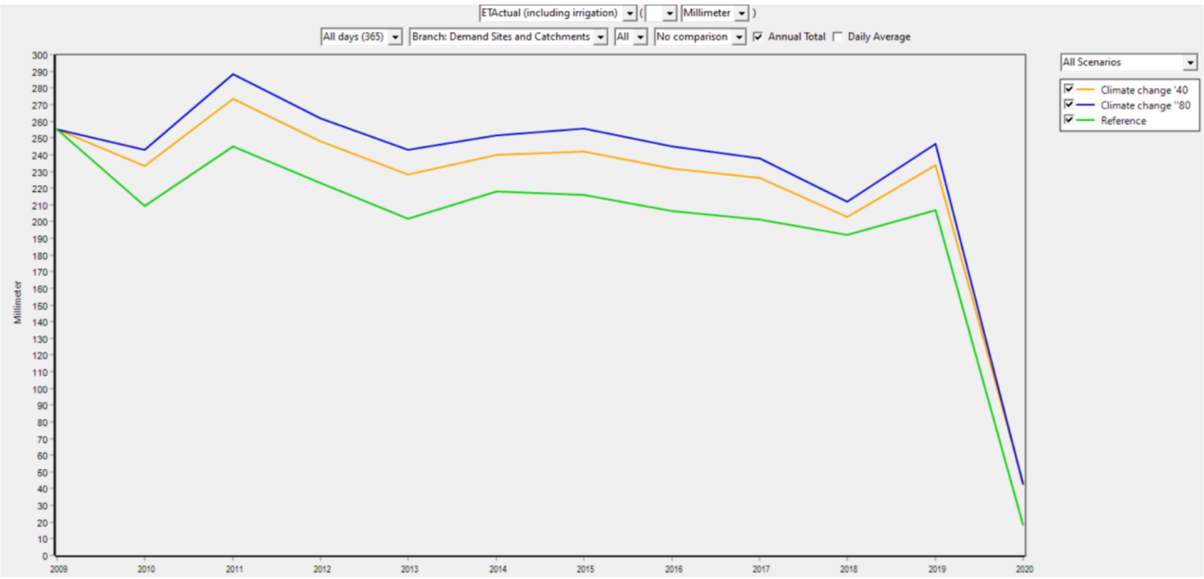


Figure 4.38: The evapotranspiration rate of Glomma catchment

4.8 Summary

The results gotten from statistical analysis and model simulations have been presented in this chapter. The results include graphical representation of Daily average streamflow, annual total streamflow, evapotranspiration rate of each of the models simulated using WEAP, under present and future climate. In addition, the 7-day minimum flow, 30-day minimum flow and the average timing of annual low flow was presented.

CHAPTER 5

DISCUSSION

5.1 Introduction

This chapter discusses the results obtained from the modelling and statistical analysis made of the two sub catchments, Folldal and Brandval and the main catchment, Glomma basin. However, it is necessary to consider uncertainties in the hydrological model WEAP which may have effects on the simulated results. It should be noted that the first two years of simulation 2009 and 2010 did not reflect the result properly, hence, it should be taken that the accuracy increased as the model worked on other years. In addition to this, the peak in Summer after regulation is higher than before regulation. This may be as a result of the model simulating an increased melting than what happens in reality.

5.2 Discussion of Results

The model performance for the sub catchments and the main catchments discussed in this thesis are as follows.

5.2.1 Discussion on Folldal Sub Catchment

The daily average and the annual total streamflow simulated showed a good fit with the historical data inputted in the model as presented in Figure 4.1 to Figure 4.2. Most of the simulated low flow match the historical time series accurately even though there were few simulated peaks that were higher than the observation data. More so, the evapotranspiration rate simulated for Folldal ranges between 125mm to 148mm as presented in Figure 4.3.

5.2.2 Discussion on Brandval sub catchment

The time series data simulated for the Brandval catchment shows to be a good fit with the historical data set due to the model calibration as shown in Figure 4.4. In Brandval catchment, there were more peaks simulated in response to the input data and the low flows seems to also fit nicely with the input data simulated higher peaks than the input data. In Figure 4.5, the daily average streamflow simulated is duly presented with the simulated runoff being a good fit with the observed runoff. Furthermore, the annual total evapotranspiration rate simulated in Brandval unregulated catchment was discovered to have be an average of 320mm-410mm as shown in Figure 4.6.

5.2.3 Discussion of the Results gotten from the performance assessment of Folldal and Brandval model calibration.

In order to check the quality of the model with reference to the Goodness of fit, according to Table 4.1, NSE and R^2 result for both Folldal and Brandval catchments were close to 1, which confirms that the calibration is good.

5.2.4 Discussion on the Result obtained from Glomma catchment before reservoir regulation.

The daily time series simulated for Glomma river showed that the discharge can be as high as 3200 m^3/s as shown in Figure 4.9 due to spring flood, however, the average discharge is around 1000 m^3/s. The average annual total runoff however is around 300m^3/s as presented in Figure 4.10, with the rate of evapotranspiration annually ranging between 220- 255mm in Figure 4.12.

5.2.5 Discussion on the comparison between the River Glomma pre and post regulation simulated results.

Using the three (3) gauges; N gauge, A gauge and G gauge, pre and post regulation condition of Glomma river was discussed. Hence, the results obtained are presented below.

5.2.5.1 Discussion of the Results from N gauge.

With emphasis on the critical periods of low flow, winter and summer, it can be seen from Figure 4.14 that there was an increase in the runoff after river regulation from November till March, hence, the reservoir has helped to sustain low flow condition during the winter. This will be especially helpful to the fish population of brown trout, which is prevalent in River Glomma, as areas with low discharge is not favorable for their spawning and nursery grounds (Heggenes et al., 1996). Equally, this will limit stranding caused by the creation of isolated ponds due to low flow in the river (Lobón-Cerviá and Sanz, 2017). In addition, the runoff during the Summer months was observed to have been reduced due to regulation. However, the peak of the Spring storage after regulation is noticed to be higher than the pre regulation period. This may be as a result of a deflection caused by the averaging of all daily data for all the years in the time series as shown in Figure 4.14. Figure 4.15 presents a daily time series result before and after regulation with the Glomma 39 representing the observation data and Glomma 30 representing the simulated runoff before regulation.

5.2.5.2 Discussion of the Results from A gauge

Figure 4.16 and Figure 4.17 shows the result of A gauge which is situated in the upstream section of Glomma river as shown in Figure 4.13. In Figure 4.16, Atna 1 which is the observed data representing the post regulation runoff shows a slight increase in the low flow during the winter which will help in sustaining the biodiversity in the river especially the fishes which dominates this section of the river; graylings and trout. As periods of low river flow are related to low survival rate in graylings, especially the young ones, the increased flow will immensely improve the survival of the graylings (Gum et al., 2009). In addition to this, It can be observed from the said Figure 4.16 that reservoir regulation helped to capture the spring flood in the river during the summer and spring, as compared to the flooding that is experienced prior to regulation as shown in Atna 2. Additionally, Figure 4.17 shows the pre and post regulation daily time series that was simulated using WEAP.

5.2.5.2 Discussion of the Results from G gauge

This gauge presented similar results to N gauge, even though it is located in the mid-section of river Glomma. From Figure 4.18, it can be observed that prior to regulation as shown by Glomma 20, the flow was really low during the winter with the spring flood resulting in high flow during the summer. However, with the introduction of regulation as shown by Glomma 19, the low flows are higher to sustain the ecology in the river more than before, especially during the winter. And in the summer, river regulation has helped to reduce the flood as it is redirected to hydropower generation. Furthermore, Figure 4.19 presents the daily time series before and after river regulation.

5.2.6 Discussion of the Results of all climate scenarios using the Glomma river.

Two scenarios were considered in this study to reflect the pre regulation period and the post regulation period in Year 2009-2020. However, to simulate the climate change effect, two additional scenarios were created to represent the projections for years 2040-2051 and 2080-2091. In the model simulation, they were represented by **climate change ’40** and **climate change ”80,** respectively. Hence, this section discusses the results that were obtained with the use of IHA indices to evaluate the simulation results obtained from the three (3) gauges for all the scenarios considered under the present and future climate. It should be noted that in Norway, as a result of precipitation being stored as snow, low flow is more prevalent in the winter. However, in the coastal regions, due to higher evapotranspiration rate and low flow period occurs during the summer (Engeland et al., 2006). Hence, these critical periods were extracted from the results and discussed as well.

5.2.6.1 Discussion of the results of N gauge and G gauges using IHA indices

A comparison between all the climate scenarios shows that N gauge and G gauge have similar results even though these two gauges are situated at downstream and mid-section of river Glomma, respectively (see Figure 4.13). Therefore, I will discuss both N and G gauge results together in this section.

a) IHA Group 1 result

Results from Figure 4.20 and Figure 4.32 shows that the streamflow after regulation from November till March is higher than the all simulated flows showing the pre regulation natural streamflow condition, for all the climatic scenarios.

b) IHA Group 2 result

Results from Figure 4.21 to Figure 4.22 and Figure 4.33 to Figure 4.34 reveal that the observed discharge after river regulation is higher than the simulated discharge which represents the natural river discharge without regulation for all climate scenarios considered. Therefore, hydropower reservoirs will sustain low flow condition under both present and future climate, even till 2091.

In addition, it can be observed from Figure 4.23 and Figure 4.35, that low flow condition has improved for all years during the winter. However, for most of the summer months as presented in Figure 4.24 and Figure 4.36, the minimum flow has reduced to less than the low flow experienced prior to regulation. This period in the summer may be critical for graylings which spawns between May and early July as discussed in section 3.4 but not for the migration of brown trout on River Glomma.

c) IHA Group 3 result

According to Yang et al. (2017), Group 3 shows the alteration of the occurrence/timing of annual extreme streamflow. Hence, as shown in Figure 4.25 and Figure 4.37, the timing of the annual minimum flow is greatly reduced due to the construction of hydropower reservoir, hence the days that it takes to experience the low flow events has a longer interval than the pre regulation periods which are represented in the climate scenarios.

5.2.6.2 Discussion of the results of A gauges using IHA indices

A gauge is situated in the upstream section of River Glomma. The results of its IHA indices are discussed below

a) Group 1 result

By using A gauge to simulate climate change, it was observed from Figure 4.26 that the low flow condition is sustained by river regulation for only the present climate and climate change ’40. climate change ”80 simulated a higher flow which is more than the current regulated low flow in River Glomma. However, in the spring flood was captured by the reservoirs.

b) Group 2 result

Figure 4.27 and Figure 4.28 shows that the reservoir regulation sustained low flow condition for pre regulation condition and climate 2040-2051, however, for some years, the Climate change in 2080-2091 showed there would be higher low flow than expected. This can be as a result of the noticeable increase in evapotranspiration rate in future climates relative to the present climate, as shown in Figure 4.38.

In addition, it can be observed from Figure 4.29 and Figure 4.30 that this section of Glomma river will experience more low flow periods during winter and summer especially in 2080-2091 period. Hence, the discharge released as post regulation flow can be increased during this period, so as to sustain the biodiversity in the river.

c) Group 3 result

According to Yang et al. (2017), Group 3 shows the alteration of the occurrence/timing of annual extreme streamflow. Hence, as shown in Figure 4.31, the average number of days of the annual low flow condition is not particularly mitigated at this section of River Glomma.

This is because, the number of days on which low flow occurs prior to regulation is still higher than after regulation.

5.2.6.2 Discussion of the evapotranspiration result for all climate scenarios

In the model setup, it was observed that the actual catchment evapotranspiration rate did not change prior to and after river regulation as seen in the results shown in Figure 4.12 and Appendix D. However, the climate change scenarios simulated a higher evapotranspiration rate than the one in present climate (see Figure 4.38).

CHAPTER 6

CONCLUSION

6.1 Summary

This thesis has assessed the impacts of reservoirs on low flow condition in Glomma basin with reference to present and future climate using WEAP model.

6.2 Contribution

With the use of historical data, the streamflow in river Glomma was calibrated with two smaller basins Folldal and Brandval to simulate the pre regulation natural streamflow conditions, after which three (3) gauges were inputted to simulate the post regulation streamflow condition while monitoring the time series simulated accordingly. Hence, the catchment evapotranspiration rate (ET Actual), daily average river runoff and annual total river runoff was simulated. In addition, the melting point, freezing point, and the initial snow was employed in testing the snow module in this calibration process and found to work well in relation to the result simulated.

The result obtained was split according to the seasons which are summer, autumn, winter, and spring before extracting the data for the critical periods of winter and summer when low flow is prevalent in Norway. Then the low flow was calculated for the present and future climate using the Indicators of Hydrologic Alteration (IHA) Indices for both the pre and post regulation streamflow. Hence, results were derived from Group 1 to 3 of the IHA, which for the purpose of this thesis entails the 1-day minima, 7-day minima and 30-day minima. In addition, the timing of the low flow for each of the years was analyzed. The results are projected as tables, graphs, and maps. Therefore, the effect of climate change on the low flow was assessed and the scenarios analyzed for climate change can be used for advising stakeholders and policy makers.

6.3 Limitations

Although this thesis has explored and assessed the role that hydropower reservoirs play in sustaining ecologically viable low flow condition under present and future climate, it does have some limitations.

In this study, the contribution of the ground water to the precipitation and temperature data was not considered. Also, the thesis focused on the impact pathway of climate change in relation to low flow condition, however, it did not incorporate hydropower plants and their influence due to system priority and energy demand.

6.4 Future works

This thesis looked at only one function of WEAP which is its simulation of Streamflow. However, there are a lot of other interesting functionalities which can be used to create a bigger perspective of water resource management. hence:

- it would be good to consider the economic impact of climate change on hydropower reservoirs.
- More data can be collected to incorporate the effect of the power stations and ground water inflow and outflow in the study.
- The reservoir operating rules can be incorporated to better simulate the effect of drought on low flow condition.
- The economic consequences of the low flow condition and climate change can be considered.

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APPENDIX

APPENDIX A: N GAUGE

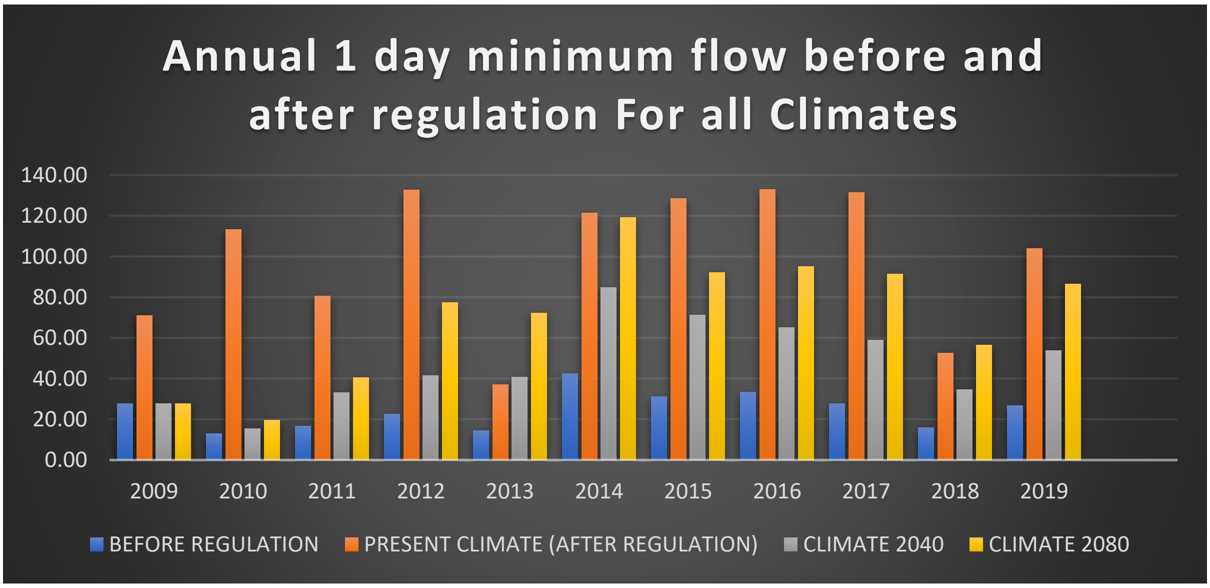
IHA GROUP 1 RESULT

Months	1	2	3	4	5	6	7	8	9	10	11	12
BEFORE REGULATION	59.9	34.4	35.9	177.6	505.6	574.7	453.8	482.5	379.3	242.3	158.7	85.9
PRESENT CLIMATE (AFTER REGULATION)	189.9	170.7	171.3	344.7	738.7	486.9	342.7	393.8	366.1	285.3	284.7	197.6
CLIMATE 2040	99.3	65.9	88.0	296.7	528.2	431.8	378.8	468.6	391.2	273.5	235.7	139.7
CLIMATE 2080	144	111	136.5	339.1	526.7	418.2	375.8	477.8	402.7	282.6	244.9	177.0

IHA GROUP 2 RESULT

ANNUAL 1 DAY MIN

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
BEFORE REGULATION	27.87	13.02	16.74	22.63	14.56	42.50	31.20	33.54	27.67	16.05	26.69
PRESENT CLIMATE (AFTER REGULATION)	71	113	81	133	37	121	129	133	131	53	104
CLIMATE 2040	28	15	33	42	41	85	71	65	59	35	54
CLIMATE 2080	28	20	41	77	72	119	92	95	92	57	87



ANNUAL 7 DAYS MIN

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
BEFORE REGULATION	28.35	13.27	17.19	23.06	14.82	43.43	31.74	34.29	29.10	16.46	27.19
PRESENT CLIMATE (AFTER REGULATION)	73	116	86	136	49	124	162	144	146	61	117
CLIMATE 2040	28	16	34	43	42	89	75	69	63	36	56
CLIMATE 2080	28	20	42	81	76	126	100	100	97	60	90

ANNUAL 30 DAYS MIN

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
BEFORE REGULATION	30.52	14.50	17.96	24.03	17.02	46.28	33.74	38.28	31.39	18.44	27.87
PRESENT CLIMATE (AFTER REGULATION)	87	125	95	157	76	156	181	148	156	70	151
CLIMATE 2040	31	17	38	49	46	112	83	82	73	41	58
CLIMATE 2080	31	22	57	93	84	157	122	129	119	68	104

ANNUAL MIN FLOW DURING SUMMER

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
BEFORE REGULATION	165	295	289	367	187	279	176	293	322	218	168
PRESENT CLIMATE (AFTER REGULATION)	192.4	253.4	349.0	320.9	144.3	172.4	191.1	167.5	210.8	52.7	104.0
CLIMATE 2040	165	279	287	246	173	197	169	175	232	137	116
CLIMATE 2080	165	282	289	227	172	188	170	155	192	133	109

ANNUAL MIN LOW FLOW DURING WINTER

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
BEFORE REGULATION	41	15	18	23	22	42	32	38	28	22	27
PRESENT CLIMATE (AFTER REGULATION)	129	120	98	152	117	150	162	141	131	143	133
CLIMATE 2040	41	16	33	42	41	85	71	65	59	45	54
CLIMATE 2080	41	20	41	77	72	119	120	95	92	78	87

IHA GROUP 3 RESULT: TIMING

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Average
BEFORE REGULATION	79	69	79	59	90	44	65	72	49	78	65	**68.09**
PRESENT CLIMATE (AFTER REGULATION)	85	330	80	65	103	276	327	312	54	206	218	**186.9**
CLIMATE 2040	79	66	21	52	83	37	54	25	47	77	40	**52.82**
CLIMATE 2080	79	57	8	49	48	37	310	25	47	77	38	**70.45**

APPENDIX B: A GAUGE

IHA GROUP 1 RESULT

Monthly averages all years

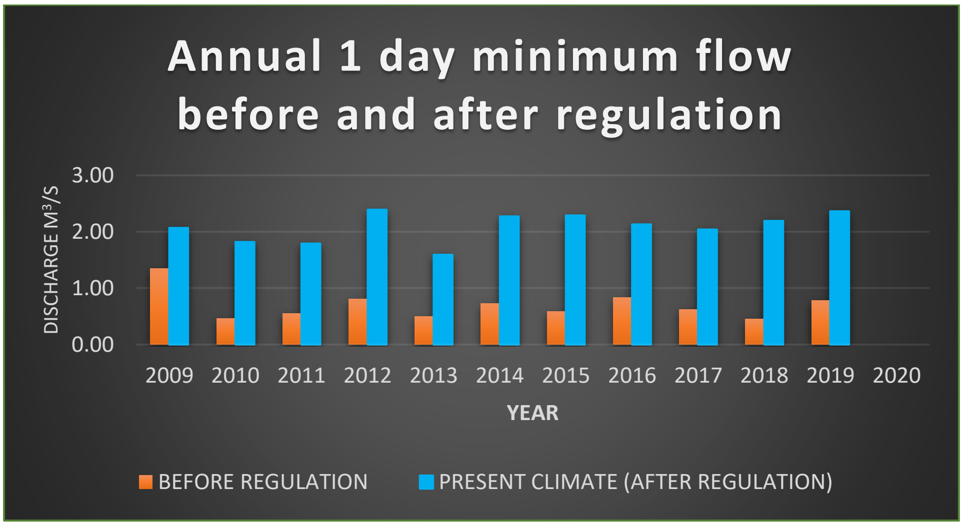
Months	1	2	3	4	5	6	7	8	9	10	11	12
BEFORE REGULATION	2.1	1.2	0.9	2.2	15.4	35.2	26.4	26.3	16.9	9.6	5.0	2.7
PRESENT CLIMATE (AFTER REGULATION)	3.4	2.6	2.5	4.7	21.4	21.9	19.4	18.6	16.0	11.1	7.1	4.7
CLIMATE 2040	3.0	1.8	2.1	6.9	23.4	23.4	24.1	26.6	17.5	10.9	7.5	4.0

CLIMATE 2080	3.8	2.6	3.4	9.3	24.1	23.0	24.6	27.1	17.9	11.1	7.7	4.5

IHA GROUP 2 RESULT

ANNUAL 1 DAY MIN

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
BEFORE REGULATION	1.34	0.46	0.55	0.81	0.50	0.73	0.59	0.83	0.62	0.45	0.78
PRESENT CLIMATE (AFTER REGULATION)	2	2	2	2	2	2	2	2	2	2	2
CLIMATE 2040	1	1	1	1	1	1	1	2	2	1	2
CLIMATE 2080	1	1	1	2	2	3	2	2	3	1	3



ANNUAL 7 DAYS MIN

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
BEFORE REGULATION	1.41	0.48	0.57	0.84	0.51	0.75	0.61	0.87	0.65	0.47	0.81
PRESENT CLIMATE (AFTER REGULATION)	2.10	1.85	1.81	2.46	1.60	2.31	2.36	2.16	2.13	2.21	2.39
CLIMATE 2040	1.41	0.56	0.78	1.45	0.81	1.51	1.54	1.60	2.06	0.71	1.66
CLIMATE 2080	1.41	0.57	0.93	1.71	1.77	2.81	2.00	2.52	3.48	0.84	2.94

ANNUAL 30 DAYS MIN

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
BEFORE REGULATION	1.41	0.50	0.63	0.95	0.59	0.80	0.70	1.00	0.73	0.53	0.93
PRESENT CLIMATE (AFTER REGULATION)	2.20	1.94	1.88	2.59	1.66	2.49	2.53	2.29	2.35	2.26	2.62
CLIMATE 2040	1.65	0.60	0.82	1.53	0.94	1.77	1.81	1.87	2.40	0.76	1.93
CLIMATE 2080	1.42	0.63	1.02	1.81	2.06	3.16	2.24	2.96	3.48	0.95	3.43

ANNUAL MIN FLOW DURING SUMMER

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
BEFORE REGULATION	10.06	17.42	15.65	12.65	11.81	10.98	10.36	11.84	14.50	10.58	8.10
PRESENT CLIMATE (AFTER REGULATION)	11.48	12.71	13.12	12.29	9.04	9.65	11.02	10.63	11.05	6.40	8.32
CLIMATE 2040	10.06	17.12	15.99	12.00	11.22	5.79	9.69	7.54	10.81	6.93	6.62
CLIMATE 2080	10.06	14.50	16.24	12.20	11.28	5.56	9.51	7.01	10.14	7.44	6.55

ANNUAL MIN LOW FLOW DURING WINTER

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
BEFORE REGULATION	1.35	0.60	0.78	0.92	0.82	0.74	0.89	1.00	0.85	0.78	1.08
PRESENT CLIMATE (AFTER REGULATION)	2.22	2.07	1.99	2.39	1.91	2.61	2.88	2.24	2.40	2.85	2.82
CLIMATE 2040	1.35	0.59	0.80	1.41	1.39	1.45	1.46	1.92	2.02	0.96	2.03
CLIMATE 2080	1.35	0.60	0.90	1.66	2.22	2.69	1.89	3.07	3.26	1.11	3.16

IHA GROUP 3 RESULT

TIMING ANNUAL MIN

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Average
BEFORE REGULATION	92	97	91	70	105	65	96	72	84	103	86	**87**
PRESENT CLIMATE (AFTER REGULATION)	92	72	80	59	102	87	97	72	84	104	86	**85**
CLIMATE 2040	92	66	79	68	104	53	37	72	43	94	79	**72**
CLIMATE 2080	92	66	56	53	104	40	27	71	365	80	78	**94**

APPENDIX C: G GAUGE

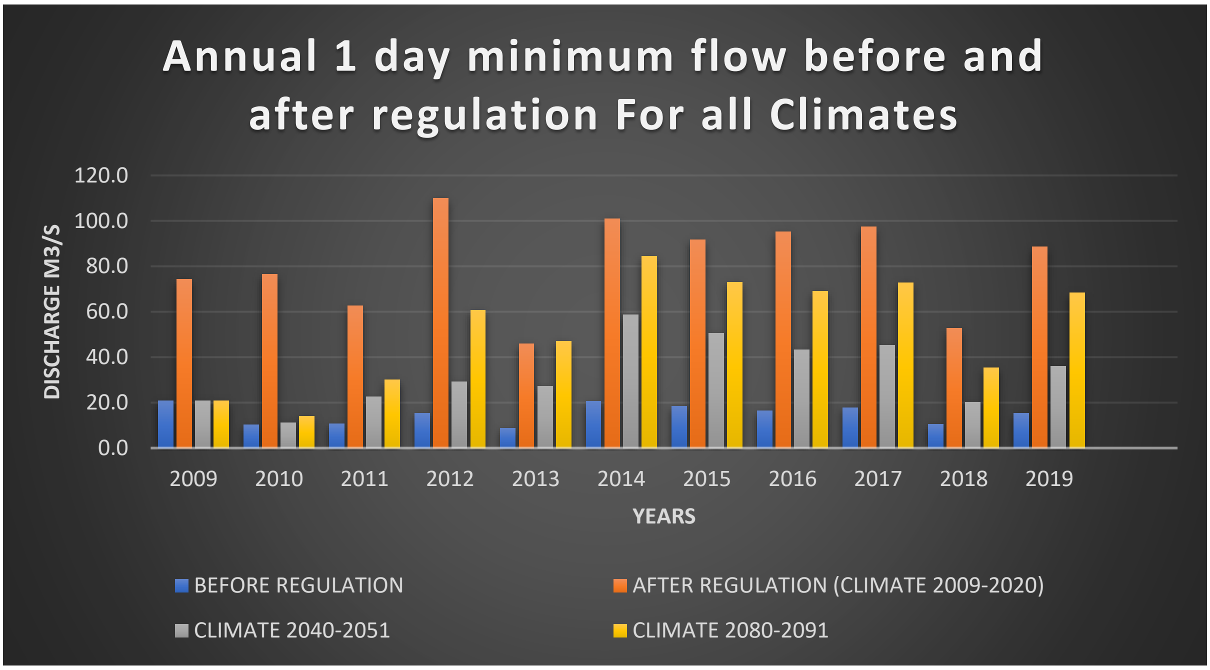
IHA GROUP 1 RESULT

Months	1	2	3	4	5	6	7	8	9	10	11	12
BEFORE REGULATION	40.2	22.8	20.7	99.5	402.2	524.4	415.4	415.1	306.2	183.9	108.1	56.2
PRESENT CLIMATE (AFTER REGULATION)	152.0	141.6	128.5	218.3	603.3	411.2	298.2	328.2	283.7	222.2	197.9	142.4
CLIMATE 2040	67.8	44.7	59.7	211.8	451.0	389.2	339.4	400.9	316.4	212.7	168.6	97.1
CLIMATE 2080	99.2	77.3	98.3	255.5	451.1	374.4	335.8	408.6	325.2	219.6	175.0	123.8

IHA GROUP 2 RESULT

ANNUAL 1 DAY MIN

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
BEFORE REGULATION	20.93	10.22	10.75	15.25	8.82	20.54	18.35	16.40	17.73	10.45	15.28
PRESENT CLIMATE (AFTER REGULATION)	74.31	76.53	62.68	110.02	45.84	101.01	91.75	95.28	97.40	52.70	88.65
CLIMATE 2040	20.93	11.09	22.66	29.19	27.17	58.77	50.55	43.20	45.20	20.16	35.98
CLIMATE 2080	20.93	14.02	29.97	60.72	47.06	84.42	72.92	69.12	72.81	35.31	68.33



ANNUAL 7 DAYS MIN

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
BEFORE REGULATION	21.7	10.5	11.1	15.7	9.1	21.0	18.9	17.2	18.1	10.6	15.7
PRESENT CLIMATE (AFTER REGULATION)	75.8	84.9	74.3	116.3	46.9	104.2	98.0	110.4	108.2	54.5	100.3
CLIMATE 2040	21.7	11.3	23.5	30.4	28.0	63.2	52.7	44.3	47.8	21.0	37.0
CLIMATE 2080	21.7	14.4	30.9	63.9	50.2	89.6	77.1	72.5	77.0	37.4	71.8

ANNUAL 30 DAYS MIN

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
BEFORE REGULATION	24.8	11.6	12.2	16.7	10.2	22.7	20.5	19.9	19.5	11.1	17.7
PRESENT CLIMATE (AFTER REGULATION)	86.2	90.5	80.0	132.9	65.3	134.6	127.8	113.2	108.6	73.5	110.5
CLIMATE 2040	24.8	12.7	25.3	35.5	31.6	74.5	54.7	50.9	55.4	24.4	40.0
CLIMATE 2080	24.8	15.8	41.6	71.7	57.3	107.7	85.6	90.6	94.0	44.0	77.8

ANNUAL MIN FLOW DURING SUMMER

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019

BEFORE REGULATION	155	231	256	314	170	263	153	249	266	213	155
PRESENT CLIMATE (AFTER REGULATION)	170.6	177.7	276.3	262.3	130.8	162.4	168.6	153.1	191.5	59.9	97.0
CLIMATE 2040	155	217	249	224	153	168	147	156	221	132	103
CLIMATE 2080	155	219	251	206	153	162	148	137	181	129	96

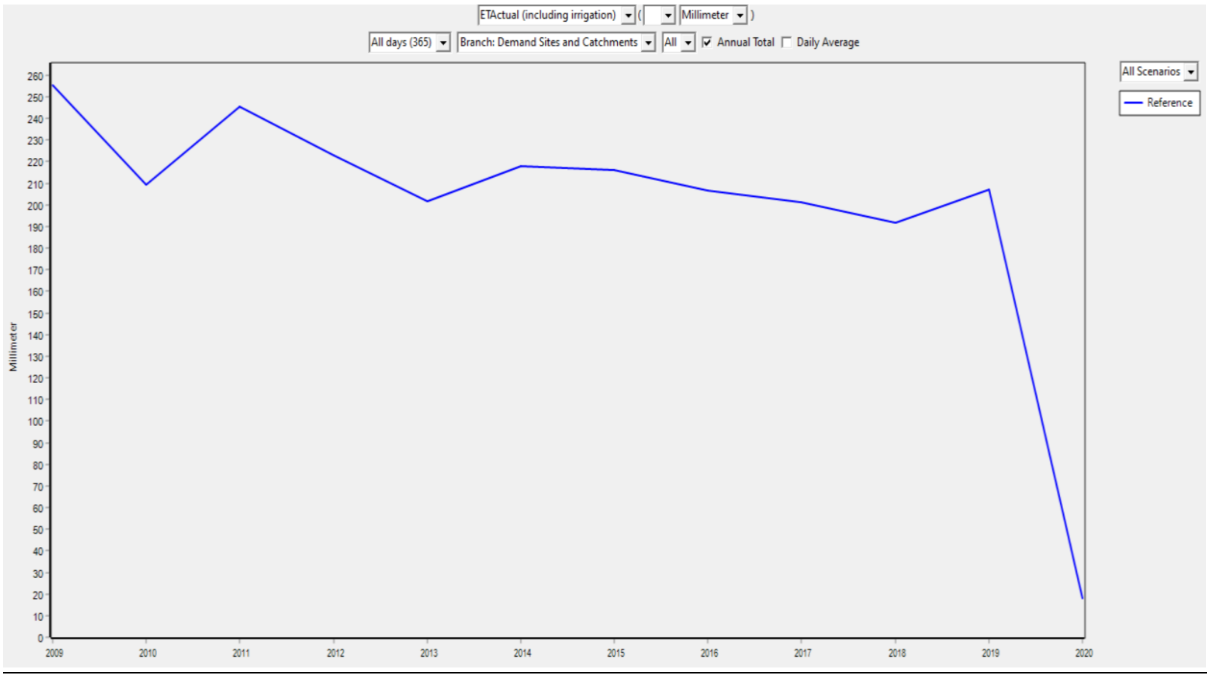
ANNUAL MIN LOW FLOW DURING WINTER

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
BEFORE REGULATION	32	12	14	15	15	21	20	20	19	14	19
PRESENT CLIMATE (AFTER REGULATION)	119	91	80	134	94	125	94	105	97	93	106
CLIMATE 2040	32	12	23	29	27	59	51	46	45	27	38
CLIMATE 2080	32	15	30	61	47	84	77	69	73	51	68

IHA GROUP 3 RESULT: TIMING

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Average
BEFORE REGULATION	90	77	79	59	102	64	65	72	70	94	78	**77.3**
PRESENT CLIMATE (AFTER REGULATION)	84	73	95	70	100	274	100	317	360	97	88	**150.7**
CLIMATE 2040	90	66	61	53	87	38	48	72	47	77	76	**65.0**
CLIMATE 2080	90	66	16	44	48	37	330	24	47	77	43	**74.7**

APPENDIX D: EVAPOTRANSPIRATION RATE OF GLOMMA RIVER AFTER REGULATION


ETActual (including irrigation) ( ) Millimeter)

All days (365) Branch: Demand Sites and Catchments All ☑ Annual Total ☐ Daily Average

All Scenarios

Folakemi Ope Olabiwonnu

NTNU
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