Sergey Popov

# Assessment of the effect of reservoir sedimentation and lost storage capacities in Devoll basin, Albania, on power production under present and future climatic conditions

Master's thesis in Water Resources Modeling and Engineering
Supervisor: Tor Haakon Bakken
Co-supervisor: Slaven Conevski
December 2023

**Master's thesis**

**NTNU**
Norwegian University of Science and Technology
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# ABSTRACT

Energy consumption in Albania is increasing every year and the huge potential of renewable energy sources has not yet been tapped. In 2016 and 2020, the Norwegian company Statkraft developed and put into operation two new hydropower stations in Banja and Moglice with reservoirs of the same name in the Devoll River valley. It is expected to cover 17% of the country's needs. Reservoirs can store large quantities of water for energy production and have a significant role of smoothing and protecting against flood peaks. However, the region contains enormous amounts of sediment, which reduces reservoir capacity and energy output.

The purpose of this thesis is to develop and improve the existing hydraulic model in Water Assessment and Planning (WEAP) software. A comparative analysis of climate data in the region taken from meteorological stations with those built into the WEAP was carried out. A model containing 9 sub-basins was developed, which corresponds to reality when assessing PBIAS (less that 10%) with high accuracy. Two reservoirs were added to the model and the change in reservoir capacity over time was taken into account. A set of 8 future scenarios were formulated and simulated for this system.

The main finding is that the total annual energy production at the two hydropower plants Banja and Moglice will be about 100 GWh in 2050-2060. Sediments have a huge impact on hydropower production, the difference could be up to 15% (CMIP6 ACCESS-CM2 SSP245) over the period 2050-2060, with a decrease in reservoir capacity of 0.86% per year for Banja. Comparative analysis showed that total precipitation from Princeton (built-in WEAP) differs from the Thiessen polygon-recalculated weather station series, with a PBIAS of 12.7%.

# SAMMENDRAG

Energiforbruket i Albania øker hvert år, og det enorme potensialet til fornybare energikilder er ennå ikke utnyttet. I 2016 og 2020 utviklet og satt det norske selskapet Statkraft i drift to nye vannkraftstasjoner i Banja og Moglice med magasiner med samme navn i Devollelvedalen. Det forventes å dekke 17 % av landets behov. Reservoarer kan lagre store mengder vann for energiproduksjon og har en betydelig rolle som utjevning og beskyttelse mot flomtopper. Regionen inneholder imidlertid enorme mengder sediment, noe som reduserer reservoarkapasiteten og energiproduksjonen.

Hensikten med denne oppgaven er å utvikle og forbedre den eksisterende hydrauliske modellen i programvare for vannvurdering og planlegging (WEAP). En komparativ analyse av klimadata i regionen hentet fra meteorologiske stasjoner med de som er innebygd i WEAP ble utført. Det ble utviklet en modell som inneholder 9 underbassenger, som samsvarer med virkeligheten ved vurdering av PBIAS (mindre enn 10%) med høy nøyaktighet. To magasiner ble lagt til modellen og endring i magasinkapasitet over tid ble tatt i betraktning. Et sett med 8 fremtidsscenarier ble formulert og simulert for dette systemet.

Hovedfunnet er at den samlede årlige energiproduksjonen ved de to vannkraftverkene Banja og Moglice vil være om lag 100 GWh i 2050-2060. Sedimenter har en enorm innvirkning på vannkraftproduksjonen, forskjellen kan være opptil 15 % (CMIP6 ACCESS-CM2 SSP245) over perioden 2050-2060, med en nedgang i reservoarkapasitet på 0,86 % per år for Banja. Komparativ analyse viste at total nedbør fra Princeton (innebygd WEAP) skiller seg fra Thiessen polygon-omregnet værstasjonsserie, med en PBIAS på 12,7 %.

# PREFACE

This thesis is submitted in partial fulfillment of the requirements for the Master's degree in Hydropower Development at the Department of Civil and Environmental Engineering at the Norwegian University of Science and Technology (NTNU). This contains the work done from mid-August to mid-December 2023 under the supervision of Professor Tor Haakon Bakken (NTNU) and co-supervisor Slaven Conevski (NTNU/Multiconsult).

This study attempted to develop and improve a hydraulic model to evaluate the impact of sedimentation on reservoir capacity loss and power production. It was an extremely rewarding learning experience in terms of the knowledge and skills acquired. The topic of this research is relevant and the findings might contribute to improving people’s lives in the future. All the simulations done with the model and the conclusions drawn can be used for further development and deepening of this area of research.

I would like to thank my supervisor Tor Haakon Bakken for his close collaboration, unwavering support and quick responses at any time of day. His professional expertise in the field of water resources has been truly inspirational for me. I am also very grateful to Slaven Conevski for the data provided and his assistance in writing this work. In addition, I would like to express my gratitude to Oddbjørn Bruland and all the academic staff from the Department of Hydropower Development for these 2 years of study in Norway and for imparting their knowledge and love for science. I also want to thank Christian Almestad for his very research on hydropower in the region, which I found extremely valuable. Finally, last but not least, Lika Razina’s moral support and help with creating the graphs were also of great importance to me.

While writing this thesis, I was often stressed due to the difficult political situation in Russia, but my research allowed me to become absorbed in this work and take my mind off the negative thoughts. Science is the best treatment.

Trondheim, December 2023

Sergey Popov

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# Abbreviations

**CMIP6** Coupled Model Intercomparison Project 6
**DEM** Digital Elevation Model
**GIS** Geographic Information System
**HRWL** Highest Regulated Water Level
**LAI** Leaf Area Index
**LRWL** Lowest Regulated Water Level
**NSE** Nash-Sutcliffe Efficiency
**PBIAS** Percentage BIAS
**RRF** Runoff Resistance Factor
**WEAP** Water Evaluation and Planning

# 1 INTRODUCTION

Water has been the most important resource for human survival for many centuries. On the one hand, approximately 70% of our planet is covered with water and according to various estimates, there is only 35 million km$^3$ of drinking water, of which only 0,26% is stored in lakes, rivers and reservoirs (Alsharhan, 2020). On the other hand, the possession and control of such a fundamental source which allows a person to make their life more comfortable, safer and better, is the main challenge of the 21-st century. In addition, a very important factor is the almost doubling of the population over the past 50 years, which directly affects human water consumption. Thus, if in 1970 there was an average of 12,900 m$^3$ of water per person, then by 2014 this number had already dropped to 5,926 m$^3$ (Alsharhan, 2020). Another factor at play is global warming, which may well lead to a decrease in precipitation and should also be considered when predicting future water consumption.

To better control water resources, more than 58,000 large dams (higher than 15 m) have been built around the world (Poff, 2016). These dams serve very different purposes, namely: supplying water to municipalities, irrigation, hydropower generation, reducing risks associated with flood peaks, transportation and navigation. Dams and reservoirs, depending on their purpose, can be divided into multi-purpose and single-purpose. According to ICOLD, about 70% of large dams and associated reservoirs are built for single purpose use, as this makes them more attractive to private investors.

However, one of the biggest challenges for engineers operating reservoirs for any purpose is sedimentation. Sediments are solid materials formed by weathering and erosion and that are subsequently transported by wind, water or ice or by the force of gravity that acts on particles. Sediments is the least studied topic and a parameter that is the most difficult to predict in hydropower. Meanwhile, it has a considerable impact on energy production. Reservoirs lose about 1% of their capacity each year due to sedimentation (Petkovsek, 2014). There are several methods of sediment control, namely: reducing sediment yield through erosion control and upstream sediment capture, managing flows during periods of high sediment yield to minimize entrapment in reservoirs, and removing sediment already trapped in reservoirs using a variety of techniques. But it is also very important to study this phenomenon at the design stage before it occurs.

The Norwegian energy company Statkraft AS has developed and built two of the largest hydroelectric power plants in Albania over the past few years (2016-2020). The purpose of this master thesis is to develop a hydrological model in the Water Evaluation and Planning (WEAP) tool to simulate flows similar to reality and study the impact of the two new reservoirs on agriculture, hydropower production, as well as consider possible climate and sediments scenarios in the nearest future.

# 2 DESCRIPTION OF THE STUDY AREA

This chapter describes in some detail the area that is explored in the thesis. All important aspects and assumptions which will be used further to build the model and simulate the hydraulic processes will be shown here. In order to better understand the character and features of the Devall River Basin area, it is also necessary to have a general understanding of Albania as a country. This chapter will also review and analyze data from weather stations and highlight some of the ideas Christian Almestad used when writing his master thesis.

## 2.1. Albania

Albania is a tiny country located in the western part of the Balkan Peninsula (the southeastern region of Europe). This country has a wide variety of terrain and climate. The western coastal regions of the country are bordered by the Ionian and Adriatic seas. Albania has land borders with 4 other states: Montenegro; Kosovo, North Macedonia and Greece.  (World Atlas)

**Figure 2.1.** Albania on the map (World Atlas)

The Drin and Vlore are the two largest rivers in Albania, they flow from the mountains to the Adriatic Sea. Also in Albania there are three large lakes called Shkodra, Prespa and Ohrid (Ohrid is the deepest lake in the Balkans with the depth of 284 meters). Tirana is the capital of Albania. It is the most populous city in the country (520,000 people in 2023), which is both the economic and administrative center of the country. The population of the whole of Albania is about 2.8 million people.

According to Land Cover Data Assessment in Albania: the total territory of the country is 28,748 km$^2$, of which 24% is agricultural land, 36% is forest and 16% is pasture and meadow. The remaining 24% is classified as other, which includes urban areas, lakes, waterways and unused rocky areas. More than 75% of the total relief area is mainly hilly and mountainous (Brahushi, 2018; Fra, 2010).

The land cover of Albania has undergone significant changes over the years, largely due to the influence of natural phenomena and human activity. The term "land cover/land use" in relation to Albania was first used in literature after 1990, as human factors such as land abandonment, deforestation, overgrazing and construction began to have a greater impact (Nicolli, 2010). The migration of people from rural to urban areas, as well as immigration, has resulted in more than 45% of agricultural land remaining uncultivated or abandoned for extended periods of time (Brahushi and Alikaj, 2019). Conversely, land privatization and fragmentation have led to rapid urbanization of farmland. Currently, urbanization poses a serious threat to Albania's land resources due to the construction of infrastructure and industrial development, resulting in the loss of fertile lands (Brahushi, 2018).

### 2.1.1. Climate

Albania's climate can generally be characterized as having warm and dry summers and cool and wet winters. However, due to the large differences in altitude within the country, the weather can vary greatly from region to region. For example, the western part, under the influence of warm sea air, has a more temperate climate compared to the eastern part. The average annual temperature can vary from 8 degrees Celsius in the mountains to 16 degrees Celsius in the lowlands. The amount of precipitation in Albania is quite significant, but it is also unevenly distributed over the territory and is seasonal. According to various estimates, the average annual precipitation in Albania is about 1485 mm and up to 80% falls in the winter season from October to March (Porja, 2014).

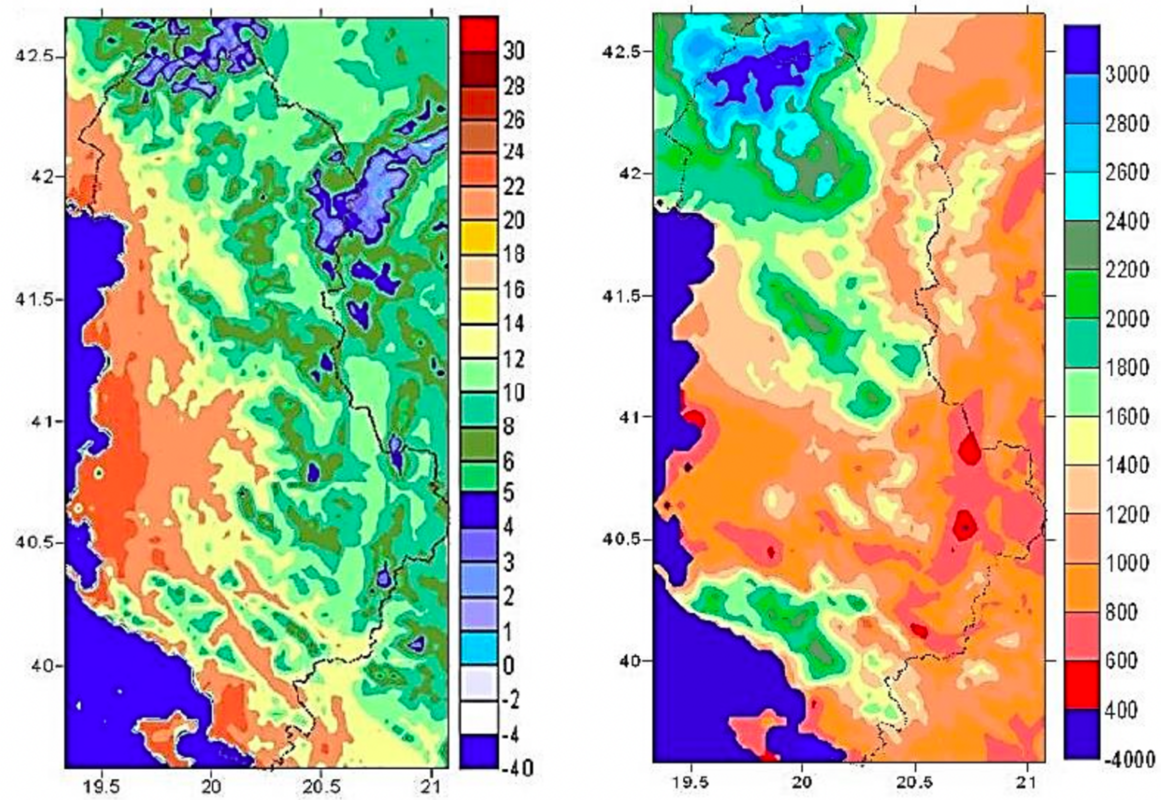


**Figure 2.2.** Distribution of mean annual temperature (C, left) and precipitation (mm, right) (Porja, 2014)

### 2.1.2. Agriculture

Agriculture has a long history in Albania and remains the main source of income for most of the population. It accounts for almost 30% of GDP and employs more than half of the workforce. About 24% of the country's land is arable, equivalent to 690,000 hectares. During the socialist regime, the amount of arable land increased significantly due to the conversion of pastures and forests, as well as land reclamation. By 1990, there were 550 state and collective farms covering an area of about 550,000 hectares. However, since the collapse of the socialist regime in 1991, the agricultural sector has undergone dramatic changes. The government redistributed and subdivided 550,000 hectares of farms into small family plots. Currently, there are approximately 400,000 smallholder farmers who own less than 1.2 hectares each, further divided into different plots. Approximately 25% of arable land is no longer in use, and only a few farms practice intensive farming for the market.

### 2.1.3. Irrigation

Irrigation plays a critical role in the agricultural sector as less than 20% of the annual rainfall falls between April and September. This results in significant water shortages in the summer, making irrigation essential for growing summer crops. The socialist era created a comprehensive network of irrigation systems, covering about 80% of state-owned farms and cooperatives by the mid-1980s. These schemes used surface water resources including reservoirs, river flow storage and pumping stations. More than 600 pumping stations and about 640 dams were built to meet irrigation needs. Most dams were small and located on small rivers and streams, while some were off-river, transferring water by diversion, pumping, or both. Drainage systems were also developed, mainly as part of irrigation schemes, and associated with embankments for flood control.

Irrigation and drainage schemes were designed in a grid pattern consisting of primary, secondary and tertiary canals. Primary channels followed the contours of the terrain, secondary channels were aligned with the slope and perpendicular to the primary ones, and tertiary channels were always perpendicular to the secondary channels and ran across the slope. Secondary schemes, such as hill schemes, were less structured and based on the topography of the site. Approximately 70% of the channels were not aligned. The control system of the irrigation system was simple, there were no cross regulators in the main canals, and simple vertical gate valves were used on the branches of the secondary canals. The irrigation system design was based on a hydro module with a flow rate of 1.0 to 1.2 liters per second per hectare, providing a control area of 100 hectares with a flow rate of 100 to 120 liters per second. The canals were expected to operate continuously, providing a minimum irrigation efficiency of 50% to meet irrigation demands during the peak summer period (July and August). In total, irrigation and drainage systems covered approximately 424,000 and 278,000 hectares, respectively (Almestad, 2015).

### 2.1.4. Infrastructure

Many (over 600) of the dams in Albania were built about 40-60 years ago. The main purpose was irrigation, but some of the dams were also used for hydropower production and flood protection. At the moment, many dams have been damaged, as a result of which the capacity of the reservoirs has been halved. According to some estimates, Albania requires about 1 billion cubic meters of water from rivers and reservoirs per season for irrigation, drainage and flood protection, however, the current supply is 30-40% lower than necessary.

In recent decades, a large number of forests have been cut down in Albania, resulting in many major floods. Another reason for this phenomenon may be improper maintenance of drainage canals and pumping stations, which makes pumping water difficult. Floods have occurred mainly between May and December over the past 20 years. Due to climate change, rainfall is expected to fall less frequently but in greater amounts, leading to even more severe impacts. This is why it is so important to work out the drainage and water storage system in advance (World Bank Group, 2022).

## 2.2. Devoll River Basin

This catchment is located approximately 50 km south of the capital Tirana. The Seman River flows predominantly from southeast to northwest and changes its name to the Devoll River. The altitude varies from 22 meters at the lowest point to 2384 meters at the highest. The average altitude of the catchment is 961 meters above sea level. The area is approximately 3130-3140 m2. A little north of the catchment there are two large lakes, Prespa and Ohrid, which also have a direct impact on the river basin (this will be discussed later). In the southeast of the basin there is also an extensive valley with the Tomorrice River, which flows into the Devoll River downstream. There are no large settlements in this area except Zemblak, Gramsh, Korce, Maliq.

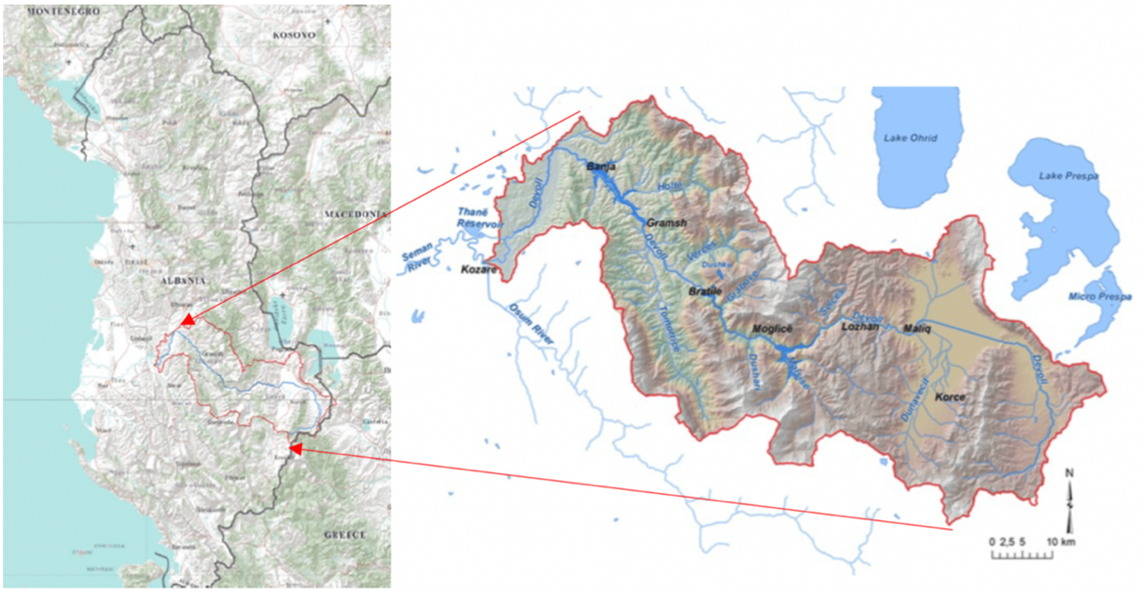


**Figure 2.3.** a) Location of the Devoll River Basin within Albania (red outline) b) Main places and tributaries (Statkraft, 2017)

### 2.2.1. Climate and Hydrology

Due to the large difference in altitude, the climate varies quite widely throughout the basin. Typically, January is the coldest month, while July is the hottest. The average annual temperature reaches 15 degrees Celsius in the mountains and only 5 degrees Celsius in the lowlands. Topography has a strong influence on the pattern and amount of precipitation. The greatest amount of precipitation falls in the winter season, and the summer months are usually quite dry. In the mountainous parts there is snow for quite a long time (sometimes more than 90 days). This causes heavy runoff in May during snowmelt. Thus, the specific flow from some subbasins is significantly higher than others.

### 2.2.2. Devoll Hydropower Project

The Devoll Hydropower Project consists of two hydropower plants: Banja (72 MW) and Moglice (184 MW), both of which are located on the Devoll River. It is planned that this project will increase electricity generation in the region by 15-17% and will help balance the system, avoiding losses during transmission from north to south.

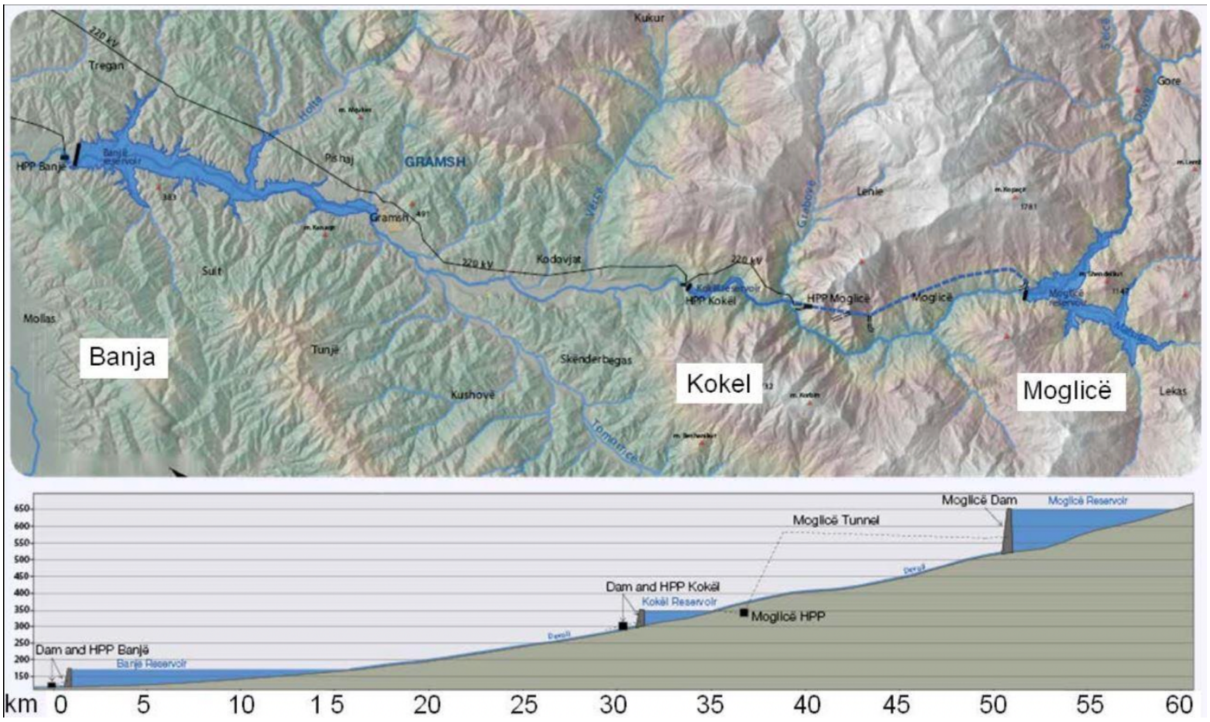


**Figure 2.4.** Devoll Hydropower scheme (Statkraft, 2017)

Devoll Hydropower Sh.A. is developing the project and is 100% owned by Statkraft AS. Previously Devoll Hydropower Sh.A. was a 50/50% joint venture between Statkraft AS and the Austrian utility company EVN AG. In

2013, Statkraft acquired EVN's share and became the sole owner of this project in 2013.

The construction of Banja used an existing cofferdam structure, which was built and abandoned in the 1980s after the USSR left the region. The height of the cofferdam was 50 meters and the flows passed through the bottom outlet of the cofferdam, resulting in the formation of a restricted reservoir whenever the flows exceeded the capacity of the bottom outlet. The new Banja reservoir extends from the dam to the town of Gramsh. Water from the reservoir is delivered to the Banja power station through a 650-meter long water pipeline. The Moglice Power Plant receives water through a 10.7 km long tunnel from the Moglice Reservoir. The Banja and Moglice projects include significant associated facilities, i.e. transmission lines and replacement roads with a total length of 100 km. (Statkraft, 2017)

Preparatory work at Banja began in April 2013, and the construction of the dam commenced at the end of 2013. The third station – Kokel (40 MW) is also included in the Devall project, but the decision on its construction will be considered 10 years after the start of operation of Banja and Moglice. Kokel is expected to generate 100 GWh per year using an altitude of 350 to 295 meters above sea level, a 50 meter high dam and a small reservoir of 0.85 km$^2$. Kokel is not included in this thesis. Full information about these stations is presented in the table below.

| | **Banja** | **Moglice** |
|---|---|---|
| Start operation | 2016 | 2020 |
| Installed capacity | 71,9 MW | 184,3 MW |
| Turbines | 2 x 32,9 MW Francis turbines<br>1 x 7,2 MW minimum flow turbines | 2 Francis turbines<br>1 minimum flow turbine |
| Maximum flow | 93 m$^3$/s | 65 m$^3$/s |
| Average annual generation | 255 GWh | 448 GWh |
| Head | Between 175 and 96 m above sea level (maximum head 79 m) | Between 650 and 349 m above sea level (maximum head 301 m) |

| | **Banja** | **Moglice** |
|---|---|---|
| Highest Regulated Water Level | 175 m | 650 m |
| Lowest Regulated Water Level | 160 m | 625 m |
| Average flows at dam site | 47 $m^3$/s at Kozare | 13 $m^3$/s at Gjinikas |
| Dam | Embankment rockfill dam with an impervious clay core with an approximate height of 80 m | 150 m asphalt-core dam, rock-filles |
| Reservoir | Surface area of 14$km^2$, storage capacity 391 million $m^3$ | Surface area of about 7.2$km^2$, storage capacity of approx. 360 million $m^3$ |
| Transmission lines | 12 km 110 kV line, Banja plant to Cerrik substation (in Gostime and Gjergjan Communes and Cerrik Municipality in Elbasan District) | 48 km 220 kV line, Moglice plant to Elbasan (passing through Kodovjat and Pushaj communes in Gramsh District and Tregan and Shirgjan Communes and Elbasan Municipality in Elbasan District) |
| Replacement roads | Banja – Drize 9,4 km including 11 bridges<br>Drize – Gramsh 6,1 km including 2 bridges<br>South shore road (Trashovice – Dushk) 11,4 km including 2 bridges | Kodovjat – Grabove 13,2 rm<br>Grabove – Moglice 12,1 km<br>North shore road (National Road M03) 14,9 rm with no bridges |

**Table 2.1.** Details of Banja and Moglice hydropower plants (Statkraft, 2017)

### 2.2.3. Hydrometric Stations

Much of the data in this section was obtained from Slaven Conevski or taken from Christian Almestad's previous work, the data for which he obtained from Statkraft. The data series have a daily resolution of measurements and include precipitation data from 20 weather stations, temperature data from one weather station, and runoff data from 10 gauging stations. The first year of observations for some stations dates back to 1950, and the most recent one to 1999. Microsoft Excel was used for calculations and graphical presentation.

## Precipitation

Figure 2.5 shows the 20 weather stations whose data were used to analyze climate and precipitation in the basin. As can be seen from the figure, the stations cover different areas of the catchment and provide a good picture of the weather in the region. But at the same time, the stations are located at different altitudes and precipitation differs significantly in mountainous and lowland areas. The table 2.2 also presents the observation time intervals for each station and the number of complete years.

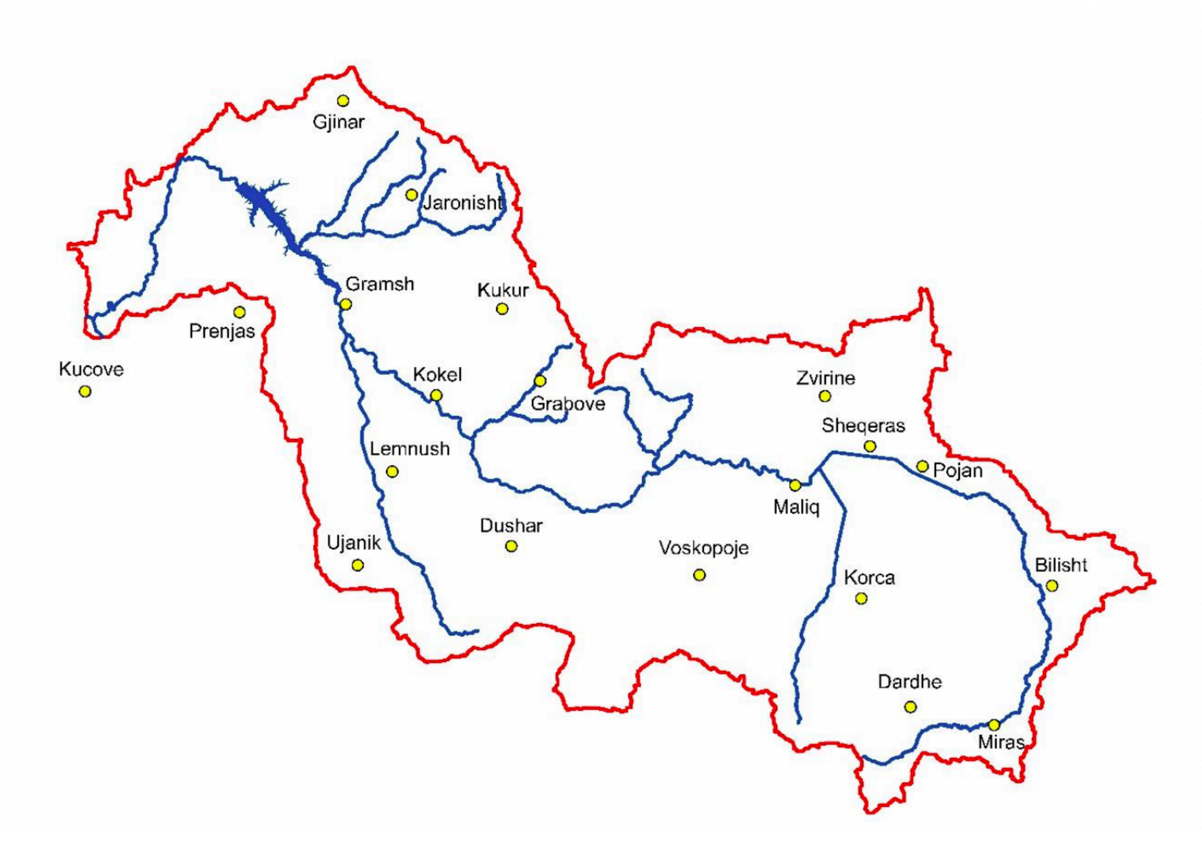


**Figure 2.5.** Meteorological stations in Devoll River Basin (Almestad, 2015)

| **Weather Station** | **Recorded period** | **Complete years** | **Elevation (m.a.s.l.)** | **Annual Precipitation (mm)** |
|---|---|---|---|---|
| Bilisht | 1950-1994 | 40 | 896 | 660 |
| Miras | 1961-1992 | 29 | 1050 | 821 |
| Pojan | 1950-1961 | 9 | 823 | 919 |
| Dardhe | 1950-1998 | 42 | 1310 | 1001 |
| Sheqeras | 1953-1999 | 46 | 817 | 603 |
| Korce | 1950-1994 | 40 | 899 | 660 |
| Zvirine | 1950-1991 | 35 | 825 | 681 |
| Maliq | 1950-1981 | 30 | 830 | 732 |
| Voskopoje | 1950-1999 | 46 | 1180 | 945 |
| Grabove | 1950-1998 | 42 | 1250 | 1272 |
| Dushar | 1950-1992 | 34 | 830 | 1332 |
| Kukur | 1950-1994 | 38 | 800 | 1236 |
| Kokel | 1950-1992 | 30 | 300 | 1007 |
| Jaronisht | 1950-1995 | 39 | 834 | 1292 |
| Lemnush | 1950-1993 | 41 | 600 | 969 |
| Ujanik | 1957-1994 | 24 | 1228 | 1320 |
| Gramsh | 1950-1991 | 36 | 200 | 1095 |
| Gjinar | 1950-1992 | 37 | 815 | 1870 |
| Prenjas | 1950-1992 | 41 | 500 | 1175 |
| Kucove | 1950-1994 | 44 | 32 | 863 |

**Table 2.2.** List of all meteorological stations in Devoll River Basin

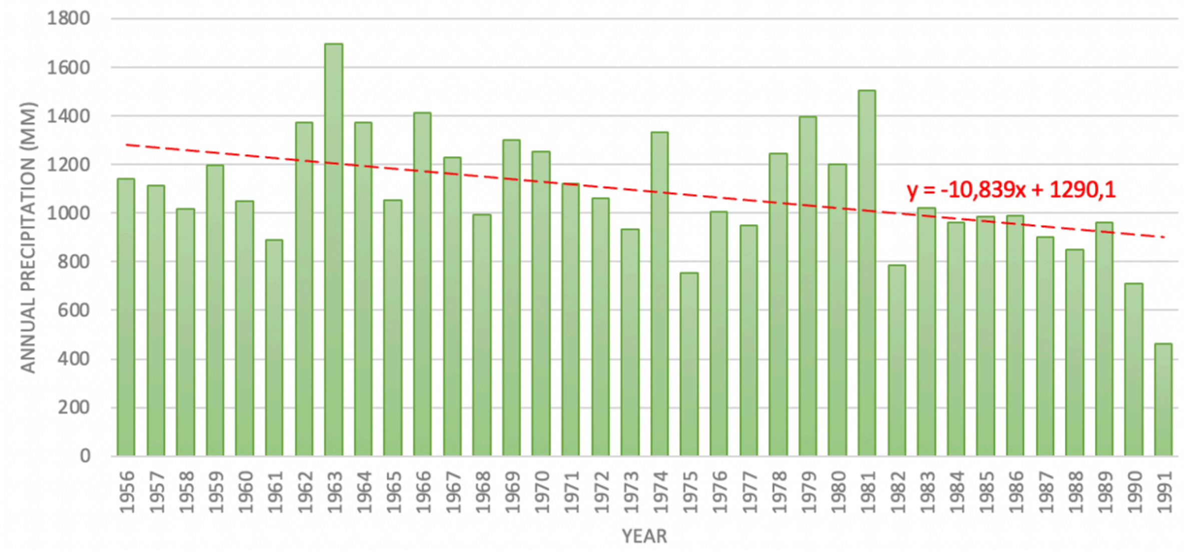


**Figure 2.6.** Annual precipitation in Kokel

As can be seen from the figure above, there is a trend towards a gradual decrease in precipitation every year, which may negatively affect hydropower production in the future.

## Temperature

The only temperature data that was available for this catchment was obtained from Bilisht station. As can be seen from Figure 2.5 and Table 2.2 above, this station is located at an altitude of 896 meters above sea level and is the easternmost of all available stations, so its data does not give a complete picture of the temperature in the basin. However, it is worth taking it into account and some conclusions can be drawn from these data series. For example, that August is the hottest and driest month of the year, while January is the coldest. The highest temperature over the entire observation period was 40.8 degrees Celsius, and the lowest was -24.8 degrees Celsius. The average annual temperature is about 10 degrees Celsius.

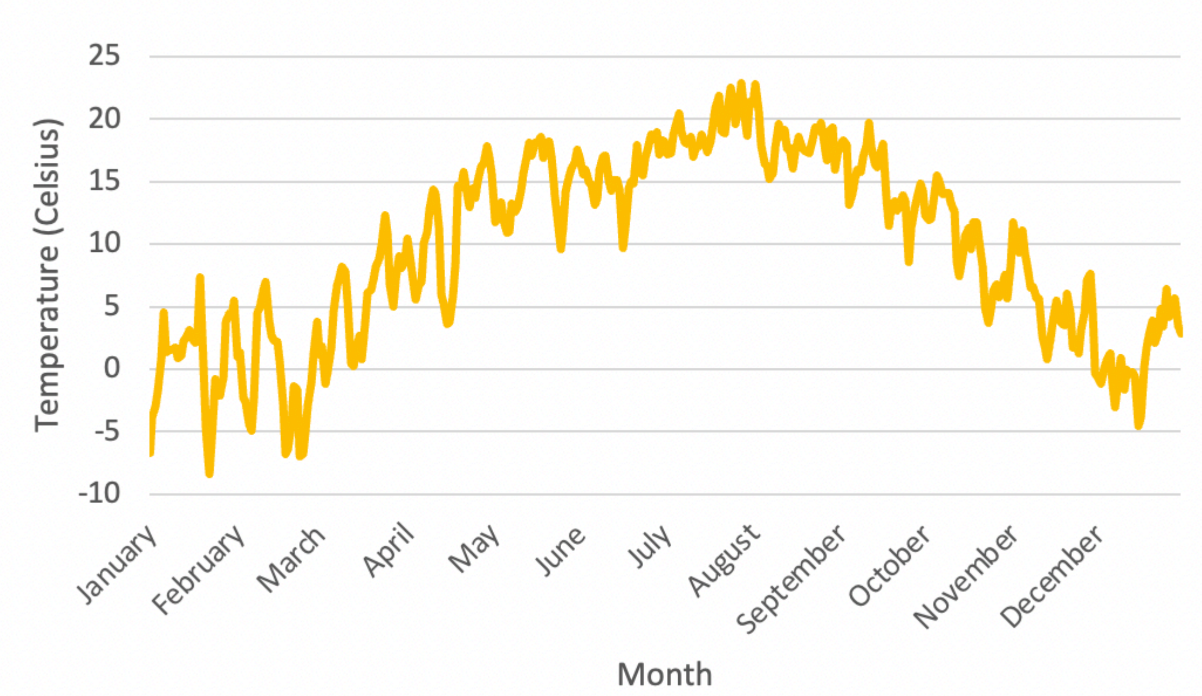


**Figure 2.7.** Daily variation of temperature in Bilisht in 1983

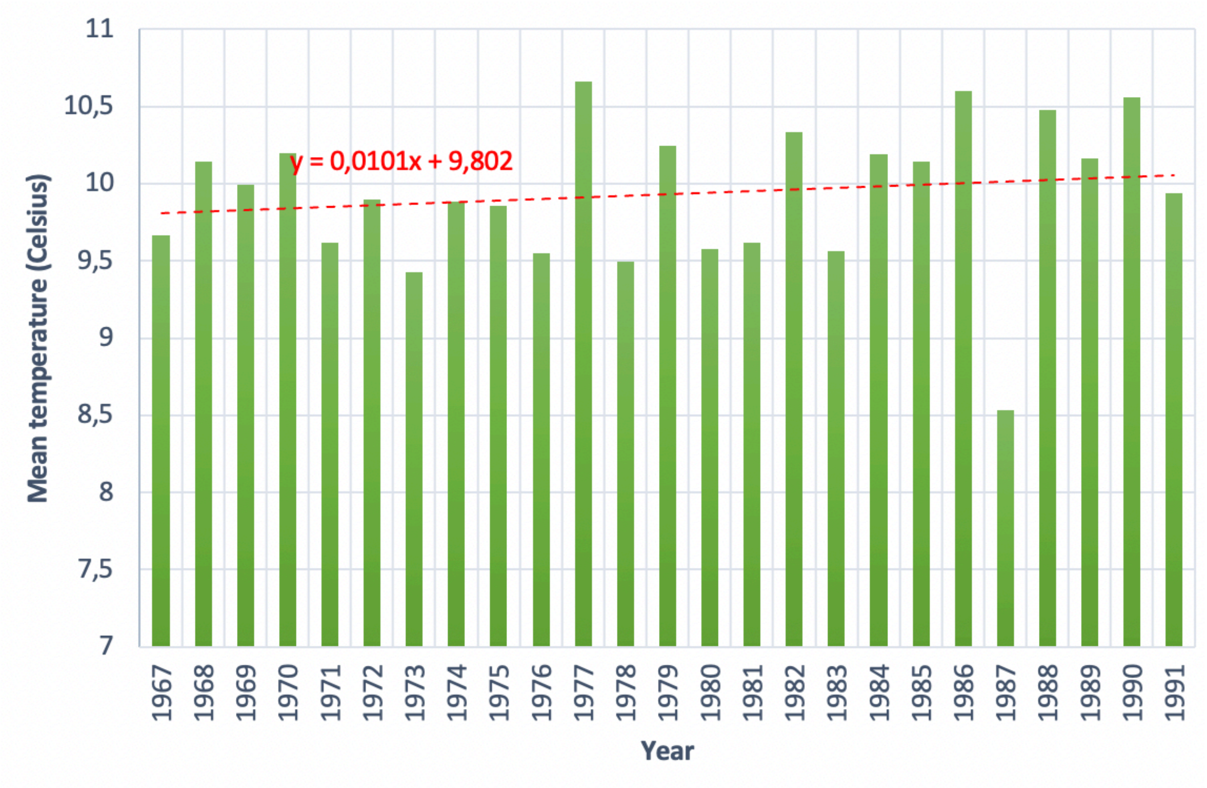


**Figure 2.8.** Annual mean temperature in Bilisht

As can be seen from the figure above, there is a trend towards an increase in temperature every year, which can negatively affect water flows in the catchment area.

### Runoff

There are only 10 flow measuring stations in the basin area, 6 of which are located directly on the Devol River and 4 on tributaries. All these stations are shown in Figure 2.9. In this thesis, series of flow from only 8 stations were used and the remaining two - Lozhan and Darzeze - have data for only 1 year, and therefore were not included in the analysis. Table 2.3 also provides more detailed data on the years of record, drainage area and mean daily runoff for each station considered separately. As can be seen, Kokel has the longest number of measurements - 36 years, moreover, its location is quite convenient for evaluating the results and the quality of this data is assessed by Norconsult as "probably adequate" in comparison with other stations, where the quality is "probably questionable or even highly questionable."

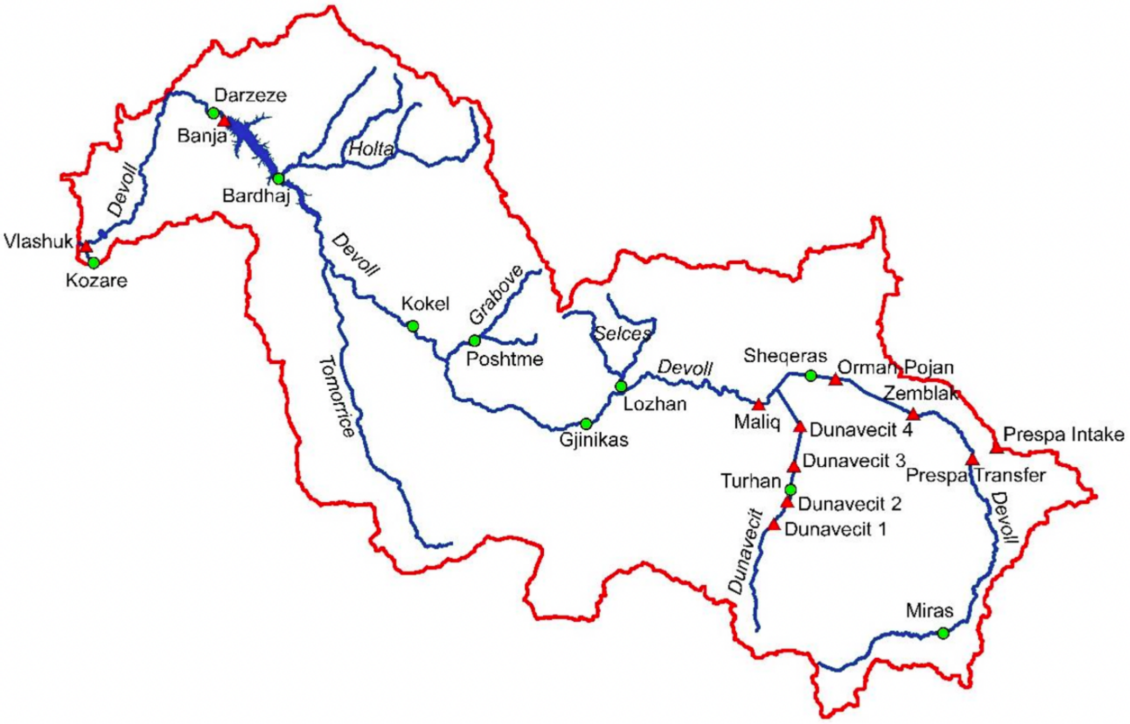


**Figure 2.9.** Gauging stations (green circles) and control structures (red triangles) in Devoll River Basin (Almestad, 2015)

It is worth noting that irrigation has a significant impact in this region. Visually assessing the graphs over a long period of time, it can be concluded that the flows varied significantly from year to year, even though there was approximately the same amount of precipitation or at least not a big variation. This confirms the point that in the period 1960-1990, this catchment underwent significant changes in the irrigation system and water flows were diverted in a different direction, which significantly complicates the forecasting and modeling of this system.

| **Gauging Stations** | **Recorded Period** | **Complete Years** | **Drainage Area (km$^2$)** | **Mean Daily Runoff(m$^3$/s)** |
|---|---|---|---|---|
| Miras | 1958-1999 | 31 | 89,4 | 1,59 |
| Sheqeras | 1956-1985 | 23 | 430,4 | 5,22 |
| Turhan | 1951-1989 | 28 | 272,8 | 3,24 |
| Gjinikas | 1970-1995 | 24 | 1357,0 | 12,38 |
| Posthme | 1976-1985 | 9 | 63,0 | 2,3 |
| Kokel | 1953-1989 | 36 | 1879,3 | 28,28 |
| Bardhaj | 1980-1989 | 10 | 375,5 | 5,74 |
| Kozare | 1950-1985 | 34 | 3120,6 | 46,6 |

**Table 2.3.** Gauging stations in Devoll River Basin

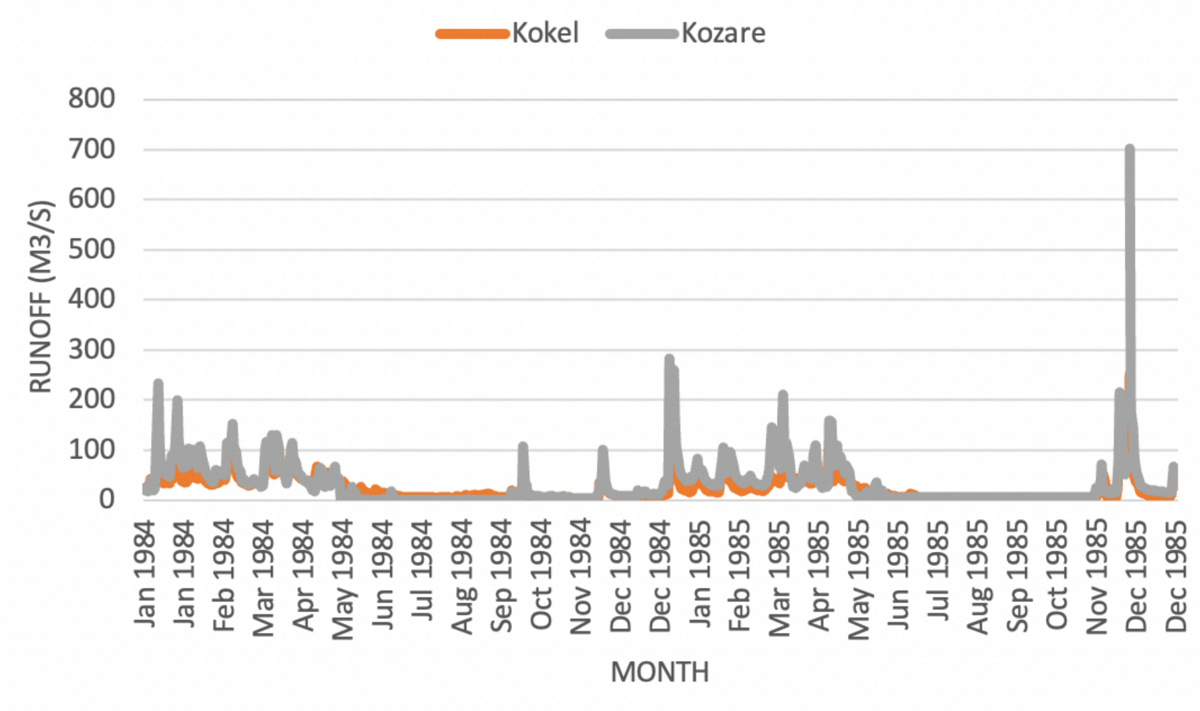


**Figure 2.10.** Runoff in Kozare and Kokel (1984-1985)

# 3 METHODOLOGY

This chapter describes all the methods, assumptions and simplifications that were used to develop the hydrological model of the Devoll River Basin. The main concepts and uncertainties that affect hydrological modelling software Water Evaluation and Planning (WEAP) were reviewed and taken into account.

## 3.1. Creating sub-basins

The basin was divided into 9 sub-basins. This choice was accepted because there are 8 runoff stations in the catchment and thus it will be possible to calibrate the model by comparing data from stations with the simulated model. It was also decided to split the largest area into two so that parameters could be set independently of each other in the Tomorrice River valley and in the westernmost part of the basin. The big advantage of using the WEAP software in 2023 is that it already has built-in digital elevation models (DEM) that are loaded from the system when creating a catchment. This significantly reduces model creation time. The DEM was selected with a resolution of 3 arcseconds, corresponding to a 90 by 90-meter grid. Initially, the model was run with a resolution of 15 arcseconds, but the results were unsatisfactory, therefore it was decided to increase the resolution. Also, initially the model was divided into elevation band branches every 1000 meters (almost every sub-basin was divided into 2-3 more areas), but this was very time-consuming and did not increase the accuracy of the calculations in any way, so this idea had to be abandoned. The daily data was used for the simulation as this data was available from weather and runoff stations. Another important stage in creating the model was dividing it into classes based on land cover. This option is also already built into WEAP, but the task was to select the necessary classes. Initially, WEAP divides the entire region into 9 classes: Agriculture, Forest, Grassland, Wetland, Urban, Shrubland, Barren or Sparse Vegetation, Open Water, Snow and Ice. But since Agriculture and Forest accounted for more than 90%, it was decided to leave only these two classes and WEAP automatically sort the remaining branches into these two groups. The total area of the basin in the model was 3133 km$^2$, which is very close to the real figure.

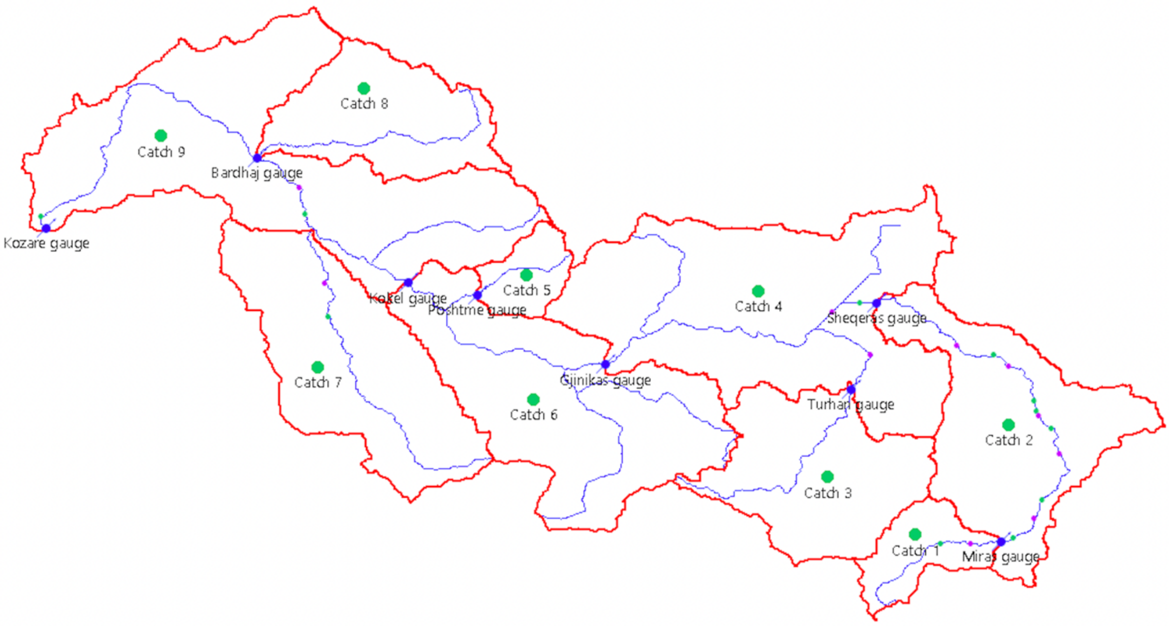


**Figure 3.1.** Delineated sub-basins with runoff gauges

| Basin | Drainage Area ($km^2$) | Land Cover (%) | | Gauge |
|---|---|---|---|---|
| | | Agriculture | Forest | |
| 1 | 88,7 | 32 | 68 | Miras |
| 2 | 369,7 | 85 | 15 | Sheqeras |
| 3 | 287,6 | 59 | 41 | Turhad |
| 4 | 577,9 | 70 | 30 | Gjinikas |
| 5 | 63,2 | 42 | 58 | Poshtme |
| 6 | 501,3 | 64 | 36 | Kokel |
| 7 | 376,8 | 42 | 58 | - |
| 8 | 226,5 | 39 | 61 | Bardhaj |
| 9 | 641,8 | 60 | 40 | Kozare |

**Table 3.1.** Characteristics of sub-basins

## 3.2. Climatic data

Usually, the main challenge of working with hydraulic data is that it is not homogeneous, and only some particular points are presented, while the model simulation takes place over a large area, as well as at different elevations, so it is necessary to somehow interpolate data from several stations to 3133 $km^2$. There are several methods for calculating average precipitation values of sub-basins, but for this thesis the method using Thiessen polygons was chosen. There is a table 3.2 with weights for each sub-basin below (Almestad, 2015).

| Meteorological Station | Basin | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| Bilisht | - | 57,7 | - | - | - | - | - | - | - |
| Dardhle | 80,4 | 5,9 | 28,9 | - | - | - | - | - | - |
| Dushar | - | - | - | - | - | 42,6 | 18,6 | - | - |
| Gjinar | - | - | - | - | - | - | - | 38.0 | 19,9 |
| Grabove | - | - | - | 12,0 | 100,0 | 5,1 | - | - | 3,0 |
| Gramsh | - | - | - | - | - | - | 8,6 | 26,3 | 18,2 |
| Kokel | - | - | - | - | - | 8,4 | 2,9 | - | 10,0 |
| Korce | - | 5,7 | 47,1 | 15,3 | - | - | - | - | - |
| Kucove | - | - | - | - | - | - | - | - | 5,3 |
| Kukur | - | - | - | - | - | - | - | 35,7 | 13,2 |
| Lemnush | - | - | - | - | - | 2,1 | 36,3 | - | - |
| Miras | 19,6 | 20,5 | - | - | - | - | - | - | - |
| Prenjas | - | - | - | - | - | - | 6,3 | - | 30,4 |
| Sheqeras | - | 10,2 | - | 22,8 | - | - | - | - | - |
| Voskopoje | - | - | 24,0 | 14,6 | - | 41,8 | - | - | - |
| Ujanik | - | - | - | - | - | - | 27,3 | - | - |
| Zvirine | - | - | - | 35,2 | - | - | - | - | - |

**Table 3.2.** Thiessen weights for all sub-basins (Almestad, 2015)

This method was used only for precipitation, since temperature values were obtained from only one Bilisht station, and other climatic factors do not have such a big impact on the modeled catchment. After calibrating the model with data from the past, it was necessary to decide which sort of data to use to predict future scenarios. To do this, a comparative analysis of the data received from the station and the data that is already built into the WEAP (Princeton v3, Global, 1948-2010, 28 km, daily) was carried out and it was found that these values are quite close to each other and can be interchangeable, so in further calculations it was decided to rely on the built-in in WEAP precipitation data and other climatic values.

As can be seen from Figures 3.2 and 3.3, the precipitation data series overlap quite well, especially if we look at overall annual values, but still the Princeton data had less precipitation and the peak values were also difficult to track. This will be discussed in more detail in the following chapters.

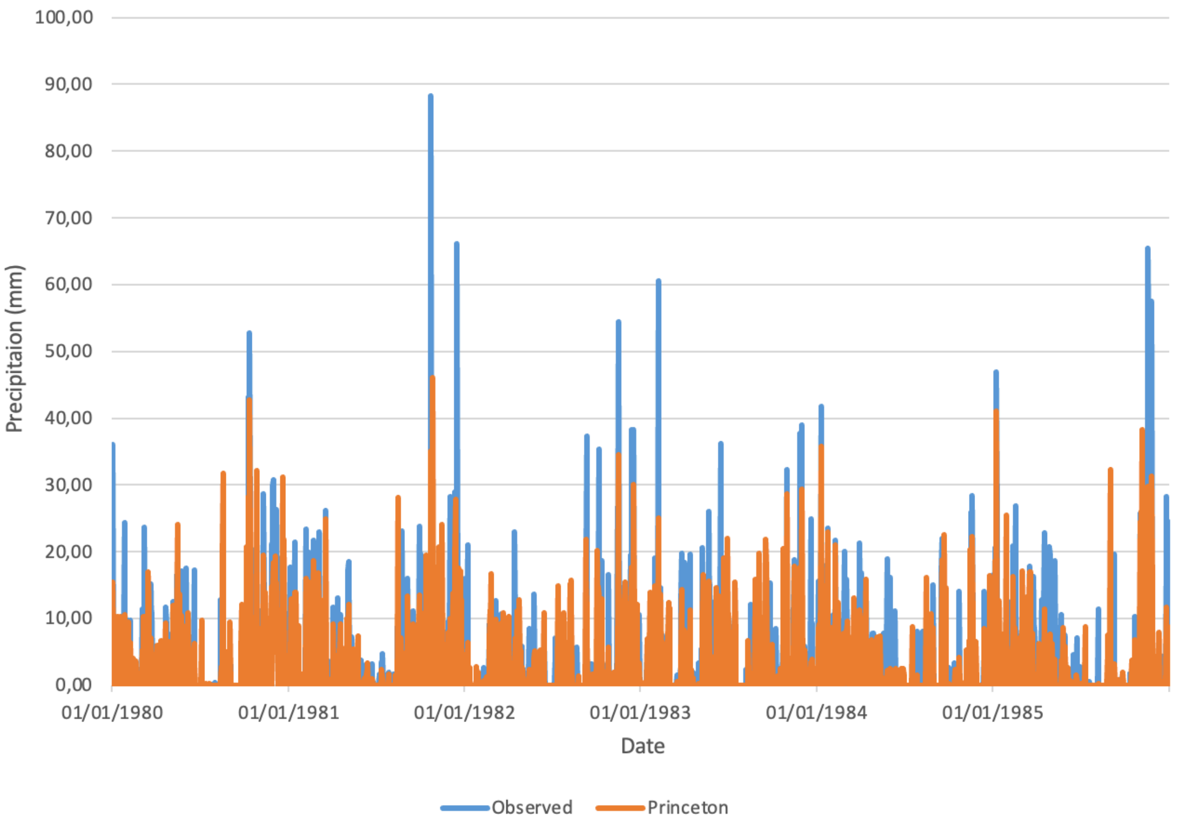


**Figure 3.2.** Comparative analysis of precipitation data series in Kokel

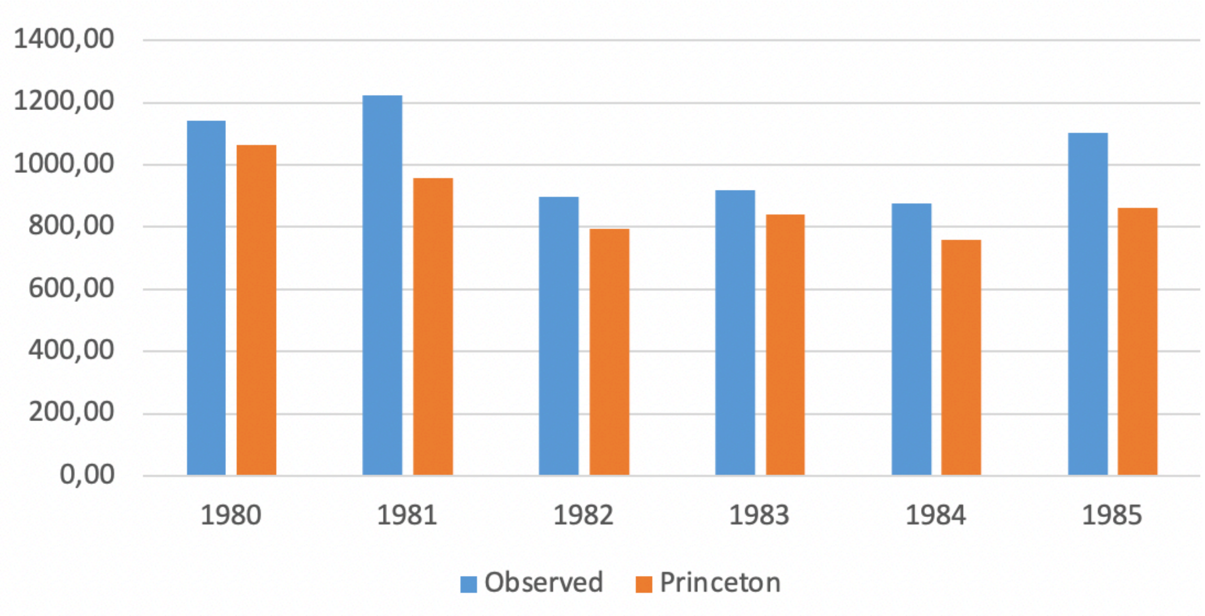


**Figure 3.3.** Comparison of annual precipitation in Kokel

## 3.3. Water demands

This paragraph describes the main assumptions and approximations about the water needs in the basin. For the calculations, 2 main purposes of water consumption were taken: water needs of population in villages along the

Devoll River, as well as irrigation of fields and pastures. Even though agriculture is one of the main sources of income in Albania, there is not much information about it in public sources and many parameters have been estimated approximately based on similar cases in other areas of the region.

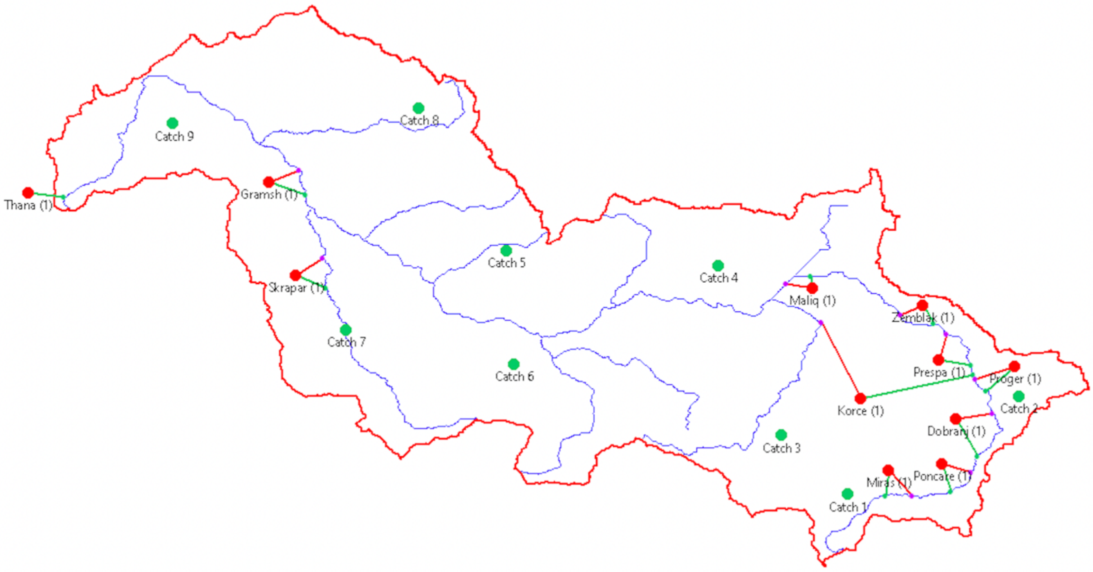


**Figure 3.4.** Water demands in Devoll River Basin

Regarding the first point, the main large villages in the catchment area were considered. Population data is presented in Figure 3.5 below. Even though the model was calibrated for 1980-1985, and future scenarios were considered for 2050-2060, the data on the number of people living there was taken for 2022-2023 and was considered constant, since according to statistical data this value has changed very slightly over the last 50 years (there were slight fluctuations within 1-2% but the figure remained the same). The minimum water requirement could be taken to calculate 135 liters/person/day (Chenoweth, 2007), but since Albania has a warm climate, the figure 150 liters/person/day was taken for a model with a constant distribution throughout the year, which is equivalent to 50 m3/person/year.

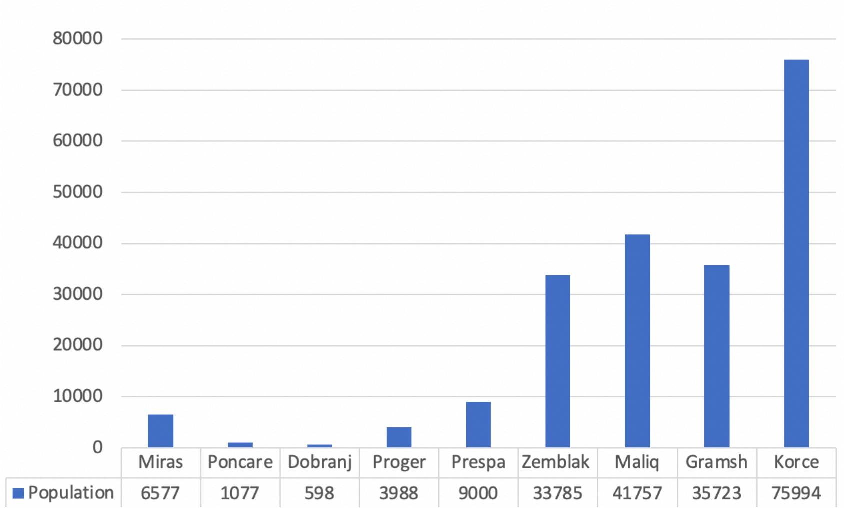


**Figure 3.5.** Human settlements in Devoll River Basin

Regarding the second point, not so much information is available in open sources except Almestad's master thesis, in which all the irrigation and pumping schemes were described in extensive detail. In this thesis, this was not the goal, so some simplifications and assumptions were made and only the largest irrigation points were added to the model. Again, the numerical value of irrigation water requirements remains controversial. According to various reports and estimates, this number usually ranges from 650 to 6500 $m^3$ per hectare. And due to the warm and dry summer, a number was taken closer to the top of the range — 6000 $m^3$ per hectare with a consumption of 80%. Data was taken from Aquastat report on the area of places that require irrigation. A visual representation of this is shown on the bar graph below.

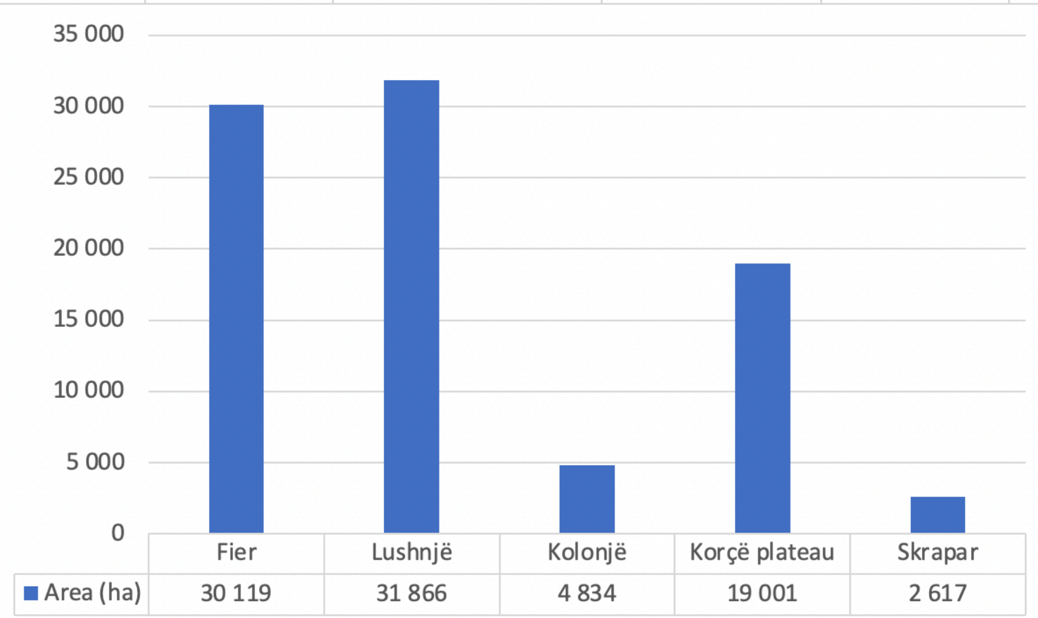


**Figure 3.6.** Reported irrigated areas in Devoll River Basin

However, it has been noted that in order to irrigate the areas of Fier, Lushnjë and Kolonjë, water must first flow into the Thana reservoir and only then is it distributed further downstream. According to the information from the reports and the temperature graph in the region, it was concluded that the distribution of water demands in the region is not constant during the year, and it is significantly greater in the summer months and completely absent in the winter. The following distribution law was adopted for the model, which is presented in the picture below.

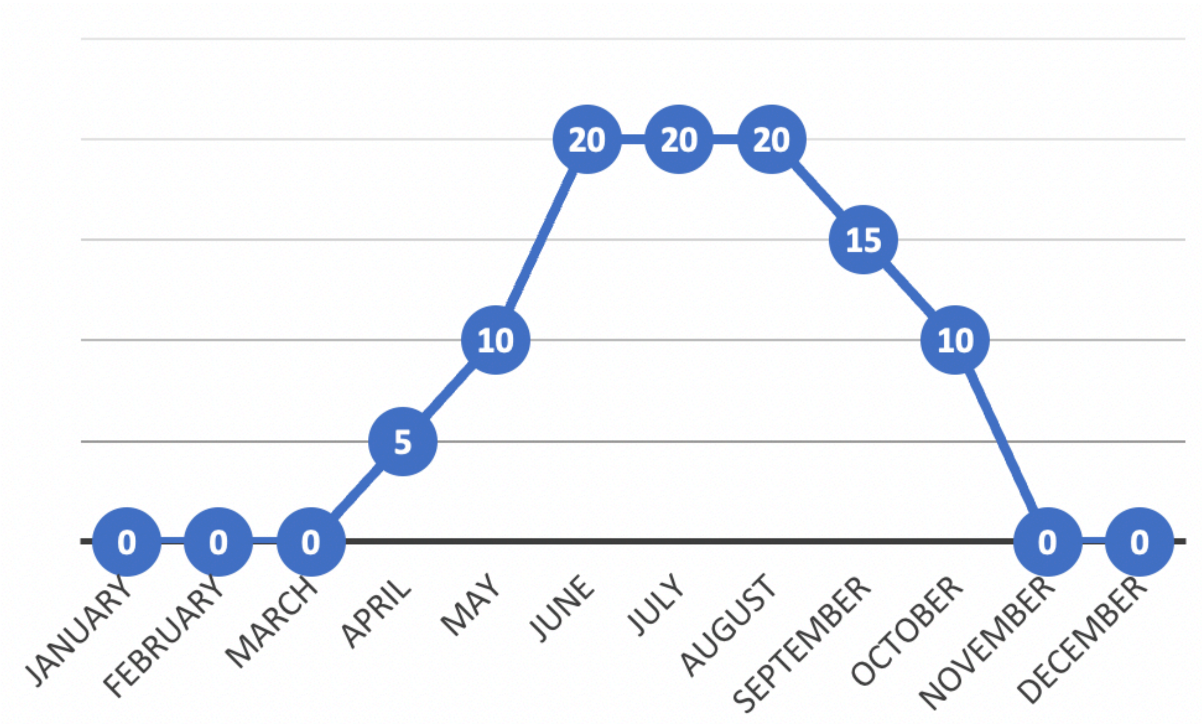


**Figure 3.7.** Monthly distribution of irrigation demands

## 3.4. The WEAP Software

WEAP is a software tool for an integrated approach to water resources planning that facilitates the work of a qualified engineer/scientist but does not completely replace a human. Using this tool, you can get a complete, flexible, and clear picture of water flows. WEAP evaluates the full range of possible scenarios depending on the settings that the user chooses. The software can work with all types of systems, such as municipal or agricultural systems, as well as individual catchments or complex river systems since it operates on the basic principle of water balance. In addition, WEAP is capable of solving more complex problems of water distribution priorities, groundwater modeling, reservoir operation and hydropower production. For each specific model, it is possible to configure its own data structure in accordance with the requirements of a specific technical specification.

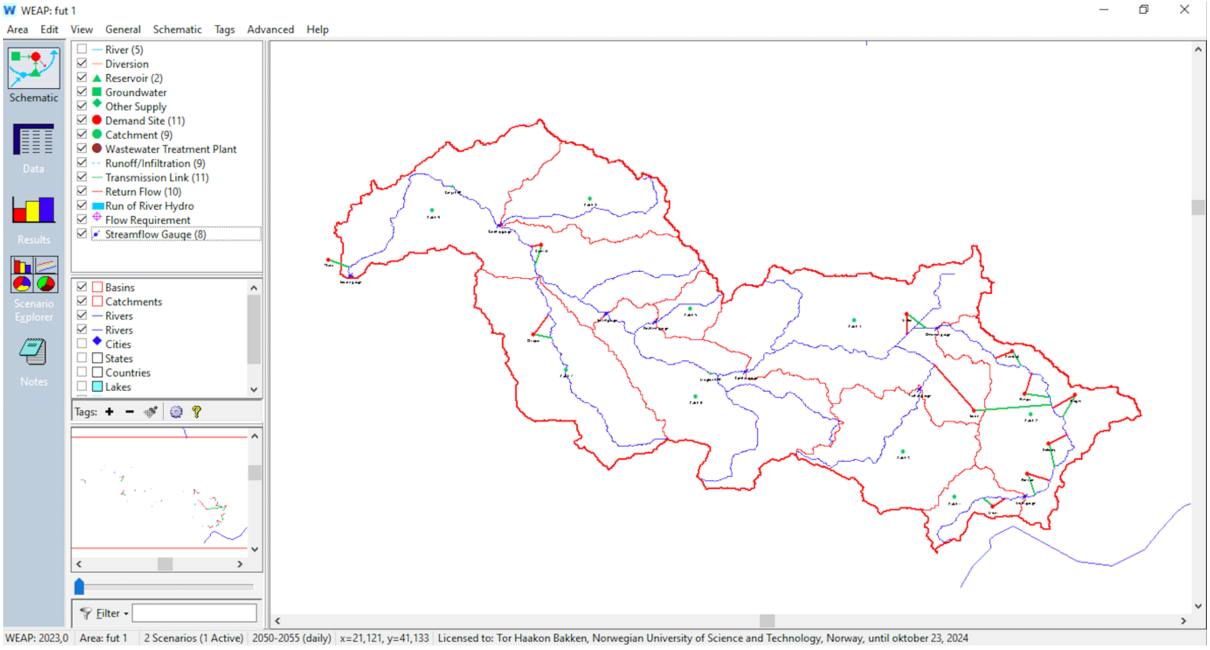


**Figure 3.8.** WEAP interface (2023 version)

As can be seen in the picture above, WEAP has a graphical interface that is intuitive for any user, which provides a simple understanding of the system being studied and the ability to clearly demonstrate the results obtained even for an unprepared user. At the top of the window, the menu consists of 7 items: Area, Edit, View, General, Schematic, Tags, Advanced and Help. WEAP has 5 other views on the left side which are selected from the view pane. Each view opens a new window and has its own set of functions:

**Schematic view** gives a good picture and visual representation of all the elements of the system in one place. The intuitive ability to drag and drop new items directly onto the map makes interacting with the program simple. For a more visual representation, it is possible to attach a file from a Geographic Information System (GIS). Right-clicking on any object opens a new menu where you can add or change any information about it.

**Data view** allows user to add new information about existing objects after they have been added to the schematic view. The structure on the left always contains such main sections as Key Assumptions, Demand Locations, Hydrology, Supply and Resources, Environment and Other Assumptions. It is very convenient to use key assumptions, since it is possible to enter a numeric value once and add it to several different fields at once, and when this value changes, the user only needs to change it in one place. The user can also enter data from a file, or use the built-in mathematical functions, or take it as a constant.

**Results view** displays the final data that the model has generated. Many different variables are available in this window, which are structured and sorted in a user-friendly manner. It is also possible to create your own variables that need to be calculated and presented. If there is data obtained from stations or other sources, then this can also be added to the model and a comparative analysis of the modeled and detected data can be carried out. When the results obtained are needed for further, more detailed processing, there is an option to download an Excel file with all numerical values.

**Results** is used to view and analyze "Favorite" charts collected in one place. It is possible to create several reviews, each of which will display several different favorites. The user can also look at several different scenarios at once and compare them with each other, with the ability to change the data on the spot and then recalculate and update the results.

**Notes** view allows the user to leave comments while simulating each individual scenario. This tool can also be used for exchanging information between different users. It is also possible to export notes to Microsoft Word and print this document.

There are 5 different methods for simulating and modeling catchment processes in WEAP: (1) Rainfall Runoff and (2) Irrigation Demand only Simplified Coefficient Approach versions only, (3) Soil Moisture Method, (4) MABIA Method and (5) Plant Growth Model or PGM. In each individual case, the user has to choose the method in the settings that will be used in this model, depending on the complexity of the process representation and the availability of data. For this thesis, the Rainfall Runoff Method (Soil Moisture Method) was chosen.

## 3.5. Soil Moisture Method

This method is the most demanding and complex of all 5 mentioned above, since it involves a catchment with two layers of soil, as well as the possibility of snow accumulation. Agricultural irrigation, shallow water interfluves, and changes in soil moisture are considered when modeling evapotranspiration. An important feature of this method is the ability to characterize the influence of land use, as well as soil type, on hydrological processes. In turn, the lower soil level has a direct impact on the direction of the main flow to the river. Based on this, it can be concluded that this method requires a more careful selection of soil parameters and climatic data in the catchment.

The method is based on empirical functions that describe evapotranspiration, surface and subsurface flows, and deep percolation into the catchment. Figure 3.9 shows what a one-dimensional two-component model (bucket) consists of. The bottom layer characterizes the deep soil layer while the top represents the root zone layer. For the model to work correctly, it is necessary to divide the entire basin into several sub-basins, and then each sub-basin into several fractional areas, which are characterized by their own values of soil and plant parameters, but a common climate for all.

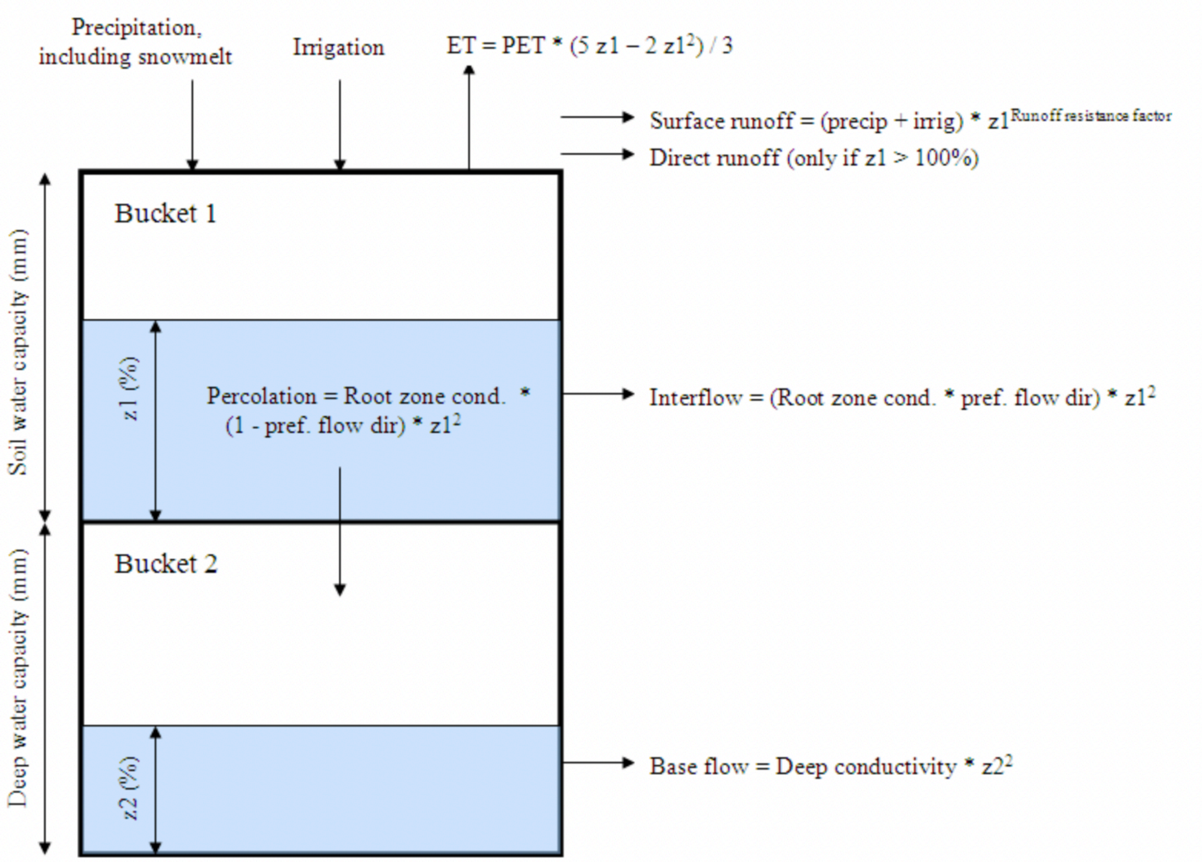


**Figure 3.9.** Conceptual diagram and equations incorporated in the Soil Moisture model (Stockholm Environmental Institute, 2023)

The most important parameters in this view are the soil moisture capacity and the hydraulic conductivity of the saturated layer. During the simulation of the hydrological process, the software solves systems of many water balance equations for each fractional area in a separate time period based on inflows, outflows and relative storage within the soil layers. Below are the main 9 parameters of land use that have a greater impact on the system and their short description (according to WEAP):

**Crop coefficient**: relative to the reference crop. For Simplified Coefficient Method, Kc = 0 means this area is double cropped with another area. Increases in Kc lead to more evapotranspiration – a net loss of water from WEAP’s accounting system, and loss of water that could contribute to streamflow volume. (Default: 1)

**Runoff Resistance Factor**: used to control surface runoff response. Related to factors such as Leaf Area Index (LAI) and land slope. Increasing this parameter allows less water to become streamflow as it instead percolates into the soil immediately. While it is in the soil, more evaporation is possible – enabling a higher water loss from WEAP’s accounting system and the loss of water that could contribute to streamflow. (Default: 2)

**Root Zone Conductivity**: root zone (top “bucket”) conductivity rate at full saturation (when relative storage $z_1 = 1$), which will be partitioned, according to Preferred Flow Direction, between interflow and flow to the lower soil layer. (Default: 20 mm/day)

**Soil Water Capacity**: effective water holding capacity of upper soil layer (top “bucket”). Increasing will increase travel time for any water in the upper bucket (more evaporation possible, more loss of water from the system). (Default: 1000 mm)

**Preferred Flow Direction**: 1 = all water leaving the upper bucket flows to the river, and none to lower bucket, 0 = all water leaving the upper bucket flows to the lower bucket, and none to river. Used to partition the flow out of the root zone layer (top “bucket”) between interflow and flow to the lower soil layer (bottom “bucket”). (Default: 0,15)

**Deep Conductivity**: conductivity rate (length/time) of the deep layer (bottom “bucket”) at full saturation (when relative storage $z_2 = 0$), which controls transmission of baseflow. Increasing will shorten travel time for any water in the lower bucket before it flows into the river. There is no evaporation in the lower bucket. (Default: 20 mm/day)

**Deep Water Capacity**: effective water holding capacity of upper soil layer (bottom “bucket”). This is ignored if the demand site has a runoff/infiltration link to a groundwater node. Increasing will increase travel time for any water in the lower bucket before it flows into the river. (Default: 1000 mm)

**Initial $z_1$**: initial conditions determine the amount of water that is already available in the top / deep soil layer and affects what happens to the new water that reaches the layer. It drastically affects the response in the first year, after which tends to adjust itself. (Default: 30%)

**Initial $z_2$**: The percentage of soil moisture must be relatively stable over time, except in very extreme circumstances. The result of the first is used to set the initial $z_2$. (Default: 30%)

## 3.6. Erosion and Sedimentation

The construction and filling of two huge reservoirs will certainly make a significant contribution to various aspects of hydrology and life in the region. The Banja Reservoir existed previously as a «run-off-river», with an unfinished dam from 1970-1980, the construction of which began by the Soviet Union and was never completed. A new type of dam from Statkraft was put into operation only in 2016 in Banja and in 2020 in Moglice. These reservoirs are expected to better regulate flows and prevent severe flooding due to heavy and intense rainfall or melting snow, which is very common in this catchment. In addition to protecting against severe floods, the reservoirs should also facilitate the production of hydroelectric power, allowing turbines to be run not only during the rainy season, but also at any time of the year to meet the needs of the population.

However, when designing reservoirs, there is one important feature — sedimentation and erosion of rocks, which is very specific to a given catchment area. There are two types of rocks present in the valley, namely, sedimentary flysch and the harder magmatic ophiolite. Landslides here occur quite often and even very large ones, such as the 1974 landslide of 1 million $m^3$ near Moglice. This basin has enormous sediment yields and, for example, in the Osum River reaches 2.85 million $m^3$ per year. Moreover, what is typical for this region is that the sediment load is distributed unevenly throughout the year and amounts to 50,000 tons per month in summer and 200,000 tons per month in winter in Kokel, when the runoff is higher. Soil erosion occurs largely due to forest degradation and reforestation can significantly improve the sustainability of slopes.

One of the main problems associated with sediments in any region is that they are very complex to measure and there is limited amount of data on them. For the Devoll River Basin there are two series of data for the period from 1974 to 1983 and from 1965 to 1996, and as a result it was decided to carry out new research. Thus, from May 2013, Statkraft began collecting and analyzing data on grain sizes and sediment concentrations on a weekly basis. The latest acoustic monitoring techniques (Acoustic Doppler Current Profiler), turbidity meters and manual bottle sampling were used. In addition, a numerical sediment balance model was developed and used to estimate the lifetime of the Moglice and Banja reservoirs. Many specialists in the field were brought in to assess erosion and sedimentation, such as scientists from the University of Bologna and the Norwegian University of Science and Technology, as well as the principal geological and geotechnical engineer from Statkraft.

As a result of the latest combined analysis, it was revealed that initially the sediment load in the Banja reservoir will be 7,260,000 tons per year and after 4 years (after the filling of Moglice) it will decrease to 4,863,000 tons per year, for the Moglice reservoir this value is 2,397,000 tons per year. However, the rate of loss of reservoir capacity is adjustable and can be 1.29% in the first 4 years and then 0.86% per year for Banja and 0.47% per year for Moglice. (Assessment protocol, Statkraft, 2017)

## 3.7. Future scenarios

WEAP 2023 already integrates Coupled Model Intercomparison Project 6 (CMIP6 ACCESS-CM2), which includes the latest 21st century scenarios. The difference is that they include not only changes in the concentration of greenhouse gases in the atmosphere, but also socio-economic changes. There are five narratives, known as “Shared Socioeconomic Pathways” (SSPs), that describe different ways of development of society:

**SSP1**: The most sustainable way, which includes preserving the boundaries of nature. Human well-being is valued more than economic growth. People and states are striving to consume less and less goods and resources.

**SSP2**: "Middle of the Road" shows current global development into the future. Countries cooperate with each other, but this cooperation is not increasing, and there is moderate population growth.

**SSP3**: Regional rivalry. Global problems fade into the background due to global conflicts. Investments in education and science are significantly reduced. There is an increasing focus on national security issues. Inequality is growing.

**SSP4**: Inequality. There is a huge difference in the standard of living and income of people living in developed countries and those who are at a lower stage of development. Concern for the environment is a focus only in some regions.

**SSP5**: Fossil fuel development. Integrated global markets lead to new discoveries and innovations. High intensity of exploitation of fossil fuel resources with the use of coal leads to economic development. (O'Neill, 2016)

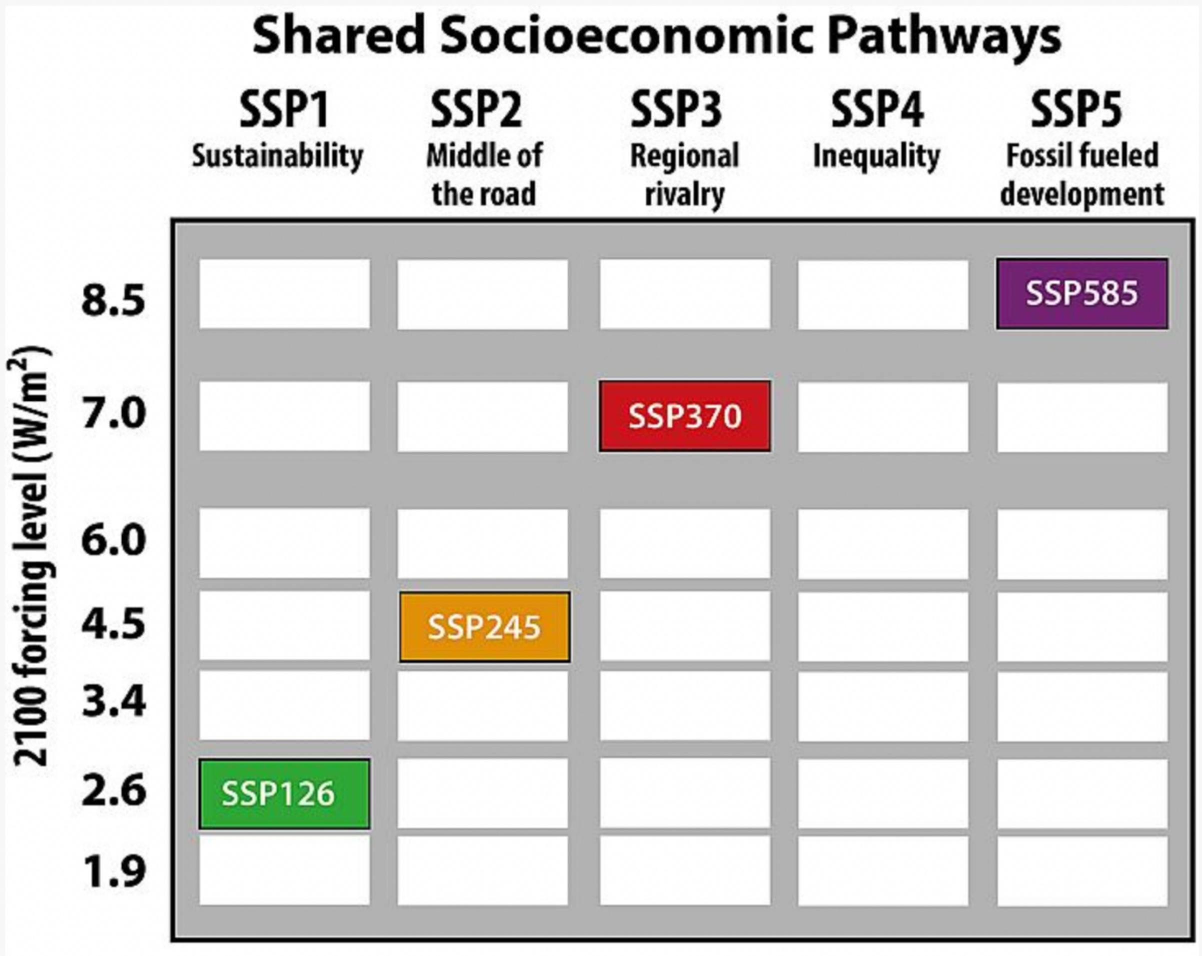


**Figure 3.10.** Standard scenarios in ScenarioMIP (O'Neill, 2016)

For ScenarioMIP, four scenarios were selected and will be used as standard. They can be seen in Figure 3.10. Each scenario name contains 3 digits, where the first indicates the name of the main path and the next two indicate the radiative forcing that will be achieved by 2100, expressed in tenths of Watts.

**SSP126**: the most optimistic scenario of all and includes the adoption of climate protection measures. It is a converted RCP2.6 in the past.

**SSP245**: Some update of the RCP4.5 method in the past.

**SSP370**: Update of the RCP7.0 method.

**SSP585**: The upper limit of the range of scenarios, previously it was the RCP8.5 method, but socio-economic factors also added to it.

## 3.8. Reservoir and Hydropower

Taking into account the information presented above in chapters 3.6 and 3.7, it was decided to create several scenarios that the WEAP will simulate. The time period for modeling was chosen as 2050-2060. The first year is to establish stable operation of the system and then another 10 years for further analysis and comparison. These years were chosen because 30 years after the construction of the reservoirs, the effect of sedimentation will already be observed, and the capacity of the reservoirs should be significantly reduced. Also, too long a waiting period was not considered since the uncertainty of many factors would be too high and there are many things that can significantly change the characteristics of the simulated system.

Two reservoirs with reduced volumes were added to the WEAP system. It is estimated that the volume of the Banja and the Moglice reservoir will decrease from 391 to 286 million $m^3$, and from 362 to 314 million $m^3$, respectively. The generated efficiency was taken as 90%. The annual energy production is expected to be 254 GWh for Banja and 475 GWh for Moglice. It is obvious that both hydropower plants do not operate at full capacity all 365 days a year and based on the data on turbines power, water flow and head, plant factors were calculated, they amounted to 41% for Banja and 39% for Moglice. However, as it became clear after the first simulations, for future scenarios and to display a more realistic picture, these factors were reduced by approximately half and the following numbers were taken for the WEAP calculations: 18% for Banja and 20% for Moglice. This will be explained in more detail in the following chapters.

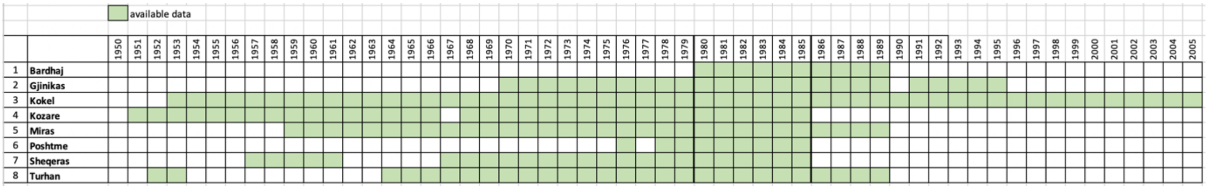
Calculations were carried out according to two scenarios, which were called “Constant volumes” - without reducing the capacity of the reservoirs and “Sediments -1%” - taking into account the influence of sediments on the capacity of the reservoirs (however, the real value is not 1%, it was described in more detail in Chapter 3.6). In addition, 4 different climate scenarios were taken, which were described in Chapter 3.7 (SSP126, SSP 245, SSP370, SSP585). And since 2 hydropower stations were modeled, there were 16 possible combinations in total.

# 4 MODEL CALIBRATION

In order to be able to predict and simulate the future, it’s necessary first to build a good model for the past. This chapter describes the process of calibrating and selecting hydrological parameters for the Devoll River Basin.

## 4.1. Period of Calibration

The calibration period is a very important aspect for building any hydraulic model, since the accuracy and performance of the model will depend on it. As a rule, the longer the calibration period is, the more accurate and realistic the results will be, but the limiting factor here is the flow data. Since the entire catchment was divided into 9 sub-basins and there were data series from 8 runoff stations, it was necessary to use data from all stations for correct calibration. The figure below shows a timeline of available data from weather stations.



🟩 available data

| | | 1950 | 1951 | 1952 | 1953 | 1954 | 1955 | 1956 | 1957 | 1958 | 1959 | 1960 | 1961 | 1962 | 1963 | 1964 | 1965 | 1966 | 1967 | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 | 1974 | 1975 | 1976 | 1977 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Bardhaj | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | Gjinikas | | | | | | | | | | | | | | | | | | | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| 3 | Kokel | | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| 4 | Kozare | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| 5 | Miras | | | | | | | | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| 6 | Poshtme | | | | | | | | | | | | | | | | | | | | | | | | | | | 🟩 | |
| 7 | Sheqeras | | | | | | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| 8 | Turhan | | | 🟩 | 🟩 | | | | | | | | | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |

| | | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Bardhaj | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | | | | | | | | | | | | | | |
| 2 | Gjinikas | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | | | | | | | | |
| 3 | Kokel | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| 4 | Kozare | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | | | | | | | | | | | | | | | | | | |
| 5 | Miras | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | | | | | | | | | | | | | | |
| 6 | Poshtme | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | | | | | | | | | | | | | | | | | | |
| 7 | Sheqeras | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | | | | | | | | | | | | | | | | | | |
| 8 | Turhan | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | | | | | | | | | | | | | | |

**Figure 4.1.** Timeline for runoff series

The system was initially modeled using monthly data from 1980 to 1990. This interval was chosen because changes in the irrigation system were actively taking place in the region, and therefore the later the period is chosen, the more we can trust the data series from the stations and the more reliable the assumptions about irrigation will be. Besides, 11 years is quite a long period. However, the system showed unsatisfactory results with this calculation, and it was decided to switch to daily simulation, since the data allows this, although it is not completely reliable.

After much thought, it was decided to model the system for 1980-1985, since for this period there is data from all 8 runoff stations and 6 years will be a sufficient interval for setting up the model.

## 4.2. Metrics for evaluating model performance

There are a huge number of ways to assess the accuracy of a system, and for each specific task and research purpose it is necessary to choose the right one. Observed and simulated data may be similar in some metrics, but completely different in others. When plotting graphs in the "results" tab, WEAP automatically displays various criteria for model accuracy, such as: NSE, KGE, NRMSE, PBIAS, RSR, $r^2$. Based on experience with data and other similar studies, two main factors were taken into account during model calibration: Percentage BIAS (PBIAS) and Nash-Sutcliffe Efficiency (NSE).

PBIAS, or percentage deviation, is a statistical metric used to evaluate the accuracy of a model's predictions. It is calculated as the average difference between the predicted and observed values, expressed as a percentage of the observed values. BIAS value equal to 0 indicates perfect accuracy, while a positive value indicates overestimation, and a negative number indicates underestimation. BIAS is often used in hydrological and environmental modeling to evaluate model performance. The formula for PBIAS is written in equation 4-1, where PBIAS is expressed as a percentage. $Q_i^{obs}$ and $Q_i^{sim}$ are the i-th observed and simulated flow, and *n* is the total number of observations.

$$PBIAS = \frac{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{sim}\right) * 100}{\sum_{i=1}^{n} Q_i^{obs}} \tag{4-1}$$

Nash-Sutcliffe Efficiency (NSE) is a normalized metric that determines the relative amount of residual variance compared to the variance of the measured data (Nash and Sutcliffe, 1970). Nash-Sutcliffe efficiency measures how well a plot of observed and simulated data fits a 1:1 ratio. NSE = 1 corresponds to a perfect fit of the model to the observed data. NSE = 0, indicates that the model's predictions are as accurate as the mean of the observed data; $-\infty < \text{NSE} < 0$, indicates that the observed mean is a better predictor than the model. For this model, the NSE formula will take the form as in equation 4-2.

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_{mean}\right)^2} \tag{4-2}$$

Moriasi in his study on a method for assessing watershed models (2007), determined the boundary values of these metrics. They are presented in the table below. It is worth noting that these values correspond to modeling hydrological processes with a monthly time step, but for daily modeling, less strict limits may be allowed.

| **Performance** | $\|PBIAS\|$ (%) | $NSE$ |
|---|---|---|
| Very good | $\|PBIAS\| \leq 10$ | $0{,}75 \leq NSE \leq 1$ |
| Good | $10 \leq \|PBIAS\| \leq 15$ | $0{,}65 \leq NSE \leq 0{,}75$ |
| Satisfactory | $15 \leq \|PBIAS\| \leq 25$ | $0{,}5 \leq NSE \leq 0{,}65$ |
| Unsatisfactory | $\|PBIAS\| \geq 25$ | $NSE \leq 0{,}5$ |

**Table 4.1.** General performance ratings for PBIAS and NSE (Moriasi, 2017)

## 4.3. Calibration routine

The process of calibrating the model parameters was the most challenging and time-consuming task, mainly due to the number of sub-basins, as well as the uncertainties associated with irrigation water withdrawals. The thing is that initially the system was divided into 9 sub-basins, each of which was further divided into 2-3 subsections depending on the altitude and all the space inside them was also divided into 9 classes depending on the land use. Moreover, each such subsection had 9 independent variables according to Soil Moisture Method. Thus, this gives several thousand variables, which made the task of fitting all the coefficients accordingly almost impossible, at least manually. WEAP has a built-in function for automatic calibration of parameters in each range, but now this does not work very well, or a higher computing power is required. Based on all this, it was decided not to divide the sub-basins into subsections by altitude and to leave only 2 main land use classes (Agriculture and Forest) of the 9 ones, as mentioned in Chapter 3.1. Thus, it was possible to reduce the number of unknown variables to 162, which is also a significant number. It was decided to leave the parameters to which the system is not very sensitive, as suggested by WEAP, while the rest were changed manually by trial and error and based on experience of similar studies. Calibration was carried out using these 9 parameters and the table below shows the corresponding values:

**$K_c$** Crop coefficient
**RRF** Runoff Resistance Factor
**$K_s$** Root Zone Conductivity
**$S_w$** Soil Water Capacity
**f** Preferred Flow Direction
**$k_2$** Deep Conductivity
**$D_w$** Deep Water Capacity
**$z_1$, $z_2$** Initial moisture content of the root and deep layer

| Sub-basin | | $K_c$ | RRF | $K_s$ | $S_w$ | f | $k_2$ | $D_w$ | $z_1$ | $z_2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Agriculture | 1 | 2 | 10 | 150 | 0,3 | 15 | 3000 | 30 | 15 |
| | Forest | 0,5 | 6 | 20 | 300 | 0,7 | | | 30 | |
| 2 | Agriculture | 1 | 2 | 20 | 1000 | 0,15 | 20 | 1000 | 100 | 30 |
| | Forest | 0,5 | 2 | 20 | 1000 | 0,15 | | | 100 | |
| 3 | Agriculture | 1 | 6 | 10 | 200 | 0,3 | 0,1 | 3500 | 50 | 80 |
| | Forest | 0,5 | 10 | 5 | 500 | 0,5 | | | 55 | |
| 4 | Agriculture | 1 | 2 | 20 | 1000 | 0,15 | 20 | 1000 | 30 | 30 |
| | Forest | 0,5 | 2 | 20 | 1000 | 0,15 | | | 30 | |
| 5 | Agriculture | 1 | 1 | 20 | 1000 | 0,15 | 7,5 | 20000 | 60 | 50 |
| | Forest | 0,5 | 2 | 50 | 1000 | 0,9 | | | 60 | |
| 6 | Agriculture | 1 | 2 | 20 | 1000 | 0,15 | 20 | 1000 | 30 | 30 |
| | Forest | 0,5 | 2 | 20 | 1000 | 0,15 | | | 30 | |
| 7 | Agriculture | 1 | 2 | 30 | 200 | 0,2 | 0,1 | 3000 | 30 | 40 |
| | Forest | 0,5 | 6 | 5 | 300 | 0,8 | | | 30 | |
| 8 | Agriculture | 1 | 2 | 20 | 1000 | 0,5 | 4 | 5000 | 50 | 60 |
| | Forest | 0,5 | 4 | 40 | 1000 | 0,5 | | | 50 | |
| 9 | Agriculture | 1 | 2 | 20 | 1000 | 0,15 | 20 | 1000 | 30 | 30 |
| | Forest | 0,5 | 2 | 20 | 1000 | 0,15 | | | 30 | |

**Table 4.2.** Calibrated parameters for the catchment

Refer to chapter 3.5 for a more detailed explanation of what the variables are responsible for. The freezing point was set to 0 degrees Celsius and the melting point to 1 Celsius. The initial snow level was chosen in the range of 50-100 mm depending on the average height of the sub-basin. In fact, some variables, such as the crop coefficient, change throughout the year depending on the season, but in this work all variables were taken constant to simplify the calculations. Climate data such as precipitation, temperature, humidity and wind were taken from the built-in source in WEAP (Princeton v3, Global, 1948-2010, 28 km, daily).

| Sub-basin Station | $Q_{obs}$ | $Q_{sim}$ | NSE | PBIAS |
|---|---|---|---|---|
| 1 Miras | 1,63 | 1,79 | 0,05 | 10,0 |
| 2 Sheqeras | 3,78 | 1,09 | -0,35 | -72,0 |
| 3 Turhan | 2,65 | 2,65 | 0,10 | -0,1 |
| 4 Gjinikas | 13,78 | 11,51 | 0,27 | -17,0 |
| 5 Poshtme | 2,46 | 2,28 | 0,02 | -7,0 |
| 6 Kokel | 26,43 | 25,33 | 0,28 | -4,2 |
| 7 Tomorrice | no data | 5,23 | - | - |
| 8 Bardhaj | 5,95 | 5,95 | 0,17 | 0,0 |
| 9 Kozare | 35,26 | 31,98 | 0,29 | -9,3 |

**Table 4.3.** Performance of calibration

Since there is no runoff station for sub-basin 7, it is difficult to calibrate the parameters for this and they were selected based on neighboring areas. Although NSE for all sub-basins showed an unsatisfactory value, this is not so important, since water flow peaks greatly influence this value and are very difficult to model and calibrate, and this was not the main goal of the project. This means that the values of PBIAS for sub-basins 3,5,6,8 and 9 should be given more attention, as they are located downstream and have a larger area and significance.

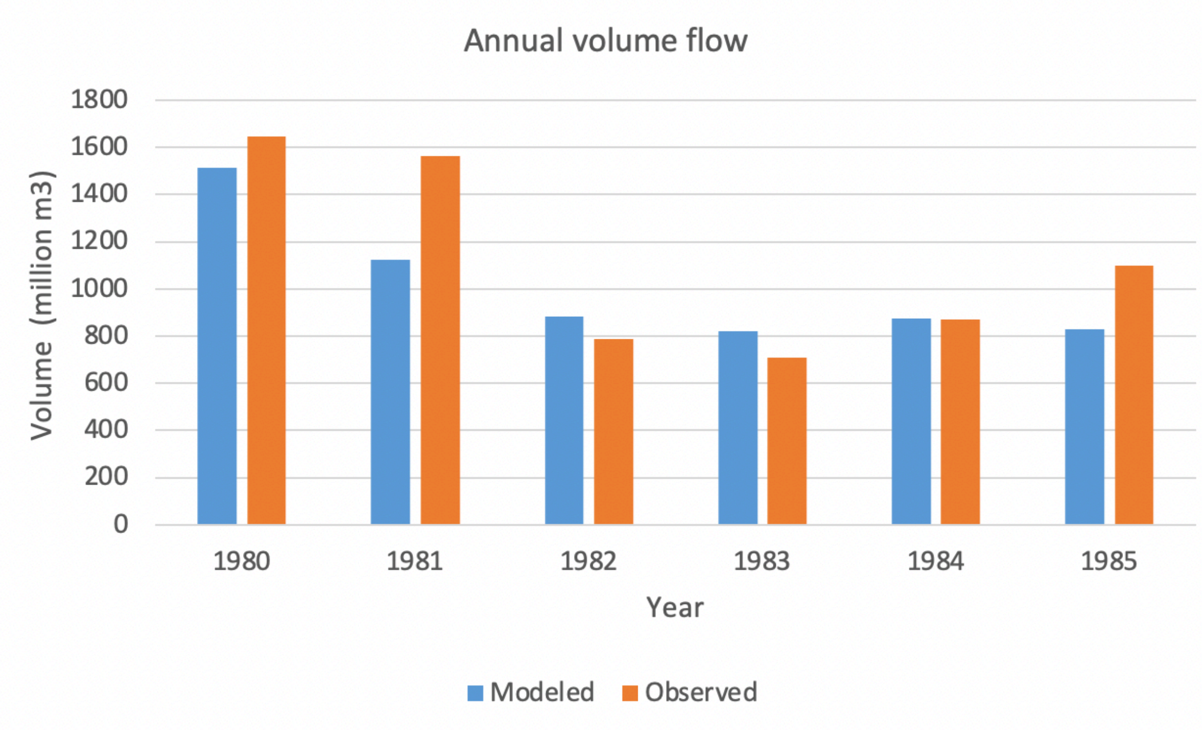


**Figure 4.2.** Modeled and observed annual volume flow in Kozare

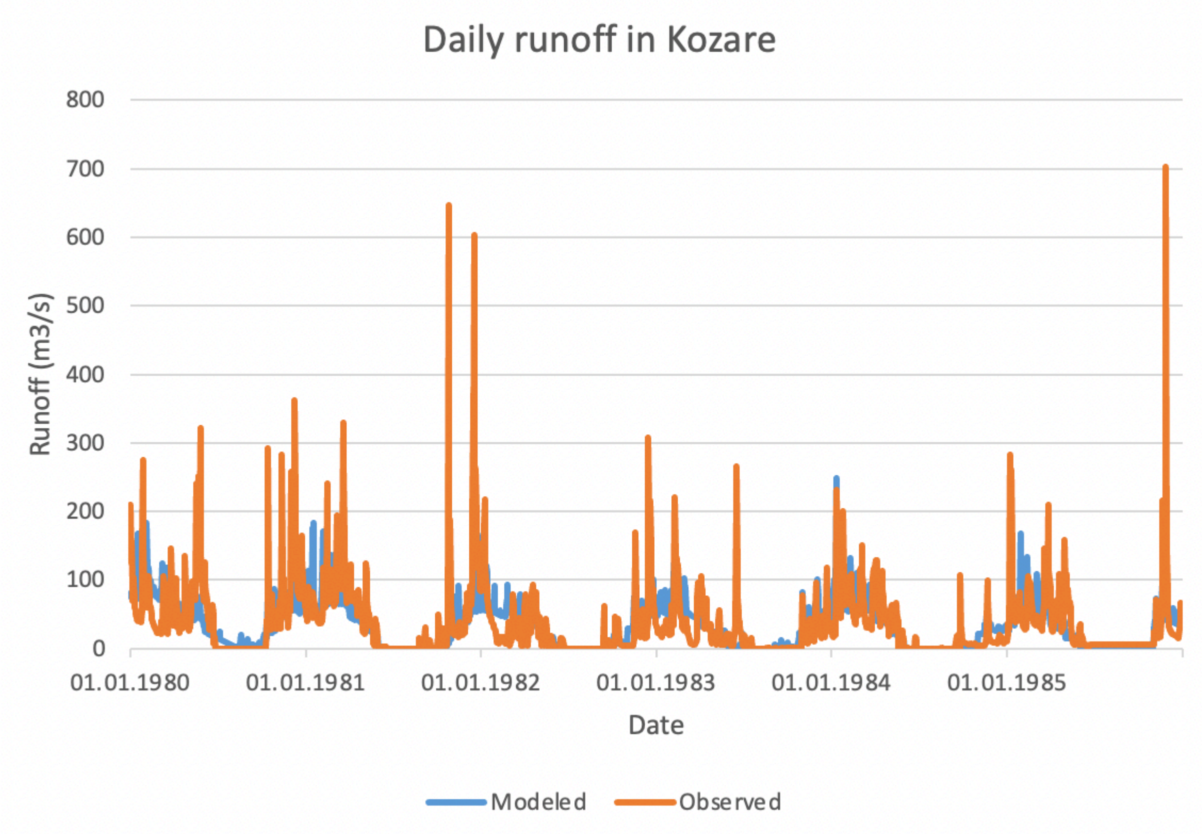


**Figure 4.3.** Modeled and observed runoff in Kozare

Kozare station was taken for comparison as the most important one since it is located downstream and most of the water from the catchment reaches this point. As can be seen from the two figures above, the total annual water flows in the model almost completely correspond to the observed ones, but a visual assessment of the hydrograph makes it clear that the system does not work well with flow peaks. The reasons and consequences of this will be discussed in more detail in next chapters.

## 4.4. Sensitivity Analysis

Sensitivity analysis is needed to understand which system parameters have the greatest impact. In this work, this process has already been done many times during the calibration process and this paragraph only shows a small part of what was actually done. Sub-basin 3 was selected for this analysis because it does not include flows from upstream sub-basins and has no irrigation demands. The parameter for comparison will be the total water flow for all 6 years of the calibration period, and all parameters except $k_2$, $z_1$ and $z_2$ will change since it will not be possible to change them by 50% due to model/program restrictions. The parameters will change simultaneously for agriculture and forest by 50% up and down.

| Par. | Parameter value | | | Flow volume (mill m3) | | | Relative change | |
|---|---|---|---|---|---|---|---|---|
| | Initial | +50% | -50% | initial | +50% | -50% | +50% | -50% |
| $K_c$ | 1/0,5 | 1,5/0,75 | 0,5/0,25 | 501 | 416 | 600 | -17% | +20% |
| RRF | 6/10 | 9/15 | 3/5 | 501 | 494 | 535 | -1% | +7% |
| $K_s$ | 10/5 | 15/7,5 | 5/2,5 | 501 | 509 | 512 | +2% | +2% |
| $S_w$ | 200/500 | 300/750 | 100/250 | 501 | 497 | 516 | -1% | +3% |
| f | 0,3/0,5 | 0,45/0,75 | 0,15/0,25 | 501 | 667 | 340 | +33% | -32% |
| $D_w$ | 3500 | 5250 | 1750 | 501 | 491 | 543 | -2% | +8% |

**Table 4.4.** Results of the sensitivity analysis

From the changes made, it can be concluded that this sub-basin is sensitive to any fluctuations in parameters, and that is why it was possible to calibrate the variables for it in such a way as to obtain a very good PBIAS value. From the table above it can be seen that the crop coefficient and preferred flow direction are the most sensitive parameters of this model.

# 5 RESULTS

This chapter presents the main process modeling results for future scenarios for 2050-2060, which are described in more detail in section 3.8, and also provides comparative precipitation plots from different sources, as well as past and future model simulation periods.

## Dynamics of reservoir capacity loss

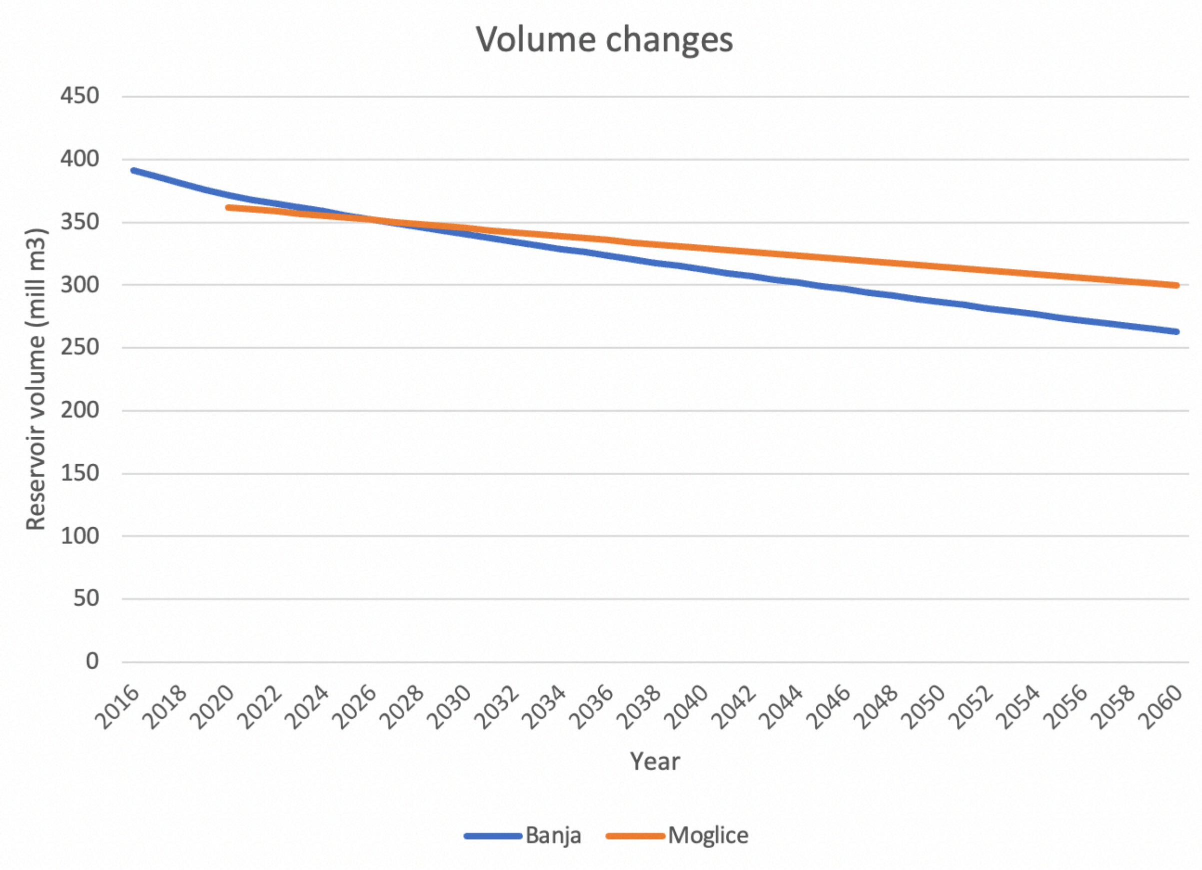


**Figure 5.1.** Changes in reservoir capacities over time

One of the most interesting questions of this project was to understand how the filling of reservoirs will change during the production of hydropower if the capacity does not change, and also if the capacity decreases as in Figure 5.1. The next two figures show the differences in hydropower production and the filling of the Banja reservoir for the SSP370 scenario.

## Reservoirs filling and hydropower generation

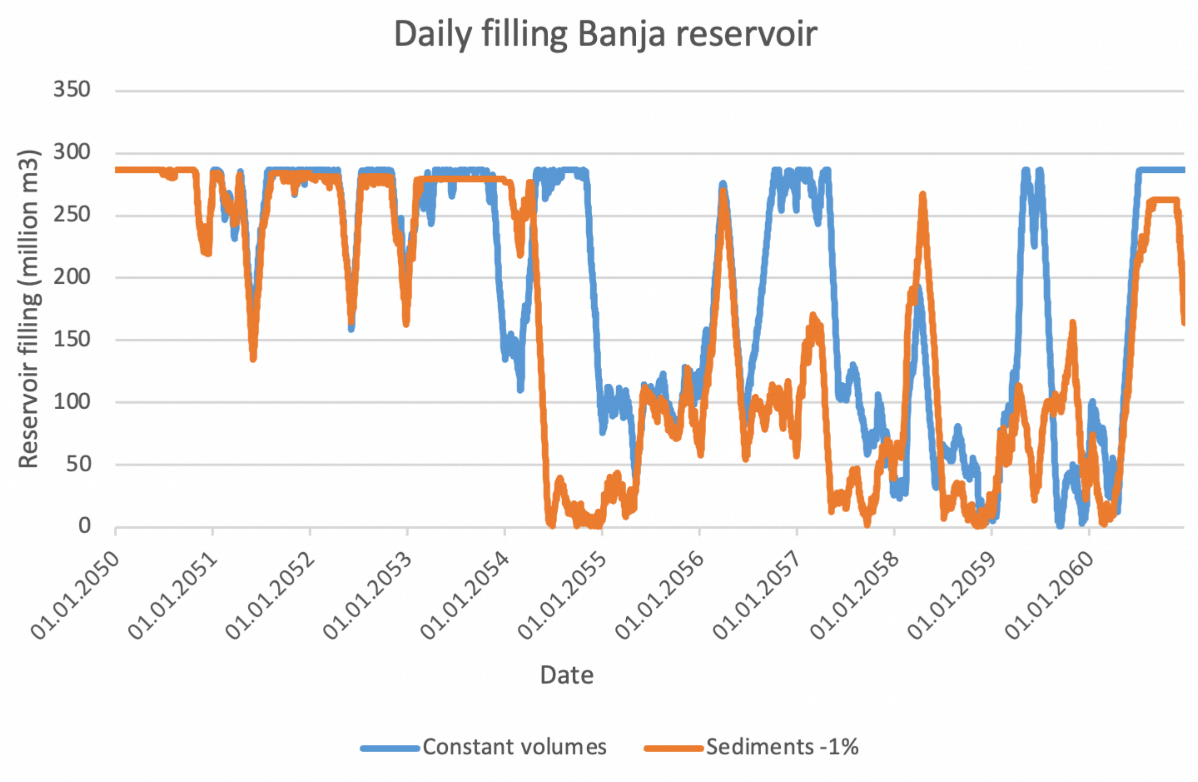


**Figure 5.2.** Daily filling Banja reservoir for SSP370 scenario

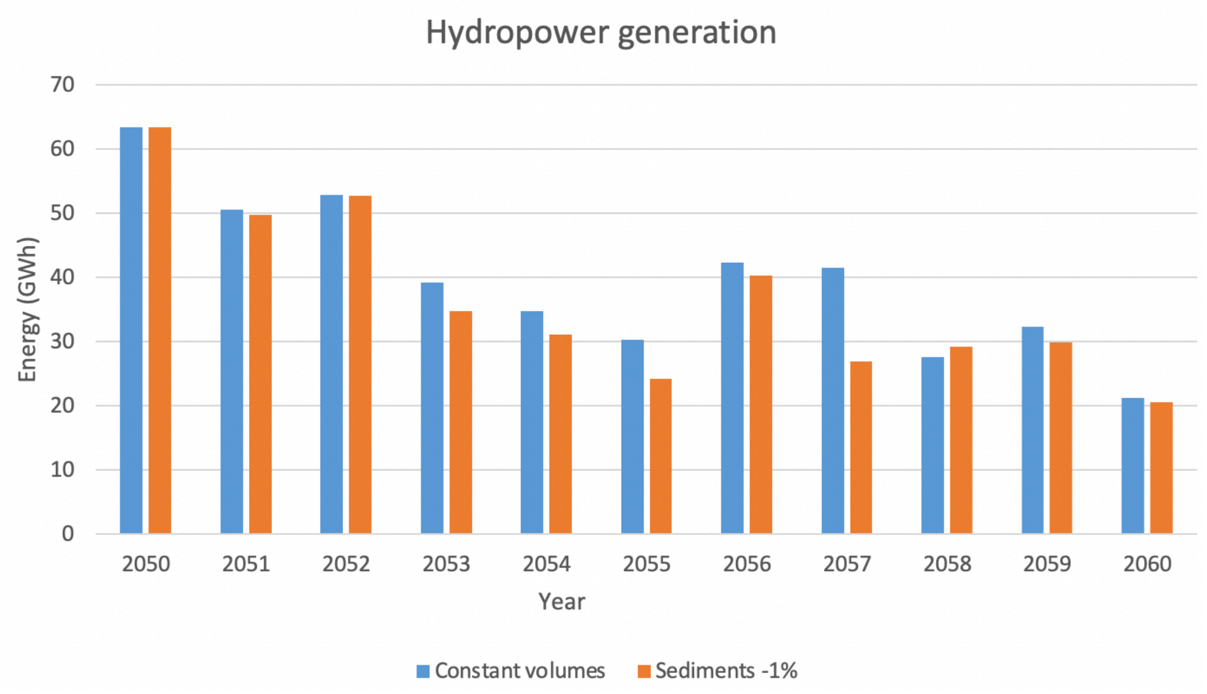


**Figure 5.3.** Hydropower generation in Banja for SSP370 scenario

As can be seen from these experiments, even though the capacity changed by less than 1% per year, sediments have a huge impact on power generation over the course of several years.

It was also useful to compare different climate scenarios with each other for a more realistic case where sediments are present in the system («Sediments -1%»). As can be seen from the figure below, climatic conditions also greatly influence hydropower stations in the region and the differences can be as high as of 2-3 times.

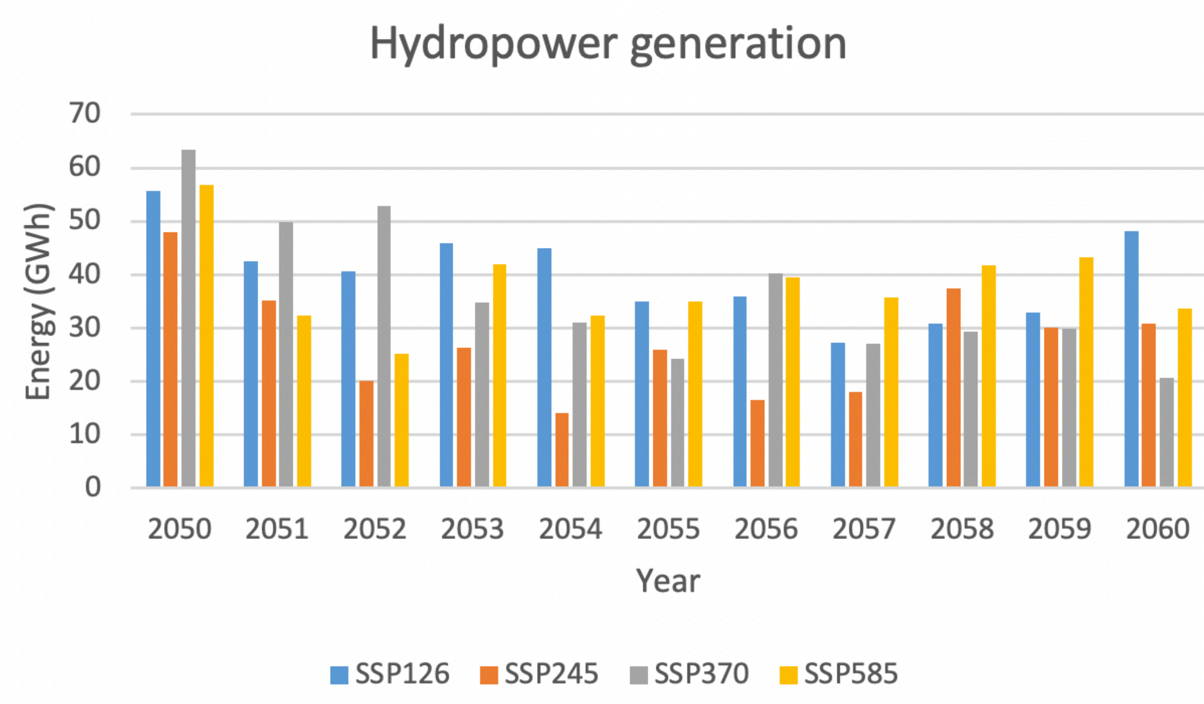


**Figure 5.4.** Hydropower generation in Banja for a set of scenarios

For the Moglice reservoir, similar graphs look very different, and this reservoir is completely emptied in the first year and then only occasionally fills up a little during heavy floods. The reason for this is that WEAP forces water to pass through the turbine and does not allow it to accumulate in a reservoir for further use. This is the explanation for the following chart 5.6 where a large amount of energy is generated in the first year due to a large head and the presence of water in the reservoir. It was these same results that Almestad obtained in 2015 when writing his master’s thesis. This phenomenon will be explained in more detail in the following chapters.

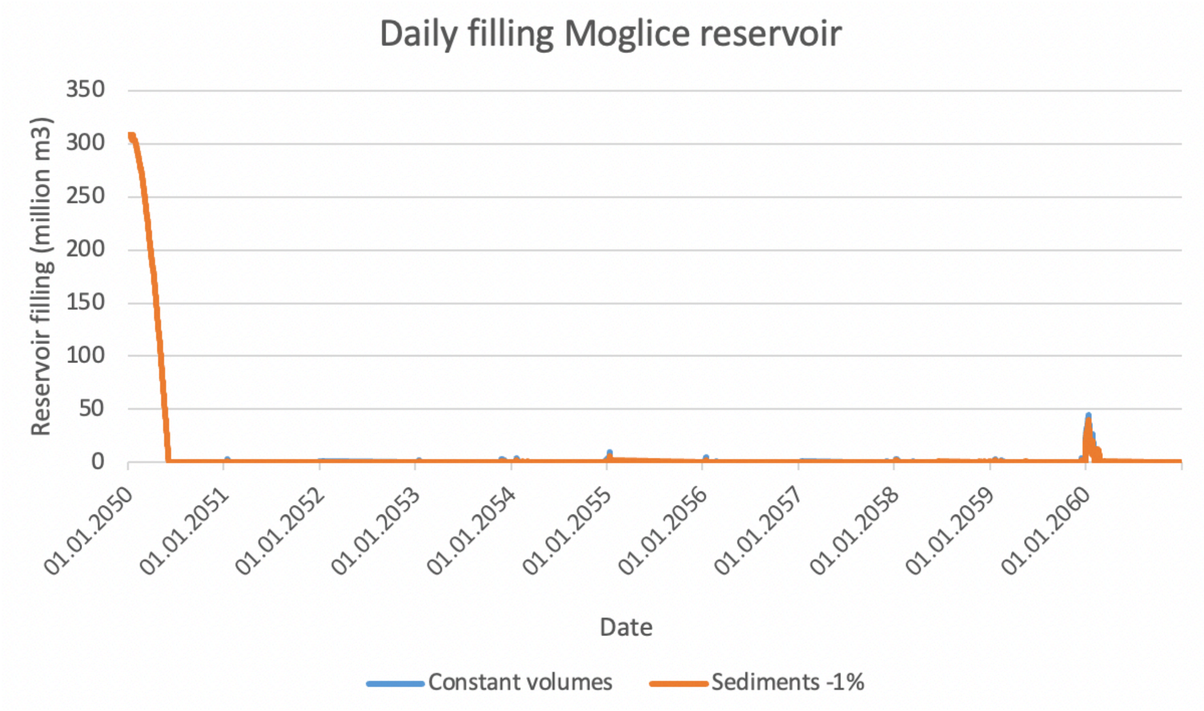


**Figure 5.5.** Daily filling Moglice reservoir for SSP126 scenario

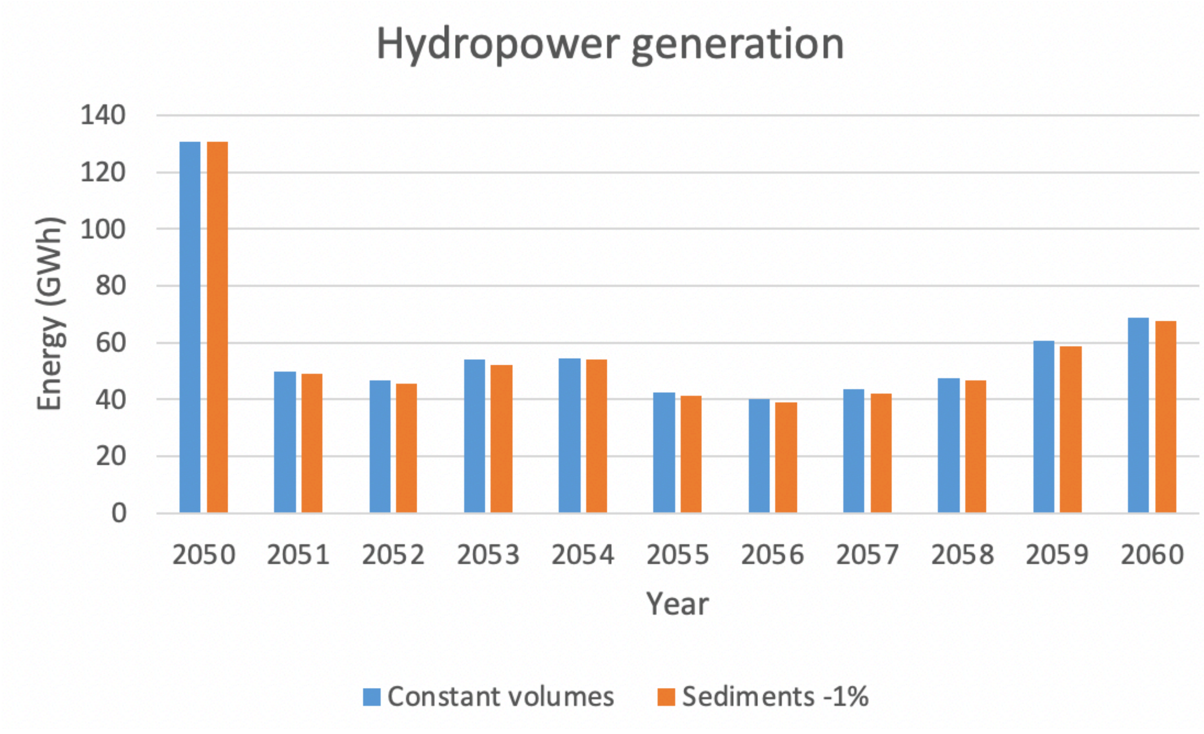


**Figure 5.6.** Hydropower generation in Moglice for SSP126 scenario

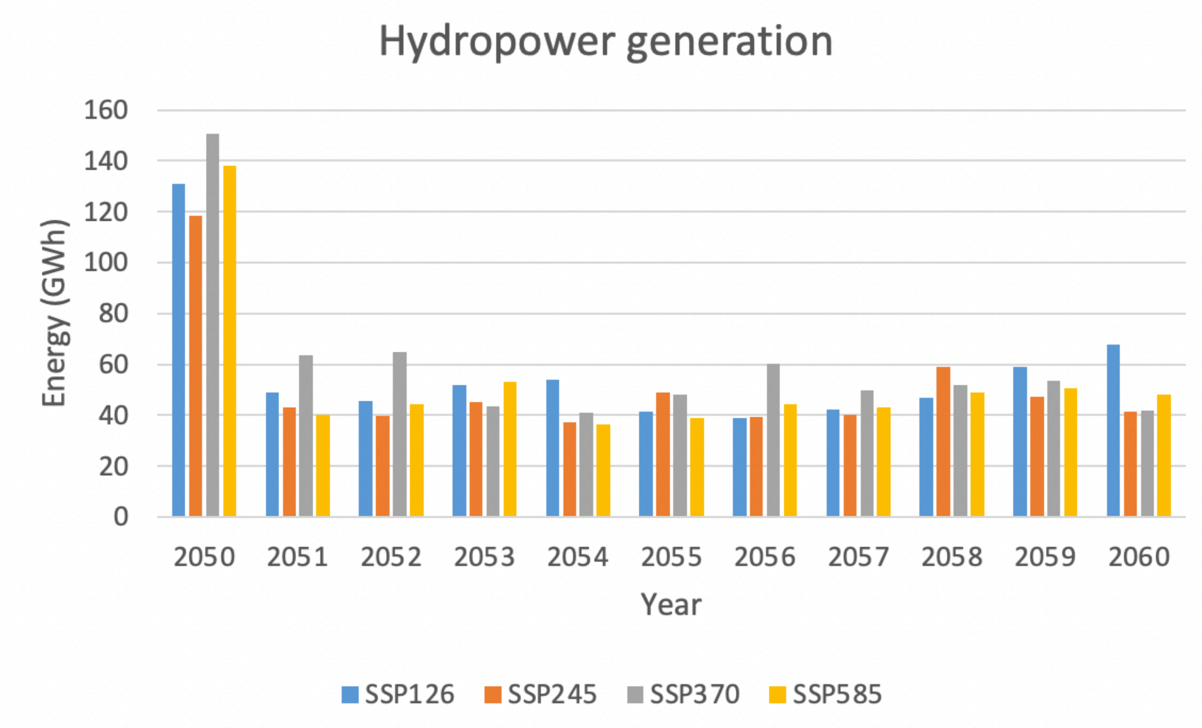


**Figure 5.7.** Hydropower generation in Moglice for a set of scenarios

The table below shows the average annual energy production for the entire model simulation period. The Banja hydropower plant is more susceptible to sediment loads, while different climatic conditions have a greater impact on the Moglice hydropower plant with an almost constant reservoir volume.

| | Banja | | | | Moglice | | | |
|---|---|---|---|---|---|---|---|---|
| | SSP 126 | SSP 245 | SSP 370 | SSP 585 | SSP 126 | SSP 245 | SSP 370 | SSP 585 |
| «Constant volumes» | 44 | 33 | 40 | 33 | 58 | 52 | 62 | 54 |
| «Sediments» | 40 | 28 | 37 | 37 | 57 | 51 | 61 | 53 |
| Relative change | -9 % | -15% | -8% | +12% | -2% | -2% | -2% | -2% |

**Table 5.1.** Simulated annual average hydropower generation for all scenarios (GWh)

## Comparative analysis of precipitation

As a follow-up to Chapter 3.2 on comparing climate data, this chapter will also provide several more precipitation graphs based on information obtained from stations and adapted to sub-basins using Thiessen polygons along with Princeton data, which are built into the WEAP system.

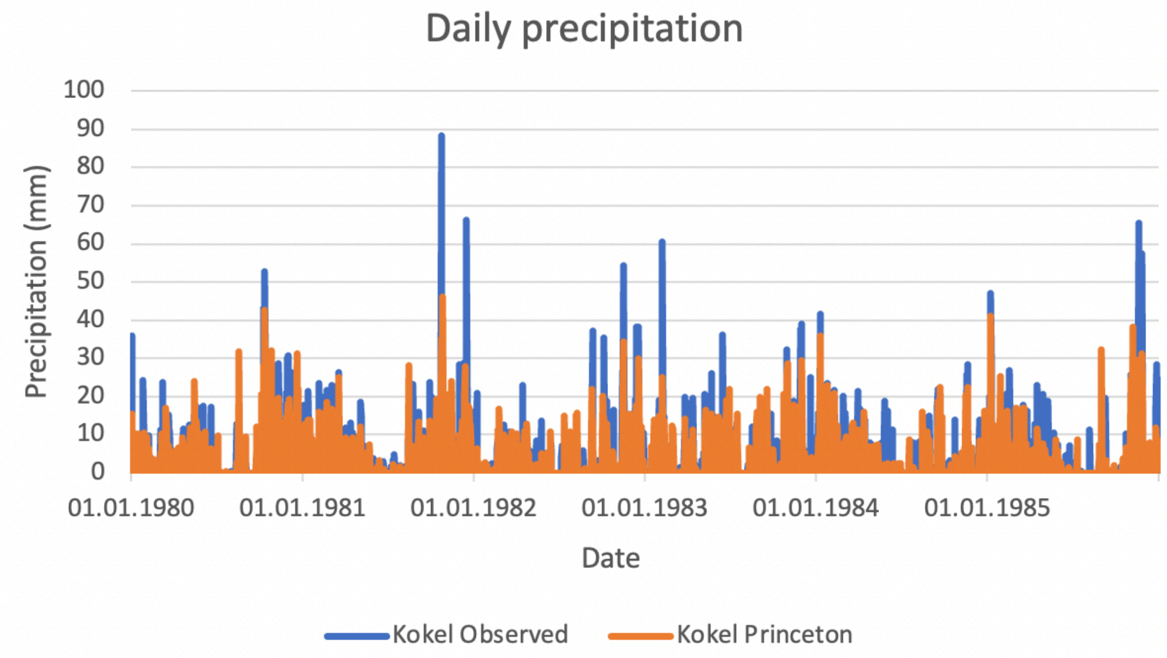


**Figure 5.8.** Daily data series of precipitation from the stations and Princeton

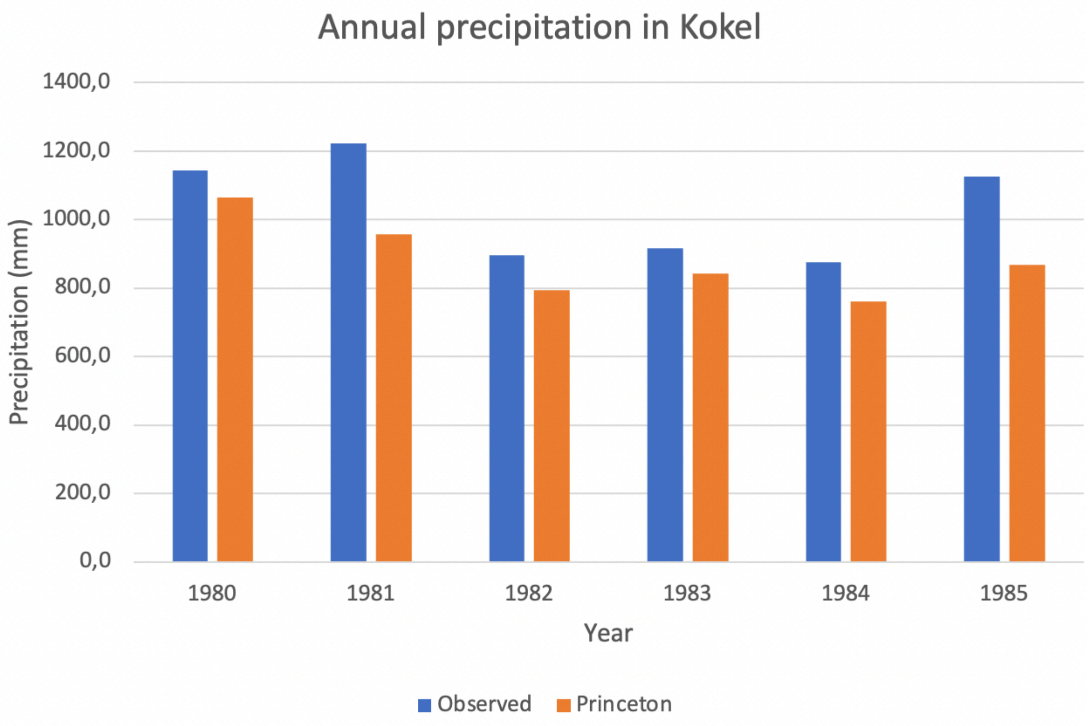


**Figure 5.9.** Annual precipitation in Kokel

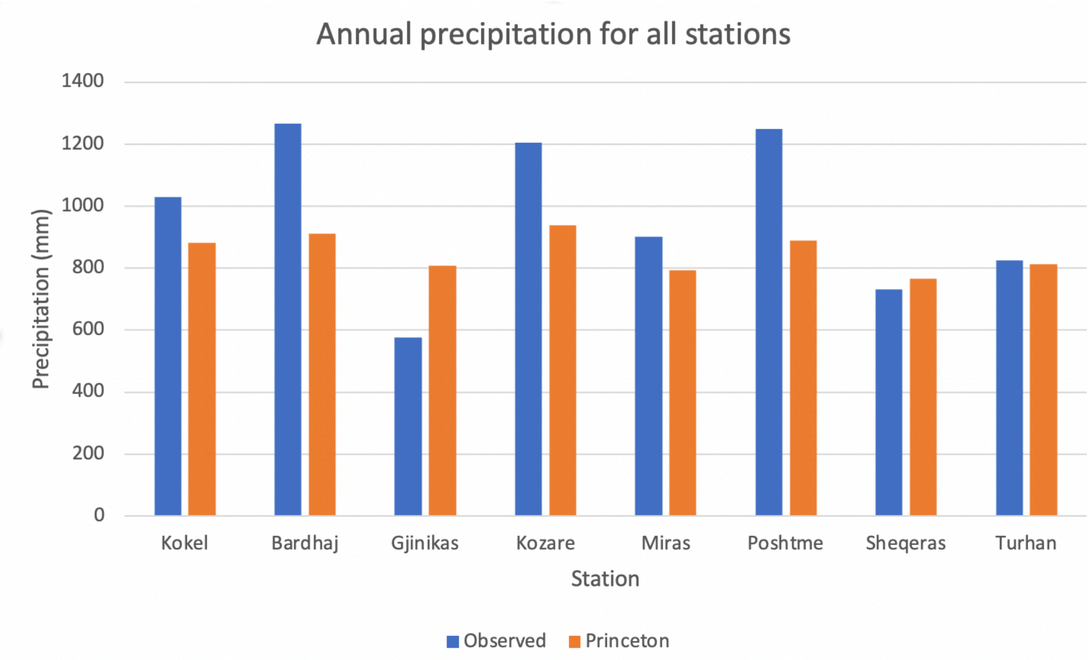


**Figure 5.10.** Comparison average annual precipitation for all stations

It can be seen that the precipitation data sets are comparable to each other and the annual averages are almost the same, but the peak precipitation does not coincide well, making peak flow modeling a challenge. PBIAS for 6 years of calibration based on precipitation data is 14.5%.

Also, for a more accurate assessment of future forecasts, the precipitation values built into the WEAP system for the past (1980-1985) and the future (2050-2056) were compared.

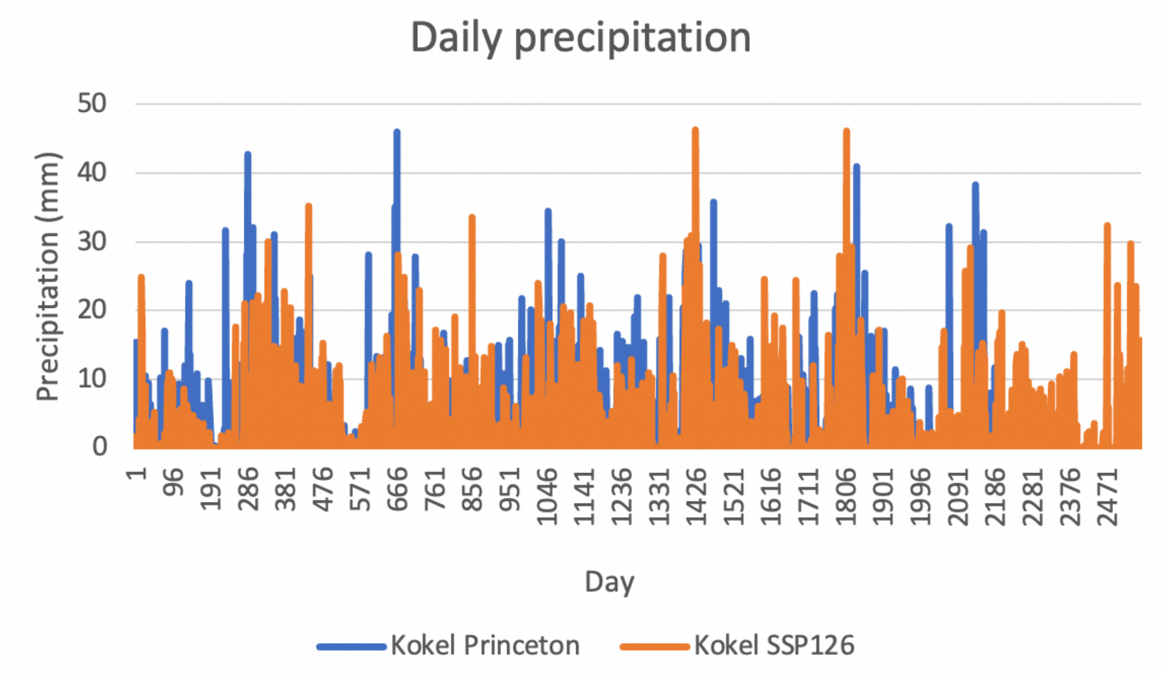


**Figure 5.11.** Daily data series of precipitation for past and future

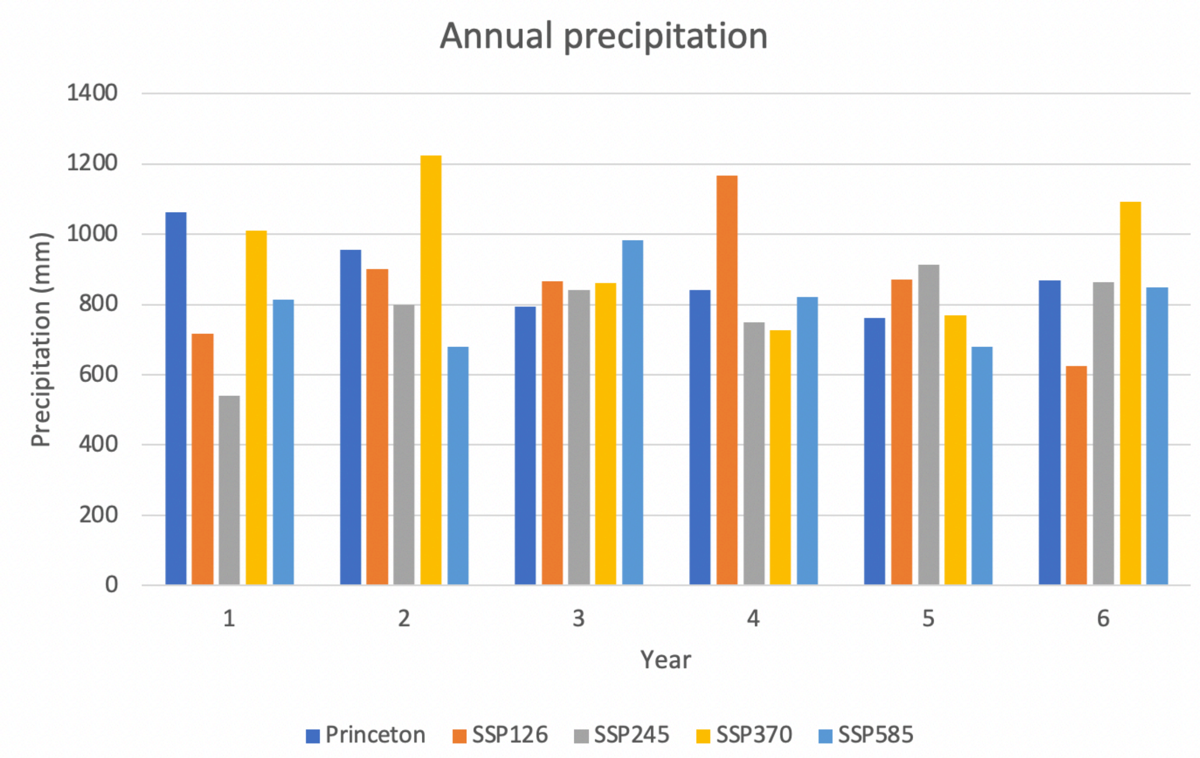


**Figure 5.12.** Average annual precipitation for different future scenarios (2050-2055) and past (1980-1985)

In this case, there is no expectation that the graphs will overlap each other, since these are completely different time intervals and significant climate changes can occur over 70 years. Rather, these graphs show that future rainfall amounts are comparable to those in the past. For the SSP126 scenario, for example, the total difference for the Kokel station (sub-basin 6) is only 2.7%.

# 6 DISCUSSION

This chapter will discuss all the results obtained from the model and the validity and applicability of simplifications and assumptions made throughout the master's thesis. It should be understood that this hydrological model is a simplified representation of the real world, which can be used for some purposes, but still needs further development.

## Input data

The first factor that brings uncertainty when creating a model, of course, is the input data. Despite the fact that there were a fairly large number of stations in the basin: 20 stations with precipitation and 10 runoff stations, but only 1 station with temperatures for an area of 3130 km$^2$, this does not add clarity, since these data series contain a large number of missing years and we found only 6 years where there would be data from all stations. In addition, the geographical diversity of the catchment with large variations in elevation also adds complexity to the input data estimation process, as precipitation and temperature are highly dependent on altitude.

Furthermore, data from stations show values at a specific place and in order to display climatic conditions over a large area it is necessary to somehow "stretch" the data, for example, using Thiessen polygons. There are several other methods, but they all bring uncertainty into further modeling of the system. Also, one of the tasks was to compare the data built into WEAP with data from the stations, which was done, and the results turned out to be quite positive. It was noticeable that precipitation in different regions quite accurately matched the data from weather stations. However, this does not provide clarity or increase confidence in these values. Since it was necessary to model the system for the future, it was decided to configure the model using data from Princeton, which is already built into WEAP, and trust them. However, the resolution with which they considered it was 28 by 28 km, which gives only 5-10 cells for the entire catchment and, of course, is not the most precise. The temperature data was difficult to compare with anything, so it was decided to trust Princeton data.

## Methodological assumptions

Another important detail is the division of the catchment into sub-basins and calibration of parameters. Sub-basin 7 does not have a station with runoff data, so its calibration was largely done using the data from other neighboring sub-basins. The Soil Moisture Method itself is quite time-consuming and complex, although it can describe a system quite accurately. However, manually selecting more than a thousand variables is impossible (even though their number was reduced to 162 after many simplifications), but still, within the framework of a master's thesis, it is not possible to accurately select all the coefficients. As a result of the sensitivity analysis, it was revealed that the crop coefficient and preferred flow direction are the most influential parameters in the system, so they were selected with high precision based on the previous work by Almestad in 2015. And even if the coefficients for the calibration period are selected successfully, this does not guarantee that the properties of the system will not change after several years. Moreover, endless hours of improving system parameters and increasing accuracy are useless since the input data is more likely to be questionable than reliable. It turns out that one uncertainty gives rise to another.

The next point of uncertainty is water intake for irrigation. It involves several problems. First of all, there is a lack of input data. It is extremely difficult to find information that may not exist. Apart from Almestad's master's thesis, there were no other sources and it was unclear what resources could be considered reliable. The second aspect here is the change in irrigation systems, which was especially active during the calibration period. Apparently, many canals fell into disrepair and new ones began to be built, and no accurate data on water consumption could be expected. Further causing uncertainty is the water demand of residents of villages located near the river. The huge number of farmers who have their own private pastures and farms cannot be accurately accounted for in the model. Also, system parameters may change over time, however, the system is calibrated based on the best available knowledge at a specific simulation period and it is not possible predict the future changes in the system.

## Results

As for WEAP, its strengths include the visual presentation of data and the ability to allocate water resources to various demands depending on water availability and priorities, but the calculation of hydroelectric power clearly needs improvement. The fact is that WEAP forces energy production if there is some available water in the reservoir, that is why it is impossible to accumulate water in Moglice, despite the fact that there is a sufficient amount of water that passes through the turbine there. The reservoir is emptied, thereby reducing the head and, therefore, amount of energy. It is for this reason that the plant factor values that were taken were smaller than they are supposed to be, otherwise both reservoirs would be empty in the first few months, as was happening with Moglice. It was experimentally found that for Moglice this plant factor should be only 1-2% in order to have a big head. The system is set to plant factors of 18% for Banja and 20% for Moglice in order to show both situations, when in one case the reservoir (Moglice) never fills, and in the other (Banja) it functions as it is supposed to be. In t Baja case, the impact of loss of reservoir capacity due to sedimentation on energy production is clearly visible.

As a result of such factors, the total amount of generated energy is just under 100 GWh instead of the planned 729 GWh. However, this can be explained by several reasons: 1) when analyzing data from weather stations, a downward trend was apparent in precipitation and an upward trend in temperature, and in 50 years, climatic conditions may be very different, 2) 729 GWh is a possible average estimate of hydropower generation for the first years of turbine operation, but this cannot last indefinitely, 3) the capacity of reservoirs has decreased by 20-25% over 30 years, which does not allow to store more water and distribute it correctly. It is also worth adding that WEAP does not take into account the efficiency of the turbine and its dependence on the passing water flow and head, as well as the fact that there are 3 turbine units at each hydropower station and energy production can be adjusted depending on the available amount of water.

But despite all the shortcomings and inaccuracies described above, the modeled hydrological system can be considered successful in terms of PBIAS, especially for some sub-basins where this indicator is 0%. During the creation of this model, many ideas were taken from Almestad's master’s thesis, but some things were simplified and others, on the contrary, were improved, so this model and the results obtained can be trusted with the above conditions and these settings can be a good basis for further improvement taking into account new, more accurate climatic and irrigation data from the future.

# 7 CONCLUDING REMARKS

The developed calibrated model corresponds to reality in some aspects, but still requires improvement. Good PBIAS values were obtained for sub-basins 1, 3, 5, 6, 8, 9 (no more than 10%), which is a very good indicator and shows that the water balance is maintained, but NSE for all sub-basins does not exceed 0.35, which can be considered unsatisfactory due to the poor behavior of the model during peak floods. Sensitivity analysis revealed that the preferred flow direction is one of the most important system calibration parameters and with a change of 50% for sub-basin 3, the annual volume flow changes by 32-33%. No less important is the crop coefficient, when doubled, the annual volume flow decreases by 17%, and when halved, it increases by 20%.

The comparative analysis showed that total precipitation from Princeton (built-in in WEAP) differs from the Thiessen polygon-recalculated weather station series, with a PBIAS of 12.7%, but the peak values are poorly matched. It was also calculated that the total amount of precipitation for 1980-1985 (Princeton) and 2050-2055 (CMIP6 ACCESS-CM2) for Kokel differs by only 2.7%.

Energy production at the Banja hydropower station has an average value of 40 GWh in the period 2050-2060. Sediments have a huge impact on hydropower production, the difference can reach 15% (CMIP6 ACCESS-CM2 SSP245) over the period 2050-2060, with a 0.86% decrease in the capacity of a reservoir per year.

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# APPENDICES

**Appendix A:** Description of master thesis

**Appendix B:** Daily runoff comparison

**Appendix C:** Annual flow comparison

**Appendix D:** Reservoir volume changes

**Appendix E:** Irrigation distribution over year

**Appendix F:** Precipitation comparison

**Appendix G:** Reservoir filling and hydropower generation

**Appendix H:** Digital appendix that includes:

- 2 WEAP models with corresponding data
- Excel-file with precipitation and irrigation data

# APPENDIX A: DESCRIPTION OF MASTER THESIS

**NTNU**
**Norwegian University of**
**Science and Technology**

**Faculty of Engineering**

**Department of Civil and**
**Environmental Engineering**

**M.Sc. Thesis in**
**Water Resources Modelling and Engineering**

## Candidate: Sergey Popov

### Title: Assessment of the effect of reservoir sedimentation and lost storage capacities in Devoll basin, Albania, on power production under present and future climatic conditions

## 1 BACKGROUND

Reservoirs are key-stones in the management of water resources and a prerequisite in the supply of regulated energy from hydropower projects, as such an enabler of the integration of intermittent sources of power (solar and wind). Besides that, reservoirs can dampen floods with their empty capacity in periods of high inflow. As such, river basins regulated for hydropower benefit from reduced flood peaks and volumes and reduced societal losses during flood events. In river basins with high sediment loads, the reservoir capacities/storage volumes are reduced over time, as sediments tend to deposit in reservoirs unless they are removed by heavy machinery by some form of flushing. This will reduce the power plant's flexibility over time, and also reduce the potential to dampen floods.

This study will analyze the changes in power production over time and the ability to dampen floods due to the gradual reduction of storage capacity. The study will be carried out using Devoll River Basin in Albania as a case, where two reservoirs have been constructed in the last few years (by Statkraft). The Devoll River is the main tributary of the Seman River and is located about 70 km southeast of Tirana. The river basin has an area of approximately 3,140 $km^2$ and stretches from the border of Greece to the east, to the confluence with the Seman and Osum Rivers in the west. At the confluence, the Devoll River changes its name to the Seman River. There are several tributaries joining Devoll along its course and the biggest is the Tomorrice River.

The development of the basin has been accompanied by extensive research program where sediment transport and handling has been central. This study will benefit from these previous studies and will build on their findings.

## 2 MAIN QUESTIONS FOR THE THESIS

The overall objective of the thesis is to assess the effect of the reservoir sedimentation and lost storage capacities on power production and flood dampening in Devoll basin, Albania, under present and future climatic conditions. In order to do so, the key steps and questions to be addressed are:

1. Data collection and preparations: collect and compile data from Devoll basin for the purpose of water resources modelling.
2. Configure WEAP as the hydrological model and calibrate the model against historical data.
3. Analyze and compare data obtained from meteorological stations with climatic data from WEAP.
4. Represent all recent water related infrastructure and simulate the role of the reservoir with respect to power production.
5. Select a set of scenarios from CMIP6 for climate change as well as sediment impacts on storage capacities, and simulate the changes in power output.
6. Discuss the findings in terms of the long-term viability of the reservoirs.

## 3 SUPERVISION, DATA AND INFORMATION INPUT

Professor Tor Haakon Bakken will be the main supervisor of the thesis work, with Slaven Conevski as co-supervisor (NTNU/Multiconsult). Discussion with and input from colleagues and other researchers or engineering staff at NTNU, power companies or consultants are recommended, if considered relevant. Significant inputs from others shall, however, be referenced in a convenient manner.

The research and engineering work carried out by the candidate in connection with this thesis shall remain within an educational context. The candidate and the supervisors are therefore free to introduce assumptions and limitations, which may be considered unrealistic or inappropriate in a contract research or a professional engineering context.

## 4 REPORT FORMAT AND REFERENCE STATEMENT

The report shall be typed by a standard word processor and figures, tables, photos etc. shall be of good report quality. The report shall include a summary, a table of content, lists of figures and tables, a list of literature and other relevant references. All figures, maps and other included graphical elements shall have a legend, have axis clearly labelled and generally be of good quality.

The report shall have a professional structure and aimed at professional senior engineers and decision makers as the main target group, alternatively written as a scientific article. The decision regarding report or scientific article shall be agreed upon with the supervisor. The thesis shall include a signed statement where the candidate states that the presented work is his/her own and that significant outside input is identified.

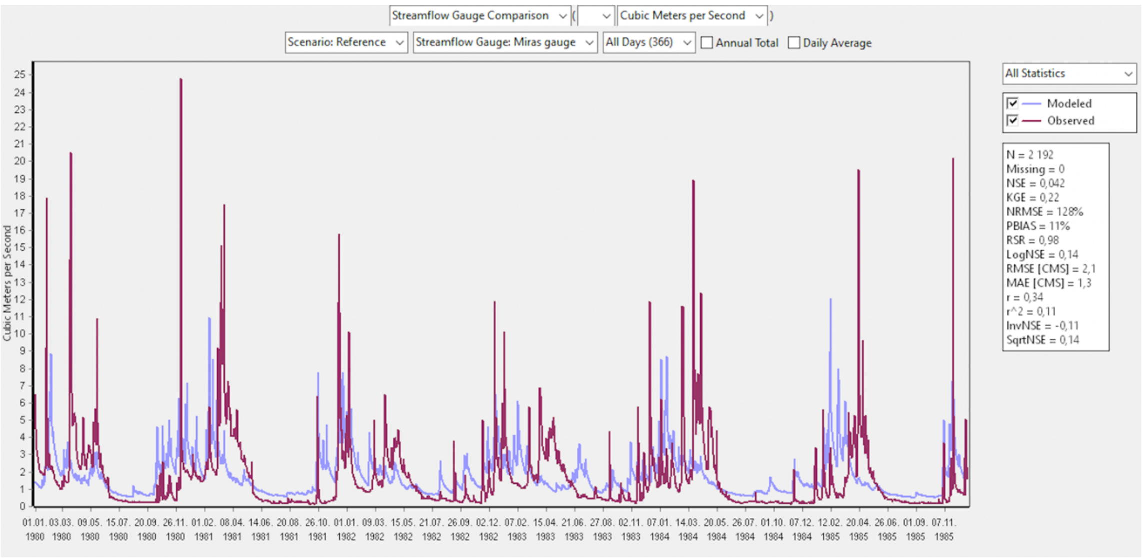
This text shall be included in the report submitted. Data that is collected during the work with the thesis, as well as results and models setups, shall be documented and submitted in electronic format together with the thesis.

The thesis shall be submitted no later than 17th of December, 2023.

Tor Haakon Bakken

Tor Haakon Bakken, professor Trondheim 15th of January 2023

# APPENDIX B: DAILY RUNOFF COMPARISON

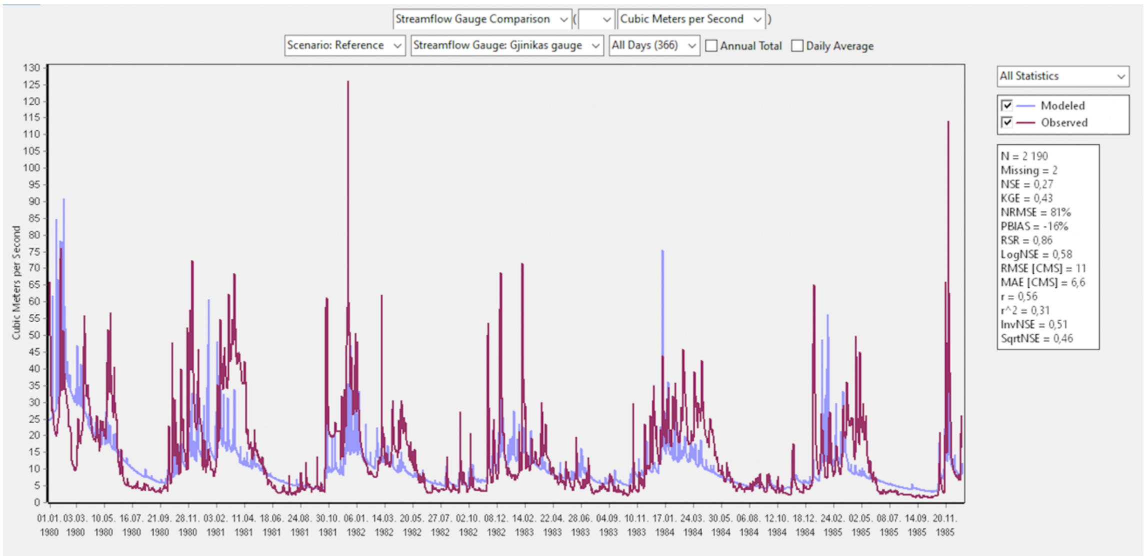


Streamflow Gauge Comparison ( Cubic Meters per Second )
Scenario: Reference | Streamflow Gauge: Miras gauge | All Days (366) | ☐ Annual Total ☐ Daily Average

All Statistics
☑ Modeled
☑ Observed

N = 2 192
Missing = 0
NSE = 0,042
KGE = 0,22
NRMSE = 128%
PBIAS = 11%
RSR = 0,98
LogNSE = 0,14
RMSE [CMS] = 2,1
MAE [CMS] = 1,3
r = 0,34
r^2 = 0,11
InvNSE = -0,11
SqrtNSE = 0,14

Miras

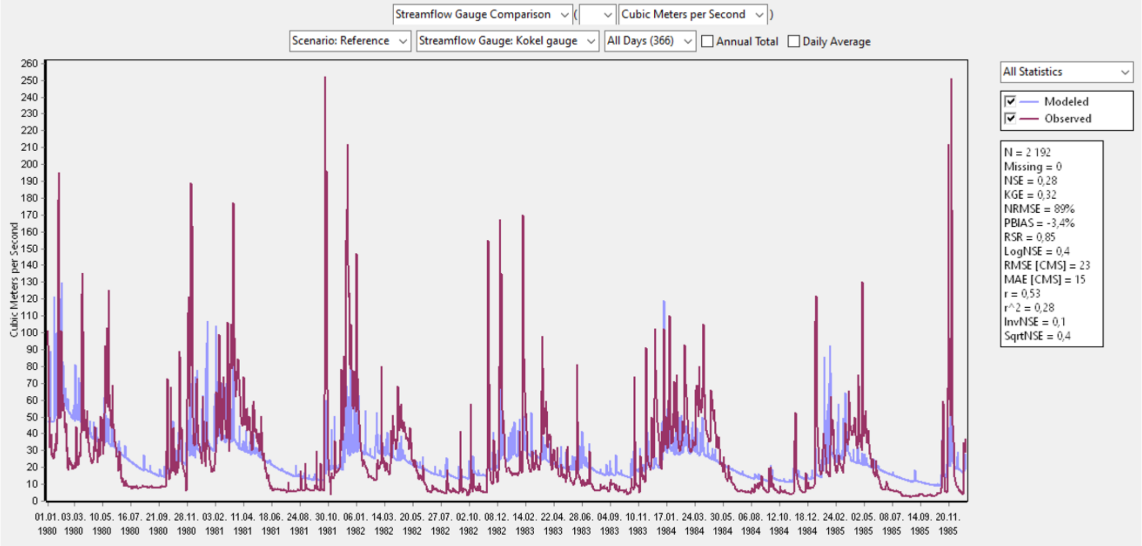


Streamflow Gauge Comparison ( Cubic Meters per Second )
Scenario: Reference | Streamflow Gauge: Gjinikas gauge | All Days (366) | ☐ Annual Total ☐ Daily Average

All Statistics
☑ Modeled
☑ Observed

N = 2 190
Missing = 2
NSE = 0,27
KGE = 0,43
NRMSE = 81%
PBIAS = -16%
RSR = 0,86
LogNSE = 0,58
RMSE [CMS] = 11
MAE [CMS] = 6,6
r = 0,56
r^2 = 0,31
InvNSE = 0,51
SqrtNSE = 0,46

Gjinikas

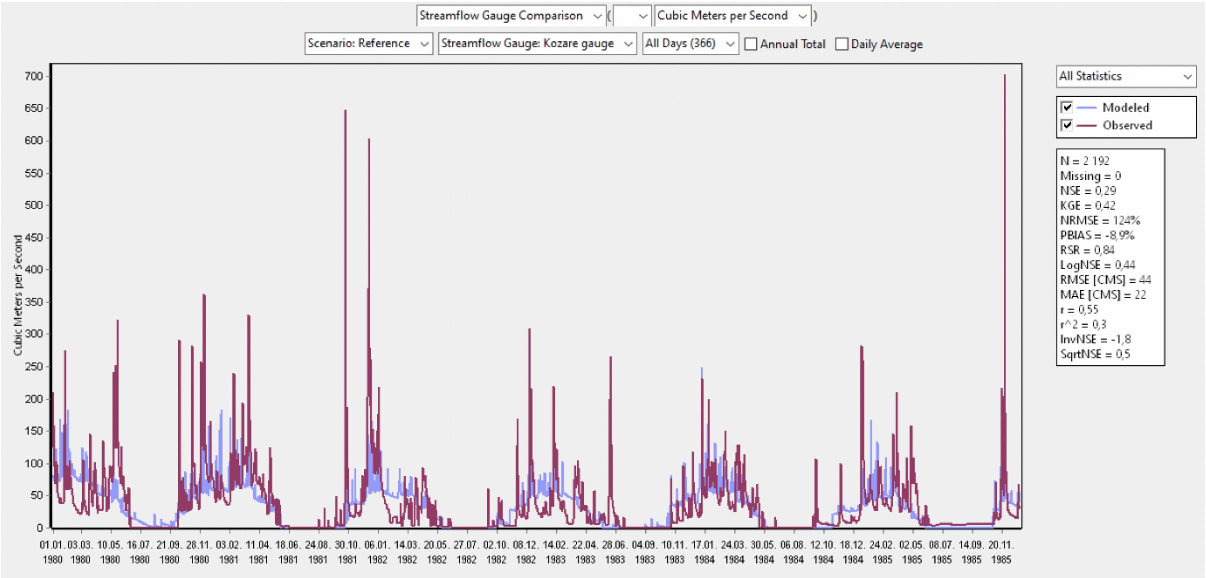


Streamflow Gauge Comparison ( Cubic Meters per Second )
Scenario: Reference | Streamflow Gauge: Kokel gauge | All Days (366) | ☐ Annual Total ☐ Daily Average

All Statistics
☑ Modeled
☑ Observed

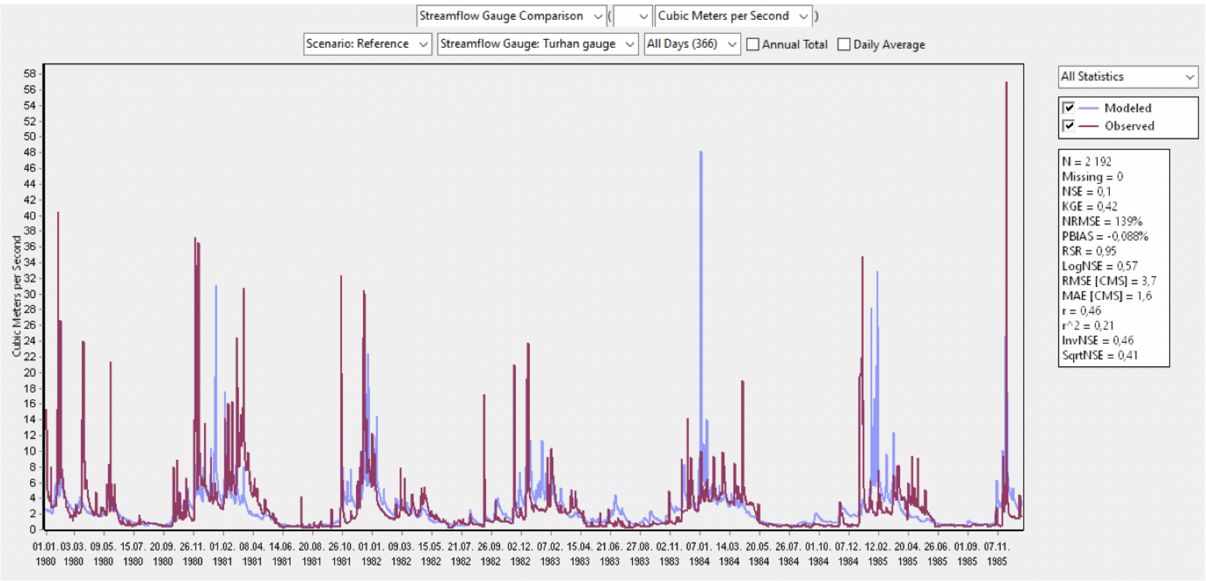
N = 2 192
Missing = 0
NSE = 0,28
KGE = 0,32
NRMSE = 89%
PBIAS = -3,4%
RSR = 0,85
LogNSE = 0,4
RMSE [CMS] = 23
MAE [CMS] = 15
r = 0,53
r^2 = 0,28
InvNSE = 0,1
SqrtNSE = 0,4

Kokel



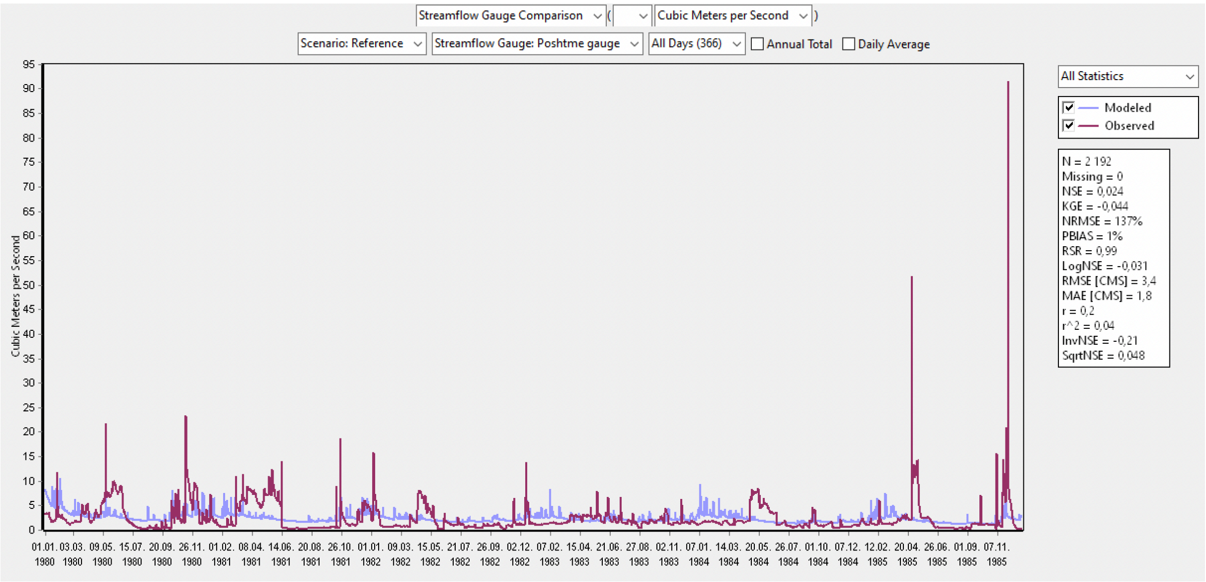
N = 2 192
Missing = 0
NSE = 0,29
KGE = 0,42
NRMSE = 124%
PBIAS = -8,9%
RSR = 0,84
LogNSE = 0,44
RMSE [CMS] = 44
MAE [CMS] = 22
r = 0,55
r^2 = 0,3
InvNSE = -1,8
SqrtNSE = 0,5

Kozare



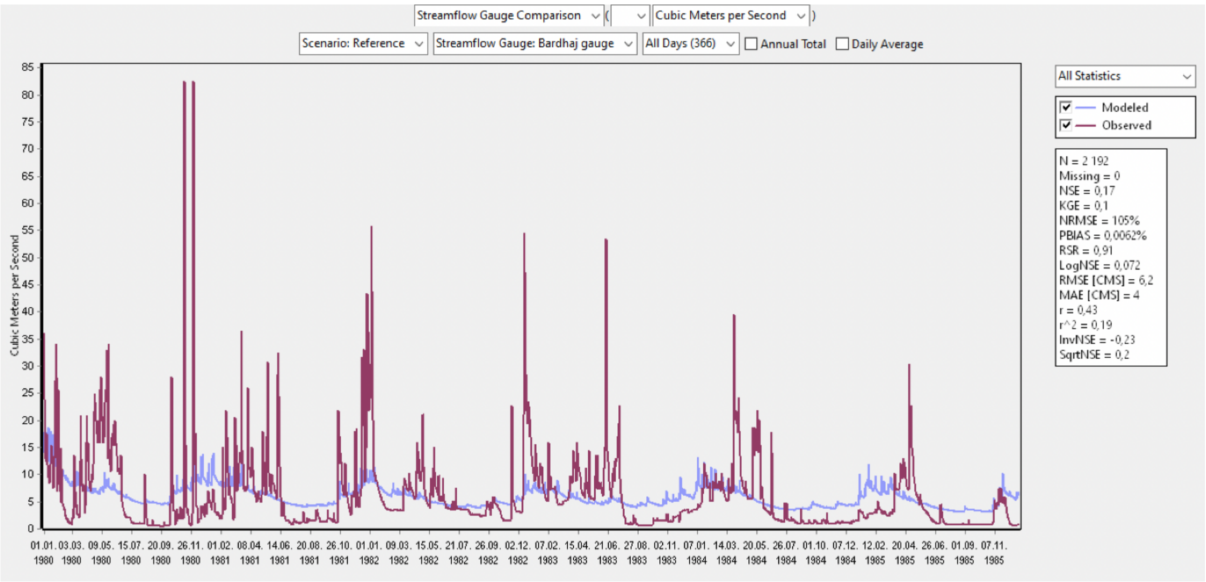
N = 2 192
Missing = 0
NSE = 0,1
KGE = 0,42
NRMSE = 139%
PBIAS = -0,088%
RSR = 0,95
LogNSE = 0,57
RMSE [CMS] = 3,7
MAE [CMS] = 1,6
r = 0,46
r^2 = 0,21
InvNSE = 0,46
SqrtNSE = 0,41

Turhan



N = 2 192
Missing = 0
NSE = 0,024
KGE = -0,044
NRMSE = 137%
PBIAS = 1%
RSR = 0,99
LogNSE = -0,031
RMSE [CMS] = 3,4
MAE [CMS] = 1,8
r = 0,2
r^2 = 0,04
InvNSE = -0,21
SqrtNSE = 0,048

Poshtme



Streamflow Gauge Comparison ( Cubic Meters per Second )

Scenario: Reference | Streamflow Gauge: Bardhaj gauge | All Days (366) | ☐ Annual Total | ☐ Daily Average

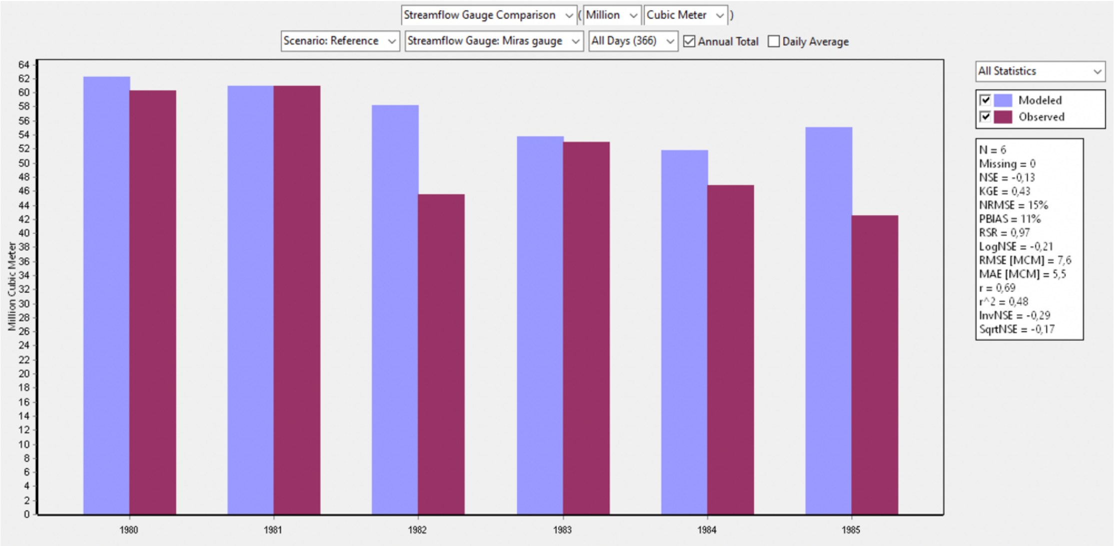
All Statistics

☑ Modeled
☑ Observed

```
N = 2 192
Missing = 0
NSE = 0,17
KGE = 0,1
NRMSE = 105%
PBIAS = 0,0062%
RSR = 0,91
LogNSE = 0,072
RMSE [CMS] = 6,2
MAE [CMS] = 4
r = 0,43
r^2 = 0,19
InvNSE = -0,23
SqrtNSE = 0,2
```

Bardhaj

# APPENDIX C: ANNUAL FLOW COMPARSION



Streamflow Gauge Comparison ( Million Cubic Meter )

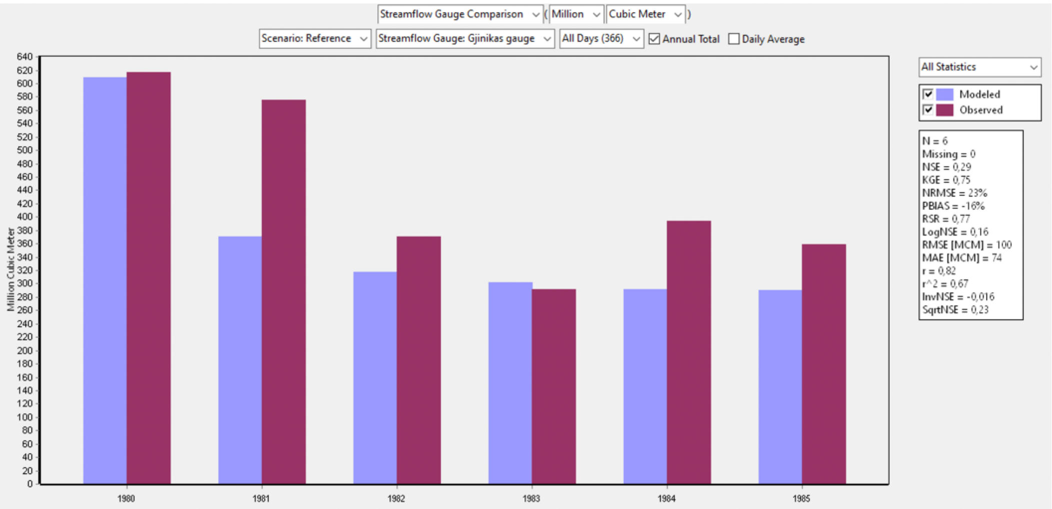
Scenario: Reference | Streamflow Gauge: Miras gauge | All Days (366) | ☑ Annual Total ☐ Daily Average

All Statistics

☑ Modeled
☑ Observed

N = 6
Missing = 0
NSE = -0,13
KGE = 0,43
NRMSE = 15%
PBIAS = 11%
RSR = 0,97
LogNSE = -0,21
RMSE [MCM] = 7,6
MAE [MCM] = 5,5
r = 0,69
r^2 = 0,48
InvNSE = -0,29
SqrtNSE = -0,17

Miras



Streamflow Gauge Comparison ( Million Cubic Meter )

Scenario: Reference | Streamflow Gauge: Gjinikas gauge | All Days (366) | ☑ Annual Total ☐ Daily Average

All Statistics

☑ Modeled
☑ Observed

N = 6
Missing = 0
NSE = 0,29
KGE = 0,75
NRMSE = 23%
PBIAS = -16%
RSR = 0,77
LogNSE = 0,16
RMSE [MCM] = 100
MAE [MCM] = 74
r = 0,82
r^2 = 0,67
InvNSE = -0,016
SqrtNSE = 0,23

Gjinikas

Streamflow Gauge Comparison ( Billion Cubic Meter )

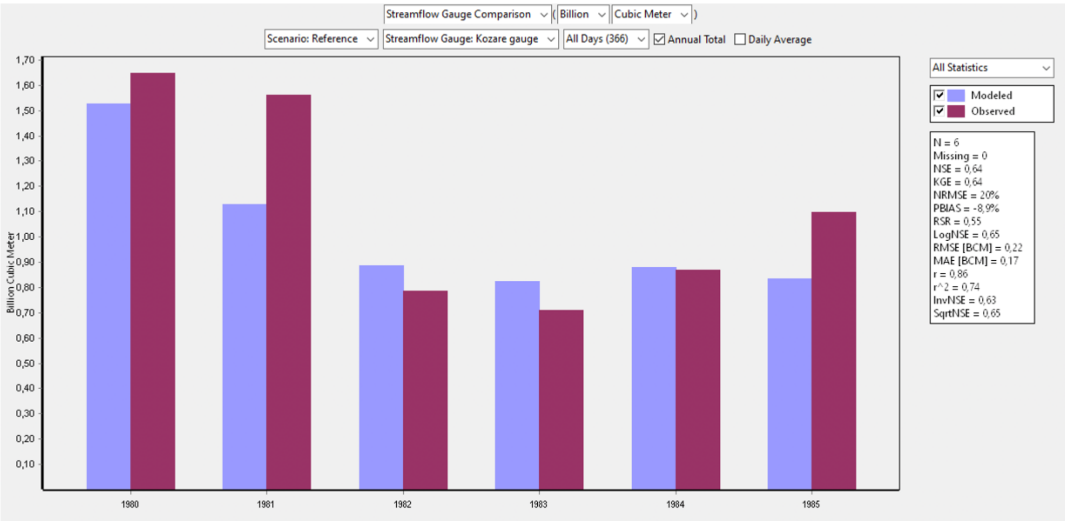
Scenario: Reference | Streamflow Gauge: Kokel gauge | All Days (366) | ☑ Annual Total ☐ Daily Average

All Statistics

☑ Modeled
☑ Observed

N = 6
Missing = 0
NSE = 0,6
KGE = 0,78
NRMSE = 14%
PBIAS = -3,4%
RSR = 0,57
LogNSE = 0,65
RMSE [BCM] = 0,12
MAE [BCM] = 0,091
r = 0,8
r^2 = 0,64
InvNSE = 0,67
SqrtNSE = 0,63

Kokel



Streamflow Gauge Comparison (Billion Cubic Meter)

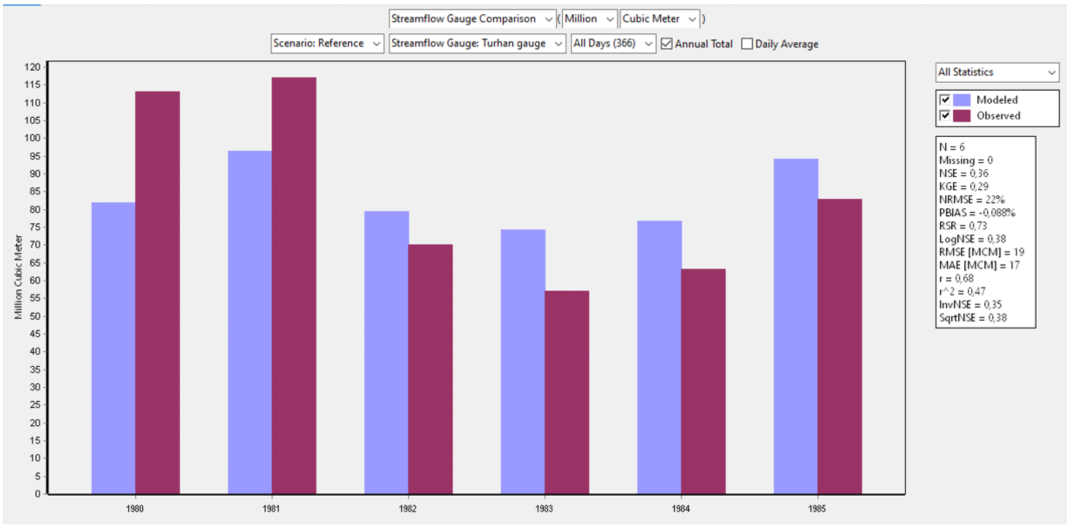
Scenario: Reference | Streamflow Gauge: Kozare gauge | All Days (366) | ☑ Annual Total | ☐ Daily Average

All Statistics

☑ Modeled
☑ Observed

N = 6
Missing = 0
NSE = 0,64
KGE = 0,64
NRMSE = 20%
PBIAS = -8,9%
RSR = 0,55
LogNSE = 0,65
RMSE [BCM] = 0,22
MAE [BCM] = 0,17
r = 0,86
r^2 = 0,74
InvNSE = 0,63
SqrtNSE = 0,65

Kozare



Streamflow Gauge Comparison (Million Cubic Meter)

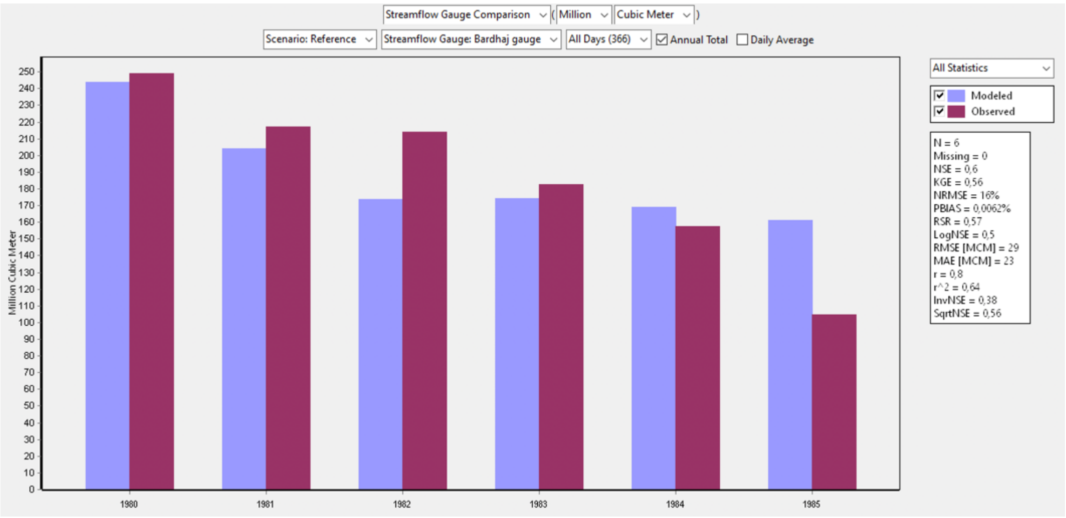
Scenario: Reference | Streamflow Gauge: Turhan gauge | All Days (366) | ☑ Annual Total | ☐ Daily Average

All Statistics

☑ Modeled
☑ Observed

N = 6
Missing = 0
NSE = 0,36
KGE = 0,29
NRMSE = 22%
PBIAS = -0,088%
RSR = 0,73
LogNSE = 0,38
RMSE [MCM] = 19
MAE [MCM] = 17
r = 0,68
r^2 = 0,47
InvNSE = 0,35
SqrtNSE = 0,38

Turhan



Streamflow Gauge Comparison (Million Cubic Meter)

Scenario: Reference | Streamflow Gauge: Bardhaj gauge | All Days (366) | ☑ Annual Total | ☐ Daily Average

All Statistics

☑ Modeled
☑ Observed

N = 6
Missing = 0
NSE = 0,6
KGE = 0,56
NRMSE = 16%
PBIAS = 0,0062%
RSR = 0,57
LogNSE = 0,5
RMSE [MCM] = 29
MAE [MCM] = 23
r = 0,8
r^2 = 0,64
InvNSE = 0,38
SqrtNSE = 0,56

Bardhaj

Scenario: Reference
Streamflow Gauge: Poshtme gauge
All Days (366)
☑ Annual Total
☐ Daily Average

N = 6
Missing = 0
NSE = 0,66
KGE = 0,69
NRMSE = 14%
PBIAS = 1%
RSR = 0,54
LogNSE = 0,56
RMSE [MCM] = 11
MAE [MCM] = 9,5
r = 0,81
r^2 = 0,66
InvNSE = 0,46
SqrtNSE = 0,61

Poshtme

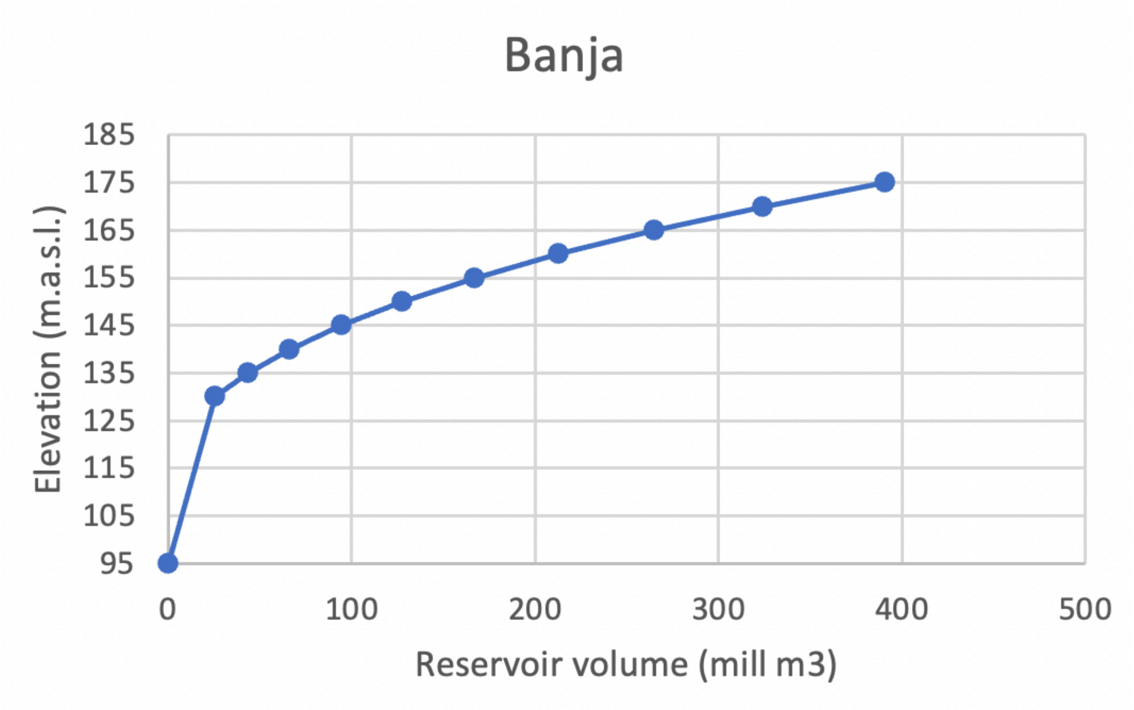
# APPENDIX D: RESERVOIR VOLUME CHANGES

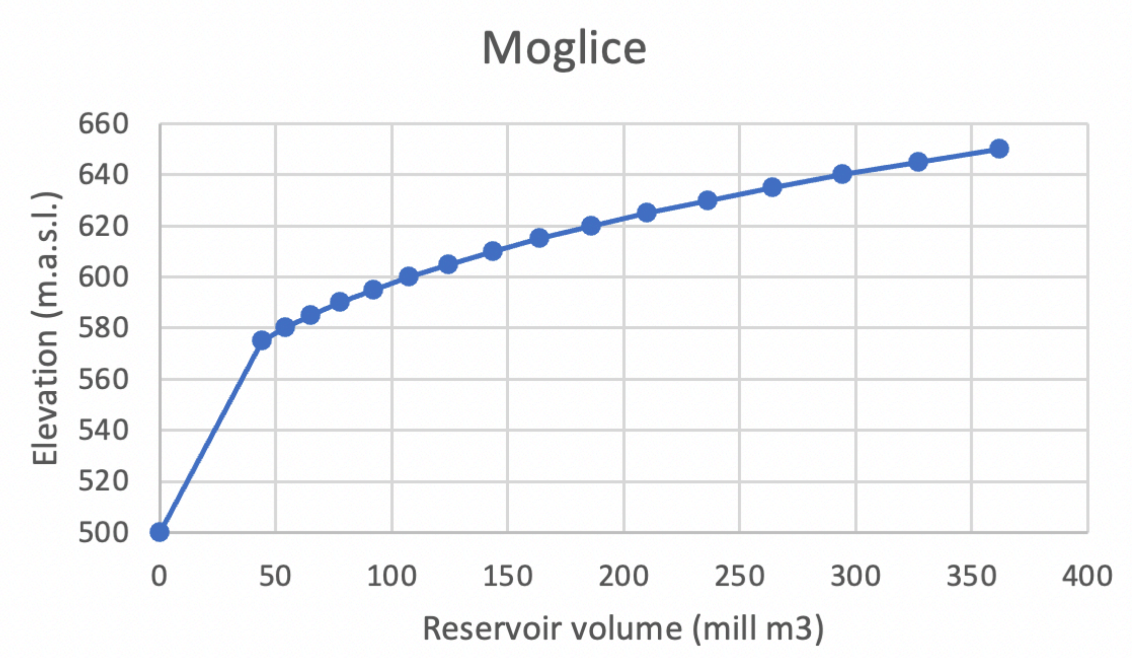
**Banja**

| Elevation (masl) | Volume (mill m3) |
|---|---|
| 95 | 0 |
| 130 | 25,9 |
| 135 | 43,8 |
| 140 | 66,6 |
| 145 | 94,6 |
| 150 | 128 |
| 155 | 167,2 |
| 160 | 212,9 |
| 165 | 265,2 |
| 170 | 324,5 |
| 175 | 391 |

**Moglice**

| Elevation (masl) | Volume (mill m3) |
|---|---|
| 500 | 0 |
| 575 | 44,2 |
| 580 | 54,2 |
| 585 | 65,4 |
| 590 | 78 |
| 595 | 92,1 |
| 600 | 107,7 |
| 605 | 124,8 |
| 610 | 143,6 |
| 615 | 164,1 |
| 620 | 186,3 |
| 625 | 210,3 |
| 630 | 236,3 |
| 635 | 264,4 |
| 640 | 294,6 |
| 645 | 327,2 |
| 650 | 362 |



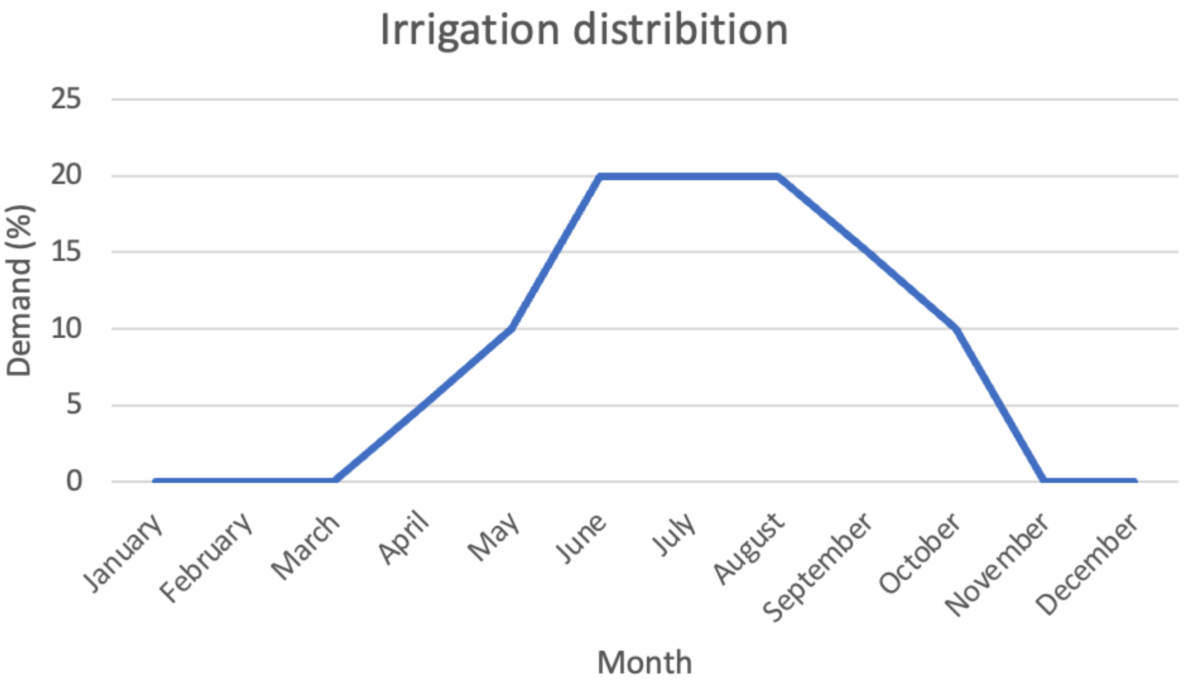


| Year | **Banja** | **Moglice** | Year | **Banja** | **Moglice** |
|---|---|---|---|---|---|
| 2016 | 391 | | 2038 | 318 | 333 |
| 2017 | 386 | | 2039 | 315 | 331 |
| 2018 | 381 | | 2040 | 312 | 329 |
| 2019 | 376 | | 2041 | 310 | 328 |
| 2020 | 371 | 362 | 2042 | 307 | 326 |
| 2021 | 368 | 360 | 2043 | 304 | 325 |
| 2022 | 365 | 359 | 2044 | 302 | 323 |
| 2023 | 362 | 357 | 2045 | 299 | 322 |
| 2024 | 359 | 355 | 2046 | 297 | 320 |
| 2025 | 356 | 354 | 2047 | 294 | 319 |
| 2026 | 352 | 352 | 2048 | 291 | 317 |
| 2027 | 349 | 350 | 2049 | 289 | 316 |
| 2028 | 346 | 349 | 2050 | 286 | 314 |
| 2029 | 343 | 347 | 2051 | 284 | 313 |
| 2030 | 340 | 345 | 2052 | 282 | 311 |
| 2031 | 338 | 344 | 2053 | 279 | 310 |
| 2032 | 335 | 342 | 2054 | 277 | 308 |
| 2033 | 332 | 340 | 2055 | 274 | 307 |
| 2034 | 329 | 339 | 2056 | 272 | 306 |
| 2035 | 326 | 337 | 2057 | 270 | 304 |
| 2036 | 323 | 336 | 2058 | 267 | 303 |
| 2037 | 321 | 334 | 2059 | 265 | 301 |
| | | | 2060 | 263 | 300 |

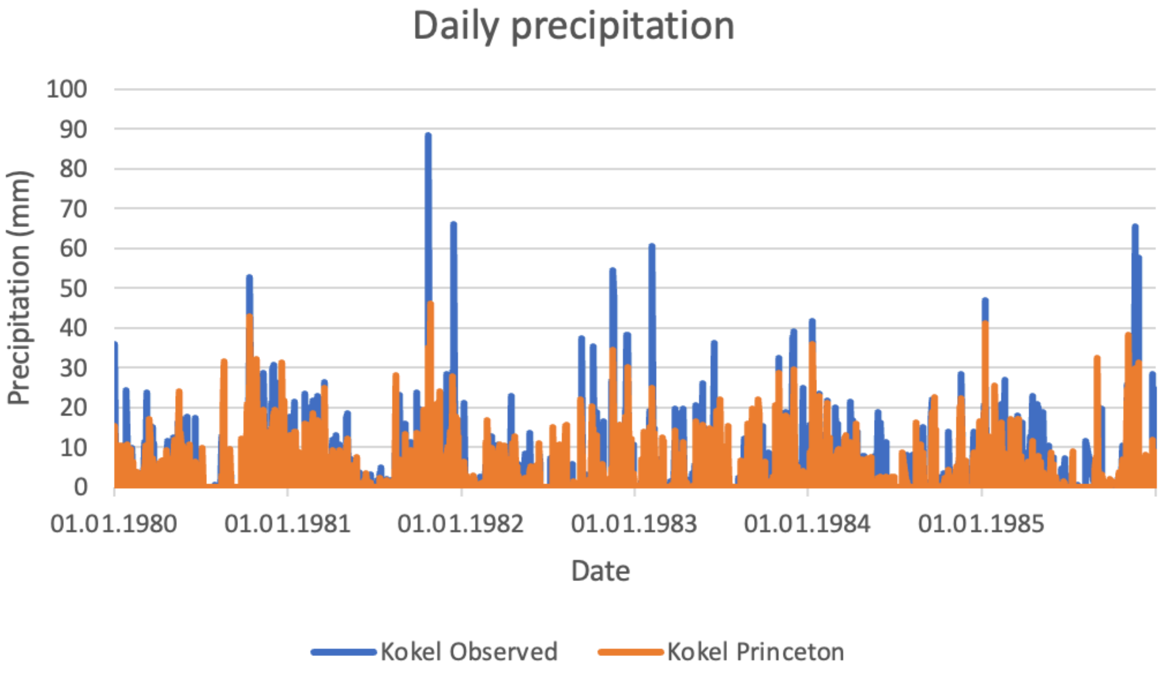
Reservoir capacity changes over years

# APPENDIX E: IRRIGATION DISTRIBUTION

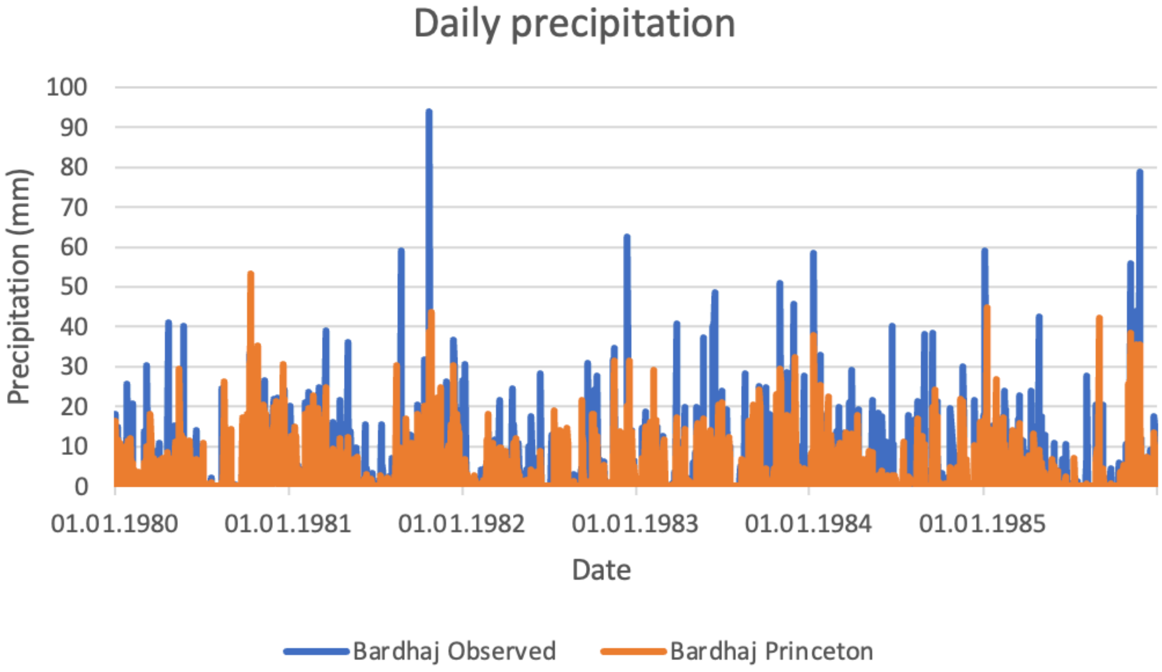
| Month | demand (%) |
|---|---|
| January | 0 |
| February | 0 |
| March | 0 |
| April | 5 |
| May | 10 |
| June | 20 |
| July | 20 |
| August | 20 |
| September | 15 |
| October | 10 |
| November | 0 |
| December | 0 |



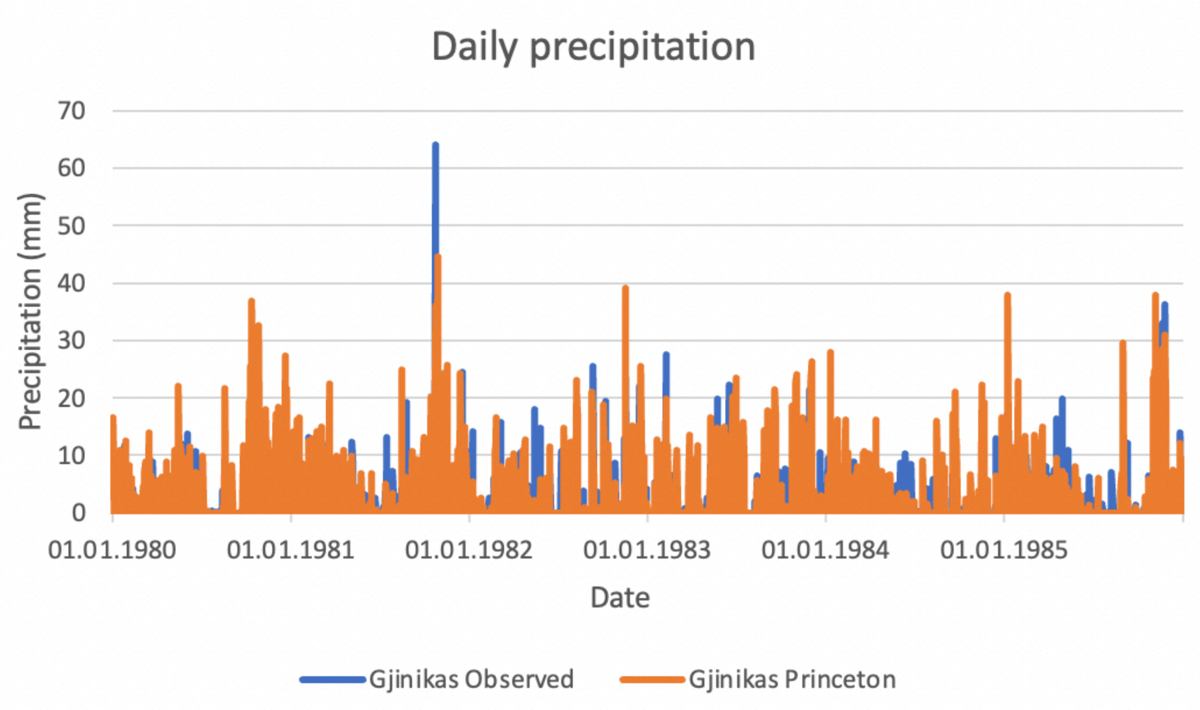
# APPENDIX F: PRECIPIRATION



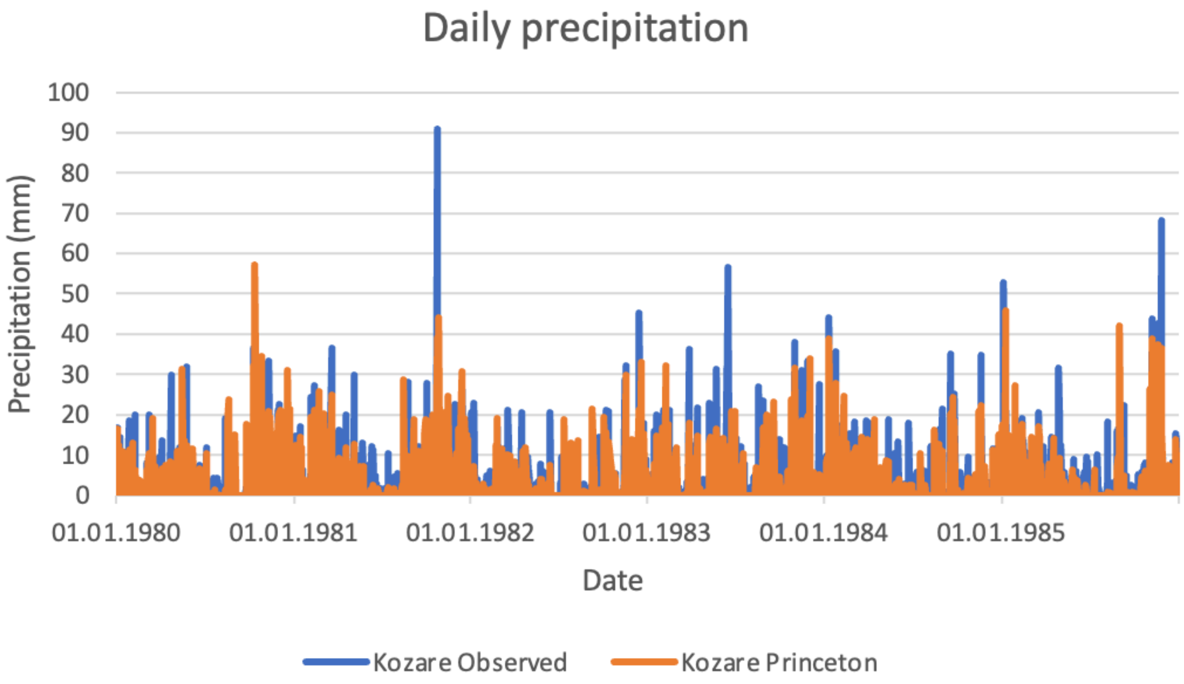
Kokel



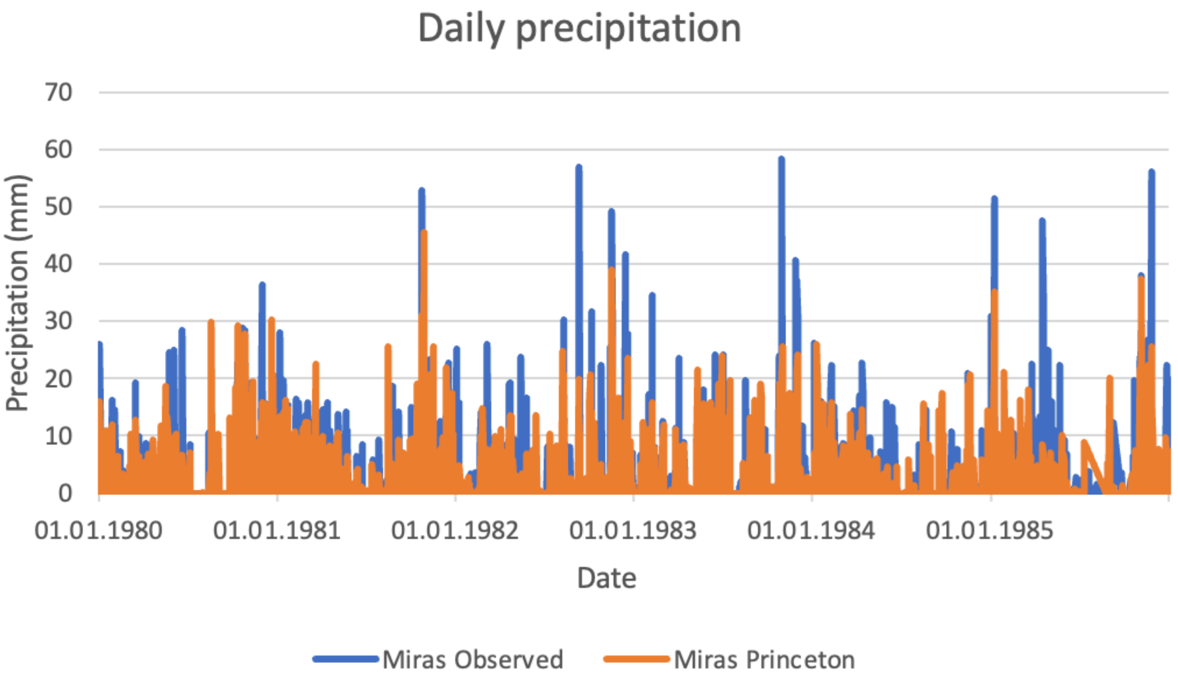
Bardhaj



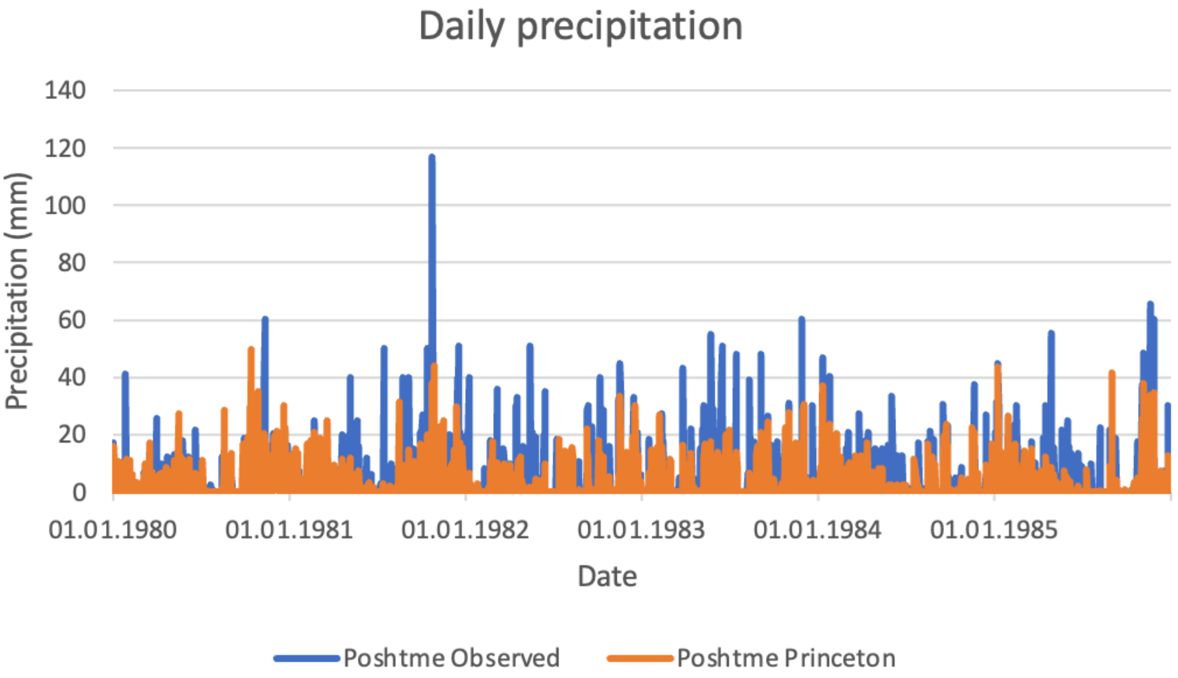
Gjinikas



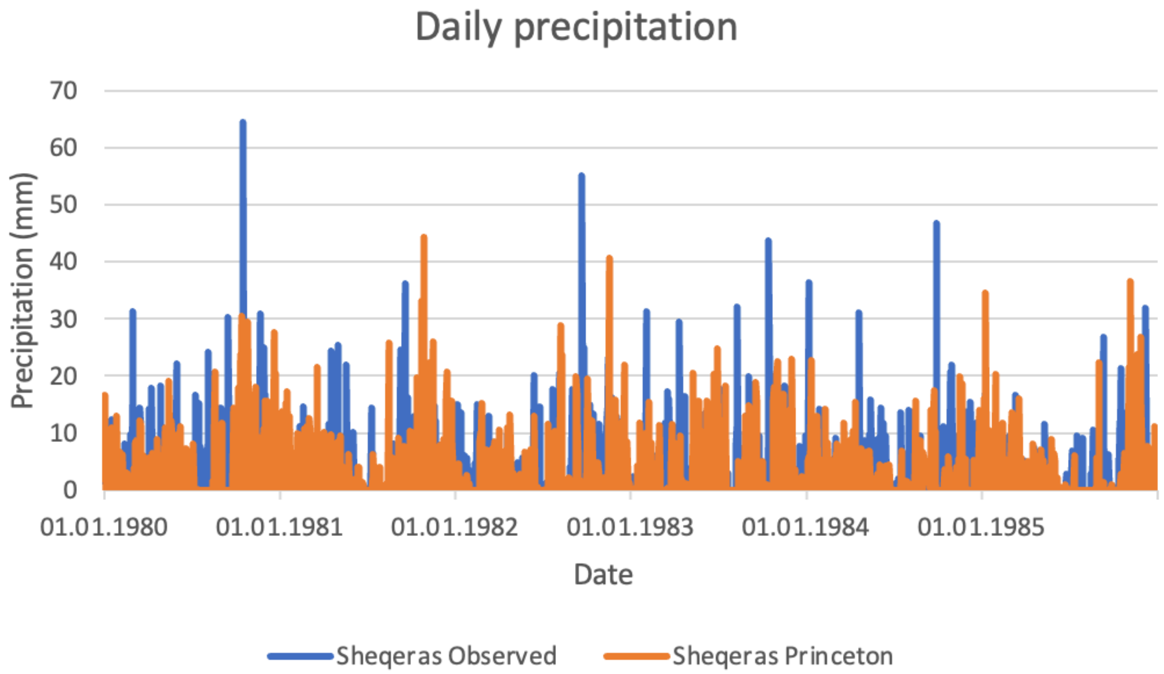
Kozare



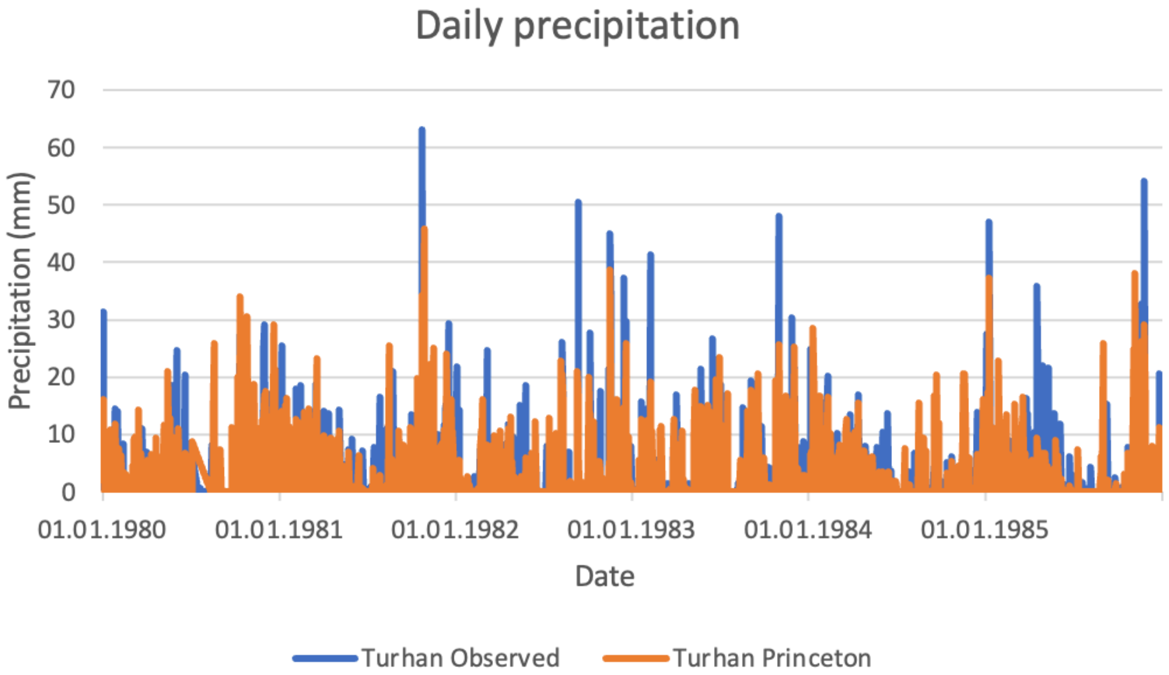
Miras



Poshtme

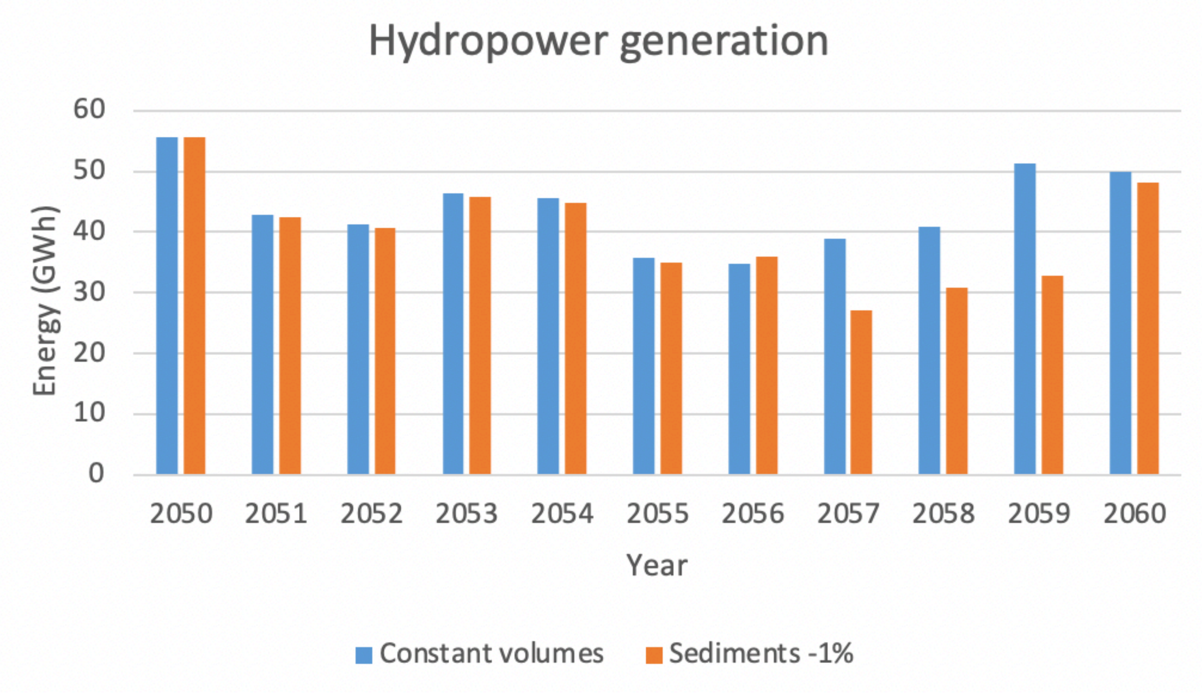


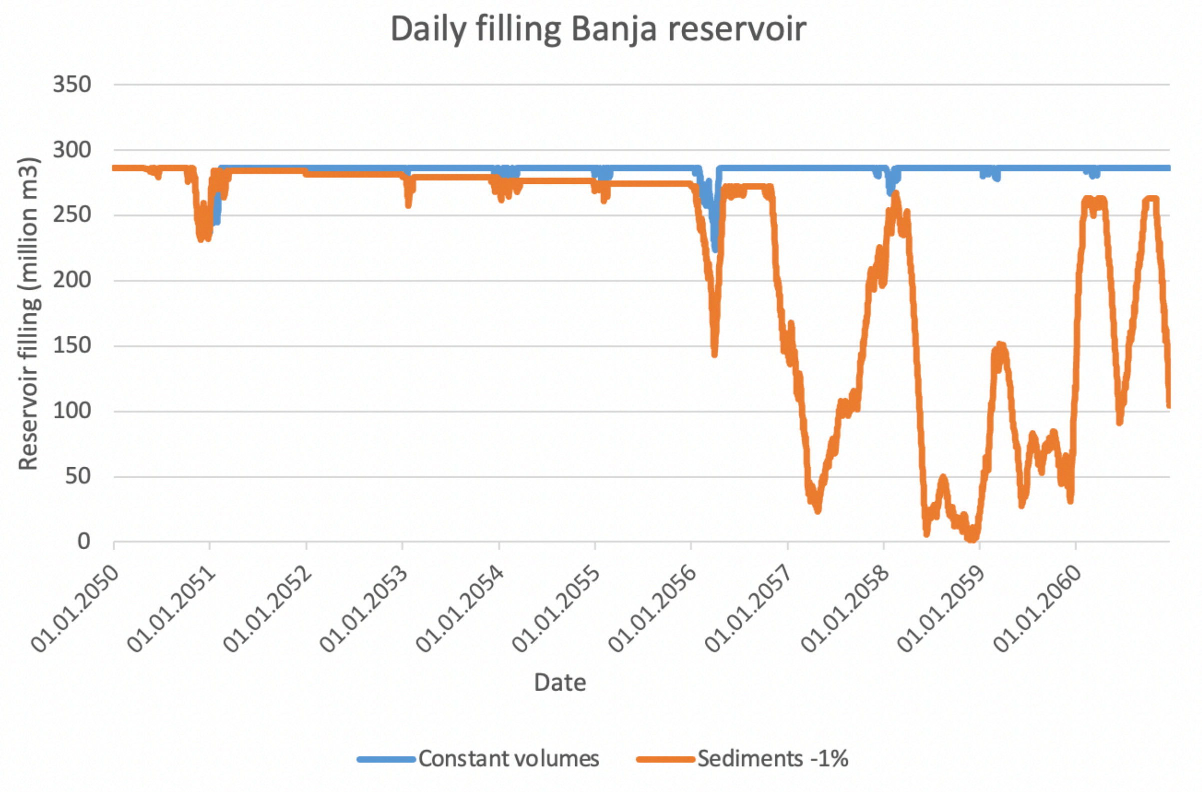
Sheqeras



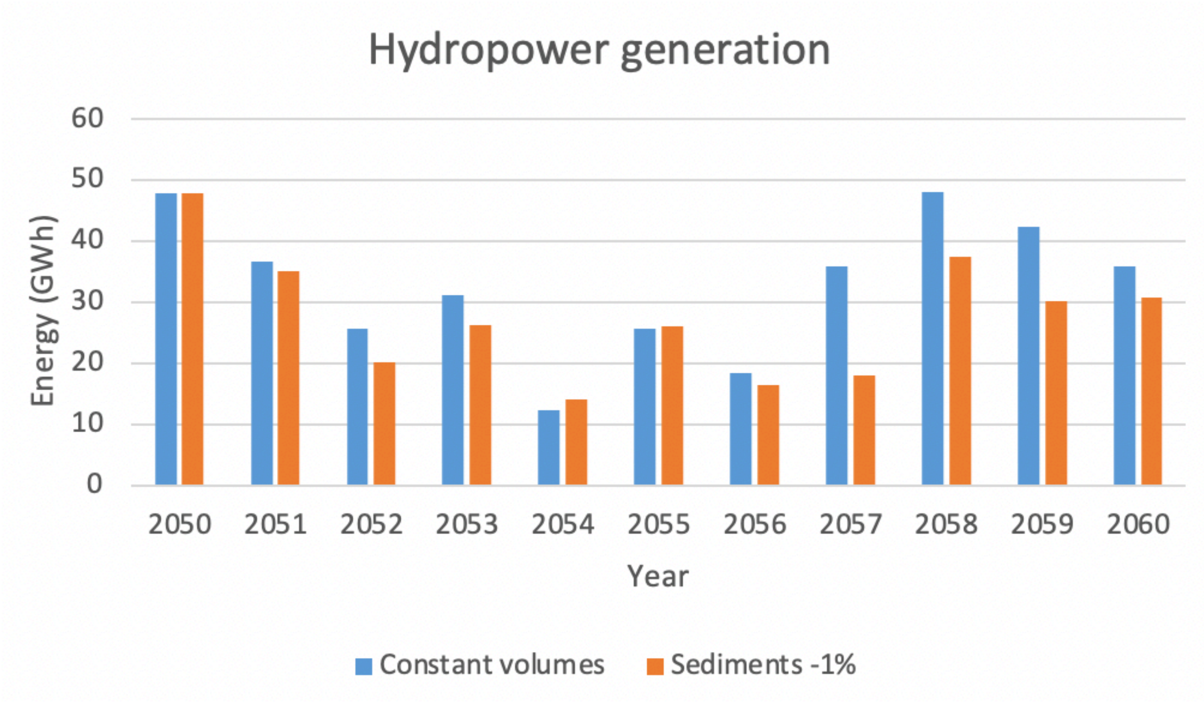
Turhan

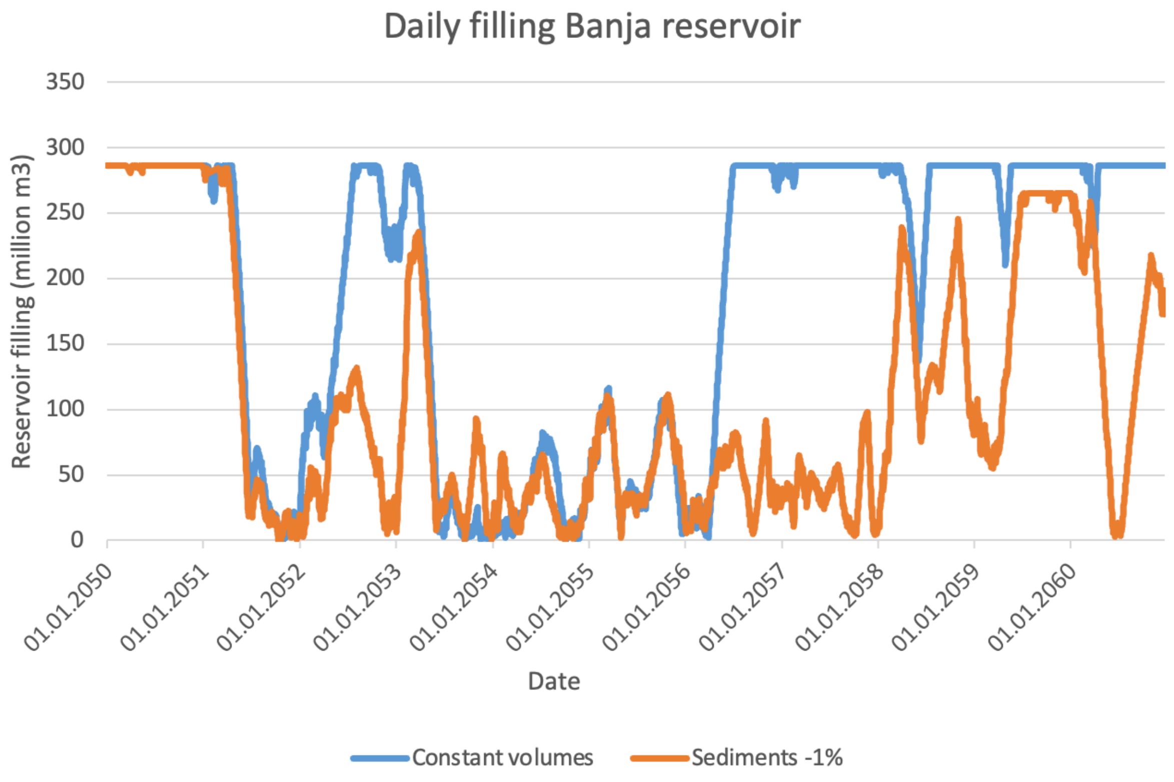
# APPENDIX G: RESERVOIR FILLING AND HYDROPOWER GENERATION





Banja SSP126





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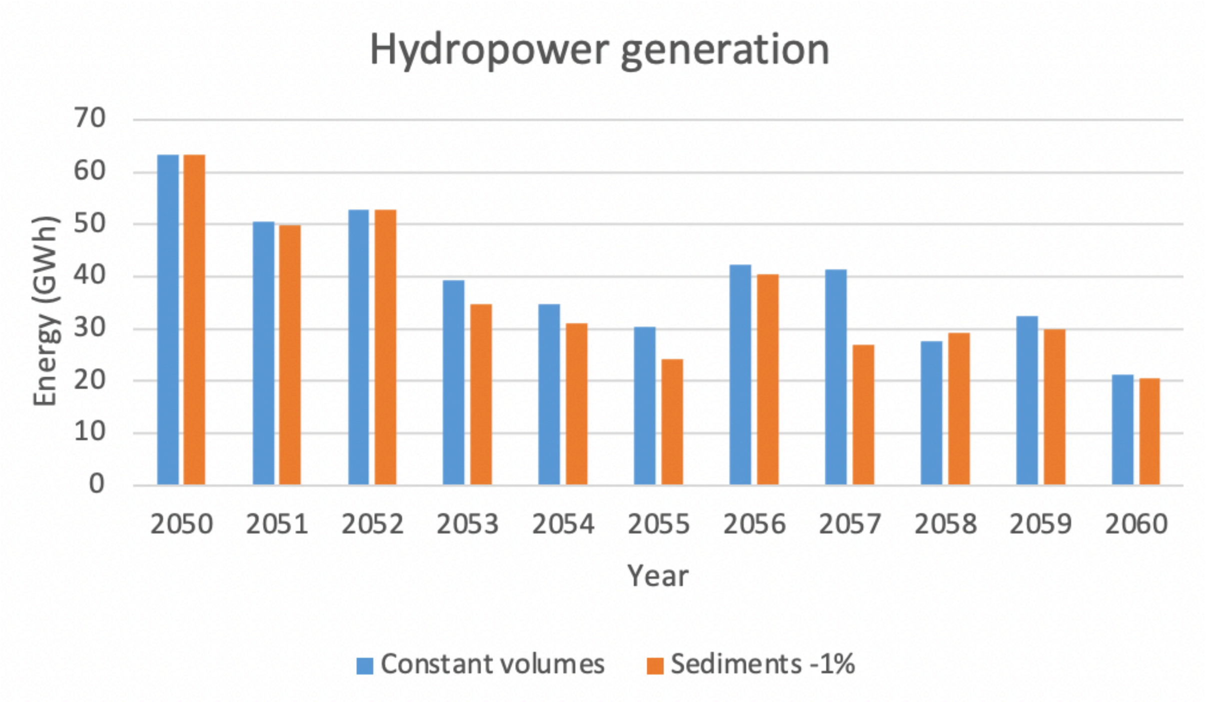
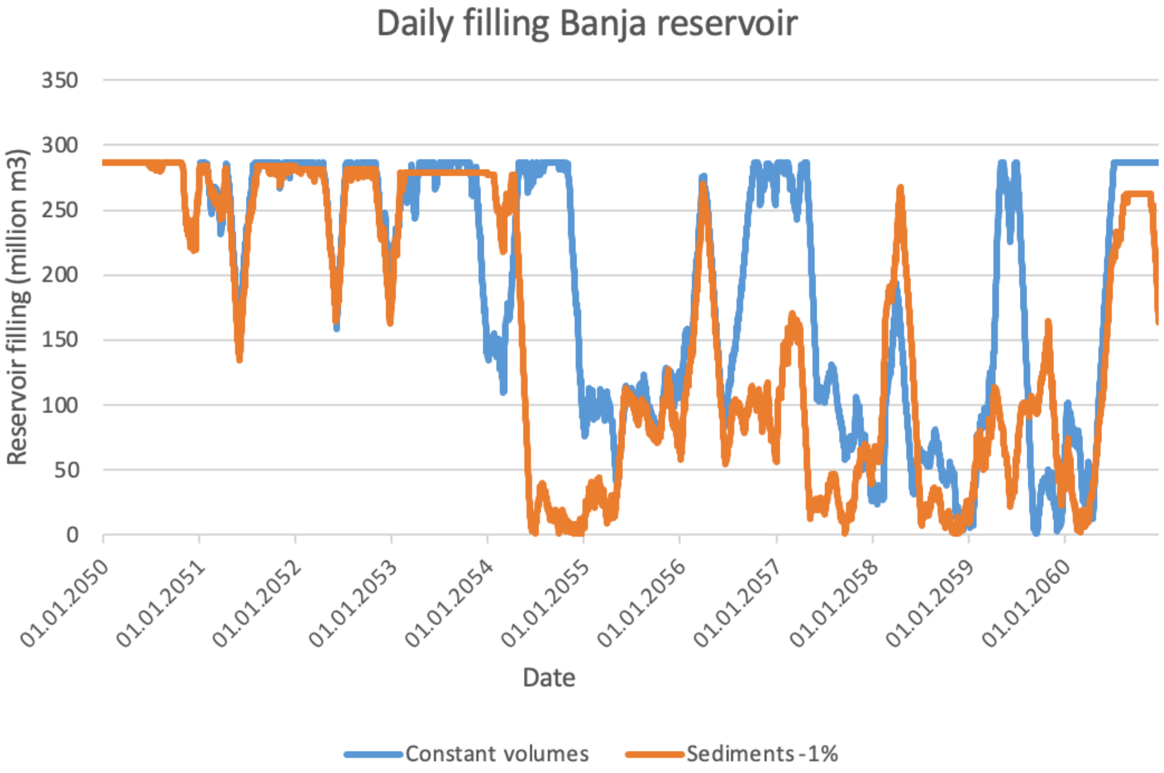
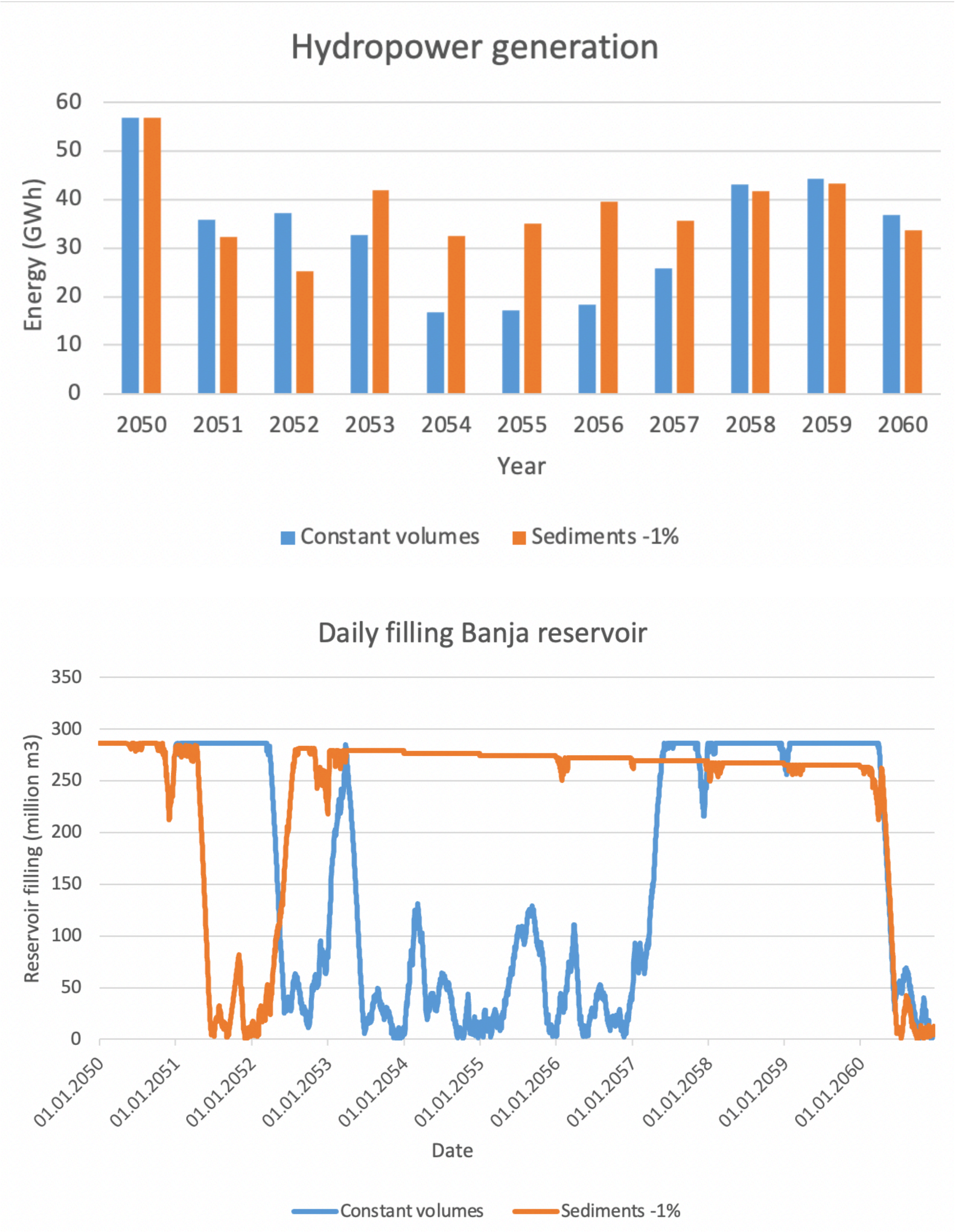




Banja SSP370



Banja SSP585

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