Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
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Hydrological forecasting and seasonal planning using PineHBV and ProdRisk

A case study for Enguri Powerplant cascade in Georgia

Master's thesis in Hydropower Development
Supervisor: Oddbjørn Bruland
Co-supervisor: Nisal Deelaka Halaba A. Senarathna
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Table of Contents

Abstract

Hydrological modelling is a crucial part of the power market, being an important factor for the financial success and ensured safety of hydropower projects. This study implements PINE-HBV model to get the long-term forecasts for the Enguri power plant system in western Georgia. The Forecast is then used as an input for the production optimization model created with ProdRisk software. The two models are tested for the case-study, because the methods currently used are empirical. This study is meant to be one of the steps towards optimization of the Georgian hydropower system.

Introduction

Project description

The Enguri Hydropower Plant, situated in the captivating landscapes of Georgia, stands as an engineering marvel, with its double arched dam, and a cornerstone of the nation's power system. As one of the largest hydropower facilities in the world, the Enguri plant utilizes the prodigious hydroelectric potential of the Enguri River, making an indelible impact on Georgia's energy landscape. Its substantial capacity and consistent energy generation have rendered it a pivotal asset, bolstering the country's energy security, supporting economic growth, and mitigating greenhouse gas emissions. Over the years, the Enguri Hydropower Plant has demonstrated unwavering reliability, reinforcing its significance as a sustainable and dependable source of electricity, contributing significantly to the social and economic well-being of the nation.

The Enguri Power Plant is important for the stability of the Caucasus region and is currently at the unrecognized border of the Abkhazia and Samegrelo regions. The reservoir and intake being on the Samegrelo side and the power plant with the cascade being on the Abkhazia side, the power production is shared almost equally by the Georgian government and the unrecognized Abkhazian government. The effects of the civil war in the 1990's is evidently seen in the results of this study, as it was one of the reasons why the meteorological and hydrological stations stopped working for around two decades.

Long-term forecasting

Hydropower constitutes a fundamental component of the global energy mix, and meticulous management of hydropower resources is critical for ensuring sustainable energy production and optimal water resource utilization. In this context, long-term forecasting emerges as a vital tool in the hydropower planning and operation process, specifically in the face of inherent hydrological variability and uncertainty. The importance of accurate long-term discharge forecasting for the Enguri Hydropower Plant cannot be overstated, as it underpins informed decision-making by utility companies and policymakers in matters of reservoir management, electricity generation scheduling, and future infrastructure investments. Additionally, precise long-term forecasts facilitate the development of optimized operational strategies, ensuring a harmonious balance between energy production, environmental conservation, and water resource management. As the ramifications of climate change become increasingly apparent and water resources exhibit heightened unpredictability, robust long-term forecasting for hydropower plants assumes paramount importance in securing sustainable and reliable electricity generation, providing a firm foundation for Georgia's energy security and sustainable growth in the foreseeable future.

Description of the study area

Sources of main data

The meteorological and hydrological data, as well as the Digital Elevation Model (DEM) of the area, land use and shapefiles for sub-catchments were provided by the Georgian State Electrosystem (GSE).

Software needed for the research, like Pine-HBV, Arc-GIS, R-studio and ProdRisk was provided from NTNU and SINTEF.

Exposition of glaciers in the catchment is taken from a Levan Tielidze work, Glaciers of Georgia.

Identification of the catchment

Scheme of the Enguri hydropower cascade

The main criterion for selecting a catchment was to have a moderately complex system of power plants with an appropriate reservoir for long-term forecasting. The schematic map on Figure 1 shows the main components of the current hydropower system on the Enguri river. The hydrological model was created for the catchment starting from a discharge measuring station at the potential dam location on Figure 1 and then the parameters were transferred to the catchment starting from the existing dam of the Jvari Reservoir.

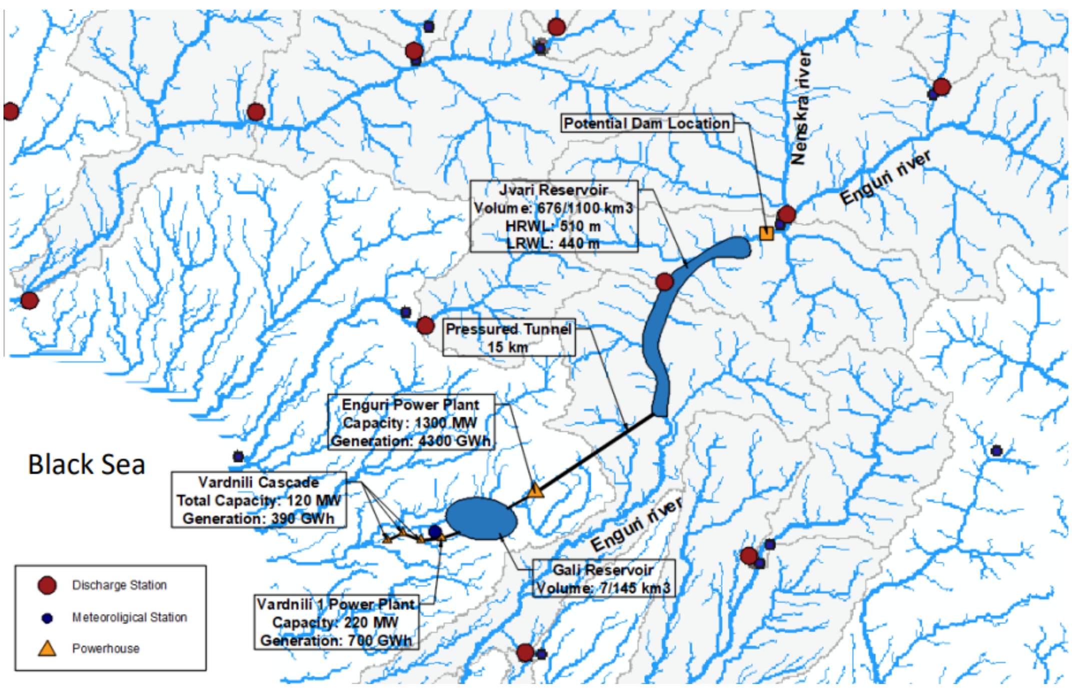

Figure 1. Schematic map of the cascade on Enguri river

Hystorical planning of the power system on the Enguri river

Table 1. Design capacities and yearly generation for Enguri hydropower system

Power Plant	Capacity, MW	Av. Yearly Generation, GWh
Enguri	1300	4300
Vardnili I	220	700
Vardnili II	40	390
Vardnili III	40	
Vardnili IV	40	

Table 2. Dimensions of Jvari and Gali reservoirs

Reservoir	Basin Area km2	Surface Area km2	Total Volume km3	Regulated Volume km3	LRWL - HRWL	Av. Depth m	Max. Depth m
Jvari	3170	13.5	1100	676	440 - 510	81.5	226
Gali	166	8.2	145	7 (?)	?	17.7	42.3

Figures in Table 1 and Table 2 show main dimensions of the components of the hydropower system to illustrate the scale of the project. Data is acquired from 7 hydrological and 6 meteorological stations along the Enguri river network.

Studied Area

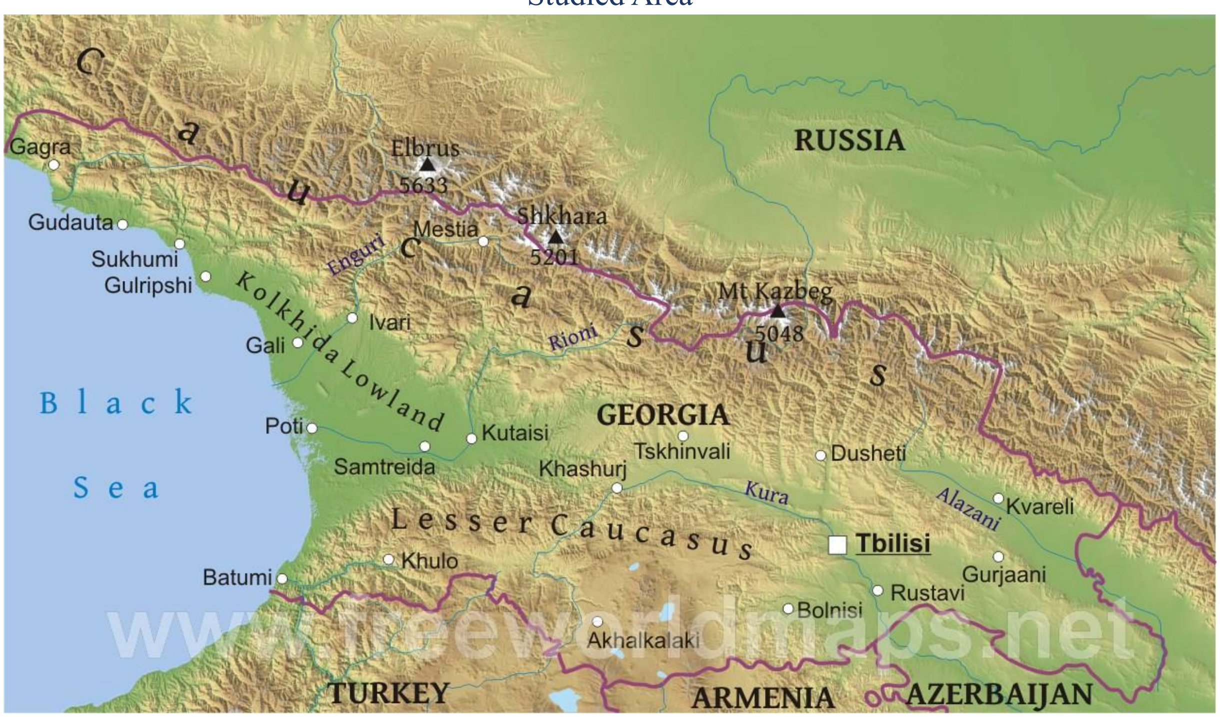

Figure 2. Physical map of Greater and Lesser Caucasus mountain systems

Enguri river is located in the western mountainous Georgia, on the southern slope of the Greater Caucasus mountain system (Figure 2). Hypsography of the catchment shows that the highest and lowest points are 5143 and 589 m.a.s.l., respectively. The western Georgia is characterized by a humid climate because the water evaporated from the black sea is trapped between the Greater and Lesser Caucasus mountains and the Likhi Range in the middle of them.

The Enguri river is fed by two major sources: Precipitation and Snow melt or Glacial melt. To illustrate how much the runoff of the river depends on melting the accumulated snow and glaciers, relationship between precipitation and discharge can be observed in these two hydrological years from the calibration period (Figure 3).

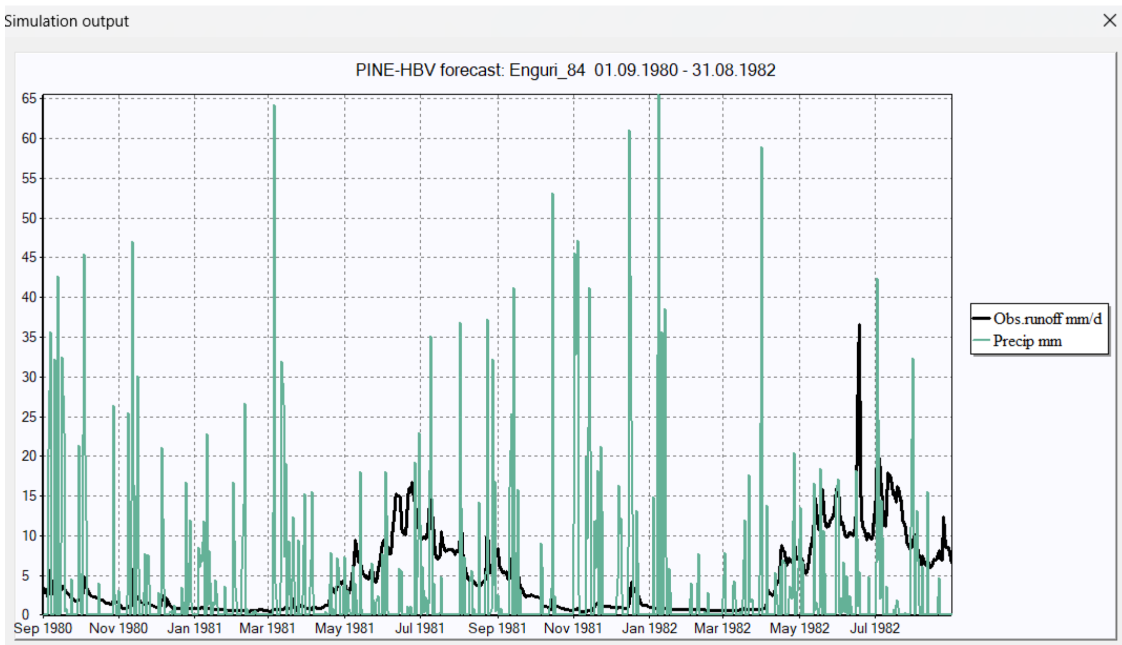

Figure 3. Precipitation vs observed runoff over 1980-82 period

High precipitation in winter and early spring are not depicted in observed runoff series and this doesn't change by altering model parameters.

Land type

Distribution of land types is an important input for the HBV model. The data acquired from the GIS file for each land use class with their descriptions can be found in the table from Appendix 1. 1. The HBV model is depended on the amount of water bodies in the catchment (Class 16 from Appendix 1. 1) and the glacier percentage. Class 15 from the table called "snow and ice" shows 0%, which can't be representing the glaciers in the region, because it's a well-known fact that part of the Enguri river runoff comes from the glacier melt. Instead, the Class 16 called "Barren" is used, giving 311 km^2 of glaciers, which is close to 323 km^2 of glaciers in the Enguri catchment reported by Tielidze in his book Glaciers of Georgia (Tielidze, 2017).

Choosing the glacier percentage is further discussed in the calibration and validation chapter of this work.

Topography of the catchment

Topography of the catchment is having an impact on the runoff generation.

One of the important parameters in an HBV model is PGRAD, the vertical gradient of precipitation. However, mountainous catchments like the one of Enguri river are often changing their behavior in terms of the vertical variation of precipitation. Elizbarashvili in Climate of Georgia explains that the vertical precipitation gradient depends on slope exposition (aspect) and type of vegetation in the catchment, as well as elevation distribution (Elizbarashvili, 2017). Even though the author gives single TGRAD values for most of the major rivers in Georgia, for the Enguri river it's given by a 2nd degree curve by specified parameters, which cannot be used in the pine-HBV model. Furthermore, there are critical altitudes above which the precipitation doesn't increase anymore as the elevation increases (Elizbarashvili, 2017). For the western part of the south slope of the Greater Caucasus it's between 2400-3000 m.a.s.l., which is well inside the Enguri catchment with a peak of 5143 m.

Because of this inaccuracy the calibration was performed with a PGRAD value of 0. This was decided after the first calibration, where PGRAD was 5% and model was trying to deal with excessive precipitation in the high elevation zones by giving unrealistic values for other model parameters, like TX and TS.

Area below, %	altitude m.a.s.l.
0	589
10	1477
20	1744
30	1963
40	2170
50	2371
60	2571
70	2773
80	2998
90	3299
100	5143

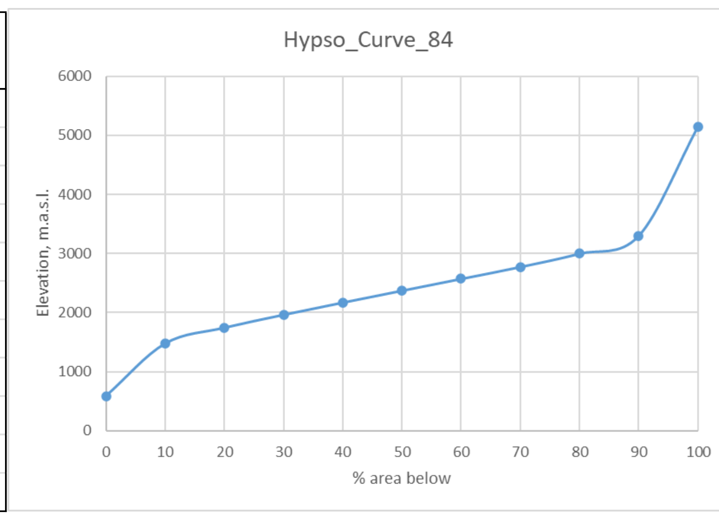

Figure 4. Hypsographic curve and data of the catchment

Even though the difference between highest and lowest points of the catchment is quite high, the slope of the river is moderate – 16.8 m/km. Comparing the whole study area to the catchment areas of the right-side tributaries of the Enguri river (Figure 5) shows that the tributary catchments have a little steeper hypsographic curves, but there's not a significant difference.

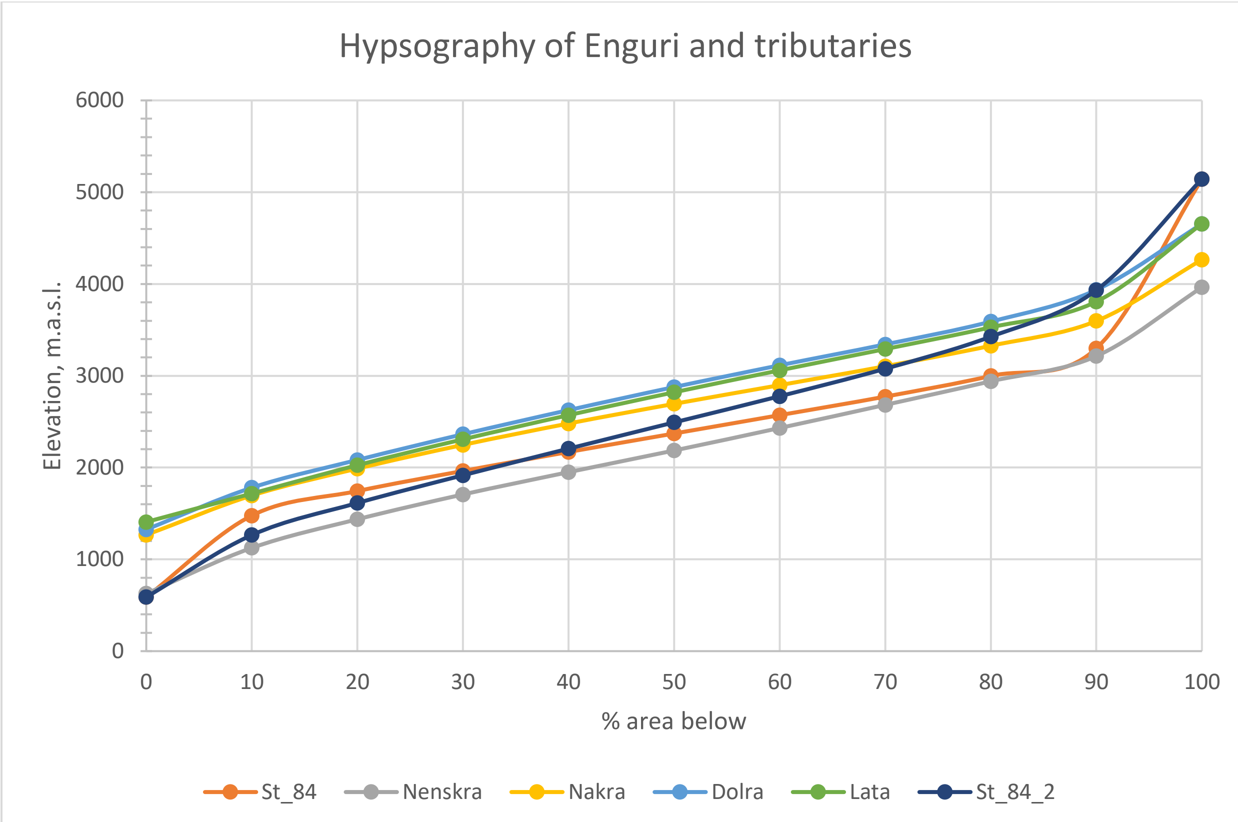

Figure 5. Hypsographic curves for the Enguri river and its right-side tributaries

Glaciers

There are ~2000 glaciers currently in the Caucasus with a total area of ~1100 km^2 and volume ~68 km^2 and approximately 33% of the glaciers of the Caucasus is located in Georgia (Tielidze, 2017). Many of the rivers in the Western Georgia (like Enguri[1], Nenskra[2], Rioni, Tskhenistskali, Kodori) are largely fed by glacier melt. It's estimated to be around 220 km^2 of glaciers in the Enguri river basin, but the changes in the previous 100 years have been significant. The dynamics of the glacier balance in the region is well described by Tielidze and it will also be assessed in the last chapters of this work based on the results from the HBV model simulations.

The process of choosing the area of glaciers and distributing it to the elevation zones is described in the section for PINE-HBV parameters.

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[1] Enguri river basin has more glaciers than any other river in Georgia (Tielidze, 2017)

[2] Note that Nenskra is one of the right-hand tributaries of the studied Enguri river (Figure 1)

Data acquisition and control

Meteorological data

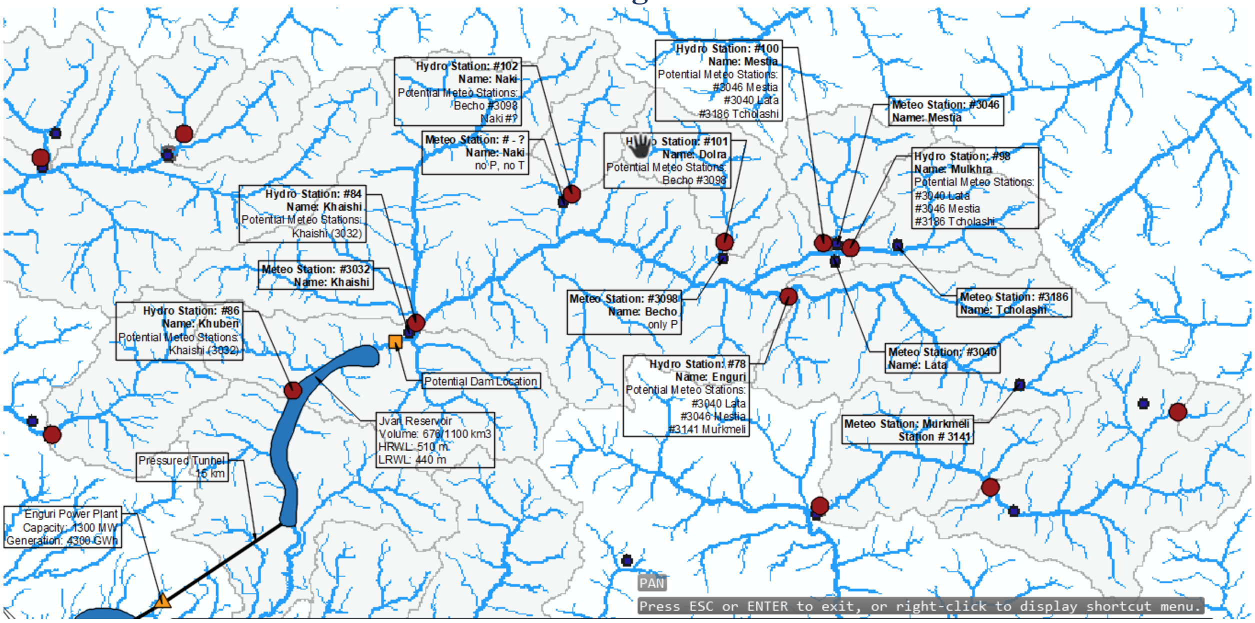


Figure 6. Meteorological stations in the Enguri river basin

Six meteorological stations were available in the catchment. Three out of them had only precipitation data, but no temperature data. At the first stage a distributed hydrological model was planned to be built, where these stations additional would be very beneficial, as this is a catchment that goes from the mountains of Caucasus to the Kolkhida Lowland and the Black Sea very fast. However, to fit in the time available for the project, a lumped model was chosen and, therefore, only one of these stations called Khaishi was used, which was then transferred to the dam location to include all the catchment.

The original purpose of the study was to forecast discharge for the current dates. However, in the end it became impossible due to large gaps with no meteorological or hydrological data. All the stations stopped working in 1991, in the process of the collapse of the Soviet Union. Some of the hydrological stations restarted working from around 2007, but no meteorological data was available for the study for the recent 30 years. So, the hydrological model was built for the years 1960-1961, which would be updated in accordance the modern climate conditions and used for forecasting.

Before using the historical data from the Khaishi meteorological station, its quality was inspected. The first step is to plot the data and identify any periods with gaps, outliers and physically suspicious trends. An accumulation plot was also checked for the precipitation data.

P data

In the period of interest, 1960-1991 no problem is observed in the precipitation series for Khaishi (Figure 7). There are no gaps in this period and the accumulated curve has a consistent grow rate.

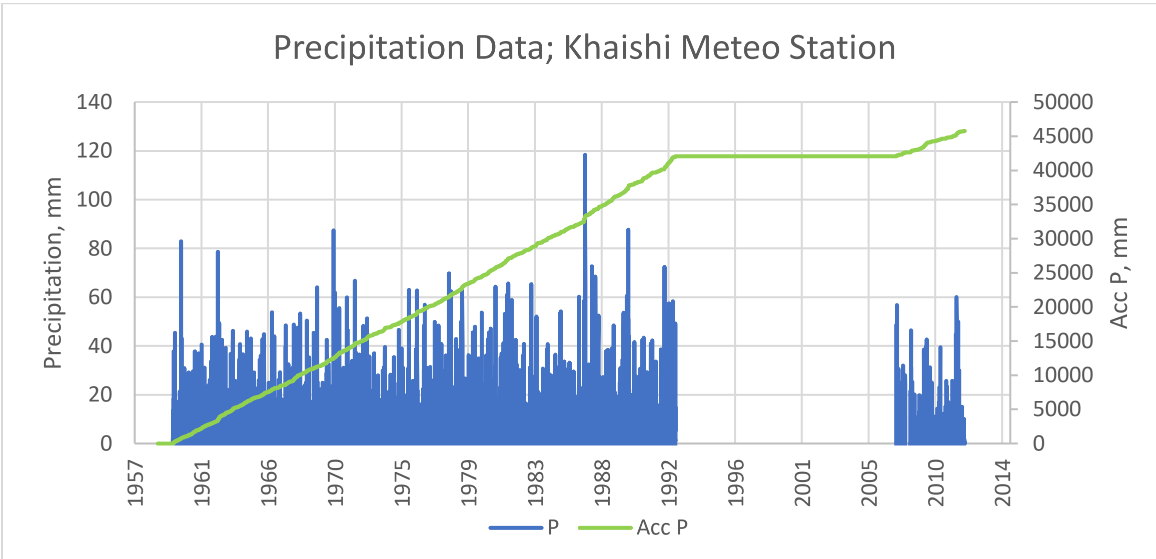


Figure 7. Precipitation series and accumulated precipitation for Khaishi meteorological station

T data

Temperature data at the Khaishi station (Figure 8) is also consistent throughout the study period. There was one possibility to improve the temperature input. The station stops working on 30.06.1991, which is two months before the hydrological year ends. Neighboring stations of Lata and Mestia cover this period without gaps and using a vertical gradient the missing period could have been filled in. The vertical gradient in this region, however, is not well-defined, as explained in the section about fixed parameters for PINE-HBV.

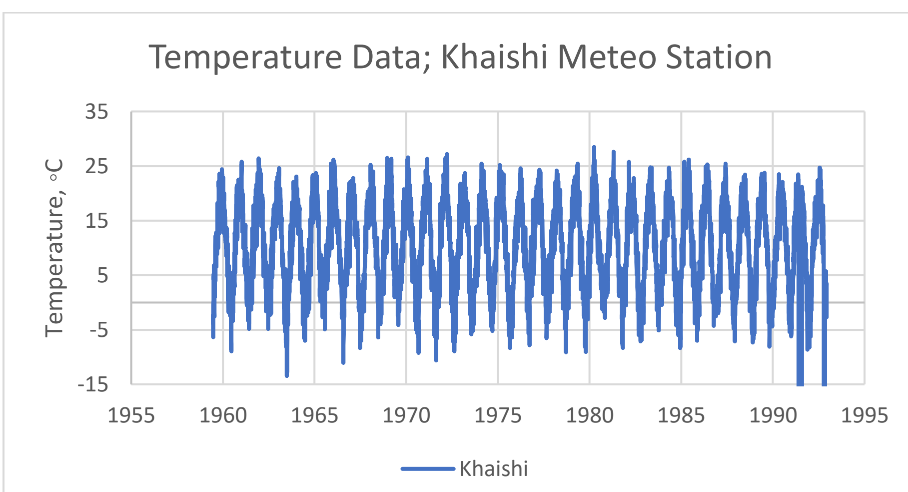


Figure 8. Temperature data for Khaishi meteorological station

E data

Evaporation is another important input for the PINE-HBV model. The model can use monthly varied data, which is more effective than using an annual total value. Mean annual evaporation in the region is roughly described by the map from NVE (Figure 9). Most of the catchment lies in an area with evaporation values between 600-1000 mm/year.

However, for the monthly distribution of this annual value, the Thornthwaite method was used, with the help of a code run in R-Studio. This method uses an empirical formula, where the variables are average daily air temperature, monthly mean temperature, and the duration of sunlight (WSL, n.d.), which is defined by inserting exact latitude of the meteorological station into the code. Summing up the resulted monthly evaporation values gave 660 mm/year of evaporation, which is inside the rough range provided by the NVE map.

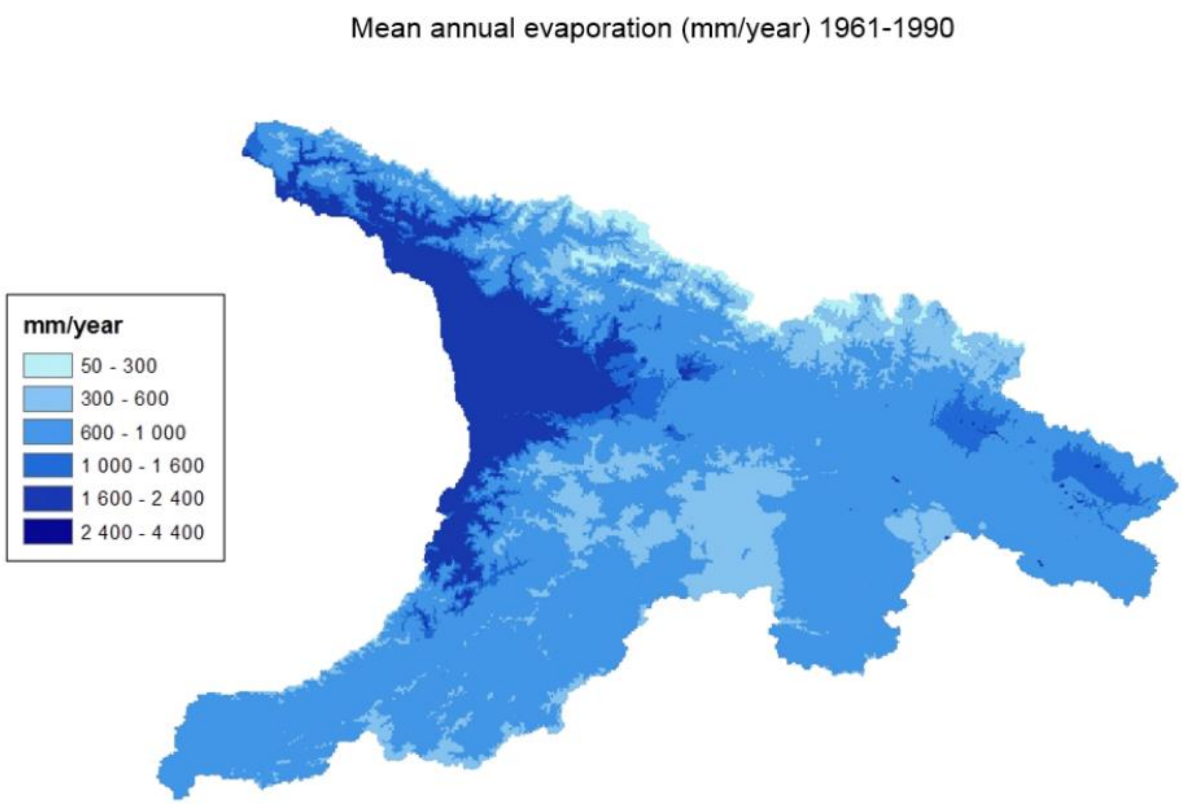


Figure 9. Mean annual evaporation (mm/year) for the period 1961-1990 for Georgia and upstream areas in Turkey and Armenia draininig to watersheds in Georgia (Beldring, et al., 2017).

Creating PINE-HBV model

Background of Hydrological modelling

Hydrological models establish a relationship between the meteorological series and resulting discharges. This is done by mathematically describing the catchment conditions using parameters. A PINE-HBV model was used for this study.

PINE is short for Process Integrating Network, which intends to link different systems into a single simulation process (Rinde, n.d.). In this case it implies connecting different parts of HBV model introduced in the next section.

PINE-HBV model uses Parameter Estimation, or PEST method for parameter calibration. The key feature of this method is that the calibration process is not random, it's directed from the parameter set of the previous time step towards a better parameter set, which decreases the calculation time. With this method, a linear function is creating that expresses "the relationship between the model parameters and the simulated values" (Lawrence, et al., 2009). It's logical that this method needs a reasonably good starting point, where the user takes the responsibility. The section about parameters describes how the initial parameter set was set for the catchment of study.

This is a deterministic, steady, and, in most cases, lumped model. It can serve as a distributed model if it's run for each grid in the catchment. One of the inputs is the hypsographic curve, which divides the catchment into 10 elevation zones with equal areas and some of the model states (like snowpack and ice balance) are represented in the output file for each elevation zone, but this doesn't make it a distributed model, as the model parameters are the same for every elevation zone. It can still be called a semi-distributed model, because it treats snow and ice separately in every elevation zone and glacier percentage, one of the fixed inputs, is defined for every zone separately.

HBV model concept

The HBV model is the basis of the modelling used in this study. This is a conceptual model that follows the water path vertically using four routines: Snow, Soil Moisture, Upper Zone and Lower Zone routines. The schematic illustration along with the calculation process for every state in the system is shown on the Figure 10.

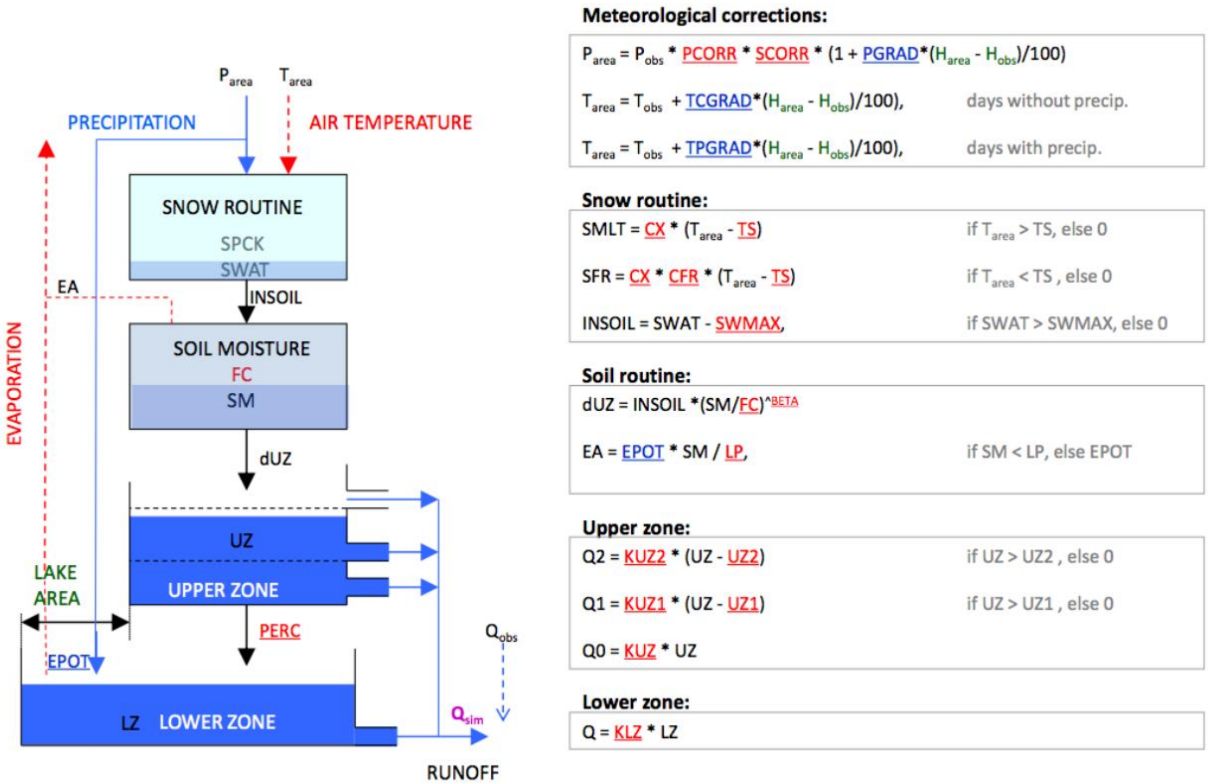


Figure 10. HBV model illustration; from the lectures of Hydrological Modelling course at NTNU by Knut Alfredsen

Structure of the model

Introduction

PINE-HBV interface consists of several important sections that follow each other through the working process. First, the model setup is created, defining paths to the input and output files of the model. It's important that the input is organized in a specific data format. It's first saved as a .txt file and then transformed into a PINE-format with the file extension of ".dat". After that the parameter set is defined with its initial values, as well as the initial states of the model states before the first time step. Then the simulation is run for the period of interest, which is followed by calibration. The final purpose of the model is to generate a short-term forecast and a long-term prediction based on the historical weather. Calibration and forecasting are discussed in their respective sections.

The parameter set (Figure 11) is divided into three main categories: Catchment characteristics, fixed model parameters and free model parameters. The abbreviations of the HBV model parameters are explained on Appendix 1. 2 and Appendix 1. 3.

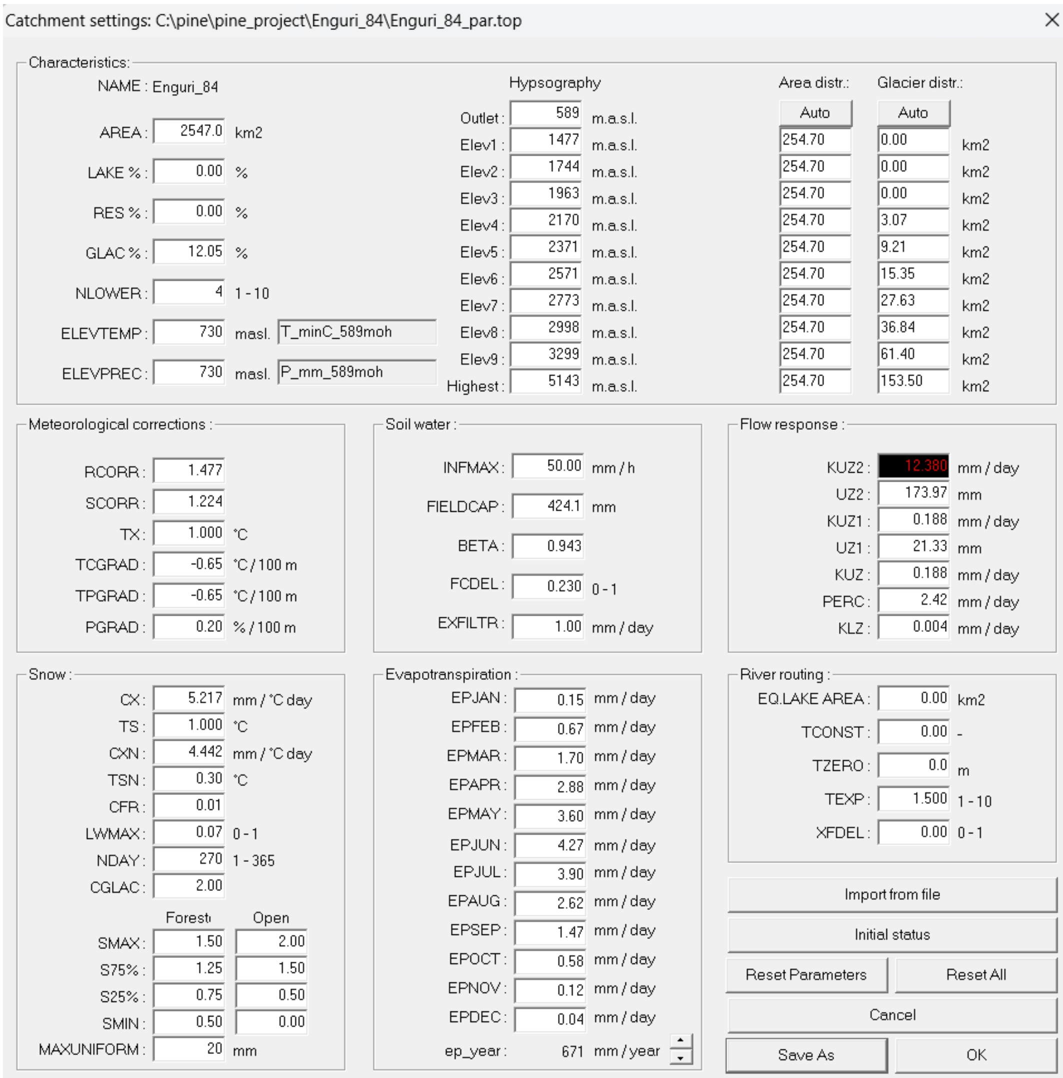


Figure 11. PINE-HBV parameter set after calibration

Catchment Characteristics

The catchment is described with the hypsographic curve, the monthly evaporation through the year and glacier distribution between the elevation zones. Catchment area, lake percentage, total glacier percentage should also be defined. One more way of describing the catchment to specify the highest elevation zone, where the forests are found and is called NLOWER.

The Digital Elevation Model of the region was used in GIS to get the catchment area and hypsographic curve. Forests in southern slope of the Greater Caucasus are found in the range of 0-1900 m.a.s.l. (Nakhutsrishvili, 2012). Therefore, NLOWER was set to elevation zone 4. And the R-Studio was used to get the monthly evaporation values, as explained above. However, defining glacier percentage and its distribution between the elevation zones was not as straightforward. The process is described below.

Glacier percentage and vertical distribution

Various methods were tried to find the glacier percentage in the catchment. The land use data provided by GSE showed 12.2% for the land type "barren", as mentioned in the catchment description chapter. Online maps from Google Earth were also checked to identify glacier areas and their vertical distribution. The most accurate number however was given by Tielidze (2017), as he is comparing values from 1960 (maps based on aerial images from 1955-60 years) to 2014 (based on Landsat and ASTER imagery). A decrease of $323\ km^2$ to $221\ km^2$ is observed through these years and the latter value. The HBV model is created based on the data from the years 1960-1991 and the glacier percentage needs to be chosen for the same period. The decrease of the glacier area was estimated using two known values with a function of $y = -0.03 * x^2 + 323$ (see Figure 12), assuming a parabolic decrease. An average value of 1960 and 1991 ((323+291)/2 $= 307\ km^2$) was chosen for the model calibration, but for forecasting an estimated current value of $188.5\ km^2$ is used.

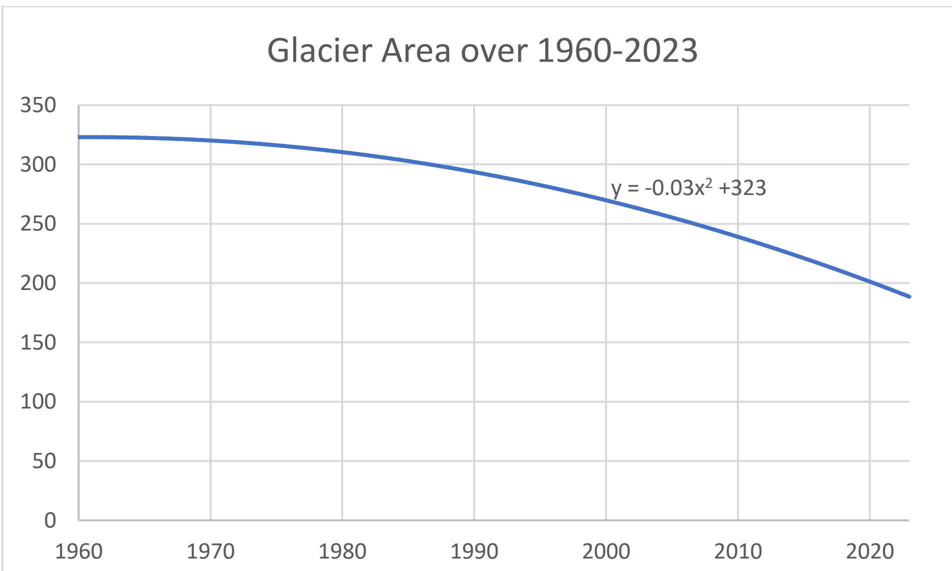


Figure 12. Estimated glacier area decrease in Enguri river basin over the 1960-2023 period

Another issue is the vertical distribution of the glaciers. It was specified by checking the lowest and the highest possible points for the glaciers and then using a commonsense distribution between these two elevations. The firn line[3] for the glaciers in the Enguri river basin is at 3320 m.a.s.l. (Tielidze, 2017), but a more useful data is given in another article analyzing glacier area loss through 2000-2020 years period (Tielidze, 2022). Histograms on the Figure 13 illustrate vertical distribution of glaciers in the Greater Caucasus based on Landsat data. The study area of the Enguri river basin is assumed to have a typical vertical distribution of the southern part of the

[3] The boundary line for a glacier above which snow doesn't melt in summer. The PineHBV model turns all the remaining snow into a glacier at the end of a hydrological year.

Greater Caucasus.

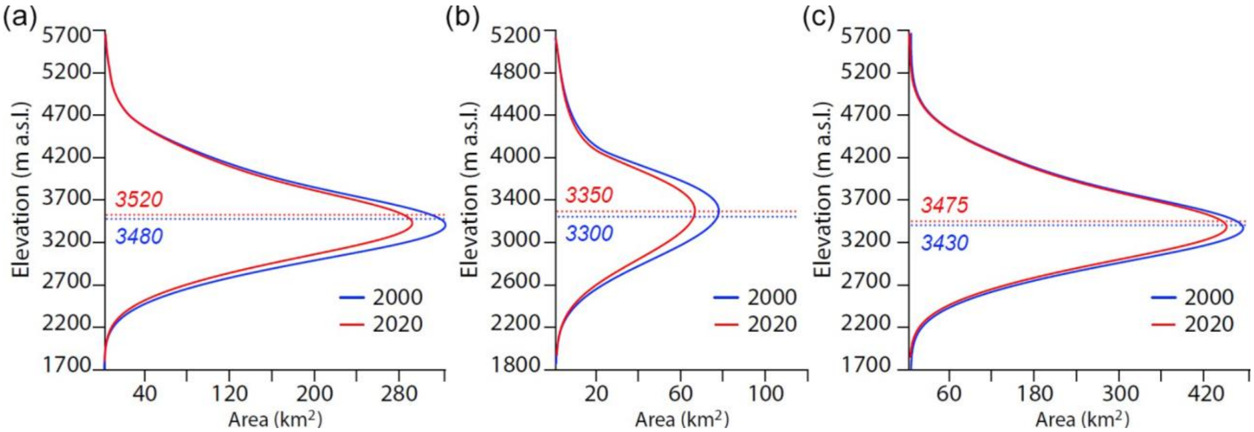


Figure 13. Glacier area vertical distribution for (a) northen, (b) southern and (c) entire Greater Caucasus (Tielidze, 2022)

The (b) histogram on Figure 13 shows that half of the glacier area on the southern part of the Greater Caucasus is located above 3350 m (10^{th} elevation zone of the HBV model). The rest of the 50% was distributed between zones 4-10 with a linearly increasing difference between areas in each zone (see Figure 11).

Correction of meteorological data

This part of the parameter set consists of two free parameters of PCORR and SCORR that correct precipitation and snow, respectively. They are optimized during the calibration. And there are three fixed parameters defining vertical gradients for temperature and precipitation. These were not easy to define.

The TGRAD is defined in Climate of Georgia (Elizbarashvili, 2017) as a monthly variable value for each sub-region of the Southern Caucasus, while the PINE-HBV model requires one parameter for wet conditions and one for dry conditions. At the end of the calibration an average of the monthly values was used for both parameters. Even though the TPGRAD should commonly be less than TCGRAD, this showed a better result while manually updating the parameter set during the calibration.

PGRAD, on the other hand, was defined as an empirical second degree relationship with the elevation:

$$P = \frac{aZ^2}{10^4} + bZ + 10^3 * c$$

Where $a = 5.5, b = -1.88, c = 2.55$ for the Enguri river basin.

However, the PINE-HBV requires a fixed value and after a consultation with Professor Knut, it was decided to set to a minimal value of 0.2%. This was because when it was set to more common values in the range of 2-6 %, it was causing a problem with Tx, TS and TSN, the boundary temperatures for rain to snow transition and snowmelt. These values were unreasonably higher than 0 °C. This was caused by the model trying to decrease the unnaturally big runoff on the weight of the snow (glacier) melt, which would be considerably lower when those parameters were in the range of $5-8$ ℃. The unnatural runoff was being created by converting the precipitation from a station at 700 m.a.s.l. to the territories up to 5143 m.a.s.l.

The snow routine

Snow routine entirely consists of free parameters. However, the boundary temperatures, TS and TSN needed to be manually fixed, as described in the section "Free parameter ranges and initial model states".

The soil moisture routine

Soil moisture routine is also made up of free parameters. FIELDCAP and INFMAX have defining significance for describing permeability of the catchment and the timing of the discharge response.

The runoff response routine

Same can be said for the Flow response routine. UZ2 and KUZ2 define the fast runoff, while KUZ, UZ1 and KUZ1 correspond to the slow runoff and PERC and KLZ define the runoff from the lower zone routine.

Free parameter ranges and initial model states

Free parameters must have their ranges that serve as boundaries during the calibration process. This became very important with Tx, TS and TSN, as described in the section "Correction of meteorological data". The problem was solved when the upper boundary for these free parameters was restricted to 1 ℃.

Calibration and Validation

Procedure

Once the parameter set is complete with reasonable initial values, the calibration process can be started. First, the calibration period of 5-10 years should be selected that will represent the whole study period the best. It should be high-quality data, with all kinds of temperature and precipitation periods and also matching the simulation results from un-calibrated initial parameter set as much as possible. Then the model states should be updated so that the simulated runoff for the first weeks of the calibration period is close to the observed runoff and the calibration can then be run.

PINE-HBV model gives flexibility to define the focus of the calibration, before running it. It can be optimizing the peak runoff modelling, or optimizing the overall water balance throughout the study period. As this study focuses on the long-term forecasting, the generation of peak runoffs was not given the priority.

The main criterion for calibration evaluation is the Nash-Sutcliffe efficiency coefficient, R^2. However, even if a desirable R^2 value is reached, the parameter set needs to be inspected carefully to ensure that all the parameters are in the reasonable range and represent the specific catchment. Some of them might need to be manually restricted, like it happened in this study and some unrealistic values might also be needed, like it happened with PGRAD in this study, as described in “Correction of meteorological data” section.

The final step is the validation of the calibrated parameter set for a different time period from the dataset.

Calibration Period

To choose the calibration period, variation of precipitation and temperature was observed. From the observed runoff curve (Figure 14. Observed discharge from Khaishi hydro station) two possible calibration periods were identified: 1972-1979 and 1982-1987. The latter gave worse results when validating for whole study period. This was probably because this period had much more total runoff than most of the other years.

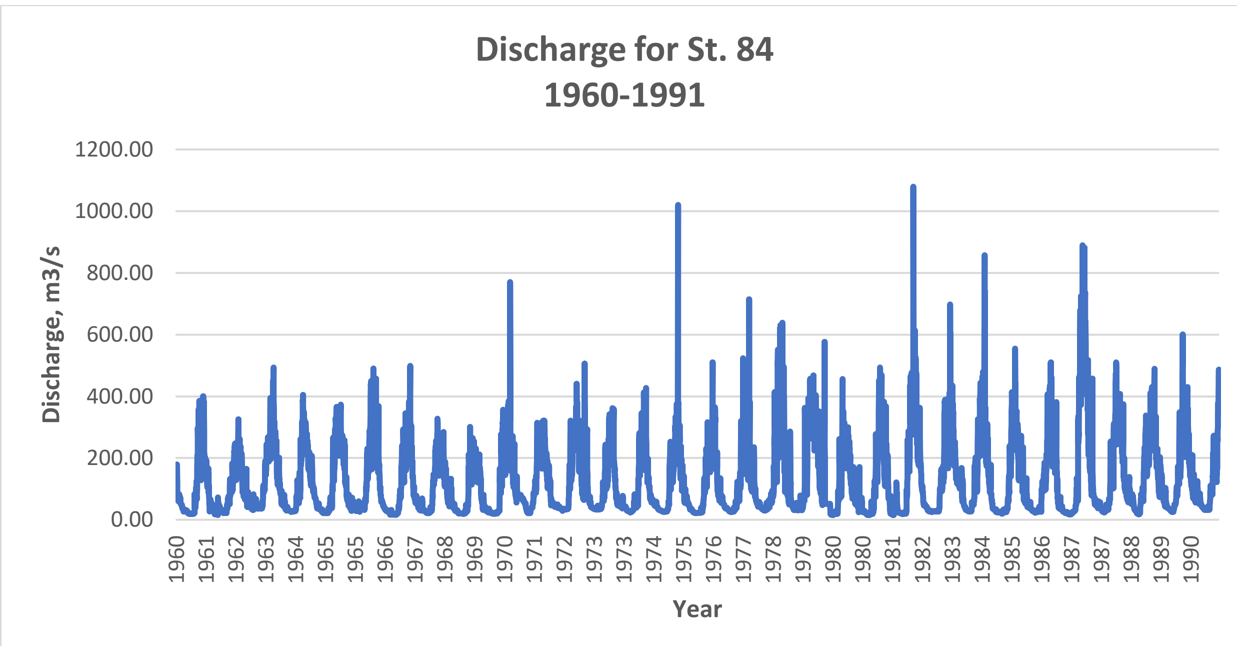


Figure 14. Observed discharge from Khaishi hydro station

1972-79 period performed the best in terms of the total simulation period. The precipitation and temperature variation through this period can be seen on Figure 15. Precipitation and Temperature variation for the calibration period. Tmean describes seasonal mean values of Temperature.

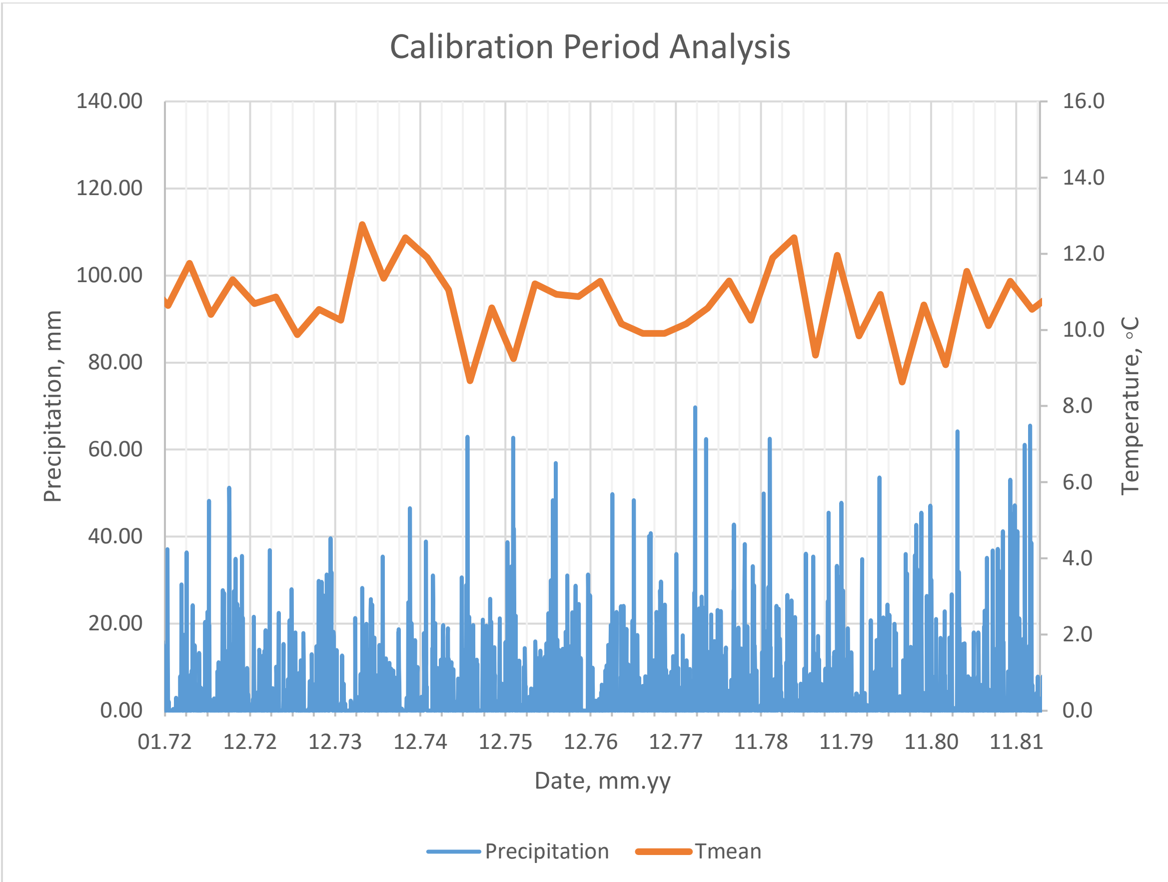


Figure 15. Precipitation and Temperature variation for the calibration period. Tmean describes seasonal mean values of Temperature

Calibration and validation

Calibration gave satisfactory results for the 1972-1979 period, with $R^2 = 78.8$ % and Water Balance = -26.3 mm. The water balance was forced to be small. Some individual years inside the calibration period performed better and worse than the overall value of 78.8%. The resulted R^2 values can be seen on Figure 16. R^2 values for the years in the calibration periodFigure 16.

The comparison of simulated and observed runoff for this period can be seen on Figure 17. It's easily observed that some simulated peak discharges are off with the observed peaks. However, this was intentional, as explained above.

The parameter set was then validated for 1980-1990 period, where the model performed well, giving results of $R^2 = 79.1\%$ and water balance of -907 mm. For the full study period the model gave $R^2 = 75.1$ % and water balance = 75.1 mm.

This parameter set was transferred to the dam intake location by updating the catchment characteristics. Scaling the meteorological data to the dam location and creating a separate parameter set was considered but neglected. The reason for this decision was the nature of the

Enguri rive, which is fed primarily by the glaciers and the simple scaling of the catchment area would overestimate the runoff.

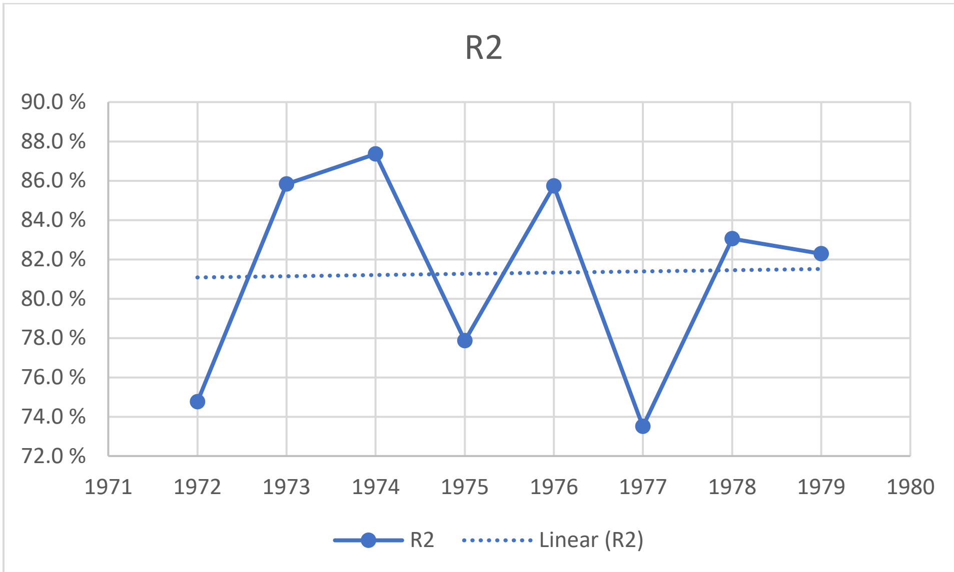


Figure 16. R^2 values for the years in the calibration period

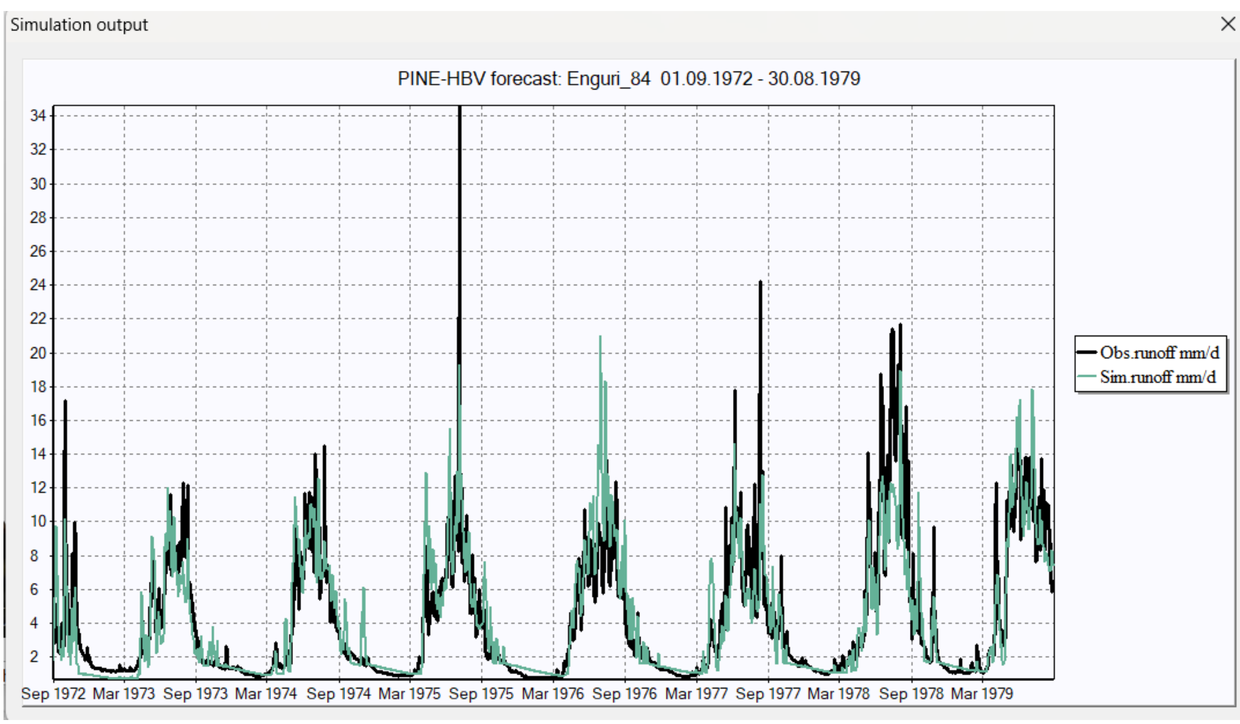


Figure 17. Comparing Simulated and Observed runoff for the calibration period

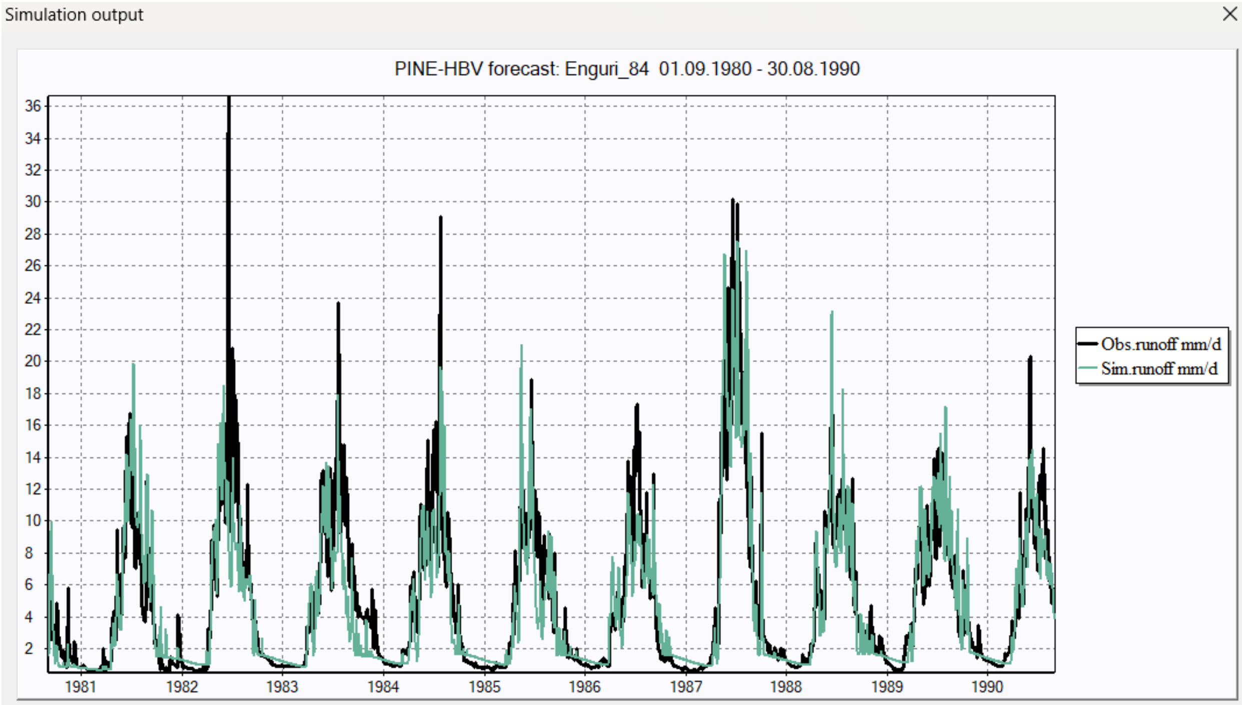


Figure 18. Comparing Simulated and Observed runoff for the validation period

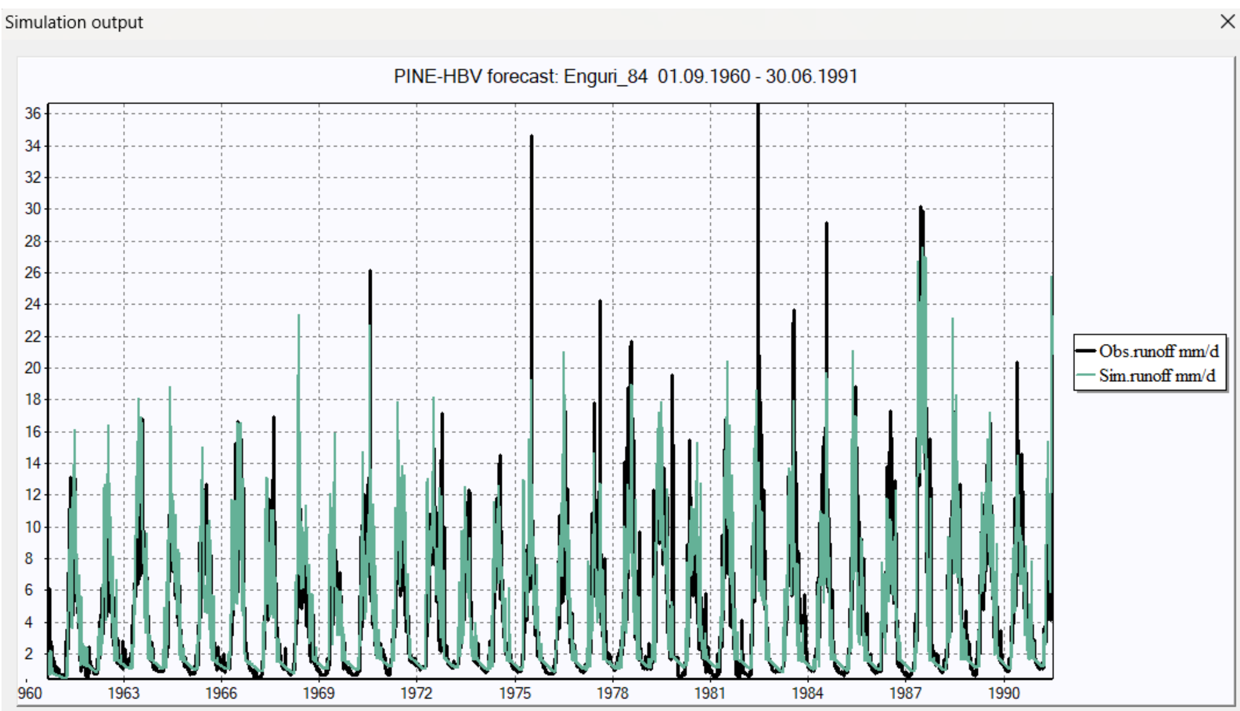


Figure 19. Comparing Simulated and Observed runoff for the whole study period

Forecasting

Process and Challenges with forecasting in PineHBV

The original plan was to forecast the long-term runoff for the catchment in the current time. However, the model transfer over the past 30 years was not as effective as expected. The simulation of the updated parameter set at the dam location didn't reach a positive R^2 value. Glacier percentage, which has decreased in the catchment was updated, but the climate seems to have changed more than that.

Forecasting in the current time would need the meteorological data for past several years, which was not available, as discussed in the section "Meteorological data".

Precipitation data was given by GSE for last two years, but for the Mestia station, not for the Khaishi station. This meant that it needed to be transferred by the precipitation gradient, which is not a known value, as discussed in the section "Correction of meteorological data". So it was obtained by setting a linear relationship between two stations from the historical data.

Temperature data was also given by GSE for the last two years, from their archive of forecast evaluations. However, this data lacked values for every other month, which had to be filled from the meteoblue.com archive, as the data was for only one station, and it was Mestia station again, not Khaishi. And the archive used is a simulation of temperature by a distributed model, not an observed data.

Fore this reason, the option of updating the model to the current climate in the catchment was neglected and forecast was made for the last years of the historical data. To have the opportunity to compare the results with real data, the years 1989-1991 were chosen.

The short-term forecast was run for 10 scenarios (Figure 21), that were based on the actual precipitation and temperature data through the period. The scenarios were created to show the effect of inaccurate weather forecasts. The long-term prediction was based on the historical data and three representative years were chosen for dry, wet and normal years (Figure 22). The R^2 values for each scenario can be seen on the Figure 20.

Simulation	R2
Qsim Original	76 %
1.5P; C	1 %
0.5P; C	67 %
1.5P; +5C	13 %
0.5P; +5C	21 %
P; +5C	14 %
1.5P; -5C	55 %
0.5P; -5C	81 %
P; -5C	77 %
wet	69 %
dry	65 %
normal	61 %

Figure 20. Forecasted runoff results for each scenario

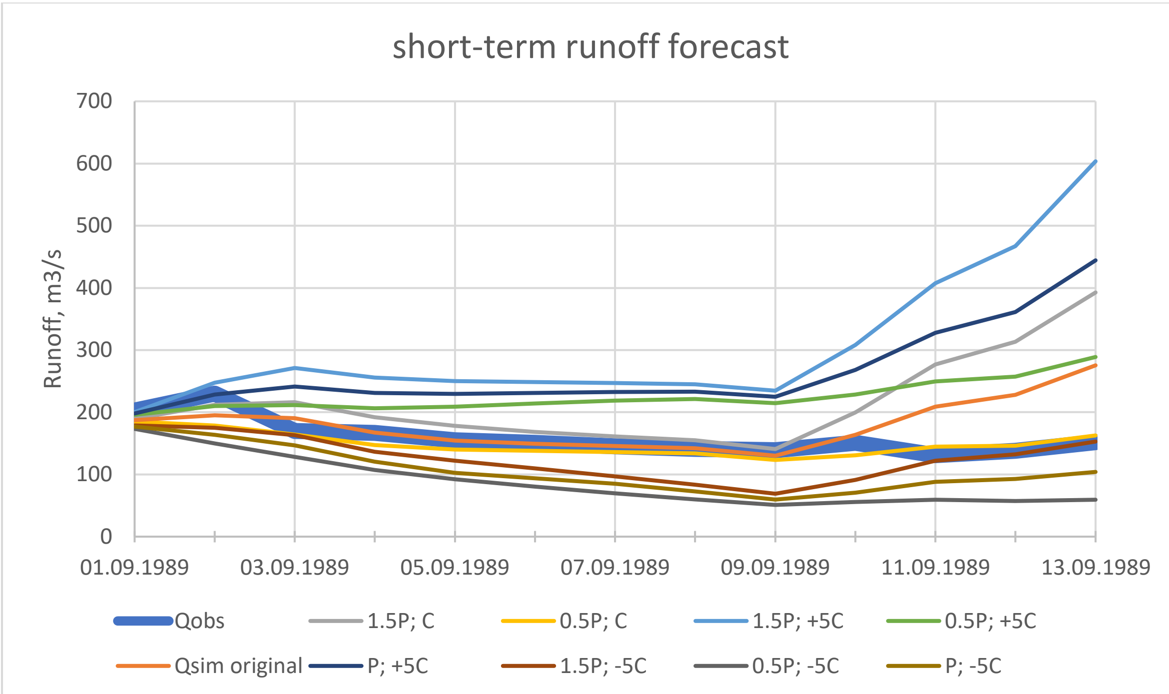


Figure 21. Short-term runoff forecast compared to the observed runoff

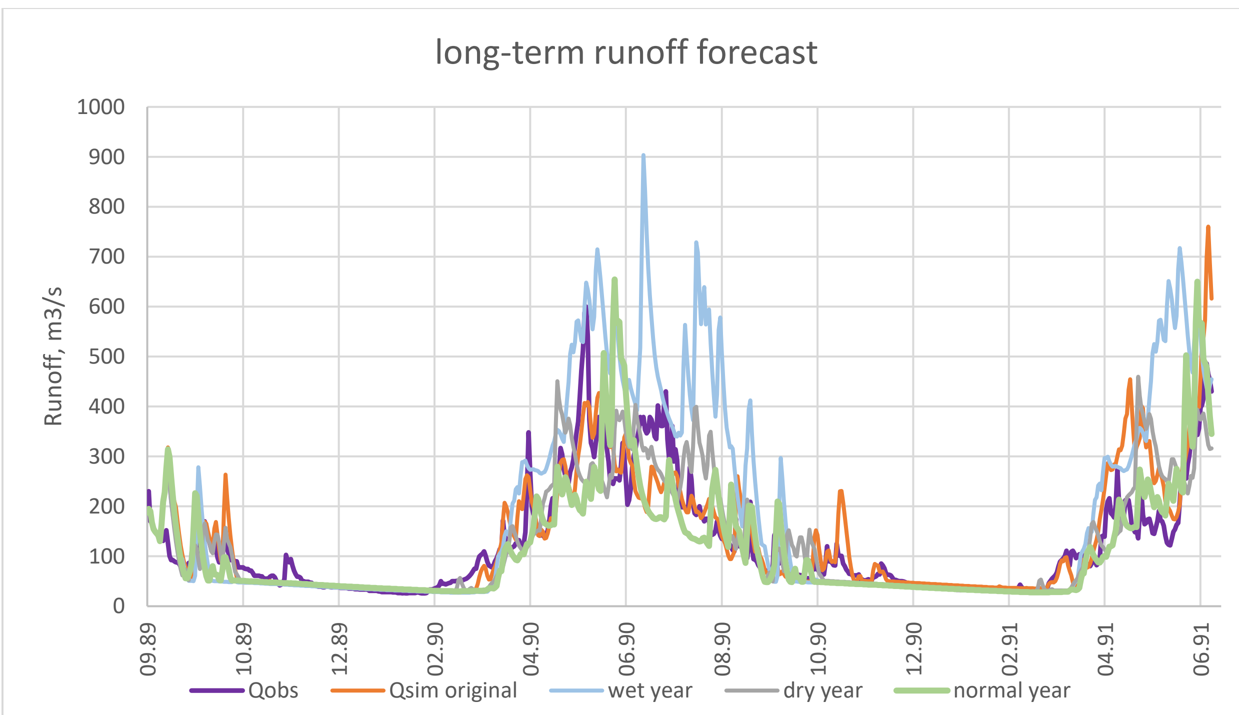


Figure 22. Long-term runoff forecast compared to the observed runoff

Optimizing Production with ProdRisk

Working Mechanism

ProdRisk is a production-optimizing program designed by SINTEF for complex hydropower systems with seasonal reservoirs. The program currently uses a python interface and is commercially available on the market. As an input it uses system description, and stochastic inflow and price series to get water values for the reservoirs over the study period. Then it suggests the most efficient plan of utilizing the reservoirs. Companies run the ProdRisk model periodically to update the plan and try to follow it.

ProdRisk is regularly used by Nordic companies in hydropower planning process along with prices models and a short-term optimization program called SHOP. The optimal period to run SHOP with reasonable calculation time is 1-2 weeks, while ProdRisk can solve the optimization problems for several years and the time resolution can be weekly, daily and if needed, hourly as well. It uses a relatively simple mathematical model, which converts the time-series to be convex, while this is not a restriction for SHOP. While the input series for ProdRisk is stochastic (meaning different possible scenarios), for SHOP has a deterministic input.

Purpose

As the Engury hydropower system, with a seasonally regulated Jvari reservoir, is the largest in Georgia, it's encouraging to see what benefits can be achieved by using ProdRisk here. The system also has a relatively complex structure, having a smaller Gali reservoir downstream the main one of Jvari, along with a cascade of four hydropower plants.

Most importantly, the Georgian power market is soon going to be transformed into a free market, making it possible to regulate power prices on an hourly basis. For these reasons this work could become interesting in near future.

Input

The inflow series is generated based on historical data. Three representative years were chosen, and ten different scenarios were created with their combination (Figure 24). Numpy library was imported in the Python code to read the data and generate scenarios (Figure 23). The input uses weekly averages of the daily historical data from the Khaishi meteorological station.

```python
# --- add inflow series to the session ---

datafile_1 = open('1968.csv', encoding='utf-8-sig')
datafile_2 = open('1985.csv', encoding='utf-8-sig')
datafile_3 = open('1987.csv', encoding='utf-8-sig')


y1 = np.loadtxt(datafile_1) #dry
y2 = np.loadtxt(datafile_2) #normal
y3 = np.loadtxt(datafile_3) #wet

inflow_df = pd.DataFrame(
    index=[prodrisk.start_time + pd.Timedelta(weeks=i)
           for i in range(prodrisk.n_weeks)],
    data={
        "scen0": np.concatenate((y1,y1,y1)),
        "scen1": np.concatenate((y1,y2,y1)),
        "scen2": np.concatenate((y1,y2,y2)),
        "scen3": np.concatenate((y1,y2,y3)),
        "scen4": np.concatenate((y1,y3,y2)),
        "scen5": np.concatenate((y2,y2,y2)),
        "scen6": np.concatenate((y2,y1,y3)),
        "scen7": np.concatenate((y2,y3,y1)),
        "scen8": np.concatenate((y3,y1,y2)),
        "scen9": np.concatenate((y3,y3,y3)),
    },
)

ser = prodrisk.model.inflowSeries.add_object('Serie1')
ser.seriesId.set(1)
ser.inflowScenarios.set(inflow_df)
```

Figure 23. Defining the inflow series in ProdRisk

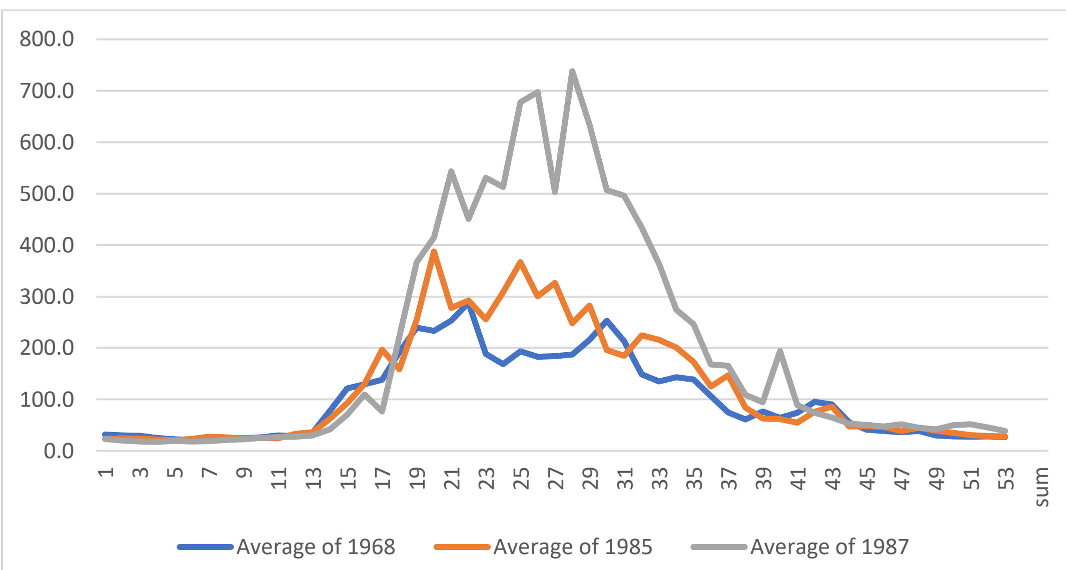


Figure 24. Three representative years: 1968 for dry year, 1985 for wet year and 1987 for normal year

Price is another important input for ProdRisk. Currently the Enguri power plant is selling energy at a constant price of 20 GEL (6.9 Eur) per MWh. The reason for this kind of policy is unknown to me, but the power plant is in a conflict zone, and it can easily be political. Anyway, as this isn't an optimal solution in a free power market, a second simulation was also run with ten different scenarios of prices in the study period. The scenarios were obtained as a result of combination of scaling the original constant price according to the monthly average prices used by the Electricity Market Operator in Georgia, Esco in 2022 (Figure 25).

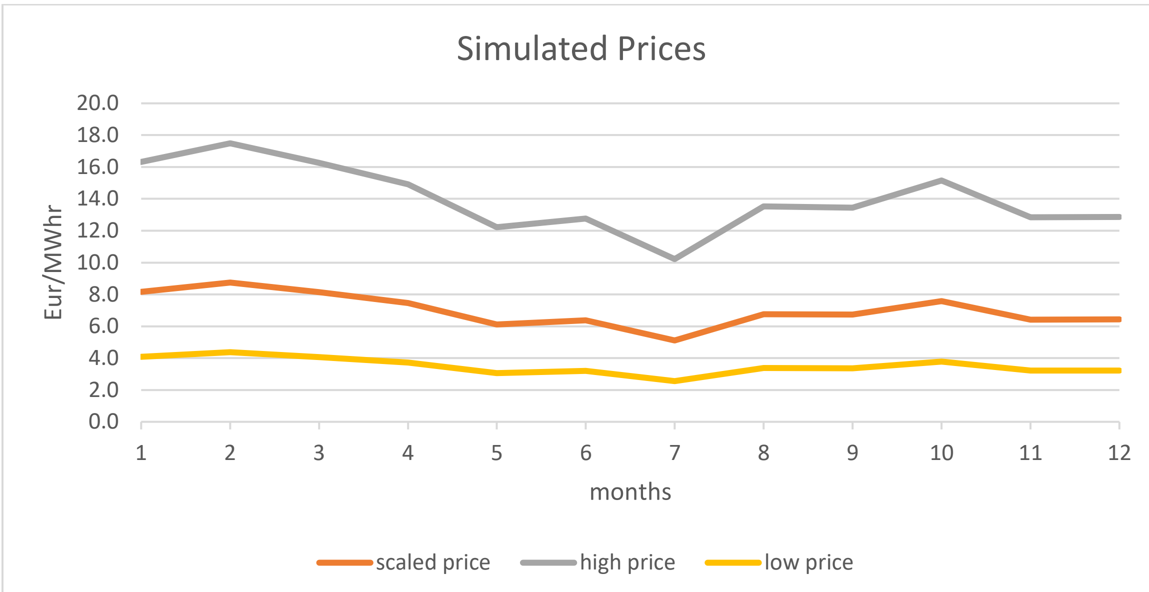


Figure 25. Three representative years for price series; Scaled based on the monthly electricity price accounts from Esco

The structure of the system was described with modules as follows:

The Gali reservoir was modelled as a buffer reservoir, instead of a regulation reservoir, following the guidelines from the official website (SINTEF, 2022). Each power plant in the system was described with one module in the program. Because of the specifics of the program, the power plants in the cascade downstream are also described as having a regulating reservoir, but with a total volume of 0 m^3.

Each module defines reservoir volume, mean regulated and unregulated inflows, nominal head, volume vs head curve, production vs discharge curve, starting reservoir volume and restrictions as minimum discharge downstream, maximum bypass, maximum production and discharge.

For the Jvari reservoir there's no environmental restriction currently in the system for leaving a part of inflow to the Enguri river downstream. However, as this is an important part of every modern project, two parallel simulations were run in this research, one with a seasonally varying downstream restriction and one without it.

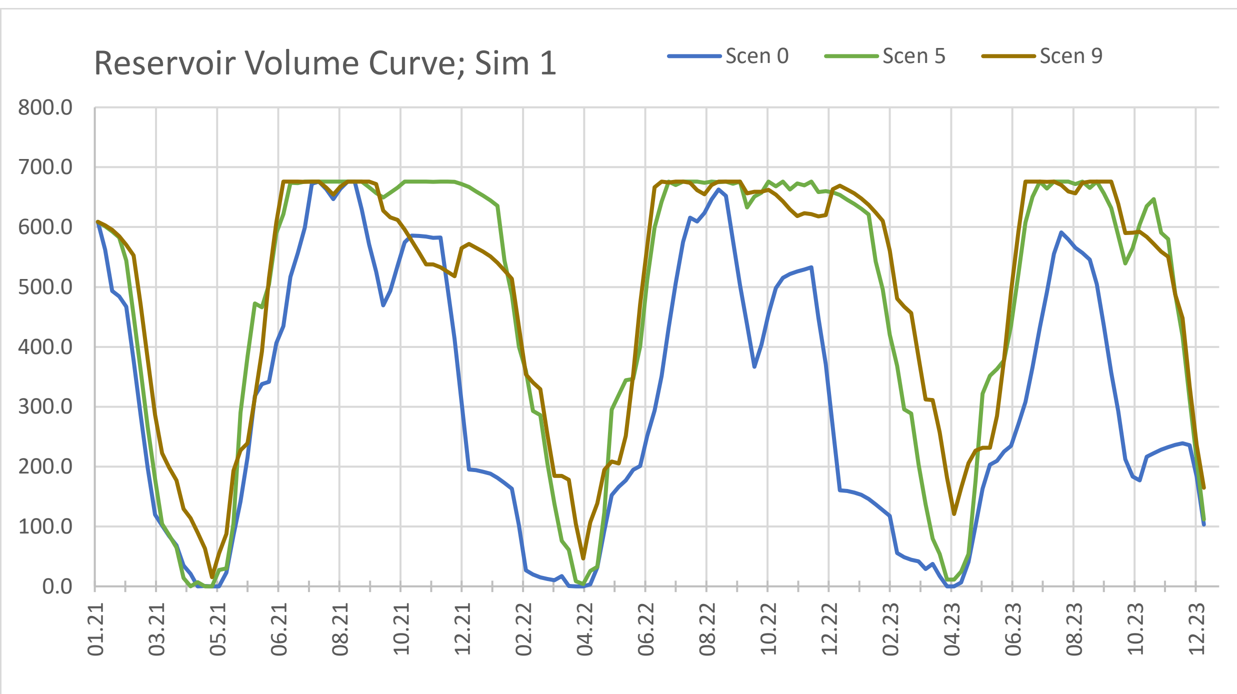
Another important input is setting the boundaries for the production planning and introducing penalties for breaching them.

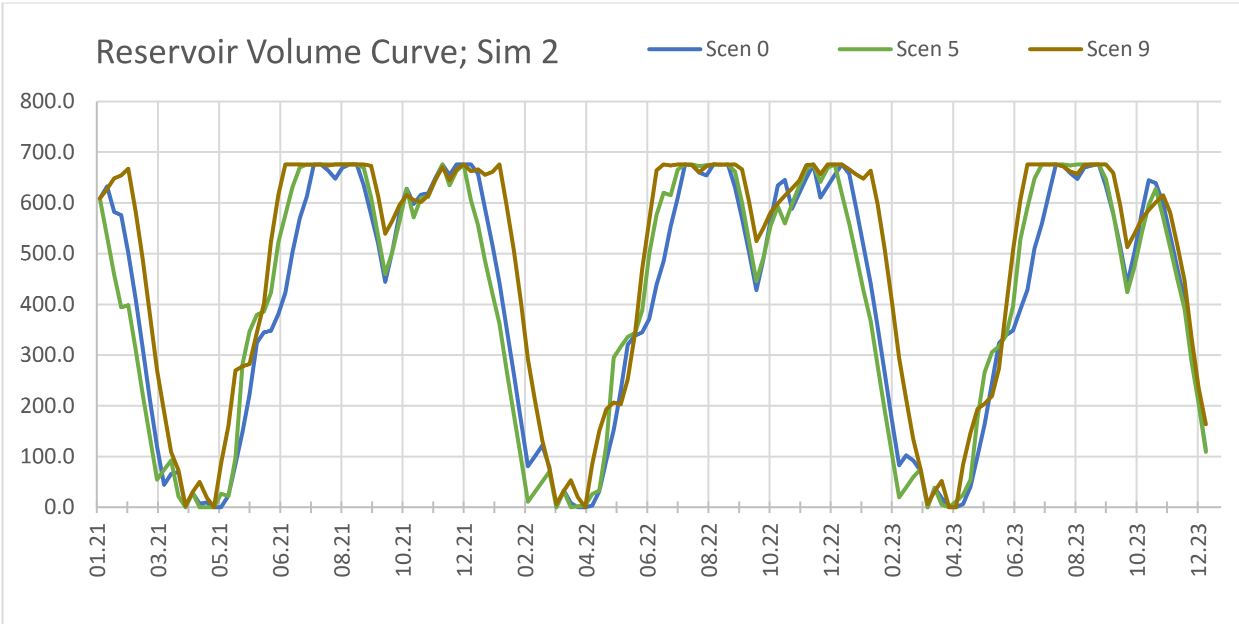
Output

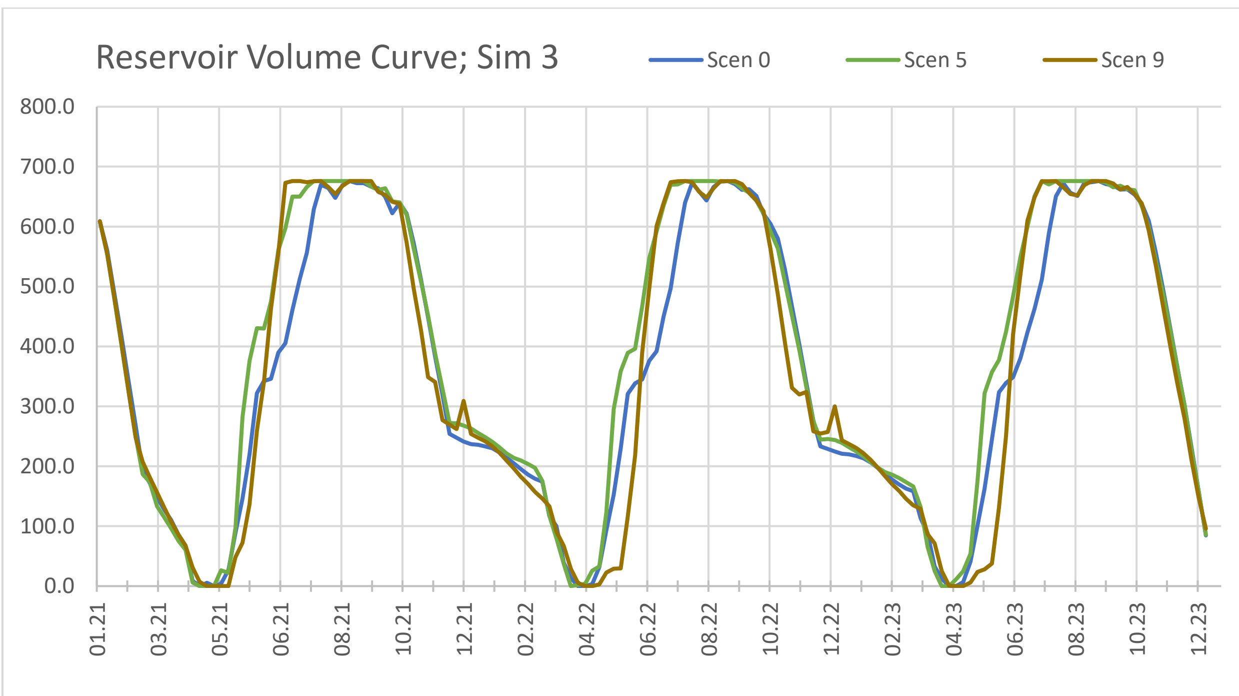
Four different simulations were run to get a planned production with and without downstream ecological restrictions and variable prices. Curves for reservoir volume can be seen on the graphs below for each case. Each simulation was run with ten scenarios, but for a better illustration, only three scenarios are shown on the graphs (Scen 0, Scen 5 and Scen 9). The abbreviations used on the graphs are defined in the table below (Figure 26). Curves for planned discharge (), planned production (), and planned income () can be seen in the appendix, as well as the reservoir volume curve with every scenario.

Abbreviation	Discription		
Sim 1	Variable Price	Seasonal Minimal Flow	
Sim 2	Constant Price	No Minimal Flow	
Sim 3	Constant Price	Seasonal Minimal Flow	
Sim 4	Variable Price	No Minimal Flow	
Scen 0	Dry	Dry	Dry
Scen 1	Dry	Normal	Dry
Scen 2	Dry	Normal	Normal
Scen 3	Dry	Normal	Wet
Scen 4	Dry	Wet	Normal
Scen 5	Normal	Normal	Normal
Scen 6	Normal	Dry	Wet
Scen 7	Normal	Wet	Dry
Scen 8	Wet	Dry	Normal
Scen 9	Wet	Wet	Wet

Figure 26. Defining abbreviations for simulation runs and scenario.




Reservoir Volume Curve; Sim 2
Scen 0
Scen 5
Scen 9
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
01.21
03.21
05.21
06.21
08.21
10.21
12.21
02.22
04.22
06.22
08.22
10.22
12.22
02.23
04.23
06.23
08.23
10.23
12.23


Reservoir Volume Curve; Sim 3
Scen 0
Scen 5
Scen 9
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
01.21
03.21
05.21
06.21
08.21
10.21
12.21
02.22
04.22
06.22
08.22
10.22
12.22
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04.23
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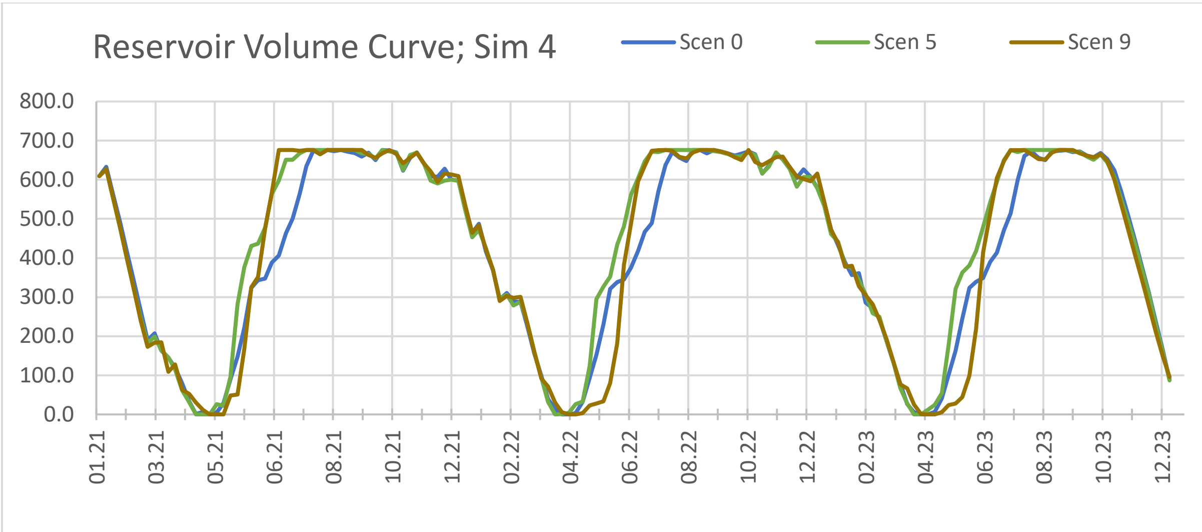
08.23
10.23
12.23

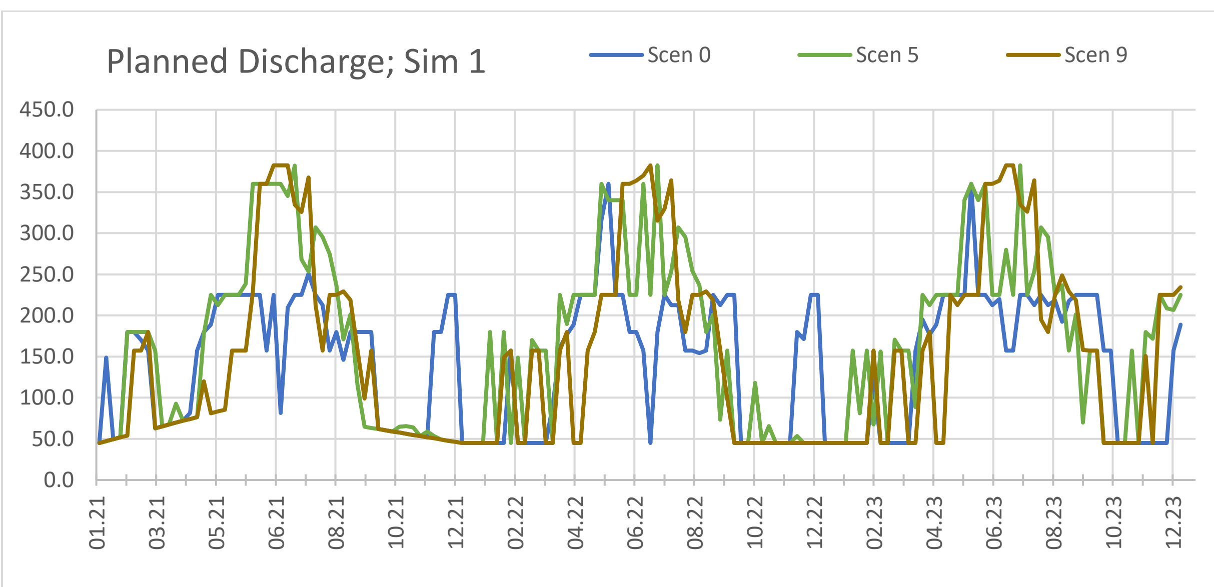


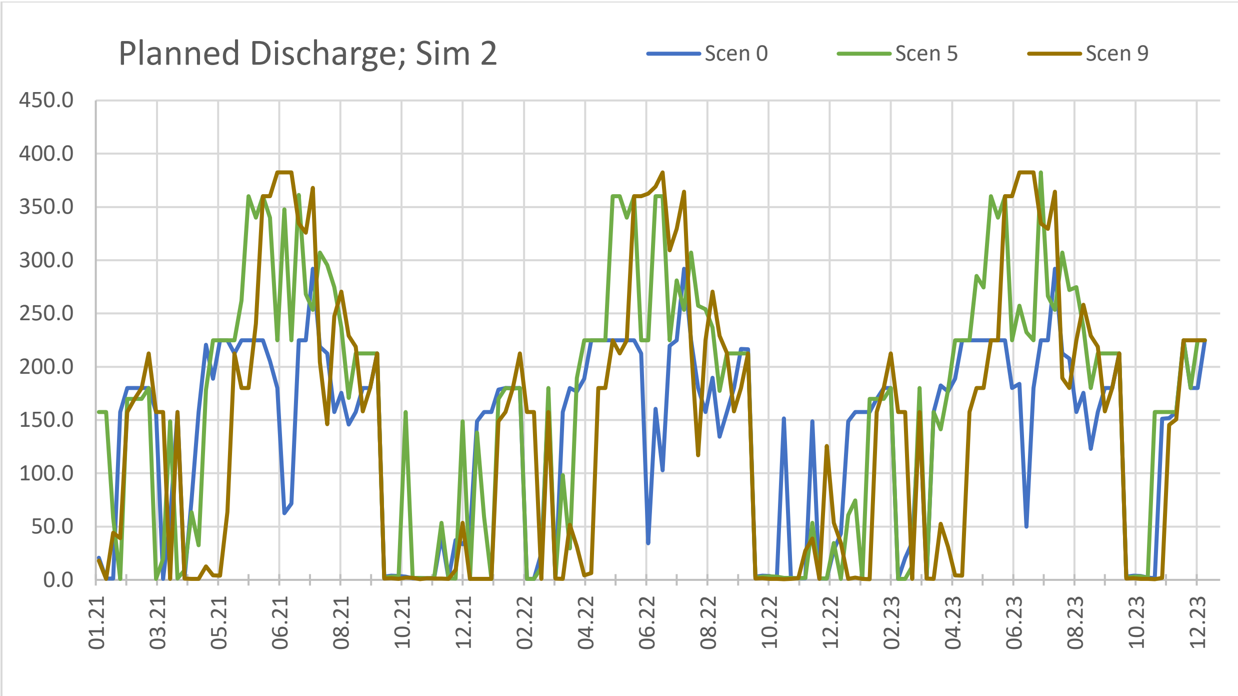
While analyzing the resulted curves it should be noted that in most cases (except for scenario 9 for simulation 1) the reservoir is entirely empty at some point in the middle of each spring. This is usually not optimal and shows that the penalties for violating boundary conditions like rationing cost, surplus cost, are not set effectively.

Another detail can be noticed for scenario 9 with three wet years in a row on the simulation 2 with variable prices and no minimal flow condition. The reservoir starts to get emptied in September each year, but fills up again until November, unlike any other simulation. It is hard to tell why this is happening.

Simulation 3, which has no price variation, has the smoothest, and therefore the slowest curve for the emptying reservoir, but the empty periods last same as for other simulations.

It's interesting to compare simulations 1 and 2 for the planned discharge curves below.





The minimum flow restriction in simulation 1 can be seen having an impact on the curves. While for the second curve the discharge through the turbine goes down to zero in many periods, on the first curve it's guaranteed that the restrictions are followed. The linear growth or the first year follows the seasonal restrictions being stricter in spring season.

Conclusion

The PINE-HBV model performed well for the time period with available meteorological and hydrological data. It was not possible to use it for the current time for forecasting due to lack of available data in recent years. The production optimization model created in ProdRisk didn't use a real-life input with the forecasted runoff, but was able to return reasonable values from the inflow series based on the historical data. Working on this project gave me a valuable knowledge and experience, which can be soon used in the Georgian power market, which is stepping into a new age by implementing a free power market, in parallel with the planning of doubling the hydropower capacity in near future.

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[Accessed 2023].

Appendix

Class	%	Class name	Description
1	3.9	Evergreen needleleaf forests	Lands dominated by needleleaf woody vegetation with a percent cover >60% and height exceeding 2 m. Almost all trees remain green all year. Canopy is never without green foliage
2	0.0	Evergreen broadleaf forests	Lands dominated by broadleaf woody vegetation with a percent cover >60% and height exceeding 2 m. Almost all trees and shrubs remain green year round. Canopy is never without green foliage.
3	0.0	Deciduous needleleaf forests	Lands dominated by woody vegetation with a percent cover >60% and height exceeding 2 m. Consists of seasonal needleleaf tree communities with an annual cycle of leaf-on and leaf-off periods.
4	9.6	Deciduous broadleaf forests	Lands dominated by woody vegetation with a percent cover >60% and height exceeding 2 m. Consists of broadleaf tree communities with an annual cycle of leaf-on and leaf-off periods
5	1.6	Mixed forests	Lands dominated by trees with a percent cover >60% and height exceeding 2 m. Consists of tree communities with interspersed mixtures or mosaics of the other four forest types. None of the forest types exceeds 60% of landscape
6	1.9	Closed shrublands	Lands with woody vegetation less than 2 m tall and with shrub canopy cover >60%. The shrub foliage can be either evergreen or deciduous.
7	17.9	Open shrublands	Lands with woody vegetation less than 2 m tall and with shrub canopy cover between 10% and 60%. The shrub foliage can be either evergreen or deciduous
8	8.6	Woody savannas	Lands with herbaceous and other understory systems, and with forest canopy cover between 30% and 60%. The forest cover height exceeds 2 m.
9	0.0	Savannas	Lands with herbaceous and other understory systems, and with forest canopy cover between 10% and 30%. The forest cover height exceeds 2 m
10	4.8	Grasslands	Lands with herbaceous types of cover. Tree and shrub cover is less than 10%.
11	1.8	Permanent wetlands	Lands with a permanent mixture of water and herbaceous or woody vegetation. The vegetation can be present either in salt, brackish, or fresh water
12	5.4	Croplands	Lands covered with temporary crops followed by harvest and a bare soil period (e.g., single and multiple cropping systems). Note that perennial woody crops will be classified as the appropriate forest or shrub land cover type.
13	0.0	Urban and built-up lands	Land covered by buildings and other man-made structures
14	32.4	Cropland/natural vegetation mosaics	Lands with a mosaic of croplands, forests, shrubland, and grasslands in which no one component comprises more than 60% of the landscape
15	0.0	Snow and ice	Lands under snow/ice cover throughout the year.
16	12.2	Barren	Lands with exposed soil, sand, rocks, or snow and never have more than 10% vegetated cover during any time of the year.
17	0.0	Water bodies	Oceans, seas, lakes, reservoirs, and rivers. Can be either fresh or salt water bodies

Appendix 1. 1. The land use data for the catchment

INPUT CORRECTION

Parameter	Explanation
PCORR	Precipitation correction (usually around 1.05)
SCORR	Snow correction (usually around 1.2)
TCGRAD	Temperature lapse rate dry day (degree/100 m)
TPGRAD	Temperature lapse rate wet day (degree/100 m)
PGRAD	Precipitation lapse rate (%/100 m)

SNOW ROUTINE

State	Explanation
SN	Dry snow (mm)
SW	Water content in snow (mm)

Response	Explanation
SMLT	Computed snow melt (mm)
SR	Computed refrozen water (mm)
ST	Computed free water limit in the snow pack (mm)
INSOIL	Computed water going to the soil routine (mm)

Parameter	Explanation
T_X	Transition temperature snow – rain (deg.C)
T_S	Boundary temperature for snowmelt (deg.C)
CX	Degree day factor (mm/deg.C * day)
CFR	Refreeze factor (mm/deg.C * day)
CPRO	Liquid water content in snow (%)
CXN	*Degree day factor in forested areas (PINEHBV)*
TSN	*Boundary temperature in forested areas (PINEHBV)*

SOILROUTINE

State	Explanation
SM	Soil moisture content (mm)

Response	Explanation
EA	Actual evaporation (mm)
dUZ	Water to upper zone (mm)

Parameter	Explanation
FC	Field capacity (mm)
Beta	Exponent in function defining storage and output (-)
LP	Boundary for full evaporation (0-1)

Appendix 1. 2. Abbreviations for Input Correction, Snow Routine, and Soil Routine for PINE-HBV

UPPER ZONE

State	Explanation
UZ	Water content in upper zone (mm)

Response	Explanation
Q11	Runoff from upper outlet (mm)
Q10	Runoff from lower outlet (mm)

Parameter	Explanation
KUZ1	Upper outlet constant (-)
KUZ	Lower outlet constant (-)
UZ1	Treshold for activation of upper outlet (mm)
PERC	Percolation, water transport from upper to lower zone (mm)

Note that KUZ1 is always lager than KUZ. Sometimes names vary between implementations of the HBV model, but remember that the largest of the constants is always the upper zone.

Note that PINEHBV has a third outlet in the upper zone adding an extra threshold (UZ1) and an extra outlet constant KUZ2.

LOWER ZONE

State	Explanation
LZ	Water content in lower zone zone (mm)

Response	Explanation
Q2	Runoff from lower zone (baseflow) (mm)

Parameter	Explanation
KLZ	Outlet constant for the lower zone (-)
LA	Lake Area (%)
PERC	Percolation, water transport from upper to lower zone (mm)

CATCHMENT DESCRIPTORS

Descriptor	Explanation
Area	Catchment area (km^2)
Hypsographic curve	Hypsographic curve, divides catchment into 10 elevation zones
Lake percentage	Percentage of lakes (LA in lower zone). NB. Not the efficient lake %
Elevtemp	Elevation of temperature station
Elevprec	Elevation of precipitation station
GLAC	*Glacier percentage (%) PINEHBV*
NLOWER	*Boundary between forested and non-forested areas. Referring to an elevation zone. PINEHBV*

Appendix 1. 3. Abbreviations for Upper Zone, Lower Zone, and Catchment Descriptors for PINE-HBV

NTNU

Norwegian University of
Science and Technology