Modelling Implementation Report
WATER BALANCE: STABILIZING SKADAR LAKE WATERSHED

ENVPRO

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Water Balance: Stabilizing the Skadar Lake Watershed

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Executive sumamry

From a water resources perspective, three key indicators are used to identify areas of instability or lack of resilience within the Skadar Lake Basin. A decrease in water yield signals reduced streamflow, which can limit downstream water availability and affect aquatic biodiversity. An increase in evapotranspiration reflects greater water loss to the atmosphere, resulting in drier soils and heightened stress on vegetation and ecosystems. Finally, a negative change in soil water storage indicates that soils are retaining less water over the year, increasing drought risk and reducing the steady baseflow that sustains rivers during dry periods.

In order to undertake this analysis, for each LSU[3] and for each period, the mean annual values for "Water Yield", "Evapotranspiration", and "Change in Soil Water Storage" were calculated.

These LSUs have been mapped (Figure 1) for easy identification of the issues. The highlighted LSUs (21, 26, 66, 107, 108, 109, 170, 172, 173, 134, 145, 110, 115, 149, 138, 153, and 175) correspond to areas with the most severe hydrological imbalances, including declining water yield, increasing evapotranspiration, and negative soil water storage.
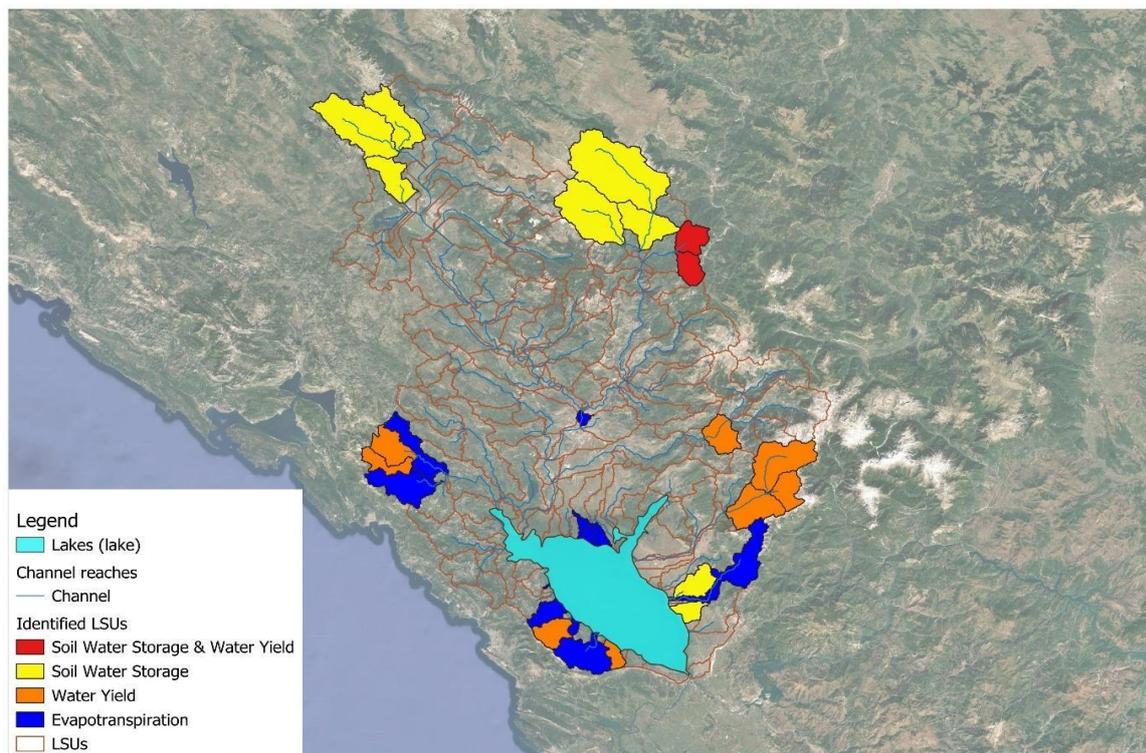
Figure 1. Identified LSUs

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[3] LSUs = "Landscape Units" (model zones with similar terrain/soils/land cover). The numbers (e.g., LSU 21) are model IDs for specific mapped areas.

Within the Skadar Basin modelling, the most critical areas were identified in the north and northeast, where landscape units such as LSU 134, 145, 110, 115, 149, 138, 153, and 175 showed a strong decline in soil water storage. This indicates that soils are becoming increasingly dry and more vulnerable to drought, while at the same time the highest levels of erosion and sediment yield are recorded. Due to high runoff coefficients, water quickly drains from the surface, creating flash flows and increasing flood risk in these parts of the basin. In addition, river flow reductions have been observed in the Sušica, Zeta, and upper Morača, confirming the negative trend in water resources.

At the basin's edges, particularly in the south and along the western and eastern rims, units such as LSU 66, 107, 108, 109, 170, 172, and 173 experience a sharp increase in evapotranspiration – in some cases by more than 60%. This means that large amounts of water are lost to the atmosphere rather than remaining available in soils and streams. In parallel, certain northern units, especially LSU 21 and 26, show a significant reduction in overall water yield, which implies that rivers are receiving less contribution from these catchment areas.

The area immediately surrounding Lake Skadar is particularly sensitive, with the highest runoff coefficients indicating risks of flash floods and surface waterlogging. However, the main concern is that the lake already has a negative balance – more water leaves than enters. Projections suggest that the annual deficit will reach about -1.52×10^8 m³, and cumulatively by mid-century it could amount to -8.24×10^9 m³, leading to a gradual reduction in lake volume and posing direct risks to ecosystems and local communities.

Land-use analysis shows that the greatest erosion originates from dry cropland areas (Dry Cropland – CRDY, over 55 t/ha/year), while urban zones record extremely high runoff and contribute additional sediments. In contrast, forested and grassland areas contribute minimally to erosion and provide a stabilizing effect on the watershed. Figures 2 and 3 present sediment yield patterns across the basin. The northeast, north, and northwest subcatchments are erosion hotspots, with dry cropland contributing the highest sediment loads. Climate change scenarios indicate that these hotspots will persist or intensify, underscoring long-term watershed instability.
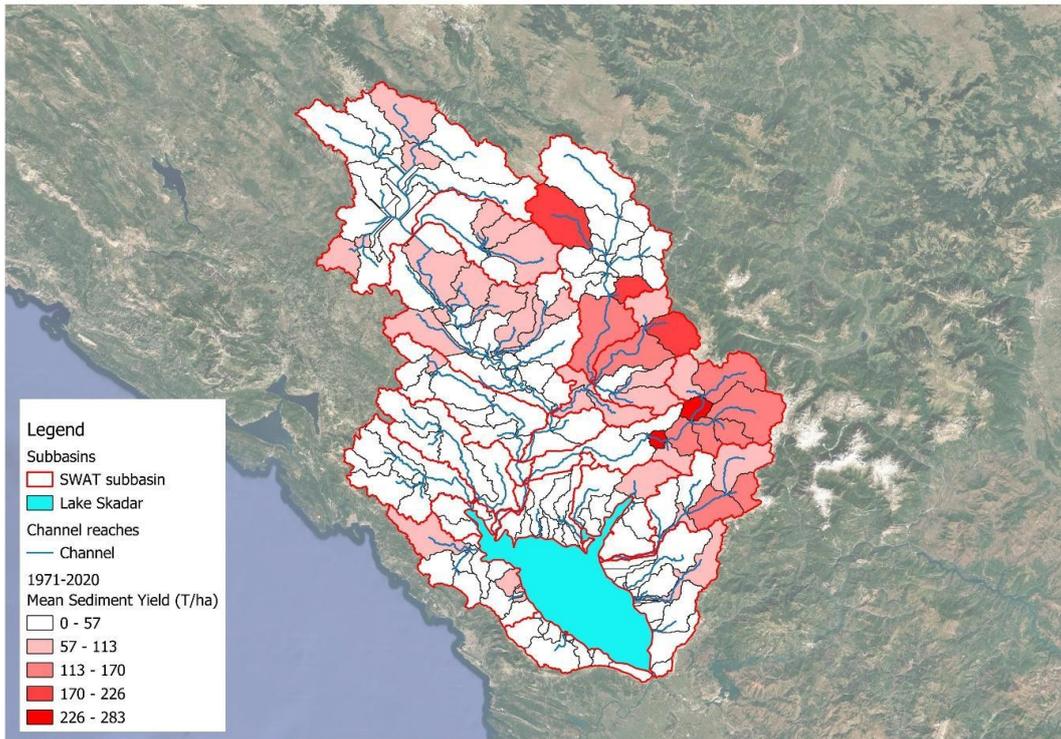
Figure 2. Mean sediment yield from 1971 to 2020
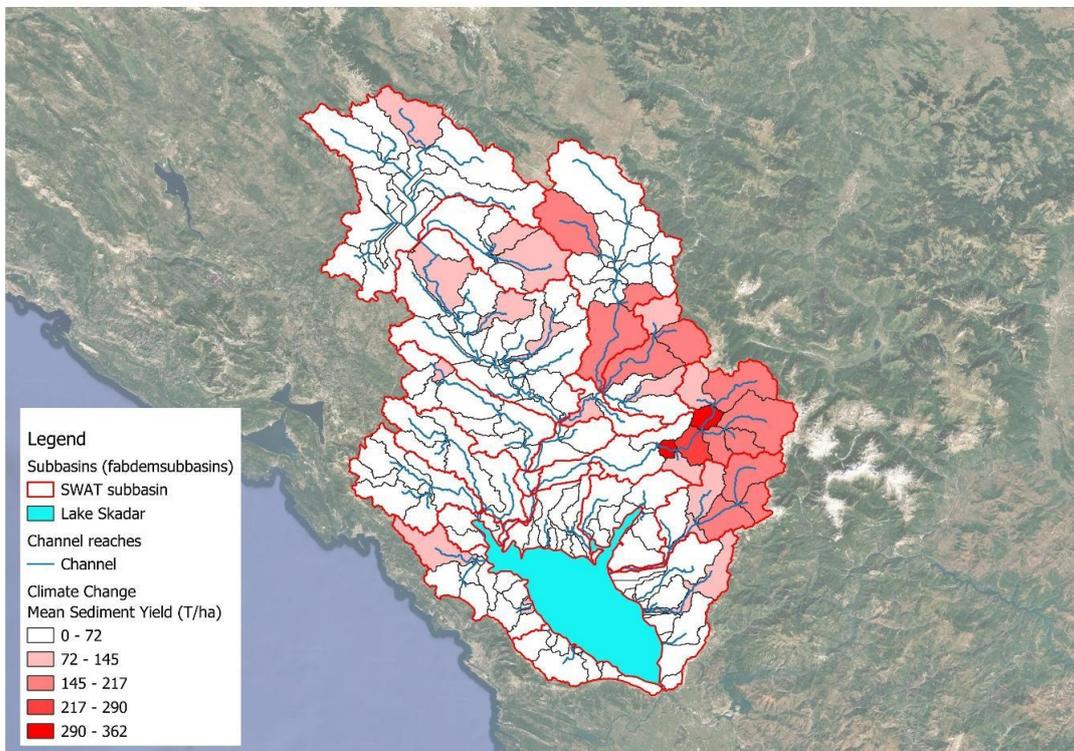
Figure 3. Sediment yield under Climate Change conditions (2021-2049)

The runoff coefficient analysis was conducted to assess infiltration capacity and flash flood risk at the LSU scale, using the ratio of total surface runoff to total precipitation. Results (Figure 4) show that mountainous areas in the north and northwest exhibit a flashy hydrological response, with values above 0.5. The highest runoff coefficients, however, were observed in LSUs located closest to Lake Skadar, indicating elevated risk of flash flooding and surface water accumulation in this zone.
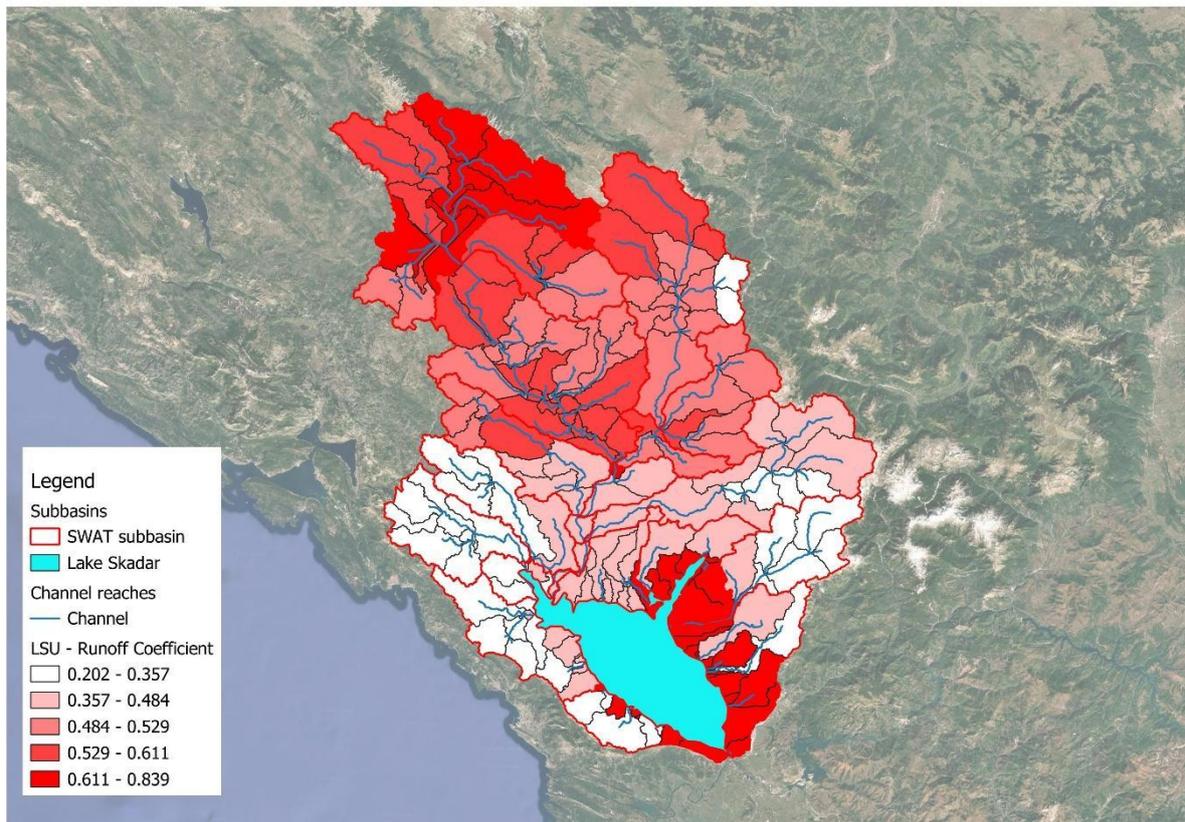
Figure 4. Runoff Coefficient

1. Introduction

This project aims to conduct a comprehensive analysis of the hydrological water balance in the Skadar Lake Basin over a period of 20 years. By implementing a detailed water balance model, the project will assess hydrological dynamics across different subcatchments within the basin. This approach will help identify critical areas where watershed instability is most pronounced. Based on the findings, the project will develop and recommend actionable strategies to mitigate these issues, promoting sustainable watershed management and ecological conservation.

In addition to this, the expected climate change impacts on the catchment will also be analysed. This will be undertaken using the resulting modelling framework to model the condition of the basin from 2020 to 2050.

2. Methodology

The Lake Skadar Basin faces increasing pressures on its water resources due to a combination of factors including rapid urbanisation, population growth, and the exacerbating impacts of climate change. A comprehensive understanding of the basin water balance is essential for effective water resource management and sustainable development. This study aims to develop a robust water balance model that provides a scientific foundation for informed decision-making.

2.1. Full Water Balance Overview

This study will adopt an integrated approach to assess the complete water balance of Lake Skadar Basin, aiming to provide a comprehensive understanding of the basin's water resources. By simulating surface water and groundwater, the methodology will capture the complex interactions between these components, considering current climate scenarios.

2.1.1. Conceptual Framework

The water balance concept is grounded in the principle of mass conservation, which states that the change in water storage within a defined system is equal to the difference between water inputs and outputs. In this study, the water balance will be assessed for the entire Lake Skadar Basin water resource system, encompassing the lake's watershed.

2.1.2. Water Balance Equation and Component Definitions

The water balance for the Lake Skadar Basin system can be expressed using the following equation:

$$P + Q_{in} + R_{gw} = E + Q_{out} + E_{gw} + Q_{gw} + \Delta S$$

Where:

- P (Precipitation): This represents the total amount of atmospheric water deposited onto the watershed, including rainfall, snow, and other forms of precipitation. It is a primary input to the hydrological system and a key driver of surface runoff and groundwater recharge.

- Qin (Water input from other sources): This term accounts for any water entering the system from external sources, such as inter-basin transfers or artificial diversions. In the context of Lake Skadar Basin, this may include water imported from other watersheds or water released from upstream reservoirs. This parameter is important for accounting for man-made changes to the natural water system.

- Rgw (Groundwater recharge): This represents the amount of water that infiltrates the soil and recharges the groundwater aquifers. It is a critical component of the water balance, as it influences groundwater availability and baseflow in streams. Factors affecting groundwater recharge include soil type, land cover, and precipitation patterns.

- E (Evapotranspiration): This encompasses the combined processes of evaporation (water loss from soil and water surfaces) and transpiration (water loss from vegetation). Evapotranspiration rates are influenced by temperature, solar radiation, humidity, and vegetation cover.

- Qout (Surface runoff): This represents the water that flows over the land surface and into streams, rivers, and other surface water bodies. It is a primary component of the streamflow and is influenced by precipitation, land cover, and topography. Surface runoff is how water is transported out of the watershed.

- Egw (Groundwater evapotranspiration): This is the water lost from the groundwater system through evapotranspiration. It occurs where the water table is shallow enough for plant roots to reach it, or for direct evaporation to occur.

- Qgw (Groundwater discharge): This represents the outflow of groundwater from the system, including baseflow to streams and groundwater extraction. It is a critical component of streamflow during dry periods and is influenced by groundwater levels and aquifer properties.

- ΔS (Change in storage): This represents the change in water storage within the system, including changes in soil moisture, groundwater storage, and surface water storage. It accounts for the temporal variability of water availability and is influenced by seasonal and long-term climate patterns. This term is important for understanding the overall health of the water system.

Through the quantification of each of these components, the water balance model will provide a comprehensive assessment of Lake Skadar Basin's water resources, supporting the development of sustainable water management strategies.

2.2.   Software Selection

The selection of appropriate modelling tools is crucial for the success of any water balance study. This project suggests the Soil and Water Assessment Tool (SWAT) for hydrological process simulation. The rationale behind this selection is rooted in the proven capabilities of this model to address the specific challenges and objectives of this study, as well as their widespread acceptance and robust documentation.

Lake Skadar Basin's watershed is characterised by complex topography, diverse land cover, and varying climatic conditions. SWAT is designed to handle such complexities by discretising the watershed into sub-basins and Hydrological Response Units (HRUs). This spatial disaggregation allows for the representation of heterogeneous hydrological processes across the watershed. SWAT excels at large scale hydrological modelling, such as the Lake Skadar Basin watershed.

SWAT's ability to model a wide range of hydrological processes, including surface runoff, groundwater recharge, baseflow, and evapotranspiration, is essential for capturing the complete water balance. It provides a process-based simulation, allowing for a detailed understanding of the interactions between different hydrological components.

SWAT's open-source nature promotes transparency and accessibility, facilitating model customization and adaptation. Its compatibility with GIS tools, such as ArcGIS and QGIS, streamlines data preparation and visualisation, allowing for better collaboration, and model sharing.

2.3.   Surface and Groundwater Water Balance

The primary objective of this section is to develop a robust SWAT model capable of accurately simulating surface and groundwater processes within the Lake Skadar Basin watershed. The goal is to provide a reliable representation of the hydrological cycle, enabling accurate assessment of water availability and its response to climate variability and change.

2.3.1.   Model Configuration

In order to configure the SWAT model to represent the water resources and the hydrological cycle in Lake Skadar Basin, the following activities will be undertaken:

1. Watershed Delineation: A high-resolution Digital Elevation Model (DEM) will be used to delineate the watershed boundaries. In order to represent the watershed as accurately as possible, an assessment of several open-source (and global) DEMs will be undertaken, considering the SRTM[4], the ASTER[5] and the FabDEM[6] sources. The DEM will be pre-processed to remove sinks and pits, ensuring accurate flow accumulation.

   As noted above, the AoI of the study, and that will be used in SWAT is shown in **Error! Reference source not found.**. In a second stage, the watershed will be divided into sub-basins based on topographic characteristics, facilitating the representation of spatial variability in hydrological processes. A stream network will be generated based on flow accumulation thresholds, accurately representing the drainage patterns within the watershed. Outlet points will be defined at strategic locations, to facilitate model calibration and validation. The size and number of subbasins will be determined based on the size of the watershed, the resolution of the DEM, and the location of the gauging stations.

2. Input Data Preparation: the following data will be required for the implementation of SWAT:

   a. Climate Data: climate data will be one of the key inputs for the modelling. Data from meteorological stations within and surrounding the watershed, remote sensing data (CHIRPS), and meteorological reanalysis data (ERA5) will be used.

      The variables that will initially be used are:

      - Daily/monthly precipitation
      - Maximum and minimum temperature
      - Solar radiation
      - Relative humidity
      - Wind speed.

      Data quality control, gap filling using statistical methods, spatial interpolation using techniques will be undertaken. The SWAT weather generator will also be used to fill in missing data, or to create longer time series.

   b. Land Use and Soil Data: Land cover maps from remote sensing imagery, soil maps from national or international databases (Soil Grids[7]) will be used in the SWAT modelling. The variables to be used will be the land cover classification, the soil

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[4] https://www.earthdata.nasa.gov/data/instruments/srtm

[5] https://catalog.data.gov/dataset/aster-global-dem

[6] https://data.bris.ac.uk/data/dataset/s5hqmjcdj8yo2ibzi9b4ew3sn

[7] https://soilgrids.org/

texture, hydraulic conductivity, the bulk density, and the organic carbon content. The data will be reclassified to SWAT categories.

2.3.2. Hydrological Simulation

The hydrological simulation in SWAT will consider the following:

1. Surface Runoff Calculation: initially the SCS Curve Number method will be used to estimate surface runoff, considering land use, soil type, and antecedent moisture conditions. The main parameter to consider in this parametrisation and during the calibration will be the Curve Number (CN2), to be calibrated with the existing streamflow data. It should be added that most studies find this parameter the most sensitive within SWAT implementations.

2. Groundwater Recharge Estimation: Groundwater recharge will be estimated through percolation processes, considering soil hydraulic properties and water balance calculations. In order to address this, the baseflow will be separated from streamflow using digital filtering techniques, providing an estimate of groundwater contribution to streamflow, and SWAT will be calibrated, mainly considering the ALPHA_BF parameter.

2.3.3. Calibration and Validation

During the calibration of the SWAT model, model parameters will be adjusted iteratively to match simulated streamflow and groundwater recharge with observed data. Also, as noted above, a Sensitivity analysis will be conducted to identify key parameters, and calibration will be performed using automated calibration tools (e.g., SWAT-CUP).

Regarding the validation, simulated outputs will be compared with independent data, such as groundwater levels and streamflow data from a different time period.

Considering the existing data at the moment of submitting this report, the following calibration and validation periods are proposed:

- Calibration: from 1970 to 2000
- Validation: from 2000 to 2005.

It should be noted that it would be desirable that more (and recent) data is acquired, in order to undertake the calibration for a longer and more recent period.

In order to undertake the calibration and validation, the Nash-Sutcliffe Efficiency (NSE), Root Mean Square Error (RMSE), and Coefficient of Determination (R^2) will be used.

The following outputs are expected based on the calibrated and validated model:

a. Streamflow at sub-basin outlets.

b. Groundwater recharge rates.

c. Evapotranspiration rates.

d. Baseflow contributions.

e. Soil moisture content.

2.3.4. Baseline Scenarios

The calibrated model will be used to assess the baseline situation, from 2005 to 2020. While the model was calibrated for the 1970 to 2000 period and validated from 2000 to 2005, the resulting model was applied to assess the water resources in the Skadar Lake Basin from 2005 to 2020.

2.3.5. Climate Change Scenarios

As noted above, in addition to the baseline assessment, for the period from 2005 to 2020, the model will be used to assess climate change conditions. This will be undertaken from the period from 2020 to 2050, using projection data for the RCP8.5 scenario.

2.4. Area of Interest

In the Figure 1 below the Area of Interest (AoI) for this study can be observed. This area of interest has been selected considering the watershed area as identified by the DEM, and also considering the hydrological features and the hydrological modelling implementation.

Figure 1. Area of Interest (AoI)

2.5.   Assessment

The assessment of the water resources will be done in several phases:

2.5.1.   Initial Assessment

The calibrated SWAT+ model outputs will be used to analyse the key hydrological processes across all subcatchments, focusing on spatial and temporal variability. Specifically, the following will be considered:

- Water Balance Components: the different components of the water balance will be analysed, considering the precipitation, surface runoff, evapotranspiration, infiltration, percolation, lateral flow, and baseflow. A seasonal and annual trend assessment will be undertaken to identify shifts or anomalies.
- Flow Regimes and Discharge: streamflow at key gauge stations (especially near river inflows to Skadar Lake) will be analysed to detect flow variability, baseflow contributions, and potential drought or flood-prone sub-basins.

This assessment to provide initial information about the water balance in the catchment. This will be undertaken for three periods:

- Calibration and validation period: 1970-2005
- Baseline period: 2005-2020
- Climate change period: 2020-2050

2.5.2. Identification of Watershed Instabilities

In order to identify some instabilities in different subcatchments, such as erosion, degradation, or flash floods, the following will be evaluated:

- Sediment Yield: the sediment outputs yielded by the modelling framework will be analysed to identify hotspots of soil erosion.
- Land Use Change Sensitivity: the land use categories contributing to high surface runoff or erosion (e.g., bare lands, steep agriculture) will be analysed.
- Runoff Coefficient and Flashiness: the runoff-to-precipitation ratios and high event-based flow variability will be calculated per subcatchment in order to identify areas with reduced infiltration and flash flood risk.

3. SWAT Modelling Implementation

The SWAT modelling implementation will analyse the water resources in the catchment area upstream of Dushanbe, considering both the surface water and the groundwater resources, as well as their interactions. The following has been undertaken.

3.1. SWAT Data Inputs

3.1.1. DEM processing

One of the first steps in the implementation of the SWAT model for Dushanbe would be the selection and processing of the DEM (Digital Elevation Model). The DEM will represent the topographical features of the catchment, as well as being the basis for the subcatchment delineation and the calculation of the stream network.

Three different DEM have been considered for the modelling, namely the SRTM[8], the ASTER[9] and the FabDEM[10] DEMs. In order to select the most appropriate DEM as assessment has been undertaken of the quality of these three sources, as well as a comparison among the three options.

Features of the three DEMs are outlined below:

- ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer):

  • Derived from stereo-pair images.

  • Global coverage.

  • Resolution: 30 meters.

  • Potential issues: Cloud cover interference, artifacts in areas with low texture, and lower accuracy in steep terrain.

- SRTM (Shuttle Radar Topography Mission):

  • Derived from radar interferometry.

  • Global coverage.

  • Resolution: 30 meters (originally 90 meters, but often refined).

  • Potential issues: Voids (especially in mountainous regions), radar artifacts, and lower accuracy in heavily vegetated areas.

- FabDEM:

  • AI-enhanced SRTM.

  • Global coverage.

  • Resolution: similar to SRTM, 30 meters.

  • Potential issues: While it improves on SRTM, it still relies on the original SRTM data, so it might inherit some of its limitations. The AI enhancement may introduce new errors, and the degree of improvement varies geographically.

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[8] https://www.earthdata.nasa.gov/data/instruments/srtm

[9] https://catalog.data.gov/dataset/aster-global-dem

[10] https://data.bris.ac.uk/data/dataset/s5hqmjcdj8yo2ibzi9b4ew3sn

In order to compare the three DEMs, profiles have been undertaken in key locations in the catchment area, especially following the river profiles and taking cross-sections of main rivers.

After this assessment, it was evident that FabDEM presents more refined profiles, especially considering the longitudinal profile of the river. In addition to this, comparisons have been undertaken basin-wide, with each of the DEMs, and again the FabDEM presented a more consistent topography as compared to the ASTER and the SRTM DEMs, and therefore this has been the DEM selected for this study.

3.1.2. Climate data

Climate data was acquired from global resources for the implementation of the SWAP model, using the information for

- Daily/monthly precipitation
- Maximum and minimum daily temperature
- Solar radiation
- Relative humidity
- Wind speed.

This information was created in virtual weather stations across the basin, following the coordinates given below in Table 1.

Table 1. Virtual weather stations

ID	Latitude (degrees)	Longitude (degrees)
1	41.68	18.75
2	41.68	19.06
3	41.68	19.38
4	41.68	19.69
5	41.68	20
6	41.99	18.44
7	41.99	18.75
8	41.99	19.06
9	41.99	19.38
10	41.99	19.69
11	41.99	20
12	42.31	18.44
13	42.31	18.75

14	42.31	19.06
15	42.31	19.38
16	42.31	19.69
17	42.31	20
18	42.62	18.44
19	42.62	18.75
20	42.62	19.06
21	42.62	19.38
22	42.62	19.69
23	42.62	20
24	42.93	18.44
25	42.93	18.75
26	42.93	19.06
27	42.93	19.38
28	42.93	19.69
29	42.93	20
30	43.24	18.44
31	43.24	18.75
32	43.24	19.06
33	43.24	19.38
34	43.24	19.69
35	43.24	20

3.1.3. Climate Change Data

The climate change data was extracted from the Open-Meteo application, for the following climate change projections:

Climate Model	Origin	Run by	Resolution
CMCC-CM2-VHR4	Italy	Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici, Lecce (CMCC)	30 km
FGOALS_f3_H	China	Chinese Academy of Sciences, Beijing (CAS)	28 km
HiRAM_SIT_HR	Taiwan	Research Center for Environmental Changes, Academia Sinica, Nankang, Taipei (AS-RCEC)	25 km
MRI_AGCM3_2_S	Japan	Meteorological Research Institute, Tsukuba, Ibaraki (MRI)	20 km

EC_Earth3P_HR	Europe	EC-Earth consortium, Rossby Center, Swedish Meteorological and Hydrological Institute/SMHI, Norrkoping, Sweden	29 km
MPI_ESM1_2_XR	Germany	Max Planck Institute for Meteorology, Hamburg 20146, Germany	51 km
NICAM16_8S	Japan	Japan Agency for Marine-Earth Science and Technology, Kanagawa 236-0001, Japan (MIROC)	31 km

The following data was acquired:

- Maximum Temperature (2 m)

- Minimum Temperature (2 m)

- Mean Wind Speed (10 m)

- Shortwave Radiation Sum

- Mean Relative Humidity (2 m)

- Precipitation Sum

The data from the different climate models was processed in order to obtain an ensemble climate prediction for the 2015-2050 period for the higher emission scenario (RCP 8.5).

3.1.4. Land-use/Land-cover

Land cover maps from remote sensing imagery from international databases (USGS EROS Archive - Land Cover Products - Global Land Cover Characterization (GLCC)[11]) was acquired for its use in the SWAT modelling.

3.1.5. Soil Data

Soil maps international databases (FAO Digital Soil Map of the World[12]) was acquired for its use in the SWAT modelling.

3.1.6. Groundwater Data

At the moment of submitting this report, the only information available regarding groundwater is shown in Figure 2, as collected from the Worldwide Hydrogeological Mapping and Assessment Programme[13].

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[11] https://www.usgs.gov/centers/eros/science/usgs-eros-archive-land-cover-products-global-land-cover-characterization-glcc

[12] https://swat.tamu.edu/media/116412/readme.pdf

[13] https://whymap.bgr.de/
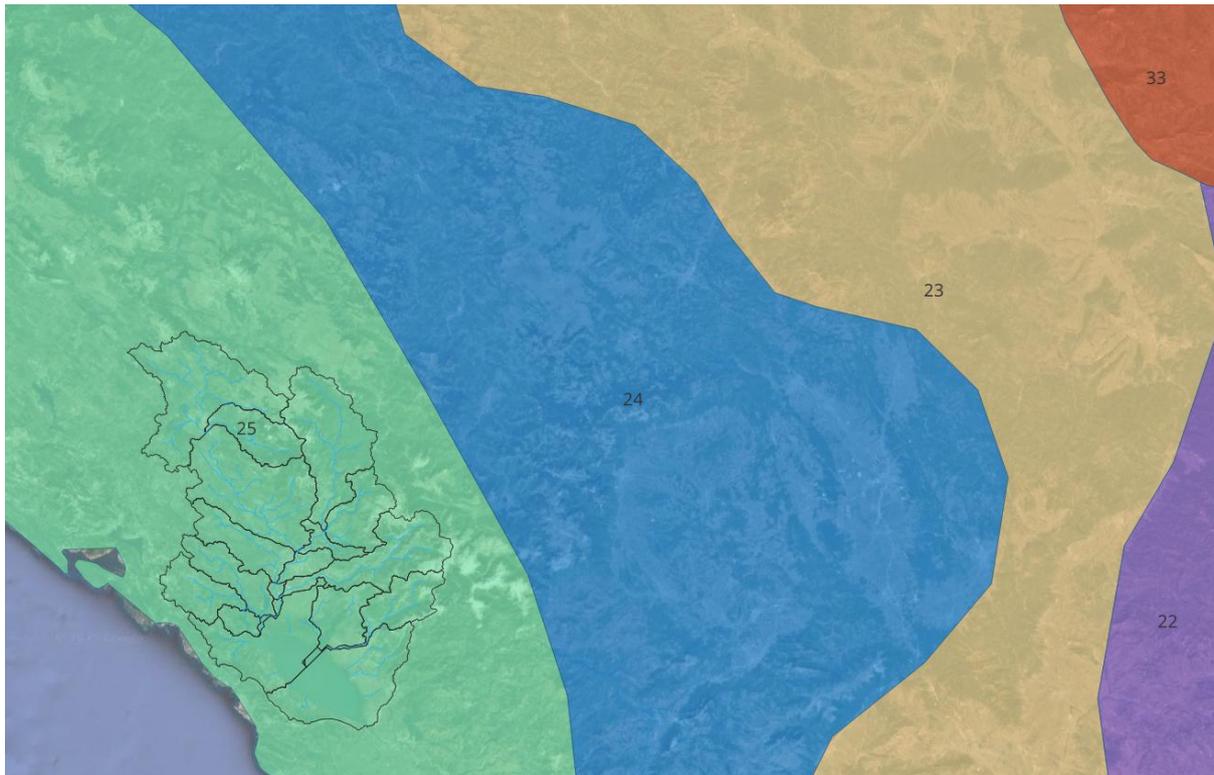
Figure 2. Groundwater

As it can be seen, one major aquifer is present in the study area, with the following recharge rate (Table 2):

Table 2. Aquifers

Aquifer	Recharge (mm/a)	Aquifer Type
25	Very high (>300)	Complex hydrogeological structures

3.1.7.   Hydrological Data

Hydrological data will be used for the calibration of the SWAT hydrological model. Data for the calibration was acquired from the "Institute of Hydrometeorology and Seismology" website. These data were processed (Table 3 and Figure 3).

Table 3. Hydrological station Data

ID	River	Period Start	Period end	Latitude (º)	Longitude (º)
60132	Susica	1948	2004	42.848	18.922

60113	Mrtvica	1948	2005	42.719	19.37
60155	Zeta - Danilovgrad	1948	2001	42.554	19.106
60135	Zeta - Duklov Most	1955	2005	42.66	19
60115	Moraca - Pernica	1956	2005	42.713	19.371
60160	Moraca - Podgorica	1948	2005	42.453	19.262
60128	Moraca - Zlatica	1983	2005	42.484	19.307
60058	Rij. Crnojevica	1987	2002	42.356	19.021
60168	Cijevna	1949	1986	42.395	19.383

Figure 3. Hydrological Stations

3.2.   SWAT Data Processing

3.2.1. Watershed and Subcatchment Delineation

The QGIS plug-in has been used to define the watershed of the study area and the subcatchments, using the FabDEM, and defining an outlet in the location of the most downstream point in the area of interest (as previously defined in Deliverable 1). The resulting watershed and subcatchments are shown in Figure 4.
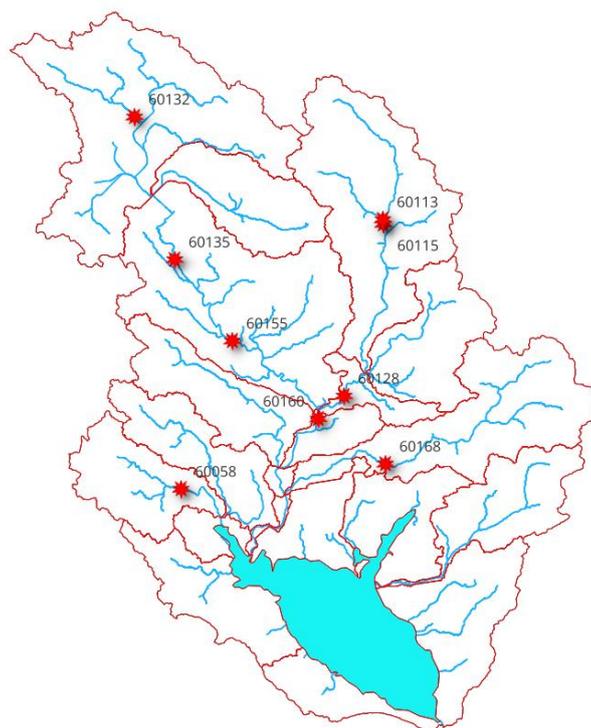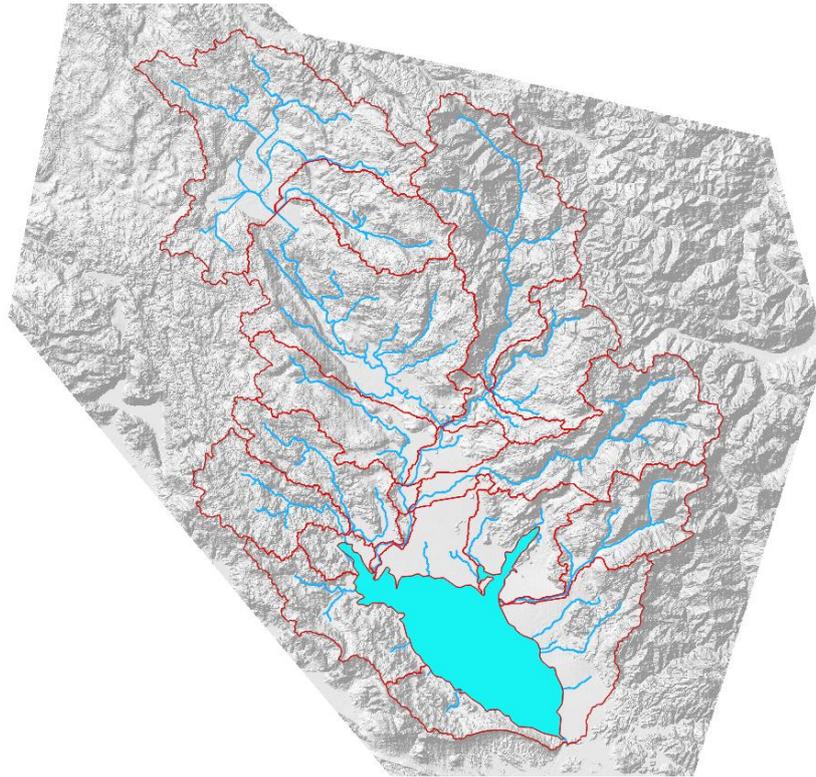
Figure 4. Sub-catchments

3.2.2. Land-use/Land-cover

The land-use data has been further processed, in order to ensure that the data used in the definition of the Hydrologic Response Units (HRUs) is appropriate. The following land-uses have been identified in the watershed (Table 4).

Table 4. Land-uses codes

id	code	land-use
1	crdy	Cropland/Arable Land/Cultivated Land
2	crwo	Forest/Woodland
3	fodb	Floodplain/Wetlands/Water Bodies
4	migs	Pasture/Grassland
5	urmd	Urban/Residential/Developed Areas
6	wetw	Wetlands or Water

This information has been mapped (Figure 5) and the distribution of each of the category has been analysed (Table 5). The land use distribution in the Skadar Lake Basin suggests a landscape significantly shaped by human activity, particularly agriculture (crdy), which dominates the basin's land use. This extensive agricultural presence likely plays a crucial role in the local economy but also presents

potential challenges related to nutrient runoff and water quality in the lake. The significant area attributed to floodplain/wetlands/water bodies (fodb, wetw) highlights the importance of the lake and its associated wetland ecosystems, which are internationally recognised for their biodiversity. While forest/woodland (crwo) contributes to the natural cover, urban development (urmd) appears to be concentrated in relatively small areas, indicating that large-scale urbanization might not be as widespread as agricultural activities. The presence of pasture/grassland (migs) further indicates diverse land management practices within the basin. Overall, the basin appears to be a mosaic of agricultural and natural areas, with the lake and its wetlands being a central and ecologically vital component, necessitating careful management to balance human activities with environmental protection. From a hydrological perspective, the dominance of cropland/arable land (crdy) suggests a high potential for surface runoff and sediment transport, especially if agricultural practices do not incorporate conservation measures. These areas can contribute significantly to nutrient and pesticide loading into the lake, impacting water quality. The substantial presence of floodplain/wetlands/water bodies (fodb, wetw) highlights the crucial role these areas play in the basin's water balance; they act as natural sponges, attenuating floods, filtering pollutants, and regulating streamflow. The relatively smaller areas of forest/woodland (crwo) and pasture/grassland (migs), while important for infiltration and groundwater recharge, will have a lesser overall impact on the basin's hydrology compared to the more extensive agricultural and wetland areas. Finally, the limited urban/residential/developed areas (urmd) suggest that impervious surfaces, a major contributor to increased runoff and flash floods in urbanised catchments, are not the primary hydrological concern across the entire basin.
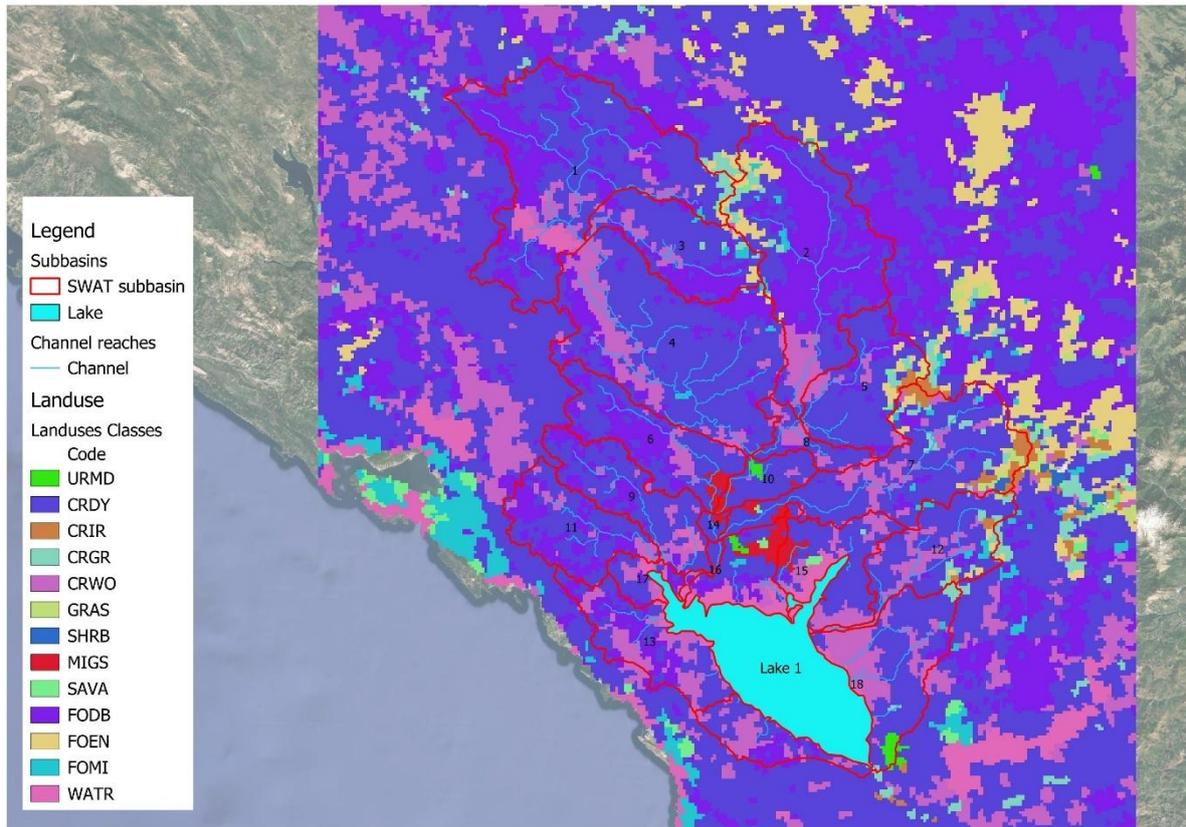
Figure 5. Land-uses

Table 5. Distribution of land-uses

id	Category	Area (m²)	Percetange
crdy	Cropland/Arable Land/Cultivated Land	347905.4	71.7%
crwo	Forest/Woodland	42258.9	8.7%
fodb	Floodplain/Wetlands/Water Bodies	82099.2	16.9%
migs	Pasture/Grassland	3713.1	0.8%
urmd	Urban/Residential/Developed Areas	393.9	0.1%
wetw	Wetlands or Water	9104.7	1.9%
Total		485475.2	100.0%

3.2.3. Soil

The soil data has also been acquired and processed, as it can be observed in Figure 6, with four main soil classes present, the "E24-2c-6496" in the north side of the catchment, the "Bc27-2-3b-6400" in the centre, close to the Skadar Lake, the "Jc49-1-3a-3139" in the East section of the basin, and the "I-Bc-Lc-2-3086" in the West side. A brief description of each class and their hydrological implications are outlined below:

- E24-2c (Rendzinas, Medium Texture, Steep Slope): These soils are typically shallow with limited water storage. While they can have moderate infiltration, the dominant factor is the steep slope, leading to high surface runoff potential and significant erosion risk during rainfall events, especially if vegetation is sparse. They contribute to a rapid and "flashy" hydrological response.

- Bc27-2-3b (Chromic Cambisols, Medium Texture, Rolling to Hilly Slope): Generally well-drained with good infiltration and moderate water holding capacity. The rolling- to-hilly slopes contribute to elevated surface runoff and erosion risk during intense storms, but less so than very steep areas. These soils offer a more balanced hydrological response than the E24-2c.

- Jc49-1-3a (Calcaric Fluvisols, Coarse Texture, Level to Gently Undulating Slope): Characterised by very high infiltration rates and low water holding capacity due to their coarse texture and flat terrain. They exhibit very low surface runoff potential under normal conditions and promote rapid groundwater recharge. They are susceptible to inundation from external sources (e.g., river flooding) rather than generating significant runoff themselves.

- I-Bc-Lc-2 (Lithosols, Chromic Cambisols, Luvic Chernozems, Medium Texture - Soil Complex): This complex represents a highly varied hydrological regime. It includes very shallow soils (Lithosols) with high runoff potential and minimal storage, alongside well-drained soils with moderate infiltration (Cambisols), and deep, highly permeable soils with high water storage capacity and excellent infiltration (Chernozems). The overall hydrological response will be a mix, highly dependent on the spatial distribution of these components within the basin, leading to diverse water flow paths and retention times.
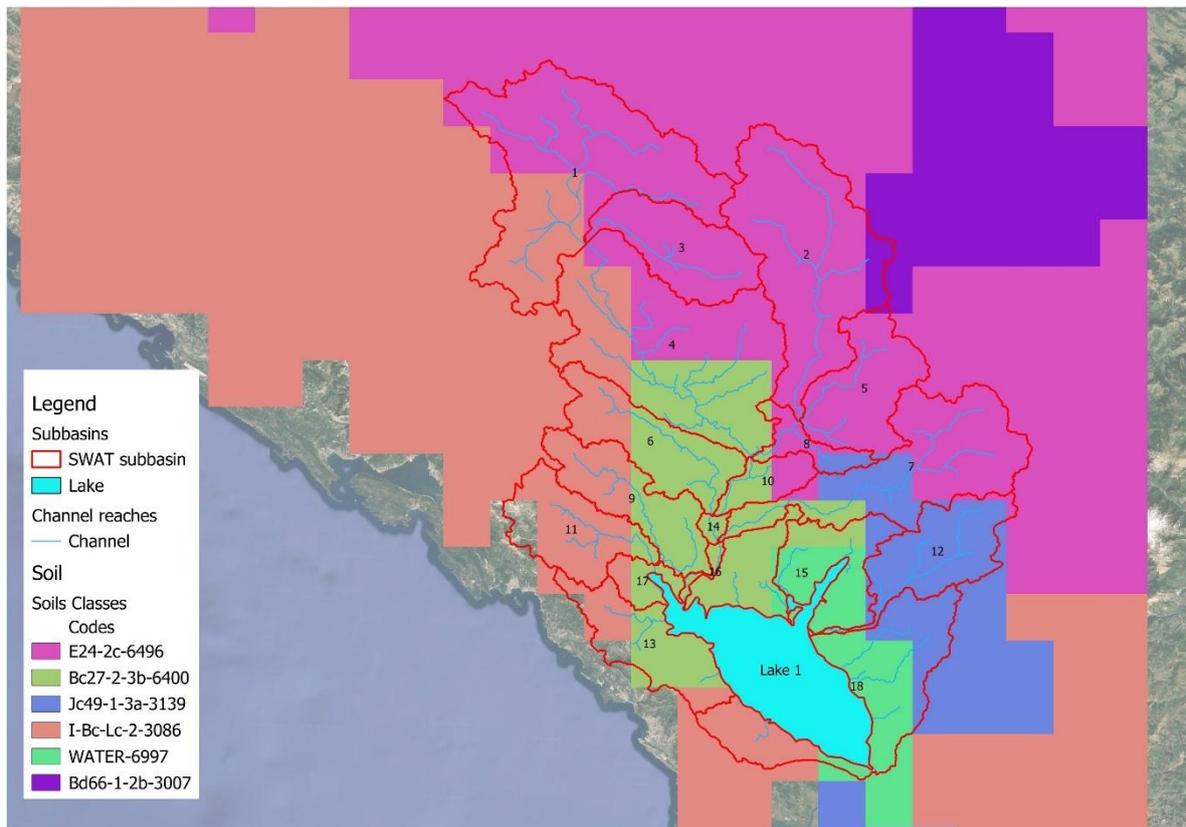
Figure 6. Soil Data

3.2.4. Snow

Snow melting is included by default within the SWAT calculations. This is based on the elevation provided to the model (and assigned to HRUs), and the climate input (temperature and precipitation), and SWAT will automatically simulate snowpack and melting using the temperature index (degree-day) method.

3.2.5. Groundwater

Considering the very limited data regarding groundwater (just information about the recharge rate within the basin), the same groundwater parameter values have been used for all the subcatchments and HRUs.

3.3. SWAT Parametrisation

3.3.1. HRU Definition

The delineation of Hydrologic Response Units (HRUs) was based on a combination of land use, soil, and slope data. Land use and soil maps were obtained from the official SWAT database, ensuring consistency with the model's internal classification schemes. Slope was derived from the digital elevation model (DEM) and classified into four slope bands: [0–5%], [5–15%], and [>15%].

To reduce fragmentation and maintain computational efficiency, HRUs were filtered using thresholds of 20% for land use, 20% for soil type, and 15% for slope. This filtering approach resulted in a total of 713 HRUs distributed across the delineated subbasins. These HRUs represent unique combinations of land cover, soil, and topography and form the fundamental units for simulating runoff generation, infiltration, evapotranspiration, and other hydrologic processes.

3.3.2. Potential Evapotranspiration (PET)

Given the absence of field-measured meteorological variables such as solar radiation and wind speed, the Hargreaves method was selected to estimate potential evapotranspiration (PET). This method, which relies on temperature extremes and extraterrestrial radiation, is suitable for data-sparse environments and performs reasonably well under such conditions. The PET calculation method was set in the basin configuration within SWAT Editor, under the basin codes section.

No external PET time series was included, as the weather data were generated internally using the weather generator. The Hargreaves method was applied uniformly across the watershed.

3.3.3. Snow Processes

Snowmelt processes were included in the simulation by enabling snow dynamics in the SWAT configuration. Elevation bands were assigned to subbasins using the FabDEM, which provided sufficient resolution to capture altitudinal differences that influence snowfall and melt rates. The snow simulation used default temperature thresholds for snowfall and melt, with adjustments made during the calibration process if required.

3.3.4. Climate Forcing

Climate forcing for the model was generated using the built-in weather generator in SWAT Editor, sourcing data from the SWAT2012 global database. The generator produced daily time series of precipitation, minimum and maximum temperature, solar radiation, wind speed, and relative humidity. These synthetic time series were used due to the absence of station data in the study area.

The weather generator ensures internal consistency among variables and reflects general climatic trends derived from regional climate zones in the SWAT global database. However, real station data would be preferred for calibration purposes, and the consultant is waiting for this information to improve the model confidence.

3.3.5. Topography and Channel Definition

Topographic data were derived from the FabDEM digital elevation model, which offers a high-resolution and globally consistent elevation dataset. The DEM was used for watershed and subbasin delineation, stream network extraction, and slope calculation.

Stream channels were automatically defined from the DEM using the terrain processing tools in SWAT+ Editor. This process included calculating flow direction and accumulation, defining outlet points, and assigning stream reaches to each subbasin. Channel geometry (e.g., length, slope, and width) was computed from the DEM and standard empirical equations embedded within the model.

3.3.6. Groundwater and Aquifer Configuration

Groundwater processes were represented using the SWAT aquifer module. No deep aquifer flow or lateral flow between aquifers was explicitly simulated, and no groundwater pumping or abstraction was included due to lack of data.

3.4. SWAT Calibration and Sensitivity Testing

3.4.1. Initial Results and Calibration

The model, as noted, was calibrated from 1970 to 1999, during the period when discharge data are available in most stations within the basin, and considering the data availability and reliability, nine stations within the pre-defined watershed. The calibration points and the initial results are showed by the modelling framework can be analysed in Table 6 and Figure 7, where the main watercourses are shown.

Table 6. Stations used in Calibration

River	Period Start	Period end	Latitude	Longitude	SWAT Channel
SUSICA	1948	2004	42.848	18.922	11
MRTVICA	1948	2005	42.719	19.37	15
ZETA – DANILOVGRAD	1948	2001	42.554	19.106	37

MORACA - PODGORICA	1948	2005	42.453	19.262	66
MORACA – ZLATICA	1983	2005	42.484	19.307	73
RIJ. CRNOJEVICA	1987	2002	42.356	19.021	119
CIJEVNA	1949	1986	42.395	19.383	120
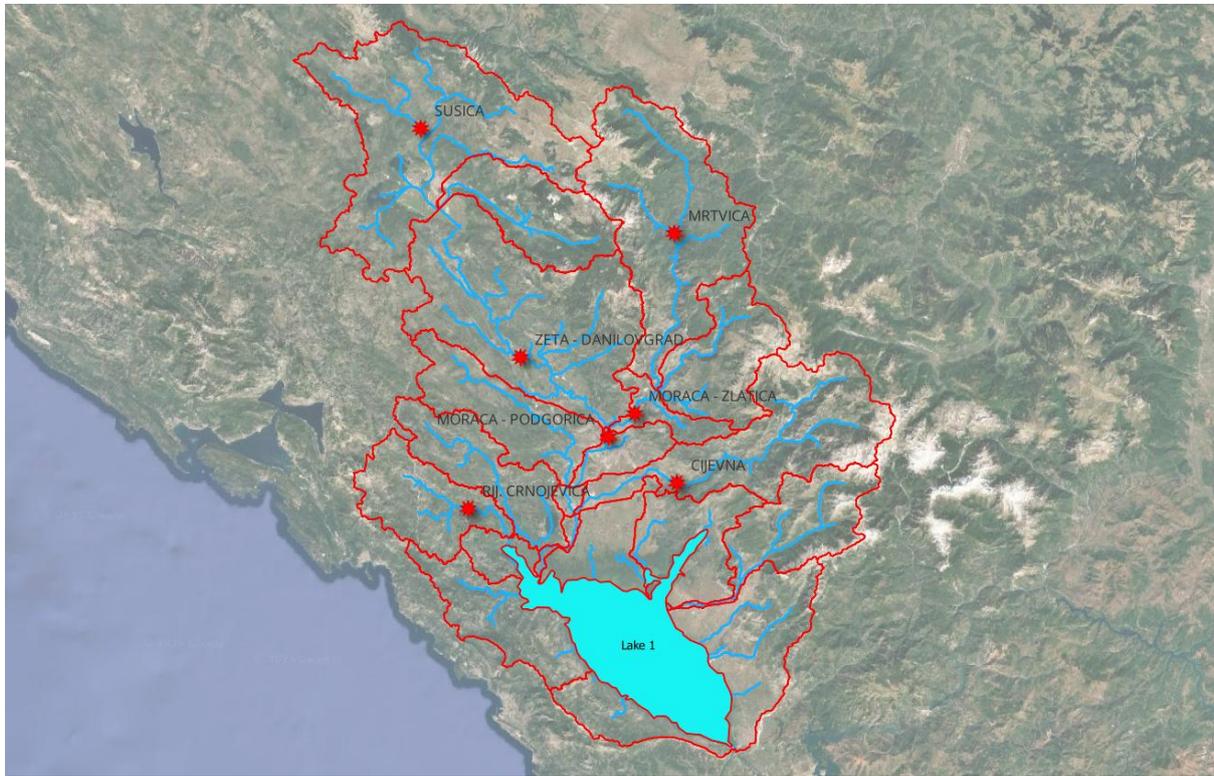
Figure 7. Calibration Points

The results for this period in the nine calibration points are shown in figures below. These values are a result of the calibration attempted in these locations, and considering the data available. During the calibration process, the following parameters have been adjusted (Table 7):

Table 7. Calibration Parameters

Code	Parameters	Change Type	Best Fit
cn2	Initial SCS runoff curve number for moisture condition II	Percent	-5.09204
esco	Soil Evaporation Compensation Factor	Replace	0.204152
epco	Plant Uptake Compensation Factor	Percent	0.989025
canmx	Maximum Canopy Storage	Replace	70.36473
perco	Percolation Coefficient	Replace	0.968067

lat_ttime	Lateral Flow Travel Time	Percent	3.170355
cn3_swf	Soil Water Factor for CN3	Replace	0.94948
alpha	Groundwater alpha factor (baseflow recession constant)	Replace	0.511838
flo_min	Minimum Aquifer Storage to Allow Return Flow	Percent	11.96441
revap_co	Groundwater Revap Coefficient	Replace	0.033992
revap_min	Minimum Water Table Depth for Revap	Replace	20.40513
bf_max	Maximum Baseflow Alpha Factor	Replace	0.817745

Figure 8. Calibration results
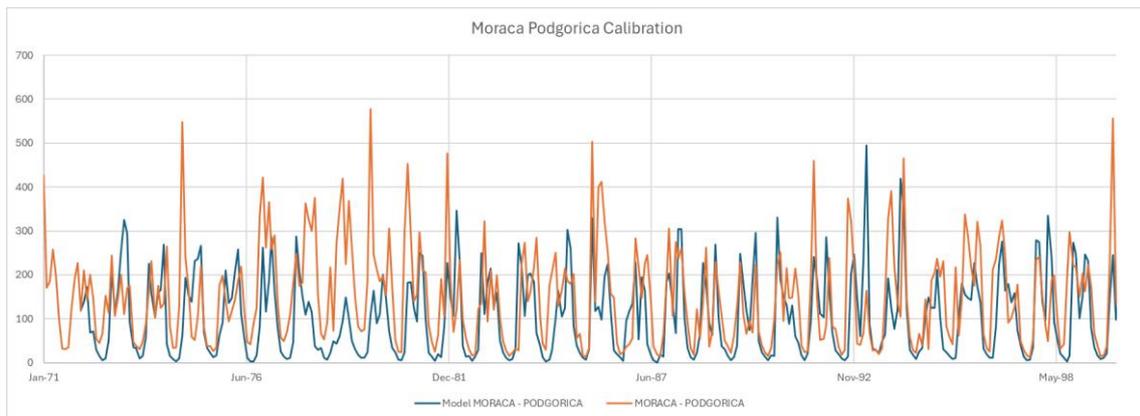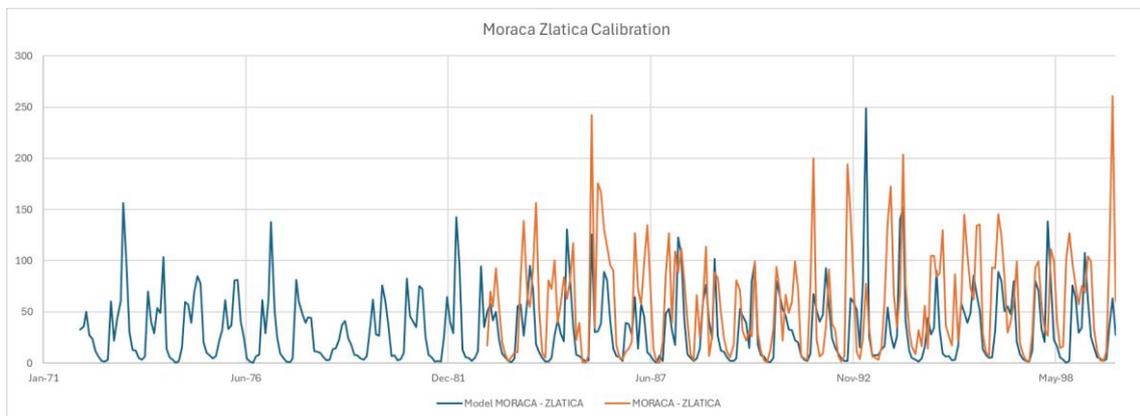

Figure 9. Calibration results
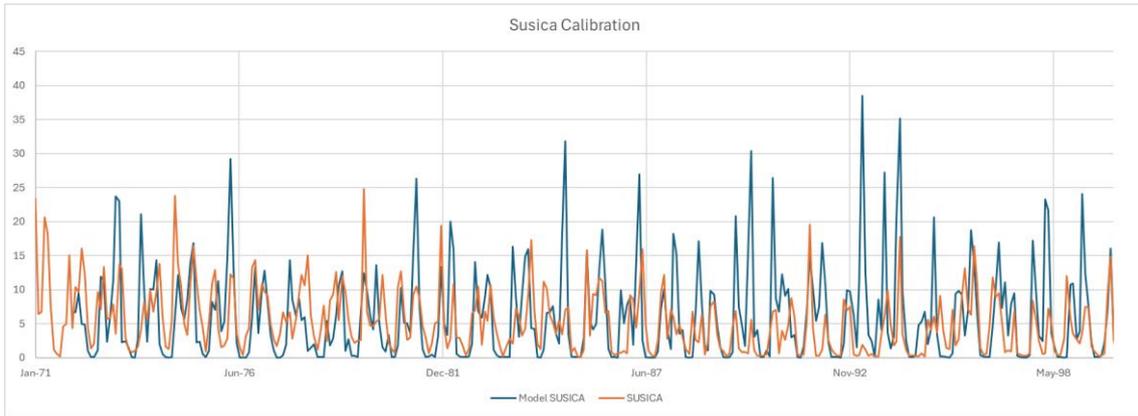
Figure 10. Calibration results
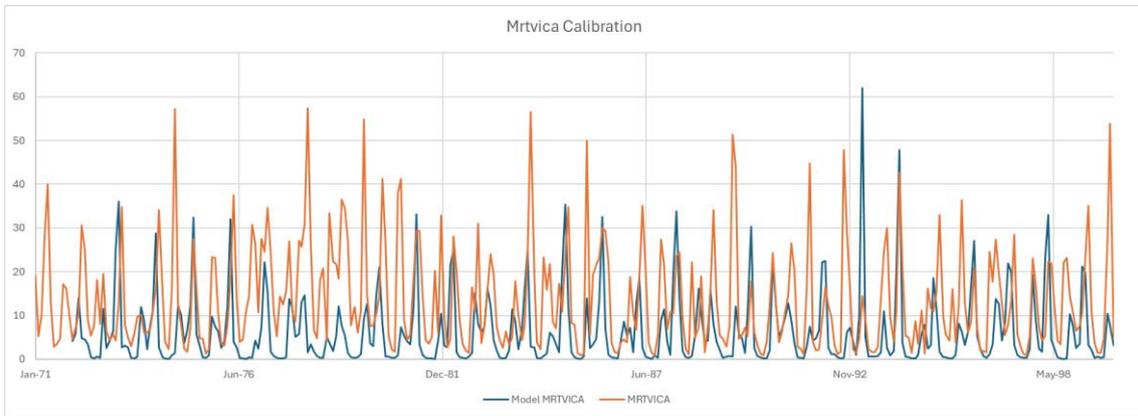
Figure 11. Calibration results
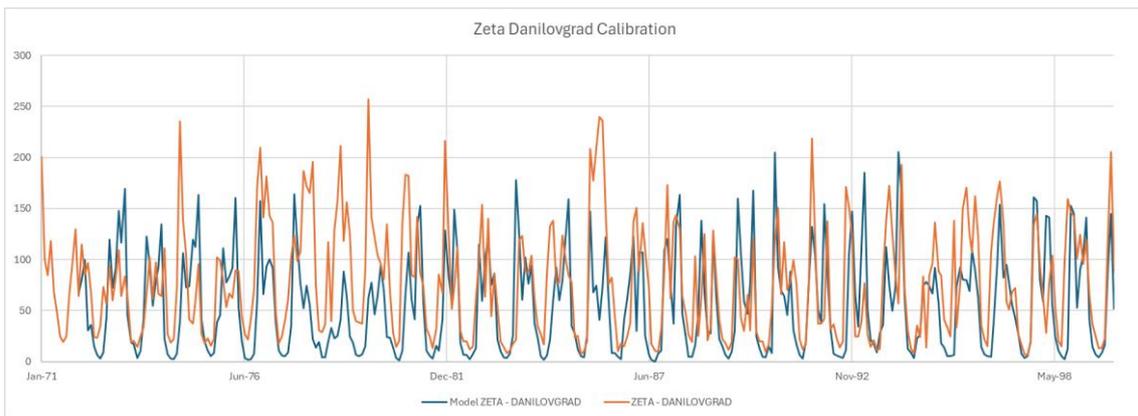
Figure 12. Calibration results
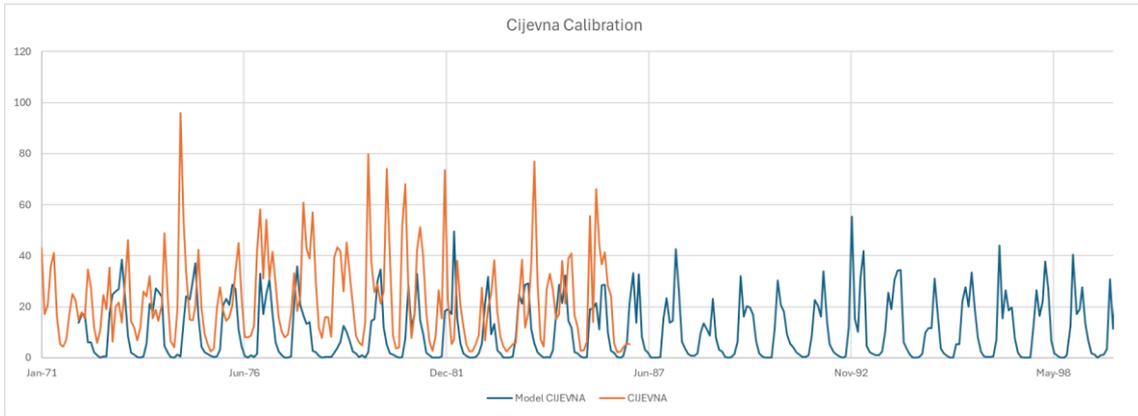
Figure 13. Calibration results
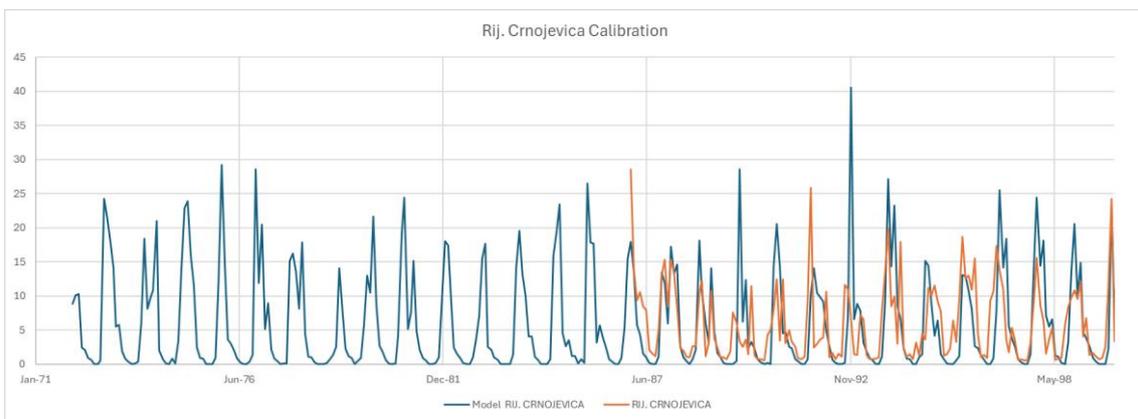
Figure 14. Calibration results

3.4.2.   Validation

The validation results are presented in the figures below. As it can be seen, there is a good agreement between the observational data and the simulated one.
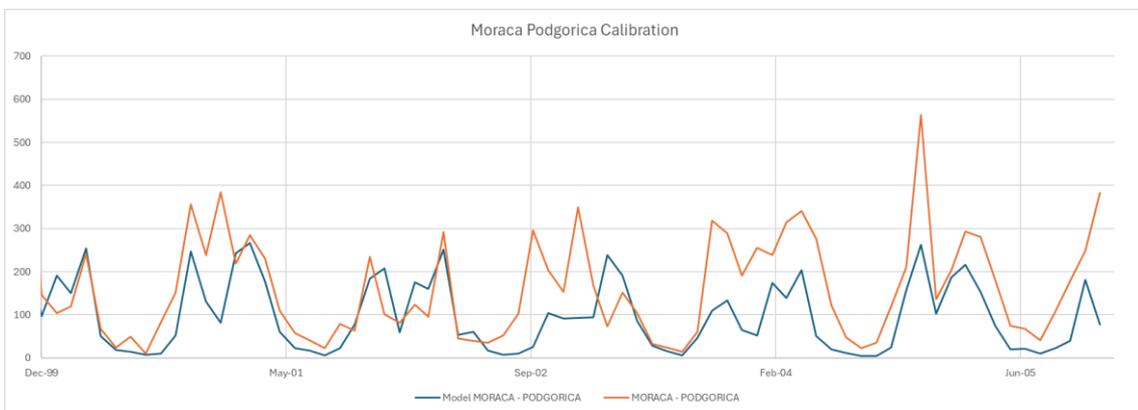
Figure 15. Validation results

Moraca Zlatica Calibration

— Model MORACA - ZLATICA — MORACA - ZLATICA
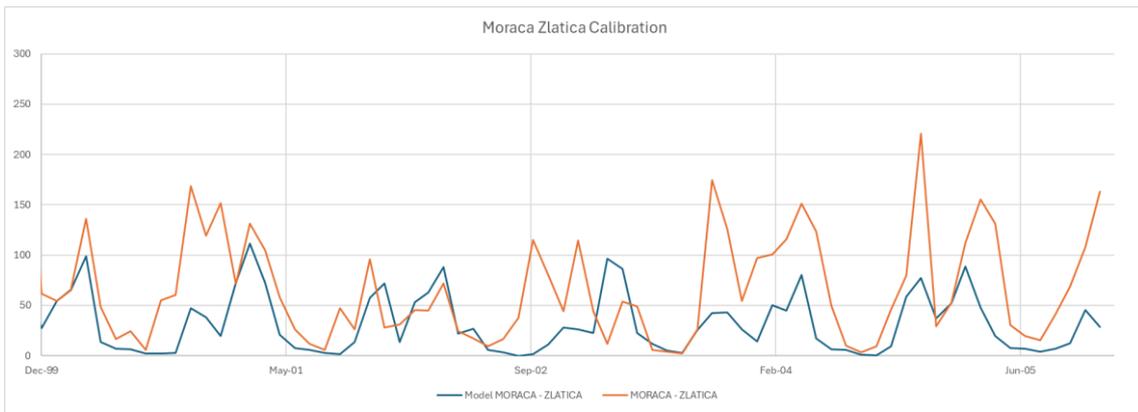
Figure 16. Validation results

Mrtvica Calibration

— Model MRTVICA — MRTVICA
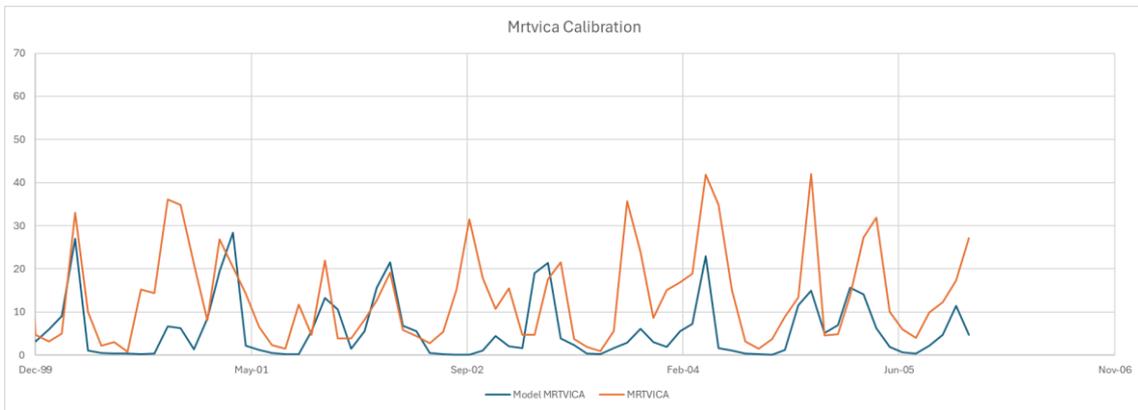
Figure 17. Validation results

Zeta Danilovgrad Calibration

— Model ZETA - DANILOVGRAD — ZETA - DANILOVGRAD
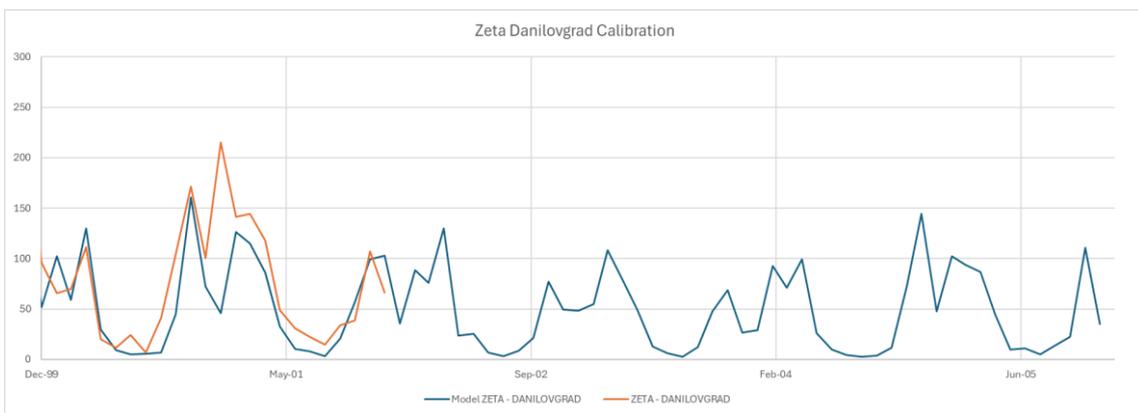
Figure 18. Validation results

4. Assessment

4.1. Initial Assessment

The calibrated SWAT+ model outputs was used to analyse the key hydrological processes across all subcatchments, focusing on spatial and temporal variability. This assessment provides initial information about the water balance in the catchment, and it has been undertaken for three periods:

- Calibration and validation period: 1970-2005
- Baseline period: 2005-2020
- Climate change period: 2020-2050

4.1.1. Water Balance Components

The general water balance parameters were analysed, both from an average perspective (Table 8), for the three main periods outlined above.

Table 8. Average Water resources Water Balance

Water Balance	Unit	Calibration (1971-2005)	Baseline (2006-2020)	Climate Change (2021-2049)
Precipitation	mm	1830	1810	1900.00
Snowfall	mm	481	476	404.00
Snowmelt	mm	470	471	403.00
Surface Runoff Generated	mm	898	876	965.00
Lateral Flow	mm	40	38.9	53.40
Water Yield	mm	938	915	1020.00
Percolation	mm	177	170	227.00
Evapotranspiration	mm	723	725	658.00
Evaporation from canopy	mm	4.42	4.01	8.88
Plant uptake/transpiration	mm	2.71	2.88	2.62
Soil evaporation	mm	716	718	647.00
Surface Runoff Contribution	mm	898	876	965.00
Initial Soil Water Content	mm	322	318	326.00
Final Soil Water Content	mm	319	320	325.00
Average Soil Water Content	mm	251	243	295.00
Soil Water Content at 300 mm depth	mm	73.5	71.4	91.10
Initial Snow Water Equivalent	mm	0	0	51.90
Final Snow Water Equivalent	mm	0	48.7	0.00
Snow Water Equivalent	mm	23.1	21.3	5.74
Potential Evapotranspiration	mm	876	934	719.00
Surface Runoff to Channel	mm	835	818	896.00

Surface Runoff to Reservoir	mm	63.6	58.7	69.30
Lateral Flow to Channel	mm	39.1	38.1	52.20
Lateral Flow to Reservoir	mm	0.934	0.795	1.15
Wetland/Pond/Reservoir Evaporation	mm	6.69	7.14	2.91
Wetland/Pond/Reservoir Overflow	mm	32.8	32.1	35.00
Wetland/Pond/Reservoir Storage	mm	0.663	0.648	0.79

the following main observations and trends can be identified:

- Precipitation: the mean precipitation shows a slight increasing trend from the Calibration (1830.57 mm) to the Baseline (1811.33 mm) and then a bit more prominently into the Climate Change period (1860.32 mm). However, the standard deviation for precipitation significantly increases in the Climate Change period (310.90 mm) compared to Calibration (159.00 mm) and Baseline (203.50 mm), what suggests greater variability in annual precipitation, indicating more extreme wet or dry years in the future climate.

- Surface Water Runoff: similar to precipitation, the mean surface water runoff also shows an increasing trend across the periods, from Calibration (896.71 mm) to Baseline (874.93 mm) and then notably higher in Climate Change (946.09 mm). The standard deviation for surface runoff is highest in the Baseline period and slightly decreases in the Climate Change period compared to the Baseline, but is still higher than Calibration.

- Lateral Flows: there is a noticeable increase in mean lateral flows in the Climate Change period (52.29 mm) compared to both Calibration (39.90 mm) and Baseline (38.93 mm), which were quite similar. The standard deviation for lateral flows also shows a substantial increase in the Climate Change period (7.96 mm), indicating greater variability.

- Evapotranspiration: The mean evapotranspiration significantly decreases in the Climate Change period (645.11 mm) compared to the Calibration (728.40 mm) and Baseline (730.40 mm) periods, which had similar values. The standard deviation for evapotranspiration dramatically increases in the Climate Change period (107.82 mm), indicating much higher variability in water loss through evapotranspiration under future climate conditions.

- Water Storage (soil water): the mean change in soil water storage shifts from slightly positive in Calibration (0.35 mm) and Baseline (1.66 mm) to slightly negative in Climate Change (−0.10 mm). While the absolute values are small, a negative mean suggests a slight overall decrease in soil water storage in the Climate Change period, potentially indicating drier conditions or more efficient runoff. The standard deviation for water storage change drastically decreases in the Climate Change period (7.89 mm) compared to Calibration (20.38 mm) and Baseline (30.01 mm). This implies less variability in annual soil water change in the future, which could be a consequence of the reduced evapotranspiration variability and/or more consistent water balance dynamics.

Overall, the most significant findings are:

1. Increased Variability in Precipitation and Evapotranspiration in Climate Change: While mean precipitation slightly increases, its variability is much higher. Conversely, mean

evapotranspiration decreases, but its variability increases significantly. This suggests potentially more erratic rainfall patterns and less consistent water loss from the basin.

2. Slightly Negative Soil Water Storage Change in Climate Change: This suggests a trend towards drier conditions in the basin's soil profile annually.

4.1.2. Flow Regimes and Discharge

The annual discharge has been analysed in key locations across the catchment (Figure 19), in order to identified trends in the three analysed periods (

Table 9), and especially to ascertain the discharge patterns in the current and climate change conditions.
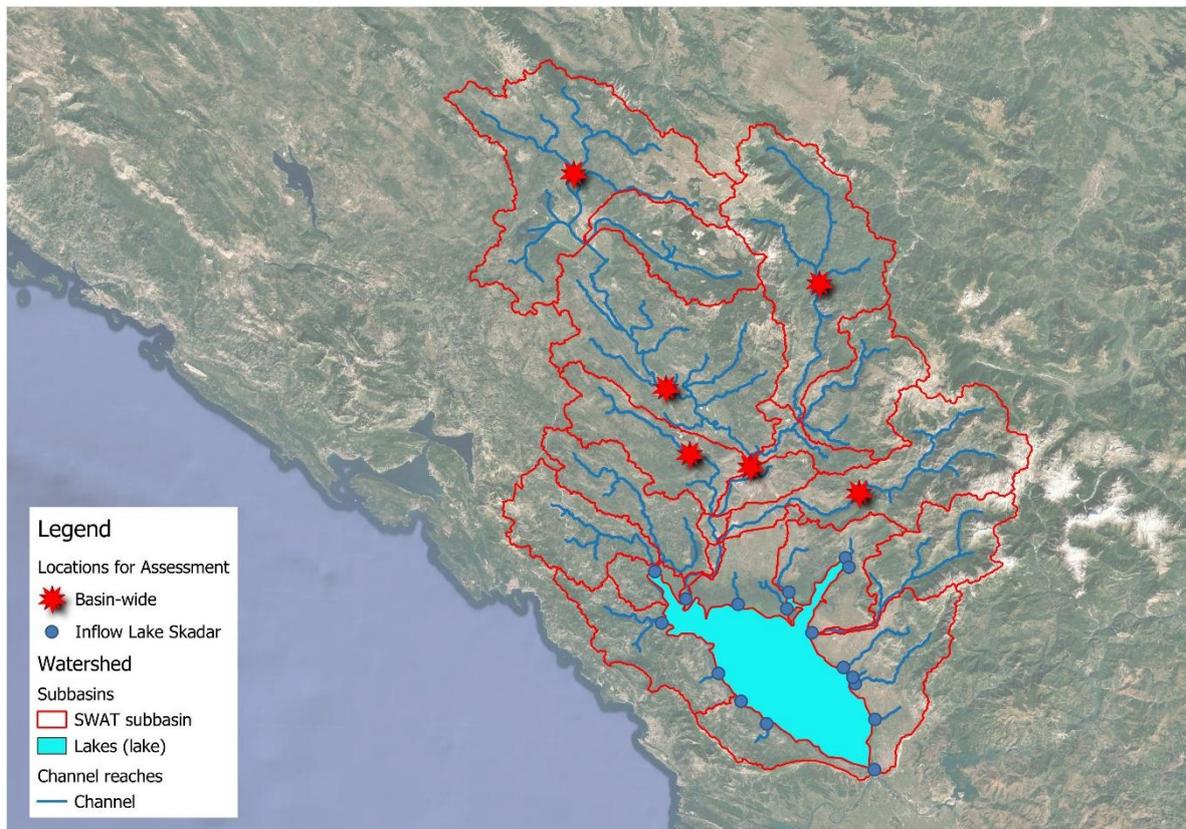
Figure 19. Flow analysis locations

Table 9. Discharge trends

Channel	River	Calibration					Baseline					Climate Change				
		Mean (Flow)	Median (Flow)	Std Dev (Flow)	Min (Flow)	Max (Flow)	Mean (Flow)	Median (Flow)	Std Dev (Flow)	Min (Flow)	Max (Flow)	Mean (Flow)	Median (Flow)	Std Dev (Flow)	Min (Flow)	Max (Flow)
6	Susica	8.16	3.61	11.5	0	79.65	15.18	10.24	16.91	0.05	87.97	8.12	3.78	11.56	0	77.29
37	Zeta	48.82	42.87	38.24	0.39	172.7	55.45	44.5	47.33	0.46	177.5	48.69	40.49	38.57	0.36	174.4
43	Moraca - Pernica	7.28	3.12	10.25	0.01	90.6	13.44	8.58	14.84	0.23	64.32	7.32	2.9	10.38	0.02	91.75
66	Moraca - Podgorica	103.28	92.87	81.44	0.69	441.1	105.57	91.96	90.6	0.77	358	103.19	91.63	82.06	0.68	453.3
120	Civejna	10.78	8.04	10.97	0	54.26	10.83	5.43	11.54	0	52.86	10.78	7.86	11.09	0	53.33
159	Skadar Outflow	170.92	187.3	148.18	0	662.9	167.44	96.91	149.55	0	569.5	170.64	187.4	147.81	0	663.8

In the Susica, Zeta and upper Moraca rivers, the flows during the baseline period (2005-2020) are generally higher than in the 'Calibration' and 'Climate Change' periods, while in those two periods the flows are similar. This suggests a notable reduction in river flow from the 'Baseline' period (2005-2020) to the subsequent 'Climate Change' period (2020-onward), while the earliest 'Calibration' period (1970-2005) also exhibited lower flows, perhaps reflecting different hydrological conditions or data characteristics in that initial period.

However, in the Moraca lower (at Podgorica) and in the River Cijena, the mean and median flows across all three periods ('Calibration', 'Baseline', and 'Climate Change') are relatively consistent, with no major shifts. The standard deviations are also quite similar, indicating consistent variability across the periods. This implies that these areas are less sensitive to the changes observed in other areas, which are further upstream, with a lesser contributing area, and therefore the Civejna and the Moraca at Podgorica reflect a flow dynamics more stable across these periods.

In summary, While in the Susica, Zeta and Moraca there is a general decrease in flow predicted in the 'Climate Change' period, the predicted flows further downstream demonstrate relative stability.
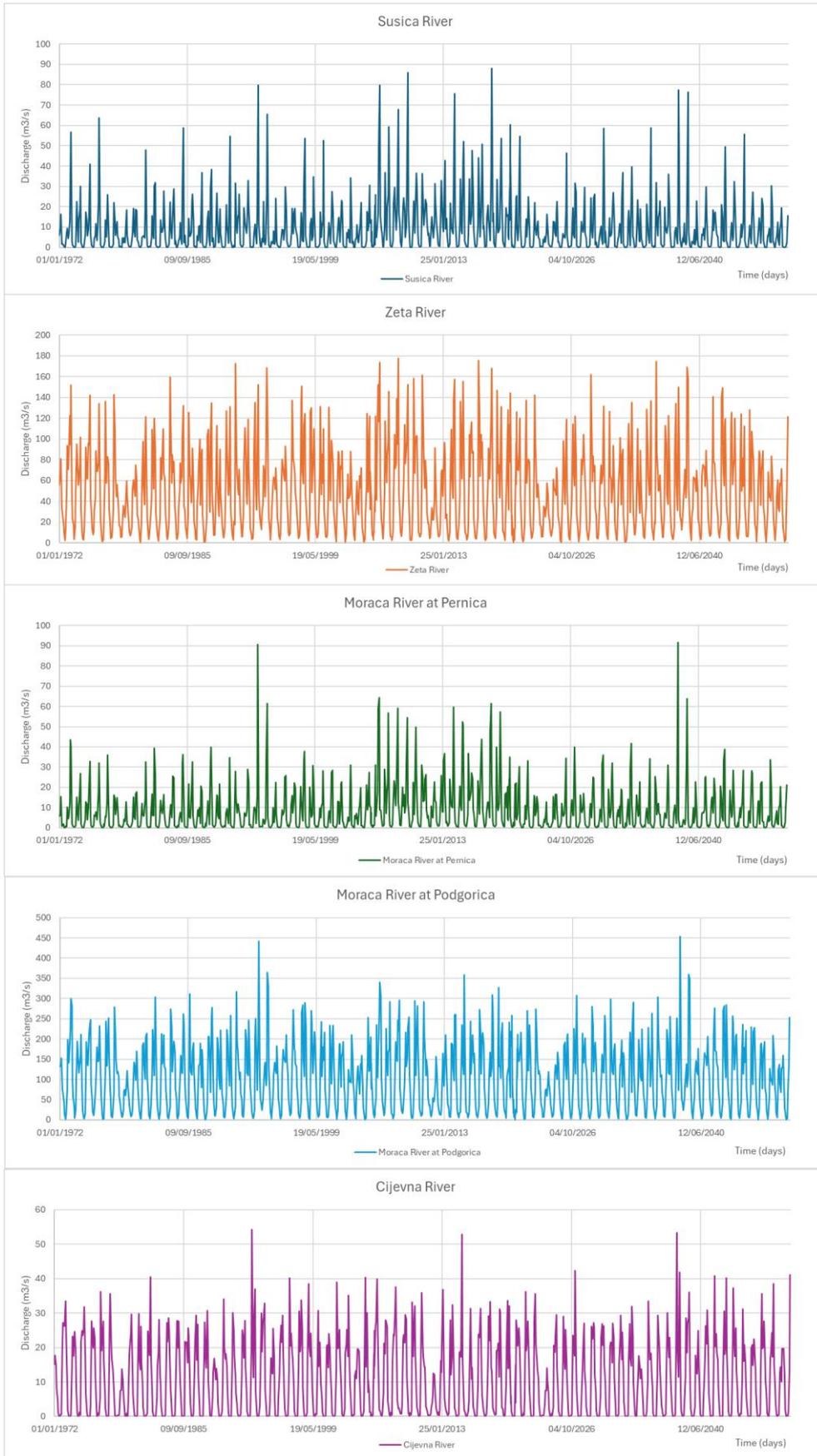
Figure 20. Flow at the analysis locations

4.1.3.   Lake input

In addition to the flow at those key locations discussed in the last section, all the inflows into the Lake Skadar were also analysed. In most channels (namely 118, 123, 131, 136, 139, 143, 149, 156, 158, 172, 177, 181) the mean and median river flows are highest in the 'Baseline' period (2005-2020) and generally lower in both the 'Calibration' (1970-2005) and 'Climate Change' (2020-onward) periods. This suggests a decline in river flow from the baseline period into the climate change period. The standard deviations also tend to be highest in the baseline period, indicating greater variability in flow during that time. Some other channels, including the Moraca River (Channel 114) and channels 155, 173, 180 show a more stable, pattern. However, in the Moraca input into the Lake Skadar it can be observed that the median flow is slightly higher in the 'Climate Change' period, indicating that while the overall average remains consistent, the *typical* flow might be trending slightly higher.

In summary, the data for Skadar Lake input channels largely mirrors the pattern observed in the first set of channels, with many showing a decrease in river flow from the 2005-2020 baseline period into the 2020-onward climate change period. However, some channels (114, 155, 173, 180) appear more resilient or have different hydrological responses, exhibiting more consistent flow patterns across the analysed periods.
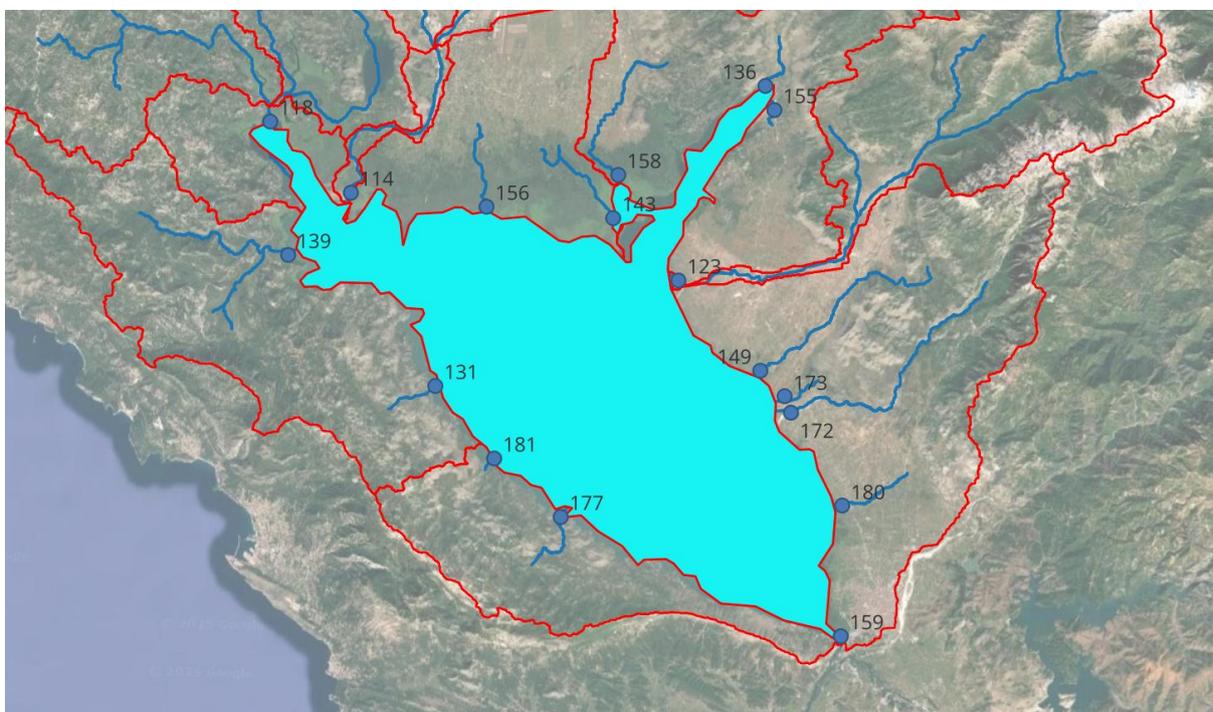

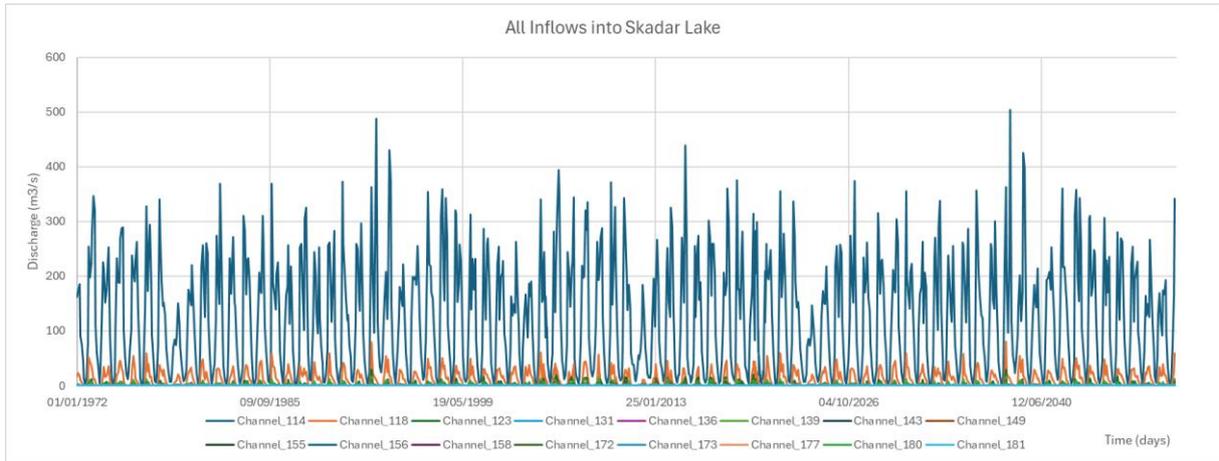*Figure 21.Inflows into Lake Skadar*

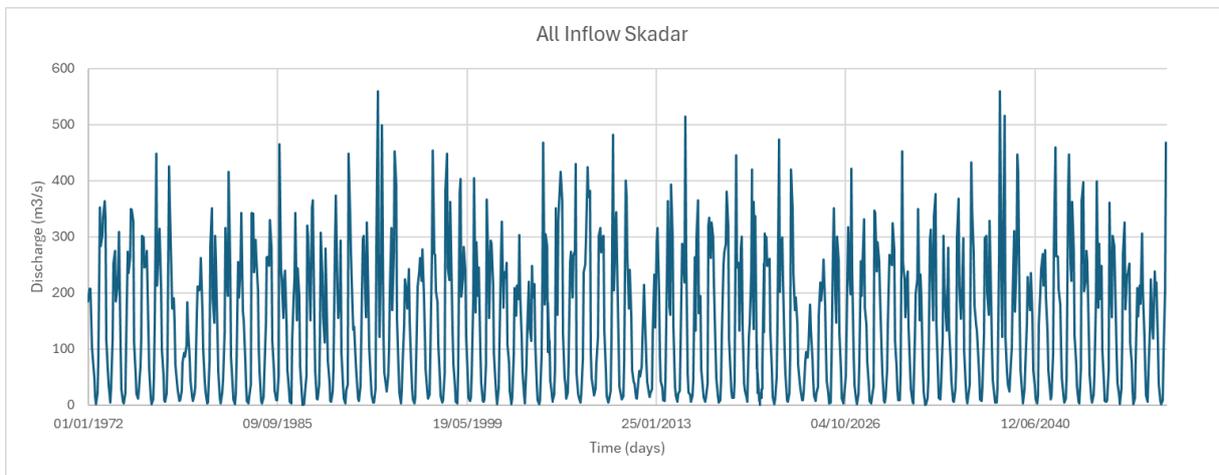*Figure 22. Discharge values at inflow locations*

Figure 23. All inflows into Skadar combined

Regarding the outflow from the lake, while this is regulated the flow resulting from the modelling (Figure 24) framework is calculated based on the hydrological characteristics of the basin.
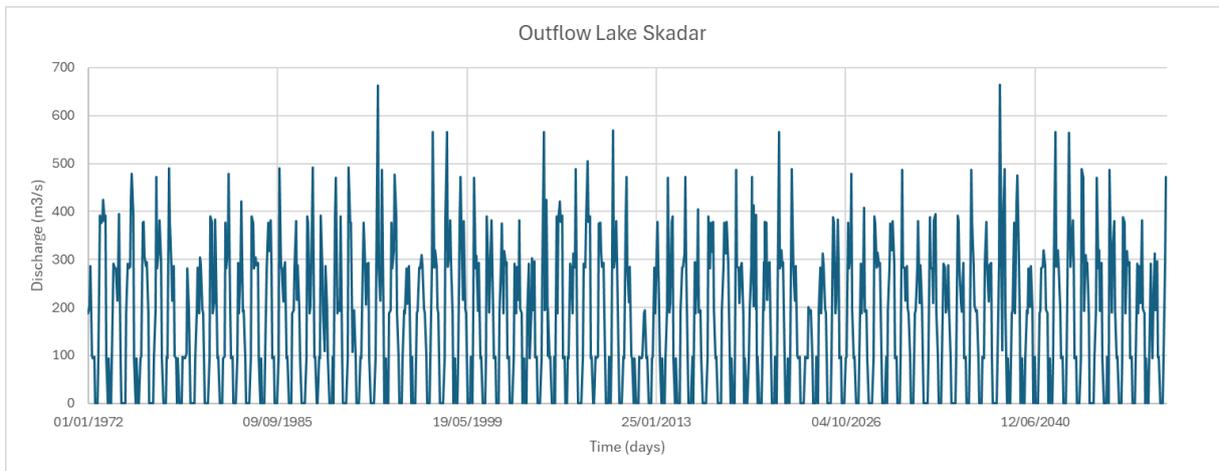

Figure 24. Outflow of Lake Skadar

As it can be seen in Figure 25, there is a difference between the inflow and the outflow in the Skadar Lake. While sometimes there is a positive difference (the inflow is higher than the outflow), in most cases and in total, the outflow is higher than the inflow.
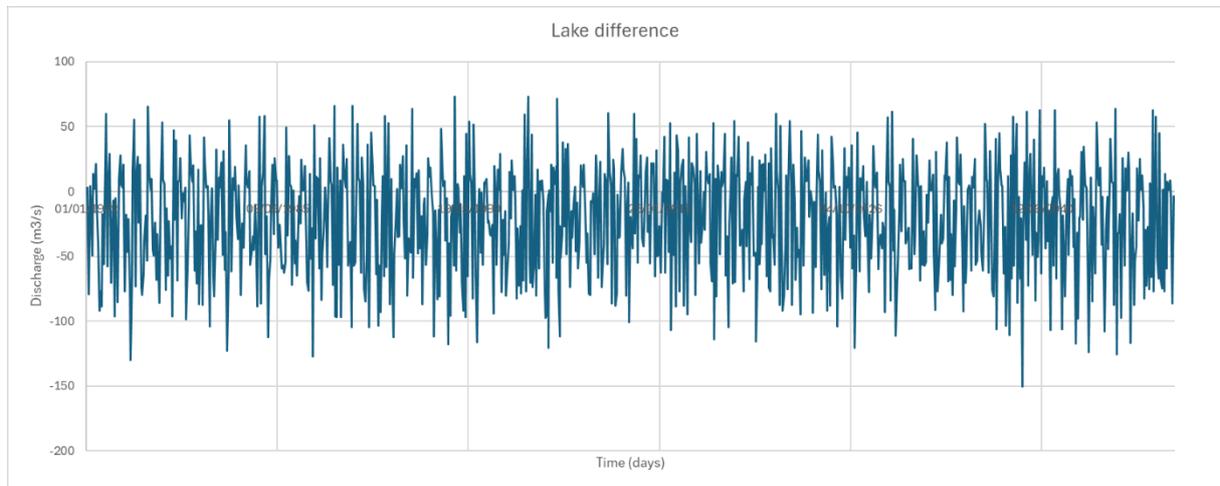
Figure 25. Difference between outflow and inflow

This difference was analysed in more detail, also considered other lake variables, and focusing on the periods of Calibration (1971-2005), Baseline (2006-2020), and Climate Change (2021-2048) as in previous analyses. The full assessment of the lake dynamics examines the relationship between inflow, outflow, evaporation, and lake storage.

1. Net Surface Water Balance (Inflow - Outflow): The simulation results indicate a consistent net surface water deficit for Skadar Lake across all analysed periods, meaning as previously noted that the total annual outflow from the lake via surface channels generally exceeds the total annual surface inflow.

- Calibration Period (1971-2005): The mean annual net deficit was approximately $-8.86\text{x}10^7\text{m}^3$.

- Baseline Period (2006-2020): The mean annual net deficit slightly reduced to approximately $-5.87\text{x}10^7\text{m}^3$.

- Climate Change Period (2021-2048): The mean annual net deficit significantly increased to approximately $-1.52\text{x}10^8 \text{ m}^3$.

Based on this trend, mean annual deficit (outflow exceeding inflow) becomes more pronounced in the simulated future climate conditions, suggesting a growing imbalance where surface water discharge increasingly surpasses surface water inputs. Over the entire simulated period (from 1971 to 2048), the cumulative net surface water deficit amounts to a substantial $-8.24\text{x}10^9\text{m3}$ (the equivalent of approximately 3.3 million Olympic swimming pools).

2. Lake Evaporation Trends: contrary to expected trends, that increasing temperatures might lead to a corresponding increase in lake evaporation, the SWAT model results for Skadar Lake's annual evaporation show a different trend:

- Calibration Period: Mean annual evaporation was approximately 7.63×10^7 m³.

- Baseline Period: Mean annual evaporation was similar, at approximately $7.65t \times 10^7$ m³.

- Climate Change Period: Mean annual evaporation actually shows a slight *decrease* to approximately $7.28t \times 10^7$ m³.

This indicates that while climate change projections often include rising temperatures, other factors influencing evaporation in the model (e.g., changes in wind speed, humidity, or even simulated lake surface area/temperature feedback) might be leading to this observed reduction in lake evaporation. Crucially, this reduction suggests that increased evaporative losses are not contributing to the observed growing net surface water deficit.

3. Lake Storage Dynamics: The change in lake storage (volume) reflects the overall balance of all inputs and outputs. The annual changes in lake storage are as follows:

- Calibration Period: The mean annual change in storage was slightly positive, approximately 2.94×105 m3, resulting in a total storage increase of 1.00×10^7 m³ over the period. This implies that during this period, unquantified inputs like direct precipitation on the lake surface or groundwater inflow were sufficient to offset the observed net surface outflow and evaporation, leading to a slight accumulation of water.

- Baseline Period: The mean annual change in storage became negative, approximately -1.27×10^7 m³, leading to a total storage decrease of -1.90×10^8 m³. This indicates a net decline in lake levels/volume during this period.

- Climate Change Period: The mean annual change in storage continued to be negative, approximately -1.07×10^6 m³, resulting in a total storage decrease of -3.00×10^7 m³. This further reinforces the trend of declining lake levels under future climate scenarios.

Overall, the total change in reservoir storage from the first year (1971) to the last year (2048) of the dataset is a deficit of $-2.10 \text{times} 10^8$ m³, indicating an overall reduction in the lake's water volume over the entire simulation period.

It is critical to contextualise these findings within the known limitations of the modelling framework and available data:

- Groundwater Representation: While groundwater interaction is included in the SWAT modelling framework, there is a significant lack of actual field data for groundwater flows in the region. Consequently, the reliability of groundwater components within the model, and their influence on the overall water balance, is subject to high uncertainty.

- Calibration Extent: The model was primarily calibrated in specific locations, and only for the period up to 2005. For the subsequent Baseline (2006-2020) no direct observational data were available for calibration or validation. This means that the results for this later period are predictive and rely heavily on the model's extrapolated performance and the accuracy of the climate forcing data.

- Proximity of Monitoring Stations: Monitoring stations used for input data were not located immediately adjacent to Skadar Lake. The closest stations were in Podgorica, Cijevna, and Crnojevica. This geographical distance introduces a degree of uncertainty regarding how well these data represent the immediate hydrological conditions of the lake's basin.

- Absence of Outflow Data: Crucially, there were no direct measurement stations for the lake's outflow. All outflow data in the simulation are entirely model-derived, which further emphasises the predictive nature of the outflow component and the overall water balance.

4.2.   Identification of Watershed Instabilities

In order to identify some instabilities in different subcatchments, such as erosion, degradation, or flash floods, the following will be evaluated.

4.2.1.   Identification of Issues in Landscape Units

In order to identify issues at a local scale within the Skadar lake basin, the Landscape Units of SWAT have been used. A Landscape Unit (LSU) in SWAT is a fundamental modelling unit used to represent areas within a subbasin that share similar hydrological and environmental characteristics. Unlike Hydrologic Response Units (HRUs) which are defined by unique combinations of land use, soil type, and slope within a subbasin, LSUs are typically larger, more aggregated spatial units, often representing specific landscape elements or hydrological features.

Their purpose is to simplify the representation of complex landscapes while still capturing the spatial variability in hydrological processes.

The analysis of the LSU water balance data was undertaken for the three periods previously outlined, calibration period, baseline period and climate change period. While the definition of these periods is arbitrary, this facilitates the understanding of the conditions at three snapshots, one in the recent past, one current and finally the climate change projections. The main objective of this analysis is to identify specific areas that may be more vulnerable to changes in water resources; the aim is to present a holistic view of how water yield, evapotranspiration, and soil water storage have evolved and are projected to change at a LSU scale. The justification for these three key indicators of "instability" or "lack of resilience" from a water resources perspective is shown below:

- Decrease in Water Yield: A reduction in water yield means less water is flowing out of that LSU, which can lead to reduced streamflow, impacting downstream water availability for various uses and potentially affecting aquatic biodiversity.

- Increase in Evapotranspiration: Higher evapotranspiration indicates more water is being lost to the atmosphere, either through plant transpiration or direct evaporation. This can lead to drier soils and increased water stress for vegetation and ecosystems.

- Negative Change in Soil Water Storage: A more negative change (or a shift from positive to negative) suggests that the soils within that LSU are, on average, retaining less water over the year. This can lead to increased drought risk for terrestrial ecosystems and reduced baseflow contributions to streams.

In order to undertake this analysis, for each LSU and for each period, the mean annual values for "Water Yield", "Evapotranspiration", and "Change in Soil Water Storage" were calculated.

The selection of vulnerable LSU was considering the ones showing a more significant change in those variables, for instance decreases in water yield and soil water storage and increases in evapotranspiration across both the "Baseline to Climate Change" and "Calibration to Climate Change" comparison scenarios. The following tables showcase the mean values of the key water balance indicators for the identified vulnerable LSUs, allowing for direct comparison across the Calibration, Baseline, and Climate Change periods.

Thie Table 10 illustrates the average annual water yield for selected (with the higher decrease) LSUs across the three periods. A decreasing trend indicates reduced water availability over time.

Table 10. Changes in water yield

unit	Calibration	Baseline	Climate Change	Change WYLD (Climate Change - Calibration)	Change WYLD (Climate Change - Baseline)	% Change WYLD (Climate Change - Calibration)	% Change WYLD (Climate Change - Baseline)
175	9.26	9.26	-0.71	-9.97	-9.97	-107.67%	-107.67%
177	10.9	10.9	0.92	-9.98	-9.98	-91.56%	-91.56%
154	7.28	7.28	0.34	-6.94	-6.94	-95.33%	-95.33%
126	7.27	7.27	0.35	-6.92	-6.92	-95.19%	-95.19%
130	7.22	7.22	0.35	-6.87	-6.87	-95.15%	-95.15%
80	7.2	7.2	0.62	-6.58	-6.58	-91.39%	-91.39%
90	7.82	7.82	0.91	-6.91	-6.91	-88.36%	-88.36%
89	7.56	7.56	0.95	-6.61	-6.61	-87.43%	-87.43%
21	907.4	870.6	543.59	-363.81	-327.01	-40.09%	-37.56%
26	915.54	877.53	558.14	-357.4	-319.39	-39.04%	-36.40%

Most of the LSUs identified for water yield decrease (e.g., LSUs 21, 26, 14, 13, 33) show a consistent decreasing trend from Calibration to Baseline and a more pronounced drop into the Climate Change period. This indicates a worsening trend of water scarcity over time in these units.

The table below presents the average annual evapotranspiration for LSUs with the higher increase across the three periods. Increasing values suggest higher water loss to the atmosphere.

Table 11. Change in evapotranspiration

unit	Calibration	Baseline	Climate Change	Change ET (Climate Change - Calibration)	Change ET (Climate Change - Baseline)	% Change ET (Climate Change - Calibration)	% Change ET (Climate Change - Baseline)
66	320.11	320.87	525.52	205.41	204.65	64.17%	63.78%
107	765.31	764.27	874.95	109.64	110.68	14.33%	14.48%
173	810.11	812.67	926.29	116.18	113.62	14.34%	13.98%
109	780.57	779.33	884.57	104	105.24	13.32%	13.50%
108	778.14	776.93	879.21	101.07	102.28	12.99%	13.16%
168	750.66	753.33	852.31	101.65	98.98	13.54%	13.14%
172	809.89	812.13	918.31	108.42	106.18	13.39%	13.07%
170	815.26	816.93	920.76	105.5	103.83	12.94%	12.71%
76	872.23	866.13	976.13	103.9	110	11.91%	12.70%
88	859.53	859.53	960.84	101.31	101.31	11.79%	11.79%

LSUs like 66, 173, 107, 172, 170, and 109 show a consistent increasing trend in evapotranspiration from Calibration through Baseline and into the Climate Change period. This signifies ongoing and projected intensification of water loss from these areas.

This table (Table 12) displays the average annual change in soil water storage. Negative values indicate a net decrease in water stored in the soil, which can lead to drier conditions.

Table 12. Change in soil water storage

unit	Calibration	Baseline	Climate Change	Change Delta SW (Climate Change - Calibration)	Change Delta SW (Climate Change - Baseline)	% Change Delta SW (Climate Change - Calibration)	% Change Delta SW (Climate Change - Baseline)
21	907.4	870.6	543.59	-363.81	-327.01	-40.09%	-37.56%
26	915.54	877.53	558.14	-357.4	-319.39	-39.04%	-36.40%
14	1395.63	1336.07	1183.14	-212.49	-152.93	-15.23%	-11.45%

13	1385.74	1327	1176.69	-209.05	-150.31	-15.09%	-11.33%
33	1386.71	1329.07	1179.34	-207.37	-149.73	-14.95%	-11.27%
169	1124.91	1121.53	1008.1	-116.81	-113.43	-10.38%	-10.11%
174	1124.8	1121.67	1009.55	-115.25	-112.12	-10.25%	-10.00%
15	1117.57	1076.8	982.69	-134.88	-94.11	-12.07%	-8.74%
31	1089.66	1040.73	979.41	-110.25	-61.32	-10.12%	-5.89%
34	1083.91	1035.27	976.14	-107.77	-59.13	-9.94%	-5.71%

Several LSUs (e.g., 107, 109, 108, 153, 149, 138) show a concerning shift from positive or slightly negative soil water change in the Calibration/Baseline periods to significantly negative values in the Climate Change period. This indicates a clear trend towards drier soils and increased drought risk over the long term.

The analysis of vulnerable LSUs across all three periods reveals consistent and often worsening trends in water balance indicators:

- Declining Water Availability: Several LSUs show a clear progression towards reduced water yield, with a sharp decline projected in the Climate Change period. This points to increasing pressure on water resources for both human and ecological needs.

- Increased Atmospheric Water Loss: LSUs with consistently rising evapotranspiration are experiencing and are projected to continue experiencing greater water loss to the atmosphere. This compounds the problem of reduced water availability.

- Drier Soils: A notable shift towards negative soil water storage changes indicates that soils in several LSUs are becoming drier, increasing the susceptibility to drought and impacting agricultural productivity and vegetation health.

By examining water balance trends across the three periods from 1970 to 2050, a clearer picture of long-term hydrological vulnerability emerges. LSUs such as 21, 26 (for water yield decrease), 66, 173, 107, 108, 109, 172, 170 (for ET increase), and those with consistent negative soil water changes such as 134, 145, 110, 115, 109, 108, 153, 149, 138, 107, 175) stand out as critical areas r. These units demonstrate a compounding of water-related challenges, including decreased water supply, increased atmospheric water loss, and reduced water retention in soils.

These LSUs have been mapped (Figure 26) for easy identification of the issues.
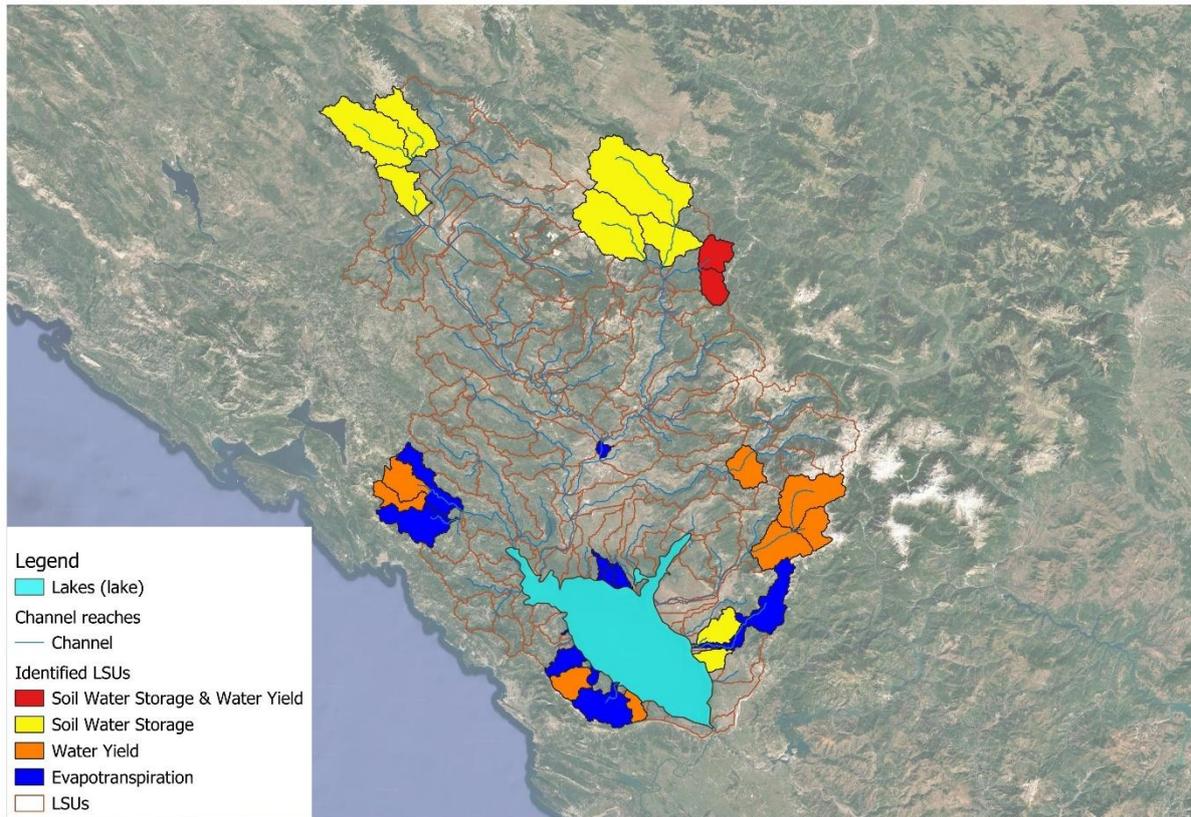
Figure 26. Identified LSUs

As it can be observed, soil water storage issues are predominant in the north of the catchment, while water yield and evapotranspiration issues are identified in the southern part of the catchment, mostly on the western and eastern edges of the basin. Special attention should be paid to two LSUs in the north of the basin with identified issues both regarding water yield and soil water storage.

In order to analyse other issues within the basin, the sediment yield, the land use sensitivity and the runoff coefficient were analysed.

4.2.2. Sediment Yield: Identify Erosion Hotspots

The sediment yield in the different LSUs was analysed, in order to pinpoint subcatchments with high soil loss due to water erosion. In order to undertake this, the sediment yield per LSU was analysed across the whole simulation period. The climate change and the historical period (1971-2020) showed similar trends, as it can be observed below (Figure 27 and Figure 28, for historical and climate change results respectively).
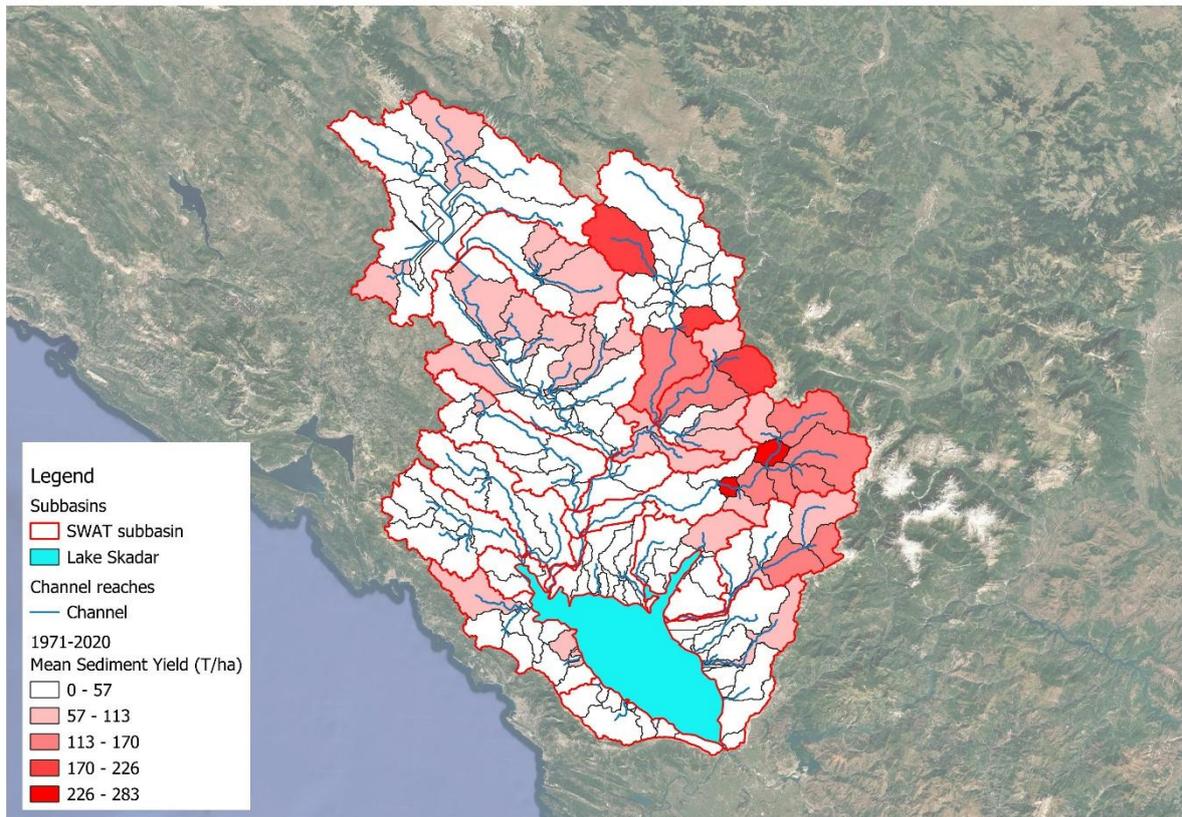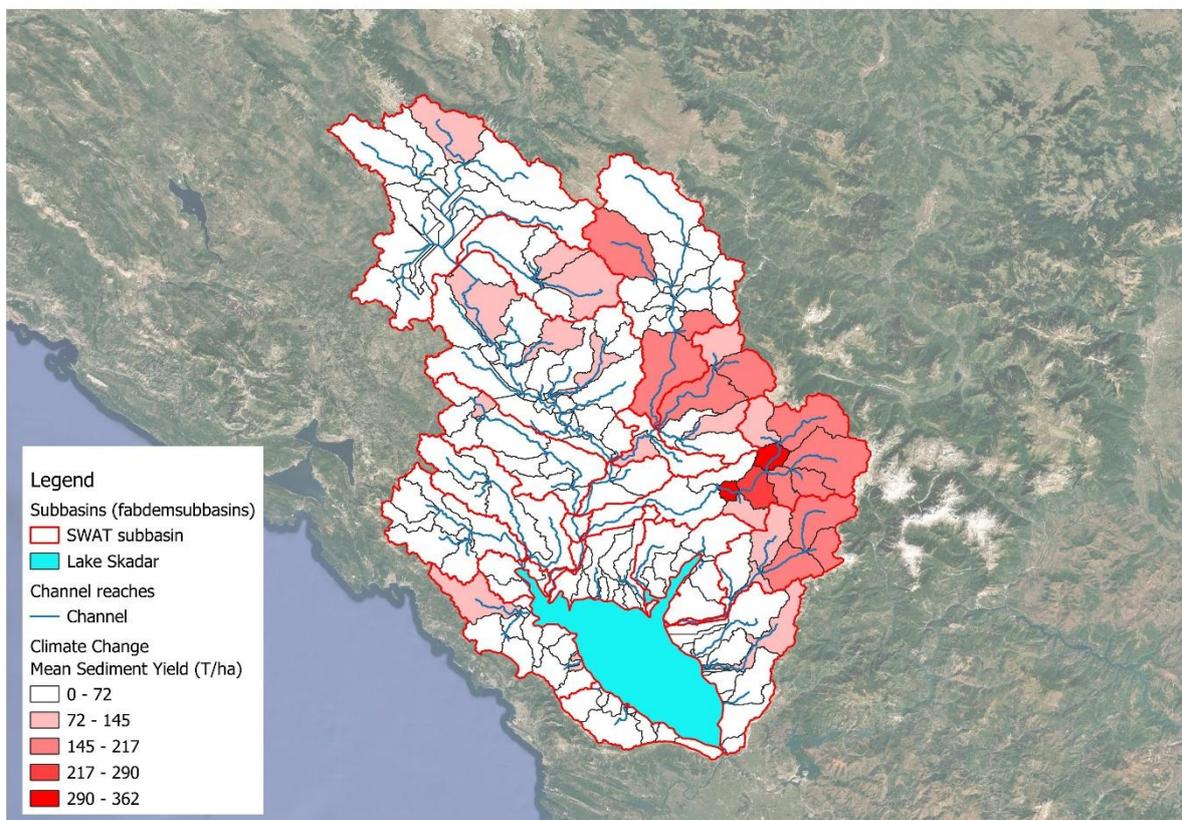
Figure 27. Mean sediment yield from 1971 to 2020

Figure 28. Sediment yield under Climate Change conditions (2021-2049)

As it can be observed, there is a higher erosion in the northeast of the catchment, although some hot-spots in the north and north-west should also be considered.

4.2.3. Land Use Change Sensitivity

In terms of land use sensitivity, the objective was to identify the land use types that contribute most to runoff and erosion. In order to undertake this, the assessment was carried out at HRU level, and calculating the average runoff and sediment yield for the main land-use classes. The resulting analysis is shown in Table 13.

Table 13. Land use Analysis

Land Use ID	Land Use	Avg. Runoff (mm/yr)	Avg. Sediment Yield (t/ha/yr)	Comments
CRDY	Dry Cropland	890.6	55.1	Rainfed agriculture on exposed soils or sloped terrain, generating high runoff and very high erosion.
CRWO	Cropland–Woodland Mosaic	958.1	27.6	Moderate erosion, due to tree cover reducing sediment loss despite high runoff.
FODB	Deciduous Forest	847.1	≈ 0	Relatively high runoff (due to steep slopes in some regions), but excellent ground cover prevents sediment yield.
MIGS	Mixed Grassland/Shrubland	741.7	0.07	Lower runoff, minimal sediment yield, typical of semi-natural or lightly grazed areas.
URDM	Medium-Density Urban	1276.7	45.5	Very high runoff due to impervious surfaces, and significant sediment, possibly from construction or poor drainage.
WATR	Water bodies	1632.5	≈ 0	Runoff is very high (likely rainfall directly into water bodies). No erosion

In summary, the 'Dry Cropland' is the main is the main contributor to erosion, despite not having the highest runoff, what suggests that some areas are cultivated on slopes and/or with poor soil protection. Also, the 'Medium-Density Urban' shows the highest runoff, as expected, and also significant sediment, likely due to disturbed surfaces or unpaved areas. The natural covers, 'Deciduous Forest' and 'Mixed Grassland/Shrubland' are hydrologically active (runoff present) but are functionally stable with almost no erosion — a key benchmark for good land cover.

4.2.4. Runoff Coefficient

The objective of the runoff coefficient analysis is to evaluate the infiltration capacity and flash flood risk at a LSU scale. In order to do this, a relationship between the total surface runoff generated and the total precipitation was carried out (Total Surface Runoff / Total Precipitation). Values close to 1 indicate low infiltration and high overland flow (potential flashiness).

The results are shown in Figure 29. As it can be expected, the more mountainous areas in the north, and north-west, they show a very flashy response, with values over 0.5; although the LSUs with higher Runoff Coefficient were identified closer to the Lake Skadar.
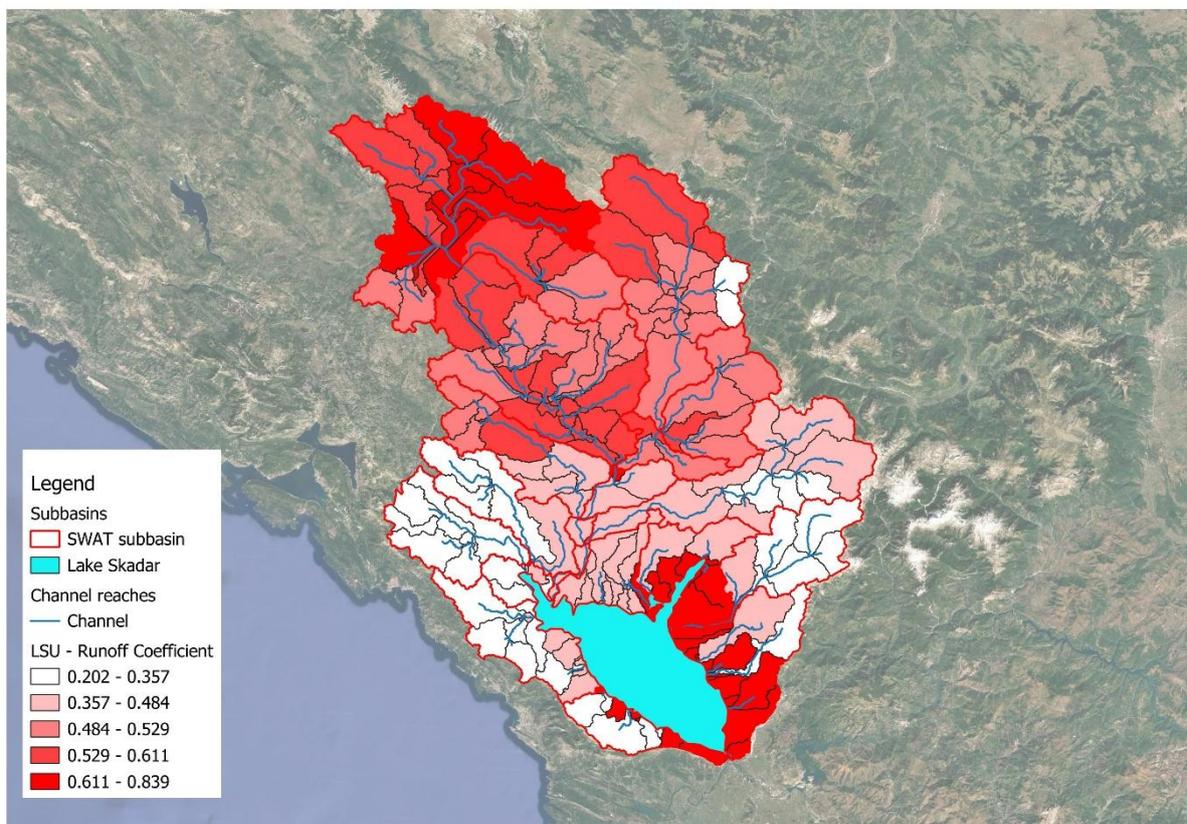

Figure 29. Runoff Coefficient

5. Conclusions

This project has provided the first integrated hydrological water balance analysis of the Skadar Lake Basin over a 20-year period using the SWAT+ model. The modelling framework has captured the main dynamics of precipitation, evapotranspiration, runoff, and lake inflows and outflows, allowing

for a detailed assessment of changes across different subcatchments. Results show that the basin is already experiencing significant variability in water availability, with some upstream tributaries and erosion-prone areas showing higher sensitivity to changing climatic and land use conditions. Climate change projections for 2020–2050 indicate increased extremes, with more variable rainfall and runoff patterns, reduced soil water retention in critical locations, and greater risks of both erosion and flash flooding.

From this analysis, it is possible to identify hydrological "hotspots" where watershed instability is most pronounced. These include steep agricultural lands, degraded areas contributing high sediment loads, and urbanised zones with excessive runoff. By highlighting these areas, the project provides the evidence base needed for prioritising watershed management and ecological conservation measures.

The responsibility for developing and implementing actionable strategies lies with a combination of institutions. National water agencies and hydrometeorological services should lead the technical planning and integration of climate projections into basin management. Local municipalities and protected area authorities around Skadar Lake will play a crucial role in enforcing land use regulations and coordinating on-the-ground interventions. Implementation should be pursued in the short to medium term (within the next five years) to anticipate climate pressures, while continuous monitoring and adaptive management should be maintained in the longer term.

In practical terms, the strategies should focus on reducing soil erosion through reforestation and sustainable land management, improving drainage and runoff control in urban and agricultural areas, and maintaining the ecological buffer function of Skadar Lake. By combining these interventions, the basin can enhance its resilience to both current pressures and future climate change impacts.

In summary, the project confirms that hydrological dynamics in the Skadar Lake Basin are increasingly unstable under climate change, but it also provides a clear roadmap of where and how to act. The findings are intended to guide decision-makers, from national ministries to local stakeholders, in designing effective and timely watershed management strategies that safeguard both people's livelihoods and the ecological health of the basin.