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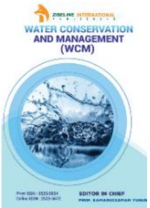

*RESEARCH ARTICLE*

# IMPACT OF CLIMATE CHANGE ON THE INFLOW OF CHARVAK LAKE BY THREE RIVERS (PSKEM, KOKSU, CHATKAL), UZBEKISTAN, DURING THE POST-SOVIET PERIOD (1990-2022) MODELLED BY QSWAT+

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## ABSTRACT

Our study examines the impact of climate change on the hydrology of the Charvak Lake watershed in Uzbekistan, focusing on streamflow from the Pskem, Chatkal, and Koksu rivers during the 1990–2022 period. The analysis evaluated the contributions of snowmelt and glaciers to river flows while addressing modelling limitations, including the absence of dedicated land classes for snow cover and glaciers. This study, conducted under the CGIAR NEXUS Policy Innovation initiative, focused on hydrological modeling using the QSWAT+ tool to better understand these dynamics. Calibration efforts improved model performance, with statistical parameters indicating a correlation coefficient (R) of 0.77, a coefficient of determination ($R^2$) of 0.59, and a percent bias (PBIAS) of –15%, demonstrating reasonable agreement between observed and simulated data. However, the Nash–Sutcliffe Efficiency (NSE) was low at 0.27, highlighting challenges in accurately simulating extreme flows during peak and low-flow periods. Mann–Kendall and Sen's slope tests showed no statistically significant trends in streamflow for both simulated and observed flows ($p = 0.69$ and $p = 0.31$, respectively), though observed data suggested a slight potential increase likely linked to glacier melt.

**KEYWORDS**

QSWAT+; streamflow; climate change; Uzbekistan.

## 1. INTRODUCTION

### 1.1 Global Climate Change

Our planet continues to face unprecedented and historical challenges, such as population growth, mass migration, environmental degradation, political tensions, military conflicts, and natural and social calamities (Alikhanov et al., 2024 ; Narain et al., 2022). Global climate change is a significant issue, not only because it touches every other corner of the planet but entails so many ramifications which is hard to encompass and understand entirely even today. Besides just global temperature rise, it causes average sea temperature to rise due to the planet's ice resources melting, putting into danger coastal countries such as Bangladesh, Thailand, Indonesia, Netherlands, India and others. According (Cunningham, 2015), global climate change can cost the world's economy from 5 to 72 trillion US dollars only in the 21st century. There are numerous other implications GCC causes, such as an increasing level of drought and floods, climate migration, acceleration of desertification, an increase in soil erosion, widening of forest fires, changes in precipitation patterns (with higher percentage of rainfalls and lower snowfalls) and many more.

Many politicians, intellectuals, philosophers and social activists say that GCC is one of the biggest existential problems we encounter since the dawn of human civilization. A clear indicator of the impact of climate change on the hydrological cycle is the changes in river stream flow, especially in mountain regions, where river streams are formed from mountain springs and the melting of the cryosphere (Huss and Hock, 2018).

Changes in snow and glaciers are leading to localized decreases in agricultural yields in mountainous regions such as the Hindu Kush Himalayas and the tropical Andes, although the certainty of these impacts is considered medium (Zhang et al., 2013). Similarly, the effects on hydropower facilities remain uncertain. In some areas, like the European Alps and the Andes, variations in water flow have influenced the operation and productivity of these facilities, though the evidence supporting these findings is limited (Haeberli, 2004). Overall, the melting of snow and glaciers is altering water flow patterns in mountainous areas, affecting agriculture and hydropower production (Intergovernmental Panel On Climate Change (Ipcc), 2023 ; World Bank Climate Finance, 2023).

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### 1.2 Uzbekistan and climate change

Uzbekistan, the most populous nation in Central Asia, is projected to have a population of 50 million by 2050 (www.kun.uz, 2025). The country is still grappling with the negative environmental legacies of the Soviet era. One of the most notable examples is the shrinking of the Aral Sea, once the fourth-largest lake globally, which highlights the significant developmental challenges facing vast regions of Uzbekistan. The country is increasingly experiencing the adverse effects of climate change, including droughts, extreme heat, shifting precipitation patterns, and dust storms, which are impacting both the population and the economy (UNDP, 2023). The rising levels of PM2.5 air pollution, particularly in Tashkent, have emerged as a significant environmental and public health issue (www.iqair.com, 2025). Uzbekistan is highly susceptible to hydrometeorological hazards and natural disasters, especially those affecting agriculture, such as seasonal floods and droughts (Uzbekov et al., 2021). The country also faces risks from landslides, locust infestations, and mudslides (Juliev et al., 2019). During crop production periods, land degradation and drought risks are particularly severe, exacerbated by the growing water demand driven by economic development and population growth (Alikhanova and Bull, 2023). Among the most pressing climate change risks in Uzbekistan nowadays are water scarcity, heatwaves, and an increasing number of days with temperatures exceeding 39°C. The southern and eastern regions of the country are notably prone to landslides, which pose a significant natural hazard (climateknowledgeportal.org, 2025). These dynamics are particularly relevant for our study region, where understanding climate-driven vulnerabilities is critical for sustainable land and water management.

### 1.3 Climate change impact on the hydrological cycle

Climate change is profoundly changing the hydrological cycle, leading to increased cloudiness and latent heat flux, leading to more extreme precipitation events, such as droughts, floods, landslides, and storms (Wang and Liu, 2023). Due to the severe economic impact of such events, this put the spotlight on the research of local climate fluctuation on the hydrology of the region. Among the overt direct impacts of climate change of hydrological balance is the impact on catchment water (increase or decrease) and nutrient cycle (Mahmood et al., 2019). Besides climate, hydrological cycles are largely impacted by land use, population growth, soil type and terrain characteristics. Therefore, shifts in weather patterns and land cover entail inevitable changes in hydrology of a region (Tan et al., 2022).

Accurate hydrological predictions are crucial for formulating climate-adaptive strategies across various water-related sectors (Alikhanov et al., 2021). This is especially important at the regional or basin level, as these are the scales at which the impacts of climate change are most directly experienced and where adaptation strategies are developed and put into practice (Anand et al., 2018).

Uncertainty in hydrological process modelling can originate from multiple sources, impacting estimates from the past, present, and future. The uncertainties in historical and current assessments are predominantly due to two main factors: the limitations of field-measured data and the challenges in interpreting the causes of complex hydrological processes, which result from the interplay of biological, physical, climate and human systems (McMillan et al., 2018). This show up the critical need for a deep understanding of the hydrologic system and the acquisition of high-quality, comprehensive data to construct a robust and trustworthy hydrological model (Banda et al., 2022).

The Soil and Water Assessment Tool (SWAT) are famous ecohydrological watershed model that was initially created in the early 1990s by integrating various pre-existing models and concepts. These foundational elements were primarily developed at the Texas A and M University and the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) laboratories, which are both based in Temple, Texas (P. W. Gassman et al., 2007).

The application of SWAT for research and monitoring purposes has significantly expanded on a global scale during this same period, as demonstrated by various review studies and special issue or section overview articles (Janjić and Tadić, 2023). The growth of SWAT's application is further evidenced by the extensive body of peer-reviewed literature and bibliometric analyses, which highlight SWAT's impact across water resource management, geographic information systems (GIS), and other related disciplines (Arnold and Fohrer, 2005).

The development of SWAT builds on over three decades of USDA-ARS modelling expertise. From its wide usage, SWAT has employed a physically based modelling approach, integrated with essential empirical routines, designed for continuous daily time-step simulations. In our study, we used SWAT to model seasonal water balance in a semi-arid watershed in Uzbekistan. This approach is supported by a lumped modelling strategy, where users divide a watershed into sub-watersheds, which are further subdivided into hydrologic response units (HRU) characterized by uniform soil, vegetation, land use, landscape, and management attributes. Hydrological and pollutant outputs are generated at the HRU level, aggregated at sub-watershed outlets, and eventually routed to the watershed outlet. This modelling framework is highly flexible and understandable, leading to its widespread adoption across a diverse range of watershed scales, environmental conditions, and scenarios involving management, land use, and other factors (Williams et al., 2008).

The goal of the research is to analyse the impact of climate change on the inflow of water from three mountainous rivers (Pskem, Chatkal, Koksu) to the Charvak Lake during the post-Soviet period of time (1995 -2022).

## 2. RESEARCH METHODS

### 2.1 Study area

The study area is located in the Bostonliq district, Tashkent province, Uzbekistan. Charvak Reservoir, also known as Lake Charvak, is a prominent artificial lake situated approximately 60 kilometres northeast of Tashkent city, Uzbekistan. Nestled in the western Tian Shan mountains, it is formed by the confluence of the Pskem, Koʻksuv, and Chatkal rivers. The reservoir was created by constructing a 168-meter-high stone dam, known as the Charvak Hydropower Station, on the Chirchiq River. The reservoir has a capacity of about 2 cubic kilometres and serves multiple purposes, including hydroelectric power generation, irrigation, and providing a recreational area for locals and tourists. The surrounding region offers a variety of activities such as swimming, boating, hiking, and paragliding, making it a popular destination for outdoor enthusiasts. The shoreline of Charvak Reservoir stretches nearly 100 kilometres, with numerous resorts, guesthouses, and recreational facilities dotting its perimeter (Alikhanov et al., 2021).

The Chatkal, Pskem, and Koksu rivers are the main tributaries feeding the Charvak Reservoir in Uzbekistan's western Tian Shan mountains. The Chatkal River originates in the Kyrgyz part of the Tian Shan mountains, extending approximately 223 kilometres. It provides a substantial amount of water to the reservoir, fed by snow and glacial melt, and is known for its rugged terrain and popularity among trekkers (Uzbekov et al., 2021). The Pskem River, about 70 kilometres long, also stems from the glacial and snowmelt waters of the Tian Shan. It is a significant contributor to the reservoir, particularly during the spring and summer, and flows through the scenic Pskem Valley. The Koksu River is the smallest of the three, at around 50 kilometres in length. It originates in the same mountainous region, fed by snowmelt and rain, and flows through picturesque gorges before entering the reservoir. Together, these rivers supply water essential for hydroelectric power generation at the Charvak Hydropower Station, irrigation for agriculture in the Chirchiq basin, and recreational activities in the reservoir area (www.orexca.com ,2025).

However, for the proper simulation of the three rivers, it was decided to take as a major outlet the Chinaz hydropost, which is located at the end of the Chirchiq river basin. Ugam, Pskem Koksu, Chatkal and Chirchiq rivers and their sub-basins altogether form a large watershed that covers most of Tashkent province and extends to Kyrgyzstan and Kazakhstan (Figure 1).

**Table 1 :** Land use and land cover classes and their SWAT codes

| **Land cover class** | SWAT code | Area, % |
|---|---|---|
| **Water** | WATR | 1.4 |
| **Snow** | SHRB | 43 |
| **Grasslands** | GRASS | 23.6 |
| **Tree cover** | FOMI | 4.6 |
| **Barren soil** | BSVG | 16 |
| **Urban** | URMD | 0.7 |
| **Rocks** | BSVG | 10.4 |

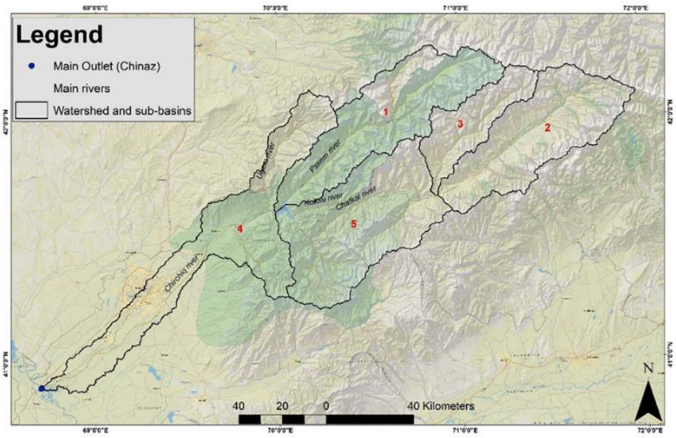

**Figure 1 |:** Study area – a large watershed with sub-basins. Pskem, Koksu, and Chatkal tributaries flow into Charvak Lake. Water from the reservoir then flows into the Chirchiq River through hydroposts.

## 2.2 Input data

SWAT+ requires standard data for hydrological modelling – Land use and land cover, soil types, elevation and weather data (namely humidity, wind speed, solar radiation, precipitation and air temperature).

For land cover classification, it was decided to choose Landsat 5 TM satellite images for the year 1993 (since the simulation period was from 1990 to 2022). The classification was done in the Google Earth Engine platform with the Random Forests machine classification tool. The cloud cover was set to 10 % in order not to distort the surface land cover, and the final classification accuracy for the whole watershed was 88 %. The land cover was divided into six classes: bare soil, tree cover, snow cover, urban cover, agriculture (was validated in Google Earth Pro since it can be confused with other vegetation covers), water, grasslands and rocks. However, when it comes to SWAT+ global land uses, it does not have all these classes, whereas the rest need to be corroborated. For example, the major disadvantage of the SWAT+ model is that it does not have glaciers and snow cover classes. Despite the model including snow cover melting and initial snow cover parameters and considering the temperature, precipitation (during cold seasons) and snow melting thresholds that directly impact the stream flows, the absence of these land classes is still considered a major flaw of SWAT+. Therefore, the snow cover alternative from the SWAT+ database was taken as bare soil (BSVG) that has a closer CN2 (curve number) and other parameters to the snow cover compared to others. Anyways, when other land cover classes were chosen as a snow cover substitute (for example, bare land tundra (TUBG) or mixed tundra (TUWO), the model was significantly overestimating the water flow. The rest of the land cover SWAT codes can be seen in Table 1.

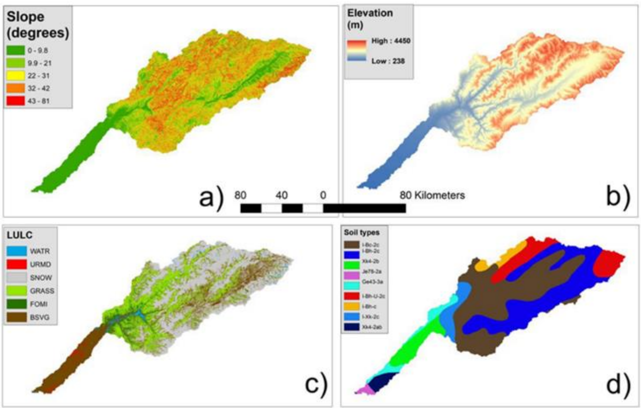

**Figure 2** : Slope (a), elevation (b), land cover (c) and soil types (d) for the watershed

Elevation plays a crucial role in hydrological processes. The accurate digital elevation model is necessary for many reasons: accurate stream, watershed and sub-basins delineation, HRU's creation, flood-prone areas detection, snowfall and melting (depending on altitude and season), etc. As a major outlet, Chinaz town, which is located at the end of the Chirchiq river and the starting point of the Syrdaraya inflow, was taken. The total area of the watershed is 13,389 km$^2$, with 5 sub-basins.

The Chatkal, Pskem, and Koksu rivers flow through the rugged western Tian Shan mountains, characterized by steep gorges, high-altitude peaks (up to 4,500 meters), and diverse landscapes. The Chatkal originates above 3,000 meters, the Pskem above 3,500 meters, and the Koksu between 2,500–3,000 meters, all fed by glaciers and snowfields. These rivers descend through rocky valleys and alpine meadows before converging into the Charvak Reservoir at 900 meters. The region features permanent snow at higher elevations, forests and meadows at mid-levels, and milder climates in the valleys, blending natural beauty with hydrological significance.

The slope of the watershed varies significantly from completely flat land surface to high hills and steep slopes. The southern part of the watershed predominantly belongs to flat surface area, ranging from 0 to 10 degrees (Chirchiq river basin). Whereas the northern part of the watershed (Ugam, Pskem and Chatkal river basins) belongs to steep slopes and rugged Tian Shan mountains, in some areas, slopes range from 40 to 80 degrees. These areas are highly prone to water erosion, landslides and accumulating snow and glaciers during cold seasons.

The study area contains a variety of soil types classified under the FAO soil classification system, with significant variability in their distribution and characteristics. The dominant soils include shallow, calcareous, and humic soils over hard rock, situated on moderately steep slopes, with textures such as clay loam and loam. For instance, the "I-Bc-2c" soil, which has a clay loam texture, covers 39.45% of the area, while the "I-Bh-2c" soil, with a loam texture, accounts for 28.32% of the watershed. These soils are prevalent in the moderately steep terrains of the watershed, reflecting the influence of slope and underlying geology on their formation.

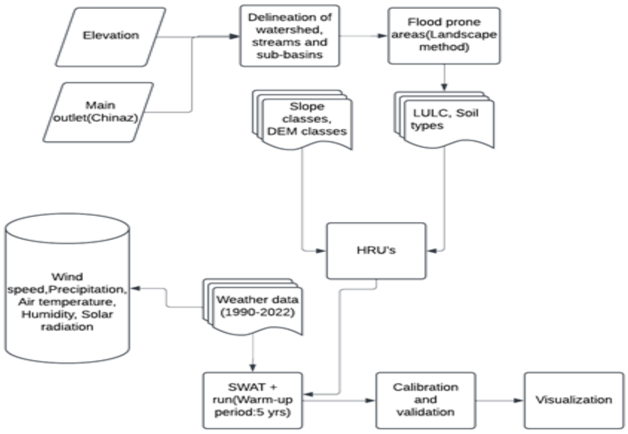

**Figure 3** : Model framework

Smaller proportions of the area are occupied by soils such as Solonetz soils with calcic horizons, like "Xk4-2b" (6.26%), and Eutric Cambisol soils like "Je78-2a" (0.86%). Other minor contributors include "Ge43-3a" (Eutric Gleysol) with 3.82% coverage and additional variations of humic soils, such as "I-Bh-U-2c" (11.13%) and "I-Xk-2c" (5.03%). These soils are generally found on steep to moderately steep slopes and exhibit diverse textures, including clay, clay loam, and loam, indicating varied hydrological and physical properties.

This distribution of soil types demonstrates the heterogeneity of the study area's landscape. The dominance of clay loam and loam textures highlights the area's potential for water retention and erosion susceptibility, which are critical considerations for watershed management, land-use planning, and hydrological modelling.

**Table 2 :** Used data and their sources

| Data | Source | Format |
|---|---|---|
| Land cover and land use | Landsat satellite | GeoTIFF |
| Elevation | ASTER GDEM | GeoTIFF |
| Slope | ASTER GDEM | GeoTIFF |
| Soil types | FAO soil classification | ESRI Shapefile |
| Weather data | SWAT+ database | |
| Observed water flow | UzHydromet | Csv |

**Table 3 :** Soil types and their descriptions

| Name | Description | Texture | Area % |
|---|---|---|---|
| I-Bc-2c | Shallow, calcareous soil over hard rock, situated on moderately steep slopes with a coarse texture | CLAY LOAM | 39.45 |
| I-Bh-2c | Shallow, humic soil over hard rock, situated on moderately steep slopes with a coarse texture | LOAM | 28.31 |
| Xk4-2b | Solonetz soil with a calcic horizon, clay texture, situated on moderately steep slopes with a medium texture | LOAM | 6.25 |
| Je78-2a | Eutric Cambisol soil unit, situated on moderately steep slopes with a fine texture | LOAM | 0. 8 |
| Ge43-3a | Eutric Gleysol soil unit, situated on steep slopes with a coarse texture | CLAY | 3.82 |
| I-Bh-U-2c | Shallow, humic soil over hard rock, situated on moderately steep slopes with a loamy texture | LOAM | 11.13 |
| I-Bh-c | Shallow, humic soil over hard rock, with a coarse texture | LOAM | 2.9 |
| I-Xk-2c | Shallow, calcareous soil over hard rock, situated on moderately steep slopes with a coarse texture | LOAM | 5.03 |
| Xk4-2ab | Solonetz soil with a calcic horizon, clay texture, situated on moderately steep slopes with both fine and medium textures | LOAM | 2.22 |

**Table 4 :** Elevation and slope classes for HRU delineation

| Elevation classes | Slope classes |
|---|---|
| 238-738 m | 0- 5 |
| 738 – 1238 m | 5-15 |
| 1238 m -1738 m | 5-30 |
| 1738 m – 2238 m | 30-45 |
| 2238 – 2738 m | 45-60 |
| 2738 m – 3238 m | >60 |
| >3238 m | |

### 2.3 Uzhydromet data

In Uzbekistan, the Hydrometeorological Service (Uzhydromet) monitors river flow for rivers such as the Ugam, Pskem, and Chatkal using a network of hydrological gauging stations. These stations measure water level and flow velocity, which are then used to calculate the average daily discharge in cubic meters per second ($m^3/s$) and average daily, weekly, monthly and yearly water volume of these rivers in millions of cubic meters. The process involves traditional velocity-area methods, where river cross-sections are surveyed and flow velocity is measured manually or with instruments, as well as automated sensors that transmit real-time data. These calculations are essential for managing water resources, especially in mountain-fed rivers that contribute to reservoirs like Charvak (www.hydromet.uz ,2025).

In recent years, Uzhydromet has undergone modernization supported by UNDP and the Global Environment Facility, receiving new high-precision instruments to monitor streamflow and water levels. These improvements enhance early warning systems for floods, mudflows, and landslides, which are especially critical in the spring-summer season due to snowmelt and glacier runoff from the Tien Shan mountains. Enhanced real-time monitoring also enables more efficient transboundary water management and supports water-sharing agreements with neighbouring countries in the Syr Darya basin (UNDP, 2023).

### 2.4 SWAT model

The SWAT model (Soil and Water Assessment Tool) is a strong, widely tested hydrological model designed to predict the effects of land management practices and weather fluctuations on water flow, sediment, and agricultural chemical yields in complex watersheds over time (Tigabu et al., 2024). Developed by the USDA, the model operates on a continuous, daily time step and divides watersheds into subbasins and HRU's to account for spatial heterogeneity in land use, soil types, and topography. It integrates climatic, hydrological, and land-use data to simulate complex interplay between nutrient cycling, hydrological and chemical processes, making it an essential tool for watershed management, climate change studies, and assessing the impact of agricultural practices on water resources (Sánchez-Gómez et al., 2025). Moreover, its ability to model diverse scenarios over long time periods makes SWAT invaluable for sustainable water resource planning and environmental conservation for both small and large areas. For this reason, its comprehensiveness and accuracy, the model was deliberately integrated into many GIS platforms, such as ArcGIS (ArcSWAT) and QGIS (QSWAT and SWAT+).

The SWAT+ model for QGIS is an enhanced version of the Soil and Water Assessment Tool integrated with QGIS, providing a efficient and user-friendly environment for watershed modelling and analysis. This integration allows users to leverage QGIS's powerful geospatial capabilities to preprocess input data, such as digital elevation model (DEM), land use, and soil map, directly within the platform. SWAT+ in QGIS improves workflow efficiency by enabling the creation of hydrological response units (HRUs), subbasins, and other watershed components with higher precision than any other existing hydrological model (www.swat.tamu.edu ,2025). By combining SWAT+'s advanced simulation capabilities with QGIS's visualization tools, this setup provides an accessible and versatile solution for researchers, planners, and environmental professionals working on watershed management and water resource planning. For our research, we worked with the 3.02 version of SWAT+ developed for the 3.34 version of QGIS.

### 2.5 Statistical tools for trend analysis and validation

The Mann-Kendall test is a non-parametric statistical tool used to detect monotonic trends in time-series data. It evaluates whether a variable exhibits a consistent upward or downward pattern over time, without assuming any specific data distribution. The test ranks data pairs to compute the strength and direction of the trend, making it robust against outliers and missing values. It is commonly used in environmental sciences, climate studies, and hydrology for analysing changes over time in various parameters, such as temperature, precipitation, or pollutant levels (Alikhanov et al., 2024 ; Mann, 1945).

To complement this, we applied Sen's slope estimator, which calculates the median of all pairwise slopes between data points to quantify the rate of change. Unlike traditional regression methods, Sen's slope calculates the median of all pairwise slopes in a dataset, providing a robust estimate of the rate of change that is less influenced by extreme values or non-linear variations. Its simplicity and resilience to data irregularities make it a preferred choice for analysing trends in environmental and ecological studies (Sen, 1968).

These tools are particularly valid for analysing water flow trends because hydrological data, such as streamflow or discharge, often include irregularities, seasonal fluctuations, and missing values. The Mann-Kendall test provides a reliable method for detecting statistically

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significant trends in water flow data, while Sen's slope quantifies the magnitude of those trends. This combination is well-suited for identifying long-term changes in hydrological systems due to factors like climate change, land-use modifications, or human interventions, offering critical insights for water resource management and planning. Their non-parametric nature ensures that the results are reliable, even when the data does not meet strict parametric assumptions, which is often the case in water flow datasets.

For the comparison between observed data and simulated data, we used the most widely used statistical tools for SWAT analysis, namely the Nash-Sutcliffe Efficiency (NSE) and the Percent Bias (PBIAS).

The Nash–Sutcliffe Efficiency is one of the most commonly used metrics for evaluating hydrological model performance. It quantifies how closely the simulated streamflow matches the observed values, with values ranging from −∞ to 1. An NSE of 1 indicates perfect agreement, while 0 implies that the model is no better than using the mean of the observed flow as a predictor (Nash and Sutcliffe, 1970 ; Uzbekov, 2021). Negative values suggest that the model performs worse than the mean. In our study, NSE was particularly useful for evaluating the model's ability to capture both the magnitude and timing of peak flow events, which are often challenging to simulate accurately.

The Percent Bias (PBIAS) is another key performance indicator used to evaluate model performance in SWAT. It measures the average tendency of the simulated data to be larger or smaller than observed values. A PBIAS of 0 indicates perfect model performance, whereas positive values mean the model is underestimating, and negative values suggest overestimation. According to literature study for monthly streamflow simulations, NSE > 0.5 and |PBIAS| < 25% are generally considered acceptable, though these thresholds may vary depending on the study context. Together, NSE and PBIAS help hydrologists evaluate both the accuracy and bias of SWAT simulations for watershed hydrology (D. N. Moriasi et al., 2007).

## 3. RESULTS AND DISCUSSION

### 3.1 Hydrological modelling results

The study period for the research was considered from 1990 to 2022 (post-Soviet period). The warm-up period for the SWAT was set to 4 years. For large watersheds, a longer warm-up period in SWAT (e.g., 5 years or more) is justified due to the slower response times of hydrological processes and the extensive variability in soil moisture, groundwater recharge, and nutrient cycling across the basin. Large watersheds often encompass diverse land uses, soil types, and climatic conditions, which require more time for model parameters like soil water content, aquifer levels, and streamflow routing to reach equilibrium. Additionally, processes such as sediment transport and nutrient loading, which are influenced by cumulative upstream contributions, take longer to stabilize in large-scale systems. Using a longer warm-up period ensures that the model eliminates any artificial transients and accurately reflects the baseline conditions of the watershed, leading to more reliable calibration and validation results.

In general, for the whole watershed, the model delineated 1309 HRU's, 51 channels, 11 aquifers and 102 landscape units (LSU). The initial average annual CN2 for the whole watershed was too high (92). This resulted in the exaggeration of surface water flow by 2-3 times. Therefore, it was reduced multiple times during the calibration period and eventually constituted 70 % of the initial calibration. Meanwhile, the alpha factor (groundwater contribution to the baseflow) was increased by 20 %, because the initial model showed an underestimation of water flow during the hot periods compared to the observed data (Figure 4).

The average annual precipitation for the whole watershed for 32 years was 1122 mm per year. Snowfall from this makes up 606 mm per year, predominantly falling in mountainous areas. From this potential evapotranspiration equals 900 mm, with actual evapotranspiration being 509 mm/year for 32 years (Figure 5).

Snowpack amount (mm) represents the snow accumulation on the ground at a specific time. For the 32 years, the average snowpack amount in water equivalent made up 104 mm/year. Mostly, the Pskem and Chatkal areas have high snowfall, snowpack water equivalent and snowmelt compared to the Chirchiq river basin, which is located in the southern part of the watershed with no mountain hills (Figure 5). Initial percolation was low for the region (70 mm/year), but after calibration (reducing CN2) it made up 200-400 mm per year, depending on the sub-basins.

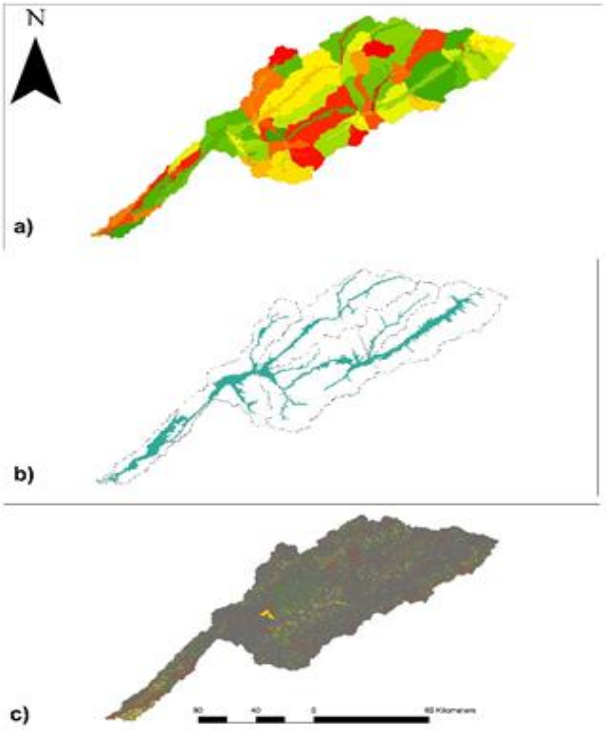

**Figure 4:** a) Landscape Units; b) Flood-prone areas; c) Hydrological response units.

The lateral flow from the aquifers is shown, with higher values concentrated near the main streams (blue areas, up to 1499.8 mm/year), indicating significant groundwater contribution to streamflow in these zones. The green areas, representing lower lateral flow, indicate regions where aquifer contributions are less prominent (Figure 6, a). The annual depth to the water table, with deeper water tables (35.7–38.6 m/year) in the eastern regions and shallower depths (24.8–30.2 m/year) closer to the central and western areas, likely influenced by topography and recharge rates (Figure 6, b).

Re-evaporation rates are depicted, ranging from 9.98 mm/year (red) to 21.78 mm/year (yellow). Higher re-evaporation is concentrated in central regions with shallower groundwater, as seen in map 6, b), suggesting a stronger connection between the aquifer and surface evaporation processes (Figure 6, c). Finally, map (d) provides another perspective on the annual depth to the water table, emphasizing shallow groundwater conditions (2.1–3.2 m/year) in localized regions. Together, these maps highlight the interplay between aquifer lateral flows, re-evaporation, and groundwater depth in shaping the hydrology of the watershed (Figure 6, d).

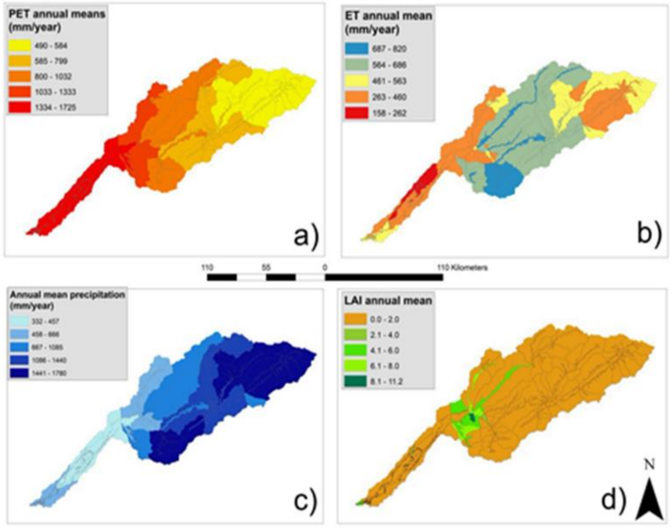

**Figure 5 :** PET (a), ET(b), Precipitation (c), LAI (d) for the watershed

As we can see from the Table 5 and Figure 7, SWAT+ accurately modelled the streamflow of three tributaries flowing into the Charvak Lake. The correlation between observed and simulated is high, -0.77, with $R^2$ equating to 0.59, which is moderate. Nevertheless, the Nash-Sutcliffe Coefficient is considered low (0.27). The reason behind this is the difference between observed and simulated during high peak streamflow months (April, May, June), sometimes with simulated outperforming observed 1.5 times. NSE is very sensitive to large differences, even though they might not occur frequently. On the contrary, observed water flow for three rivers is also 1.5-3 times higher than simulated during the cold period (December, January, February).

PBIAS, at the same time, made up -15 %, which means that our simulated model slightly underestimates the real flow based on observed data. This is because of cold months, where observed flow is higher than simulated (Figure 7). Overall, -15 % is considered a good or satisfactory value for the model (Table 5).

**Table 5 :** Statistical parameters between simulated and observed

| | |
|---|---|
| **R** | 0.77 |
| **R2** | 0.59 |
| **NSE** | 0.27 |
| **PBIAS** | -15% |

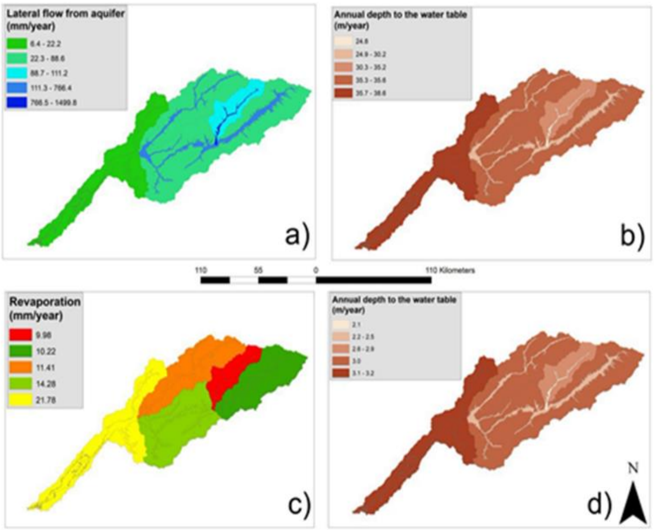

**Figure 6** : Annual lateral flow from aquifer (a), annual depth to water table (b), revaporation (c), monthly depth to water table (d)

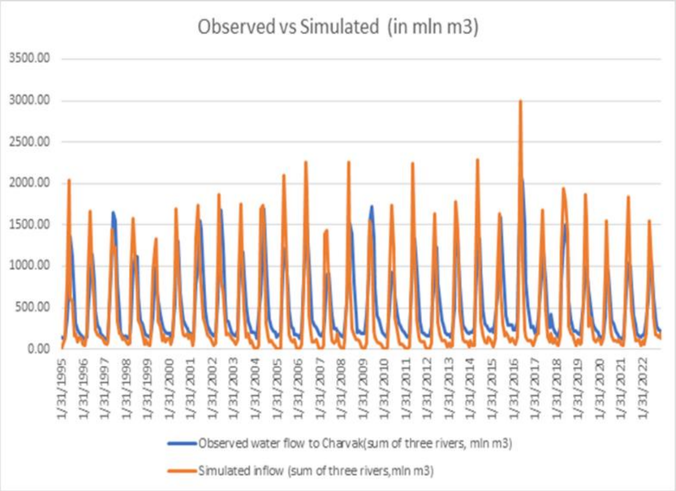

**Figure 7** : Simulated(orange) and observed (blue) water flowing into Charvak Lake from 1995 to 2022.

The biggest difference between observed and simulated was observed in the years 2016 (May and June), 2005 (May and June), 2003 (May and June),2019 (June) and 2010 (May and June). However, despite having different values for months, the SWAT+ model shows similar patterns to observed data throughout the study period. Only two times observed data exceeded simulated during peak months – in 1997 and 2009.

### 3.2 Trend analysis with Mann-Kendall's test and Sen's slope

Non-parametric tools, namely Mann-Kendall's test and Sen's slope were used to analyse the ongoing trend of inflowing water to Charvak Lake during the post-Soviet period by three river streams. As can be seen in Table 6, both simulated and observed flows do not show statistically significant values to confirm upward or downward trends ($p_{obs}$ =0.31 and $p_{sim}$ =0.69, respectively). This shows that despite the fluctuation of water and hydrological processes for the study period, the general water level is not significantly going down or up. However, the two datasets showed different results. If statistical analysis showed some positive trend for observed inflow to Charvak (tau =0.07, Sen's slope =0.77), the simulated one, on the contrary, showed negative results (tau =-0.022, Sen's slope = -0.029). If we consider observed data by UzHydromet as more reliable, one can observe that the inflow might be increasing from 1995 to 2022 due to glaciers melting on the peaks of the Pskem and Chatkal mountain ranges. However, the results are not statistically significant to claim with certainty.

**Table 6 :** Trend analysis of observed and simulated data

| Trend analysis | Observed | Simulated |
|---|---|---|
| Kendall's tau | 0.073 | -0.022 |
| Sen's slope | 0.77 | -0.029 |
| p-value | 0.31 | 0.69 |

### 3.2 Discussion

Our research explores the impact of global climate change and weather fluctuations on hydrological processes and water balance in a large mountainous watershed in Uzbekistan spanning 13,000 km², using the QSWAT+ model to simulate streamflow fed predominantly by snowmelt and glaciers. The interconnected sub-basins and the reliance of rivers on cryosphere inputs shows the complexity of the study area. While QSWAT+ offers advanced tools for watershed modelling, it has notable limitations, particularly the absence of dedicated land classes for snow cover, ice and glaciers. These omissions presented challenges since snowmelt and glacier dynamics are critical for sustaining river flows, especially in the northern part of the watershed, during late spring and summer (melting period in the Western Tian Shian). Addressing these limitations required from authors creative adjustments to the model parameters and land cover classifications, which highlighted both the strengths and limitations of the QSWAT+ framework.

The absence of snow cover and glacier classes necessitated approximations in land cover classification, where snow-covered areas were initially represented as bare soil and sparse vegetation (BSVG). However, this resulted in overestimated streamflow due to the high curve number (CN2) of the BSVG class, leading to streamflow estimates 3–4 times higher than observed values. The modelled results aligned more closely with observed flows by reclassifying snow-covered areas as shrublands, which have lower CN2 values and higher percolation. Nevertheless, discrepancies persisted, with simulated flows exceeding observed values during peak flow months (April to June) and underestimating them during colder months (December to February). These mismatches are mentioned by numerous SWAT+ model users, highlighting the need for enhanced calibration techniques and more precise modelling of cryosphere processes to improve simulation accuracy.

Statistically, the model captured general streamflow patterns reasonably well (R = 0.77, $R^2$ = 0.59), but the low Nash-Sutcliffe Efficiency (NSE = 0.27) and moderate bias (PBIAS = -15%) suggest it struggles with extremes—particularly under colder conditions. This is a common challenge when simulating mountainous watersheds, where snowmelt, glacier input, and seasonal temperature shifts interact in complex ways.

Looking forward, a potential solution lies in testing SWAT-GL, which includes glacier melt modules. Glaciers, unlike snowpacks, contribute to delayed runoff and help buffer seasonal extremes—an important feature in the Western Tian Shan basin. Integrating these dynamics could improve seasonal flow predictions and better reflect long-term hydrological changes under climate pressure. This refinement is critical for Central Asia, where glacier-fed rivers support both agriculture and transboundary water sharing. Improving model realism now will allow for more reliable planning in the face of accelerating environmental change.

## 4. CONCLUSION

We conducted hydrological modelling of streamflow for three rivers — Ugam, Koksu, and Chatkal — which flow into the Charvak Lake (reservoir), using the SWAT+ model within the QGIS platform. The study period covered the post-Soviet era from 1995 to 2022, with a 5-year warm-up period from 1990 to 1994. The primary objective of the research was to assess the impact of global and local climate change on the streamflow of these mountain rivers and their combined inflow into Charvak Lake.

Our analysis did not reveal any statistically significant increasing or decreasing trend in streamflow volumes for the simulated period, based on the Mann-Kendall test (p = 0.69; Kendall's tau = -0.022). The comparison between simulated and observed streamflow (from UzHydromet gauging stations) indicated that SWAT+ provided a reasonable level of accuracy in representing hydrological processes (NSE = 0.27; PBIAS = -15%; R = 0.77). Notably, the observed monthly inflow volumes into Charvak Lake also showed no statistically significant trend (Mann-Kendall test: p = 0.31; Kendall's tau = 0.073) for the same period.

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