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Assessment of Climate Change Impacts on Streamflow in the Maidan Sub-River Basin

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ABSTRACT

Climate change severely affects water resources in arid and semi-arid regions, including Afghanistan's Maidan Sub RB, which has been identified as highly vulnerable due to limited WR. The 2012 Global Adaptation Index ranks Afghanistan among the countries most susceptible to climate change, particularly regarding river flow changes. This study analyzes the Maidan River's streamflow using the Soil and Water Assessment Tool (SWAT), specifically at the Tang-i-Sayedan station, to forecast future streamflow under climate change conditions. The study projects a significant decline in streamflow of approximately 12.54% to 21.23% by the century's end, posing significant challenges to agricultural water supply in a region reliant on irrigation. This underscores the critical relationship between climate variability and local environmental factors, highlighting the necessity for adaptive management strategies for the region's hydrological dynamics. Therefore, policymakers must prioritize sustainable water management practices incorporating climate predictions and actively engage local communities in adaptation efforts. This approach will enhance Afghanistan's resilience to climate change, ensure water availability, and support sustainable agriculture, ultimately protecting livelihoods for future generations.

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INTRODUCTION

Climate change is broadly recognized as a significant factor that impacts and influences streamflow patterns on a global scale (UNEP, 2023). Climate change has gained recognition as an essential environmental concern in the twenty-first century, exerting substantial influence on the hydrological cycle, ecology, and overall environment. Recently, many researchers have focused on climate change and its effects on hydrology and water resources. By the 2050s, climate change is expected to affect seasonal flow patterns significantly. This impact will influence over 90% of the Earth's land area more than dam construction and water withdrawals do. Climate change is leading to a redistribution of water resources. This may increase the frequency and intensity of droughts and floods, causing more disasters (Yeh et al., 2020).

Greenhouse gas (GHG) emission is the leading cause of climate variation because of human population growth and their activities. The Intergovernmental Panel on Climate Change (IPCC, 2018) has issued warnings of significant and considerable temperature increases in both the Earth's oceans and atmosphere, and the Spatial Report on Global Warming 1.5°C (SR1.5) highlights that we are in the Anthropocene, marked by significant human influence on Earth's systems. This calls for a closer examination of our actions on climate and the planet, emphasizing the importance of respecting planetary boundaries, especially the complex relationship between climate change and biodiversity (Stehr et al., 2008). Human activities, particularly greenhouse gas emissions, have undeniably caused global warming, with a 1.1°C temperature increase from 1850-1900 observed during 2011-2020. Emissions continue to rise (2010-2019), driven by unsustainable practices in energy, land use, and consumption.

The optimistic scenario (RCP4.5) indicates that Afghanistan's warming will increase by approximately 1.5°C by 2050, followed by a stabilization period and an additional increase of around 2.5°C by 2100. On the other hand, the pessimistic scenario (RCP8.5) shows a bleaker picture, with the entire country facing extreme warming of about 3°C by 2050 and the potential for further warming of up to 7°C by the end of the century and conventional climate change considerations into Afghanistan's development is a crucial step toward enhancing its adaptive capacity (World Bank., 2018). Afghanistan's climate change has significantly impacted the average annual temperature since the 1950s and reported an increase of 1.8°C and a decrease in annual average precipitation with a notable increase in extreme weather events since the 1950s (Sarwary et al., 2021). Traditionally, Afghanistan has predominantly been an agricultural country (Bromand et al., 2015). Agriculture contributes approximately 22 percent to the country's Gross Domestic Product (GDP) and remains a primary source of livelihood. It is estimated that at least 70 percent of the population remains engaged in farming (Sadid et al., 2017). Agriculture will continue to play a crucial role in Afghanistan's progress and prosperity while simultaneously being the sector most susceptible to the impacts of climate change (Zhang et al., 2015).

Kabul River Basin is a transboundary watershed. It is located in the eastern part of Afghanistan and the Chatral valleys of Pakistan. It lies between latitudes 33°-37°N and longitudes 67°-74°E as shown in Figure 1.1, with a catchment area of 65202 km2. This river basin is divided into 12 sub-basins. The upper basin of the Kabul River Basin consists of steep mountain valleys in the Hindu Kush Mountain range, which is over 7500 meters above sea level. The Kabul River Basin is divided into three distinct areas. (1) The Logar-maidan areas of Kabul include three river branches, such as the Maidan, Paghman, and Qargh rivers, which originate from upstream of Kabul (2) The Panjshir-Ghorband area contains three tributaries such as the Ghorband, Salang, and Shatul rivers (3) Lower Kabul encompasses an area influenced by the Panjshir and Maidan rivers in this particular area. It consists of two major sub-basins in the north and contains rivers such as the Kunar and Laghman Rivers. Eventually, these tributaries and rivers converge in the Basual Daka area of Nangarhar province and cross the border across Pakistan territory (Akhundzadah et al., 2020).

This study encounters significant limitations, including insufficient data that hamper the accuracy of hydrological modeling. Additionally, general adaptation strategies frequently fail to account for local perceptions, highlighting the need for more tailored approaches. There is also a lack of comprehensive exploration into the intricate interactions between climate change, land use, and their impacts on water systems. This indicates a necessity for advanced modeling techniques. Furthermore, the predominant focus on ecosystem management overlooks vulnerable communities' socio-economic impacts and adaptation capacities. Maidan sub-River Basin (MSRB) is located in the eastern part of Afghanistan at 2210m high from sea level; it is counted as a central part of the country, and it is located 35km south-east of Kabul province, and the water flow of Maidan River finally joins with Indus River. Maidan Shahr River has a crucial role in the region, and it is also a supportive part of the Kabul River, which flows through the Tangi-e-Saydan valley. Maidan River originates from the Sanglakh and Sadmorda valleys of Jalriz and Nirkh districts. The total length of the river is almost (173km), and 75% of people are busy with agriculture [MoEW,2023]. Maidan River joins with the Paghman and Qargha rivers at the heart of Kabul city. This river primarily serves and provides water for different purposes, such as irrigation and groundwater recharge, and there is a plan to construct a reservoir across the river. The main river's primary water sources are snowmelt and early spring rainfall. The Maidan River's catchment area consists of approximately 10% irrigated agricultural land, 73% rangeland, and 12% barren land, with the remainder predominantly covered by fruit trees Akhundzadahet al., 2020). This study examines the increasing vulnerability of the Maidan River Basin in Afghanistan to climate change, which significantly affects its streamflow patterns and water availability. Despite the region's reliance on limited water resources for agriculture and livelihoods, there is a lack of comprehensive understanding regarding how future climate scenarios will influence hydrological dynamics. This gap in knowledge poses challenges for sustainable water management practices and adaptive strategies necessary to mitigate the adverse effects of climate variability. Consequently, this research aims to provide critical insights into climate change's current and projected impacts on streamflow in the Maidan River Basin, facilitating informed decision-making for water resource management. The main objectives of the study are as follows:

1. To comprehensively assess the current and projected impacts of climate change on the streamflow patterns of the Maidan Sub-River Basin
2. Assessment of Future Water Availability through Climate Change Scenario.

This research addresses the following research questions:

1. What are climate change's current and projected impacts on the streamflow patterns in the Maidan Sub-River Basin?

2. How will future climate change scenarios affect water availability in the Maidan Sub-River Basin?

MATERIALS AND METHODS

This research simulates hydrological conditions using a model to analyze the influences of climate change, land use, land cover (LULC) change, and soil conditions on surface runoff in the Maidan River streamflow. The study employs the Arc SWAT 2012 model, a robust watershed simulation tool, to assess the effects of these factors on water resources. As an influential watershed model, SWAT facilitates the exploration of hydrological conditions, specifically focusing on understanding the repercussions of climate change on water resources. Recognizing the intricate interplay of variables such as soil characteristics, soil moisture, land use, and land cover, using a hydrological model is deemed indispensable for a comprehensive analysis of hydrological responses. The methodological framework, depicted in Figure 3.1, involves several steps: (I) converting spatial and climate data into the SWAT format, (ii) setting up the model, including watershed delineation and identification of Hydrologic Response Units (HRUs), (iii) calibrating and validating the model, and (iv) examining the potential impacts of future climate change on streamflow.

The study employed various statistical methods to analyze hydrological and climatic data, emphasizing calibration and validation metrics to evaluate model performance. Key metrics included the Coefficient of Determination (R^2), Nash Sutcliffe Efficiency (NSE), and Percent Bias (PBIAS), which measure the model's explanatory power, predictive accuracy, and deviation of simulated from observed values, respectively. Scatter plots were used to compare observed and simulated streamflow, assessing model effectiveness visually. Specific performance benchmarks for R^2, NSE, and PBIAS were established to ensure a thorough evaluation of the hydrological model's predictive capabilities regarding streamflow dynamics affected by climate change.

Data collection

The data collection method involved acquiring essential datasets for hydrologic modeling and climate change assessment of the Maidan River. This included a Digital Elevation Model (DEM) from the Ministry of Energy and Water (MoEW) for topographical analysis, hydrological and meteorological data from DoWR providing daily precipitation and temperature, and additional climate data from the Climate Forecast System Reanalysis (CFSR). Land use information was sourced from the Food and Agriculture Organization (FAO), while soil datasets came from FAO and UNESCO. Future climate scenarios were retrieved from the Global Climate Model CMIP6 and techniques such as GIS were utilized for spatial analysis and integration of these datasets into the Soil and Water Assessment Tool (SWAT) model for hydrologic analysis.

Digital Elevation Model

Topography was characterized using a Digital Elevation Model (DEM) that provides elevation data for all points within a specified area at a particular resolution. A DEM with (30*30) meters resolution was used, as illustrated in Figure 3.2. These datasets were then seamlessly integrated and transformed into the Universal Transverse Mercator (UTM) projection using GIS 10.5. The DEM served as a fundamental input in the SWAT (Soil and Water Assessment Tool) model to delineate watersheds and analyze the drainage patterns of the terrestrial terrain. It facilitated the calculation of sub-basin parameters, such as slope gradient and length, and identified the stream network characteristics, including primary and secondary streams and rivers. All of this information was derived from the DEM dataset.

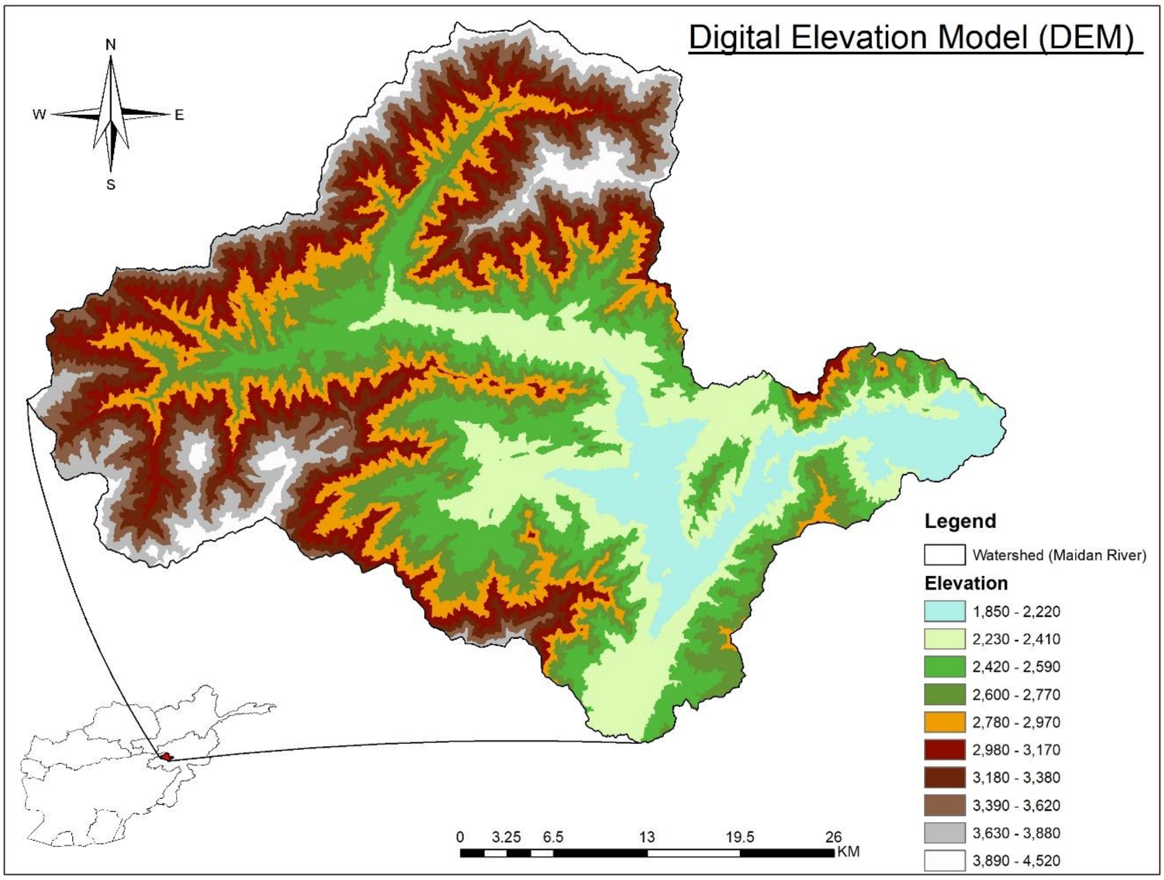

Figure 1: DEM map of the study area

Hydro-meteorological Data

There are 2 Hydro-meteorological and 1 Metrological station available in the study area, as shown in Figure 3.3, and the details are provided in Table 1 below; the precipitation data were available from the hydro-meteorological station from the period 2008 up to 2022 and from the metrological station from 2012 up to 2020 the data of metrological station has a gap before the year 2012 and after 2020 because of a technical problem. Meteorological data between 1967 and 2008 faced significant disruptions in the study area due to regional instability and civil conflict. Following this period, the Ministry of Energy and Water installed three stations on the watershed of the Maidan River, including Tang-i-Sayedan station. To calibrate the SWAT model, this research utilized daily data encompassing precipitation observations, air temperature, relative humidity, sunshine hours, and wind speed. These observations were complemented with discharge data obtained from hydro-meteorological stations operating under the supervision of MoEW of Afghanistan.

Table 1: Study area stations

No	Station location	Station type	Coordinates	
1	Pul-i-Surkh	Hydro-meteorological	Lat=34.36684	Long=68.76965
2	Tang-i-Sayedan	Hydro-meteorological	Lat=34.40898	Long=69.10441
3	Maidan Central	Metrological	Lat=34.39494	Long=68.86507

Consequently, to execute an effective and precise SWAT model and mitigate data gaps for a more resilient simulation process, we acquired information on wind speed, solar radiation, and relative humidity from various segments of the river basin through the (CFSR) website.

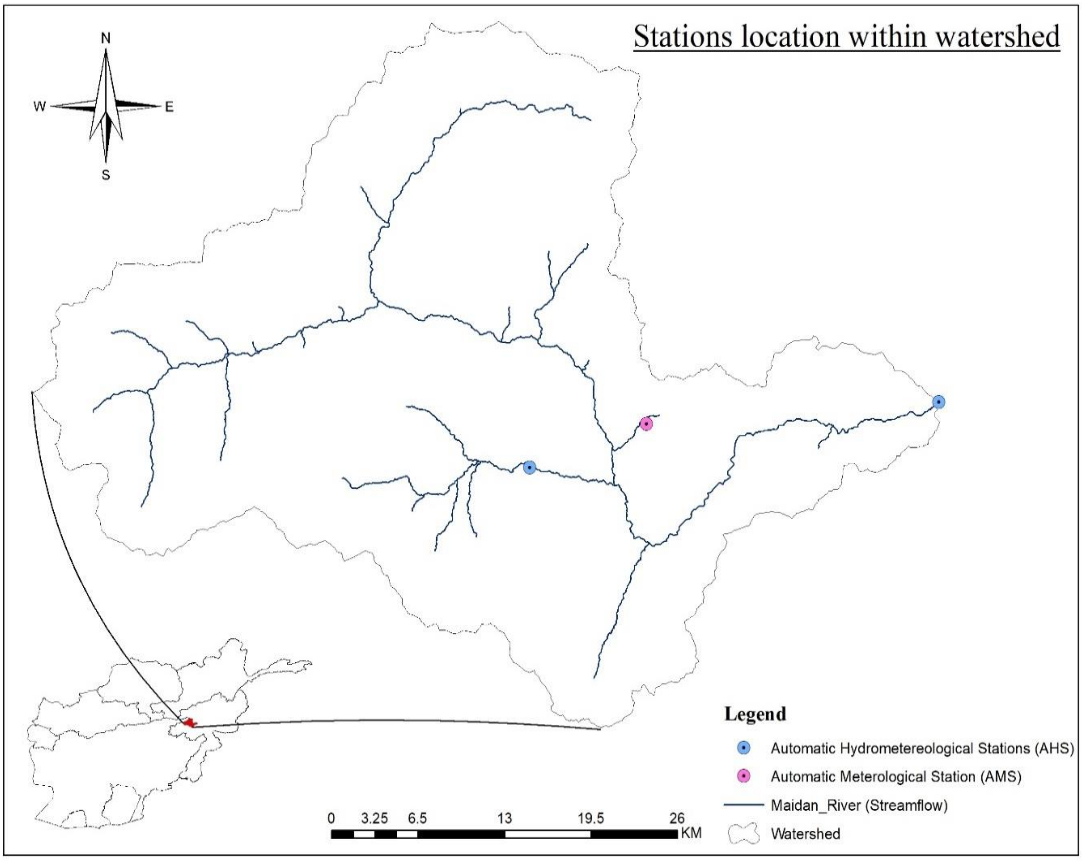

Figure 2: AHS & AMS stations location

Land Use/Land Cover Map

In this study, the land cover datasets were sourced from the Afghanistan Land Cover dataset (2010), generously provided by the Food and Agriculture Organization (FAO). The land cover characteristics were comprehensively presented and visually depicted in Figure 3, providing a clear and illustrative overview. The land cover map has been meticulously generated, revealing that rangeland encompasses 75% of the study area. The graphical representation of land use and land cover is shown in Figure 3.

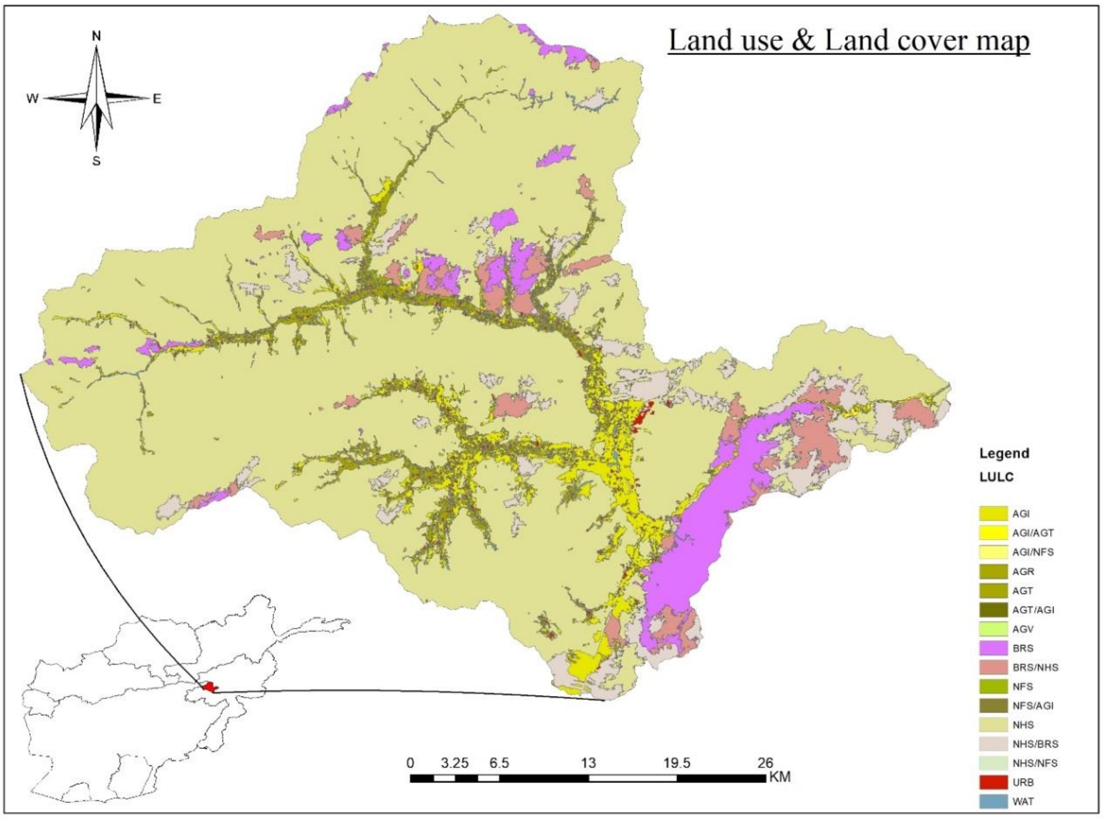

Figure 3: Land use and land cover map

Soil Map

The SWAT model requires diverse soil properties, encompassing soil texture, available water content, hydraulic conductivity, bulk density, and organic carbon content for different soil types. For this research, we obtained the soil dataset from the FAO/UNESCO website, with a spatial resolution of 90 meters by 90 meters. Subsequently, this dataset was projected to the Universal Transverse Mercator (UTM) coordinate system and integrated into the SWAT model at the Hydrological Response Unit. Figure 4 below shows the soil map and the comprehensive characteristics of the soil are presented in Table 2 below.

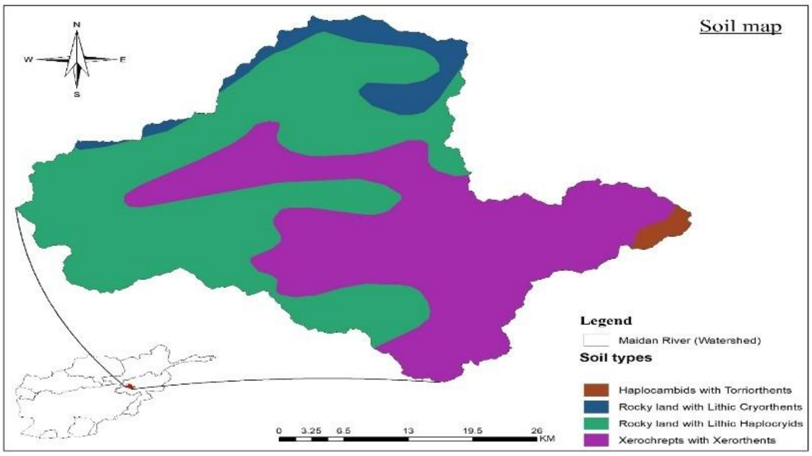

Figure 1: Soil Map of Maidan River watershed

Table 1: Soil types of Maidan River watershed

No	**Soil type**	**Area**	
		Square KM	Percentage (%)
1	Xerochrepts with Xerorthents	719.38	43.81
2	Rocky land with Lithic Cryorthents	102.40	6.24
3	Haplocambids with Torriorthents	16.73	1.02
4	Rocky land with Lithic Haplocryids	803.57	48.94

Watershed Delineation

The initial phase in creating input for the SWAT model entails delineating the watershed using the Digital Elevation Model (DEM). The inputs integrated into the SWAT model were systematically arranged to account for spatial characteristics. A crucial step in establishing the watershed model and defining Hydrological Response Units (HRUs) involved projecting the DEM into the UTM zone with N42, tailored to Afghanistan's projection parameters. The watershed was partitioned into 25 sub-basins for modeling purposes, as depicted in Figure 5.

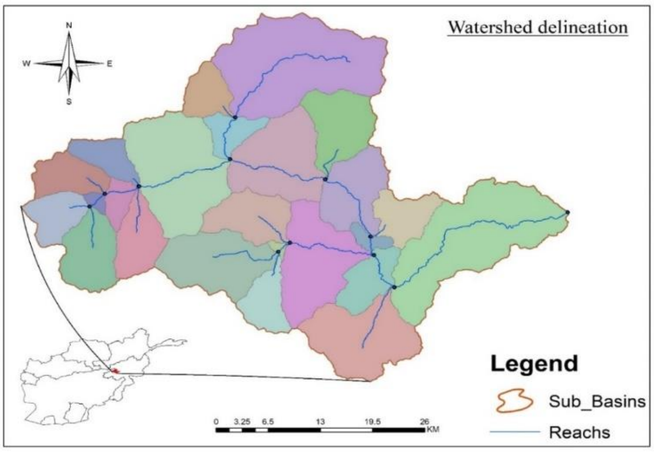

Figure 5: Watershed delineation map

The watershed delineation process involves five key steps: DEM setup, stream definition, outlet and inlet definition, and watershed outlets definition. Threshold-based stream definition options were applied to establish the optimal size of the sub-basins.

Model Performance

The analysis of SWAT performance in simulating surface flow involves the assessment of key parameters, including the coefficient of determination (R2), Nash Sutcliffe efficiency (NSE), and present bias (PBIAS). Various researchers commonly recommend these parameters. The determination of the coefficient of determination, Nash Sutcliffe efficiency, and present bias parameters are conducted using Equations 4, 5, and 6, respectively.

$$R^2 = \frac{\sum_{i=1}^{n}(Q_{o,i} - \bar{Q}_o)(Q_{s,i} - \bar{Q}_s)}{\sqrt{\sum_{i=1}^{n}(Q_{o,i} - \bar{Q}_o)}\sqrt{\sum_{i=1}^{n}(Q_{s,i} - \bar{Q}_s)}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. (4)$$

$$NSE = \frac{\sum_{i=1}^{n}(Q_{s,i} - Q_{o,i})^2}{\sum_{i=1}^{n}(Q_{o,i} - \bar{Q}_o)} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. \dots\dots\dots\dots\dots\dots\dots (5)$$

$$PBAIS = \frac{\sum_{i=1}^{n}(Q_{s,i} - Q_{o,i})}{\sum_{i=1}^{n}(Q_{o,i})} * 100 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (6)$$

In this context, the variables are defined as follows: R² represents the coefficient of determination, NSE stands for Nash Sutcliffe efficiency, PBIAS denotes the present bias, and n signifies the period. In contrast, Qo and Qs represent the observed and simulated streamflow. Additionally, $\overline{\text{Qo}}$ and $\overline{\text{QS}}$ signify the mean values of observed and simulated discharge, respectively.

Table 3: Calibration and Validation parameters efficiency ranges

Objective function	**Performance Rating**			
	Very Good	**Good**	**Satisfactory**	**Unsatisfactory**
PBIAS (%)	PBIAS < ± 10	10 ± ≤ PBIAS ≤ ± 15	15 ± ≤ PBIAS ≤ ± 25	PBIAS ≥ ± 25
R2	75 < R2 ≤ 1	0.65 < R2 ≤ 0.75	0.5 < R2 ≤ 0.65	R2 ≤ 0.5
NSE	75 < NSE ≤ 1	0.65 < NSE ≤ 0.75	0.5 < NSE ≤ 0.65	NSE ≤ 0.5

RESULTS

Impact on Precipitation

The analysis in Figure 6 shows that precipitation is on a decreasing trend. While the sequential scope of this study may be limited, covering only the period from 2009 to 2022, the findings show a significant downward trajectory in precipitation levels. This observation assumes significance given the broader context of climate change research. The study provides a simplified yet crucial insight into the changing precipitation patterns, indicating a substantive reduction in the overall volume of precipitation. This straightforward analysis aligns with the broader efforts in climate change studies, underscoring the need for ongoing investigations to deepen our understanding of evolving climatic conditions and their impacts on water resources.

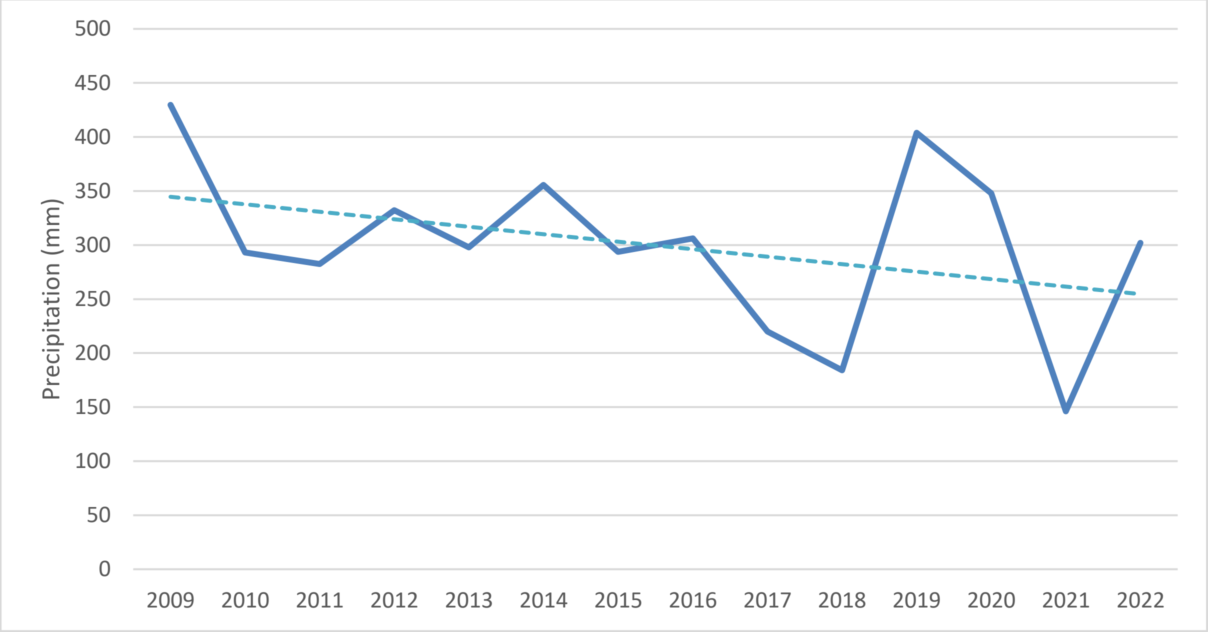

Figure 6: Annual precipitation trend from 2009 to 2022

Impact on Temperature

The analysis of temperature data from 2009 to 2022, presented in Figure 7, reveals a significant and consistent upward trend, indicating a noticeable shift in temperature patterns. This observed increase in temperatures underscores remarkable changes in our climate. Despite potential regional variations, the overall trend points toward a warming environment. The primary purpose of this temperature analysis is to comprehend and document the changing climate conditions over this specific timeframe. By examining temperature trends, the study aims to contribute to our understanding of the broader impacts of climate change.

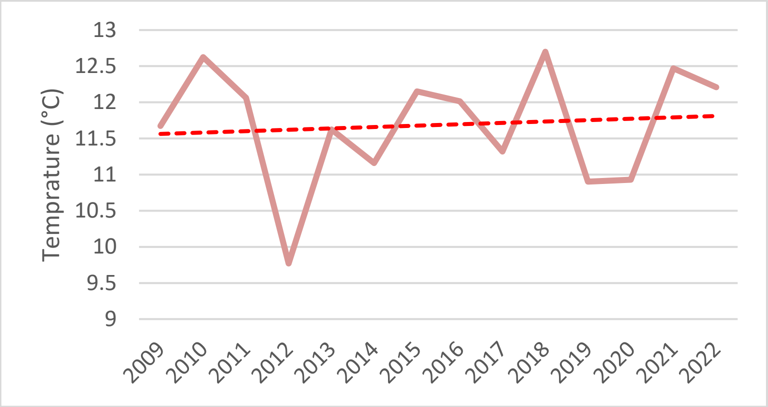

Figure 7: Annual temperature trend from 2009 to 2022

Impact on Streamflow

In Afghanistan, the flow of rivers relies heavily on rain, snow, and the melting of glaciers. Climatic shifts, particularly rising temperatures, are triggering the melting of glaciers, resulting in a temporary increase in river water. The ongoing analysis emphasizes changes in the peak river flow as a prominent indicator of climate change. A comparison between historical data (1962-1980), as illustrated in Figure 8, and present data (2008-2017), as shown in Figure 9, reveals a significant shift. In the past, the highest river flow occurred in April and May, but it entirely happens in March. This alteration points to earlier snow melting due to warming temperatures.

The temperature rise, indicative of climate change, is associated with heightened greenhouse gas levels. The analysis further discloses a subtle decrease in the peak river flow compared to the past, indicating a reduced water supply. These findings underscore the tangible impact of climate change on water resources in Afghanistan. Understanding these alterations is crucial for effective water resource management and underscores the need for sustainable strategies in evolving climate conditions.

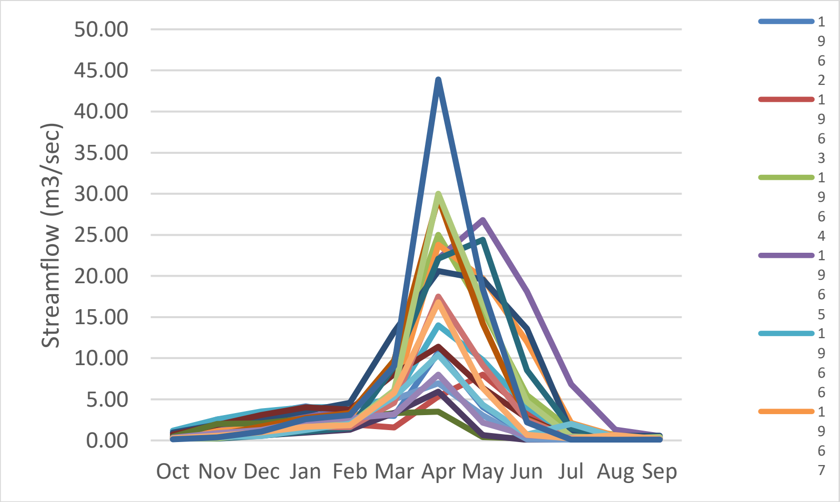

Figure 8: Mean monthly average streamflow from 1962 to 1980 in Tang-i-Sayedan

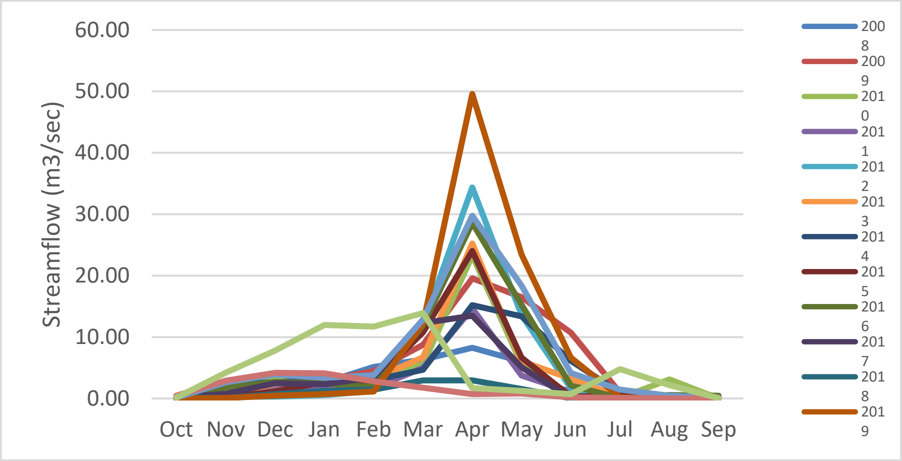

Figure 9: Mean monthly average streamflow from 2008 to 2022 in Tang-i-Sayedan

Future Analysis of Climate Change and Streamflow

In future climate change and streamflow analysis, particular attention is directed towards the critical elements of temperature, precipitation, and streamflow dynamics. Employing advanced climate models, the analysis seeks to project future scenarios, considering the anticipated shifts in temperature patterns and their impact on precipitation. These changes are expected to influence streamflow dynamics, affecting the timing and volume of water flow in rivers and streams. As temperatures rise, the potential for altered precipitation patterns and subsequent shifts in streamflow becomes increasingly apparent. The analysis aims to discern the intricate interplay between these key variables, contributing to a nuanced understanding of the evolving relationship between climate change, temperature, precipitation, and streamflow patterns. This knowledge is essential for formulating adaptive strategies and sustainable water resource management in the face of climate variability.

Selection of Suitable Climate Change Model

Global Climate Models (GCMs) are essential tools scientists employ to project and analyze future climate conditions. In climate research, the Coupled Model Intercomparison Project Phase 6 (CMIP6) represents a significant collaborative effort where numerous models contribute to our understanding of climate. Among the diverse array of GCMs available within CMIP6, this research has specifically chosen the CESM2 model for predicting daily precipitation and temperature data from 2030 to 2099.

CESM2, or the Community Earth System Model version 2, is a state-of-the-art climate model developed by the National Center for Atmospheric Research (NCAR). It is renowned for its comprehensive representation of Earth's climate system, including the atmosphere, ocean, land surface, and sea ice. The model incorporates advanced features, such as improved spatial resolution and enhanced simulations of complex climate processes. The selection of CESM2 for this research underscores its suitability for capturing the intricate interactions within the Earth's climate system over an extended timeframe by focusing on the period from 2030 to 2099.

Table 4: List of CMIP6, GCMs

NO	Model Name	Modeling Center/Nation	Horizontal Resolution (lat. x lon.)
1	ACCESS–CM2	Commonwealth Scientific and Industrial Research Organization/Australia	1.25° x 1.875°
2	ACCESS–ESM1–5		1.25°x 1.875°
3	BCC–CSM2–MR	Beijing Climate Center China Meteorological Administration/China	1.125°x1.125°
4	CanESM5	Canadian Centre for Climate Modelling and Analysis/Canada	2.8° x 2.8°
5	CNRM–CM6–1	Centre National de Recherches Météorologiques–Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique/France	1.4°x 1.4°
6	CNRM–ESM2–1		1.4°x 1.4°
7	EC–Earth3–Veg	EC–EARTH consortium/Europe	0.7° x 0.7 °
8	FGOALS–g3	Chinese Academy of Sciences/China	2.25°x 2°
9	GFDL–CM4	NOAA Geophysical Fluid Dynamics Laboratory/USA	1° x 1.25°
10	GFDL–ESM4		1° x 1.25°
11	HadGEM3–GC31–LL	Met Office Hadley Centre/UK	1.25°x1.875°
12	INM–CM4–8	Institute for Numerical Mathematics, Russian Academy of Science/Russia	1.5°x 2°
13	INM–CM5–0		1.5°x 2°
14	IPSL–CM6A–LR	L'Institut Pierre–Simon Laplace/France	1.26° x2.5°
15	MIROC6	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute,	1.4°x1.4°
16	MIROC–ES2L	The University of Tokyo, National Institute for Environmental Studies, and RIKEN Center for Computational Science/Japan	1.4°x1.4°
17	MPI–ESM–1–2–HR	Max Planck Institute for Meteorology/Germany	0.9375° x 0.9375°
18	MPI–ESM–1–2–LR		1.875°x 1.875°
19	CESM2	National Center for Atmospheric (USA)	0.94°x1.25°
20	MRI–ESM2–0	Meteorological Research Institute/Japan	1.125° X 1.125°
21	NESM3	Nanjing University of Information Science and Technology/China	1.875°X1.875°
22	NorESM2–LM	Norwegian Climate Centre/Norway	1.875°X 2.5°

23	NorESM2–MM		0.9375° X 1.25°
24	UKESM1–0–LL	Met Office Hadley Centre/UK	1.25°X1.875°

Climate Change Scenarios

Climate change scenarios are hypothetical representations of future conditions used in climate science to explore a range of possible futures based on different assumptions about human activities, socio-economic development, and policy choices. These scenarios help scientists and policymakers understand the potential impacts of climate change and develop strategies for mitigation and adaptation. There are some scenarios, such as SSP1 (Sustainability), SSP2 (Middle of the Road), SSP3 (Regional Rivalry), SSP4 (Inequality), and SSP5 (Fossil-Fueled Development). In this research, the two most common scenarios, SSP2-4.5 and SSP5-8.5, are considered to analyze the future climate change and its impact on the streamflow of Maidan River. These scenarios are selected to systematically analyze the anticipated climate changes and their subsequent impacts on the streamflow of the Maidan River.

SSP245 and SSP585 are Shared Socio-economic Pathways used in climate change research to explore future scenarios. They represent contrasting narratives of potential global development and greenhouse gas emissions.

SSP2-4.5: This pathway describes a future world where moderate efforts are made to address societal and environmental challenges. It envisions a balanced approach focusing on sustainable development and moderate greenhouse gas emissions.

SSP5-8.5: This pathway portrays a world with high challenges to mitigation and adaptation. It assumes a future with limited efforts to address environmental concerns, resulting in a high greenhouse gas emissions scenario and significant climate change impacts.

Projected Temperature

Examining the future trajectory of average temperature changes under the two distinct Shared Socio-economic Pathways (SSPs), SSP4.5 and SSP8.5, across three temporal intervals: near future (2030-2050), mid-future (2051-2070), and far future (2071-2099) presented in figure 10 and comprehensively illustrated in Table 5 reveals a consistent pattern of temperature increase. These projections are compared against a baseline period of 2008-2022, offering insights into the potential impacts of different socio-economic and emissions scenarios on global temperatures. The comparison between the baseline and projected values underscores a concerning trend of rising mean temperatures. Soon, temperatures are estimated to increase by 2.03°C under SSP4.5 and 2.68°C under SSP8.5, relative to the 2008-2022 baselines. The mid-future projections indicate a more substantial temperature rise, with an anticipated increase of 2.77°C under SSP4.5 and 4.32°C under SSP8.5. Looking further into the future, the temperature projections accentuate the gravity of the situation, revealing an even more pronounced elevation of 3.24°C under SSP4.5 and a staggering 6.17°C under SSP8.5.

Table 5: Projected mean temperature changes under SSP4.5 and SSP8.5

		Baseline	**2030-2050**		**2051-2070**		**2071-2099**	
			Average	Change	Average	Change	Average	Change
Temperature	SSP2-4.5	11.5°C	13.53°C	2.03°C	14.27°C	2.77°C	14.74°C	3.24°C
	SSP5-8.5		14.18°C	2.68°C	15.82°C	4.32°C	17.67°C	6.17°C

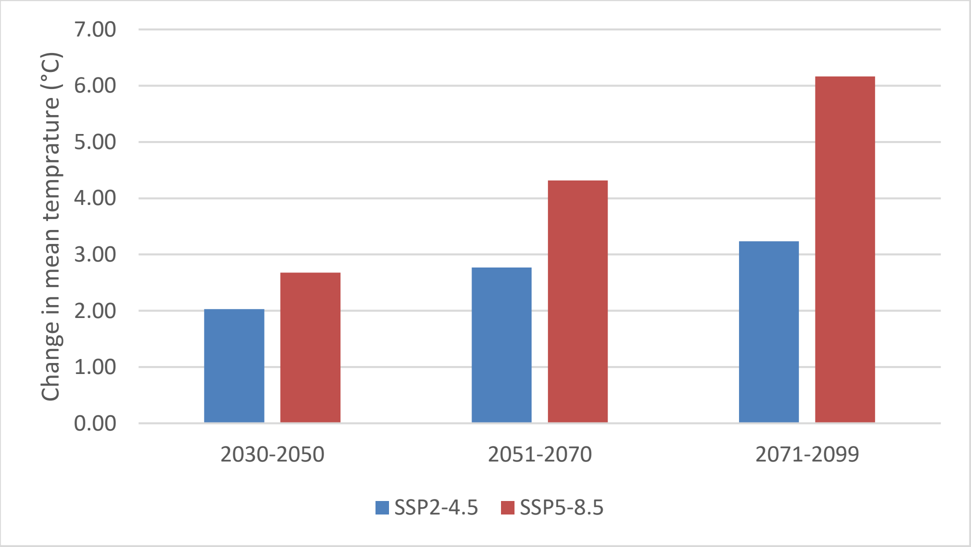

Figure 10: Projected Change in mean temperature for horizon near future, mid-future, and far future under SSP4.5 and SSP8.5

The monthly mean changes in temperature are analyzed in Figure 11 and Figure 12, showing that there are positive changes in temperature in all months; considering the far future, the most significant increase in average temperature occurs in February, rising by approximately 3.64°C under SSP4.5. Conversely, the slightest change in average temperature during this period is observed in May, with an increase of about 2.58°C under SSP4.5. In contrast, under SSP8.5, the maximum temperature change is also noted in February, with a more substantial rise of approximately 6.71°C. Similarly, the least change in average temperature for SSP8.5 in the far future is found in May, showing an increase of about 5.49°C. These observations highlight the variability in temperature changes across months and underscore the distinct impacts of different emissions scenarios on future climate conditions.

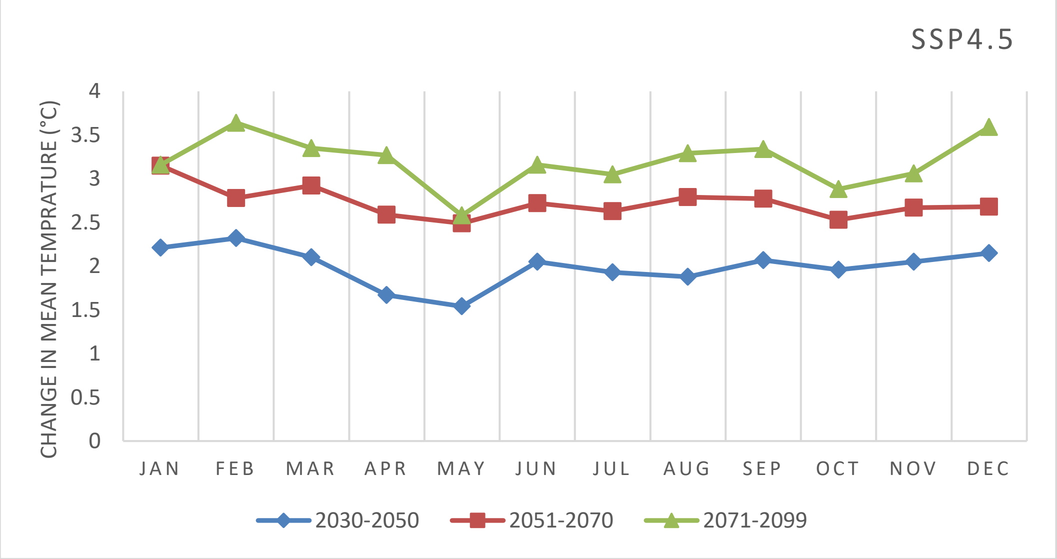

Figure 11: Change in mean monthly temperature for horizon near future, mid-future, and far future under SSP4.5

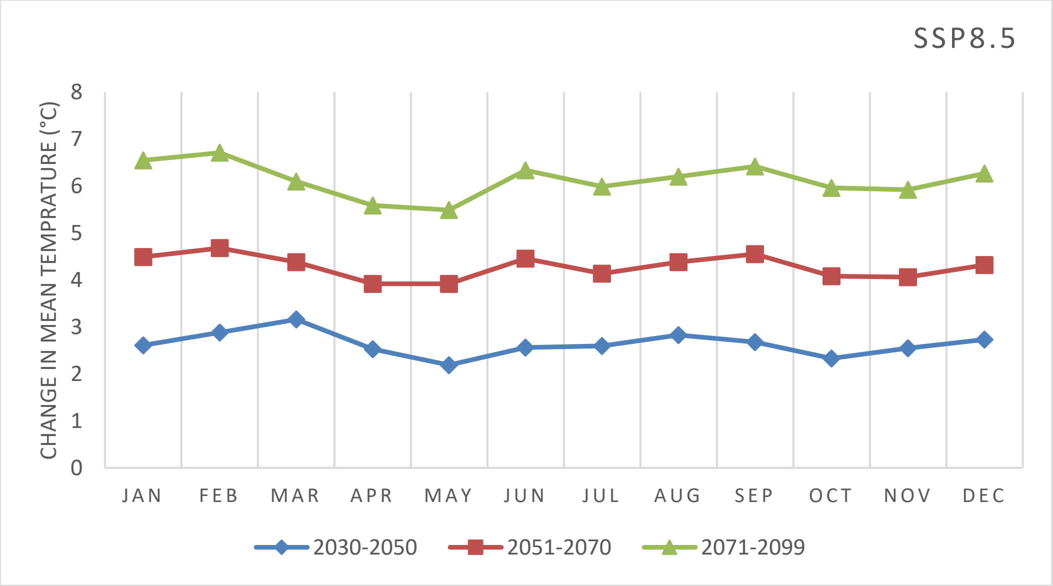

Figure 12: Change in mean monthly temperature for horizon near future, mid-future, and far future under SSP8.5

Projected Precipitation

Examining the future changes in average precipitation under the Shared Socio-economic Pathways (SSPs) of 4.5 and 8.5 across three time intervals (near future, mid-future, and far future) reveals distinct patterns. The analysis, as depicted in Figure 13 and illustrated in Table 6 below, shows a consistent decrease in precipitation under SSP4.5, amounting to approximately 1.16% shortly, 3.5% in the mid-future, and 1.89% in the far future, when compared to a baseline period of 2008-2022. Conversely, contrasting trends are observed under SSP8.5, where precipitation is projected to increase by 1.11% shortly and 0.55% in the far future but decrease by 1.05% in the mid-future.

Table 6: *projected precipitation change under SSP4.5 and SSP8.5*

		Baseline (mm)	**2030-2050**		**2051-2070**		**2071-2099**	
			Average (mm)	Change (%)	Average (mm)	Change (%)	Average (mm)	Change (%)
Precipitation	SSP2-4.5	315	301.83	- 4.18	275.31	- 12.6	293.58	- 6.8
	SSP5-8.5		327.6	+ 4	303.25	- 3.73	321.3	+ 2

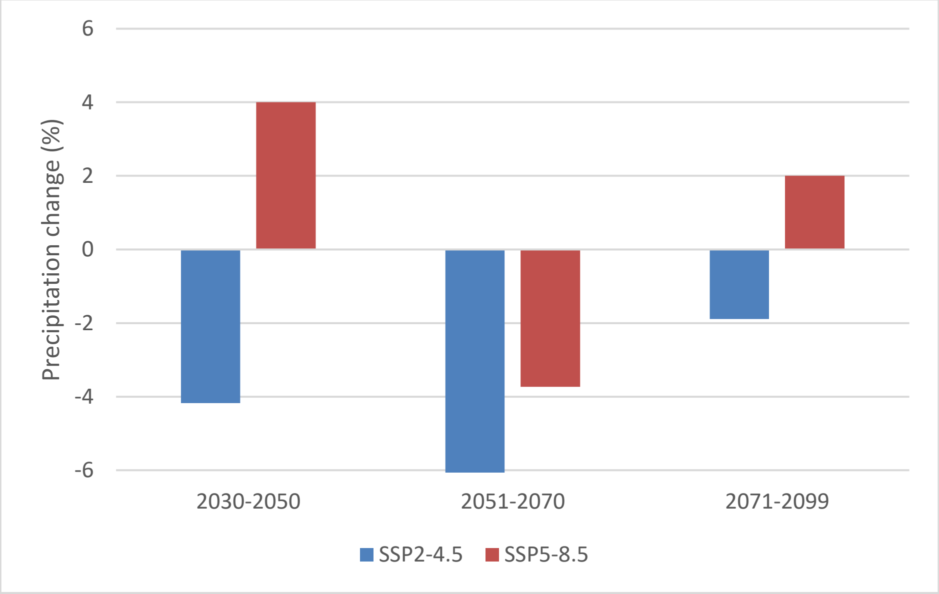

Figure 13: Change in mean precipitation for horizon near future, mid-future, and far future under SSP4.5 and SSP8.5

The examination of monthly projected precipitation, as illustrated in Figure 12 and Figure 13 under Shared Socio-economic Pathways (SSPs) 4.5 and 8.5, reveals a dynamic and varied pattern. The data indicates precipitation levels fluctuate across different months, showcasing increases and decreases. This nuanced approach to understanding monthly precipitation changes highlights the complexity of climate dynamics under these distinct SSPs. In some months, there is a noticeable rise in precipitation, potentially leading to concerns related to increased flooding or altered hydrological patterns. Conversely, certain months depict a decrease in precipitation, signaling potential challenges related to water scarcity. These findings emphasize the importance of considering the monthly variability in precipitation trends under different future scenarios.

Calibration and Validation of Streamflow

Calibration and validation are indispensable in developing and evaluating hydrological models, ensuring they accurately represent specific conditions. In this study, the Tang-i-Sayedan gauging station, strategically positioned at the outlet of the Maidan River watershed, played a pivotal role by recording daily and monthly river flow. The monthly dataset is used for both model calibration and validation analyses. Daily to monthly analyses were conducted on the data. Hydrological models are vital for simulating river flows and require a "warm-up" period to eliminate initial biases. In this investigation, the period from 2000 to 2007 served as the "warm-up" phase, facilitating the initialization of hydrological parameters. The calibration, particularly streamflow, involved iterative adjustments of parameters to optimize the model's representation against observed data. Key metrics such as Nash-Sutcliffe efficiency (NSE), coefficient of determination (R2), and percent bias (PBIAS) were employed to assess model performance.

This study's calibration process was iteratively conducted, refining parameter ranges to enhance the model's ability to replicate observed Streamflow. Model performance was rigorously evaluated by applying NSE, R2, and PBIAS. The calibration continued until the model achieved specific benchmarks: NSE more significant than 0.5, R2 greater than 0.5, and PBIAS less than the range of ±12, as outlined in Table 7. The parameter values obtained, such as R2=0.71, NSE=0.66, and PBIAS=10.9, fall within the specified range, indicating a satisfactory performance in calibrating monthly and streamflow data. This means the model adjusted its settings well to match real-world observations.

Table 7: Sensitive analysis parameters in Calibration and Validation

No	Parameter	Description	Values		
			Fitted	Min	Max
1	CN2.mgt	SCS runoff curve number	0.103	-0.2	0.2
2	ALPHA_BF.gw	Baseflow alpha factor (days)	0.402	0	1
3	GW_DELAY.gw	Groundwater delay time (days)	456.786	0	500
4	GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	4546.429	0	5000
5	SURLAG.bsn	Surface runoff lag time	19.124	0.05	24
6	SOL_AWC(..).sol	Available water capacity	0.139	0	1
7	SOL_K(..).sol	Saturated hydraulic conductivity (mm/h)	1558.571	0	2000
8	TLAPS.sub	Temperature lapse rate	-2.129	-10	10
9	EPCO.hru	Plant uptake compensation factor	0.586	0	1
10	ESCO.hru	Soil evaporation compensation factor	0.169	0	1

11	TIMP.bsn	Snow pack temperature lag factor	0.028	0	1
12	SMTMP.bsn	Snow melt base temperature	4.714	-20	20
13	SMFMN.bsn	Minimum melt rate for snow during the year	2.271	0	20
14	SMFMX.bsn	Maximum melt rate for snow during year	7.614	0	20
15	SFTMP.bsn	Snowfall temperature	-4.679	-5	5

The observed and simulated streamflow were also compared visually in Figure 14.

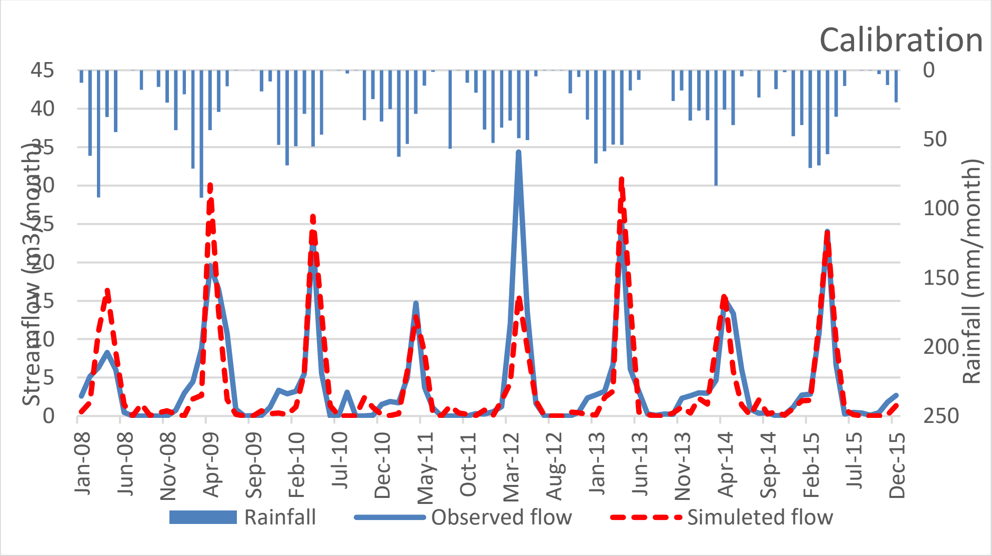

Figure 14: Hydrograph of Monthly Simulated and Observed streamflow for Calibration Period (2008-2015)

This careful and detailed approach ensured that the calibrated model met and surpassed the minimum requirements for accuracy and reliability. Consequently, the simulated results closely mirror the actual discharge patterns, demonstrating the model's effectiveness and dependability in accurately representing streamflow behavior.

The validation process is essential in evaluating the calibrated model's accuracy. The results of particular model validation affirm the calibrated model's effectiveness, revealing notable R2=0.73, NSE=0.69, and PBIAS=1.25 during the validation period, as meticulously presented in Table 8.

Table 8: Statistical Analysis of Streamflow Simulation for Calibration and Validation Period

No	**Period**	**Statistical metrics**		
		R2	NSE	PBIAS
1	Calibration (2008-2015)	0.71	0.66	10.9
2	Validation (2016-2022)	0.73	0.69	1.25

The comprehensive comparison of simulated and observed streamflow, as illustrated in Figure 15 below, is a testament to the model's reliability. These robust outcomes also highlight the model's capacity to consistently yield accurate results during the validation period and underscore its adaptability when applied to projected discharge data for future periods. The demonstrated reliability positions the calibrated model as a robust tool for confidently simulating and predicting streamflow dynamics in various hydrological scenarios.

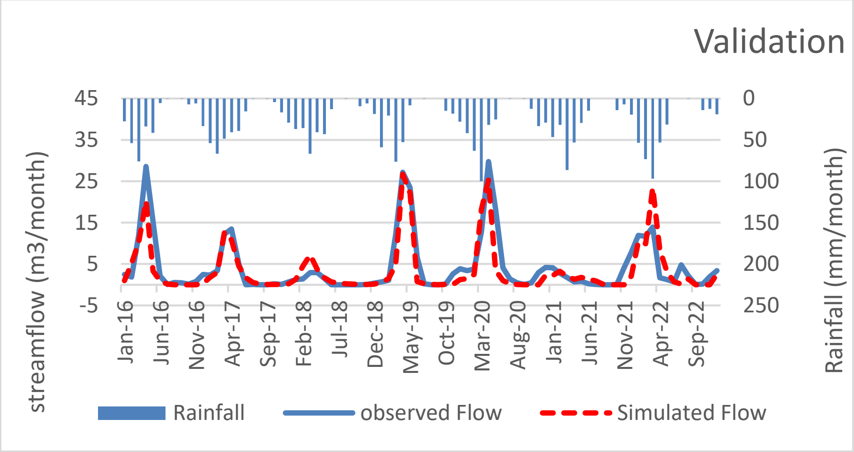

Figure 15: Hydrograph of Monthly Simulated and Observed streamflow for Validation Period (2016-2022)

The study utilizes scatter charts to calibrate and validate the hydrological model, as illustrated in Figure 16. In the calibration scatter chart, observed and simulated streamflow points closely align along a diagonal, indicating a well-calibrated model. The validation scatter chart is expected to follow a similar diagonal trend, affirming the model's reliability. These visualizations and metrics, like R2 and NSE, provide a concise and comprehensive evaluation of the model's accuracy in capturing observed streamflow dynamics.

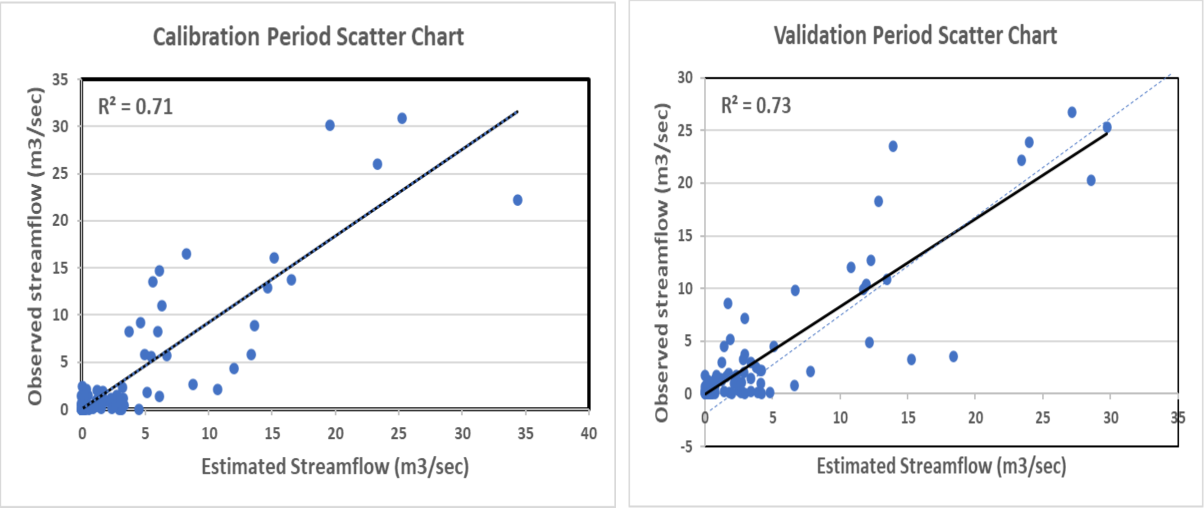

Figure 16: Calibration and Validation periods scatter charts

Analyzing Projected Streamflow

The assessment of future streamflow at the Tangi-Sayedan outlet considers two climate scenarios, SSP2-4.5 and SSP5-8.5. Figure 17 depicts the average annual periodic streamflow changes by percentage of Maidan River flow relative to the historical baseline period. In particular, both scenarios show a decrease in streamflow, with a more significant reduction evident for SSP5-8.5, as illustrated in Table 9.

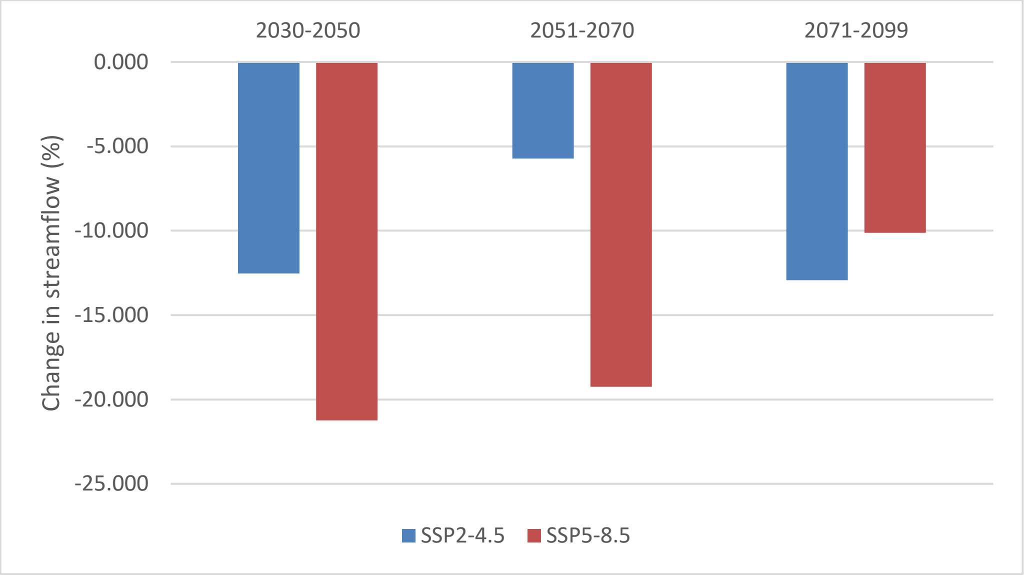

Figure 17: Streamflow annual average changes (%) under SSP4.5 and SSP8.5

Table 9: Streamflow changes under SSP4.5 and SSP8.5

		Baseline (2008-2022)	**2030-2050**		**2051-2070**		**2071-2099**	
			Average (m3/s)	Change (%)	Average (m3/s)	Change (%)	Average (m3/s)	Change (%)
Streamflow	SSP2-4.5	4.258 (m3/s)	3.724	-12.54	4.01	-5.72	3.7	-12.93
	SSP5-8.5		3.35	-21.23	3.44	-19.26	3.83	-10.13

This scenario presents the most adverse situation compared to the baseline, with streamflow decreasing by 12.54% shortly, 5.72% in the mid-future, and 12.9% in the far future under SSP4.5. Under SSP8.5, the reductions are more pronounced, with streamflow decreasing by 21.23% shortly, 19.26% in the mid-future, and 10.13% in the far future. These findings highlight the potential substantial impact of climate change on Maidan River streamflow across different future scenarios.

DISCUSSION

The anticipated decline in streamflow within the Maidan Sub-River Basin, as projected under the SSP2-4.5 and SSP5-8.5 scenarios, underscores a pressing issue for water resource management in Afghanistan, particularly in light of the country's heightened susceptibility to climate change impacts. The SWAT model's capability to accurately replicate historical discharge data enhances its role as a valuable predictive instrument for estimating future water availability. This precision is crucial for stakeholders, including government bodies and local populations, as it informs the development of adaptive strategies to mitigate the detrimental effects of water scarcity. Several noteworthy similarities and differences surface when juxtaposing our results with prior research conducted in the Kabul River Basin and other areas throughout Afghanistan. For example, Akhundzadah et al. (2020) indicated a forecasted reduction in water resources across various basins in the country, which corresponds with our findings concerning the Maidan River.

Nevertheless, the extent of streamflow reduction reported varies considerably among studies. This variation may stem from localized climatic differences, distinct watershed characteristics, and methodological disparities in the modeling approaches. While some studies suggest a more tempered decline—possibly attributable to anticipated increases in precipitation under specific future scenarios—our research points to a more significant reduction, showcasing the distinct hydrological characteristics of the Maidan Sub-River Basin. Additionally, although some regions may witness more frequent and intense rainfall events that could temporarily elevate streamflow, the overarching trend within the Maidan River indicates that diminishing snowpack—essential for sustaining summer flows—will likely compromise future water availability. The repercussions of declining streamflow extend beyond numerical evaluations; they significantly impact Afghanistan's socio-economic stability and food security. As Jawid and Khadjavi (2019) pointed out, the reduction in water resources threatens agricultural productivity, which remains a vital source of income for many Afghans. The disparity between urban and rural water needs is pronounced. Urban areas might adapt by pursuing alternative water supply systems; in contrast, rural communities that depend heavily on seasonal streamflow are more likely to encounter severe shortages, exacerbating their vulnerabilities. Consequently, the urgency for sustainable management practices becomes increasingly critical. The current trajectory suggests that traditional water governance structures may be inadequate in tackling the complex challenges presented by climate change. This situation necessitates innovative strategies, such as adaptive management practices that engage stakeholder participation and leverage scientific insights into local water management techniques. The partnership between researchers and policymakers is vital, as indicated by Lawler (2009), who emphasizes the importance of data-driven decision-making to facilitate effective conservation planning amid climate uncertainties.

In a nutshell, the outcomes of this study serve as an urgent reminder to acknowledge and proactively confront the looming challenges posed by climate change in the Maidan Sub-River Basin. By comparing our findings with existing literature, we highlight the distinctiveness of our results and their alignment with broader regional patterns, thereby enriching the discussion on climate adaptation in the Afghan context. Future inquiries should prioritize integrating localized water management practices with advanced climatic modeling efforts, ensuring resilience and sustainability in water resource governance as environmental conditions evolve.

CONCLUSION

This research aimed to analyze the impacts of climate change on the hydrological patterns of the Maidan River Basin in Afghanistan, utilizing the Soil and Water Assessment Tool (SWAT) to model and predict future streamflow dynamics. The findings underscore a notable alteration in streamflow due to anticipated shifts in precipitation and temperature, aligning with global trends of increased frequency and intensity of extreme weather events. Our analysis highlights a concerning downward trend in precipitation over the last thirteen years, emphasizing the need for region-specific assessments to forecast hydrological impacts accurately. Moreover, this study challenges prevailing theories of uniform climate influence by illustrating the significant role of local land use and soil conditions in shaping hydrological responses. The application of the CESM2 model provides critical projections indicating substantial reductions in water availability, posing serious challenges for local agriculture and water resource management. These findings emphasize the urgent need for adaptive management strategies and the integration of climate predictions into policymaking, ensuring that local approaches to water resource management are resilient and responsive to the profound shifts brought about by climate change. By utilizing the Soil and Water Assessment Tool (SWAT), this study seeks to provide clear insights into future streamflow changes, which are essential for developing effective water resource management strategies in response to the anticipated challenges posed by climate change.

Conflict of Interest: The authors declare no conflicts of interest.

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