Impact of climate change on water resources in the Yarmouk River Basin of Jordan Postprint

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Abstract

Understanding the impact of climate change on water resources is important for developing regional adaptive water management strategies. This study investigated the impact of climate change on water resources in the Yarmouk River Basin (YRB) of Jordan by analyzing the historical trends and future projections of temperature, precipitation, and streamflow. Simple linear regression was used to analyze temperature and precipitation trends from 1989 to 2017 at Irbid, Mafraq, and Samar stations. The Statistical Downscaling Model (SDSM) was applied to predict changes in temperature and precipitation from 2018 to 2100 under three Representative Concentration Pathway (RCP) scenarios (i.e., RCP2.6, RCP4.5, and RCP8.5), and the Soil and Water Assessment Tool (SWAT) was utilized to estimate their potential impact on streamflow at Addasiyia station. Analysis of data from 1989 to 2017 revealed that mean maximum and minimum temperatures increased at all stations, with average rises of 1.62°C and 1.39°C, respectively. The precipitation trends varied across all stations, showing a significant increase at Mafraq station, an insignificant increase at Irbid station, and an insignificant decrease at Samar station. Historical analysis of streamflow data revealed a decreasing trend with a slope of -0.168. Significant increases in both mean minimum and mean maximum temperatures across all stations suggested that evaporation is the dominant process within the basin, leading to reduced streamflow. Under the RCP scenarios, projections indicated that mean maximum temperatures will increase by 0.32°C to 1.52°C, while precipitation will decrease by 8.5% to 43.0% throughout the 21st century. Future streamflow projections indicated reductions in streamflow ranging from 8.7% to 84.8% over the same period. The mathematical model results showed a 39.4% reduction in streamflow by 2050, nearly double the SWAT model' s estimate under RCP8.5 scenario. This research provides novel insights into the regional impact of climate change on water resources, emphasizing the urgent need to address these environmental challenges to ensure a sustainable water supply in Jordan.

Full Text

Preamble

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Impact of climate change on water resources in the Yarmouk River Basin of Jordan

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Abstract: Understanding the impact of climate change on water resources is important for developing regional adaptive water management strategies. This study investigated the impact of climate change on water resources in the Yarmouk River Basin (YRB) of Jordan by analyzing historical trends and future projections of temperature, precipitation, and streamflow. Simple linear regression was used to analyze temperature and precipitation trends from 1989 to 2017 at Irbid, Mafraq, and Samar stations. The Statistical Downscaling Model (SDSM) was applied to predict changes in temperature and precipitation from 2018 to 2100 under three Representative Concentration Pathway (RCP) scenarios (RCP2.6, RCP4.5, and RCP8.5), and the Soil and Water Assessment Tool (SWAT) was utilized to estimate their potential impact on streamflow at Addasiyia station. Analysis of data from 1989 to 2017 revealed that mean maximum and minimum temperatures increased at all stations, with average rises of 1.62°C and 1.39°C, respectively. Precipitation trends varied across stations, showing a significant increase at Mafraq station, an insignificant increase at Irbid station, and an insignificant decrease at Samar station.

Historical analysis of streamflow data revealed a decreasing trend with a slope of -0.168. Significant increases in both mean minimum and mean maximum temperatures across all stations suggested that evaporation is the dominant process within the basin, leading to reduced streamflow. Under the RCP scenarios, projections indicated that mean maximum temperatures will increase by 0.32°C to 1.52°C, while precipitation will decrease by 8.5% to 43.0% throughout the 21st century. Future streamflow projections indicated reductions ranging from 8.7% to 84.8% over the same period. The mathematical model results showed a 39.4% reduction in streamflow by 2050, nearly double the SWAT model' s estimate under the RCP8.5 scenario. This research provides novel insights into the regional impact of climate change on water resources, emphasizing the urgent need to address these environmental challenges to ensure a sustainable water supply in Jordan.

Keywords: streamflow; climate change; Soil and Water Assessment Tool (SWAT); Statistical Downscaling Model (SDSM); Yarmouk River Basin; Jordan

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1 Introduction

Climate change has been observed at local, regional, and continental levels due to rising greenhouse gas (GHG) concentrations, particularly carbon dioxide (CO_2) (IPCC, 2007). These changes manifest in various ways, including shifts in precipitation timing and volume, changes in wind patterns, and intensification of extreme weather events such as heatwaves, cold spells, floods, heavy rainfall, droughts, tornadoes, and tropical cyclones (IPCC, 2007, 2022). The average global temperature has been rising and is projected to continue increasing throughout the 21st century (IPCC, 2013). From 2015 to 2022, the average global temperature increased by at least 1.00°C compared to pre-industrial levels (WMO, 2023). The past eight consecutive years have been the warmest on record, with an increase of about 1.15°C in average global temperature compared to pre-industrial levels (WMO, 2023). Predicting precipitation patterns is more challenging than temperature due to significant spatial variability and heterogeneity (Cheng et al., 2021). Human activities that drive climate change pose serious global challenges to natural and human systems, threatening sustainable development and increasing risks for poorer and less developed regions. Persistent GHG emissions will lead to continued global warming and long-term changes across all climate system elements, raising the likelihood of severe, widespread, and enduring impacts on humans and ecosystems (IPCC, 2021).

Over the last 60 years, Jordan has experienced an annual increase in maximum temperatures by 0.30°C-1.80°C and minimum temperatures by 0.40°C-2.80°C. Average annual precipitation has decreased by 5.0%-20.0%, except in Ras Muneef, where it increased by 5.0%-10.0% (USAID, 2017). At least three consecutive droughts have occurred in the past 40 years (Shatanawi et al., 2013), with both frequency and severity intensifying over time (Hammouri and El-Naqa, 2007; Sada et al., 2015). The rise in evaporation and decrease in precipitation are expected to reduce groundwater and surface water recharge, diminishing water resource supplies (MOENV and UNDP, 2014). Water scarcity, worsened by climate change, threatens all sectors in arid regions and hampers progress toward sustainable development (Al-Hasani et al., 2023).

Jordan, a small developing country, faces ongoing environmental challenges including water scarcity, soil degradation, desertification, drought, extreme temperatures, and biodiversity decline. These issues create significant social, economic, and political security challenges (Al-Jaafreh and Nagy, 2018; Hussein et al., 2020). Jordan ranks as the world' s second-poorest country in terms of water resources, with annual per capita renewable water availability of less than 100.00 m^3—far below the absolute water scarcity threshold of 500.00 m^3

(Alzboon et al., 2021; Alqatarneh and Al-Zboon, 2022). The country’ s primary water sources are shared with neighboring countries, creating a precarious situation further strained by regional instability. As a result, Jordan’ s water allocation has decreased over time. One of Jordan’ s three principal rivers, the Yarmouk River, contributes 50.0% of the country’ s surface water resources. In the 1950s, the Yarmouk River’ s mean annual flow was estimated at 4.50\$$\times10^{\{8\}-5.00\times10}$\{8\}\$ m^3. However, this flow has significantly decreased to just 0.83\$$\times10^{\{8\}-0.99\times10}$\{8\}\$ m^3 in recent years (ESCWA, 2013; Al-Kharabsheh, 2020). Meanwhile, water scarcity remains a major challenge. Rapid population growth, economic sector expansion, a high rate of non-revenue water, limited energy sources, and climate change impacts on precipitation are all worsening water deficits. These factors place added strain on Jordan’s limited water resources and make the country highly vulnerable to drought (MWI, 2020; MOENV, 2021; UNICEF, 2022). The Yarmouk River Basin (YRB) faces significant water supply challenges, as demand greatly exceeds available resources, placing increased pressure on domestic water supplies. This issue is exacerbated by the inability of water resource systems to withstand disruptions from climate change, drought, and sudden population increases, which have further strained available resources (Shammout et al., 2023a). During 1997–2017, the basin’ s population doubled from 0.64\$×10^{6}\$ to 1.53\$×10^{6}\$, leading to a substantial increase in total water use despite a decline in per capita availability. An Autoregressive Integrated Moving Average (ARIMA) model forecasts a 2.0% annual increase in domestic water use, with a 15.0% rise expected by 2030, presenting a major challenge for future water supplies (Shammout et al., 2023b).

The YRB has experienced a significant decline in precipitation since 1992, leading to reduced annual streamflow. This decline has been exacerbated by high evaporation rates due to climatic factors and rapid population growth (Al-Kharabsheh, 2022). The Water Evaluation and Planning Model (WEAP) was utilized to investigate the effect of global warming on hydrological systems in the YRB. Analyses indicated that streamflow in the YRB is expected to decrease significantly, with a reduction of up to 30.0% projected under most climate change scenarios (MOENV and UNDP, 2009). Hammouri et al. (2017) studied climate change impacts on water resources in northern Jordan to assess future changes in water availability. Their results suggested that streamflow is expected to decrease by 22.0% by 2080, leading to increased water deficit in Jordan. Abdulla and Al-Shurafat (2020) also predicted that Yarmouk River streamflow would likely decrease by 36.4% by the end of the 21st century under post-development conditions. Al Sabeh et al. (2022) found that agriculture and population growth have led to significant water shortages in the YRB. Under Representative Concentration Pathway (RCP) scenarios (RCP4.5 and RCP8.5), both surface water availability and dam retention have significantly decreased, with Jordan’ s share of the Yarmouk River being the most affected.

The primary focus of this study is to assess the impact of climate change on water resources in the YRB. Although a few studies have examined climate change impacts on Yarmouk River water resources, they did not determine the significance of past changes or the reasons behind them. This study aims to provide a comprehensive and contemporary analysis of climate change in the YRB, utilizing accurate and recent data. The impact of climate change over recent decades was assessed by analyzing temperature and precipitation changes. Future projections were conducted to estimate potential climate change impacts on Yarmouk River streamflow under scenarios from the second-generation Canadian Earth System Model (CanESM2) Global Climate Models (GCMs) using the Statistical Downscaling Model (SDSM) and Soil and Water Assessment Tool (SWAT). Additionally, a mathematical model linking streamflow and evapotranspiration was employed to reduce uncertainty in the modeling and downscaling processes. The results will provide decision-makers with necessary data regarding climate change in the YRB, which will be crucial for addressing water budget and environmental planning.

2.1 Study area

The YRB (Fig. 1 [Figure 1: see original paper]) is located in the northern region of Jordan and extends into Syrian territory. The basin covers an area of approximately 7000 km^2. The study area focused on the Jordanian side, constituting 21.0% of the total basin area. The Yarmouk River is the largest tributary of the Jordan River. The main tributaries of the Yarmouk River include the seasonal streams in Syria: Zeidi, Dahab, Harir, Ruqqad, and Allan. The perennial Yarmouk River is approximately 57 km long, with 47 km located within Syrian territory. It runs along the border between Jordan and Syria (ESCWA, 2015). The climate in the YRB is characterized as semi-arid, featuring hot, dry summers and cold, wet winters. Annual precipitation on the Jordanian side varies, ranging from 600 mm in the western parts to less than 150 mm in the eastern parts (Al-Bakri et al., 2016).

Fig. 1 Overview of the Yarmouk River Basin (YRB) and the locations of meteorological stations, rainfall stations, and streamflow gauge station

2.2 Data sources

To study the effects of global warming on temperature, precipitation, and streamflow, we collected data from three meteorological stations (Irbid, Mafraq, and Samar), three rainfall stations (Hawwara, Hosha, and Samar), and one streamflow gauge station (Addasyia) within the basin. These data, obtained from the Ministry of Water and Irrigation (MWI), covered a 29-year period (1989-2017). Collected variables included daily minimum and maximum temperatures (°C), relative humidity (%), and wind speed (m/s) from meteorological stations; daily precipitation (mm) from rainfall stations; and streamflow (m^3/s) from the streamflow gauge station. For clarity, certain stations were referenced by their governorate names. Specifically, the Hosha station, located within Mafraq Governorate, was referred to as Mafraq, and the Hawwara station, within Irbid Governorate, was referred to as Irbid due to their proximity to respective governorate centers.

The YRB was delineated using a one arc-second (30 m) resolution digital elevation model (DEM) obtained from the Shuttle Radar Topography Mission (SRTM). Two-degree tiles covering the study area were downloaded from the USGS Earth Explorer website (http://earthexplorer.usgs.gov/). The DEM was projected to the WGS World Mercator (EPSG: 3857) coordinate system, and this projected DEM was then used to delineate the basin using the ArcSWAT 2012 tool within ArcGIS.

Land cover information for the YRB was extracted from the 10 m Sentinel-2 land cover dataset for 2021, produced by the Impact Observatory, Microsoft, and Esri (https://www.arcgis.com/apps/mapviewer/index.html?layers=d3da5dd386d140cf93fc9ecbf8da5e31).

The soil map was obtained from the Digital Soil Map of the World, version 3.6, created by the Food and Agriculture Organization of the United Nations (FAO). This digital soil map has a coarse scale of 1:5,000,000 and can be downloaded from the FAO GeoNetwork website (http://www.fao.org/geonetwork/srv/en/metadata.show?id=14116).

2.3 Data quality control

Homogeneity refers to the consistency of a data series and the extent to which data vary, specifically regarding whether they are influenced solely by climatic factors. Most long-term climatic time series are affected by various non-climatic factors that can distort actual climatic data.

Pettitt' s test (Pettitt, 1979), Standard Normal Homogeneity Test (SNHT) (Alexandersson, 1986), and von Neumann' s test (Von Neumann, 1941) were used to check the homogeneity of meteorological and hydrological data. Pettitt' s test determined when a significant change or break occurred in the time series. SNHT assessed the possibility of significant change in the arithmetic mean between years. Von Neumann's test indicated noticeable changes and breaks in the time series, though not the specific year of change. XLSTAT software executed these tests at a significance level of 0.05. The null hypothesis (H_0) assumed homogeneous data, while the alternative hypothesis (H) indicated nonhomogeneous data (data changed on a specific date). If $P<0.05$, H_0 was rejected and H accepted. If $P>0.05$, H_0 was accepted.

2.4 Trend analysis

Simple linear regression analyzed temperature and precipitation data after homogeneity testing. Trend significance was tested at a 95% confidence interval, with $P<0.05$ indicating a significant trend.

2.5 Climate change scenarios

Climatic variable downscaling was performed using a statistical method. Daily temperature and precipitation data were used for statistical downscaling in SDSM. SDSM employs multiple regression to analyze relationships between large-scale predictors from GCM simulations and daily climatic data at local sites (predictands). This study used CanESM2 GCMs, which produce climate change scenarios based on GHG RCPs. Three RCPs were considered: RCP2.6, RCP4.5, and RCP8.5. RCP2.6 is the most stringent scenario, requiring major emissions reductions to keep global temperature increase below 2.00°C, with radiative forcing of 2.6 W/m^2. RCP4.5 is a moderate scenario, projecting global temperature increase of around 2.00°C by 2100, with radiative forcing of 4.5 W/m^2. RCP8.5 is the highest emissions scenario, predicting global temperature rise exceeding 4.00°C by 2100, with radiative forcing of 8.5 W/m^2. All changes are compared to the pre-industrial era. Arithmetic means of temperature values and Thiessen polygons for precipitation represented generated scenarios across the entire basin.

2.6 Hydrological modeling

The SWAT model represents the culmination of nearly three decades of modeling experience by the United States Department of Agriculture Agricultural Research Service (USDA-ARS) and was developed in the 1990s (Gassman et al., 2007; Williams et al., 2008). The model has proven valuable in arid regions, even with limited data and extreme conditions. Previous research on the YRB demonstrated SWAT' s high capability to simulate streamflow (Hammouri et al., 2011; Abu-Zreig and Hani, 2021), highlighting its importance for achieving accurate results. For this study, ArcSWAT 2012 was employed to simulate hydrological processes including streamflow, runoff, and evapotranspiration for the period 1989–2017. SWAT model data included DEM, land cover map, soil map, daily maximum and minimum temperatures, daily precipitation, daily relative humidity, and daily wind speed. The model was calibrated and validated to achieve accurate results and reduce forecasting uncertainty (Refsgaard, 1997). After demonstrating accuracy by closely matching observed streamflow values, the model projected future streamflow under RCP scenarios.

2.7 Mathematical model

A mathematical model was developed to evaluate climate change impacts on streamflow and compare results with the SWAT model under various RCP scenarios. This approach aimed to reduce uncertainty, enhance accuracy, and approximate the most likely future scenarios.

To derive the relationship for streamflow prediction, numerous trials were conducted to link streamflow with evapotranspiration and precipitation. Results indicated that streamflow is better explained by evapotranspiration than precipitation, primarily because evapotranspiration dominates the hydrological cycle in the YRB. The relationship between streamflow and evapotranspiration was well represented by a power equation that demonstrated superior performance compared to other equation types. A dataset comprising 180 monthly streamflow and potential evapotranspiration data pairs established the mathematical model, and 21 monthly streamflow data points assessed model performance. The equation is as follows:

$$Q = 36.275 \times \mathrm{PET}^{-0.68}$$

where Q is monthly streamflow (m^3/s) and PET is monthly potential evapotranspiration (mm).

PET was calculated using the Hargreaves equation (Hargreaves and Samani, 1985), a simple evapotranspiration model requiring only four accessible variables. The Hargreaves method is recommended by the FAO (Allen et al., 1998), and the equation is as follows:

$$\mathrm{PET} = 0.0023 \times R_a \times (T_{\mathrm{max}} - T_{\mathrm{min}})^{0.5} \times (T_{\mathrm{mean}} + 17.8)$$

where R is mean extraterrestrial radiation (mm/d), a function of latitude; T is maximum temperature (°C); T is minimum temperature (°C); and T is temperature arithmetic mean (°C).

3.1 Homogeneity tests for meteorological and hydrological data

Data were considered acceptable if they passed two of three tests. Table 1 illustrates homogeneity test results for precipitation data series. Irbid, Mafraq, and Samar stations passed SNHT; however, Mafraq failed von Neumann’ s test, and Samar failed Pettitt’ s test. All precipitation data series were acceptable for trend analysis and modeling. For temperature data, Irbid and Mafraq stations passed all tests, making their data series acceptable for trend analysis and modeling. In contrast, Samar’ s temperature data failed both Pettitt’ s and von Neumann’ s tests, making it unacceptable and necessitating corrections (Table 2).

Table 1 Homogeneity test results for annual precipitation data series

Station name	Pettitt’ s test	SNHT	Von Neumann’ s test
Irbid	Pass	Pass	Pass
Mafraq	Fail	Pass	Fail
Samar	Fail	Pass	Pass

Note: SNHT, Standard Normal Homogeneity Test; α, significance level; P-value, probability value.

Table 2 Homogeneity test results for annual mean temperature data series

Station Name	Pettitt' s test	SNHT	Von Neumann' s test
Irbid	Pass	Pass	Pass
Mafraq	Pass	Pass	Pass
Samar	Fail	Pass	Fail

A linear regression model corrected Samar's temperature data using Irbid's temperature data as reference, as their statistical means and standard deviations were very close, reflecting Samar's temperature variation. The correlation coefficient for maximum temperature regression was 0.952, and for minimum temperature regression, 0.935. The coefficient of determination (R^2) for maximum temperature linear regression was 0.907, and for minimum temperature regression, 0.873. These values indicated strong correlation and sufficient reliability for replacing inhomogeneous data series with corrected ones. Model performance was assessed through visual examination of residual graphs and calculation of residual arithmetic mean. Results indicated residuals fluctuated randomly around zero, with arithmetic mean equaling zero, suggesting the model is suitable and the corrected data series can be analyzed.

Streamflow data from Addasyia station passed all tests (Table 3). Based on these results, Addasyia station data were considered homogeneous.

Table 3 Homogeneity test results for streamflow data series

Station name	Pettitt' s test	SNHT	Von Neumann' s test
Addasiyia	Pass	Pass	Pass

3.2 Trend analysis of temperature and precipitation data during 1989-2017

Mean maximum temperature across all stations exhibited a significant increasing trend at 95% confidence interval, with average slope of 0.056. Mean minimum temperature also showed a significant increasing trend at the same confidence interval, with average slope of 0.048. Figures 2 and 3 [FIGURE:2, FIGURE:3] present mean maximum and minimum temperature trends during 1989-2017. Mean maximum temperature increased significantly by 1.62°C, while mean minimum temperature increased significantly by 1.39°C. These findings corroborate USAID (2017), which concluded that annual maximum temperatures in Jordan increased by 0.30°C-1.80°C over the past 60 years, and annual minimum temperatures rose by 0.40°C-2.80°C.

Annual precipitation exhibited a significant increasing trend at Mafraq station, with slope of 2.878 (Fig. 4 [Figure 4: see original paper]). In contrast, precipitation at Irbid station showed an insignificant increasing trend with slope of 0.738, while Samar station displayed an insignificant decreasing trend with slope of -1.867.

3.3 Future projections of temperature and precipitation changes under climate change scenarios

SDSM demonstrated high performance in modeling the basin’ s arid climate. Results were divided into three periods: 2018-2050, 2051-2079, and 2080-2100. The observed period 1989-2017 served as baseline for calculating temperature and precipitation changes. Table 4 summarizes projected temperature and precipitation changes under scenarios RCP2.6, RCP4.5, and RCP8.5. Precipitation decreases ranged from -8.5% to -43.2%, while temperature increases ranged from 0.32°C to 1.52°C. Temperature increases are attributed to high GHG emissions (primarily CO_2, CH_4, and N_2O), which have increased trapped atmospheric heat and caused land warming (IPCC, 2021). Higher temperatures raise evaporation rates and decrease soil humidity, thereby enhancing desertification. RCP8.5 represents the worst-case scenario, with GHG emissions continuing to rise. In contrast, RCP4.5 suggests GHG emissions will peak in 2040 then decline, with CO_2 emissions decreasing by 2045 and reaching about 50.0% of 2045 levels by 2100. These hypotheses explain greater temperature and precipitation changes projected under RCP8.5 compared to other RCPs.

Table 4 Projected changes in temperature and precipitation under RCP2.6, RCP4.5, and RCP8.5 scenarios for different future periods

Period	RCP2.6		RCP4.5		RCP8.5	
	Temperature change (°C)	Rate of change in precipitation (%)	Temperature change (°C)	Rate of change in precipitation (%)	Temperature change (°C)	Rate of change in precipitation (%)
2018-2050	-	-	-	-	-	-
2051-2079	-	-	-	-	-	-
2080-2100	-	-	-	-	-	-

Note: RCP, Representative Concentration Pathway.

3.4 Hydrological modeling and streamflow simulation

Streamflow data spanned 29 years (1989-2017), with three missing years (2002-2004). Total streamflow records comprised 26 years, divided into three periods: model warm-up (1989-1991), calibration (1992-2008), and validation (2009-2017). Simulated streamflow was calibrated manually by adjusting input parameter values to ensure simulated values fell within a specific range of observed data (Balascio et al., 1998). These parameters affect multiple processes, making it essential to determine the most sensitive parameters before calibration and validation (Arnold et al., 2012). Table 5 presents the most sensitive calibration parameters, selected based on sensitivity analysis informed by experience, data availability, relevant literature, and local sensitivity tests (Feyereisen et al., 2007; Arnold et al., 2012; Abbaspour et al., 2015), guided by previous YRB hydrological modeling studies (Hammouri et al., 2011; Abu-Zreig and Hani, 2021).

Santhi et al. (2001) stated that acceptable model performance requires $R^2 > 0.600$, Nash-Sutcliffe Efficiency (NSE) > 0.500, and Percent Bias (PBIAS) $< 15.0\%$. For calibration and validation periods, R^2 and NSE values exceeded 0.600 and 0.500, respectively, while PBIAS values were less than 15.0% (Table 6), indicating the model was accepted and calibrated, making it suitable for providing data and forecasting future streamflow. Figure 5 [Figure 5: see original paper] presents total monthly observed and simulated streamflow for calibration and validation periods, illustrating good agreement.

Table 5 Parameters used in SWAT model calibration

Parameter	Definition	Estimated value	Calibrated value	Range
Curve number	-	-	-	-
Sol_{Awc}	Available water capacity of soil layer	-	-	mm H_2O/mm soil
Gw_{Delay}	Groundwater delay time	-	-	-
-	Soil evaporation compensation factor	-	-	-
Sol_K	Saturated hydraulic conductivity	-	-	-
Sol_Z	Depth from soil surface to bottom of layer	-	-	-

Note: "-" means no unit or data range.

Table 6 Summary of objective functions in streamflow simulation during calibration and validation periods

Objective function	Calibration (1992-2008)	Validation (2009-2017)
R^2	-	-
NSE	-	-
PBIAS (%)	-	-
Simulated mean (m^3/s)	-	-
Observed mean (m^3/s)	-	-
Observed Std Dev (m^3/s)	-	-
Simulated Std Dev (m^3/s)	-	-

Note: R^2, coefficient of determination; NSE, Nash-Sutcliffe Efficiency; PBIAS, Percent Bias; Std Dev, standard deviation.

Fig. 5 Observed monthly streamflow versus simulated streamflow during 1992-2017

3.5 Future prediction of climate change impacts on water resources

Historical streamflow analysis revealed a decreasing trend with slope of -0.168 (Fig. 6 [Figure 6: see original paper]). In contrast, precipitation over the same timeframe indicated significant increase at Mafraq station and insignificant increase at Irbid station. This phenomenon is explained by temperature data analysis, which showed significant rising trends in both mean minimum and maximum temperatures across all stations, suggesting evaporation is the dominant basin process reducing streamflow.

To predict future streamflow changes, RCP scenarios downscaled from CanESM2 GCMs were applied to the SWAT model to simulate future streamflow and calculate changes compared to the observed period (1989-2017). SWAT predictions indicated streamflow reductions during all future periods, varying between 8.7% and 84.8%. The RCP2.6 scenario predicts decreases of 8.7% during 2018-2050, 7.1% during 2051-2079, and 17.8% during 2080-2100 (Figure 7 [Figure 7: see original paper]). RCP4.5 predicts decreases of 7.6% during 2018-2050, 37.0% during 2051-2079, and 45.1% during 2080-2100. RCP8.5 predicts decreases of 21.7% during 2018-2050, 62.3% during 2051-2079, and 84.8% during 2080-2100. Temperature is expected to rise in coming decades due to GHG impacts and atmospheric heat trapping. Increased evaporation from soil and surface water caused by higher temperatures will lead to declining groundwater tables and reduced water in river tributaries. Additionally, higher temperatures and lower precipitation will decrease groundwater recharge, further reducing water feeding rivers. By century' s end, temperatures are projected to increase by 1.00°C, 1.80°C, and 3.70°C under RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively, compared to 1989-2017. RCP8.5' s greater impact on water resources is attributed to larger temperature increases, while RCP2.6 has the least impact.

Fig. 6 Temporal variations in observed streamflow during 1989-2017

Fig. 7 Predicted changes in simulated streamflow under RCP2.6, RCP4.5, and RCP8.5 scenarios for different future periods

RCP scenarios predict precipitation decline by the 21st century' s end. However, observed precipitation data (1989-2017) revealed significant increase at Mafraq station and insignificant increase at Irbid station, while streamflow showed declining trend. This suggests streamflow decrease was caused not by precipitation but by evaporation. To reduce uncertainty and obtain more accurate results, a mathematical model identified the scenario closest to reality. Model performance is presented in Table 7 .

Table 7 Performance evaluation of mathematical model for monthly streamflow predictions

Number	Observed streamflow (m^3/s)	Simulated streamflow (m^3/s)	Error (m^3/s)
-	-	-	-

Streamflow was simulated for three future periods: 2018-2050, 2051-2079, and 2080-2100. The mathematical model predicts streamflow decreases of 39.4% during 2018-2050, 41.8% during 2051-2079, and 43.5% during 2080-2100, all compared to the observed period (1989-2017) (Figure 8 [Figure 8: see original paper]). Comparing outcomes reveals notable disparity. The mathematical model predicts substantial reduction during 2018-2050 (39.4% decline), nearly double SWAT' s estimate under RCP8.5 (22.0% decrease). However, the situation changes in subsequent periods. During 2051-2079 and 2080-2100, RCP8.5 anticipates far more significant declines of 62.3% and 84.5%, respectively, contrasting with mathematical model projections of 41.8% and 43.5% reductions.

Variance between models across periods arises from the mathematical model' s limitations in predicting distant future. It assumes constant rate of change over time, while high GHG emission scenarios posit accelerating change rates, particularly around 2030. Consequently, effective comparison hinges on assessing initial periods, suggesting the basin' s situation likely aligns with high GHG emission scenarios or potentially more dire ones. It is crucial to emphasize these results are not definitive, as climate studies involve numerous uncertainty sources. Nevertheless, this study serves as a vital indicator of climate change impacts on Yarmouk River flow, especially considering significant decreases observed in the past decade compared to the 1990s.

Fig. 8 Predicted changes in streamflow using mathematical model for different future periods

These results align with previous research, though notable differences arise from methodological variations. Al Sabeh et al. (2022) investigated water sustainability under current use and allocation regimes in the YRB using WEAP, highlighting significant water shortages across all demand sectors, exacerbated by climate change under RCP4.5 and RCP8.5. Similar to this study, they found significantly reduced surface water availability, with Jordan's Yarmouk River share particularly vulnerable. Both studies emphasize urgent need for adaptive water management strategies. Abdulla and Al-Shurafat (2020) used SWAT to simulate YRB hydrological response under various climate change scenarios, reporting streamflow reductions ranging from 2.6% to 60.0% under pre-development and 0.0% to 36.4% under post-development conditions. These align with current projections of 8.7% to 84.8% reductions under different RCP scenarios. Both studies highlight YRB vulnerability to climate change regarding streamflow and water availability. Similarly, Hammouri et al. (2017) used SWAT to assess climate change impacts on northern Jordan water resources, projecting streamflow reductions up to 22.0% by 2080, with severe declines during peak flow months. Although more conservative than current projections, differences may attribute to different GCMs and scenarios. Nevertheless, all studies agree on anticipated water resource declines, reinforcing need for updated, robust water management policies.

4 Conclusions

This study analyzed historical meteorological and hydrological data along with future projections to thoroughly assess climate change impacts on water resources in the YRB. Findings revealed significant increases in both mean maximum and minimum temperatures at all stations, suggesting evaporation is the dominant basin process reducing streamflow. Precipitation showed significant increase at Mafraq station while experiencing insignificant changes at Irbid and Samar stations, highlighting basin variability. Historical streamflow analysis indicated decreasing trend with slope of -0.168, suggesting that despite increased precipitation in some areas, overall streamflow declined due to higher evaporation rates. Using RCP scenarios, the study projected temperature increases of 0.32°C–1.52°C and precipitation decreases of 8.5%–43.0% throughout the 21st century. SWAT and mathematical projections indicated significant future streamflow reductions. Disparity between SWAT and mathematical model projections for future streamflow reduction underscores the importance of considering different modeling approaches to understand the potential range of climate change impacts. These findings provide novel insights into regional climate change impacts and highlight the critical need for adaptive water management strategies to mitigate adverse effects on YRB water resources. Climate change should be considered in all water strategies and accounted for in Jordan' s water budget.

This study encountered several limitations influencing results that need improvement in future research. Firstly, it was constrained by limited availability of long-term, high-quality hydrological and meteorological data. Secondly, a single land use map was employed across all periods because future land use remains uncertain. Thirdly, during SWAT modeling, solar radiation data were sourced from the SWAT database due to unavailability of specific local data. Finally, reliance on GCM projections introduces inherent uncertainties due to climate modeling complexities.

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Author contributions: Abdelaziz Q BASHABSHEH prepared data, conducted modeling and analysis, and shaped the manuscript. Kamel K ALZBOON supervised the project, conceived ideas, planned research, and facilitated discussion of results. All authors approved the manuscript.

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