Projecting the climate change impact on water yield in a cold mountainous watershed, Ardabil

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Abstract

Population growth and climate change are worsening pressure on water supplies, altering rainfall-runoff patterns, and posing significant challenges for water management. Climate change profoundly affects society, particularly water reserves, through temperature shifts, precipitation changes, and disruptions to river flows, ultimately impacting water scarcity and ecosystem services. The objective of this study is to project the possible effects of climate change on water yield in a cold-climate watershed located in Ardabil province. The GR4J conceptual model used to simulate the hydrologic watershed response to changes in climatic factors. The HadCM3 model, was used to examine meteorological parameters under the A1B climate scenario through implementing LARS-WG. The GR4J has been calibrated using trial-and-error method to maximize the NS coefficient. he validation results were evaluated using NS and RE. The results showed a significant variation in water yield values across different periods. The highest yearly water yield is in 2030, dropping to 49.79 million cubic meters in 2050, representing a 13.6 million cubic meters decrease. Based on the results, the highest positive change occurred in February, where the percentage increased from 93% in 2030 to 138% in 2060, representing a 45% increase. Additionally, the highest negative change is projected in October, where the percentage decreased from 27% in 2030 to -11% in 2060, representing a decrease of -38%. The results suggests that flood and extreme flow events will increase, while low flow events will decrease significantly under climate change conditions, and the simulated flow values also show more fluctuations in the projected periods.

Keywords: Water Balance, Watershed response, River flow discharge, Climatic variables, Environmental Management

1. Introduction

1.1. Background

Climate change poses a major challenge to human life, significantly impacting environmental, economic, and social resources, particularly water (Shilky et al., 2023; Tsakiris & Loucks, 2023; Lee et al., 2023). Population growth and climate change exacerbate pressure on water resources, with altered precipitation and runoff affecting water management (Oliazadeh et al., 2022; Ho et al., 2022). Changes in temperature, precipitation, evapotranspiration, and runoff disrupt river flow regimes, increasing water stress and reducing ecosystem water supply services (Barrow & Yu, 2005; Moafi Madani et al., 2012; Felisa et al., 2022). Winter warming destabilizes snow conditions, reduces snowy days, and alters runoff patterns, impacting snow-dependent watersheds (Whitfield et al., 2003; Štefunková et al., 2013; Ivanov et al., 2022). Climate change also intensifies water erosion by influencing land use, biomass production, and soil microbial activity (Kumar et al., 2022; Elaloui et al., 2022; Barati et al., 2023). Furthermore, climate change increases the frequency of extreme events, such as floods, heavy rainfall, droughts, and heatwaves, affecting the flow rate, peak flows, flow volume, and base flow rates, as well as sediment, organic matter, toxins, and other pollutants (Van Liew et al., 2013; Espinosa et al., 2022). Surface runoff, precipitation, and evapotranspiration are critical components of the hydrological cycle and are impacted by human activities aimed at water supply (Luo and Moiwo, 2023). This makes important the impact of runoff on various social issues related to climate change, such as access to water, floods, or droughts (Mishra et al., 2010; Li et al., 2020). Given the significant impact of water resources on various dimensions of communities, such as water supply, agriculture, hydroelectric energy, tourism, and transportation, projecting climate change is an essential management method to help with proper planning for the appropriate use of limited water resources (Barrow and Yu, 2005; Kriauciuniene et al., 2008).

1.2. Literature review

Previous research has investigated the impact of climate change on river flow and runoff. Pruski and Nearing (2002) investigated the effect of changes in precipitation patterns on runoff in eight regions of America using the HadCM3 model. Their findings showed that annual precipitation varies from 1.1% to 6.1%, and changes in runoff range from -2.42% to 14%. Gosain et al. (2006) studied the effect of climate change scenarios on river flow in 12 watersheds in India for the period 2041-2060 and found that streamflow will decrease, and the intensity of floods and droughts will increase. Steele-Dunne et al. (2008) investigated the effect of climate change on river flow for nine basins in Ireland using the ECHAM5 model and scenario A1B. Their findings showed that winter and summer precipitation will increase and decrease, respectively, and the river flow rate will be affected by climate change. Chang and Jung (2010) examined the annual, seasonal, minimum and maximum streamflow and their uncertainty in 218 sub-basins of the Willamette River in Oregon and found that seasonal changes in streamflow are in the form of an increase in winter flow and a decrease in summer flow, and temporal and spatial changes in streamflow may change in the future, depending on the properties of the sub-basin. Senatore et al. (2011) analyzed climate change impacts on the Krati River basin in southern Italy using A2 and A1B scenarios. They projected a 3.3-5.3°C temperature rise and a 9-12% precipitation decrease by 2070-2099, resulting in reduced snow accumulation, groundwater, and runoff. Al-Hasani (2019) studied streamflow sensitivity in the Tigris River Basin, finding greater sensitivity to precipitation in Mediterranean areas and to evapotranspiration in semi-arid regions. A rising trend in precipitation elasticity over four decades indicates changing precipitation-streamflow dynamics and climate adaptation needs in Iraq. Sha et al. (2019) used the LARS-WG model to study climate impacts in northeastern China’s cold regions, projecting warming, increased precipitation, and reduced snowfall. These changes affect agriculture and hydrology, emphasizing the need for climate adaptation strategies. Bayatvarkeshi et al. (2020) analyzed climate change impacts on ET0 using data from 30 Iranian stations (1981-2010) and HadCM3/LARS-WG models. They projected increased ET0 across all stations, peaking in 2080-2113 under the A1B scenario, with the southeast and west showing the highest values.

The A2 scenario provided the most reliable estimates. Shahani et al. (2023) applied deep learning and LARS-WG6 to assess climate change impacts on river flow in Iran. Rainfall is projected to increase in cold arid and semi-arid regions but decrease in humid temperate areas. Maximum discharge changes emphasize region-specific water management needs. Overall, the literature review highlights the impact of climate change on the hydrological regime of different river basins across the world. The studies show that changes in precipitation patterns will lead to changes in river flow rates, and in most cases, the average annual runoff will decrease, while the intensity of floods and droughts will increase.

1.3. Scope and objective

The research also suggests that these changes will vary depending on the location and regional factors such as temperature, precipitation, and land use. Therefore, it is crucial to consider the specific characteristics of each river basin when projecting the impact of climate change on the hydrological regime and to adopt appropriate strategies for sustainable water resources management. Water yield is expected to change due to climate change in future periods compared to the baseline period, but these changes will vary depending on the location and time. To prevent issues related to available water resources, it is necessary to project the conditions, stability, and variability of surface runoff in the future (Lee et al., 2014). Precipitation-runoff modeling at the watershed scale is a useful method for estimating runoff and is a core topic in hydrology. Hydrological modeling provides a sustainable water resource management platform (Stoter and Zlatanova, 2003) and is a crucial first step in water resource management and planning initiatives. Simulating runoff processes in a typical and representative watershed can be extended to similar watersheds without statistics, saving time and costs (Aghabeigi et al., 2019). Controlling surface waters and identifying river behavior for long-term planning and better use of their potential is essential. Climate change in cold mountainous regions has resulted in the retreat of snowpacks, leading to altered water availability for downstream communities. It has also increased the frequency and intensity of extreme weather events, such as flood and droughts, impacting local water needs and river ecosystems. Furthermore, shifts in temperature and precipitation patterns have disrupted the delicate balance of river flow availability and environmental flow requirements. Given the cold climate and the rapid hydrological response of the study area, this research focuses on assessing the impact of climate change on the daily flow hydrograph, river flow regime characteristics, and discharge at monthly and seasonal scales. This research aims to project the effects of climate change on streamflow characteristics and runoff in the steep Nirchai watershed, located in a cold climate in Ardabil province, Iran. The GR4J conceptual model was used to simulate the hydrological response of the streamflow to changes in climatic components.

2. Material and Methods

2.1 Study Area

The Nirchai watershed covers an area of 168 square kilometers and is located in Ardabil and East Azerbaijan provinces. It is one of the sub-basins of the Balikhlouchai watershed, with its outlet connected to the Balikhlouchai River at the Nir city. The maximum elevation of the watershed is 4300 meters, while the minimum elevation is 1600 meters at the outlet and southeastern part. The length of the largest stream in the watershed is 35.5 kilometers. About 65% of the watershed area is rangeland, and it is bounded by Sabalan Mountains to the north and Saieen pass and the headwaters of the Balikhlouchai River to the south. The annual average temperature is 9 degrees Celsius, with a moderate summer and a very cold winter. The average annual precipitation in the southern slopes of Sabalan is approximately 351.8 millimeters. Based on the Emberger classification, the studied region's climate is of a cold semi-arid type, while the vegetation cover of the area is of a steppe type. Figure 1 shows the location of the Nirchai watershed in Iran and Ardabil province.

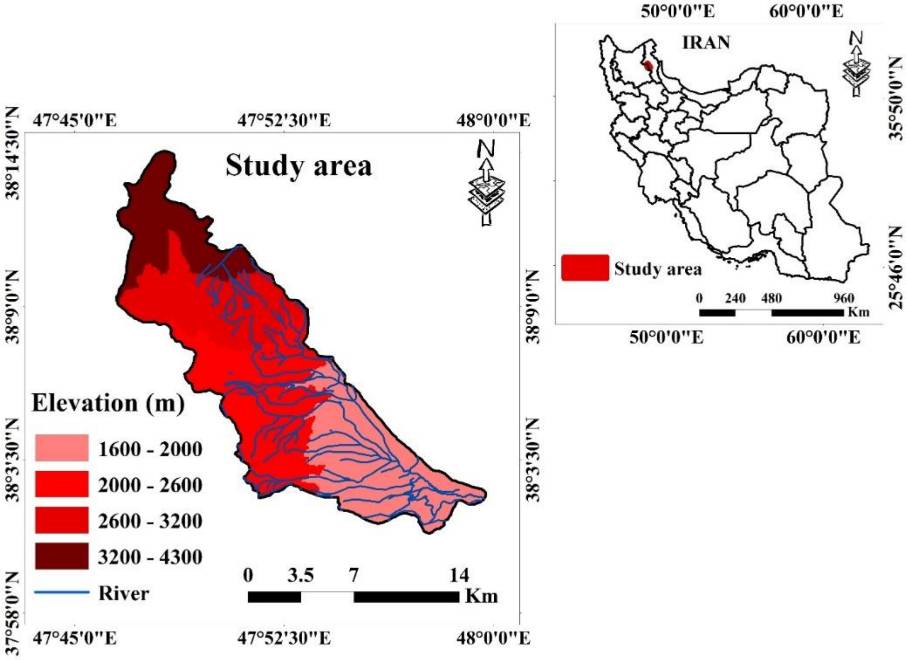


Figure 1. Location of the Nirchai Watershed in Iran and Ardabil Province

2.2 Methodology

Various methods are available for producing future climate scenarios, but the most reliable method is the use of Atmosphere-Ocean General Circulation Models (AOGCMs) (Knutti et al., 2017; Stouffer et al., 2017; Taylor et al., 2012). AOGCMs are based on mathematical equations that represent physical laws (Flato et al., 2014). The HadCM3 model is a widely used GCM (Wilby and Harris, 2006). The LARS-W V5 model is used to simulate climate data by obtaining the statistical correlation between the model output and the weather station data in the statistical period. If the model-generated data are acceptable, they can be used to create future climate scenarios (Hawkins et al., 2016). The LARS-WG model can produce artificial data for weather stations that lack statistical data if they are similar to observational data in terms of climate and statistics. In this study, the HadCM3 model output from the Hadley Centre for Climate Prediction and Research in the UK was used to examine temperature and precipitation climate parameters during future decades under the A1B emission scenario. After obtaining daily precipitation, minimum and maximum temperatures, and solar hours data from the Ardabil synoptic station. The potential evapotranspiration was calculated based on the method proposed by Oudin et al. (2005) using daily temperature data. Then, evapotranspiration, precipitation, minimum and maximum temperatures, and solar radiation have been projected using the HadCM3 model under the A1B scenario. The A1B scenario assumes a balanced combination of technologies and resource supply with advances in technology and energy resources, assuming a group of resources as an energy source (O'Neill et al., 2017; Kriegler et al., 2017). It is the most common and widespread scenario globally, with a significant increase in the use of renewable energy sources, such as solar energy, wind, and hydropower (Pfenninger et al., 2014).

Since simulations of the LARS-WG model are stochastic, the model's climatic outputs for future periods (the years 2030, 2040, 2050, and 2060) are considered as representatives of the upcoming decades.

In the next step, the simulation results for climate components, including precipitation and evapotranspiration, were used as input to the GR4J model, and daily flow rate simulation was performed under future conditions.

2.3 Hydrological modelling

In order to explore the impact of climate change on future runoff, it is essential to use precipitation-runoff models. Therefore, this study utilized the GR4J model to simulate daily runoff, as a conceptual rainfall-runoff model that provides a reliable understanding of hydrological processes, and its components are calculated consistently. Its practical superiority, especially in simulating river flow, has led to widespread attention and acceptance (Perrin et al., 2003). Since the GR4J model allows for simulating flow rate on a daily scale, it was used to simulate daily flow rate in future years (2030 to 2060) based on projected scenarios (Perrin et al., 2003). Hydrological data from the Nirchai watershed, including daily precipitation and potential evapotranspiration, were used in this study. After obtaining daily precipitation and potential evapotranspiration data, the model was validated using observed flow rate data. The GR4J model has four independent parameters, X1 (the capacity of water storage in surface soil layers in mm), X2 (the coefficient of exchange between surface and subsurface runoff in mm), X3 (the capacity of previous-day storage or storage in the soil in mm), and X4 (the time to peak in days when the hydrograph reaches its peak in the GR4J model) (Harlan et al., 2010). With its minimal parameter requirements and user-friendly approach, GR4J is widely applied in water resource management studies, climate change impact assessments, and streamflow forecasting.

In the next step, the data were divided into two periods for calibration and validation based on the length of the statistical period. The model was calibrated using the manual calibration method and the trial-and-error method, based on maximizing the Nash-Sutcliffe coefficient. The values of the GR4J model parameters were validated (Mostafazadeh and Asgari, 2021). The model validation was performed using the results obtained from model calibration, and the results were evaluated using the Nash-Sutcliffe coefficient, and Relative Error in runoff Volume (Mostafazadeh et al., 2017).

3. Results and Discussion

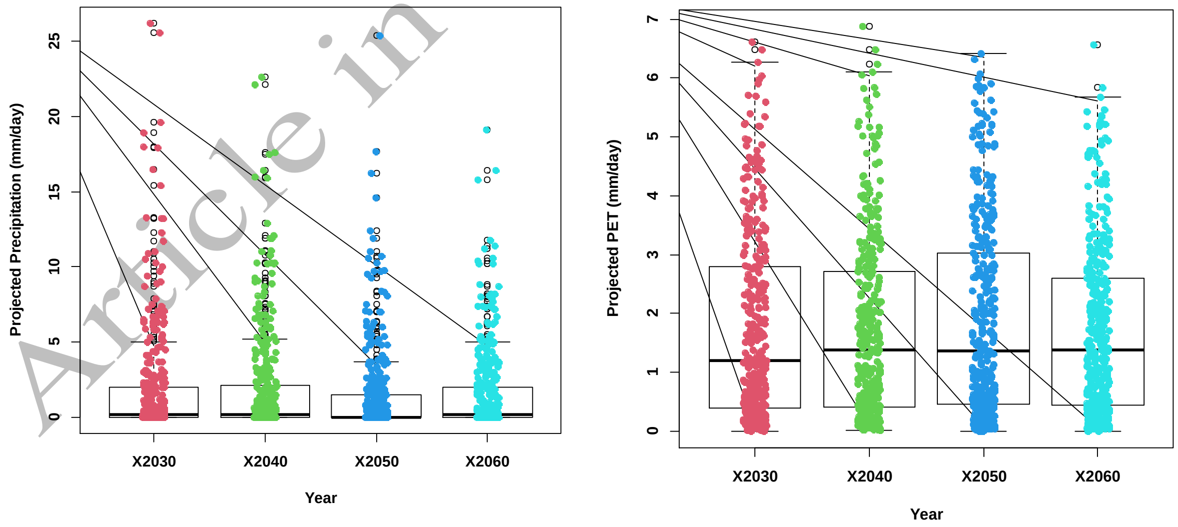
The correlation coefficients between projected climate data and observational data for temperature and precipitation were 0.85 and 0.88, respectively, which are considered acceptable values for projection accuracy. Regarding the river flow simulation, the Nash-Sutcliffe coefficient of the model for simulating daily flow rate during the calibration and validation periods were 0.543 and 0.445., respectively. The model error percentage for simulating the daily flow volume during the calibration period was -0.22%, and during the validation period, it was -27.75%. Table 1 displays the statistical characteristics of precipitation, potential evapotranspiration (PET), and discharge data for four projected typical years under climate change conditions.

Table 1. Statistical characteristics of Precipitation (mm/day), PET (mm/day), and Discharge (mm/day) data in future periods under climate change conditions

	2030			2040			2050			2060		
	P	PET	Q	P	PET	Q	P	PET	Q	P	PET	Q
Min	0.00	0.00	0.20	0.00	0.01	0.19	0.00	0.00	0.11	0.00	0.00	0.17
Max	26.20	6.61	4.27	22.60	6.88	3.82	25.40	6.42	4.41	19.10	6.56	2.80
Mean	1.92	1.75	1.01	1.95	1.75	0.98	1.44	1.87	0.70	1.57	1.74	0.77
STDEV	3.82	1.59	0.79	3.62	1.56	0.73	3.00	1.67	0.64	2.82	1.47	0.62
CV	1.99	0.91	0.78	1.85	0.89	0.75	2.08	0.89	0.92	1.79	0.85	0.80
Kurtosis	12.39	-0.06	1.42	8.48	0.20	0.61	16.57	-0.41	3.70	8.69	0.01	0.44
Skewness	3.19	0.92	1.17	2.70	0.97	1.00	3.50	0.81	1.59	2.65	0.88	1.21

Table 1 illustrates significant variations in hydrological variables across the four projected years. The maximum precipitation value in 2030 is 26.20 mm, while in 2060, it is only 19.10 mm, indicating a decrease of 7.1 mm. Likewise, the maximum discharge value in 2030 is 4.27 cubic meter per second, while in 2060, it is only 2.80 meter per second, illustrating a difference of 1.47 meter per second. The mean discharge values exhibit a decreasing trend, with the value in 2030 being 1.01 meter per second, whereas in 2060, it is only 0.77 meter per second, indicating a difference of 0.24 meter per second. This decreasing trend in discharge is attributed to the decreasing trend in precipitation and the increasing trend in potential evapotranspiration (PET). The coefficient of variation (CV) values for precipitation and PET remain consistent across the years, while the CV values for discharge show a decreasing trend. The kurtosis and skewness values for the three variables also vary across the years, suggesting a change in the hydrological response of the watershed under climate change conditions. The decreasing trend in precipitation and increasing trend in PET may lead to a reduction in water yield in the future, impacting water availability and streamflow. The increasing trend in PET can result in a decrease in soil moisture and groundwater recharge.

Figure 2 illustrates the box plot of projected precipitation and PET values and simulated discharge values over different years in the study area.



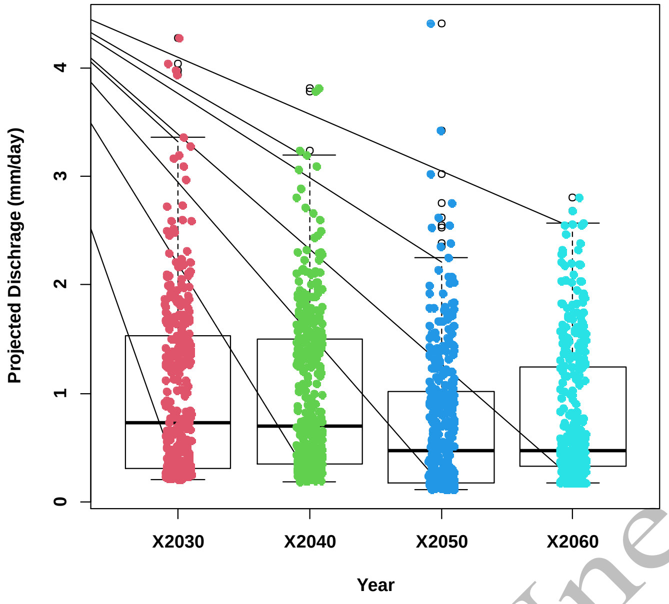


Figure 2. Box plot of projected precipitation and PET values and simulated discharge values over different years under climate change condition

The table 2 presents projected water yield (million cubic meters) in the future at different months under climate change. The projected years are 2030, 2040, 2050, and 2060.

Table 2. Projected water yield (million cubic meters) in future at different months under climate change

Projected year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
2030	1.974	1.301	1.413	1.529	4.549	8.708	8.414	9.541	7.447	11.717	4.222	2.619
2040	2.359	1.671	1.355	1.532	3.085	3.232	10.649	8.318	9.270	8.839	4.776	2.964
2050	1.490	1.943	1.877	1.631	3.175	5.356	8.462	7.835	7.252	5.510	3.550	1.712
2060	1.378	1.466	1.541	1.767	5.625	9.613	7.509	8.364	9.087	6.889	2.972	2.286

Table 2 reveals considerable variations in water yield values among the projected years, with certain months displaying significant differences. The largest increase in water yield is observed in February 2030, with a value of 4.549 million cubic meters, while in 2050, the maximum value is only 3.175 million cubic meters, representing a difference of 1.374 million cubic meters, followed by an increase in 2060 (5.625 million cubic meters). Similarly, the maximum water yield value in July 2030 is 11.717 million cubic meters, while in 2060, it is only 6.889 million cubic meters, indicating a difference of 4.828 million cubic meters. These differences suggest that the water yield in some months may significantly decrease under climate change conditions. The water yield in some months exhibits a decreasing trend over the projected years, such as October, which displays a decreasing trend from 1.974 million cubic meters in 2030 to 1.378 million cubic meters in 2060. On the other hand, water yield in some months shows an increasing trend over the projected years, such as March, which displays an increasing trend from 8.708 million cubic meters in 2030 to 9.613 million cubic meters in 2060, coinciding with periods of high water in the study area. These differences suggest that the water yield in some months may be more affected than others under climate change conditions. The increasing trend in water yield in March may also be attributed to changes in precipitation patterns resulting from climate change, as reported in various studies (e.g., Trenberth et al., 2018).

In line with the findings of Pruski and Nearing (2002) and Gosain et al. (2006), our projections for future water yield in the region show notable changes along with seasonal variations over different months. In contrast to the findings by Senatore et al. (2011), who observed a decrease in precipitation in the Krati River basin leading to reduced runoff, our study indicates mixed results with some months showing increased water yield. As Al-Hasani (2019), who found that precipitation changes have a greater impact on streamflow in Mediterranean regions, our study provides insights into how water yield in a cold climate region may respond to climate change, with some months showing significant variability.

Table 3 presents the projected water yield (million cubic meters) in different seasons and years under climate change for four projected years.

Table 3. Projected water yield (million cubic meters) in future at different seasons and years under climate change

Projected year	Fall	Winter	Spring	Summer	Yearly
2030	4.689	14.787	25.402	18.557	63.435
2040	5.385	7.849	28.237	16.578	58.050
2050	5.311	10.162	23.549	10.772	49.793
2060	4.385	17.004	24.960	12.147	58.495

The values for water yield in different seasons and years exhibit significant variation across the projected years, with some seasons and years displaying substantial differences in water yield values. The highest yearly water yield value is observed in 2030, with a value of 63.435 (MCM), while in 2050, the maximum value is only 49.793 million cubic meters, indicating a difference of 13.642 million cubic meters. Similarly, the water yield value in Fall 2040 is 5.385 million cubic meters, while in 2060, it is only 4.385 million cubic meters, representing a difference of 1.0 million cubic meters. These differences suggest that the water yield in some seasons and years may significantly decrease under climate change conditions. The water yield in Spring shows a decreasing trend from 25.402 million cubic meters in 2030 to 23.549 million cubic meters in 2050, representing a difference of 1.853. Similarly, the water yield in Summer displays a decreasing trend from 18.557 million cubic meters in 2030 to 10.772 million cubic meters in 2050, representing a difference of 7.785. On the contrary, the water yield in some seasons exhibits an increasing trend over the projected years. The water yield in Winter displays an increasing trend from 14.787 million cubic meters in 2030 to 17.004 million cubic meters in 2060, representing a difference of 2.217. Similarly, the water yield in Fall exhibits an increasing trend from 4.689 million cubic meters in 2030 to 5.385 million cubic meters in 2040, representing a difference of 0.696 million cubic meters. Recent studies have also reported significant changes in water yield due to climate change in various regions worldwide.

Figure 3 depicts the daily simulated hydrograph of river flow under future climate change conditions in the upcoming years in the Nirchai watershed.

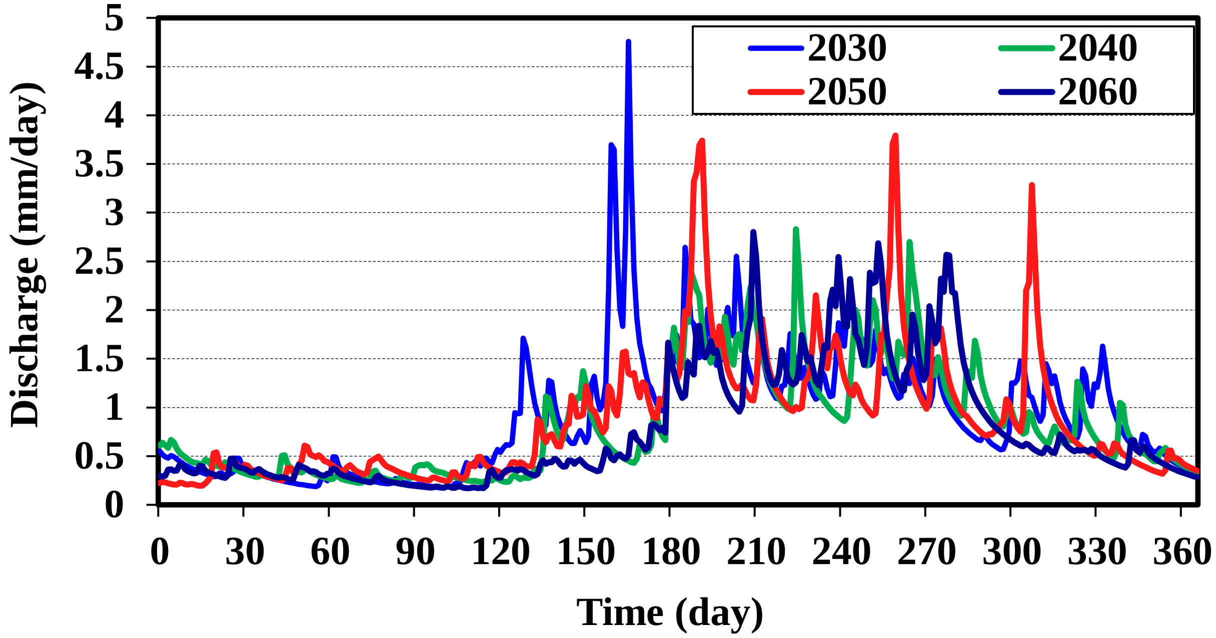


Figure 3. Daily simulated hydrograph of river flow under future climate change conditions in upcoming years

Based on the information presented in Figure 3, it appears that the frequency of flood and extreme flow events will increase in future periods under climate change conditions. Conversely, the values of low flow events will decrease significantly. It is noteworthy that the simulated flow values demonstrate more fluctuations in the projected periods. Recent studies have also reported an increase in the frequency and intensity of extreme flow events due to climate change in various regions worldwide.

Figure 4 shows the water yield values in different months under future climate change conditions.

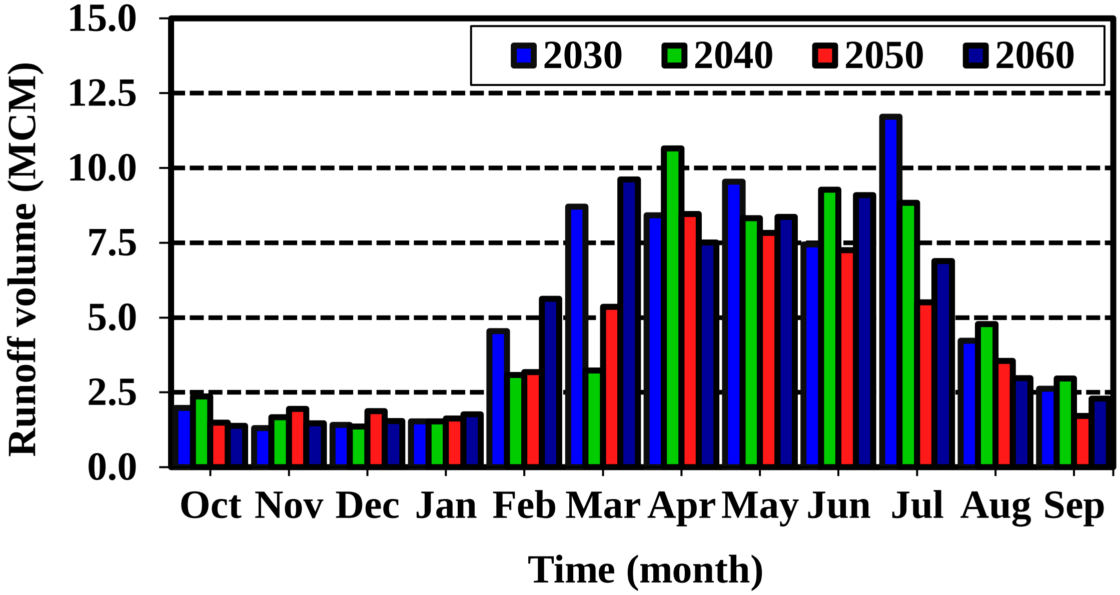
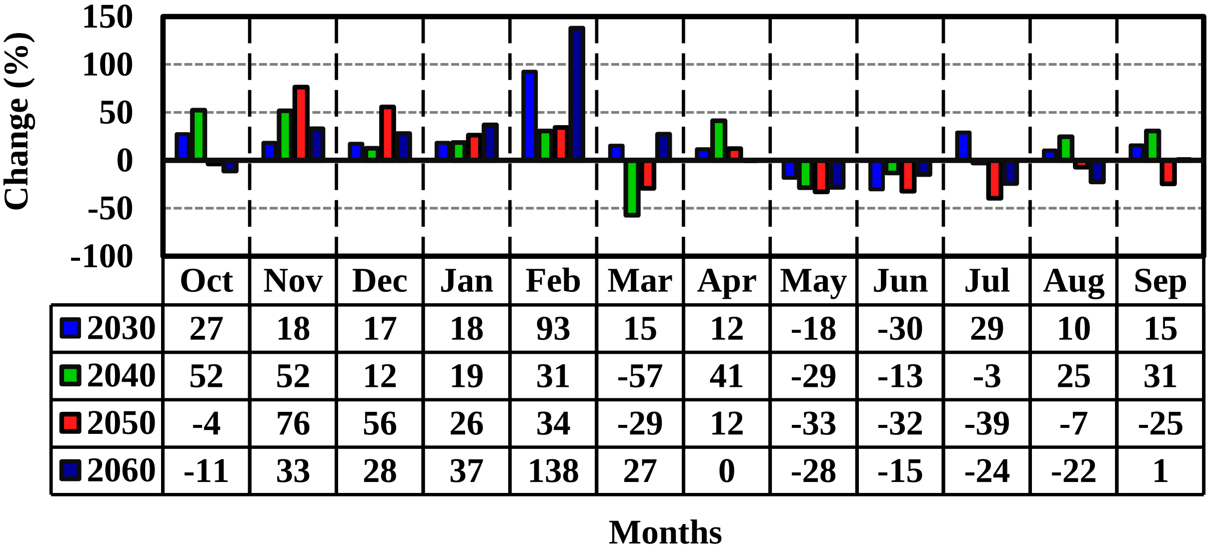


Figure 4. Water yield values in different months under future climate change conditions compared to the year 2020

Based on the data presented in Figure 4, it can be concluded that the water yield has decreased in most months, and this decline is particularly significant in the year 2050. Moreover, it is evident that the water yield has increased in February and March, while decreasing considerably in other months of the year.

Figure 5 illustrates the percentage change in monthly water yield values under future climate change conditions compared to the year 2020.



	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
🟦 2030	27	18	17	18	93	15	12	-18	-30	29	10	15
🟩 2040	52	52	12	19	31	-57	41	-29	-13	-3	25	31
🟥 2050	-4	76	56	26	34	-29	12	-33	-32	-39	-7	-25
■ 2060	-11	33	28	37	138	27	0	-28	-15	-24	-22	1

Figure 5. Percentage change in monthly water yield values under future climate change conditions compared to the year 2020

Based on the results, the highest positive change occurred in February, where the percentage increased from 93% in 2030 to 138% in 2060, representing a 45% increase. Additionally, the highest negative change is projected in October, where the percentage decreased from 27% in 2030 to -11% in 2060, representing a decrease of -38%. Recent studies have reported changes in water yield and availability due to climate change in various regions worldwide.

Table 4 presents the percentage change in seasonal and annual water yield values under future climate change conditions compared to the year 2020.

Table 4. Percentage change in seasonal and annual water yield values under future climate change conditions compared to the year 2020

Fall	Winter	Spring	Summer	Yearly
21.591	31.821	-14.992	22.124	5.460
39.643	-30.030	-5.504	9.100	-3.494
37.706	-9.410	-21.194	-29.111	-17.220
13.696	51.586	-16.471	-20.064	-2.753

Table 4 displays significant variation in water yield values across the projected years, with some seasons and years exhibiting substantial differences. Winter 2030 has the highest percentage change in water yield value, while summer 2050 has the maximum value, with a difference of 22.721%. Conversely, spring 2030 shows the minimum percentage change, while winter 2040 has the lowest value, with a difference of 15.038%. Some seasons and years, such as spring and summer, exhibit a decreasing trend in water yield over the projected years, which could significantly impact water availability. In contrast, winter and fall show an increasing trend in water yield, which may have significant implications for water availability in those seasons.

Our study's findings align with the results of Gosain et al. (2006) and Chang and Jung (2010), who both identified significant seasonal variations in streamflow under climate change. These trends emphasize the importance of considering specific seasonal shifts in water availability. The increasing water yield in winter and fall observed in our projections aligns with findings from Steele-Dunne et al. (2008), who noted an increase in winter precipitation and its subsequent impact on river flow in Ireland. In contrast to Senatore et al. (2011), who projected significant reductions in snow accumulation and runoff in southern Italy, our study suggests that some regions may experience an increase in water yield during the winter months, particularly in 2030 and 2060. This highlights the importance of localized climate impact assessments, as the responses to climate change can vary significantly between regions and may not follow the same global trends observed in Mediterranean climates.

4. Conclusions

This study projects the potential impacts of climate change on water yield in a cold climate watershed in Ardabil province using the GR4J model. The results show significant variation in water yield across months, seasons, and years. For example, the highest yearly water yield is 63.435 MCM in 2030, dropping to 49.793 MCM in 2050, a 13.642 MCM difference. Similarly, fall 2040 water yield is 5.385 MCM, decreasing to 4.385 MCM by 2060. Spring and summer yields also show significant declines, highlighting the importance of understanding climate change impacts on water resources. The results indicate that flood and extreme flow events will increase under climate change, while low flow events will decrease significantly. The highest percentage change in water yield occurs in February 2030 and 2060 (45%). Some months, like June and July, show a decreasing trend in water yield, affecting water availability, while February and November exhibit an increasing trend. Significant variations in water yield values are observed across the projected years, with winter 2030 showing the highest change, and spring 2030 the lowest. Overall, spring and summer display a decreasing trend in water yield.

4.1. Implications and future directions

This study highlights the significant impacts of climate change on water yield and the need for adaptation measures to strengthen water supply resilience. Future research could focus on optimizing water resource use considering seasonality and assessing the impact of climate change on ecological flow requirements during extreme events. Advanced hydrological models could improve water yield projections and inform future water management decisions.

Declarations

Funding

The authors did not receive support from any organization for the submitted work.

Declarations of interests

The authors declare that they have no competing interests.

Data Availability Statement

All data generated or analysed during this study are included in this published article

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