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Climate Change Scenarios and Effects on Snow-Melt Runoff

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Abstract

Climate change is an important environmental issue, as progression of melting glaciers and snow cover is sensitive to climate alteration. The aim of this research was to model climate alterations forecasts, and to assess potential changes in snow cover and snow-melt runoff under the different climate change scenarios in the case study of the Zayandeh-rud River Basin. Three cluster models for climate change (NorESM1-M, IPSL-CM5A-LR and CSIRO-MK3.6.0) were applied under RCP 8.5, 4.5 and 2.6 scenarios, to examine climate influences on precipitation and temperature in the basin. Temperature and precipitation were determined for all three scenarios for four periods of 2021-2030, 2031-2040, 2041-2050 and 2051-2060. MODIS (MOD10A1) was also applied to examine snow cover using temperature and precipitation data. The relationship between snow-covered area, temperature and precipitation was used to forecast future snow cover. For modeling future snow melt runoff, a hydrologic model of SRM was used including input data of precipitation, temperature and snow cover. The results indicated that all three RCP scenarios lead to an increase in temperature, and reduction in precipitation and snow cover. Investigation in snowmelt runoff throughout the observation period (November 1970 to May 2006) showed that most of annual runoff is derived from snow melting. Maximum snowmelt runoff is generated in winter. The share of melt water in the autumn and spring runoff is estimated at 35 and 53%, respectively. The results of this study can assist water manager in making better decisions for future water supply.

Keywords: Climate Change; Snow Cover; Snow Melt; SRM Model; RCP Scenarios.

1. Introduction

Rainfall pattern is changing in terms of volume, intensity and form around the world [1]. Snow coverage and continuity depend on the amount of precipitation and temperature, which are strongly related to climatic condition [2]. If the area of snow cover changes, future access to and management of water could be difficult in the long-term [3], because the amount of runoff and flooding are likely to increase. Since 2001 onwards, the importance of climate change for hydrologic systems which are affected by snow has been studied. Aziz et al. (2020) [4] showed that slight increases in temperature can significantly affect timing in runoff events in mountainous areas. Runoff is usually increasing in cold season and decrease e during warm period, probably because of snow melt as a result of increased temperature. Emmer et al. (2019) [5] has evaluated future runoff from three glacial areas in Peru using a hydrologic model, which included changes in snow cover. They found that the total volume of the area’s glaciers decreased by 78% between 1971 and 2015 (because of increased evapotranspiration), furthermore by 2100, under scenarios A2 and B2 the area will have no glaciers coverage. Aili et al. (2019) [6] found that up to 2100, between around 3.9 and 6.8 km of glaciers would be lost in the Rio Maipo area, in Chile.

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Studies have been also conducted in glacial basins in Asia, by for example Zhang et al. (2016) and Treichler et al. (2019) [7, 8]. The results showed that homogeneous regional variations in the Northern and Southern sites of the mountain are likely to have happened, and glacial cover is lost. Access to water in the Himalayas under climate change conditions was studied by Momblanch et al. (2019) [9]. They showed that future snowmelt runoff in different areas in the Himalayas can generate from melting between 100 or 50 percentage of glacier until 2100. The snowmelt runoff created because of temperature rise (rise by between 4 and 5 °C) in the future, and because of precipitation has risen by 7% in the period up until 2100. Liu et al. (2020) [10] showed that as little as 8% of the river basin glaciers in Central Asia might remain under scenarios A2 and B2, by the end of the 21st century, so most of the river basin glaciers are predicted to be lost by them.

The effect of climate change on streamflow is analyzed in previous researches. Hydrologic modelling is a valuable tool for flood forecasting and decision making in water resources organization [11]. Previously, various hydrologic models with a snow factor were applied to model the daily stream flows in snow- and glacier-fed catchments [12-14]. Nevertheless, most of the hydrologic models are not practical to use for daily stream flow simulation and projection in the mountainous catchments, where the snowmelt is a main parameter in the water cycle [15, 16]. Because many of these models are sensitive to the precipitation driving, the precipitation data available from the high altitude catchments is usually not of very decent quality [17]. Lack of information for temporal and spatial rainfall variability causes a huge uncertainty in snowmelt runoff forecasting [18, 19].

The effects of climate change on climatic conditions and surface water resources in Iran have also been investigated. Yoosef Doost et al. (2018) [20] used the HADCM3 climate model under the scenarios A2 and B2 to study the effects of climate alteration in the Taleghan Basin in Iran. More details about HADCM3 climate model under scenarios A2 and B2 is shown in Valdes et al. (2017) study [21]. However, there are few studies that have analyzed the effects of climate change on snowmelt runoff in Iran.

Since a significant proportion of precipitation in the Zayandeh-rud area is snow, thus snowmelt water plays a major role in the River water supply. Because there is a lack of data and numerical values for snowmelt runoff, moreover because of lack of control on the snowmelt runoff, therefore investigating the value of snowmelt runoff under the climate change effects is very important. Understanding the relationship between climate change, and snow and ice runoff is essential in water management. The purpose of this study was to investigate how future temperature might affect snow cover and snow melt in the Zayandeh-rud area. Unlike previous studies (e.g., [22]), the data presented in the fifth report (CMIP5) were considered by simulating climate change scenarios in this study. More details about CMIPS is presented in Salman et al. (2018) research [23]. In this study, the structure of climate change models and scenarios to project the future climate change effects on temperature and precipitation is given. This is including the description of the snow-melt runoff model and snow cover area, which are explained in section 2. In section 3, the results of snowfall projection, snow coverage areas and snow melting forecasts are presented. The comparison of the results with the previous studies, are explained in section 4 and the summary of new findings including the projection of seasonal climate change effects on snow melt parameters is presented in section 5.

2. Materials and Methods

2.1. Study Area

The study area is one of the main basins in the Kafrud desert, with an area of 41,548 km^2, between 32˚10´ and 33˚ 40´ N, and 50° 30´ and 53° 23´ E. It is bounded to the north by the “Salt Lake” (which is small), to the west by the Gulf of Oman and the Oman Sea, and to the east by the Kavir-siyahkooh mountain range to the south of the Kavir Sirjan sub_zone (which is located in the south of Zayandeh Rud basin). Its important rivers include the Zayandeh-rud (405 km long), the Khoshkehrood (165 km), and the Izodkhad (125 km). The catchment covers parts of Isfahan, Chaharmahal and Bakhtiari, Fars and Yazd provinces, with Isfahan Province accounting for more than 83% and Yazd province by less than 3.5%. Figure 1 illustrates the study area.

Natural flows in the Zayandeh-rud River are increased by the diversion of water through the first and second tunnels of Koohrang, originating from Koohrang River in Chaharmahal and Bakhtiari Province. Because the average rainfall in the basin is less than 150 mm/year, Zayandeh-rud Dam, in Chadegan region, stores spring and winter runoff, which then is released to the main River. The upstream parts of the basin comprise less than 10% of the whole catchment and are mostly mountainous. The central and lower parts of the basin (89%) are sedimentary plains, and are used for agriculture. Many overflows and detours have been constructed along the river, to take water for urban and industrial usage. The Zayandeh-rud Basin and water flows end in natural swamp of Gavkhoni and into the seasonal salt marshlands.

In this study, meteorological data were used to forecast the area’s possible future climate, and also the data from hydrometric stations and statistics to simulate runoff. The availability of historic data records with lower statistical errors were considered in this study as main criteria.

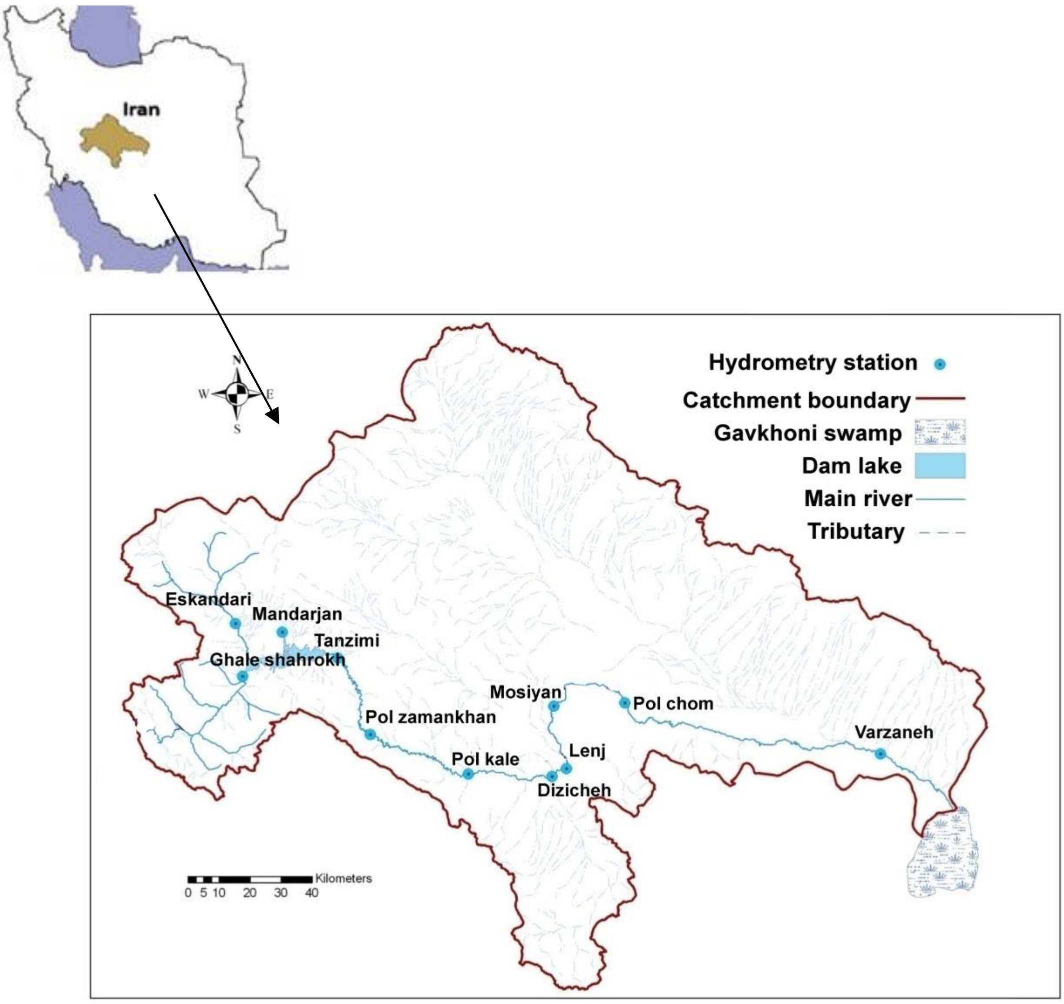

Figure 1. The location of Zayandeh-rud River Basin [24]

The flowchart of overall research methodology is shown in Figure 2.

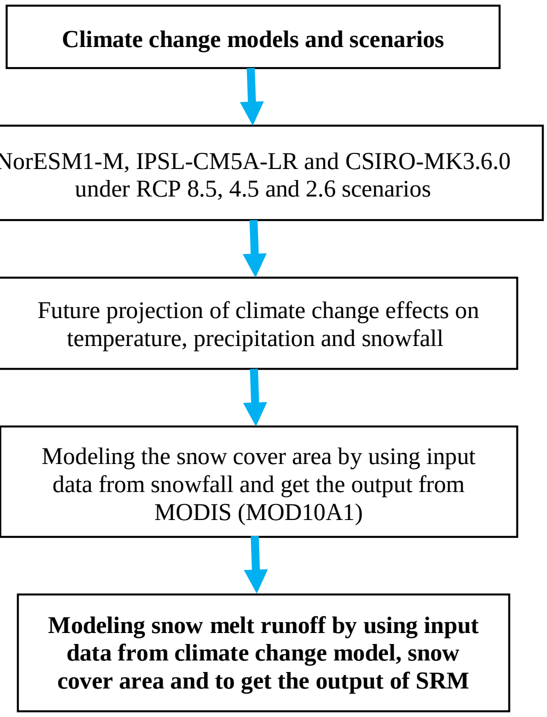

Figure 2. The structure of the methodology in this study

Snow cover data were extracted from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite and daily snow cover maps, (which used from MODIS are named MOD 10A1) for this area. Snow precipitation was modeled using the snowmelt runoff model (SRM) [25] and verified with historic data. Climate change scenarios were extracted using general flow and downscaled models (e.g., the delta change method [26]), applying statistical methods based on the delta change method for the study area, and their effect on snowmelt runoff under these scenarios was investigated.

2.2. Snow Cover

Determining the level of snow cover in the simulation of snowmelt runoff in this area is of particular importance. Some 1,450 daily snow cover images from MODIS (MOD 10A1) were used from the period between 2000 to 2007 determine the extent of the cover in this area.

2.3. Climate Change Projection

The models presented in CMIP5 have better spatial quality than those in CMIP3, so in this research different General Circulation Models (GCMs) from CMIP5 were used. The images were entered into ARCGIS 10/1 software and the daily proportion of snow cover was calculated [27]. Cloud cover is an obstacle in determining the true extent of snow cover, thus images with cloud cover exceeding 20% were eliminated, and average snow cover was considered based on linear interpolation between the days immediately before and after.

2.4. Snow-melt Runoff Model

The snow-melt runoff model is one of the most widely used for simulating daily flows in mountainous areas and has been successfully tested by the World Meteorological Organization. It is a conceptual hydrologic model, and can be used to simulate daily runoff, and to predict snow-melt and precipitation. In this study, simulated daily runoff from snow-melt and rainfall in the study area were calculated using Equation 1.

$$Qn+1= C_{sn}.\ a_n\ (T_n+\Delta T_n)\ s_n.\ A.\ 0.116\ (1+K_{n+1}) + C_m P_n.\ A.\ 0.116\ (1-K_{n+1} + (QS_n + Qr_n)\ K_{n+1} \quad (1)$$

Where Q is the daily mean discharge (m^3/s), C_s the coefficient of snow runoff, C_r the coefficient of rainfall runoff, "a_n" is a coefficient for degree-days (cm $C^{-1}d^{-1}$), T+ΔT the number of degrees and days (cd); S the ratio of snow cover to the total area, P represents daily rainfall (cm), A the basin area (km^2), K a reduction factor (Y_c, X_c), and n the number of days simulated. The factor 0.116 is a constant.

The 38 models of CMIP5 were implemented with new scenarios (e.g., Representative Concentration Pathway (RCP)). RCP scenarios represent radiative drives. A Representative Concentration Pathway (RCP) is a greenhouse gas concentration (not emissions) trajectory, adopted by the IPCC for its fifth Assessment Report (AR5) in 2014. It supersedes Special Report on Emissions Scenarios (SRES) projections published in 2000.

Three pathways have been selected for climate modeling and research, which describe different climate futures, all of which are considered as possible, depending on how much greenhouse gases are emitted in the years to come. The three RCPs, namely RCP2.6, RCP4.5, and RCP8.5, are labelled after a possible range of radiative forcing values in the year 2100. Among all scenarios, RCP 2.6 are the scenarios with low radiation propulsion patterns and consist B1 (convergence and ecologically friendly) and B2 scenarios [28] and the scenarios of RCP 8.5 show a scenario of radiative drives with high radiation propulsion patterns.

Three models, NorESM1-M, IPSL-CM5A-LR and CSIRO-MK3.6.0, were selected and used under scenarios RCP 2.6, 4.5 and 8.5 for four periods – 2021-2030, 2031-2040, 2041-2050 and 2051-2060 – to try to predict the greatest, least and most intermittent changes in climate. In this study, the three models which have been modelled showed the best fit with observed climate parameters (for example precipitation modelled by these three models is similar to the precipitation which is estimated by rain gauges for historical time period). NorESM1-M was selected as an exponential model for model calibration. In this study, among the three models, the model of NorESM1-M showed the best simulation and therefore best fit with observed climate parameters.

2.5. Estimating Future Snow Cover

Snow cover is an important parameter in the area's runoff pattern. Water storage in the form of snow and ice helps modify runoff variability, created by the rainfall pattern. Changes in snow cover area cause changes in snow-melt runoff. For this study, future snow coverage was estimated using the relationship between the snow-covered area, temperature and rainfall. Multivariate analysis based on regression using SPSS was performed with 4 predictor variables – mean monthly temperature, mean monthly precipitation, and the previous month's temperature and precipitation – to calculate snow cover at altitudes above 1,800 m.

3. Results

3.1. Analysis of Snow Covers Area

Snow cover in the area starts in November and is most extensive in January, which is a very cold month. After that, the area covered decreases because of increasing temperature and evapotranspiration. In June, the area covered by snow is at its lowest, because the temperature and evapotranspiration are both at their maximum. Figure 3 shows the monthly variation in snow cover at different altitudes (period 2000 to 2006). The extent of snow cover increases with topographic level. As Figure 3 indicates the snow cover for each month and for each year fluctuates.

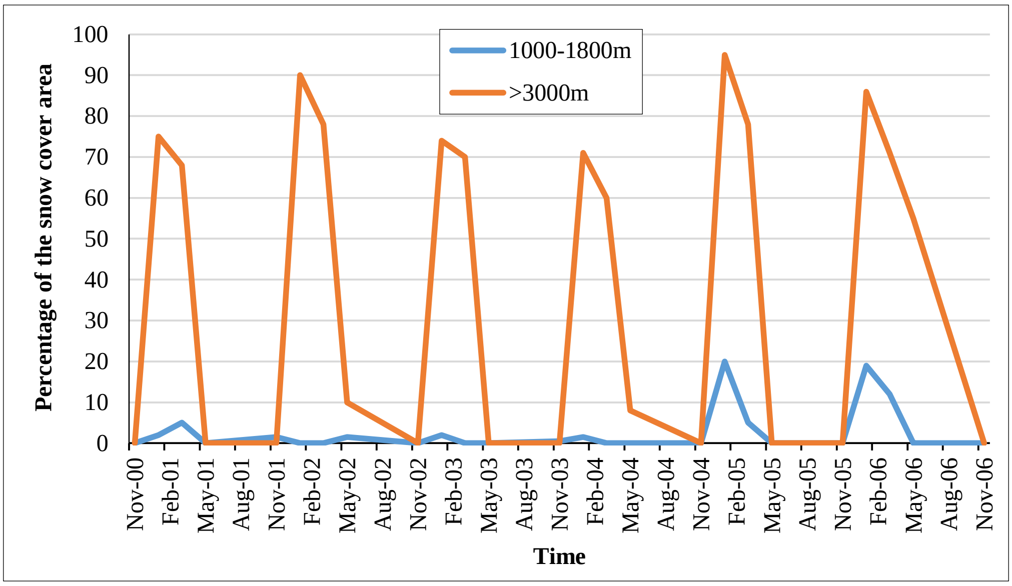

Figure 3. Proportional snow covers at different elevations – monthly, 2000 to 2006

3.2. Runoff Simulation

The runoff model was calibrated and evaluated for the period 1973 to 2006. Figure 4 shows the simulated and measured discharge variations. Because snow cover area changes a lot (as showed in Figure 3), so the runoff also has a fluctuation for each year. The coefficient of determination (R^2) is 0.70 and the percentage difference between the estimated and observed runoff is 35%. The quality of the simulation is thus acceptable. The difference is because the model cannot calculate the water seepages and water losses.

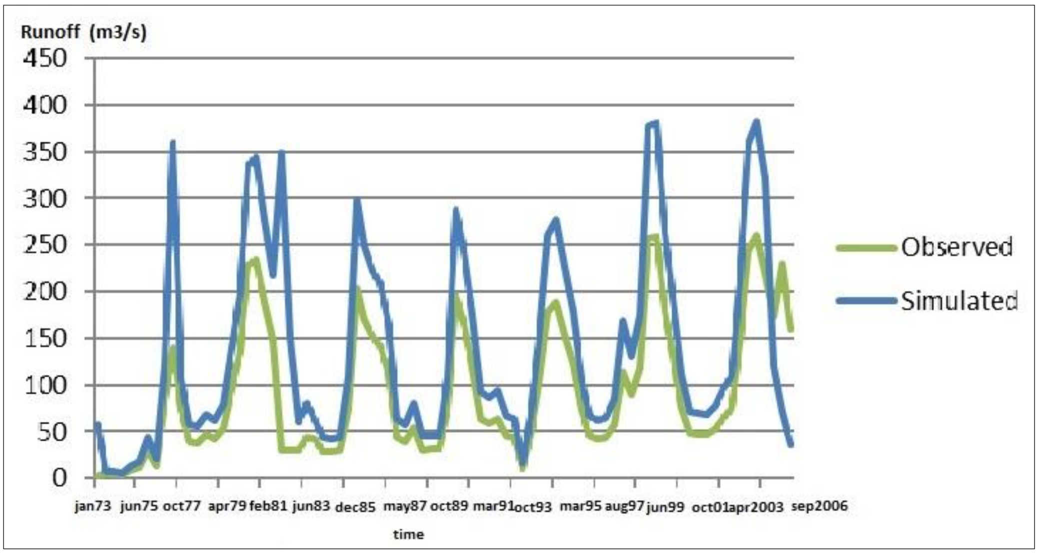

Figure 4. Comparison of observed and simulated discharges - The Zayandeh-rud basin [24]

The proportion of snow-melt in relation to a total runoff from the area for the period between 2000 to 2006 was investigated, and the results indicate that maximum snow-melt occurs in winter and spring (55%). Snow-melt runoff is highest in winter because, especially in March (late winter), the temperature rises and the speed of melting increases.

Table 1. Annual average snow-melt proportion in total runoff – 2000 to 2006

Season	Average snow-melt component (cm)	Total runoff generated (cm)
Fall	34	96
Winter	75	140
Spring	53	100
Summer	160	400

3.3. Precipitation and Temperature Forecasting

The three climate models of NorESM1-M, IPSL-CM5A-LR and CSIRO-MK3.6.0, were used to predict the temperature and precipitation under the three RCP scenarios. The model was calibrated using historical data from 2000 to 2006, and showed a high correlation between observed and simulated temperature and precipitation. In general, the model can simulate climate parameters very well.

Table 2. Correlation coefficients between observed and simulated temperature and precipitation obtained using SPSS

Parameter	Correlation coefficient
Temperature	0.80
Precipitation	0.62

The average temperature and precipitation for the period November to June were calculated, and the downscaled output of NorESM1-M, IPSL-CM5A-LR and CSIRO-MK3.6.0 was calculated according to Table 3. The grid was 1.5×1.5 km and some 18,222 grids were used. The downscaled output was used because the data from the climate model were at large scale in order to obtain data at the scale of the study area [29].

The simulation shows that the average temperature increases with respect to the base period. This means that in coming decades, there is an average increase in the different scenarios, for example the average temperature is increased between 1.1 and 3.4 °C in NorESM1-M, between 2 and 4.35 °C in IPSL-CM5A-LR, and between 1.3 and 3.5 °C in CSIRO-MK3.6.0.

Comparing the predicted temperatures in the models, the highest temperatures are found in the 2050s in IPSL-CM5A-LR under scenario RCP 8.5. The average temperature increases in the 2050s is about 1.8, 2.8 and 3.5 °C, respectively, for RCP scenarios 2.6, 4.5 and 8.5. The trend of annual average changes for November to June indicates that temperature rises by about 0.05 °C/a. The results of the study also indicate decreasing trend in annual precipitation compared to the base period. NorESM1-M indicates a greater reduction in precipitation than the other two models. The three climate models suggest that the mean rainfall in the 2050s will be 2, 3.2, and 4.5% lower for RCP scenarios 2.6, 4.5 and 8.5, respectively. The greatest reduction indicated in the 2050s is about 14 mm for RCP scenario 8.5. The average annual rainfall from November to June drops about 0.038%/a.

Table 3. Temperature and precipitation in the period November to June for different models and scenarios

Parameter	Time period	NorESM1-M			IPSL-CM5A-LR			CSIRO-MK3.6.0		
		RCP 2.6	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5
Mean annual temperature (^{0}C)	2021-30	9.1	9.31	9.41	9.71	9.83	9.90	9.51	9.37	9.51
	2031-40	9.3	9.57	9.8	9.99	10	10.50	9.90	9.90	9.97
	2041-50	9.6	10	10.3	10.17	10.59	10.97	9.30	10.20	10.57
	2051-60	9.8	10.13	10.48	10.17	11.28	11.12	9.30	10.40	10.69
Mean annual precipitation (mm)	2021-30	336.2	311.24	317.20	297.12	299.17	299.80	303	300.7	298.20
	2031-40	339.24	324.7	322.10	298.09	296.78	294.03	295	293	298.78
	2041-50	337.14	327.10	322.03	298.09	294.89	295	297	296	295.80
	2051-60	332.08	319.19	316.15	298.20	291	292.20	293.5	290	289

3.4. Forecasting Runoff

After calibration, the SRM model was used to simulate runoff using different GCM and RCP outputs for the study periods. Table 4 shows the average runoff in the simulated periods.

Table 4. Runoff from November to June for different models and scenarios

Parameter	Time period	NorESM1-M			IPSL-CM5A-LR			CSIRO-MK3.6.0		
		RCP 8.5	RCP 4.5	RCP 2.6	RCP 8.5	RCP 4.5	RCP 2.6	RCP 8.5	RCP 4.5	RCP 2.6
Runoff (m^3/s)	2021-30	157	143	150	120.50	123	118.20	123.45	125	120
	2031-40	152	142	154	119	120	118	123.50	122.20	123.20
	2041-50	154	145	154.70	115.75	114	115	117	116	115.1
	2051-60	151.50	141.50	143.1	115	96	98	120	118.8	100.01

The average runoff rate is reduced by about 0.2 m^3/s per year from the year of between 2006 to 2100. With increasing temperature and decreasing rainfall, the amount of snow cover decreases, reducing the volume of snow-melt related runoff. Total annual runoff volume is expected to decrease by about 12% (RCP 2.6), 13% (4.5), and 10% (8.5). The reduction in runoff in RCP scenario 8.5 is probably less than in the other two because of increased rainfall in the fall.

3.5. Future Snow-melt

The snow-melt proportion predicted in relation to the total runoff in the Zayandeh-rud River Basin is significantly reduced, from about 40% historically to 29% in decade 2051-60, because of a combination of reduced precipitation and some change from snow to rain. All models predict reduced snow-melt volumes, by about 28% on average. Figure 5 indicates the results of forecasting for snow melt. As figure presents, the results of different climate change scenarios are different. As shown in the figure, the proportional contribution of snow-melt to runoff is reduced in all scenarios, and most significantly in spring.

3.6. Snowfall Forecasting

Figure 6 shows the Pearson correlation coefficient for snow cover with temperature and precipitation in the area. The results show that snow melt values follow the amount of precipitation and temperature. Temperature has a negative relationship with snow cover because if temperature increases, then the area of snow cover will decrease. Precipitation in May and June has a negative relationship with snow cover, because at this time, precipitation is in form of rain instead of snow. Snow fall from December through April can increase snow cover, because at this time, precipitation is in form of snow and there is a positive relationship with snow cover. Therefore between March and April the highest correlation between precipitation and snow cover is observed and between May and June there is least correlation between temperature and snow cover. That is because of the temperature increases, and the snow cover decreases.

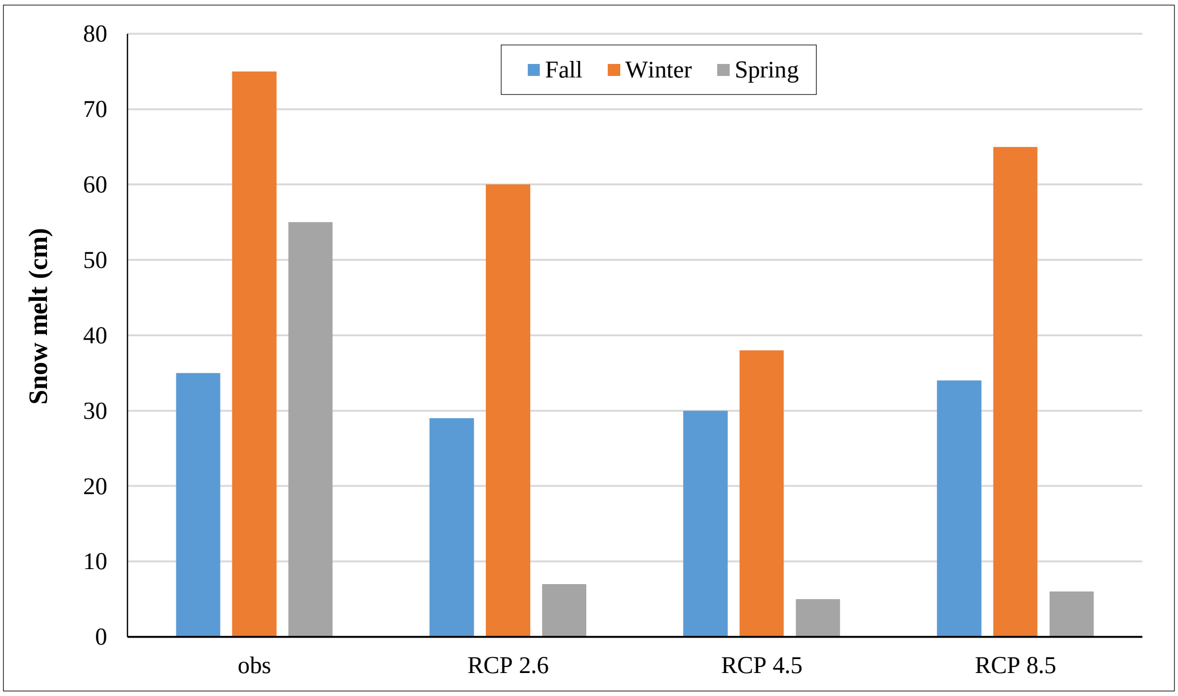

Figure 5. Proportion of snow-melt to total annual average runoff for observed data and three RCP scenarios for duration of 2006 to 2100

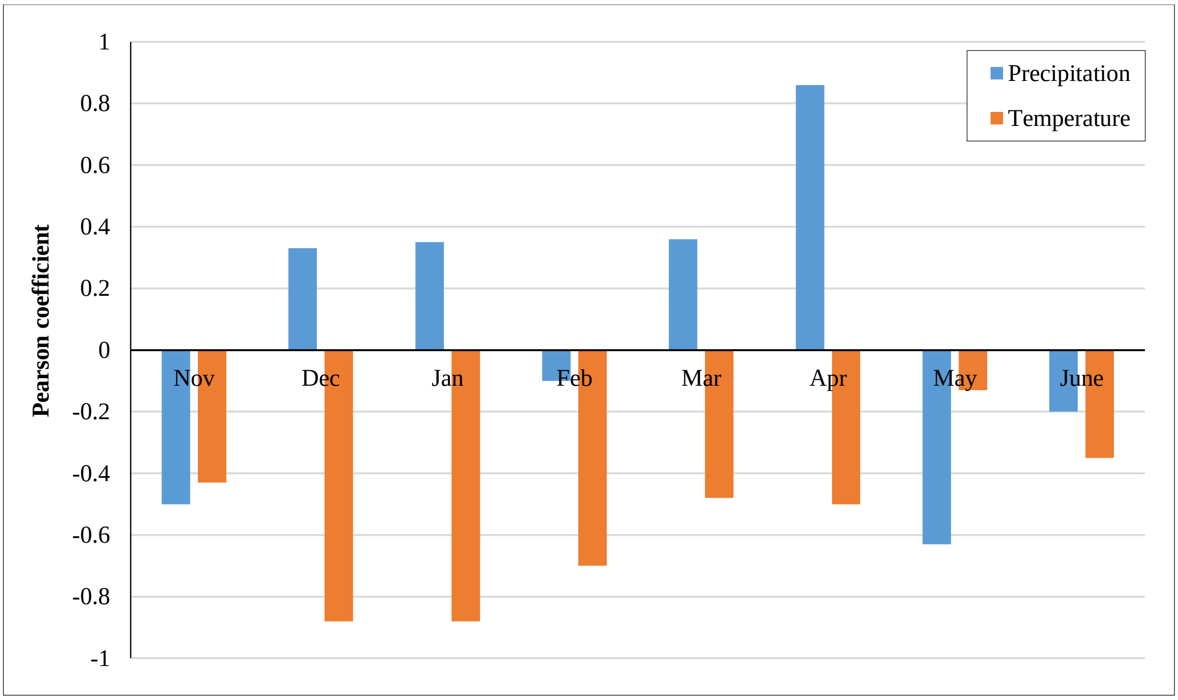

Figure 6. Pearson correlation coefficient of area of snow covers with changing precipitation and temperature (for the period November to June)

The relationship between snow cover, temperature and precipitation was analyzed using the temperature and precipitation projections, and the extent of snow cover estimated for the years 2021 to 2060. Annual snow cover is more likely to decrease 12% by 2020, 17% by 2030, 20% by 2040, and 22% by 2050, compared with the historic period. The largest reduction in snow cover is observed annually for the decade from 2050 in model IPSL-CM5A-LR under scenario RCP 8.5, and the lowest in model NorESM1-M under scenario RCP 2.6 in the decade from 2020. Table 5 shows snow cover predictions for the different models and scenarios.

Table 5. Annual area of snow covers from November to June, by decade, for different models and scenarios

Parameter	Time period	NorESM1-M			IPSL-CM5A-LR			CSIRO-MK3.6.0		
		RCP 2.6	RCP 4.5	RCP 8.5	RCP 8.5	RCP 4.5	RCP 2.6	RCP 8.5	RCP 4.5	RCP 2.6
Area of snow cover (km^2)	2021-30	2007	1797	1780	1769	1772	1775	1779	1790	1780
	2031-40	1792	1745	1722	1715	1716	1700	1780	1692	1773
	2041-50	1693	1750	1625	1650	1640	1570	1692	1800	1960
	2051-60	1650	1700	1555	1600	1557	1480	1693	1670	1599

4. Discussion

Hydrographic change forecasts are important for water resource management. Previous studies did not use the current climate models and did not attempt to forecast snow-melt runoff. Equally, they did not compare the value of snow melt runoff between current and future time period. This study provides a range of climate change predictions for future snow-melt runoff yield in the Zayandeh-rud River Basin between 2021 and 2060. The latest climate models (CMIP5) were used under the RCP 2.6, 4.5 and 8.5 scenarios. Snow cover images were used to determine the snow cover area in high altitude areas of Zagros, in places where there are relatively few snowfall stations. Images from the Zayandeh-rud Basin show extensive snow cover at altitudes above 1,800 m. snow cover is high (above 3,000 m) from December to February, but snow cover is low in May and June (less than 3,000 m).

The SRM's efficiency in mountainous catchments can be credited to the use of MODIS, which remotely sensed snow cover data as an input into the model. However, as Sharma et al. (2020) [30] mentioned still more research is needed to do this analysis. As Hao et al. (2019) [31] mentioned the analysis of the climate change impact indicated that watershed hydrology would alter under different climate change scenarios. In simulating snow-melt with the SRM model, validation indicates that the model's performance is acceptable in estimating runoff in the study area. In comparison with the observed historical period (2000 to 2007), the value of snow-melt runoff in fall and winter could be reduced by 10% and 24% in the year of 2060.

The indications are that the mean annual temperature in coming decades will increase. The results obtained and arising from temperature changes in the different scenarios, are consistent with those obtained by others recently studied [32-34].

The study's results indicate that total annual rainfall in the study area will decrease over the period up to 2060. The temperature is more likely to increase and snow areas, and snow-melt and runoff are likely to increase. The results of this study, based on reductions in runoff and snow-melt, are consistent with those of other researchers [35-37]. Also consistent to previous studies that indicate the increased/decreased snow cover area results in the increasing/ decreasing in total flow and pick flow during different season e.g. [38-40].

5. Conclusion

This research has used integrated models to model the future snow cover and snow melt under different climate change scenarios. The study forecasted climate alterations, and assessed the potential changes in snow cover and snow-melt runoff under different climate change scenarios in the Zayandeh-rud Basin. Three climate change models of cluster models (NorESM1-M, IPSL-CM5A-LR and CSIRO-MK3.6.0) applied under RCP 8.5, 4.5 and 2.6 scenarios, to examine climate influences the precipitation and temperature in the basin. Temperature and precipitation determined for all three scenarios for four periods –2021-2030, 2031-2040, 2041-2050 and 2051-2060. MODIS (MOD10A1) applied to examine snow cover. The relationship between snow-covered area, and temperature and precipitation used to forecast future snow cover. By inputting climate data into the SRM model which used climate data as an input to analyze the impact of climate change on the hydrological process. The analysis of the climate change impact indicated that watershed hydrology would alter under various time periods and different seasons. The results indicated that all three RCP scenarios will lead to an increase in temperature, and reduction in precipitation and snow cover. Investigation of snowmelt runoff throughout the observation period (November 1970 to May 2006) showed that most of annual runoff is derived from melting snow. Maximum snowmelt runoff is generated in winter. The share of meltwater in the autumn and spring runoff is estimated at 35 and 53%, respectively. In addition, the study results indicate that the total annual rainfall in the study area will decrease over the period up to 2060. The temperature is more likely to increase and snow areas, and snow-melt and runoff are likely to increase. The results of this study, based on reductions in runoff and snow-melt, are consistent with those of other researchers. However, the obtained modeling results will offer valuable decision support mechanism for water resources management and for development of local ecosystem sustainability and social-economic improvements.

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7. Conflicts of Interest

The authors declare no conflict of interest.

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