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Impact of Climate Change on Runoff from Snowmelt by Taking into Account the Uncertainty of GCM Models
(Case Study: Shahrchay Basin in Urmia)

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Abstract

According to importance of snowfall in water supply, in this study, runoff originated from snow melt in Shahrchay river basin under the terms of climate change was calculated. For this purpose, for water year of 2012-2013, by using the SRM model, run-off from snow melt was simulated. In climate phase, first output of the six models of atmospheric general circulation converted to a downscaling by using LARS-WG model. Then, in order to evaluate the uncertainty, by comparing the output of the six models in the future time period with that of the base time period in monthly time scale some indices namely R2 and RMSE applied to select the best model and scenario of air temperature and precipitation data generator of the period 2011-2030. Therefore, the HADCM3 model with the scenario A1B was used to generate the precipitation data, whereas, the MPEH5 with the A2 scenario was used to generate the air temperature data. In order to estimate the rate of change of runoff originated from snowmelt the rate of change of monthly data of air temperature and precipitation in the base time period as well as future time period under the selected model and scenario was used as input to SRM model in simulation time period. Results showed that the amount of runoff originated from snowmelt in late spring will be decreased. The peak flow appeared earlier in time in comparison with the base period and the peak discharge value would be increased comparing the base period.

Keywords: Climate change; LARS-WG; Runoff Snow; SRM; Shahrchay.

Introduction

Snow is a form of precipitation, which has special differences with other component of water balance because of its delay in converting to runoff. Temperature and precipitation changes affect the water balance and energy balance of the basin. So, snow is considered as an important factor in climate change. Determination of temporal changes of snow melt and its water equivalent is so vital in agriculture, flood forecasting and management of water storage reservoirs of a region. North West of Iran is located in mountainous area and the main portion of precipitation occurred as snow. Runoff from snow melt has important role in charging rivers of the region and it has substantial contribution in agriculture activities and economy of the area. Scientific studies show that the climate change phenomenon has a significant impact on precipitation, evapotranspiration and water supply of any region.

Climate changes, extreme weather events and damages of weather events, increased the cost of water supply against the demand (Karamouz and Araghineghad, 2014). So, evaluation of snowmelt runoff and the effects of climate change on water supply is essential for management of water resources. Exact estimation of runoff in mountainous area with seasonal snow cover needs a suitable algorithm for estimation of runoff originated from melting snow as a part of simulation system (Bails and Kelain, 2003).

The SRM model was presented in 1975 in order to simulation of snow melt runoff in small mountainous basin (Rango & Martin, 1998). Malcher and Heidinger (2001), by using modis sensors images earned the snow coverage of 4 sub-basin in Atzal basin in east Austria on the other hand by using SRM model, runoff from melting snow simulated. SRM model was used by Seidel and Martinec (2002) to simulate the runoff from melting snow on the heights of the Alps of the Swiss and runoff of snowmelt of thirteen sub-basin calculated by using satellite images of Landsat , Spot and Noaa. Recently SRM model was used to study the effect of climate change on snowmelt runoff. Najafzadeh and et al (2004) extracted the changes in snow coverage in a sub-basin of Zayandeh Rood River using the satellite images of NOAA for a couple of years including the 1990-91. The mentioned researchers also used the SRM model for runoff simulation.

The model simulated daily water flow with a coefficient of determination equaled 0.95.Ghorbani Zadeh et al (2008) predicted the time distribution of snowmelt flow for the next half of the century, which included a two distinct 25 years from 2000 until 2050 in Karun basin by using SRM, which is a snowmelt model and also ECHAM4, which is a global climate change model. Results showed that time of maximum flow occurrence will be transfer from spring to winter. Furthermore, winter discharge will be increased by 10% whereas, spring and summer discharge will be decreased.

Fattahi et al (2010) used thev8 day's images of Modis satellite and SRM model for simulation of snowmelt runoff for Bazaft basin. Results showed the acceptable and successful simulation. Tahir et al (2011), evaluated the effects of climate change on snowmelt runoff of Hunzad River in Pakistan by using SRM model. Yon gang et al (2013) studied the effect of climate change on snowmelt runoff of Kaydo basin in northwest of China. They used the output of HADCM3 model in different scenarios. Results showed increase of runoff in spring and significant decrease of runoff in summer. Elias et al. (2015), studied the effects of climate change on snow cover area (SCA), changes in flow peaks and volume of runoff under the four future scenarios in twenty-four sub-basin of the Rio Grande basin.

The results showed that about the amount of annual runoff volume will be decreased about 7 to 18 percent in different scenarios. Moreover, the runoff volume from melting of snow will be decreased in spring, considerably. Shahrchay River located in the west Azerbaijan province of Iran. This river ran from the center of Urmia city. This river is the most important source of fresh water of the Urmia city. Shahrchay dam is located in a 12 km distance from the mentioned city. This river plays an important role in supplying the drinking, agriculture and industry water. The main purpose of this study is simulation of snowmelt runoff by using the output of GCM models in SRM software for analyzing effects of climate change in Shahrchay River basin of Urmia.

Material and methods

Shahrchay River Basin of Urmia is located in the west of Urmia Lake. Its area is about 167.75km2 and is located between 44o 58/ to 44o 82/ East longitude and 37o 32/ to 37o 48/ North latitude. The altitude of BardehSour hydrometric station is about 1591 meters and maximum height of the basin is 3574 meters (located in Iran and Turkey borders). The mean of annual rainfall is 614.9 mm. Figure 1 shows the location of Shahrchay River Basin.

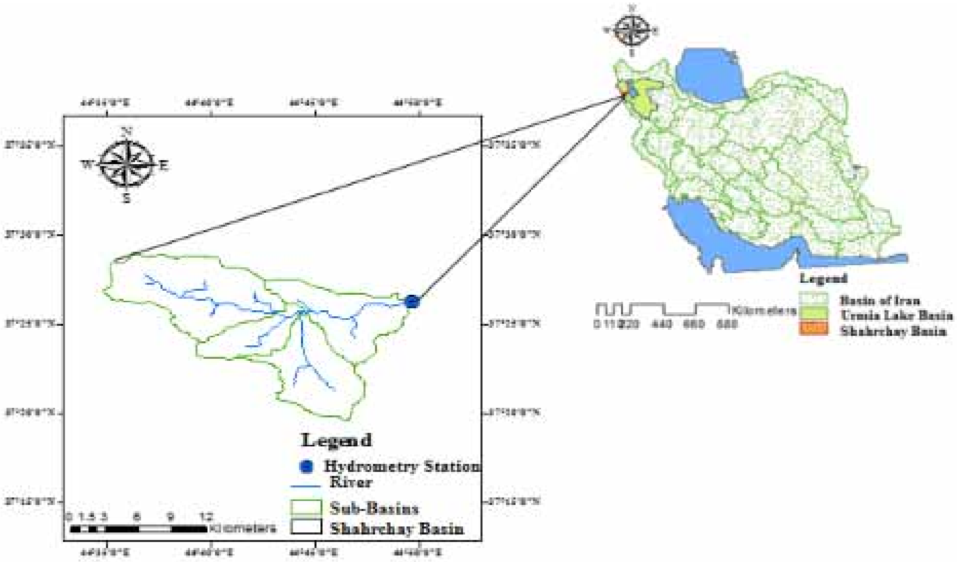


Figure 1: Location of Shahrchay River basin of Urmia in west Azerbaijan province, Iran.

Methods

In this study, in order to simulate runoff from melting snow data of satellite images and hydrological modeling of runoff were used. Then, by using the output of six atmospheric general circulation model and downscaling by LARS-WG model, namely B1, A2 and A1B the best model selected to estimate the air temperature and precipitation through calibration and validation. Changes of precipitation and air temperature in the future period of 2011-2030 calculated in the selected scenario of the period and then entered to SRM model. For this purpose, snow coverage of Shahrchay River basin of Urmia in 2013 obtained by using the satellite images of Modis sensor. Also meteorological data of Urmia synoptic station (air temperature, precipitation) as well as the amount of daily stream flow of (of BardehSour located in outlet of basin) hydrometric station from January to JUNE 2013 were used. Table 1 shows the geographical characteristics of the station.

Table 1: Geographical characteristics of the selected stations.

Station	Type of station	Longitude		Latitude		Height (m)
		Degree	Minute	Degree	Minute	
Urmia	Synoptic	37	40	45	03	1328
BardehSour	Hydrometric	37	42	44	62	1591

In this study, some meteorological data and snow coverage were used as SRM input in snowmelt runoff simulation. The mentioned data separated into two district parts as follows.

First physiographic characteristics of the basin, which includes basins border, plan of river networks, area and highlands was obtained from DEM map. For this purpose, Hec-GeoHMS of GIS software was used. Then snow coverage obtained from NOAA site and Modis sensor images within the eight days. Snow coverage of basin were interpolated within two images of this data.

As mentioned before, for simulation of stream flow originated from melting snow in the study area, SRM model was used. In this model runoff from melting snow and rainfall was calculated for each day and was added to river base flow. Then, daily runoff estimated by using the below equation (Rango and Martin, 1998).

$$Q_{n+1}=[C_{sn}.a_n(T_n+\Delta T_n)S_n + C_{rn}P_n]\frac{A.10000}{86400}(1\text{-}k_{n+1})+Q_n k_{n+1} \quad (1)$$

In the above equation Q: daily stream flow (m3. s-1), Cs: snow runoff coefficient, a :degree-day factor(cm.oC-1 d-1), T: base temperature of the station (oC), ΔT: thermal gradient of each class of altitude, S: ratio of snow coverage to basin area (percentage), CR: rainfall runoff coefficient, P:amount of rainfall and snowfall (cm), A: basin area (km2), $\frac{10000}{86400}$: coefficient for unit conversion and n: number of day in a given period.

Each of these parameters can be obtained by measuring or included based on expert opinion, by using basin characteristic, physical relations, experimental, correlation relation (McCone et al, 1998).

Model Evaluation Criteria

In this study, in order to evaluate the SRM model two performance criterion namely coefficient of determination (R2) and percent of volumetric error DV (Rango and Martin, 1998) were used. The R2 is calculated from below equation.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q_i')^2}{\sum_{i=1}^{n}(Q_i - \bar{Q})^2} \qquad (2)$$

where R2: coefficient of determination, Qi: stream flow measured in ith day (m3/s), Q/i: stream flow obtained from model in ith day (m3/s), Qa: mean daily measure stream flow (m3/s) during statistical period and n: is the number of days. The Dv is calculated from the flowing equation:

$$D_v = \frac{V_R - V_R'}{V_R} * 100 \qquad (3)$$

where DV: percent of volumetric error (which obtained by measured and simulated runoff), VR: volume of measured runoff and V1R: volume of simulated runoff.

LARS-WG Downscaling model

Downscaling model LARS-WG was presented by Racsko et al (1991) and Semenov and Barrow (1997). LARS-WG is one of the famous model for generation of random weather data. Such data can be used for producing amounts of rainfall, radiation, daily maximum and minimum air temperature in a given station under the terms of base and future time period (Babaeian et al, 2008). In this model Markov chained approach is used for modeling the rainfall data. LARS-WG was known as the famous model, which used complex statistical distributions for modeling of meteorological variables. Foundation of this model is semi experimental distribution for dry and wet period's duration length, daily rainfall, and radiation time series. In semi experimental distribution, distances divided equally between the maximum and the minimum of monthly time series classes as follows:

$$EMP = \{a_0, a_i, h_i, \ldots.. \qquad i = 0, 1, 2, \ldots..,10\} \qquad (4)$$

In the above equation, EMP is a histogram with 10 intervals (with different rainfall intensities) so that ith interval defined as follows.

$[a_{i-1}, a_i]$ $\qquad$ $a_{i-1} < a_i$

where hi indicated the number of rainfall events in the ith interval. Distances are arranged increasing order for both wet and dry periods. In this model, radiation modeled independently from air temperature. The sunshine hours can be used instead of radiation. The mechanism of data generation in LARS-WG model accomplished in the three step, which are: calibration, evaluation and generation of meteorological data.

The mechanism of data generation in LARS-WG model is as follows. First by using the scenario of monthly data generation, which includes climate demeanor, all monthly data's which include climate demeanor match with following formula:

$$F_{fut} = F_{obs} + (F_{GCM}^{fut} - F_{GCM}^{base}) \qquad (5)$$

F_{GCM}^{base}, F_{GCM}^{fut}, Fobs, Ffut indicated the forecasted meteorological parameters on climatological station, meteorological parameter, which monitored on the same station, predicted meteorological parameter on the model network for future time period and meteorological parameter which modeled on model network in the past, respectively. Then by keeping the mean, standard deviation of each parameters updated by the following formula (Babaeian and Kwan, 2004).

$$STD_{fut} = \frac{STD_{base}^{obs}}{STD_{base}^{GCM}} . STD_{GCM}^{fut} \qquad (6)$$

Where, STD: standard deviation of meteorological parameter under investigation.

Evaluation of uncertainty in the general atmosphere circulation models

Because in this study we decided to evaluate the effects of uncertainty sources, therefore, firstly six model selected among the all models for study. Reason of this choice is existence of the three scenarios in this models, whereas in some models there are less than three scenarios is available. For choosing the best model of GCM between mentioned models first daily records of minimum air temperature, maximum air temperature, precipitation, sunshine hours in the period (1970-2000) was entered to the model as input for the six mentioned model and for three scenarios (A1B, A2, and B1) data generated for the 2011-2030 time period. Generated data, consisted of 50 random time series and required parameters (mean air temperature and precipitation) where extracted in monthly time scale and in 2011-2030 time period. In order to check the models performance and to compare the results, some criteria's are necessary. In this study we used the root mean square error (RMSE) and coefficient of determination (R2), as followed:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i}^{n}(P_i - Q_i)^2}{n}} \qquad (7)$$

$$R^2 = [\frac{\frac{1}{n}\sum_{1}^{n}(P_i - \overline{P_i})(Q_i - \overline{Q_i})}{\sigma P_i * \sigma Q_i}]^2 \qquad (8)$$

In this equation Pi: data's of observation period and Qi: generated data for future, n: size of the data time series and σ: standard deviation of the data time series.

Future snow covered area

SRM was used to evaluate the impact of future temperature on snow covered area by basin. SRM uses basin snow cover estimated in the present climate from snow cover maps or remotely sensed data over the snowmelt period in order to produce snow cover in a changed climate.

Two options are available to estimate the snow cover of a changed climate with SRM. The modeler could elect to estimate future snow cover outside the SRM framework and then use the projected future snow cover within SRM or the modeler could allow SRM to adjust snow cover based upon daily time step modifications of the depletion curve using temperature, precipitation and other factors in internal calculations. Other researchers have used a combination of multiple linear regression of monthly climatic factors to estimate the change in snow cover (Khadka et al., 2014). The obvious drawback of this approach is the monthly timescale. SRM internal snow cover modification occurs one daily time step, hence the depletion curve for each simulated zone is modified for each day.

Monthly changes in snow cover based upon projected temperatures may miss important runoff events. The benefit of using multiple linear regression over decadal time frame to estimate snow cover is that it reduces the uncertainty associated with inter annual variability inherent in calibrating to a single year. This can be somewhat reduced by selecting a year of moderate precipitation, temperature and stream flow. Both approaches assume that past relationships between temperature and snow cover will persist in the future, which may not be the case.

SRM requires the following data to predict snow covered area in a changed climate: Number of elevation zones for each basin, current snow covered area, snow cover values (S, daily), average maximum and minimum temperatures (T, daily); precipitation, daily; degree-day factor (a); temperature lapse rate and critical temperature.

The critical temperature is used to decide if a precipitation event will be treated as rain or new snow. Precipitation is stored by SRM and then subsequently melted. Using snow coverage as a model input, the climate-affected runoff during the entire hydrologic year is computed within SRM. The climate affected conventional depletion curves (CDCCLIM) are derived to generate a depletion curve that accounts for new summer snow and the decrease in snow water equivalent due to increased winter snowmelt (winter deficit).

The difference between present and future area water equivalent of snow cover (ΔHw) is deter-mined by calculating how precipitation falling as snow in winter (1 October–31 March) under cooler historical conditions may be converted to rain in a warmer climate. In SRM this is formulated:

The difference between present and future area water equivalent of snow cover (ΔHw) is deter-mined by calculating how precipitation falling as snow in winter (1 October–31 March) under cooler historical conditions may be converted to rain in a warmer climate. In SRM this is formulated:

$$\Delta H_w = \sum_{n=1}^{182}[a_n.T_n.S_n + a_n.T_n(1 - S_n) + P_{Rn}] - \sum_{n=1}^{182}[a_n.T'_n.S'_n + a_n.T'_n(1 - S'_n) + P'_{Rn}] \quad (9)$$

Δ HW = difference between the present and future areal water equivalent of the snow cover on 1 April [cm].

a = degree-day factor [cm °C-1·d-1]

T = temperature in the present climate at mean hypsometric elevation, as degree-days [°C·d]

T′ = temperature in a warmer climate as degree-days [°C·d]

S = ratio of snow covered area to total area, present climate

S′ = ratio of snow covered area to total area, warmer climate

PR = rain according to TCRIT, present climate

P′R = rain according to TCRIT, warmer climate

182 = number of days October through March

For a given day (n) this formula expresses the inputs to runoff from seasonal snow cover, melting of temporary snow cover from the snow-free area (1 − S) and input from rain (PR). The prime denotes variable values in the warmer climate (Eq. (1)).

Accumulated zonal melt (AZM) is calculated from the product of snow cover and computed snowmelt depths for the historical summer (1 April–30 September).

$$AZM = \sum_{n=1}^{183}[a_n.T_n.S_n] - [a_n.T_n(1 - S_n)] \quad (11)$$

By comparing ΔHw with AZM we can identify the day on which ΔHw exceeds AZM. The value for snow cover on this day is then shifted to 1 April and snowmelt for the changed climate then follows the original depletion curve. An example given by Martinec et al. (2008) shows ΔHw exceeding AZM on 27 April. The melt depths and associated snow cover values for 27 April are shifted to 1 April, thus adjusting the conventional depletion curve for a warming climate.

SRM conducts winter and summer present and climate change simulations in a series of six steps. In the first four steps (computed within the SRM climate change module) zonal melt totals are computed which are used by the model to calculate climate modified snow depletion curves. The winter adjusted depletion curves under climate change are computed in step five. Depletion curves are derived by the following steps:

1. Compute winter change (ΔHw)
2. Develop a zonal melt curve (AZM) for each zone for the normal climate and find the date where ΔHw is equaled or exceeded.
3. Create the modified depletion curve for each zone by adjusting for winter deficits or surpluses.
4. Modify the depletion curve to account for the daily melt depths of the new snow in the future climate.
5. For each daily value of the new depletion curve adjust the percent snow cover based upon future climate temperature
6. Compute the climate change CDC by infilling any missing daily values with the earlier days' percent snow cover value. This new depletion curve is used in the climate change simulations. See the SRM manual (page 104) for further details (Rango and Martin, 1998).

Results

Using the digital elevation map (DEM) of area firstly flow direction, flow accumulation and waterways maps were plotted. Then coordination of the watershed outlet (BardehSour hydrometric station) to program border soft area was found and basin classified according to three elevation classes. Figure 2 shows altitudinal level and in chart 2 results of hypsometric calculation of Shahrchay basin has been presented.

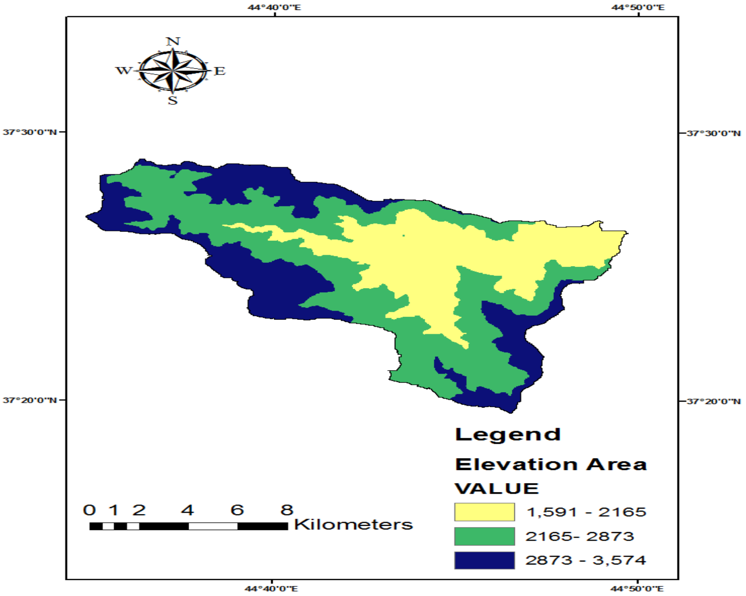


Figure 2: Map of elevation area of Shahrchay River basin.

Table 2: Hypsometric classification in the Shahrchay basin.

Classified height (m)	Area (sq. km)	Percentage of area	Average height (m)
1591-2165	31.55	17.85	1962
2165-2873	11.2	62.91	2534
2873-3574	34	19.24	3038
Sum	176.75	100	2530

In figure 3 the images of snow coverage in four distinct selected days in the statistical period were shown. In this figure areas covered with snow highlighted. As it can be seen from the figure 3 snow covers the whole of the basin on 23 January 2013. Whoever, as air temperature increases gradually in the same year, snow from lowlands of the basin melted so that on 12 April 2013, almost half of the basin is lack of the snow coverage and finally on 22 May 2013. Almost total parts of the basin (except height area of basin) had no snow.

Figure 4 shows the results of the runoff simulation of snowmelt of Shahrchay basin in the base period were shown. As it is obvious from the figure, SRM model simulated the runoff from snow melt reasonably.

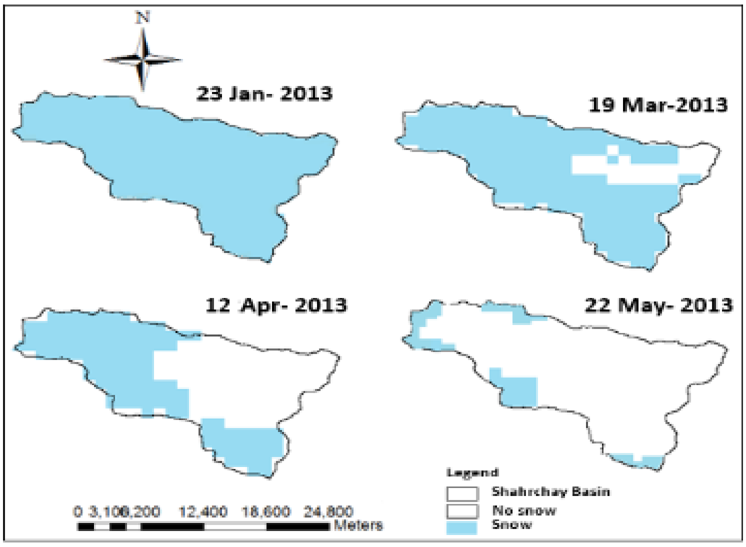


Figure 3: Images of snow coverage in the four selected days in Shahrchay basin of Urmia.

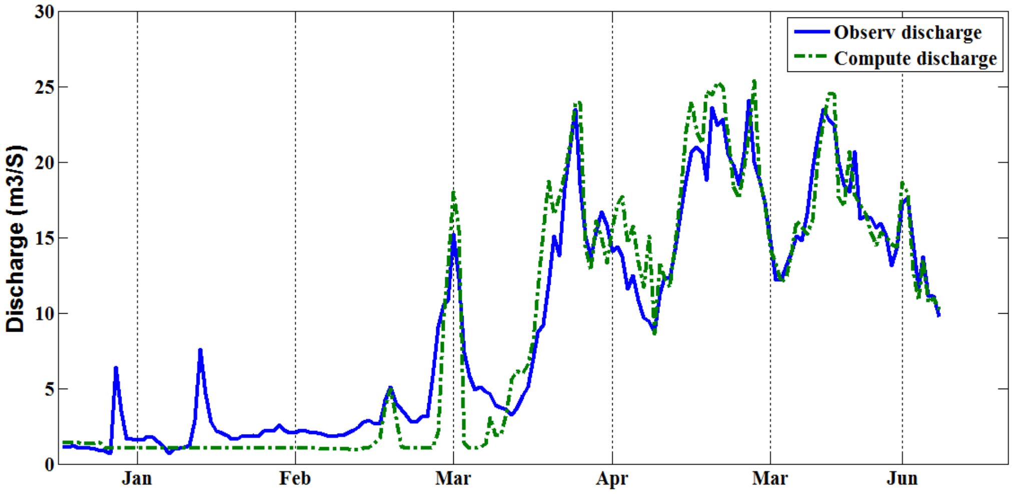


Figure 4: Changes of observed and calculated stream flow in the statistical period January 2013 to June 2013.

Validation of LARS-WG model on Urmia synoptic station

Figure 5 shows the observed and computed values of the minimum air temperature, maximum air temperature, precipitation and radiation for the base time period in Urmia synoptic station. As it can be concluded from mentioned Figure, LARS-WG to simulate the mentioned meteorological parameters accurately. Also ability of the model in rainfall simulation is acceptable as chi-square test results in 10% level. These criteria considered as bench mark in future time period.

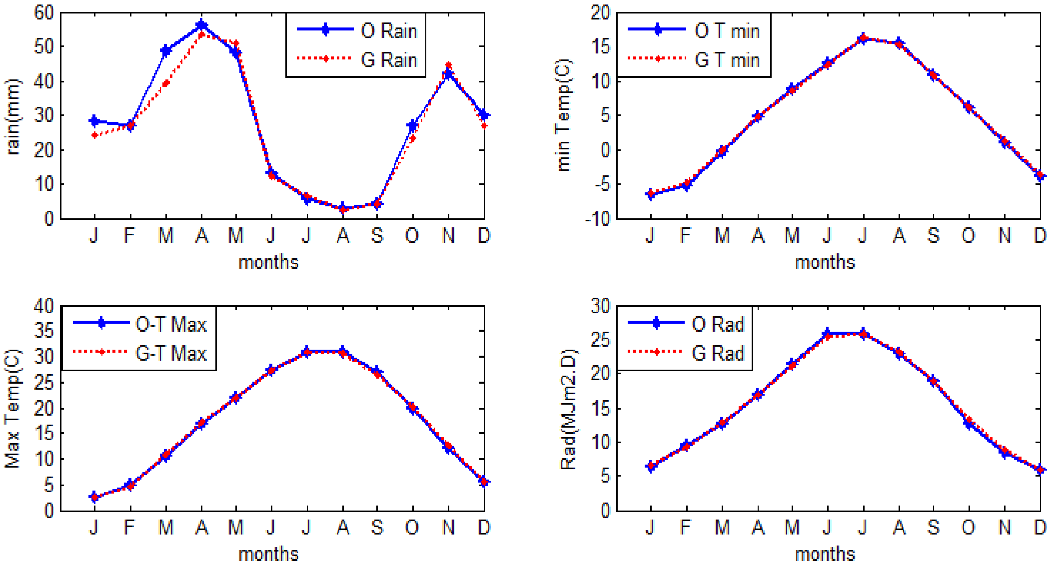


Figure 5: Comparison of observed and computed data of meteorological parameter in Urmia synoptic station.

Comparing the observed and generated data including the monthly rainfall, T mean using the six mentioned candidate models, the best model and the most appropriate scenario selected for generation of data in future time period. Results of such comparison represented in Table 3 and 4. As it can be calculated from Table 4 and 5 that among the candidate models, the HADCM3 model under the A1B scenario yielded the most appropriate result for precipitation, whereas the MPEH5 model under the A2 scenario yielded the best result for mean air temperature.

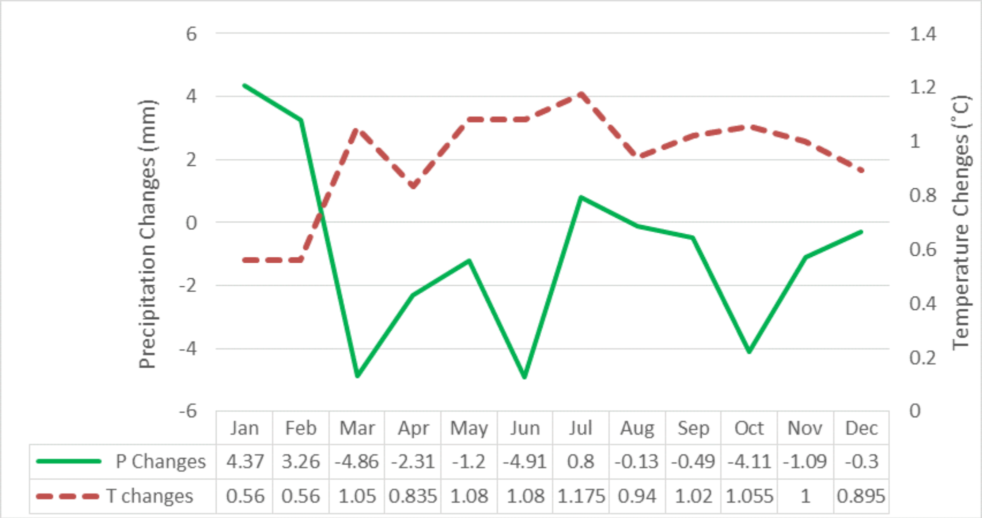
Table 3: Comparison of results of GCMs for precipitation in the base time period.

Model	Precipitation (A1B)		Precipitation (A2)		Precipitation (B1)	
	RMSE (mm)	R2	RMSE	R2	RMSE (mm)	R2
GFCM21	5.02	0.947	5.73	0.91	7.18	0.857
HADCM3	2.93	0.975	3.68	0.954	5.02	0.936
INCM3	3.57	0.97	4.77	0.932	3.12	0.976
IPCM4	4.42	0.943	4.16	0.946	4.1	0.95
MPEH5	8.38	0.815	5.22	0.918	5.16	0.917
NCCCS	4.68	0.938	3.56	0.965	4.91	0.93

Table 4: Comparison of results of GCMs for air temperature in the base time period.

Model	Temperature (A1B)		Temperature (A2)		Temperature (B1)	
	RMSE	R2	RMSE	R2	RMSE	R2
GFCM21	1	0.9998	0.98	0.9996	1.03	0.9996
HADCM3	1.07	0.9991	1.27	0.9992	1.24	0.9993
INCM3	1.15	0.9997	1.19	0.9994	1.12	0.9994
IPCM4	1.29	0.9996	1	0.9998	1.13	0.9997
MPEH5	1.05	0.9995	0.95	0.9998	1.1	0.9997
NCCCS	1.46	0.9995	1.45	0.9992	1.45	0.9998

In the next step the model was run for under the climatic changes as follows. The amount of changes for precipitation and T mean parameters in the base time comparing the future time period in the month from January up to June (which data simulated for these months) entered as input for to SRM model and the model was run under the terms of climate change. Figure 6 shows the T mean and monthly precipitation changes using the selected scenario and model. As it can be seen from figure 6 that in the simulated period (from January till June) the monthly mean precipitation decreased mean air temperature increases for the station.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P Changes	4.37	3.26	-4.86	-2.31	-1.2	-4.91	0.8	-0.13	-0.49	-4.11	-1.09	-0.3
T changes	0.56	0.56	1.05	0.835	1.08	1.08	1.175	0.94	1.02	1.055	1	0.895

Figure 6: Changes of mean air temperature and precipitation in future time period in comparison with base time period.

Figure 7 shows the results of simulation under the terms of climatic changes. According to figure 7 it can be possible compare the runoff of base period with that of the climate change scenario output. The runoff of snowmelt decreases considerably in mid-spring. Furthermore peak flow will occurred early in time with longer values. The results of this study are consistent with other relevant studies. Yang et al. (2013) reported similar results for snowmelt increases due to increasing the air temperature.

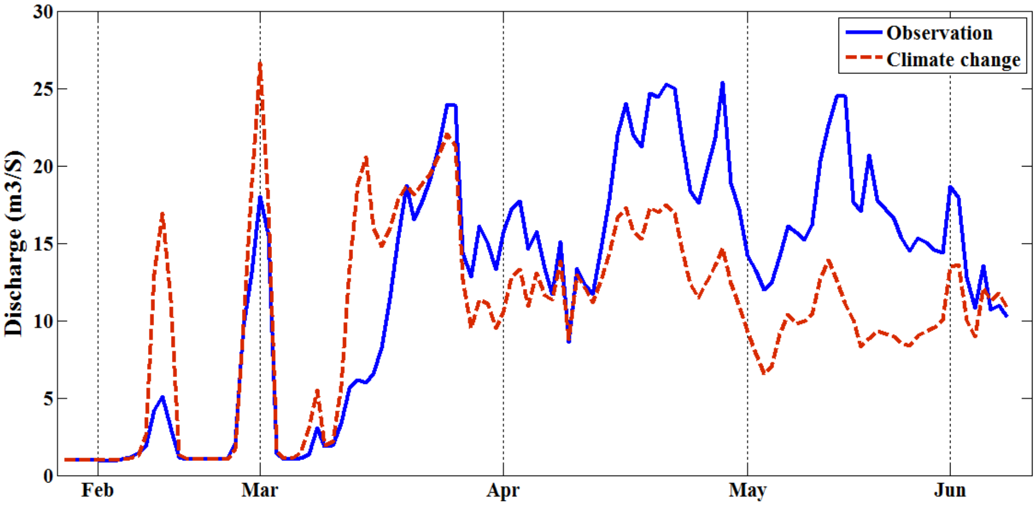


Figure 7: Observed runoff from snowmelt water in 2013(solid line) and simulated runoff from the model in future period (2011-2030).

The work of Ghorbanizadeh et al. (2009) it was found that the peak flow shifted to be appear in winter. On the other hand the amount of peak discharge decreased in their work. Table 5 summarizes the results of SRM model capability in snowmelt runoff simulation both in present period and in future period in Shahrchay basin. It can be seen from the mentioned Table that reduction in discharge especially in the warm period of year would be appeared as climate change effect.

Table 5: Results of the snowmelt runoff evaluation for Shahrchay basin simulated from the SRM model.

	Winter runoff volume (Million cubic meters)	Summer runoff volume (Million cubic meters)	Total runoff volume (Million cubic meters)
Measured runoff in the base period	9.339	123.11	132.44
Runoff in the base period	5.087	124.859	129.94
runoff in the future period	4.08	98.84	102.92

Conclusion

In this study effect of climate change on snowmelt runoff investigated taking into account the uncertainty of general circulation models of the atmosphere and available scenarios. Results showed that about 28.68 percent reduction experienced in runoff especially in late May and June, which is significant as coincided with agriculture time activities. Also peak flow time which usually occurs in May will be happened in April accompanying with more intensity flash floods. Result of this study consider the alarm to be ring for Shahrchay basin because in this basin runoff will be decreased therefore supplying water for different sections (agriculture, industry and urban) might be field. In order to resolve this problems, agricultural systems should be change from traditional to modern (drip and sprinkler). On the other hand cultivation pattern should be changed. For example onion, sugar beet and alfalfa should be less cultivate. Less water consumption crops should be cultivated instead. Scientific management of water in this area is inevitable for sustainable water use, otherwise, many problem should be arose in the context of economic, social, political feature due to water scarcity.

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