ORIGINAL PAPER

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Snowmelt runoff assessment and prediction under variable climate and glacier cover scenarios in Astore River Basin, Western Himalayas

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Abstract

Climate change is expected to have a significant impact on the Himalayan region, which may ultimately affect the water security and agriculture productivity in the region. Investigations of hydrologic regimes and their linkage to climatic trends are therefore gaining importance to reduce vulnerability of growing implications in the region. In the present study, the eWater source software implementation of GR4JSG snow melt model was used for snow melt runoff modeling of the Astore river basin, western Himalayas. The model calibration and validation indicated a close agreement between the simulated and observed discharge data. The scenario of 0.9 °C increase in temperature indicated 33% rise in the river discharge, while an increase of 10% in precipitation may exaggerate the river flows by 15%. The scenario of 100% increase in glaciated area showed 41% increase in the Astore river discharge. On the other hand, reduction of 50% glacier cover may result in 34% decline in the river discharge, while 0% glacier coverage may reduce the river discharges by 49% from that of the base year 2014. It is essential to develop a long-term water resource monitoring process and adapt water management systems taking into account the socio-economic and ecological complexities of the region.

Keywords Snowmelt · Astore basin · Climate change · Himalayas

Introduction

A fifth of world population depends on rivers originating from glaciated region of Hindu Kush Karakorum and Himalayas (HKH) of High Asia. The changes in climate and corresponding impacts on snow and glacial environment in the high mountain system have been frequently studied during the recent decades (Bolch et al. 2012; IPCC 2013; Lutz et al. 2014; Hasson et al. 2017; Shekhar et al. 2017; Pant et al. 2018; Steiner et al. 2018). The signals of global warming are causing the retreat of glaciers particularly in the Himalayas, although the pattern of climate change, glacier retreats, thinning, advances, and surges is complex (Kargel et al. 2011; Hewitt

2005; Bolch et al. 2012; Bishop et al. 2014). The climate change forecast for the Himalayan region has special concern for the Indus River System (IRS), which is heavily reliant on the snow and glacial resource of the Upper Indus basin (Kamal 2008; Ali et al. 2009; Immerzeel et al. 2009; Rasul et al. 2011). The water resources of Pakistan depend heavily on the glacial melt water from the HKH ranges (Anwar and Iqbal 2018). Any change in the flow of river Indus will not only effect the livelihood yet the economy in general (Archer et al. 2010). Previous studies on HKH have focused on the role of seasonal snow accumulation in view of remotely sensed measurements of snow-covered area (Rango et al. 1977; Dey et al. 1989; WWF 2005) and on surface runoff estimations (De Scally 1994; Bookhagen and Burbank 2010; Romshoo et al. 2015). Immerzeel et al. (2010) pointed towards increasing water availability from the Himalayas catchments throughout the twenty-first century; however, the decline in water during mid to late century, due to loss of ice/glaciers, would be compensated by the increase in precipitation. Further investigations of the hydrologic regimes and their linkage to changing climate in the Himalayan region are needed.

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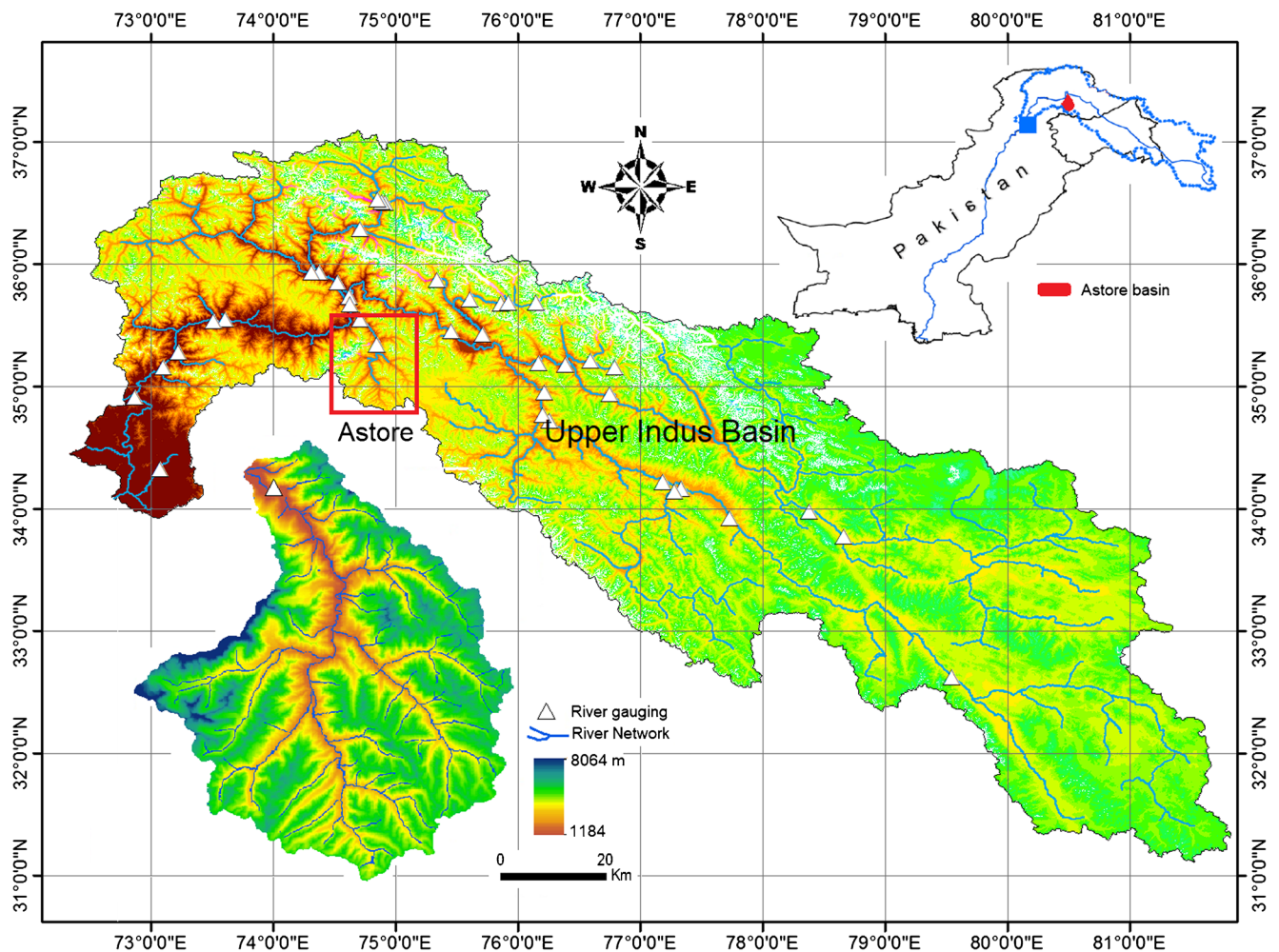
Fig. 1 Location of Astore river basin in Upper Indus basin

The focus of the present study is to apply the eWater source software implementation of GR4JSG snow melt model for runoff estimation of Astore river under variable climate and glacier change scenarios. The GR4JSG is a daily lumped rainfall runoff model (Perrin et al. 2003), which has been widely used for example in USA, Australia, and Himalayas for water resource management and climate impact studies. In this region, it was successfully applied by Nepal et al. (2015, 2016) for estimation of snowmelt contribution in the river flows of eastern Himalayas.

Study area

The study area of Astore river basin stretches over an area of about 4214 km^2 within longitudes 74°24′–75°14′ E and latitudes 34°45′–35°38′ N, in the Gilgit-Baltistan province of Pakistan (Fig. 1). About 607-km^2 area, i.e., around 15% of the total area is glaciated (Nabi et al. 2011). The elevation ranges between 1200 and 8000 m above mean sea level (masl) with mean elevation of about 4599 m (Akhtar et al. 2008). Astore river flows in the northwest direction to join

Indus river. The mean annual flows of Astore river at Doyian station were 141 m^3/s during 1980–2014. Many small snow-fed streams originate from different depressions in Himalayan ranges and join Astore river in its short course. There exist three main sources for river discharge. Firstly, glacier and snow melt form high elevations, secondly seasonal snowmelt during summer season, and lastly the direct rainfall during summer and monsoon period into the valley of the catchment. According to climatic zones classified by Survey of Pakistan, the basin falls in very cold, arid to sub-humid in less than 1000 mm rainfall zone. Snowfall usually occurs during October to March, while the melting season prevails during April to June period.

Materials and methods

GR4JSG with snow melt model

GR4JSG is composed of two main stores, i.e., the production store and routing store. The model is based upon four

Fig. 2 Conceptual representation of GR4JSG snow melt runoff model
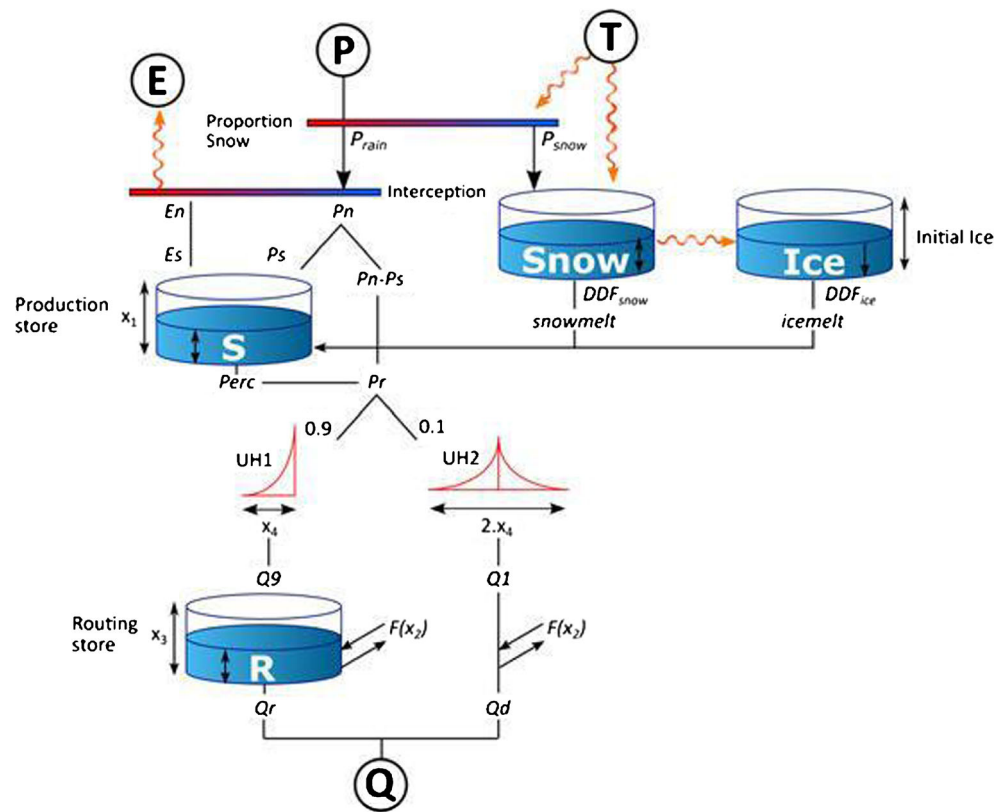
calibration parameters, X_1 (mm) is responsible for the capacity of production store, X_2 (mm) deals with flux to groundwater, X_3 (mm) manages the capacity of routing store, and X_4 (days) deals with recession of unit hydrograph. It incorporates

Fig. 3 Flow chart of methodology followed for GR4JSG modeling in the present study
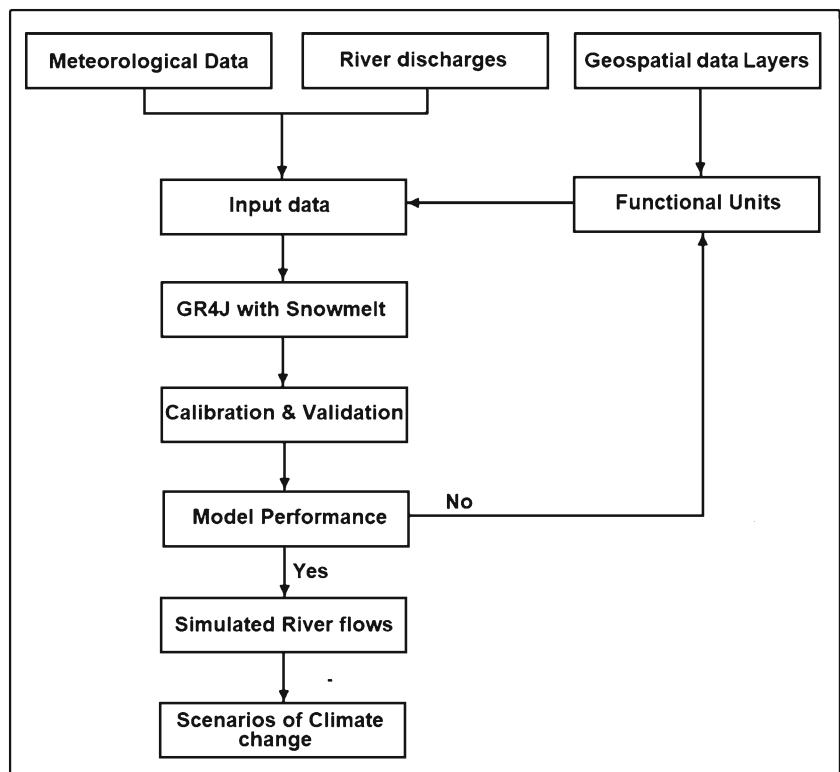
precipitation (mm) and evapotranspiration for a given day as input data. Conceptual structure of model is shown in Fig. 2. The snowpack component stores precipitation in the form of snow. The degree day factor (DDF) approach is applied to estimate contribution of snowmelt and glacier melt (Hock 2003). In this regard, GR4JSG contains two additional parameters, i.e., degree day factor of snow (DDF_{snow}) and degree day factor of ice (DDF_{ice}). The snow melt from the snow store is simulated by applying temperature index degree day factor DDF_{snow} (mm/°C-day) and when the snow storage becomes vacant, the glacier ice starts melting. The model estimates glacier ice melt by using temperature index degree day factor of ice–DDF_{ice} (mm/°C-day). The output from glacial and snow melt enters the production store. Flow chart indicating methodology followed for snowmelt runoff modeling is shown in Fig. 3. The model differentiates between liquid precipitation (rainfall) and solid precipitation (snow) on the basis of mean temperature. The daily distribution of precipitation into rain and snow is given by following equations:

$$P_{snow} = P.P_s \tag{1}$$

$$P_{rain} = P.(1 - P_s) \tag{2}$$

where P_{snow} is the amount of precipitation in the form of snow, P_{rain} is the amount of rainfall in the form of liquid, and P_s is the proportion snow.

$$P_s = TRS + TRANS - T_{avg}/(2.TRANS) \tag{3}$$

where TRS (°C) is the base temperature that distributes rain and snow above and below TRS. For this model, TRS is 2 °C where T_{avg} is daily average temperature.

Model input

For the present study, climatic data including temperature and precipitation on daily time steps (2000–2014 period) of Astore station (longitude 74°54′, latitude of 35°19′, and elevation 2168 m) was collected from Pakistan meteorological department. Lapse rate of average temperature was used from Kattel et al. (2013)). Evapotranspiration data calculated from Modified Hargreaves equation (Eq. 4) from downscaled GCM (global circulation model) data at 10-km resolution on daily steps (period 1980–2014) by Lutz and Immerzeel (2015).

$$ET = 0.0023*0.048*ER*(Tmean + 17.8)*\sqrt{TR} \tag{4}$$

where ET is the evapotranspiration (mm), ER is the extraterrestrial radiations (MJ/m^2/day), T_{mean} is the average temperature (°C), and TR is the difference between maximum and minimum temperature.

Table 1 Accuracy evaluation of the model calibration and validation results

Analysis	Period	NSC	R	P-bias	RSR
Calibration	2002–2010	0.68	0.83	− 2.7%	0.56
Validation	2011–2014	0.71	0.84	− 2.9%	0.53

The discharge data of Astore river basin at Doyian station (longitude 74° 42′ 15″, latitude 35° 32′ 42″, and elevation 1583 m) was acquired on daily time steps (1980 to 2014 period) from Surface Water and Hydrology project of Water and Power Development Authority (SWHP-WAPDA). Digital Elevation Model (DEM) data of Shuttle Radar Topography Mission (SRTM) 90-m resolution covering the study area was downloaded from http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp/. The DEM was used to make different elevation bands using functional units for snow and non-snow part necessary for snow melt runoff modeling. The MODIS snow cover data was used to determine the total snow cover area (SCA) in the study that contains maximum snow extent over an 8-day period for years 2002–2011 and has a spatial resolution of 500 m that has been downloaded from web link https://modis-snow-ice.gsfc.nasa.gov/ that is a product of MOD10A2 and MYD10A2 of Terra and Aqua Satellites. The MODIS snow cover product originally in sinusoidal projection was projected into Universal Transverse Mercator (UTM) projection (zone 42: datum WGS 1984). MODIS SCA data was reclassified into snow and non-snow parts and was assigned parameter values. Reclassified DEM and MODIS data were combined to generate a raster image for model input.

Model calibration and future simulations

The model was calibrated using discharge data of Astore river on daily time steps from years 2000 to 2010 including first 1 year of warm-up period. During calibration, the values of meta parameters of the model were adjusted through manual algorithm for optimization. The calibrated model was rerun for validation for 4-year period, i.e., 2011–2014. Accuracy of the model was evaluated using the following indices: (a) Nash

Table 2 Meta parameter values adjusted during the model calibration

Parameter	Unit	Adjusted values
DDF_{ice}	(mm/°C-day)	2.4
DDF_{snow}	(mm/°C-day)	5.7
X_1	mm	643
X_2	mm	− 9.9
X_3	mm	262
X_4	days	1.05

Fig. 4 Model agreement between observed and simulated discharge (2011–2014)
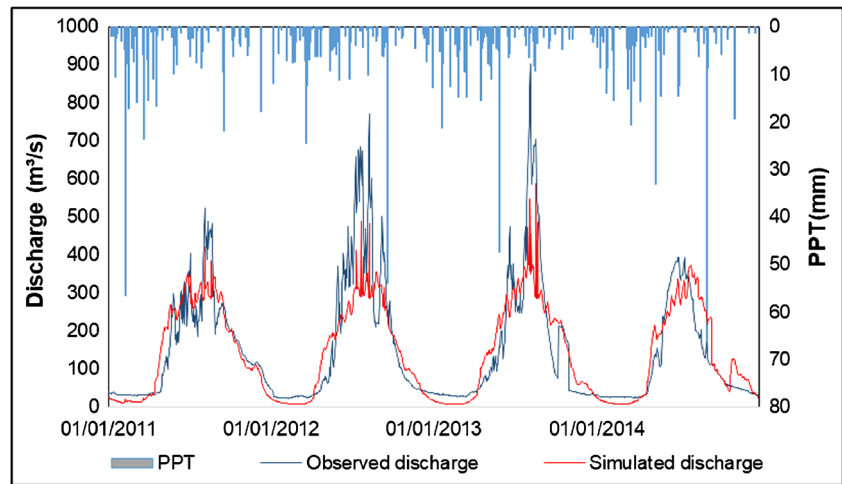
Sutcliffe coefficient (NSC), (b) Pearson correlation coefficient (R), (c) percent bias (PBIAS), and (d) root mean square error observation standard deviation ratio (RSR). Nash Sutcliffe coefficient (NSC) is commonly used to access the predictive power of hydrological model, e.g., the value closer to 1 indicates that better predictor is assumed model. Pearson correlation coefficient (R) is used to describe the strength and direction of linear correlation between model output and observed data, e.g., value $+1$ indicates a perfect agreement with an increasing linear trend and a value of -1 a decreasing linear trend, whereas value of zero means that there exists no linear relationship between the variables. Percent bias explains the tendency of deviation between simulated and observed data in percentage. Root mean square error observation standard deviation ratio (RSR) is the ratio between root mean square error and standard deviation of observed data. RSR value close to zero indicates that model provides a good match to observed data. The RSR value close to zero indicates a stronger agreement between the simulated and observed data.

GR4JSG snow melt runoff model was run to estimate the river discharge under various climatic and hydrological scenarios (PINCC 2003; Akhtar et al. 2008; IPCC 2007; Ashraf 2013) as given below.

Scenario A: Temperature is assumed to increase by 0.9 °C
Scenario B: Increase in precipitation by 10%
Scenario C: Combine effect of temperature and precipitation increase, i.e., scenarios A + B
Scenario D: River discharge was predicted under 100%, 50%, and 0% glacier coverage

Under these scenarios, changes in the river discharges were studied during various seasons, i.e., winter period from December to March (DJFM), spring from April to June (AMJ), summer from July to September (JAS), and autumn from October to November (ON).

Results and discussion

Snowmelt runoff simulation

The model calibration showed a close agreement between the simulated and the observed discharge data as indicative from Nash Sutcliffe coefficient (NSC) value of 0.68, Pearson coefficient (R) value of 0.83, PBIAS value of -2.7%, and RSR value of 0.56 (Table 1). The values adjusted for degree day factor for ice (DDF_{ice}) and snow (DDF_{snow}) were 2.4 and 5.7 mm/°C-day, respectively (Table 2). The higher value of DDF_{snow} points toward rapid simulation of snowmelt from the snow store of the model. The glacier ice melting is assumed to start after finishing of the snow storages. The higher values of X_1 parameter increase soil moisture. Meta parameter X_2 value was -9.9 mm, pointing toward minimum contribution from the ground water component into the flows. In fact, higher values of X_2 increase stream flow, while lower value means contribution to groundwater. X_3 parameter indicated a value of 262 mm. This parameter controls the capacity component of routing store. The X_4 value was 1.05 days, the higher value
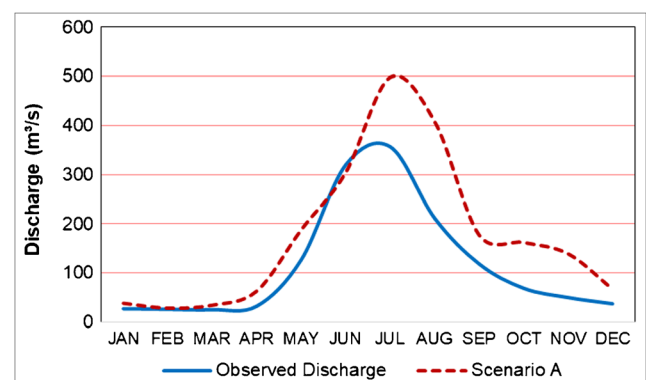

Fig. 5 Scenario A shows impact of increase in temperature by 0.9 C on the river discharge
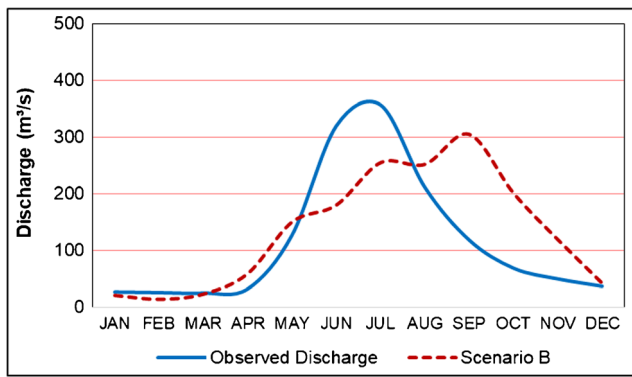
Fig. 6 Scenario B shows impact of precipitation increase on the river discharge

of this parameter delays and attenuates the hydrograph. The calibrated model indicated a good agreement for base flow and the right recession limb, whereas model was overestimating the discharge values for the right recession limbs. The meta parameter values adjusted during model calibration are shown in Table 2. The model validation indicated a reasonable agreement between the simulated and the observed discharge data (Fig. 4). The accuracy evaluated of model validation showed Nash Sutcliffe coefficient value of 0.71, Pearson correlation coefficient value of + 0.84, P-bias value of − 2.9%, and RSR value of 0.53 between the simulated and the observed discharge data (Table 1).

In Astore river basin, both snow and non-snow portion contribute to river discharge. The latter is attributed with liquid precipitation and snow melt during winter season below 2500 m. Whole catchment was divided into two elevation bands, e.g., snow area (about 88%) consisting of both seasonal snow and permanent snow and non-snow area (about 11%). At higher elevations, the model overestimated the discharge component, whereas at lower elevations due to increased rate of evapotranspiration, the model underestimated the discharge component. GR4JSG snow melt model distributes simulated flow into quick flow and base flow. Quick flow is generated as a result of snow and glacial melt and direct contribution of rainfall, whereas base flow is generated from groundwater
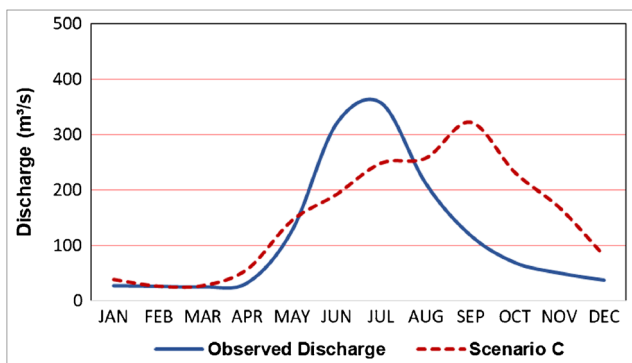

Fig. 7 Scenario C shows combined effect of rise in temperature and precipitation on Astore river discharge
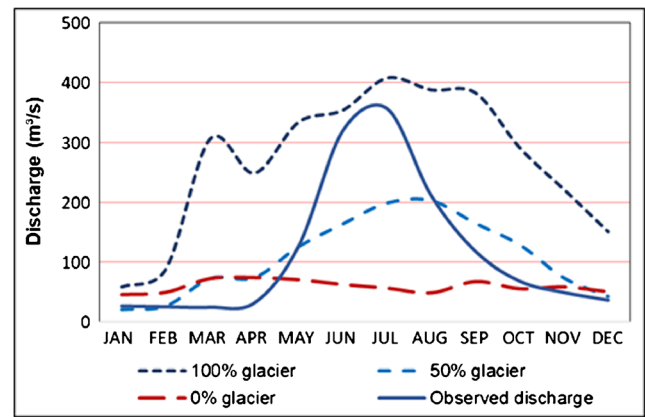

Fig. 8 Runoff simulated under 100%, 50%, and 0% glacier coverage in the Astore basin

contribution. Glacier ablation zone is the most significant zone for the contribution into river discharge. Quick flow contributes 67% to total flow and base flow contributes 33% in the total flows of Astore river. Seasonal discharge contribution in simulated discharge was in good agreement with that of observed discharge, i.e., winter (DJFM) contribution was same about 5% to the simulated as well to the observed discharge; spring (AMJ) contribution was around 32% to the simulated and 37% to the observed discharge; and summer (JAS) contributed 44% to the simulated discharge and 53% to the observed discharge. The results of seasonal basis showed that the simulated model was overestimating data for the snow accumulation period and underestimating for the snow melt period.

Scenarios of climate change

The influence of changing climate was studied on Astore river flows under variable scenarios using the base conditions of year 2014. Glaciated region, temperature, and precipitation are the key factors influencing the discharge of Astore river. The changes in seasonal runoff, i.e., of winter (DJFM), spring (AMJ), summer (JAS), and autumn (ON), were studied under these scenarios.

In scenario A, the increase of 0.9 °C in mean temperature indicated an increase of 33% in the Astore river discharge owing to increase in snow and ice melting (Fig. 5). During AMJ and JAS, temperature reached to its maximum value causing excessive snow melting and contribute in increasing river discharge. The peak flows to shift in JAS season as SCA. An increase in temperature alone will produce pronounced effects on Astore river discharge.

In scenario B, the increase of precipitation by 10% results in an increase of 15% in river discharge of base year 2014 (Fig. 6). The results show that with increasing precipitation, there is an increasing trend in Astore river discharge by as more precipitation will accumulate in the form of snow and will melt during spring (AMJ) and summer (JAS) season to

contribute in river discharge. During JAS season, temperature is high as there was more precipitation contributed to snow storage according to scenario so more will be available for melt process than AMJ season.

In scenario C, the combined effect of increase in temperature and precipitation (scenarios A + B) indicated an increase of 22% in mean annual river discharge (Fig. 7). Because of precipitation increase, more snow accumulates as storage during winter season, and at the same time, with increasing temperature, more snow melt contributes to the river flows. With increasing precipitation, more snow storage is available to melt during spring (AMJ) and summer (JAS) seasons and increase in temperature triggers the snow to melt during these seasons.

In scenario D, the response of river discharges was studied under 100%, 50%, and 0% glaciated area. The glaciers are sensitive to temperature warming that is why their observations have been used in climate system monitoring for many years (Haeberli 1990; Wood 1990). Monitoring of glacier variations is essential because they are not only important source of future water resource (Ashraf and Iqbal 2018) but also cause risk of outburst flooding (Anwar and Iqbal 2018). The 100% increase in glaciated area (keeping other climatic conditions as usual) exhibited an overall increase of 56% in Astore river discharge (Fig. 8). The spring (AMJ) indicated an increase by 68% and summer (JAS) by 69% in the river discharges. For 50% reduction in glaciated area, the river discharge had shown a decline of 34% from the base year discharge. The spring (AMJ) and summer (JAS) seasons exhibited 57% and 51% decrease in the river discharges owing to relatively less melting from the snow storage. In scenario of 0% glacier coverage, the river discharges reduced by 49% receiving only the contribution of rainfall and snowmelt (Fig. 8). The reduction in discharges was 32% during the spring and 21% during the summer season.

Conclusions

In the present study, the eWater source software implementation of GR4JSG model has been applied for simulating Astore river runoff in the western Himalaya under changing climate and glacial conditions. The findings of the study suggest that GR4JSG model is capable of simulating the hydrological dynamics of snow and glaciers in context of future changes in the Himalayan region. The GR4JSG model has advantage of dealing with snowmelt and glacier icemelt—the two important hydrological processes in this Himalayan region and producing reasonably good results inspite of being conceptual and having few parameters. The model efficiency showed a close agreement between the simulated and the observed discharge of Astore river during the calibration and validation processes. The model exhibited 67% contribution of Quick flow and

33% of base flow in the total flows of Astore river. The rise of mean temperature by 0.9 °C in future may result in 33% increase Astore river flows. The increase in precipitation by 10% may exaggerate the river flows by 15%. The scenario of 100% glaciated area showed 41% increase in the Astore river discharge. The reduction of 50% glacier cover may result 34% decline in the river discharge, while for 0% glacier coverage, the river discharge may reduce by 49% from the base year discharge. The results indicate that Astore river flows are highly dependent upon snow melt and climate variations. A long-term monitoring of the snow and glacial environment is essential for effective water resource management in this region in future.

References

Akhtar M, Ahmad N, Booij MJ (2008) The impact of climate change on the water resources of Hindukush-Karakorum-Himalaya region under different glacier coverage scenarios. J Hydrol 355(1–4):148–163

Ali G, Hasson S, Khan AM (2009) Climate change: implications and adaptation of water resources in Pakistan. GCISC-RR-13. Global Change Impact Studies Centre, Islamabad

Anwar Y, Iqbal J (2018) Spatio temporal change of selected glaciers along karakoram highway from 1994-2017 using remote sensing and GIS techniques. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. IV-3. ISPRS TC III mid-term symposium "developments, technologies and applications in remote sensing", 7–10 may, Beijing, China

Archer DR, Forsythe N, Fowler HJ, Shah SM (2010) Sustainability of water resources management in the Indus Basin under changing climatic and socio economic conditions. Hydrol Earth Syst Sci 14: 1669–1680. https://doi.org/10.5194/hess-14-1669

Ashraf A (2013) Changing hydrology of the Himalayan watershed, Current perspectives. In: Bradley P (ed) Contaminant hydrology and water resources sustainability. ISBN: 978–953–51-1046-0, InTech. https://doi.org/10.5772/54492

Ashraf A, Iqbal A (2018) Influential aspects of glacial resource for establishing Kuhl system (gravity flow irrigation) in the Hindu Kush, Karakoram and Himalaya ranges. Sci Total Environ 636:487–499

Bishop MP et al (2014) Remote sensing of glaciers in Afghanistan and Pakistan, chapter 23. In: Kargel JS, Leonard GJ, Bishop MP, Kaab A, Raup B (eds) Global land ice measurements from space. Springer-Praxis, Heidelberg, pp lvii–lxxiii

Bolch T, Kulkarni A, Kaab A, Huggel C, Paul F, Cogley JG, Frey H, Kargel JS, Fujita K, Scheel M, Bajracharya S, Stoffel M (2012) The state and fate of Himalayan glaciers. Science 336:310–314

Bookhagen B, Burbank DW (2010) Toward a complete Himalayan hydrological budget: spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. 115:1–25. https://doi.org/10.1029/2009JF001426

Dey B, Sharma VK, Rango A (1989) A test of snowmelt-runoff model for a major river basin in the western Himalayas. Nord Hydrol 20:167–178

Haeberli W (1990) Glacier and permafrost signals of 20th century warming. Ann Glaciol 14:99–101

Hasson S, Böhner J, Lucarin V (2017) Prevailing climatic trends and runoff response from Hindukush–Karakoram–Himalaya, upper Indus Basin. Earth Syst Dyn 8:337–355. https://doi.org/10.5194/esd-8-337-2017

Hewitt K (2005) The Karakoram anomaly? Glacier expansion and the elevation effect, Karakoram Himalaya. Mt Res Dev 25:332–340

Hock R (2003) Temperature index melt modelling in mountain areas. J Hydrol 282(1):104–115

Immerzeel WW, Droogers P, De Jong SM, Bierkens MFP (2009) Large scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing. Remote Sens Environ 113:40–49

Immerzeel WW, Beek LPHV, Bierkens MFP (2010) Climate change will affect the Asian water towers. Science 328:1382–1385

IPCC (2007) Cambridge contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change

IPCC (2013) Summary for policymakers. In: Stocker TF et al (eds) Climate change 2013: the physical science basis. Contribution of Working Group III to the Fifth Assessment Report of Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York

Kamal A (2008) Environmental flows indus river system in Pakistan. Presented in 3rd international conference on water resources and arid environments (2008) and the 1st Arab water forum

Kargel JS, Cogley JG, Leonard GJ, Haritashya U, Byers A (2011) Himalayan glaciers: the big picture is a montage. Proc Natl Acad Sci 108(36):14709–14710

Kattel DB, Yao T, Yang K, Tian L, Yang G (2013) Temperature lapse rate in complex mountain terrain on the southern slope of the Central Himalayas, pp 671–682

Lutz AF, Immerzeel WW (2015) HI-AWARE reference climate dataset for the Indus, Ganges and Brahmaputra River basins. FutureWater 31:34

Lutz AF, Immerzeel WW, Shrestha AB, Bierkens MFP (2014) Consistent increase in high Asia's runoff due to increasing glacier melt and precipitation. Nat Clim Chang 4(7):587–592

Nabi G, Latif M, Habib-ur-Rehman AAH (2011) The role of environmental parameter (degree day) of snow melt runoff simulation. Soil Environ 30(1):82–87

Nepal S, Zheng H, Penton D, Neumann L (2015) Comparative performance of GR4JSG and J2000 hydrological models in the Dudh Koshi catchment of the Himalayan region. In: Weber T, McPhee MJ, Anderssen RS (eds) MODSIM2015, 21st international congress on modelling and simulation. Modelling and simulation Society of Australia and New Zealand: Gold Coast, pp 2395–2401. ISBN:978-0- 9872143-5-5

Nepal S, Chen J, Penton D, Neumann L, Zheng H, Wahid S (2016) Spatial GR4J conceptualization of the Tamor glaciated alpine catchment in eastern Nepal: evaluation of GR4JSG against streamflow and MODIS snow extent. J Hydrol Process 31:51–68

Pant GB, Kumar PP, Revadekar JV, Singh N (2018) Climate change in the Himalayas. Springer International Publishing AG. ISBN: 978-3-319-61654-4

Perrin C, Michel C, Andreessen V (2003) Improvement of a parsimonious model for streamflow simulation. J Hydrol 279(1):275–289

PINCC (2003) Pakistan's initial National Communication on climate change. Ministry of Environment, Islamabad

Rango A, Salomonson VV, Foster JL (1977) Seasonal stream- flow estimation in the Himalayan region employing meteorological snow cover observations. Water Resour Res 13:109–112

Rasul G, Chaudhry QZ, Mahmood A, Hyder KW, Dahe Q (2011) Glaciers and glacial lakes under changing climate in Pakistan. Pak J Meteorol 8(15)

Romshoo SA, Dar RA, Rashid I, Marazi A, Ali N, Zaz SN (2015) Implications of shrinking cryosphere under changing climate on the stream flows in the Lidder catchment in the upper Indus Basin, India. Arct Antarct Alp Res 47(4):627–644

De Scally FA (1994) Relative importance of snow accumulation and monsoon rainfall for estimating the annual runoff, Jhelum basin, Pakistan. Hydrol Sci J 39:199–216

Shekhar M, Bhardwaj A, Singh S, Ranhotra PS, Bhattacharyya A, Pal AK, Roy I, Martín-Torres FJ, Zorzano MP (2017) Himalayan glaciers experienced significant mass loss during later phases of little ice age. Sci Rep 7:10305. https://doi.org/10.1038/s41598-017-09212-2

Steiner JF, Kraaijenbrink PDA, Jiduc SG, Immerzeel WW (2018) Brief communication: the Khurdopin glacier surge revisited –extreme flow velocities and formation of a dammed lake in 2017. Cryosphere 12:95–101. https://doi.org/10.5194/tc-12-95-2018

Wood FB (1990) Monitoring global climatic change: the case of greenhouse warming. Bull Am Meteorol Soc 71(1):42–52

WWF (2005) An overview of glaciers, glacier retreat, and subsequent impacts in Nepal. India and China. World Wildlife Fund, Nepal Program, March, 70 pp.