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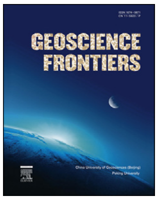

Research paper

# Snowmelt runoff prediction under changing climate in the Himalayan cryosphere: A case of Gilgit River Basin

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A B S T R A C T

There are serious concerns of rise in temperatures over snowy and glacierized Himalayan region that may eventually affect future river flows of Indus river system. It is therefore necessary to predict snow and glacier melt runoff to manage future water resource of Upper Indus Basin (UIB). The snowmelt runoff model (SRM) coupled with MODIS remote sensing data was employed in this study to predict daily discharges of Gilgit River in the Karakoram Range. The SRM was calibrated successfully and then simulation was made over four years i.e. 2007, 2008, 2009 and 2010 achieving coefficient of model efficiency of 0.96, 0.86, 0.9 and 0.94 respectively. The scenarios of precipitation and mean temperature developed from regional climate model PRECIS were used in SRM model to predict future flows of Gilgit River. The increase of 3 °C in mean annual temperature by the end of 21th century may result in increase of 35–40% in Gilgit River flows. The expected increase in the surface runoff from the snow and glacier melt demands better water conservation and management for irrigation and hydel-power generation in the Indus basin in future.

## 1. Introduction

The changes in future climate and its implications have always been very important aspect for world's water resources. The glacial region of Hindukush–Karakoram–Himalaya (HKH) often referred to as the 'water tower of Asia' stores large volumes of water in the form of ice and snow after the polar ice (Salman, 2010; Chettri et al., 2011). It supplies approximately 80% flows to the Indus River during summer (Kamal, 2008) and contributes more than 50% to the total annual runoff of the Indus River system (IRS) in Pakistan (Winiger et al., 2005). The major contribution of flows to IRS is in summer months from April to September while there is less contribution of winter flows (Qureshi, 2011). Due to the observed rapid changes in the high-mountain cryosphere, projections about future developments of different components of the environmental system are of growing importance (Haeberli and Hohmann, 2008) as changes here can effects natural and socio-economic resources the downstream.

According to Chaudhry et al. (2009) Pakistan experienced 0.76 °C rise in temperature during the last 40 years and the increase in temperature in the mountain environment hosting thousands of glaciers was recorded as 1.5 °C during the same period. Due to rise in temperature glaciers are receding in all over the world since last century but the glaciers in HKH region found to be receding faster as compared to other parts of the world (Rees and Collins, 2004). In a regional climate modeling study by Akhtar (2008), a rise up to 4.8 °C in annual mean temperature and increase in annual mean precipitation upto 16% were predicted in UIB at the end of 21st century.

Generally, there are two categories of snow models: energy base models, e.g. Utah Energy Balance Model (UEB) model and temperature index models, e.g. Snowmelt Runoff Model (SRM) (Maidment, 1993). The SRM was developed by Martinec in 1975 and first time it was tested in small European basin and has been successfully applied on more than 100 basins all over the world (Martinec, 1975; Martinec et al., 2008). SRM has been successfully tested to analyze the effects of changed climate on seasonal river flows (World Meteorological Organization, 1986); to calculate climate

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effected flow in Gangs and Brahmaputra rivers (Seidel and Martinec, 2002); in North America, the Swiss Alps, and the Himalayas (Rango and Martinec, 2008); in Nepalese Himalaya (Panday and Brown, 2010) and in Upper Indus Basin (Immerzeel et al., 2009; Nabi et al., 2011; Tahir et al., 2011). The main focus of this study is to (1) analyze the trends and variability in hydrometerological parameters of Gilgit basin; (2) estimate snow depletion rate during different months (January–December) using remote sensing and Geographic Information System (GIS); (3) perform snowmelt runoff simulation of Gilgit basin using temperature index approach and (4) predict future flows of Gilgit River under various climate change scenarios. The snowmelt runoff model was employed using MODIS satellite data to simulate the daily discharges at Gilgit stream gauging station in Gilgit River Basin.

## 2. Description of the study area

The Gilgit Basin is situated at high altitude in Hindukush–Karakoram–Himalaya (HKH) region between longitudes 72°53′30″–73°29′15″ E and latitudes 33°41′07″–34°06′00″ N in northern Pakistan (Fig. 1). It is a glacierized basin so any change in climate will impact the frozen water resource which ultimately affect the inflow to Indus Basin irrigation system. The drainage area of the basin calculated at Gilgit river gauging station is about 12,671 $km^2$ with mean elevation of about 3997 m. The part of catchment above 5000 m elevation is mainly covered with permanent snow and retains most of the glaciers. The Gilgit River network consists of Ghizar, Yaseen, Ishkuman and Hunza rivers. According to 38 years' record (1970–2008) of SWHP–WAPDA, the mean annual discharge of Gilgit River at Gilgit gauging station is about 238 $m^3/s$. The glaciers and seasonal snowmelt contributes significantly to the river flows of the basin. The glacier melting starts in July after melting of seasonal snow. The glacier melting process is slow and continues until starting of the accumulation period in October. The mean monthly maximum temperature at Gilgit station ranges between 9.5 and 36.2 °C and the mean monthly minimum temperature between −2.5 and 18.3 °C. The mean annual rainfall is about 134 mm in which about 70% is usually received during the summer period (April–September).

## 3. Materials and methods

### 3.1. Data source

The climate data (temperatures and precipitation) of Gilgit station (1460 m), Yasin station (2970 m) and Ushkore station (3150 m) on daily times steps between 1975–2010 period was collected from Pakistan Meteorological Department (PMD) and Water and Power Development Authority (WAPDA). Valley stations are not good representatives of precipitation. For example, the precipitation measured at valley station to that measured at high altitudes is 1:5 or 1:10, so both low and high altitudinal climate data were used for the calibration of SRM in this study. Thus, the

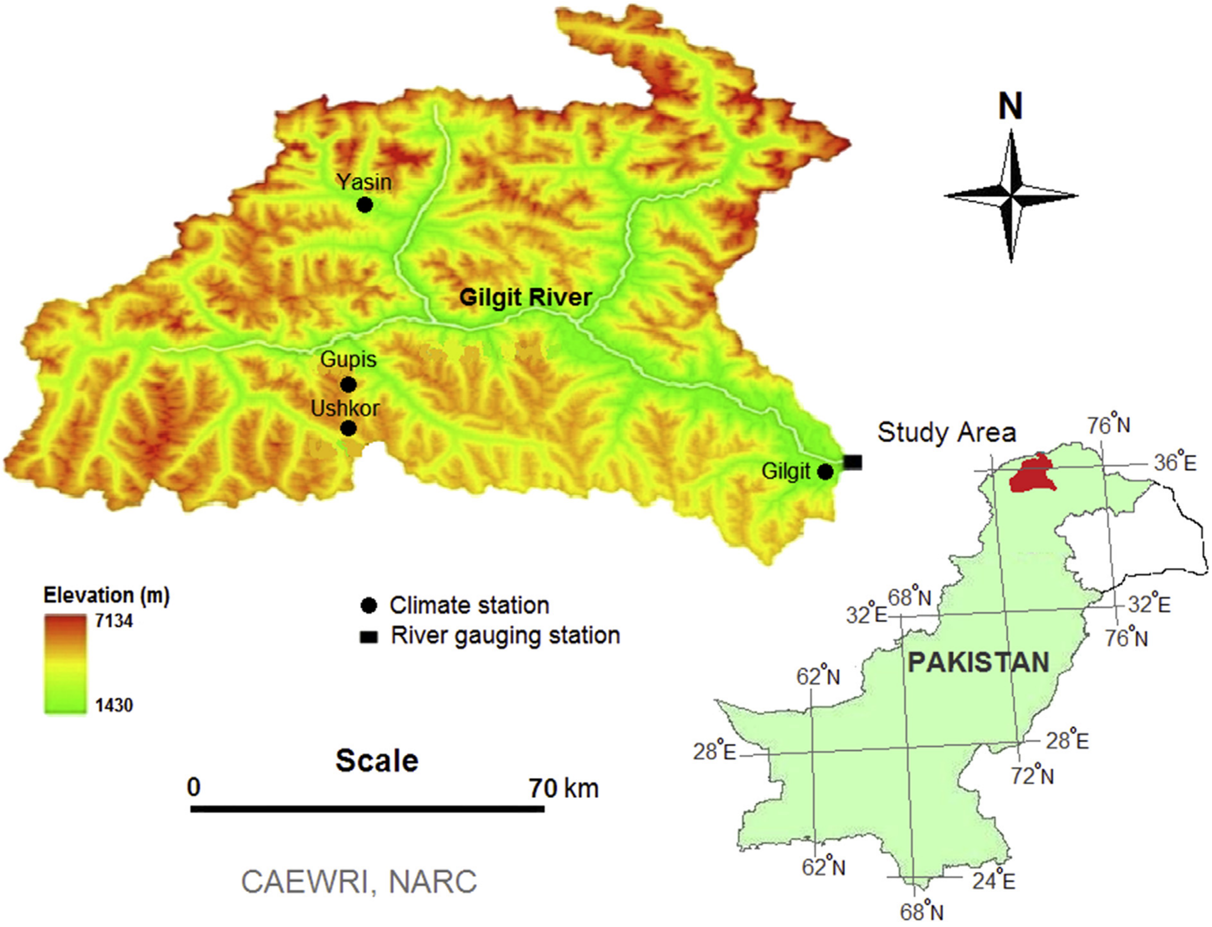

**Figure 1.** Map of the study area indicating locations of climatic and stream gauging stations.

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daily discharge data of Gilgit River at Gilgit gauging station (1981–2010 period) was acquired from Surface Water Hydrology Project (SWHP) of WAPDA.

The MODIS Terra product MOD10A1 was downloaded on daily time-step of 2001–2010 period from National Snow and Ice Data Center (NSIDC) site at http://nsidc.org/data/modis/order_data.html. The resolution of MODIS10A1 snow cover product is 500 m × 500 m. Many researcher and scientists used MODIS data in snowmelt runoff modeling and found it suitable for estimation of snow covered area and snowmelt runoff (e.g., Panday and Brown, 2010; Tahir et al., 2011). The MODIS data was in the Hierarchical Data Format–Earth Observing System (HDF–EOS) and it was converted to GEO-TIFF format using a software HEG-Tool. Gilgit watershed was delineated from SRTM Digital Elevation Model (DEM) 90 m. The DEM was reclassified into six elevation zones to estimate the snow covered area (SRA) percentage in each elevation zone (Fig. 2), the values were later used in SRM to estimate the snowmelt runoff from the basin.

### 3.2. Methodology

The snowmelt runoff model (SRM) is used to simulate and forecast daily stream flow in mountainous basins where snowmelt runoff is a major component. The Gilgit River Basin is a snow and glaciated area so snowmelt runoff model was selected to simulate and forecast the daily river flows as well as to study the effect of climate change on the flows. The model can also estimate the snow and glacier contribution in the total out flows from the basin separately. The temperature index melts modeling approach was used in mountainous basin to explain topographic effects on complex terrain with limited input data (Hock, 2003). In temperature index approach overall melt rate is considered as proportional to the air temperature and the proportional factor is called melt factor. The air temperature in this approach is expressed as degree-days. The snow density data is a good indicator of albedo to determine the degree-day factor for an area (Rango and Martinec, 1995).

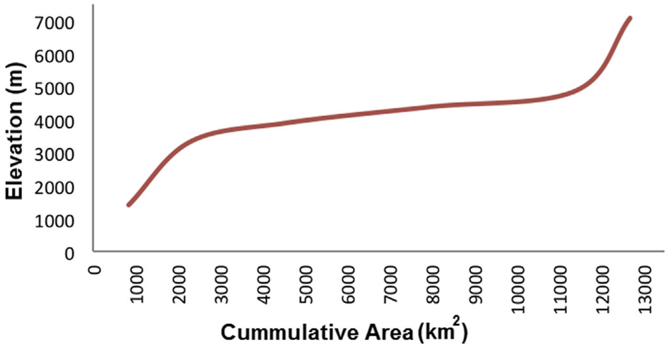

**Figure 3.** Area elevation curve of Gilgit River Basin.

The daily input data used in the model was precipitation, air temperature and snow covered area. The model also requires some basin characteristics such as latitude–longitude, number of zone, zone areas and means hypsometric elevation of each zone of basin. The area elevation curve was used to determine the mean

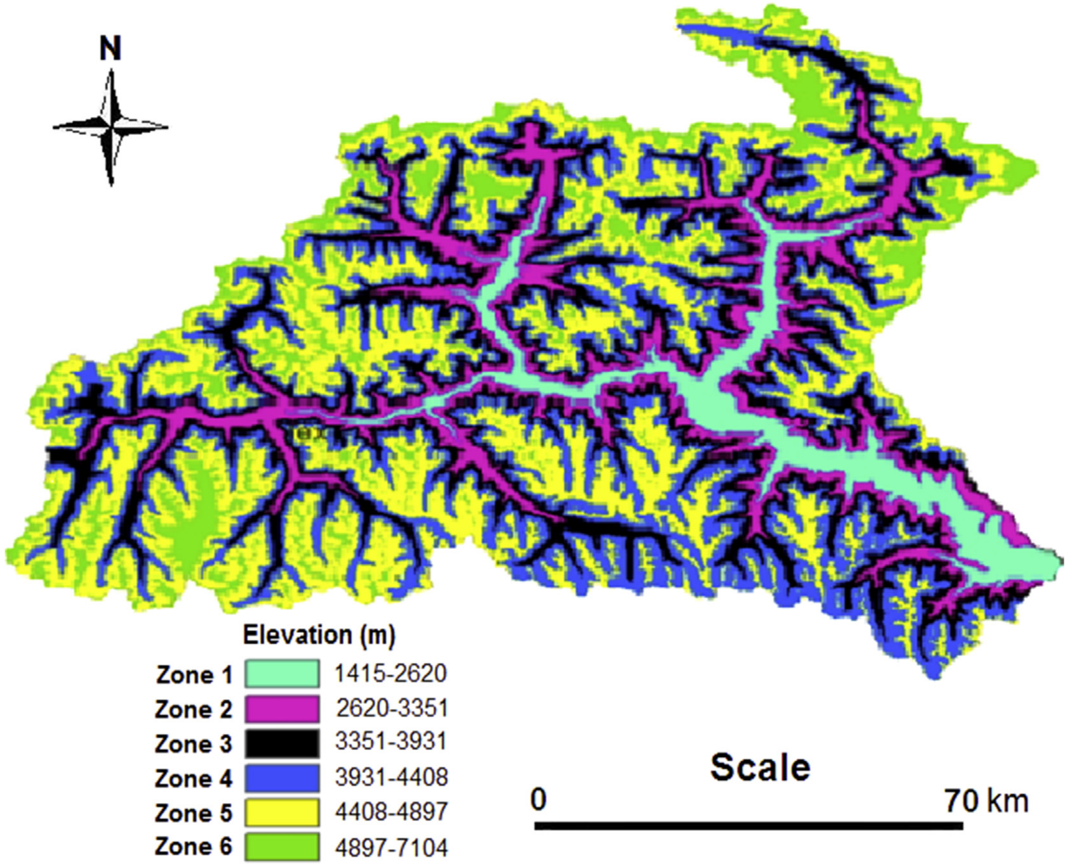

**Figure 2.** Reclassification of DEM into different elevation zones.

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**Table 1**
The river basin area under different elevation zones.

| Zone | Elevation class (masl) | Mean hypsometric elevation (masl) | Area (km$^2$) | Area (%) |
|---|---|---|---|---|
| 1 | 1415–2620 | 2193 | 826 | 6.5 |
| 2 | 2620–3351 | 3006 | 1452 | 11.5 |
| 3 | 3351–3931 | 3647 | 2318 | 18.3 |
| 4 | 3931–4408 | 4169 | 3347 | 26.4 |
| 5 | 4408–4897 | 4596 | 3445 | 27.2 |
| 6 | 4897–7104 | 5082 | 1283 | 10.1 |

hypsometric elevation ($h^{-}$) of each zone of the basin using ArcGIS and Erdas Imagine softwares (Fig. 3), the elevations at which the base station temperatures were extrapolated for the calculation of zonal degree-day values. Most of the basin area i.e. about 27.2% (3445 km$^2$) was found within 4408–4897 m elevation range (Zone 5) and about 26.4% (3347 km$^2$) within 3931–4408 m range (Zone 4). About 10.1% (1283 km$^2$) area lies above 4897 m whereas 18% lies below 3351 m elevation (Table 1). In the model phenomena, snowmelt and rain computed on daily time-steps is superimposed on the calculated recession flow and transformed into the daily discharge from the catchment. The working principle of SRM is demonstrated in Fig. 4. The snowmelt runoff simulation in SRM is executed following Eq. (1) (Martinec et al., 2008):

$$Q_{n+1} = [c_{Sn} a_n (T_n + \Delta T_n) S_n + c_{Rn} P_n] \frac{A*10000}{86400} (1 - k_{n+1}) + Q_n\, k_{n+1} \qquad (1)$$

where $Q$ is average daily discharge (m$^3$/s), $c_{Sn}$ and $c_{Rn}$ are coefficients of snow and rain respectively, $a_n$ is degree-day factor (cm °C$^{-1}$ d$^{-1}$), $T_n$ is number of degree days in (°C d$^{-1}$), $S$ is ratio of the snow covered area to the total area, $P$ is precipitation contributing to runoff (cm), $T_{\text{crit}}$ (°C) is critical temperature that differentiate between snow and rain, $A$ is area of the basin or zone in km$^2$, $k$ is recession coefficient that indicates the decline of discharge in a period without snowmelt or rainfall and $n$ is the sequence of days during discharge computation period. The long term temperature against snow or rainfall record is required for estimation of critical temperature. If $T < T_{\text{crit}}$, there is chance to occur snow fall. The recession coefficient ($k$) is an important feature of SRM and ($1-k$) is the amount of the daily melt water which directly appears in the runoff. Recession coefficients also describe the portion of the discharge contribution from previous day's snowmelt on a given day. Analysis of historical discharge data is usually a good way to determine the value of $k$. The SRM model was calibrated for four-year period 2001–2004. The model efficiency was evaluated by (a) coefficient of determination ($R^2$) and (b) volume difference ($D_v$, %). The parameters values used for calibration of the model are given in Table 2. The runoff coefficients of snow ($C_S$) and rainfall ($C_R$) used in the SRM range from 0.05 to 0.45 and 0.03 to 0.48 respectively during snowmelt period. The value of $C_S$ and $C_R$ mainly account for losses i.e. infiltration, evaporation, evapotranspiration etc.

The values of recession coefficient used in the model were $X_{\text{coeff.}} = 1.08–1.09$ and $Y_{\text{coeff.}} = 0.02$. The default value of lag time used in the model was 18 h. The SRM produces daily snow and glacial melt in each elevation zone. The contribution of glacier melt can be estimated by adding up the daily glacier melt depth (cm) from

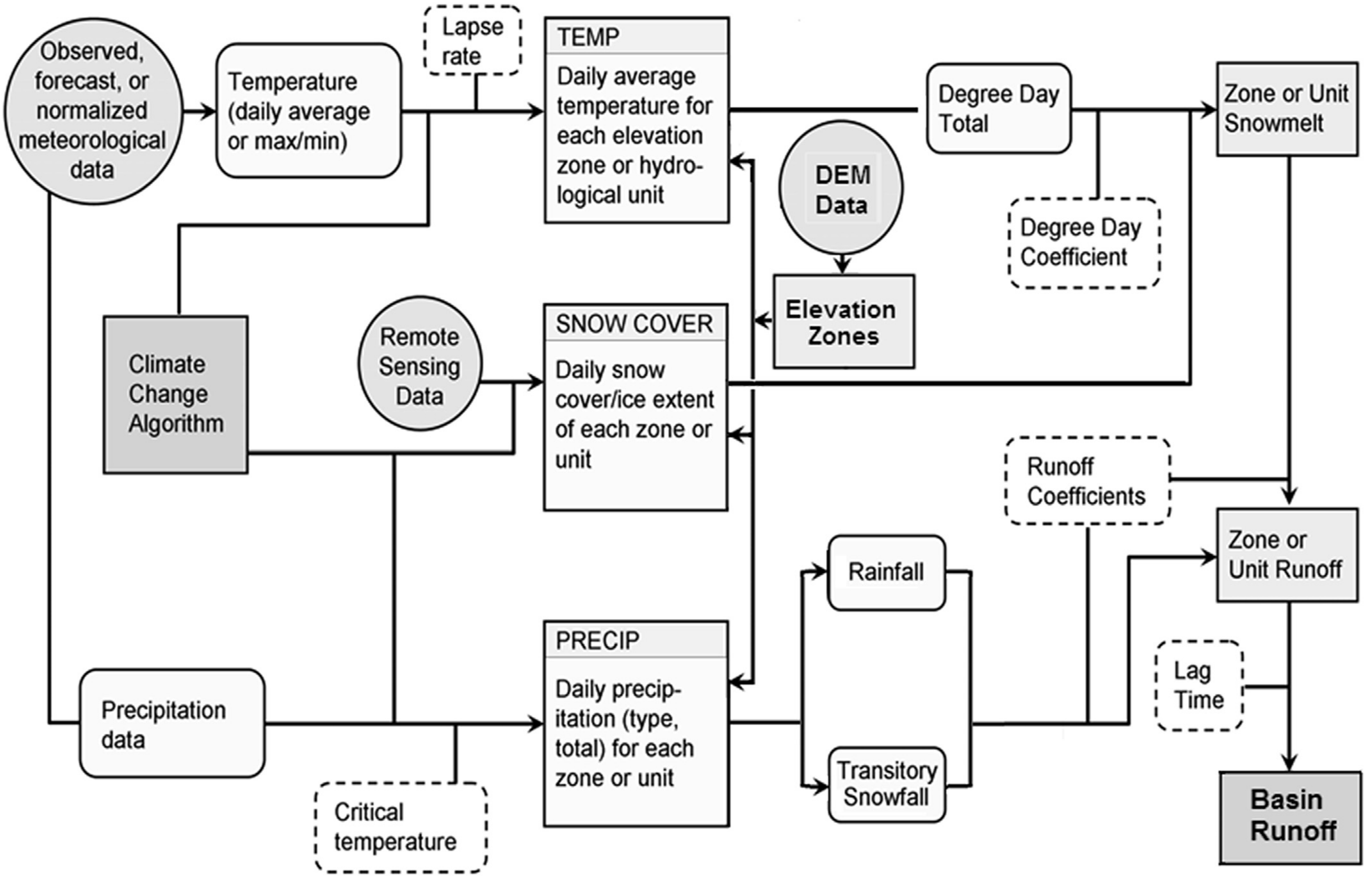

**Figure 4.** Working principle of snowmelt runoff modeling (modified after Rango et al., 2008).

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the date to which snowmelt was stopped. By adding up the daily glacier melt depth (cm) during glacier melting period e.g. from July to September, contribution of glacier can be found. The rainfall contributing area (RCA) value '0' was used for October–April period because in these months the rainfall is retained by snow while RCA value '1' was used for the snowmelt period i.e. if rain falls on snow then it is assumed that the same amount of water is released from the snowpack and so more runoff (rain + snow) would be produced.

The temperature lapse rate value of 0.64 °C/100 m was computed for Gilgit River Basin based on the lowest elevation climate station and the highest elevation climate station in the basin. The degree-day factor value 0.3 cm $^{\circ}C^{-1}$ $d^{-1}$ was used for the start of the snowmelt season and 0.75 cm $^{\circ}C^{-1}$ $d^{-1}$ for the end of the snowmelt season. In glacierized basins, the degree-day factor usually exceeds 0.6 cm $^{\circ}C^{-1}$ $d^{-1}$ towards the end of the summer when ice becomes exposed (Kotlyakov and Krenke, 1982).

The future projections generated by regional PRECIS model on 25 km resolution were used in the SRM to predict future flows of Gilgit River. The analysis was based on GCM (HADCM3) and emission scenario SRA2. Following scenarios of climate change were used to predict future river flows in the SRM:

I. According to scenario A1B, Gilgit River basin mean annual temperature would increase by 0.3 °C within 2011–2030, by 1.3 °C within 2031–2050 and by 3.1 °C during 2051–2099.
II. The scenarios if mean annual temperature fall by 1 °C and by 2 °C.
III. The increase of 10 to 20% in the cryosphere area due to increase in precipitation.

## 4. Results

### 4.1. Hydrometeorological data analysis

The past climatic data of Gilgit catchment from (1961 to 2010) in terms of average, maximum, minimum temperature and rainfall

**Table 2**
Calibration parameter values used in SRM.

| Parameter | Values |
|---|---|
| Temperature lapse rate (°C/100 m) | 0.64 |
| $T_{crit}$ (°C) | 0 |
| Degree day factor (cm $^{\circ}C^{-1}$ $d^{-1}$) | 0.3–0.75 |
| Lag time (hr) | 18 |
| Runoff coefficient for snow | 0.03–0.45 |
| Runoff coefficient for rain | 0.05–0.48 |
| Rainfall contributing area | RCA = 0–1 |
| Reference elevation (m) | 3060 |
| Initial discharge ($m^3/s$) | 85.47 |
| Rainfall threshold (cm) | 6.0 |
| Recession coefficients | $X_{coeff.} = 1.08–1.09$<br>$Y_{coeff.} = 0.02$ |

**Table 3**
Changes in climatic parameters (1961–2010).

| Climatic parameter | Season | 1961–1985 | 1986–2010 |
|---|---|---|---|
| Maximum $T$ (°C) | Annual | 0.38 | 1.36* |
| | Winter (O–M) | 0.00 | 2.57*** |
| | Summer (A–S) | 0.58 | 0.77 |
| Minimum $T$ (°C) | Annual | 0.08 | 0.53 |
| | Winter (O–M) | 0.01 | 0.02 |
| | Summer (A–S) | 0.22 | 0.52 |
| Average $T$ (°C) | Annual | 0.27 | 0.84* |
| | Winter (O–M) | −0.13 | 1.30*** |
| | Summer (A–S) | 0.48 | 0.53 |
| Rainfall (mm) | Annual | 6.7 | 26.4 |
| | Winter (O–M) | −5.0 | −3.6 |
| | Summer (A–S) | 4.9 | 28.4 |

Note: * denotes the significance level p at 5% level and *** at the 0.1% level.

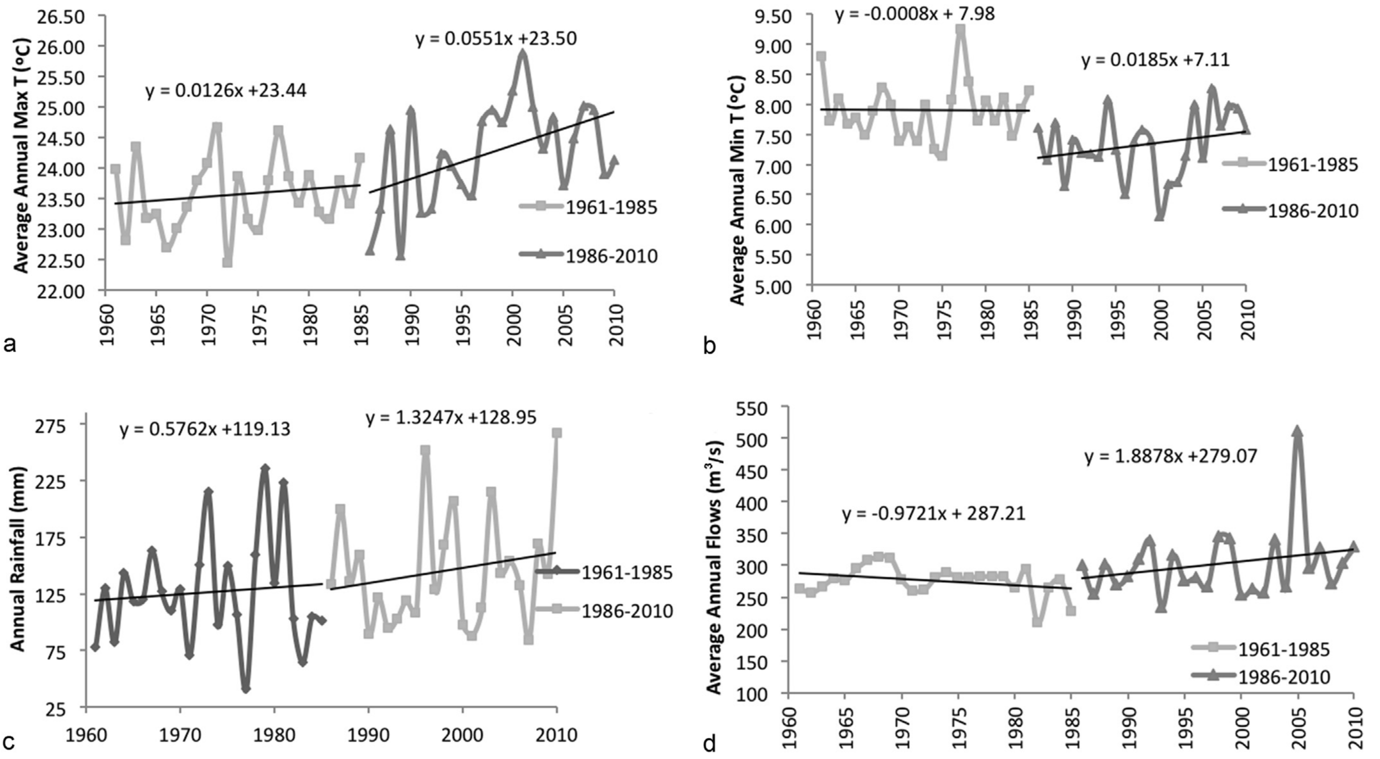

**Figure 5.** Trend of (a) average annual maximum temperature, (b) average minimum temperature, (c) annual rainfall and (d) annual flows of Gilgit river at Gilgit during 1961–2010 period.

were analyzed using regression analysis to check the trend of time series data (Fig. 5). Average annual temperature of Gilgit had increased by 0.84 °C during 1986–2010 period (significant at $p < 0.05$). Similarly annual maximum temperature had shown a significant rise of 1.3 °C during this period (Table 3). There was an increase in the summer maximum, minimum and mean temperatures observed during 1961–2010 period. The trends of maximum and mean temperatures of winter were also positive (significant at $p < 0.001$) during 1986–2010 period. However, the trend of winter average temperature was negative during 1961–1985. The annual and summer rainfall had shown an increase of 26.4 mm and 28.4 mm respectively during 1986–2010. In contrary there was a declining trend observed in the winter rainfall during from 1961 to 2010 period (Table 3). The analysis of historical flows data of Gilgit River showed an increasing trend from 1986 to 2010 likely due to increase in temperature and rainfall. The trend in flows appears to be on the negative side from 1961 to 1985 (Fig. 5).

The average snow covered area in Gilgit derived from MODIS satellite images indicated variation between 10% in the summer and 85% in the winter. The CDC values were used to construct snow depletion curves of Gilgit catchment for a period from 2005 to 2010 indicating snow depletion rate in different months of a year and in different elevation zones in the catchment. The snow depletion starts from April from low elevation zones and moves to higher elevation zone. The analysis of snow-covered area depletion during 2009 showed that in zone 1 and 2 the snow was almost melted during April (Fig. 6). In zone 3, the snow was melted completely during July, while in zone 4, it was melted completely during September. The snow in higher altitude i.e. zones 5 and 6 (above 4400 m) were not completely melted due to presence of permanent snow/glacial ice at low temperature.

### 4.2. Snowmelt runoff simulation

The SRM model was calibrated for four year period i.e. from 2001 to 2004 during which the model parameters like temperature lapse rate, degree-day factor snow and rain coefficients and recession coefficients were adjusted. The model calibration showed good correlation between observed and simulated flows (Fig. 7). Later, the model was validated for two year period (2005–2006) achieving a close agreement between the calculated and observed flows (Fig. 8). The model was applied over four year period i.e. 2007–2010, the statistical analysis of which is shown in Table 4. The values of coefficient of model efficiency (COE) achieved for the years 2007 to 2010 ranged between 0.85–0.96. The values for volume difference (%) between the observed and simulated flows acquired for years 2007, 2008, 2009 and 2010 were −1.38, 1.001, −1.35 and 10.18 respectively indicating a satisfactory application of the SRM over the catchment. The year round simulation of the flows during 2009 is shown in Fig. 9.

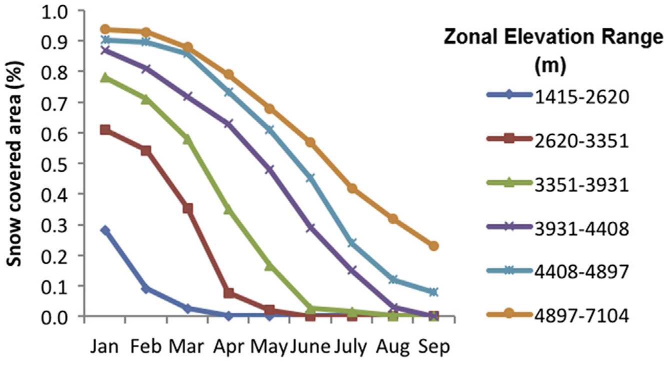

**Figure 6.** Snow depletion curve of Gilgit River Basin for the year 2009.

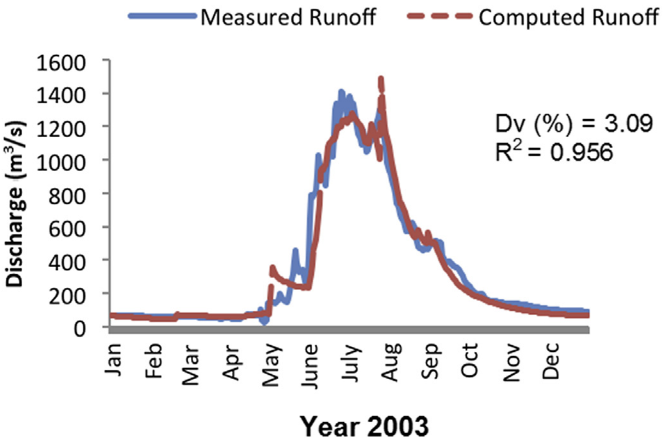

**Figure 7.** Calibration of SRM for the year 2003.

The future projections of climatic parameter generated by PRECIS climate model were used in snowmelt runoff model for prediction of future flows of Gilgit River. The rise in average annual temperature by 0.30 °C till 2030 (scenario-I) may increase the annual flows of Gilgit River by 3% (Table 5), mainly in the initial months of snowmelting i.e. April, May and remained close to the observed flows in the remaining months of the year (Fig. 10). The rise of 1.30 °C in average annual temperature till 2050 may exaggerate the river flows by 17% in the summer months from July to September (Fig. 11). Similarly, an increase of

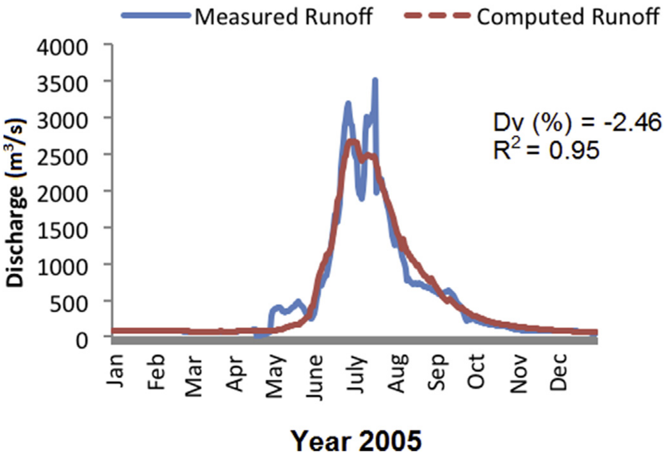

**Figure 8.** Validation of SRM for the year 2005.

**Table 4**
Statistical analysis of year round simulations in SRM.

| Statistical parameter | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|
| Volume difference ($D_v$, %) | −1.38 | 1.001 | −1.35 | 10.18 |
| Coefficient of model efficiency (%) | 0.96 | 0.856 | 0.9 | 0.939 |
| Coefficient of determination (%) | 0.92 | 0.85 | 0.92 | 0.93 |
| Pearson correlation coefficient (%) | 0.98 | 0.925 | 0.949 | 0.969 |
| Standard error ($m^3/s$) | 86.68 | 105.78 | 108.35 | 93 |
| Root mean square error ($m^3/s$) | 312.6 | 242.8 | 273 | 355.9 |
| Mean absolute error ($m^3/s$) | 4.54 | −16.12 | −43 | −33.8 |
| No. of observation | 365 | 366 | 365 | 365 |

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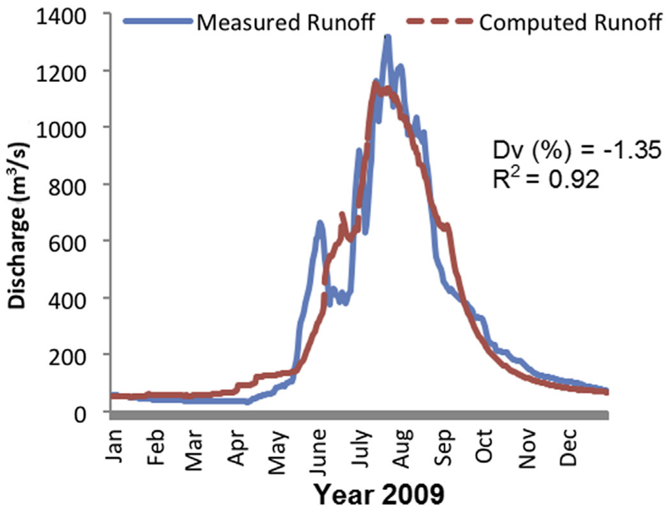

**Figure 9.** Year round simulation of SRM for 2009.

**Table 5**
Percentage change in the flows due to rise in average annual temperature.

| Year | Avg. $T$ (°C) | Winter flows (%) | Summer flows (%) | Annual flows (%) |
|---|---|---|---|---|
| 2030 | 0.30 | 2 | 4 | 3 |
| 2050 | 1.30 | 4 | 18 | 17 |
| 2099 | 3.1 | 9 | 42 | 40 |

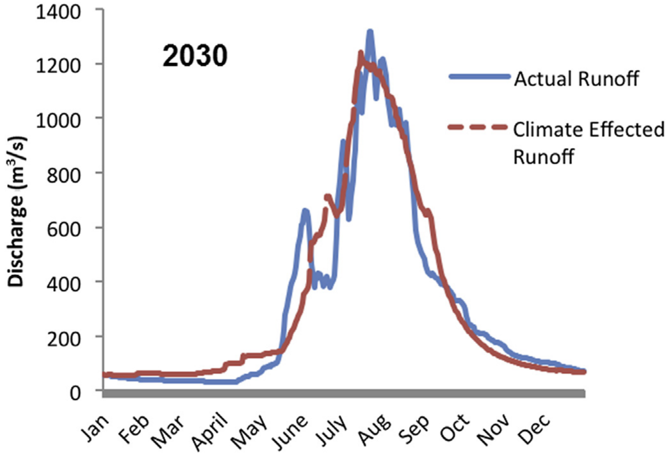

**Figure 10.** Climate effected runoff due to rise in average annual temperature till 2030.

3.1 °C till 2099 may also affect the permanent snow and ice in the form of increase in the summer flows by 40% i.e. exceeding 1800 $m^3/s$ per annum (Fig. 12). Although, the situation of rise in temperature (i.e. with no considerable change in precipitation) may exaggerate the summer flows i.e. may be useful for hydelpower and irrigation use in future, but would be critical in terms of loss in the permanent snow/glacial reserve in the basin. In cases, without adopting proper water management options, the increase in flows may create flood hazard for the downstream communities. Under scenario-II, a decrease of 1 °C in average annual temperature indicated a decline of 3% in the summer flows while a decrease of 2 °C may result in 7% reduction in the flows (Table 6). The increase of 10% in cryosphere area due to increase in precipitation till 2050 (scenario-III) may result in an increase of 13% in the summer flows. Similarly, 20% increase in the cryosphere area indicated a rise of 27% in the summer flows of the Gilgit basin (Table 7).

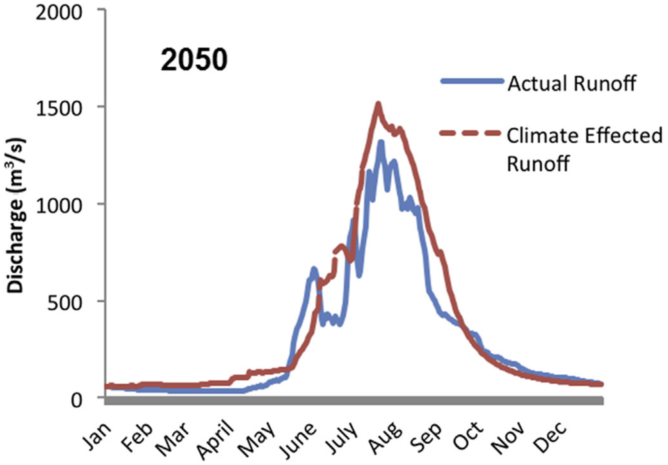

**Figure 11.** Climate effected runoff due to rise in average annual temperature till 2050.

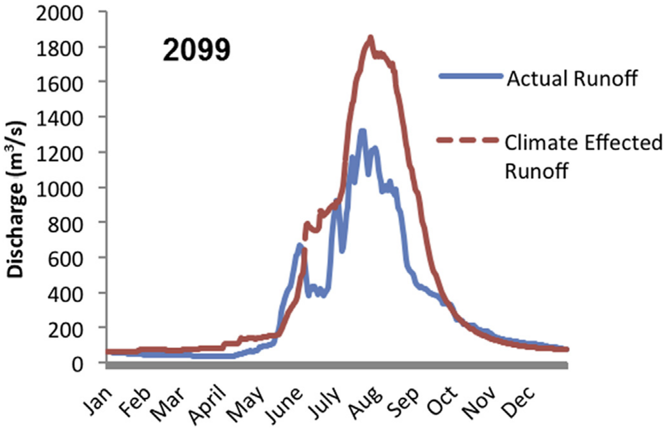

**Figure 12.** Climate effected runoff due to rise in average annual temperature till 2099.

**Table 6**
Impact of decrease in average annual temperature on Gilgit River flows.

| Scenario | Decrease in summer flows (%) |
|---|---|
| 1 °C | 3 |
| 2 °C | 7 |

**Table 7**
Impact of increase in the cryosphere area on Gilgit River flows.

| Scenario | Increase in river flows (%) |
|---|---|
| 10% | 13 |
| 20% | 27 |

## 5. Discussion

The calibrated snowmelt runoff model was used to analyze the relationship between air temperature, precipitation and runoff. The energy based models require large amount of data which is usually not available so temperature index approach was used in this study. The approach has already been applied previously in various models e.g. Stream flow Synthesis and Reservoir Regulation Model (SSARR) (1975), University of British Columbia Watershed Model (UBC) (1977), and snowmelt runoff model (SRM) (1983). Tahir et al. (2011) used snowmelt runoff model under climate change scenarios in Hunza River Basin adjacent to Gilgit basin in Central Karakoram. There was a rising trend observed in Gilgit River flows since 1986 which is contrary to the overall declining trend reported of Indus river at Tarbela. In Gilgit River flows, the contribution of initial snow was estimated about 78.3% as compared to rainfall i.e. 19.5% while the contribution of the new snow to runoff was about 2.2% only. The contribution of initial snow estimated in Gilgit River flows is conformal with the findings of Piracha and Majeed (2011) according to which over 75% of the summer flows of Indus River upstream of Tarbela Dam are contributed mainly by the tributaries of glacierized central Karakoram region. Siddique and Hashmi (2012) revealed 65%, 25% and 10% contribution of glacier melt, snowmelt and rainfall in the annual flows of Indus River at Tarbela and according to Archer and Fowler (2004) and Wake (1989), more than 65% annual flow in the UIB are contributed from the snow and glacierized fields lying in active hydrological zone above 3500 m elevation in the Karakoram–Himalayan ranges.

The increase in the summer flows under rising temperature (scenarios I) is in agreement with the findings of Singh and Kumar (1997) according to which an increase of 1 to 3 °C temperature in the western Himalayas would result in 16 to 50% increase in the glacier melt runoff. The peak seasonal (summer) flows in the Karakoram region are caused mainly by the availability of heat energy which melts the snowpack and glacial ice (Archer, 2003) and can be related to regional warming associated with global changes in air temperature resulting from anthropogenic forcing (Immerzeel et al., 2009). In our study, the summer flows seem to be varied under the dual effect of temperature and precipitation, the spatial influence (both horizontal and vertical) of which require in-depth investigations. The hypothesis of increasing cryosphere due to increase in precipitation mainly of westerly circulation resulting in an increase in the summer flows (scenario-III) is explained by Archer and Fowler (2004) beside others. A significant increase in the precipitation is reported by Archer and Fowler (2004) in the Upper Indus Basin in both winter and summer during 1961–1999 period. The increasing trends of precipitation continue to feed the high altitudes resulting in the form of expanding snow cover (Tahir et al., 2011). The precipitation in the Gilgit valleys increases with elevation to over 600 mm at 4400 m (Cramer, 1993), while several glacial studies in the Karakoram reported more than 1700 mm annual precipitation above 5500 m (Winiger et al., 2005) and from 900 to 1900 mm in the 4900 to 5400 m elevation range (Hewitt et al., 1989; Wake, 1989). Furthermore, the winter precipitation in the middle-elevation basins like Astore and Gilgit River Basins indicated was is highly correlated with the summer runoff in the Upper Indus Basin (Archer and Fowler, 2004). However, the relation of elevation with hydrological and meteorological parameters requires further study keeping in view the high relief in the basin.

## 6. Conclusions

The application of snowmelt runoff model proved to be successful for the snow and glacier fed middle-elevation region of the UIB. The basin hydrology indicated high sensitivity to the changes in climatic parameters like air temperature and precipitation. The maximum and minimum temperatures at Gilgit appear to increase since 1986 and the trend may continue in future. The rising trends in temperature may cause snow to melt earlier, affect the formation of ice in glacial system and change the runoff timings and volume. The changes in snow/ice melt pattern can affect not only the mountain ecosystem and glacial environment but also the hydropower generation and agriculture production in the downstream. The expected increase in the summer flows of Gilgit River under increase in the precipitation in the basin (scenario III) demands better conservation and management of the water resource for irrigation and power generation in future. There is a need to establish a continuous operational snow monitoring system through developing a network of low and high altitudinal weather stations. The climatic and hydrometric monitoring network extended preferably to 3000 and 5000 m elevation zone can provide base for in-depth research in glacier hydrology in general and water resource assessment in particular under changing climate in this region in future.

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