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Climate Change Impact on River Flows in Chitral Watershed

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Abstract

The impact of climate change has always been very important for water resources in the world. In countries like Pakistan where different weather conditions exist, the effects of climate change can be more crucial. Generally, the climate changes are considered in terms of global warming i.e. increase in the average temperature of earth's near surface air. The global warming can have a strong impact on river flows in Pakistan. This may be due to the melting of snow and glaciers at a higher rate and changes in precipitation patterns. Glaciers in Pakistan cover about 13,680 km^2 which is 13% of the mountainous regions of the Upper Indus Basin. Glacier and Snowmelt water from these glaciers contributes significantly to the river flows in Pakistan. Due to climate change, the changes in temperature and the amount of precipitation could have diversified effects on river flows of arid and semi-arid regions of Pakistan. This paper reviews the existing research studies on climate change impact on water resources of Pakistan. The past trend of river flows in Pakistan has been discussed with respect to the available data. Further, different projections about future climate changes in terms of glacier melting & changes in temperature and precipitation have also been taken into consideration in order to qualitatively assess the future trend of river flows in Pakistan. As a case study, the flows were generated for the Chitral watershed using UBC Watershed Model. Model was calibrated for the year 2002, which is an average flow year. Model results show good agreement between simulated and observed flows. UBC watershed model was applied to a climate change scenario of 1^{o}C increase in temperature and 15% decrease in glaciated area. Results of the study reveal that the flows were decreased by about 4.2 %.

Key Words: Global warming, UBC Watershed Model, Indus river basin, river flows, Chitral river

1. Introduction

The climate change is the greatest challenge that the whole world is facing today and especially its impact on water resources can be quite diverse and uncertain. In Pakistan where different climate conditions exist, the effect of climate change could be more significant. Pakistan's economy is based on agriculture and highly dependent on Indus irrigation system [1]. Changes in flow magnitudes are likely to increase tensions among the provinces, in particular with the downstream areas (Sindh province), with regard to reduced water flows in the dry season and high flows and resulting flood problems during the wet season [2]. Therefore, in Pakistan future water resources assessment under climate change is essential for planning and operation of hydrological installations [2]. The results of a climate change study indicate a higher risk of flood problems under climate change in three river basins: Hunza, Gilgit and Astore [2].

Seasonal flow forecasting with respect to the climate change could provide significant benefits for the management of national power strategies by providing an early indication of surplus or shortfall in hydropower which would require balancing with thermal power sources [3]. In general, the climate changes are now interpreted as 'Global Warming'. Global warming is the rise in the average temperature of the air near the surface of earth and oceans since the since the mid-20th century and its projected continuation [4]. The global warming causes increase in snow and glacier melt, drastic changes in precipitation, extreme events like floods and droughts, heat and cold, sea level rise and loss of biodiversity [5, 6]. The impact of global warming is obvious on reducing winter snowfall component in total winter precipitation on the windward side and some portions of the leeward side of the Pir Panjal Himalayan Range since 1991, which leads to delay in onset of winter and early spring and effective reduction during the snowfall period [7]. Rest of the Himalayas does not appear to have undergone any significant change in the snowfall pattern [7].

Moreover, the severe climate incidents related to global warming could also cause large scale disasters. The estimation of extreme events and their predictability is one of the main challenges for the climate change community [8]. Extreme events are by definition rare. Depending on their severity, the restoration of the local/regional climate system from an extreme event could even take several years [8].

Pakistan has one of the largest river network which consists of mainly; river Indus, river Jhelum, river Chenab, river Kabul, river Ravi and river Sutlej as shown in Figure 1.

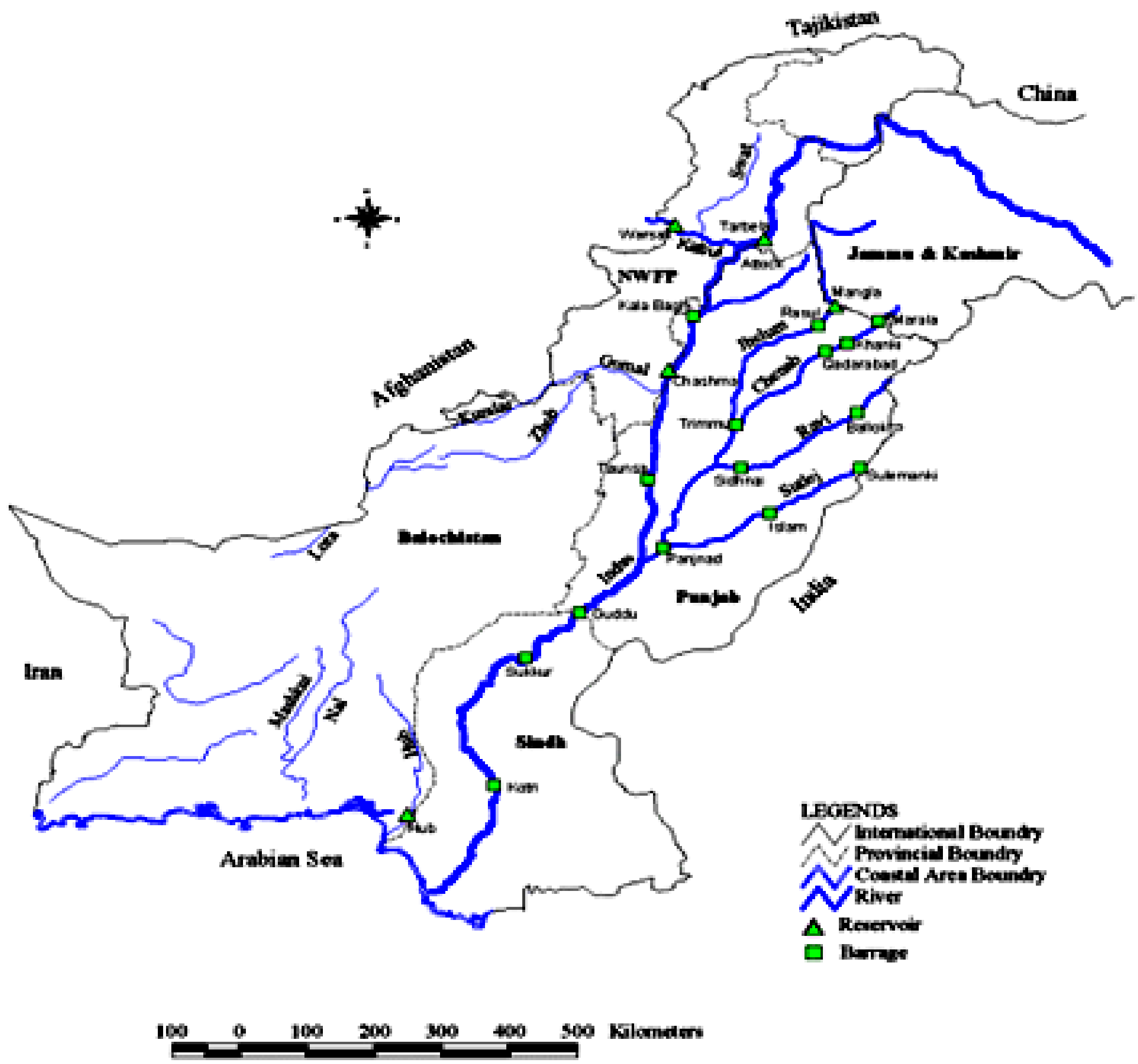


Fig. 1: The Indus river system (IRS) in Pakistan [5]

Table 1: Distribution of water in main rivers of Pakistan [5]

River Name	% IRS Inflows	% Seasonal Distribution		Dominant Source in Summer	Dominant Source in Winter
		Summer (Apr-Sep)	Winter (Oct-Mar)		
Indus	44	86	14	Snow/Glacial melt	Winter Rainfall + Baseflow
Chenab	19	83	17	Snow/Glacial melt + Monsoon	Winter Rainfall + Baseflow
Jhelum	16	78	22	Mainly Snow melt + Monsoon	Winter Rainfall + Baseflow
Kabul	16	82	18	Snow/Glacial melt	Winter Rainfall + Baseflow
Others (Ravi, Sutlej etc.)	5			Rainfall	

Table 1 shows the contribution of inflow of each river in the Indus River System (IRS) and their seasonal distribution and dominant sources. This study discusses the climate changes occurred in the past and analyzes the trend of river flows in Pakistan. Further, different projections about future climate changes in terms of glacier melting and changes in temperature and precipitation have also been considered for the prediction of future trend of river flows in Pakistan. For specific analysis, the Chitral watershed (about 11,400 km^2) in Chitral has been selected and hydro-meteorological modeling has been carried out by using UBC watershed Model in order to investigate the impact of climate changes on the flows of Chitral river

2. Climate Change in Pakistan

In this section, different research findings about the climate changes in Pakistan are discussed. As already mentioned, the climate changes are considered mainly in terms of glacier melting, changes in temperature and precipitation.

2.1 Glacier Melting in Pakistan

Glaciers in Pakistan cover about 13,680 km2 which is 13% of the mountainous areas of the Upper Indus Basin (UIB) [5, 6]. Glacial and snowmelt water from these glaciers adds considerably to the flows of UIB rivers [2, 13]. According to a report of International Commission for Snow and Ice (ICSI), "Glaciers in Himalayas are retreating at a rate higher than in any other part of the world and, if the current rate continues, the possibility of their departure by the year 2035 is very high" [5, 6]. On the other hand, the Intergovernmental Panel on Climate Change (IPCC) has accepted the errors in the estimation of glacier melting in Himalayan region [9]. The IPCC stated that, "Widespread mass losses from glaciers and reductions in snow cover are projected to accelerate throughout the 21st century, reducing water availability, hydropower potential and changing seasonality of flows in regions supplied by melt water from major mountain ranges like Hindu-Kush, Himalaya, Andes" [9]. In 2005, Hewitt described a broad evidence of glacier development in the late 1990s in the Central Karakoram, in contradiction of a worldwide reduction of mountain glaciers [10]. Moreover, based on surveys between 1997 and 2002, Hewitt also described that some of the large Karakoram glaciers, 40 to 70 km in length, depicted 5 to 15 m thickening over considerable ablation zone areas, locally more than 20 m [5, 10]. These conflicting findings by different research studies make the impact of climate change on Karakoram glaciers and Indus River flows quite vague.

2.2 Changes in Temperature

In order to understand the temperature changes in Pakistan, the past trends given by different research studies have been taken into consideration. Figure 2 illustrates the mean temperature trend in oC (annual) for the past 50 years (1951-2000) [6]. The whole Pakistan has been divided into eight regions for showing the past temperature trend [6]. Different color scales have been used to describe the positive and negative changes in various regions of Pakistan [6]. The map shows the negative trend (annual) in regions II (western highlands), I-b (sub-montane) and IV (lower Indus plains) and positive trend (annual) in all other regions [6]. According to another study, the increase in mean temperature oC in Pakistan during the years 1901-2000 is about 0.6^{o}C [5].

As already mentioned, the increase in temperature is now given main importance and it is considered in terms of global warming. The impact of temperature change on river flows in Pakistan could be much diversified from place to place.

2.3 Changes in Precipitation

Global warming can have significant effects on precipitation intensity and patterns. The change in precipitation directly affects the river flows in Pakistan. But the changes in precipitation have always been very uncertain and sometimes they could be very drastic in some areas. Figure 3 shows the average precipitation trend in % change per year (1951-2000) for different regions of Pakistan [6]. There are negative trend in regions II (western highlands) and VI (coastal areas) and positive trends in other regions [6]. Further, the increase of about 63 mm or +25% in the annual precipitation in Pakistan has been estimated during the years 1901-2000 [5].

3. Past Trends of River Flows in Pakistan

In this section, the trend of river flows in Upper Indus Basin has been discussed. In various watersheds in Pakistan, the past trends of river flows are quite different from each other due to specific climate changes occurred in the past as shown in Figures 4 and 5. The change in flows per decade has been calculated for different rivers with respect to the annual inflows during past years. In Figure 4, the change in flows per decade for Indus river at Tarbela is negative whereas it is positive for Chenab river at Marala (Figure 5) [5]. These changes in flows of different rivers are due to climate changes, developments in the watersheds such as land use changes, deforestation and also Indian interventions on some rivers like Baglihar dam project on Chenab river etc.

4. Future Projections about Climate Changes

The projected climate changes by different research studies have been discussed separately in the following sections.

4.1 Melting of HKH Glaciers

There are many statements by different studies which show the projected changes in glacier melting in future. According to Intergovernmental Panel on Climate Change

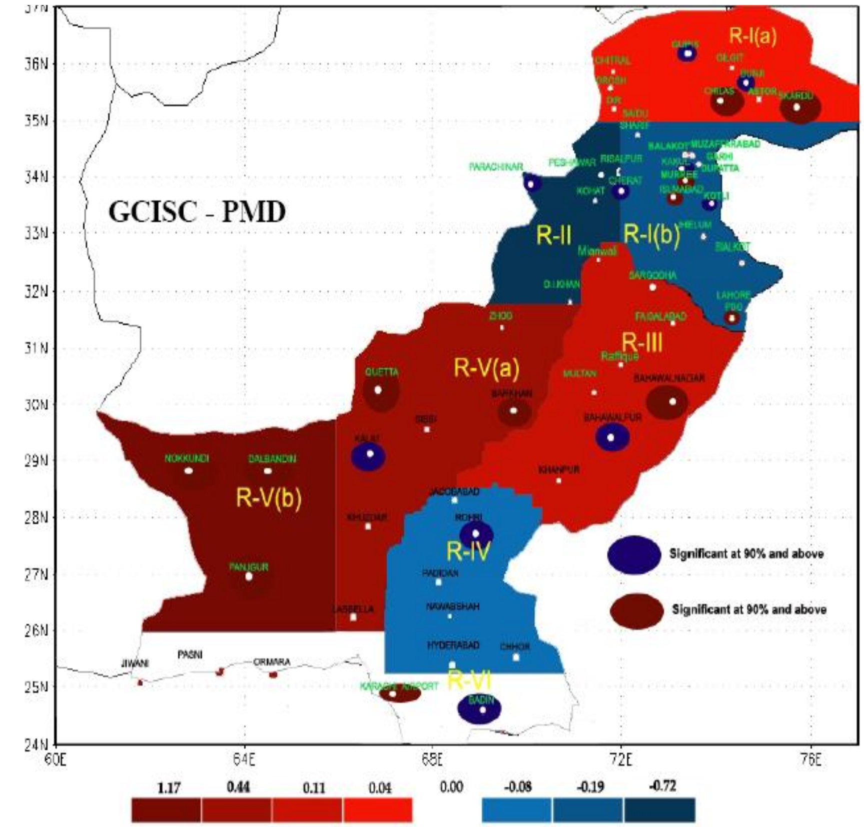


Fig.2: Mean temperature trend in ^{o}C (annual) for Pakistan (1951-2000) [6]

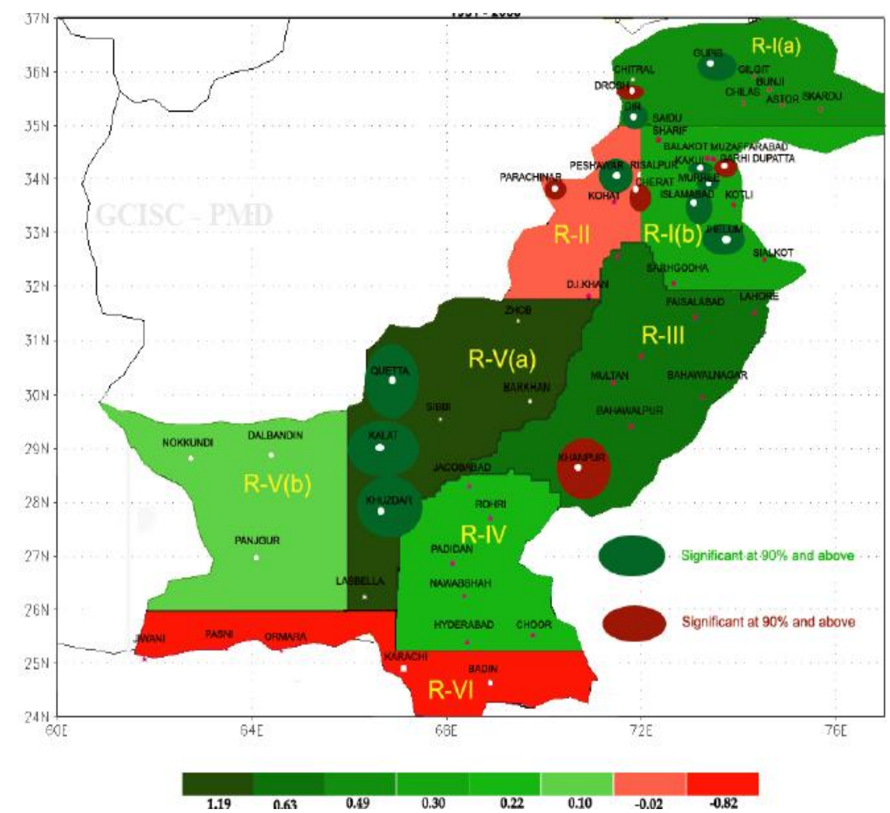


Fig. 3: Precipitation trend (% change/year) for Pakistan (1951-2000) [6]

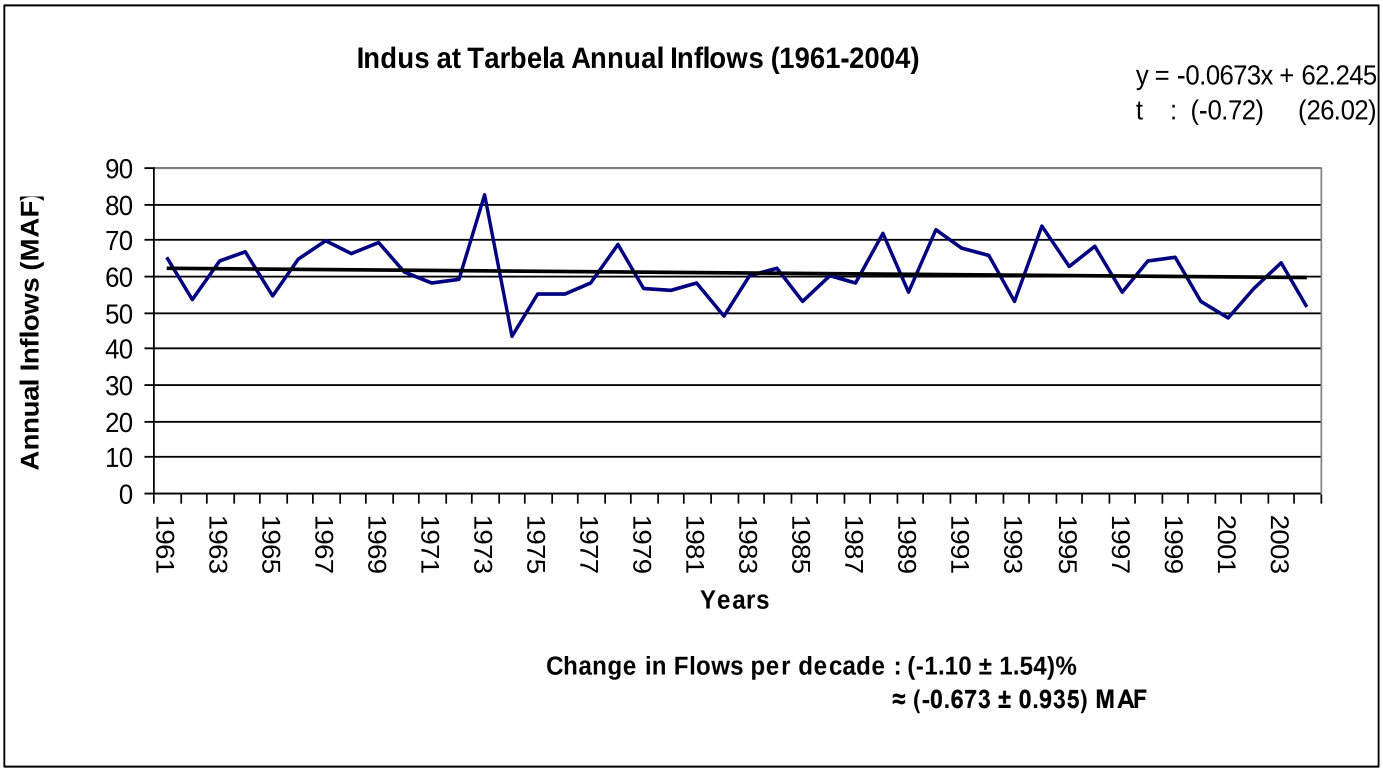


Fig. 4: Trend in annual inflows of Indus at Tarbela (source: IRSA) [5]

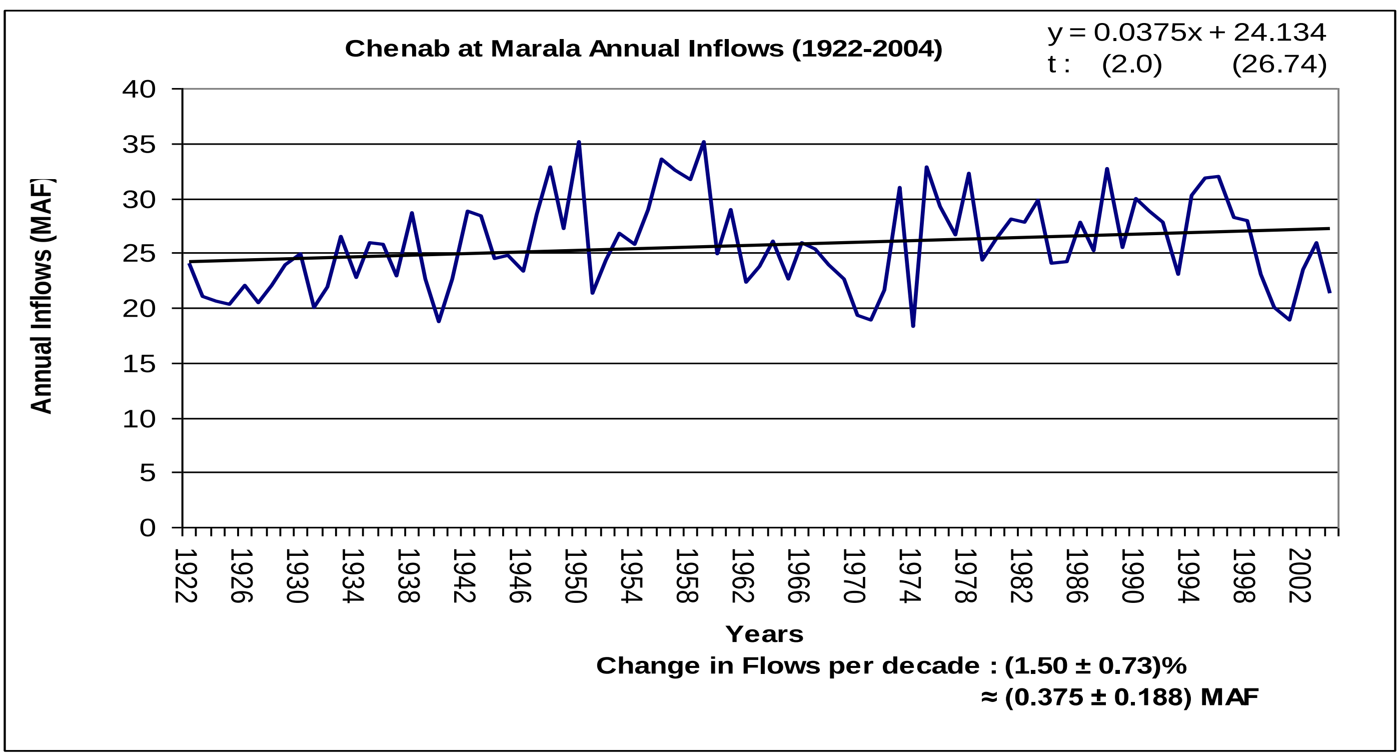


Fig. 5: Trend in annual inflows of Chenab at Marala (source: IRSA) [5]

(IPCC), "Glacier melt in the Himalayas is expected to increase flooding within next two to three decades. This will be followed by reduced river flows as the glaciers retreat" [11]. Western Himalayan glacier will recede for the next 50 years causing increase of Indus river flows. Then the glacier reservoirs will be empty, resulting in reduction of flows by up to 30% to 40% over the subsequent fifty years [12].

4.2 Projected Temperature Changes

Future projections about temperature changes in northern and southern Pakistan have been made by IPCC for two scenarios as shown in Table 2 [5, 6]. The A2-Scenario is based on the ensemble of 13 GCMs (Global Climate Models) whereas the A1B-Scenario is based on the ensemble of 17 GCMs. Moreover, fine and coarse resolution projections have also been considered for these scenarios. Temperature increases in both summer and winter are higher in northern Pakistan than in southern Pakistan. Temperature increases in northern and southern Pakistan are higher in winter than in summer.

4.3 Projected Precipitation Changes

Table 3 shows the projected precipitation changes (%) in northern and southern Pakistan for two scenarios [5], [6]. Due to many uncertainties, it is difficult to draw any clear conclusions about change in precipitation with time. But there is some indication of precipitation increase in summer and precipitation decrease in winter in the southern Pakistan.

4.4 Projected Changes in Flows

The projected changes in flows have been discussed only with respect to the glacier melting. A technical report states that "as a result of glacier melting, upper Indus will show initial increase between +14% and +90% in mean flows over the first few decades of the next 100 years, to be followed by flows decreasing between -30% and -90% of the baseline by the end of this century" [13]. There is a clear indication of increase in river flows due to glacier melting in future decades which will be followed by the decrease in river flows.

5. Case Study of Chitral Watershed

5.1 Study Area

The drainage area of Chitral River (Figure 6) in Chitral is about 11,400 km^2. The mean annual runoff of the river for 34 years of record (1964-67, 1969-98) is 8670 Mm^3. The maximum recorded discharge was 1585.5 m^3/s on 16th July, 1973 and the minimum recorded discharge was 46 m^3/s on 10th March, 1964. The river is glacier and snow fed and it flows steadily throughout the year with additional runoff during the monsoon in June through September. The data

Table 2: Projected temperature changes for northern and southern Pakistan [5]

Region: Northern Pakistan	A2-Scenario			A1B-Scenario		
	2020s	2050s	2080s	2020s	2050s	2080s
Annual	1.42 ± 0.10	2.72 ± 0.16	4.67 ± 0.23	1.55 ± 0.10	2.95 ± 0.15	4.12 ± 0.23
Summer	1.31 ± 0.12	2.62 ± 0.20	4.56 ± 0.28	1.45 ± 0.12	2.91 ± 0.18	4.07 ± 0.26
Winter	1.52 ± 0.11	2.82 ± 0.19	4.72 ± 0.24	1.67 ± 0.12	3.02 ± 0.17	4.11 ± 0.24
Region: Southern Pakistan	A2-Scenario			A1B-Scenario		
	2020s	2050s	2080s	2020s	2050s	2080s
Annual	1.25 ± 0.08	2.44 ± 0.13	4.22 ± 0.18	1.40 ± 0.09	2.64 ± 0.13	3.73 ± 0.18
Summer	1.10 ± 0.13	2.24 ± 0.20	3.90 ± 0.26	1.23 ± 0.12	2.43 ± 0.17	3.50 ± 0.22
Winter	1.38 ± 0.09	2.57 ± 0.13	4.33 ± 0.18	1.57 ± 0.10	2.81 ± 0.14	3.81 ± 0.19

Table 3: Projected precipitation changes (%) for northern and southern Pakistan [5]

Region: Northern Pakistan	A2-Scenario			A1B-Scenario		
	2020s	2050s	2080s	2020s	2050s	2080s
Annual	2.22 ± 2.29	3.61 ± 3.21	1.13 ± 3.95	-0.74 ± 1.48	-1.78 ± 2.18	-0.73 ± 3.08
Summer	5.52 ± 3.69	7.63 ± 6.52	1.08 ± 8.35	1.33 ± 3.03	1.81 ± 4.74	1.98 ± 5.74
Winter	-0.66 ± 2.33	0.71 ± 3.21	-2.24 ± 4.10	-2.60 ± 1.87	-4.72 ± 2.57	-4.10 ± 3.10
Region: Southern Pakistan	A2-Scenario			A1B-Scenario		
	2020s	2050s	2080s	2020s	2050s	2080s
Annual	3.05 ± 5.12	6.40 ± 7.48	4.28 ± 9.46	-3.20 ± 4.31	-0.32 ± 5.53	-0.89 ± 7.91
Summer	12.46 ± 9.77	42.19 ± 27.00	51.07 ± 39.78	11.21 ± 10.99	24.14 ± 18.06	37.57 ± 34.00
Winter	-7.53 ± 6.06	-12.90 ± 6.57	-20.51 ± 9.05	-16.13 ± 4.72	-9.92 ± 7.25	-15.10 ± 7.61

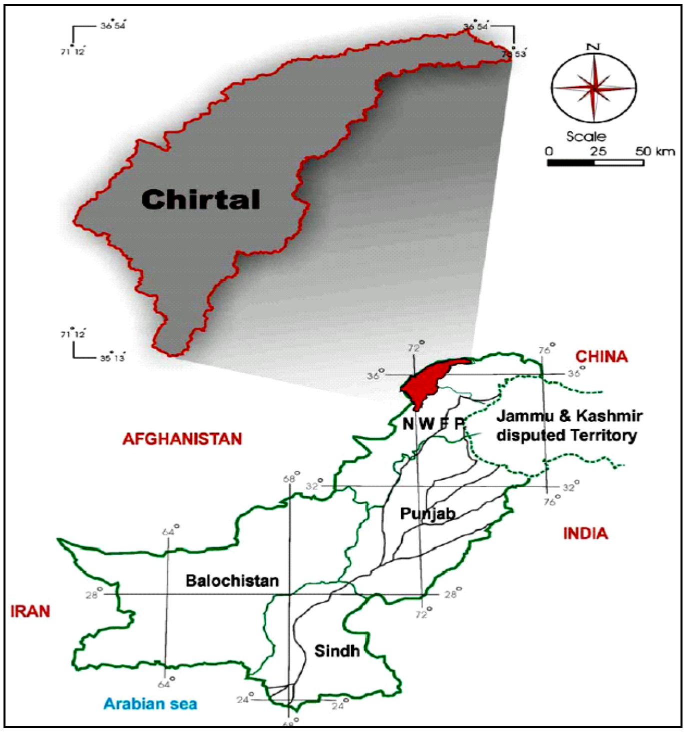


Fig.6: Chitral Watershed in Pakistan map

for 1968 is missing as the gauge was washed away by a heavy flood which damaged the suspension bridge as well.

The mean elevation of the catchment area is 3921m a.s.l. Most of the watershed remains covered with snow and glaciers in the winter season. In Figure 7, the LandSat images of Chitral watershed are shown.

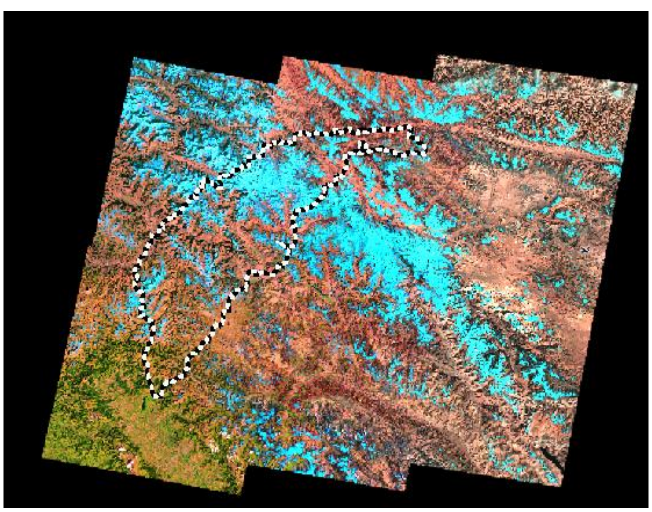


Fig. 7: Three scenes of LandSat images to cover Chitral watershed for 2002.

5.2 Model Description

The Chitral watershed has been modeled by using the UBC watershed Model. The UBC watershed model was firstly developed by Quick and Pipes (1976) [14] in the University of British Columbia. Over the years, the model has been further enhanced and tested and now includes many user-friendly features as described by Quick (1995) [15]. The model computes daily or hourly watershed outflows using daily precipitation and maximum and minimum daily temperature as inputs. The model was designed for the estimation of stream flows in mountainous watersheds where runoff is a union of snowmelt, glacier melt and rainfall. Since the hydro-meteorological response of the hilly watershed is related to elevation, the model utilizes the area-elevation band theory to deal with the orographic gradients of precipitation and temperature, which are supposed to behave in the same way for each storm. The UBC watershed model shows the snow cover area, snow-pack water equivalent, energy accessible for snowmelt, evapotranspiration, moisture contents in soil, storage of groundwater, surface and subsurface parts of runoff for each elevation band and also their mean values over the entire watershed.

The representation of a watershed is done for each elevation band individually through various variables such as band area, forested part, forest density, glaciated part, band position and small proportion of impervious area. The flow chart of UBC Watershed Model is illustrated in Fig. 8.

The UBC watershed model comprises the three main sub-models. The first sub-model is related to meteorology and it divides the point values of precipitation and temperatures to all elevation bands of the watershed. The change of temperature with elevation governs the precipitation as snow or rain and also the melting of the snow packs and glaciers. The second sub-model deals with the soil moisture and it checks the non-linear response of the watershed and distributes the water input (rain and melt) into four parts: fast runoff at surface, medium runoff as interflow, slow runoff in upper groundwater and extremely slow runoff in deep groundwater. The third sub-model is related to routing and it permits the release of runoff to the outlet of the watershed and it is based on linear reservoir theory that assures conservation of mass and water equilibrium. The UBC Watershed Model utilizes the full energy balance method to compute the snowmelt.

In high hilly areas where input data of meteorology for applying full energy balance method are generally very scarce, the UBC Watershed Model uses the full energy balance equations with only daily melt estimated by a set of very non-linear functions of temperature [15]. Through comparisons to measurements, it has been shown that the temperature-only-driven full energy balance method is not only reliable, but also provides much better results than the

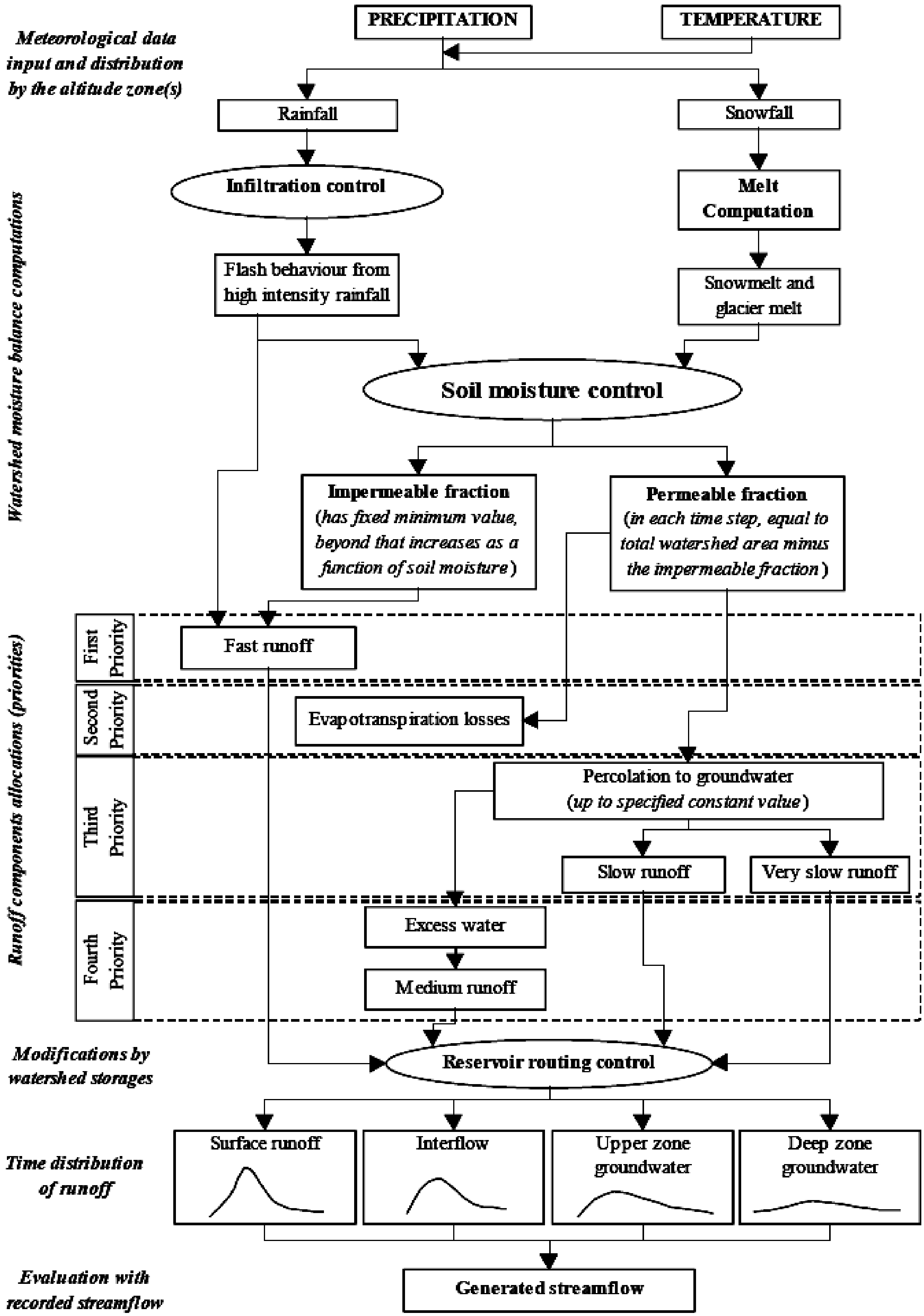


Fig.8: Flow chart of UBC Watershed Model [15]

degree-day method. The temporal input data include number of climate stations, daily precipitation, daily minimum temperature, daily maximum temperature, critical temperature etc. Whereas, the spatial input data include Digital Elevation Model (DEM), elevation bands of watershed, glaciated area in each band, canopy cover and mid elevation of the each band etc.

The UBC Watershed Model has been shown to be applicable to different climatic regions, ranging from coastal to inland mountain regions of British Columbia including the Rocky Mountains and the subarctic region of Canada [16, 17, 18]. The model has also been performing well in the Himalayas and Karakoram ranges in India and Pakistan, the Southern Alps in New Zealand and the Snowy Mountains in Australia [19, 20].

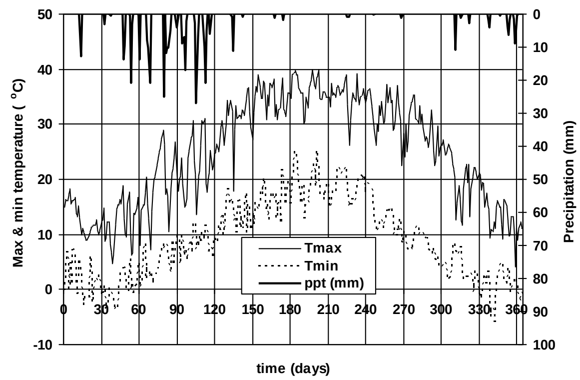
5.3 Methodology

The Chitral watershed has been modeled for the flows of year 2002 which is an average flow year. The climatological data of 2002 for modeling the Chitral watershed is illustrated in Figure 9 in terms of maximum & minimum temperature and precipitation. Depending on the available data, the model has been calibrated for the flows of year 2002 at Chitral stream gauging station as shown in Figure 10. The calibration is based on the actual glaciated areas with respect to the seven elevation bands for year 2002 as shown in Table 4 which were determined from the LandSat image for the same year. It is obvious that the calibration of flows is not exact throughout the year 2002, mainly for the peak flow. But for the purpose of this study, this level of calibration is considered to be acceptable for further analysis.

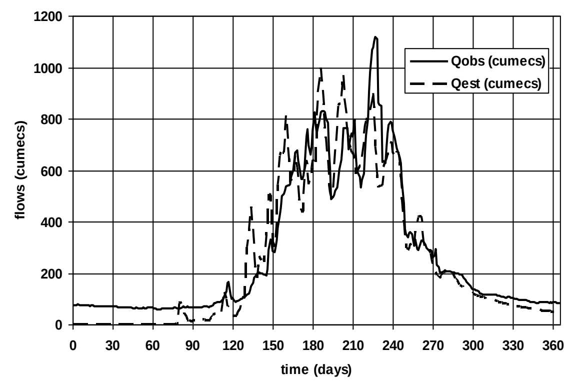
Table 4: Seven elevation bands and glaciated area for 2002 obtained from LandSat

Band No.	Mid Elevation (m)	Band Area (km^2)	Glaciated Area (km^2)
1	2072	910	80
2	2943	1556	150
3	3578	2078	266
4	4101	2324	440
5	4558	2649	409
6	5066	2103	345
7	6090	689	234

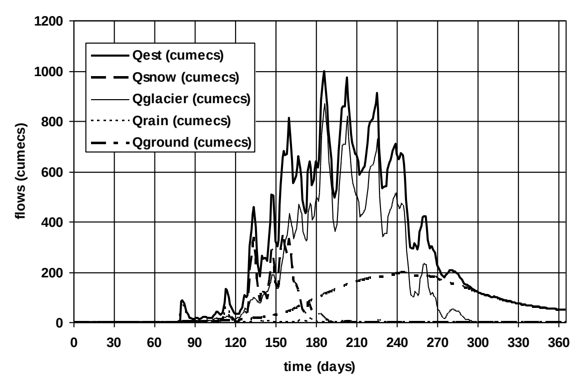
The temporal distribution of various components of runoff in Chitral river at Chitral stream gauging station is illustrated in Figure 11. These components include glacier melt flow, snow melt flow, flow due to rainfall and ground flow. The distribution of the estimated average daily flow of 250 cumecs for year 2002 is given in Figure 12. The observed flow for year 2002 is 272 cumecs and the co-efficient of determination is 0.9 and co-efficient of model efficiency is 0.84 which does not reflect a perfect calibration. This may be due to deficiency in the available data which was used for modeling. However, it is considered that the uncertainties reflected in further results due to this calibration would be very low. The major contribution to the runoff is from glacier melting (about 60%). The snow melt and ground discharge (% 40) also cover significant part of total runoff, whereas the amount of rainfall runoff is relatively not so considerable.



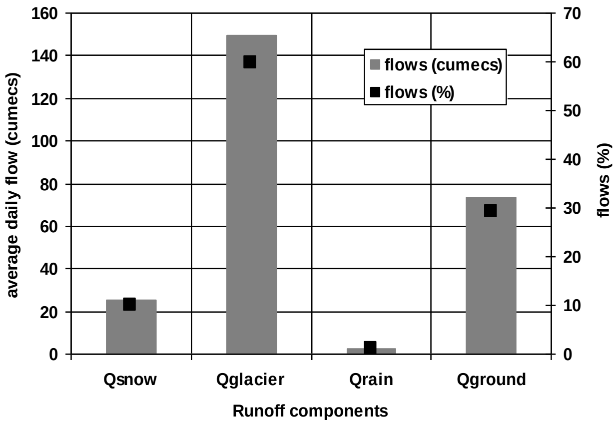
Fig, 9: Climatological data of 2002 for modeling flows of Chitral watershed



Fig,10 Calibration of UBC Model for year 2002 at Chitral stream gauging station



Fig,11: Temporal distribution of various components of runoff in Chitral river at Chitral stream gauging station



Fig,12 Components of runoff in Chitral river at Chitral stream gauging station

5.4 Application of UBC Watershed Model

In order to investigate the impact of climate changes on river flows of Chitral watershed, a scenario with assumed changes in temperature and glacier area of Chitral watershed has been analysed with UBC watershed model. The considered change in temperature has been taken as +1°C by keeping in view the global increase in temperature as well as the projections shown in Table 2. The projections of temperature changes (Table 2) are based on the data of 1990. By analyzing the projections in Table 2, the considered change of +1°C is estimated to occur until 2015. Further, the change in glaciated area is assumed to be -15% as there are no clear projections available for future changes in glaciated area. Table 5 shows the considered reduction in the glaciated area of Chitral watershed with respect to different elevation bands. The simulated flows and their temporal distribution are shown in Figures 13 and 14, respectively.

Table 5: Seven elevation bands and glaciate area for considered Scenario

Band No.	Mid Elevation (m)	Band Area (km^2)	Glaciated Area (km^2)
1	2072	910	0
2	2943	1556	0
3	3578	2078	207
4	4101	2324	440
5	4558	2649	409
6	5066	2103	345
7	6090	689	234

Apparently, there is some reduction in simulated flows over the year 2002 with the assumed climate changes in comparison to the calibrated flows (Figure 10). It should be very clear that with the temperature increase the flows would increase due to increase in glacier melting. On the other hand, the flows would decrease due to the reduction in glacier area. In this case, both impacts of climate changes, increase in temperature and reduction in glaciated area, have been considered and analysed in combination. The estimated flow is about 239.6 cumecs and the runoff components are illustrated in Figure 15. It is quite obvious that there is an overall decrease of about 4.2% in average annual flows due to the assumed climate changes. Due to decrease in glaciated area by 15% and increase in temperature by 1°C, there is slight decrease in both the glacier and ground water flows as compared to the actual runoff components for year 2002 (Figure 12) which contributes to the overall decrease in flows by 4.2%. But there is comparatively a small increase in snow melt flows due to increase in temperature by 1°C, as the reduction in glaciated area would not affect the flows by snow melt.

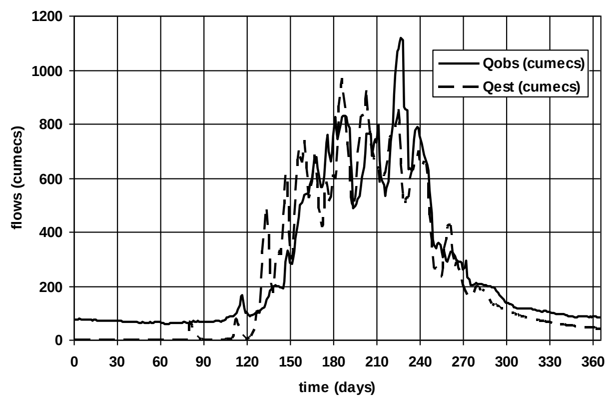
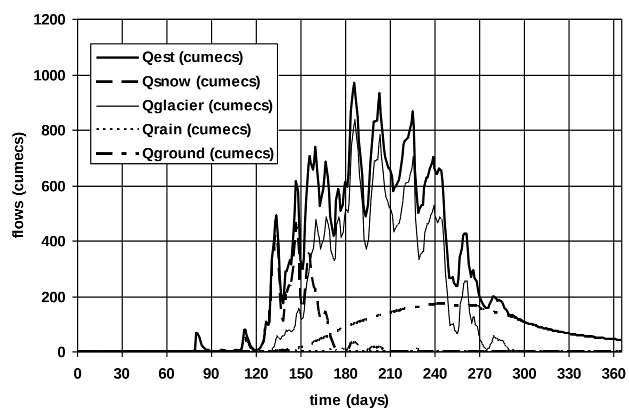
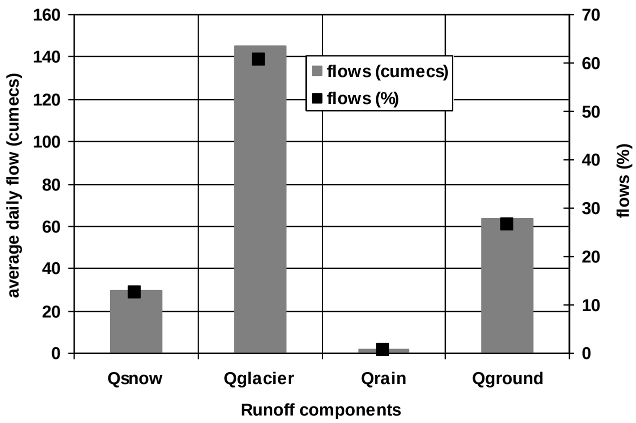


Fig.13: Simulated flows in Chitral river at Chitral stream gauging station for the considered scenario of climate change (ΔT= +1°C Change in Glaciated area = - 15%)



Fig,14 Temporal distribution of various components of runoff in Chitral river at Chitral stream gauging station for the considered scenario of climate change



Fig,15 Simulated Runoff components in Chitral river at Chitral stream gauging for the considered scenario of climate change

6. Conclusions

Climate changes can strongly affect the river flows in Pakistan. The analysis of climate change impact is very complex as it includes many climate parameters and there could also be a lot of uncertainties. The main parameters accountable for climate change are change in temperature, precipitation and glacier storage. The past trends of flows for different rivers in Pakistan are quite different from each other with respect to the specific climate changes in related watersheds which occurred in the past. The assessment for the future changes in climate parameters is also difficult, especially for precipitation. The available projections about the expected future changes in different climatic parameters are not quite sufficient and it needs further investigations to have a clear understanding of their impact on river flows in Pakistan. The available research studies provided some indication of future climate changes in Pakistan and their impact on river flows. As an attempt, the impact of climate changes in terms of assumed change in temperature and glaciated area have been modeled for the river flows of Chitral watershed. The model outputs show a meaningful impact of assumed climate changes on the flows of Chitral river. For more accurate and reliable results, such analyses require detailed input and realistic estimates of future changes in climate parameters. Finally, it is concluded that there is a strong need of further research about the possible impacts of climate changes on river flows in Pakistan.

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