A Hydrological Response Analysis Considering Climatic Variability

Case Study of Hunza Catchment

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Abstract—**The hydrological response of mountainous catchments particularly dependent on melting runoff is very vulnerable to climatic variability. This study is an attempt to assess hydrological response towards climatic variability of the Hunza catchment located in the mountainous chain of greater Hindu Kush-Himalaya (HKH) region. The hydrological response is analyzed through changes in snowmelt, ice melt and total runoff simulated through the application of the hydrological modeling system PREVAH under hypothetically developed climate change scenarios. The developed scenarios are based on changes in precipitation (Prp) and temperature (Tmp) and their combination. Under all the warmer scenarios, the increase in temperature systematically decreases the mean annual snow melt and increases significantly glacier melt volume. Temperature changes from 1°C to 4°C produce a large increase in spring and summer runoff, while no major variation was observed in the winter and autumn runoff. The maximum seasonal changes recorded under the Tmp+4°C, Prp+10% scenario.**

Keywords-mountain region; Hunza catchment; melting contribution; water resources

I. INTRODUCTION

Pakistan is an agrarian country and its agriculture is mainly dependent on one of the world's largest irrigation systems, the network of the Indus Basin (IBIS). The irrigation system is largely fed through the Indus River System (IRS) comprised of Indus River and its tributaries. Indus River and most of its tributaries originates from the greater Hindu Kush-Himalaya (HKH) region. The region is famously known as "the water tower of Asia". This mountain region works as a large reservoir, seizing precipitation and retaining it till released into various tributaries of the IRS. This system connects to the other most important reservoir, groundwater, but also constitutes a source of recharge of aquifers in the plain areas of Indus basin. The river system discharges an annual average volume of 175 billion m^3 which supports directly about 60% of total irrigation requirements, while the rest is provided through groundwater exploitation-which is already close to its maximum potential. Therefore, Indus basin is considered as a closed basin-due to the exploitation of the full potential of ground and surface water resources [1, 2]. Further burgeoning population, industrialization and urbanization will require a 30% more increase in water demand in the next 2 decades.

Moreover, it is projected that climate change will further exacerbate the problem through changes in river seasonality, time of occurrence and peak flow volume in the mountain regions [3]. Earlier studies conducted over the Himalayan part of Indus basin projected that alteration in climatic parameters would result in modification of the hydrological cycle and consequently affect the quantity and quality of river flows [4]. Likewise, numerous other authors also supported the same conclusion in the European Alps [2, 5, 6]. They concluded that any change in climatic parameters may alter the snow and ice storage. This may result in change of both the time of occurrence and the flow volume of mountain tributaries, which may have severe repercussions on adjoining plain areas. This would eventually affect seasonal water availability. The change in seasonality may hamper development in the agricultural sector, including future planning and operation of hydrological installations. Due to heavily dependent on melting runoff, the upper region of Indus basin (part of HKH) is extremely sensitive to climate change [7]. Therefore, it is worth to scrutinize the hydrological response against climatic variability of the Hunza catchment which is not thorough studied. This study investigates the hydrological response of the Hunza catchment to a warmer climate through the application of the hydrological modeling system PREVAH. The developed scenarios are based on changes in (Tmp) ranging from 1°C to 4°C and in (Prp) ranging from -10% to +10%.

II. DESCRIPTION OF THE STUDY REGION

The Hunza catchment encompasses an area of some 14746 km^2 within greater HKH region. Its altitude ranges from 968m to over 7500m a.s.l (Figure 1). Hundreds of peaks exceed 6000m elevation. One-third of the catchment area remains under permanent glacial ice fields with about 808.79km^3 ice reserves. There are hundreds of glaciers, but the 15 largest ones, like the Hispar (521km^2), Batura (336km^2) and Khurdopin (205km^2), dominate the hydrological flow regime. Figure 2 indicates the climatic conditions of the basin. The summer monsoon of the subcontinent has very little influence over the precipitation regime, as its southern borders mostly block monsoon rains. Therefore, the precipitation of the basin is very low and predominantly restricted to winter season thus feeding mostly the snow cover and the glacier ice accumulation. The temperature regime varies significantly: high in summer and very low in winter, therefore the flow in winter is very low. Overall the ice melt contribution dominates the total stream flow regime. Temperature controls the rate of glacier melting. Accordingly glaciers provide more water in warm and dry months and less water in wet and cool months.

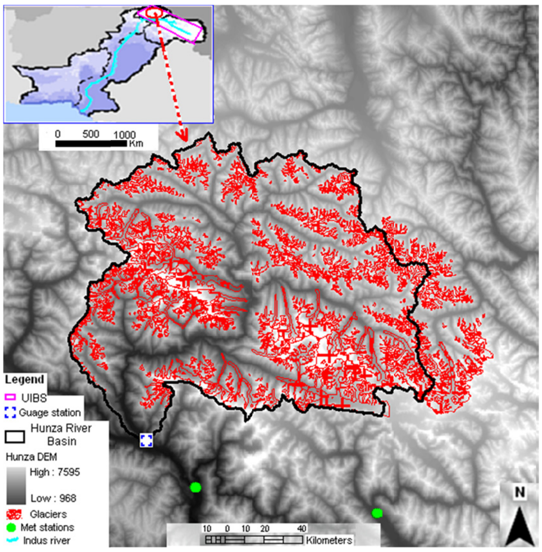

Fig. 1. Map of study area-Hunza catchment

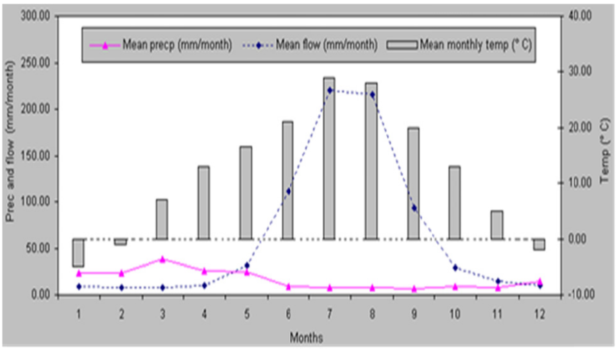

Fig. 2. The 30 year average (1960-1990) of monthly (Tmp), (Prp) and runoff computed at gauge station (Dainyor Bridge) for the Hunza catchment

III. MODEL DEVELOPMENT AND APPLICATION

The PREVAH (Precipitation-Runoff-EVApotranspiration Hydrotope) model has been developed to truly represent characteristics of mountain regions, e.g., variability in meteorological parameters and consider physical heterogeneity in soil types, land use, cover and topography [8]. Several authors have successfully applied the model to various mountainous catchments [2, 5, 6, 9, 10]. Due to its ability to represent mountain region characteristics, PREVAH has been applied to simulate the hydrological response of Hunza catchment. The model was developed and applied to available data for the years 1986-1988 and 1990-1992. Table I shows the linear Nash-Sutcliffe efficiency and volumetric deviation for the calibration and validation periods. The mean annual efficiency is above 85% and difference in flow volume is less than 5.5%. The monthly and annual calibration/validation results prove that model reproduced catchment characteristics very well. The developed model was then applied to assess hydrological response of catchment under a future warmer climate. The future warmer climate is represented through climate scenarios based on possible combinations of a 1°C to 4°C temperature increase and -10% to +10% precipitation changes.

TABLE I. MODEL EFFICIENCY (CALIBRATION AND VALIDATION)

	Calibration results			Validation results		
	Time span	**Dev (mm)**	**R^2**	**Time span**	**Dev (mm)**	**R^2**
Overall results	1986-1988	-35	0.90	1990-1992	-41	0.87
Annual results	1986	-31	0.92	1990	-36	0.90
	1987	-23	0.90	1991	34	0.85
	1988	19	0.85	1992	-39	0.85
Monthly results	1	-09	0.99	1	-11	0.98
	2	-01	0.99	2	-08	0.99
	3	-12	0.99	3	-13	0.99
	4	-03	1.00	4	-06	0.99
	5	08	0.87	5	-10	0.86
	6	-02	0.82	6	20	0.69
	7	-21	0.89	7	06	0.92
	8	-17	0.88	8	-11	0.90
	9	-11	0.83	9	13	0.74
	10	15	0.87	10	-11	0.85
	11	11	0.99	11	-01	0.99
	12	07	1.00	12	-09	0.99

IV. RESULTS AND DISCUSSION

The hydrological sensitivity of Hunza catchment is analyzed by assessing snow melt, ice melt, and total runoff parameters against climatic variability through hypothetically generated climate change scenarios. Figure 3 shows the sensitivity of snow melt against various developed scenarios on mothy basis. It is clearly indicated that under all adopted scenarios, snow melt runoff increases in April/May and decreases in June/July. The maximum increase of about 25mm is observed in April/May under warmer and dry conditions, while maximum decrease of about 45mm is observed in June under warmer and humid condition scenarios. The current snow melt duration from May/July is shifted one month earlier to April/June. The volume of peak snow melt is increased under higher precipitation scenarios and vice versa under dry scenarios, while no significant effect observed over timing of peak snow melt occurrence. In case of humid and drier conditions, increase in precipitation will grow snowpack volume but increase in temperature will trigger a faster melt runoff. This effect can be seen over a Tmp +4°C scenario with -10% to +10% changes in precipitation, where monthly snowmelt runoff varies between 5 mm to 10 mm between humid and dry scenarios. The monthly snow melt variations between the two scenarios have drastic effect on mean annual snow melt contribution in total stream flow.

Table II indicates that under the adopted warmer and dry condition (Tmp+4°C, Prp-10%) scenario, the snowmelt contribution in total stream flow reduced from the current reference contribution of 40.4% to 31.7%, while under warmer and humid condition (Tmp+4°C, Prp+10%) scenario, the current snowmelt contribution just reduced to 38.9%. The effect of different combined scenarios on glacier melt runoff is shown in Figure 4 which clearly demonstrates that monthly glacier melt runoff starts earlier under all warm scenarios and increases linearly with increasing temperature.

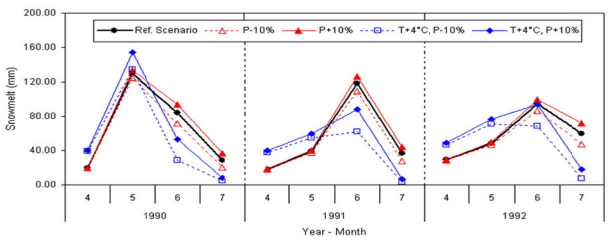

Fig. 3. Influence of climatic scenarios on snow melt runoff on monthly basis from (April to July) for 1990-1992

TABLE II. INFLUENCE OF CLIMATIC SCENARIOS ON MEAN ANNUAL SNOWMELT RUNOFF, GLACIER MELT RUNOFF, AND STREAM FLOW (1990-1992)

Climatic Scenario		% contribution to reference*		% change to reference*
		Ref. mean annual snowmelt (40.4%)	Ref. mean annual ice melt (73.3%)	Ref. mean annual stream flow (--)
Prp. Sc.	-10%	36.2%	74.9%	-0.7%
	+10%	44.3%	71.8%	0.8%
Tmp. Sc.	+2°C	38.3%	89.9%	18.5%
	+3°C	36.9%	98.9%	28.2%
	+4°C	35.4%	108.0%	37.7%
Combined Scenarios	Tmp+2°C Prp-10%	34.4%	91.4%	16.6%
	Tmp+2°C Prp+10%	42.1%	88.5%	20.4%
	Tmp+3°C Prp-10%	33.0%	100.2%	26.1%
	Tmp+3°C Prp+10%	40.5%	97.5%	30.2%
	Tmp+4°C Prp-10%	31.7%	109.4%	35.6%
	Tmp+4°C Prp+10%	38.9%	106.7%	40.0%

*mean annual value: 639.5mm

Under all the adopted scenarios, glacier melting starts 2 months earlier than existing conditions (June) and produce increased flows each month under all adopted scenarios. However, under humid conditions, the snowpack volume is increased, thus snow cover remains a bit longer over glaciated area, resulting in late start of glacier melting, which comparatively produces lower glacier runoff than dry condition scenarios. Figure 4 supports this fact, where the monthly glaciers melt runoff under humid conditions (+10% increase in Prp) are comparatively lower than dry condition scenarios (-10% decrease in Prp). It is also projected that increase in temperature linearly increases glacier melt runoff in various months. Monthly glacier melt runoff increases significantly the glacier melt contribution to total stream flow volume. Under all adopted scenarios, warmer and drier (Tmp+4°C, Prp-10%) scenario produces highest increase in glacier melt runoff, where mean annual glacier melt contribution increased from current reference contribution 73.3% to 106% (Table III). Results show that the rate of temperature controls the glacier melt runoff. In the long run, warmer and dryer conditions would result in glacier depletion and retreat.

The result of variation in Prp on monthly stream flow has been shown in Figure 5. As the average basin precipitation ranges between 200mm to 250mm annually, the changes in precipitation have very little impact over monthly, seasonal and annual stream flow volume. The effect can be observed in Table III.

TABLE III. INFLUENCE OF HYPOTHETICAL CLIMATE CHANGE SCENARIOS ON MEAN SEASONAL STREAM FLOW (1990-1992)

Climatic Scenario		Seasonal % contribution to reference*			
		Winter Ref. (1.7%)	Spring Ref. (24%)	Summer Ref. (67.7%)	Autumn Ref. (6.6%)
Prp . Sc.	-10%	1.5%	24.5%	66.9%	6.3%
	+10%	1.8%	23.5%	68.6%	6.9%
Tmp. Sc.	+2°C	1.9%	34.4%	74.8%	7.4%
	+3°C	2.2%	40.0%	78.2%	7.8%
	+4°C	2.5%	45.6%	81.5%	8.1%
Combined scenarios	Tmp +2°C Prp -10%	1.6%	35.1%	73.2%	6.7%
	Tmp +2°C Prp+10%	2.1%	33.8%	76.5%	8.0%
	Tmp +3°C Prp-10%	1.9%	40.4%	76.6%	7.1%
	Tmp +3°C Prp+10%	2.4%	39.6%	79.8%	8.4%
	Tmp +4°C Prp-10%	2.2%	45.9%	80.0%	7.4%
	Tmp +4°C Prp+10%	2.8%	45.4%	83.1%	8.8%

*mean annual value: 639.5mm

The change in precipitation from +10% to -10% will change mean seasonal flow contribution from current reference contribution (1.7%) to 1.5-1.8% for winter, 24% to 23.5-24.5% for spring, 67.7% to 66.9-68.6% for summer and 6.6% to 6.3-6.9% for autumn, while annual change will be around -0.7 to +0.8%. However, the major impact has been observed under warmer climate change scenarios, in which increases in temperature significantly increase glacier melt runoff- and subsequently increased glacier melt contribution in total stream flow. This can be seen in Figure 6, which demonstrates the influence of temperature change on monthly stream flow volumes. The highest increases in total monthly flows are recorded in May-June period, where increased snow melt amount backed with earlier glacier melt causes a surge in monthly flows. The early start of snow and glacier melt and their significant contribution in total stream flow has a major influence over stream seasonality (Tables II-III). Change in

(Tmp) from 2°C to 4°C will increase mean seasonal flow contribution from current reference contribution (24%) to 34%-46% for spring, 68% to 75-81% for summer. No significant change was observed in autumn and winter flows. The temperature sensitivity is observed to be limited to spring and summer months. In this particular catchment, variation in (Tmp) from 2°C to 4°C still seems below melting point, hence no significant impact was observed over autumn and winter flows.

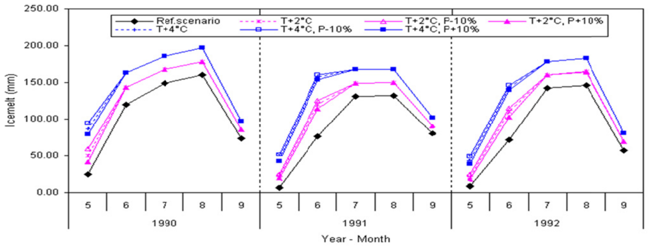

Fig. 4. Influence of climate change scenarios on the monthly (April to July) glacier melt runoff (1990-1992)

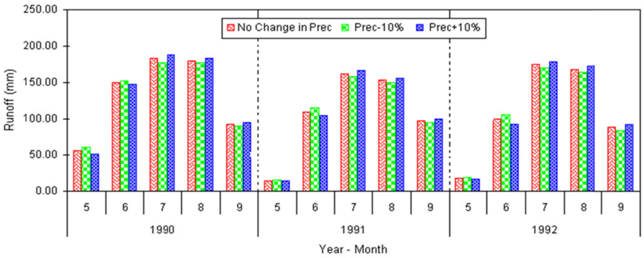

Fig. 5. Influence of precipitation changes on magnitude of monthly (April to July) stream flow (1990-1992)

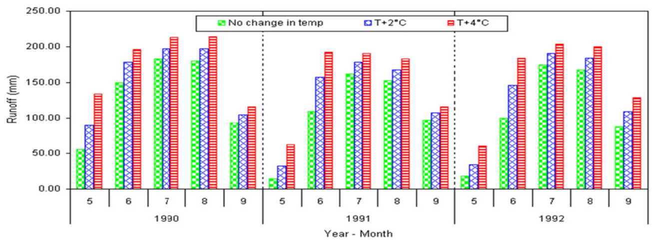

Fig. 6. Influence of temperature changes on magnitude of monthly (April to July) stream flow (1990-1992)

The change in spring and summer flows (due to increase in temperature) have drastically increased mean annual flows, where change in (Tmp) from 2°C to 4°C have linearly enhanced average annual stream flow from +18.5% to +37.7%. The maximum increase of about +40% is observed under the warmer and humid scenario (Tmp+4°C, Prp+10%). In a nutshell, the maximum effect is observed over glacier melt runoff as compared to snow and total runoff. This clearly demonstrates that if temperature continues to grow, the glaciers will be depleted and retreated in the long run. Similar conclusions can be drawn for the dry season. However, this is reversed in the case of humid conditions with no change in temperature.

V. CONCLUSION

This study analyzed the hydrological response of Hunza catchment against hypothetically developed climate change scenarios. It is concluded that under all developed scenarios, a change in temperature would significantly increase glacier melt runoff and subsequently increase total stream runoff. The gain in glacier runoff and ultimate effect over total runoff would leave a catalyst effect over seasonality of stream flow. In this particular catchment, the observed seasonal change is confined to a large increase in spring and summer runoffs, while no significant change was observed in winter and autumn flows. The maximum seasonal change was recorded under the warmer and humid condition scenario. Overall seasonal increases produce about 40% accumulative increase in mean annual stream flow volume. In a nutshell, it can be concluded that in the long run, the warm and dry conditions will be critical factors in glaciers retreating and depletion process. However this could be the vice versa in case of humid conditions with no increase in temperature.

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