IMPACT OF DECREASING GLACIER COVER ON STREAMFLOW OF THE GILGIT RIVER BASIN, KARAKORAM, PAKISTAN

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ABSTRACT

The upper catchments of the Indus river basin host large glacier masses which are projected to decrease due to temperature increase in future. This study focuses on Gilgit river basin (12745 km^2) to quantify the change in glacier contribution in case of receding glacier cover. Total glacier area is 1684 km^2 (14% basin area) and minimum elevation of glaciers is 3000 m. Four climate stations are installed and average precipitation is 240 mm / year and temperature range is -7 ◦C to 30 ◦C. For hydrological modeling, a runoff routing model with snow and glacier melt models is used. The method is simple and requires less calibration effort and flexible to accommodate various data patterns. The calibration is performed for eight years from 2000 to 2007 with Nash-Sutcliffe coefficient 0.74. Validation is done for 2008-2010 and Nash-Sutcliffe coefficient is 0.70. The streamflow is melt water dominated. Glacier contributes 60% to the streamflow annually, the contribution starts in May and lasts till October. In July, August and September the glacier contribution is greater than snow melt and rainfall runoff. To assess the decrease in glacier contribution four scenarios have been selected i.e. no glacier till 3500 meters, 4000 meters, 4500 meters and 5000 meters. In first scenario the contribution reduced by a meager 0.02% because till 3500 meters 7.8 km^2 glacier cover exists, in second scenario 2.2% of glacier cover is lost and the flow reduced by 5%, in third scenario the flow contribution drops by 20% as a result of 8.7% loss in glacier mass and in fourth scenario 73% of total glacier mass is lost and its contribution drops by 98% .The reduced streamflow will make water management more complex and demand integrated efforts.

Keywords: glacier cover, Karakoram, Indus river, climate change

1. INTRODUCTION

In Pakistan northern mountainous region holds vital water resources. These resources are not only crucial for the ecology and environment of the region but play important role in replenishing the demands in the downstream regions. The Indus river starts flowing from high mountains of Himalaya and Karakoram and passes through the northern areas of Pakistan (*Figure 1*). These areas are cold, receive heavy snowfall in winter and host large masses of glaciers (Lutz et al., 2014). The melt water from snow and glacier contributes heavily in the river flows (Zhang et al., 2013). The water resources of the region are not well understood despite being one of the most vulnerable to disasters and densely populated regions (Immerzeel et al., 2015).

Future climate projections have shown increase in the average temperature, precipitation and loss in glacier area (Wester et al., 2019). Glaciers in the region will lose substantial volume by the mid of this century, in the western Himalaya glacier will lose 30% to 40% mass by 2050s and up to 80% of their present volume by the end of 2090s (Huss & Hock, 2015). Precipitation trends across the region are projected to exhibit variable trends in space and time. It will change by ~ 25%, increasing and decreasing same time in different areas (Sanjay et al., 2017). Extreme precipitation events are expected to increase in intensity, thus increasing the risk of catastrophic flooding events and landslides (Lutz et al., 2014). Temperature will be higher by 2.5 ◦C by 2050 and up to 5 ◦C in the 2090s (Wester et al., 2019). Climate change will affect the water quantity and timings which are crucial for the economy and ecology of the region (Chaudhry, 2017). To propose sustainable mitigation and adaptation strategies against changing climate and water availability, accurate assessment of hydrologic cycle.

This study selects the Gilgit River basin, one of the sub-basins of the upper Indus basin (*Figure 1*). For hydrological modeling, snow and glacier melt models have been used with a rainfall-runoff model. The modelling approach is simple, requires less parameters and can accommodate various data patterns and climate scenarios. The objectives of the study are to investigate the suitability of observed climate data for hydrologic modeling, it uses the RRI model with snow and glacier melt modeling to quantify the effects of receding glacier cover on the streamflows.

2. STUDY AREA

Area of the Gilgit river basin's area is 12745 km^2 with elevation range between 1472 m and 6392 m. It is a tributary of Indus river basin as shown by (Figure 1). Table 1 describes the distribution of basin area and glaciers in different elevation zones. Over half of the area lies between 4000 and 5000 meters above sea level. Glacier cover is extracted from the database of ICIMOD (2011), it is generated by employing LANDSAT imageries. The clean ice and debris covered glaciers in the basin cover 1684 km^2.

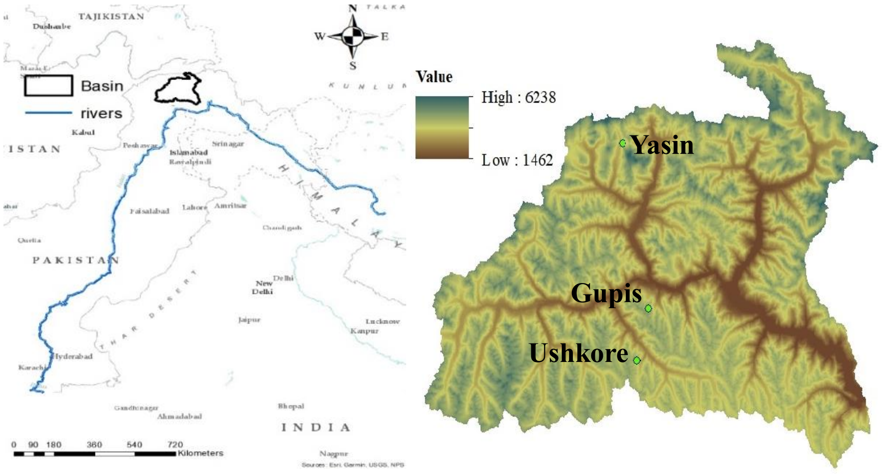

Figure 1. Map of Indus River, Gilgit river basin with climate stations (green circles).

Table 1. Distribution of basin area and glacier with elevation.

Elevation bands (meters)	Basin area (km^2)	Glacier area (km^2)-ice	Glacier area (km^2)-debris
1472-2000	174	-	-
2000-3000	1297	-	-
3000-4000	3667	3.3	34
4000-5000	7182	1147	34
5000-6392	786	466	-

There are three climate stations in the basin with maximum elevation of station is 3208 meters. The climate data of basin above this elevation is not available. Precipitation in the basin is mostly received in winters i.e. October to April in the form of snow. In summer the rainfall is relatively low albeit in monsoon it rains a little higher (Figure 2). The temperature remains below freezing at higher elevations most part of the year, in summer the temperature rises and accumulated snow in the preceding winter starts to melt.

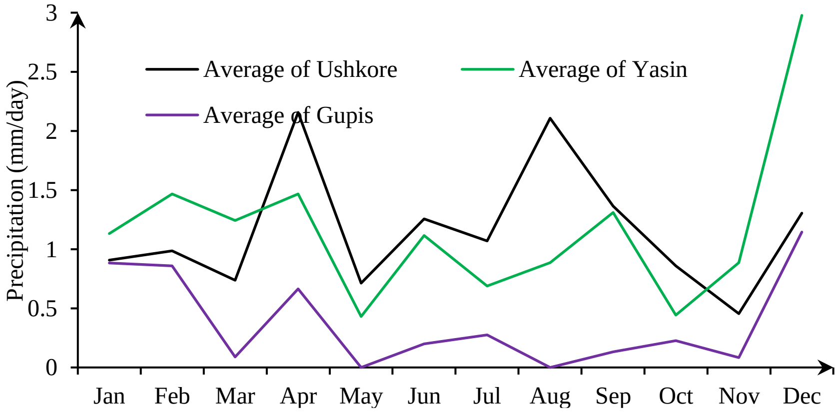

Figure 2. Monthly average precipitation at the climate stations (2008-09).

Figure 3 shows annual hydrograph where high flows are recorded in summer. The summer flows consist of rainfall, snow and glacier melt.

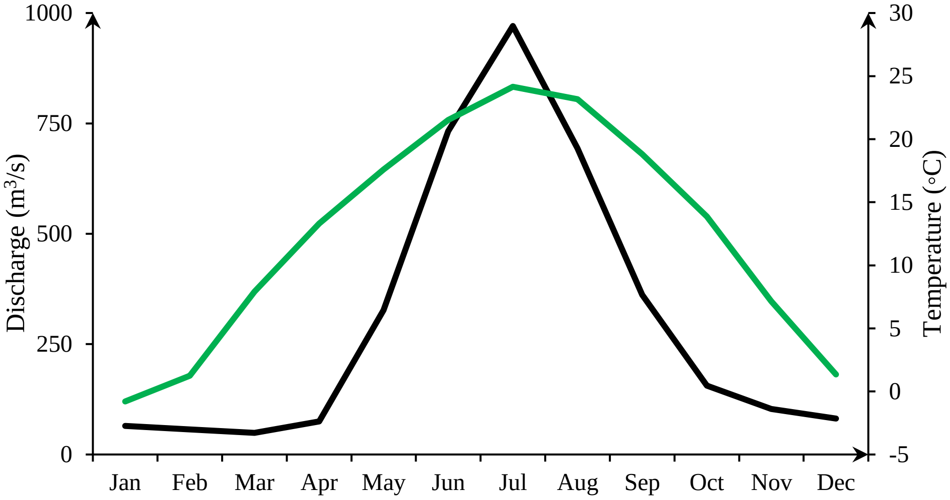

Figure 3. Monthly average river flows of the basin and temperature at 2600 meters.

3. METHODS

Melt water from snow and glacier and rainfall are used as input for the RRI model. Steps used to calculate melt and usage of data are explained below.

3.1 Climate data input

The basin is divided into 5 elevation zones as shown in (*Table 1*) because of variability of climate with elevation. A digital elevation model of 15 seconds resolution is selected from HydroSHEDS database (Lehner et al., 2006) for topographic analysis. The metrological and hydrological data for 2000 to 2010 was obtained from Water and Power Development Authority and Pakistan Meteorological Department. The data consist of daily maximum, minimum temperatures, precipitation and river flows.

The temperature data from stations have been averaged. The average time series of temperature and average elevation of the climate stations are used as benchmark for extrapolation for other elevation zones. The benchmark elevations for temperature and precipitation is 2500 m. The following equations from Valéry et al., (2010) are employed for temperature and precipitation estimation at other elevation zones.

$$T_{target}\,(t) = T_{benchmark}\,(t) + \theta_{temp}\,(Z_{target} - Z_{benchmark}) \qquad (1)$$

Where $T_{target}\,(t)$ is the air temperature at the target zone on day t; $T_{benchmark}\,(t)$ is the observed air temperature at the higher zone on day t; θ_{temp} is the correction factor (to be estimated) (in C/100 m); and Z_{target} and $Z_{benchmark}$ are the elevation of the target and current zones, respectively. To estimate precipitation at higher elevations the following Equation 2 is used.

$$log[P_{target}\,(t)] = log[P_{benchmark}\,(t)] + \theta_{precip}\,(Z_{target} - Z_{benchmark}) \qquad (2)$$

in which $P_{target}\,(t)$ is the temperature at the target zone on day t; $P_{benchmark}\,(t)$ is the precipitation observed at the current zone on day t; θ_{precip} is the altitudinal gradient in mm/m respectively.

Previous studies have proposed amendments to correct the precipitation, both Dahri et al., (2016) and Immerzeel et al., (2015) have suggested correction methods. The precipitation gradient is found to be 0.0003 m^{-1} while temperature gradient is -0.007 ◦C/m as a result of calibration of river discharge. Immerzeel et al., (2015) suggests precipitation increases with elevation at the rate of 0.044% m^{-1} in the adjacent Hunza river basin which is close to our estimate.

Snow and glacier melt models have been employed after estimating the precipitation and temperature at all elevation zones.

3.2 CEMA-NEIGE snow model

We employed Cema-Neige (Valéry et al., 2014) which is a degree-day snow melt model with snow pack updating. It uses maximum (T_{max}), minimum (T_{min}) and mean air temperatures (T_{mean}) to distinguish between rainfall and snowfall. It has additional features of calculating the percentage of snow (P_s) in precipitation.

If the maximum temperature is below $0 \circ \mathrm{C}$, all precipitation is considered as snow i.e. 100%. If minimum temperature is above $0 \circ \mathrm{C}$ all precipitation is rainfall. In all other cases the percentage is estimated by employing the third expression in the Equation (3).

$$P_s = \begin{cases} 1 \quad if \ T_{max} < 0 \circ C \\ 0 \quad if \ T_{min} > 0 \circ C \\ 1 - \dfrac{T_{max}}{T_{max} - T_{min}} \end{cases} \qquad (3)$$

The quantity if rainfall and snowfall is calculated by the (Equations 4 and 5).

$$P_{snow} = P_s * P \qquad (4)$$

$$P_{rain} = P - P_{snow} \qquad (5)$$

where P_{snow} is snow precipitation (mm/d), P is precipitation (mm/d) and P_{rain} is liquid precipitation (mm/d). Snow pack temperature ($\mathrm{Snowpack}_{temp,t}$) defines internal thermal state of the snow pack which is used to quantify the melt. If internal temperature rises to $0 \circ \mathrm{C}$ then melt takes place. Equation (6) estimates the snowpack temperature.

$$Snowpack_{temp,t} = \min\begin{cases} 0 \\ X * Snowpack_{temp\ t-1} + (1 - X) * T_{mean} \end{cases} \qquad (6)$$

where $\mathrm{Snowpack}_{temp,t}$ is snow pack temperature ($\circ$ C) and X is snow pack inertia factor which is set by calibration. Potential melt, $Melt_{pot}$ (mm/d), is computed when snowpack temperature reaches $0 \circ \mathrm{C}$ and mean air temperature is greater than $0 \circ \mathrm{C}$ (Equation 7).

$$Melt_{pot} = ddf * T_{mean} \qquad (7)$$

where *ddf* is degree-day factor and its unit are mm/ $\circ$C. Melt cannot exceed snow storage. In such case the $Melt_{pot}$ is restricted to snow storage. Accumulation of snowfall is an important part of Cema-Neige model. The accumulation is updated daily based on the previously stored snow and the sum of P_{snow} of the particular day (Equation 8 and 9).

$$SS_{update} = SS - Melt_{act} \quad (8)$$
$$SS = SS_{update,t-i} + P_{snow,t} \quad (9)$$

where SS_{update} (mm) is snow storage update after accumulation and melt of snow, SS is snow storage (mm) and $Melt_{act}$ is actual melt (mm/day). Actual Melt, $Melt_{act}$ (mm/d), which is estimated by an empirical expression is described by Equation 10. The snow cover area is also employed in this function.

$$Melt_{act} = (0.9 * snow\ cover\ area + 0.1) * Melt_{pot} \qquad (10)$$

Snow covered area (%) is a unique and simple feature of the model. The model uses P_{snow} and annual average snowfall to estimate the percentage of the river basin covered with snow (Equation 11).

$$snow\ cover\ area = \begin{cases} SS_t/TPS & if \quad SS_t < 0.9 * Z \\ & 1 \end{cases} \qquad (11)$$

where *TPS* is average annual snow precipitation (mm). Total runoff is the sum of $Melt_{act}$ and P_{rain}.

3.3 Glacier melt model

The glacier's cover of the region prepared by ICIMOD, (2011) has been used to calculate the melt from each zone. The glacier melt is quantified using a degree-day model explained by Terink et al., (2015). Equation (12) is used to calculate daily melt from clean ice and debris-covered glaciers.

$$A_{CI} = \begin{cases} T_{avg} \,.\, DDF_{CI} \,.\, F_{CI} & if \quad T_{avg} > 0 \\ 0 & if \quad T_{avg} \leq 0 \end{cases} \qquad (12)$$

In the above equation A_{CI} refers to daily melt from clean ice, DDF_{CI} (mm C^{-1} day^{-1}) is degree day factor and F_{CI} is the fraction of clean ice over the given zone. Similarly, melt from debris covered glaciers is calculated by using degree day factor for debris glaciers and their fraction in the given zone. The total glacier melt is the sum of both clean ice and debris covered glaciers. (Equation 12).

$$A_{GLAC} = (A_{CI} + A_{DC}) \ (13)$$

3.4 RRI model

The snowmelt generated from the CemaNeige model and the glacier melt as well as rainfall are used as input for routing. Rainfall-Runoff-Inundation (RRI) model is used for this purpose. It is a two dimensional model capable of representing rainfall-runoff and flood inundation at once (Sayama et al., 2012). The flow on the slope grid cells is calculated with the 2D diffusive wave model, while the channel flow is calculated with the 1D diffusive wave model. For better representations of rainfall-runoff-inundation processes, the model simulates lateral subsurface flow, vertical infiltration flow and surface flow. On the other hand, the vertical infiltration flow is estimated by using the Green-Ampt model (Sayama, 2015). The runoff generated from melt models i.e. sum of rainfall, snowmelt and glacier melt is used as forcing for RRI model.

4. RESULTS

The simulation results for 2001 to 2007 have been shown in Figure *4***.** Throughout the simulation period the observed discharge showed inconsistent trends in terms of maximum flows. The flows were around 1000 m^3/s in the first three years but increased in 2003 and 2005. The model results agree reasonably with the observed discharge nevertheless there is some inconsistency in a couple of years (Figure 4). This can be resolved by using accurately quantifying the precipitation distribution with elevation. Temperature extrapolation with elevation plays vital role in runoff generation. Spatial variation of temperature would help in minimizing the inconsistencies. Nash-Sutcliffe coefficient is selected as the criteria for the model performance. The calibration coefficient is 0.75 and validation is little less at 0.70.

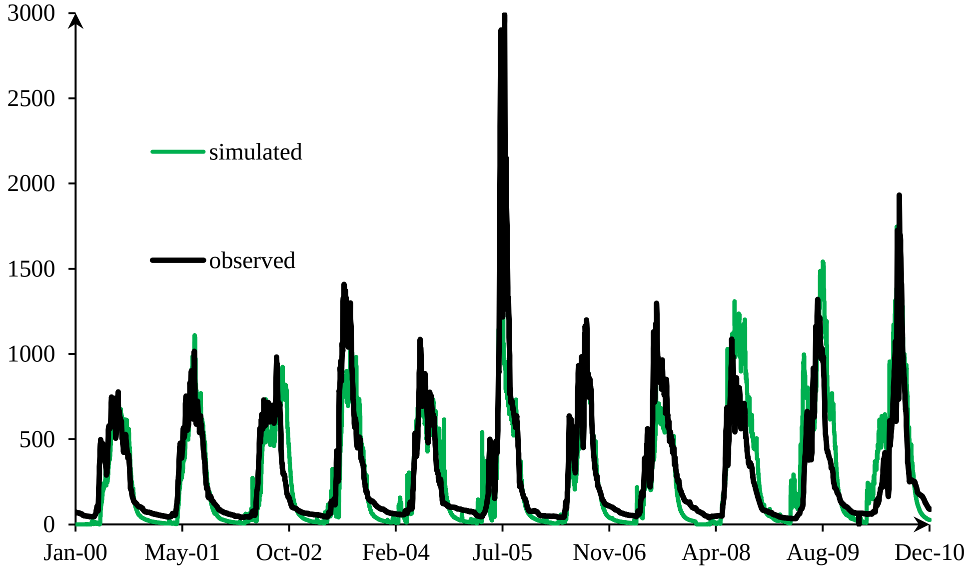

Figure 4. Simulation results of the annual hydrograph (2000-10)

Figure *5* shows the contribution of glacier in the annual hydrograph. Snow melt starts in May and glacier melt follows it and reaches maximum in August. In July, August and September the highest contribution comes from glacier alone. Annually glacier contributes 60% to the total annual flows. In winters the streamflow is generated as a result of baseflow and rainfall at lower elevations.

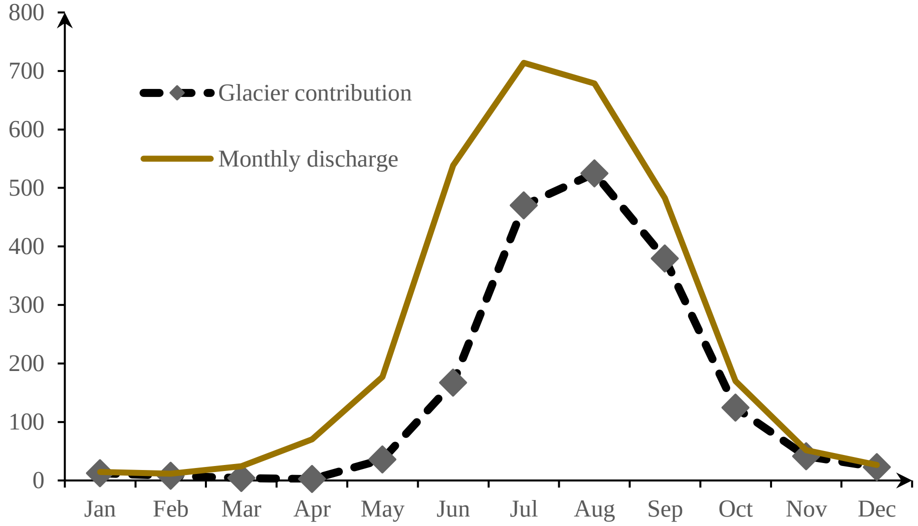

Figure 5. Comparison of annual hydrograph and glacier contribution

With decreasing glacier cover its contribution in the streamflow will reduce. Currently their contribution is 60 % annually, in August and September this contribution is 78% of average flow. Climate change will increase the melt rates and affect the annual mass balance. Four scenarios of varying glacier areas are selected i.e. no glacier till 3500 meters, no glacier till 4000 meters, no glacier till 4500 meters and no glacier till 5000 meters. The simulation shows significant reduction in the contribution of glacier melt water. The first two scenarios will result in very negligible change as compared to current trend. However, in the last two scenarios where larger reduction of glacier mass occurred the glacier contribution reduced to 20% and 98%. In last two scenarios the larger reduction is due to the glacier loss between 4000 and 5000 meters where almost 70% of the total mass lies.

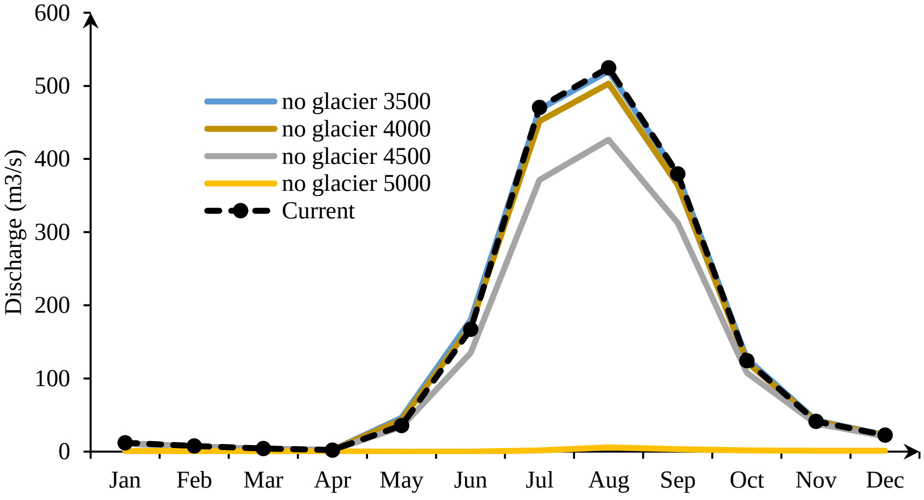

Figure 6. Change in hydrographs due to reduction in glacier cover

5. CONCLUSION

In Gilgit river basin, glacier melt water is higher than snow and rainfall contribution. The major source of this melt water is between the elevation zones of 3000 and 5000 meters where large masses of glaciers are present. For more detailed climate analysis, the climate stations' data is not preferred choice because of their poor coverage of the spatial and temporal patterns of climate. Snow melt and rainfall collectively contributes around 40% in the annual river flows. Glacier melt is the major source of river flows as it accounts for more than half of annual river flows. Its reduction under climate change will bring serious consequences for water management, hydropower and irrigation sector etc. Modern irrigation techniques and efficient water management approaches will be vital for sustainable development. This research shows the dependency of the basin on the glacier melt water and possible consequences of its loss. Integrated mitigation and adaptation approaches are the need of time to combat the change in the water supply.

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