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# A quantitative assessment of the genetic sources of the hydrologic flow regimes in Upper Indus Basin and its significance in a changing climate

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SUMMARY

Reliable quantitative estimates of contributions melt water of different genetic sources make to river flows in Himalayan river basins are largely unknown. Here we provide such estimates for Upper Indus Basin (UIB). Analyses of historical flow records at 11 gauging stations spanning 14–48 years during a period of record from 1962 to 2010 reveal: a uniform character of annual flow distributions at all gauging stations given by a Gaussian function implying a unique glacio-hydrometeorological condition prevailing throughout the basin controlling four hydrologic flow regimes within UIB. Two low flow regimes occur during the months of October to December (L1) and January to March (L2) and two high flow regimes that occur during April–June (H1) and July–September (H2). For all stations, flow magnitudes follow, H2 > H1 > L1 > L2. In the main stem of Upper Indus River, the contributions to total annual flow volumes ($m^3$) during these flow regimes are 53–62% during H2, 24–32% during H1, 8–9% during L1, and 4–6% during L2. In the main tributaries, these ranges are 47–74% during H2, 15–38% during H1, 8–10% during L1, and 4–6% during L2. Separation of annual hydrographs by linear smoothing and recursive digital filtering technique shows that the annual contribution of melt water (M2) from an elevation band 3500–5300 m to total annual flow volume ($m^3$) varies from 41% to 54% along the main stem of Indus, upstream of the Himalayan foothills. Contribution of melt water (M1) from an elevation band 2500–3500 m varies from 16% to 29%. In the tributaries, annual contributions of M2 vary from 37% to as high as 65%. Similarly, annual contributions of M1 in the tributaries vary from as low as 12% to 34%. Thus, the relative importance of melt water originating from high-altitudes far overweighs that originating from mid-altitudes, in river runoff within UIB. The chief component of M1 is seasonal snows whereas M2 is a mixture of glacial melts, seasonal snows falling in winter and spring, and monsoonal snows falling in the summer (July–September). The M2 component contributes to base flows during L1 regime. Base flow recession occurs during L2 regime. During the H2 regime, three watersheds with greatest glaciated surfaces straddling the Karakoram Mountains contribute 48–54% of flows at Shatial Bridge, a point upstream of Tarbela reservoir up to which rainfall contributions to river discharges in UIB are inconsequential. During the H1 regime, these watersheds drained by Shyok, Shigar, and Hunza rivers contribute 20–31% of flows at this point. During L1 and L2 regimes, their contributions are 33–39% and 31–32% respectively. Contributions of glacial melt and snowmelt to annual river flows vary from 18–35% and 38–50% respectively in the major tributaries and the main stem of Upper Indus, depending on the location. Upper Indus River just upstream of Tarbela Reservoir carries annual flows constituted of 70% melt water of which 21% is contributed by glacial melts and 49% by snowmelts. Thus, changes in climatic trends will greatly control the future water availability within UIB. If glacial retreat and reduction of the perennial snow and ice covers are happening in UIB in a changing climate, then there will indeed be long-term reductions in river flows in UIB and hence sustainability of water resources in this basin will potentially be at risk.



## 1. Introduction

The high altitude terrain of the Himalayan, Karakoram, and Hindu Kush mountain ranges and adjoining Tibetan Plateau (HKH-TP region) house some of the significantly large glaciers

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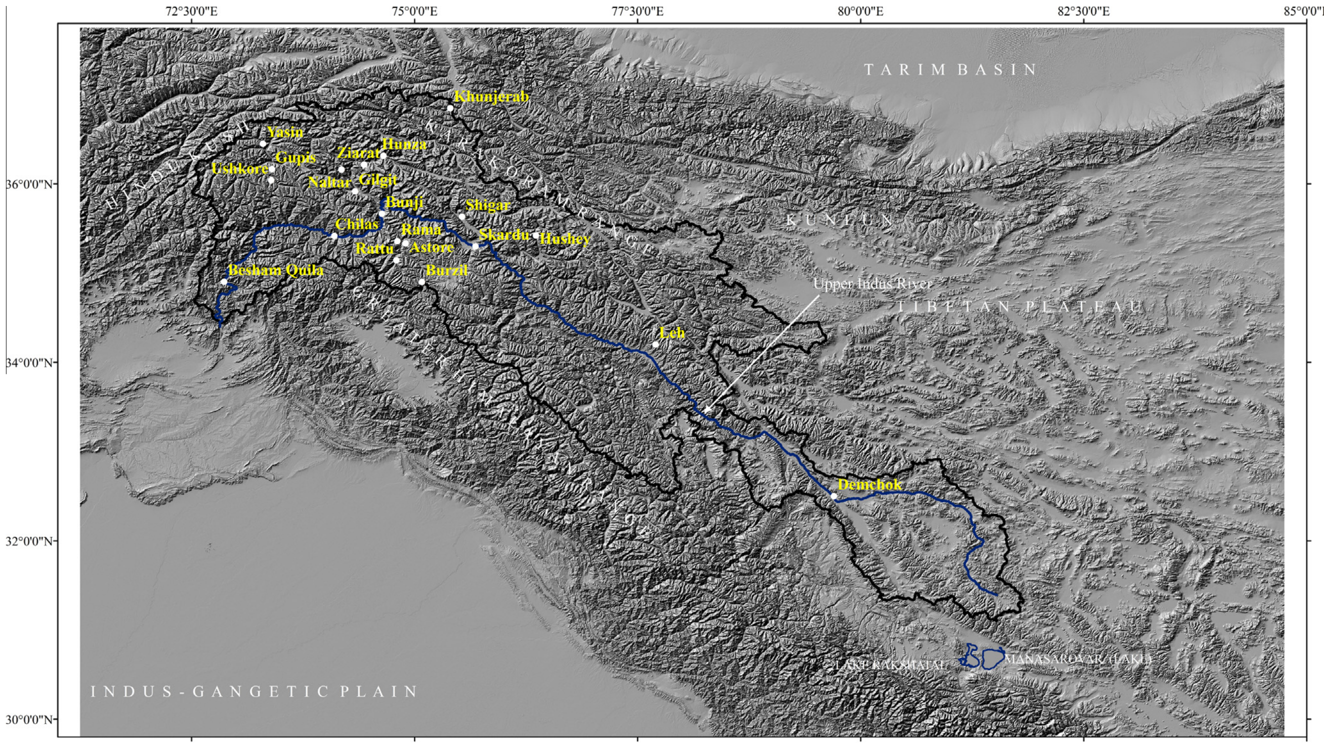


**Fig. 1.** Location and boundary of Upper Indus Basin in relation to the Himalayas and central Asian highlands and other mountain ranges. The length of Upper Indus River is 1468 km. The map also shows the locations of the meteorological stations from where precipitation data are collected (Fig. 3).

and extensive perennial snow and ice covered areas ($SCA_P$)[1] of the world outside the Polar Regions. Numerous rivers, including some of the major rivers of the world such as the Indus, Brahmaputra, and Ganga (Ganges) originate from this region and provide the water for multipurpose usage which include agricultural irrigation, water supply, and hydropower generation to a vast population of Tibet, western China, Pakistan, Nepal, Bhutan, and northern India. Any hydrologic response to climate change, such as retreat of major glaciers and decrease in $SCA_P$ will have profound effects on regional water availability and water resources management in this part of the globe (e.g. see Jianchu et al., 2009).

Snow, ice, and glacial melts constitute a significant component of the river flows in all of the river basins whose headwaters are in the HKH-TP region. For assessing their relative significance, quantification of the contributions these distinct genetic sources make separately to river runoff is a challenging problem (Savoskul and Smakhtin, 2013). The percentages of melt water from seasonal as well as perennial ice and snow packs including glaciers in the river discharges vary from one river to other (Barnett et al., 2005; Schaner et al., 2012). For example, according to Jianchu et al. (2009) glacial melt contributions are 40–45% of river flows in the Indus and the Tarim whereas 9–12% of the discharges in the Ganga and the Brahmaputra originate as melt water from the glaciers. Interestingly, in most cases, it is not known how these estimates are made and hence how accurate those estimates are. In addition, such contributions are not uniform throughout the course of a river. Thus, reliable quantitative estimates of melt water contributions from different genetic sources to river flows in individual river basins of this region are largely unaccomplished (Armstrong, 2010). On the other hand, this is an important piece of information required within the context of climate change and better understanding of its hydrologic consequences.

In spite of the fact that the great rivers of the HKH-TP region originate from certain glaciers, glacial melts are not the only melt components in stream flows. Melt waters from the entire perennial ice and snow-covered areas, seasonal snows, and monsoonal precipitation also make significant contributions to stream flows during the melting season. For this reason, it is necessary to develop quantitative estimates of the relative significance of these principal genetic sources of river flows within individual river basins. Once accurate assessments of these are available, hydrologic effects of two main manifestations of climate change namely atmospheric warming and changes in annual precipitation pattern within a river basin can be ascertained with greater certainty.

One of the major rivers of the Himalayan region is the Upper Indus, the mountainous section of Indus River. The Indus originates at an elevation of about 5166 m in the remote region of western Tibet and flows in a general northwest direction between the Great Himalayan and Karakoram mountain ranges all the way to Hindu Kush mountains and then makes a sharp turn toward south and enters the foothills and the plains (Fig. 1). Thus, Upper Indus Basin (UIB) straddles two great mountain ranges and is the abode of some of the remarkable glaciers such as Siachen, Baltoro, Biafo, and Hispar Glaciers and surrounding snow covered mountain peaks and slopes. According to Bajracharya and Shrestha (2011), there are 11,413 glaciers covering an area of 15,061.74 $km^2$ in UIB. Trustworthy quantitative estimates of relative contributions of rainwater and melt water from seasonal snows, perennial ice, snow, and glaciers to river discharge are not available for this important river basin. This information is critical in the assessment of future water availability in this river basin in a changing climate.

The objective of the present study is to conduct a detailed statistical and hydrologic analysis of the available flow records to determine quantitatively the relative significance of the principal genetic sources of river discharge within UIB. This is the first

[1] Snow covered area, designated by *SCA* includes both seasonal and perennial snow and glacier covers whereas the subscript *P* ($SCA_P$) refers only to that part of the *SCA* that is perennial. This part is most significant in contributions to river flows during the melting season (summer months). Estimate of monthly *SCA* in terms of percentages of total basin area is designated by *SCF*. The subscript *P* denotes perennial *SCF* expressed as $SCF_P$.