Journal of Hydrology 527 (2015) 119–132

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

A reevaluation of the snowmelt and glacial melt in river flows within Upper Indus Basin and its significance in a changing climate

Biswajit Mukhopadhyay [a,*], Asif Khan [b]

[a] 1514 Barclay Drive, Richardson, TX 75081, USA
[b] Department of Engineering, University of Cambridge, Cambridge CB2 1PZ, UK

ARTICLE INFO

Article history:
Received 9 April 2015
Accepted 22 April 2015
Available online 29 April 2015
This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
Upper Indus Basin
Climate change
Hydrologic flow regime
Glacial melt
Seasonal snowmelt

SUMMARY

The hydrograph separation method, previously proposed to quantify base flow, seasonal snowmelt, and glacial melt components in river flows within Upper Indus basin underestimates glacial melt component. This is particularly limiting for highly glacierized watersheds. The limitation has been corrected by a further refinement of the method. The results with the refined procedure are highly consistent with the physical characteristics such as hypsometry and glacier extents of the watershed even though the method itself is completely independent of the physical characteristics of the watershed where it is applied. Glacial melt far outweigh snowmelt in the rivers draining the Karakoram and Zanskar ranges. In the Karakoram, on an annualized basis, glacial melt proportion varies from 43% to 50% whereas snowmelt varies from 27% to 31%. On the other hand, snowmelt dominates over glacial melt in the rivers draining the western Greater Himalayas and the Hindu Kush. Here snowmelt percentage in river discharge varies from 31% to 53% whereas that of glacial melt ranges from 16% to 30%. In the main stem of Upper Indus River, snowmelt fraction in most cases is slightly greater than the glacial melt fraction. In the main stem, snowmelt percentage ranges from 35% to 44% whereas glacial melt percentage ranges from 25% to 36%. Upper Indus River just upstream of Tarbela Reservoir carries annual flows constituted of 70% melt water of which 26% is contributed by glacial melts and 44% by snowmelts. We also show that during the later part of twentieth century and continuing into the early part of twenty first century glacial melt contributions to river discharge has decreased compared to the previous decades. This phenomenon can be ascribed to either basin wide loss of glacial mass in the recent decades in the elevation range from where most of the glacial melt originates or glacier growth and stability due to either reduction in energy inputs or increase in precipitation or both at the high altitude bands wherefrom glacial melt water originates.

1. Introduction

Melt water originating from seasonal snows and glaciers constitutes the dominant component of the headwaters of the rivers descending from the high altitude terrain of the Himalayan, Karakoram, and Hindu Kush mountain ranges and the adjoining highlands of Tibetan Plateau (HKH-TP). An accurate understanding of the relative importance of snowmelt and glacial melt in various river basins of HKH-TP is an important and fundamental problem in hydrology within the context of climate change and water resources management and planning in a changing climate (Schaner et al., 2012). On the other hand, assessments and quantifications of the contributions that seasonal snows and glaciers make separately to river runoff is a challenging problem (Armstrong, 2010; Savoskul and Smakhtin, 2013; Lutz et al., 2014).

One of the major rivers of the HKH-TP region is the Upper Indus, the mountainous reach 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. Thus, Upper Indus Basin (UIB), with an area of 172,173 km^2 (Khan et al., 2014) straddles two great mountain ranges and is the abode of some of the most remarkable glaciers of the world 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

* Corresponding author. Tel.: +1 214 226 4433.
E-mail addresses: biswajitm2009@sbcglobal.net, Janmenjoy@aol.com (B. Mukhopadhyay), engrasif_civil@yahoo.com (A. Khan).

http://dx.doi.org/10.1016/j.jhydrol.2015.04.045
0022-1694/

UIB. Upper Indus Basin is one of the most melt water dependent river basins in the world.

Savoskul and Smakhtin (2013) have made a broad assessment to approximate the contributions of glacial melt and seasonal snowmelt in six major river basins of the HKH-TP region. Their approach has been a synthesis of previously published glacial mass budget estimates and snowmelt models based on temperature-index methods to arrive at estimates of specific glacier runoff in the catchments where such studies are available. It is not evident from their presentation, how snowmelt modeling by temperature-index method can distinguish between snowmelt and glacial melt. Nevertheless, according to their estimates, in the Indus Basin, melt water contributes around 35–40% to the total flow with seasonal snowmelt and glacier runoff shares being approximately equal. These estimates are for the entire Indus basin (1,207,100 km^2 with major tributaries originating from the southern slopes of western Himalayas).

Yu et al. (2013) have attempted to quantify snowmelt and glacier melt contributions to river discharge in UIB. In their approach, they have used an ablation gradient of 1 m/100 m to estimate the amount of ablation in every 100 m elevation band up to an elevation of 5000 m for the glacierized surfaces of the constituent watersheds of UIB. The calculated amount of ablation is then distributed between glacier melt and snowmelt by differentiating the snow and ice covered areas within the zone of ablation.

There are two serious weaknesses of the two approaches described above. None of these two methods provides monthly distributions of snowmelt and glacial melt fractions in an annual hydrograph. Therefore, with these methods it is not possible to detect any temporal changes that may occur in monthly contributions of these two components due to changes in climatic or other factors. Secondly, both methods completely ignore the base flow component of river discharge, which from a hydrological perspective, is not a sound assumption.

Mukhopadhyay and Khan (2014a) have developed a hydrograph separation technique to differentiate three components of river discharge within UIB. With this methodology, they have separated the base flow, mid-altitude melt (*M*1), and high-altitude melt (*M*2) components of an annual hydrograph obtained at a stream gauging station. The base flow is defined by the flows of low flow regime that starts in October and ends in April/May of the following year. The sources of the base flows are mostly remnant melt water and rainwater. However, rainwater is not a principal genetic source of river discharge in UIB due to the general aridity of the basin at elevations less than 2500 m (see Fig. 3 of Mukhopadhyay and Khan, 2014a). Occasional outbursts of heavy thunderstorms may contribute to sudden rise in flows. However, those events do not influence the general patterns of long-term averages of monthly flows in any substantial way. The seasonal snows at elevations <3500 m start to melt in April or May to produce the first pulse of high water i.e., *M*1. The *M*2 melt water starts to appear in June as the freezing level recedes above elevation 4500 m. Mukhopadhyay and Khan (2014a) have postulated that the principal source of *M*2 in June and July is high-altitude seasonal snows whereas in August and September *M*2 comes mostly from glacial melts. The *M*2 component has two annual peaks. The peak that occurs in July is likely the snowmelt peak resulting from removal of the winter snows accumulated on the glacier surface and adjacent areas. The second peak occurs in August and most likely represents the glacial melt peak. The *M*2 hydrograph shows that the cumulative flows originating in June and July are nearly equal in volumetric contributions to those originating in August and September. From this observation, Mukhopadhyay and Khan have assumed that 100% of *M*1 component is snowmelt but 50% of *M*2 represents snowmelt and the other half of it is derived from glacial melt. Accordingly, they distributed the *M*1 and *M*2 components to estimate snowmelt and glacial melt fractions in monthly average and annual river flows at various locations within the basin.

The hydrological (hydrograph separation) method to estimate the snowmelt and glacial melt fractions in river flows seems to have greater merit than the glaciological approach on several grounds. First, the hydrological method relies solely on long-term average flows that are measured at various key locations within the basin. Thereby, it seeks to unravel the signatures of these two components arrested in actual river waters on a month-by-month basis. On the other hand, glaciological measurements are extremely few in numbers compared to the extent and complexity of glaciations present in UIB. Second, the assumption of a uniform ablation gradient and a fixed upper elevation limit for the zone of ablation or equilibrium line altitude (*ELA*) in a large river basin seems too much of simplification of a highly complex system. Furthermore, direct measurements of the values of ablation gradient and *ELA* are largely unknown throughout the basin and therefore any inaccuracy in the assumed values of these two parameters can introduce large errors in the ultimate calculations.

One shortcoming of the method devised by Mukhopadhyay and Khan (2014a) has been the key assumption that July peak in an annual hydrograph solely results from snowmelt. For this reason, the proportion of glacial melts in river discharge appears too low compared to snowmelt component in the highly glacierized watersheds. Some of the researchers who have examined this problem believe that glacial melts in UIB start to contribute to river flows in July (e.g. Khan, 1999, 2001). On the other hand, monthly *SCA* data show that seasonal snows begin to accumulate in September, reach maximum extent in March of the following year, and start to recede from April (see Fig. 4 of Mukhopadhyay and Khan, 2014a). By end of July, most of the seasonal snow disappears from elevations below perennial snow and ice covers, i.e. from below *ELA*. This observation lends credence to the assertion that the August peak in the separated annual hydrograph results mostly from glacial melts. However, it also implies that part of July flows can originate from glaciers and not exclusively from seasonal snowpacks.

The objective of the present study is to present a refinement of the quantitative estimates of the three components of river flows within UIB presented earlier by Mukhopadhyay and Khan (2014a). We present a modified algorithm of hydrograph separation. This improvement offers a greater control in assigning snowmelt and glacial melt fractions to *M*2 flows originating in July and thereby removes the inadequacy of the method previously presented. With the enhancement of the technique presented here, we arrive at much better estimates, judged from watershed characteristics such as altitudinal and spatial distributions of glacierized surfaces in the watersheds. We have also used an enhanced set of flow data to have better spatial and temporal coverage. Finally, to illustrate the tremendous significance of these estimations in unraveling the hydrologic consequences of climate change in UIB, we have applied the estimates to long-term averages of monthly flows from two successive periods of record and from four distinct gauging stations.

2. Data and methods

2.1. Data

The primary dataset is comprised of monthly average river discharge values recorded at gauging stations as daily flows covering the period 1962–2010 (Table 1). Of the 13 stream gauging stations used in this investigation, 11 stations are maintained by the Water and Power Development Authority (WAPDA) of Pakistan. We have