Hydrological Management of Glacial and Non-glacial River Systems

Kireet Kumar, S. Joshi, V. Adhikari, H. Sharma and T. Pande

Abstract The present study investigates the specific features of the hydrologic behavior of glacial and non-glacial river systems. Glacial river systems are characterized as high energy landforms with less biotic activities, whereas the non-glacial river systems have gentle slopes and more intensive biotic activities. Glacial basins generate large flow variations on seasonal basis, but the mean daily discharge in different months is less variable. The role of frozen storage and difference in time of concentration is significant for maintaining the flow in compound glaciers. Non-glacial systems are more precipitation dependent and catchment characteristics play an important role in time of concentration. Headwaters of non glacial rivers have time lag of only few days and flow is not sustained after rains as reflected by the high discharge ratios. Flow duration curves with gentle slope of glacial basin indicate influence of glacier storage and release of water from different zones of the glacier which sustain the flow in the stream. The flow duration curves of non-glacial basin for different monsoon months describe the changing flow pattern. A large part of the year falls under dry weather and low flow conditions and the flow generated by the rain recedes very fast. The rate of increase and decrease of discharge with time (dry and wet season) depends upon type of source, storage characteristics of the aquifer and catchment area.

Keywords Hydrological management · Glacial river systems · Non-glacial river systems · Discharge · Glacier

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1 Introduction

Glaciers are important components of earth system; it controls the river hydrology of the mountainous area and polar region. The Himalaya constitutes one of the most important glacier systems of the world. In the Himalaya about 1,400 km^3 of snow and ice locked, and it spread over nearly 33,200 km^2 area in higher altitude above the 4,300–5,800 m, there are 9,000 glaciers in the Himalaya, this area is considered geodynamically active and it is prone to violent crustal movement causing seismicity (Valdiya 1998). The Ganga basin has 968 glaciers with a total glacier cover of 2,857 km^2 and total ice volume of 209.37 km^3 (Raina and Srivastava 2008). Himalayan glaciers are important because they are the major factors in controlling the climate in Himalayan regions and form major source of water in glacial rivers.

The Himalayan proglacial streams carry good portion of the total summer river flow, which is derived from snow and glacier ice melt (Bruijnzeel and Bremmer 1989). During the ablation season, melting of snow and ice at the glacier surface is the major source of glacier discharge, which in turn is related to the radiative energy input (Collins and Hasnain 1994). Consequently, the variations in air temperature and radiation influence ablation in the summer and monsoon seasons. As a result large variations in meltwater discharge are common (Kumar et al. 2002). Monsoon precipitation, which falls as rain under warm air temperature conditions, also accelerates the melting of new snow cover (Hasnain and Thayyen 1999).

Besides the glacial basins of Himalayan Rivers, there are non-glacial (Rain fed) systems, which contribute significant amount of water to these river systems. In fact, most of the Himalayan basins are combination of the both the systems. Glacier basins have high energy and characteristic landforms with high elevated rocky terrain and presence of snow and ice (Hewitt 1972; Barsch and Caine 1984), whereas the non-glacial watersheds have lower elevation with gentle slopes, medium to good soil depth and intensive biotic activities. Runoff patterns of both systems are different. The amount of runoff coming from glacier is the product of glacierized area and ablation rate.

Glaciers act as natural reservoirs storing water in a frozen state and releasing the most runoff during the summer when all other sources of water are at a minimum (Stenborg 1970; Fountain and Tangborn 1985). This seasonal variation characteristic mitigates low flow intervals and makes glacier runoff a valuable water resource for hydropower (Fountain and Tangborn 1985). Glacier runoff may have less influence on the annual average flow from a large basin, as the total runoff over a period of several years is determined largely by annual precipitation. Flow from non-glacier system peaks in July and August. Unlike non-glacier runoff, glacier runoff correlates better with temperature than precipitation, due to the dominant role of glacier melt compared to precipitation in summer runoff from glacierized basins. This is also the reason for the strong diurnal nature of glacier runoff. Non-glacial systems form the important resources for the local population, whereas glacial meltwater flow has more regional implications. Very little work is done to understand and compare the hydrological behaviour of these two systems which can provide insight into these systems for sustainable water management. The present paper makes such an attempt in two small watersheds of Uttarakhand Himalaya.

2 Study Area and Methodology

The glacial basin of Gangotri Glacier is studied, which is one of the largest glaciers in Himalaya located in the Uttarkashi district of Uttarakhand state. Its watershed extends from 79° 17′ 18″ to 79° 4′ 55″ E and 30° 43′ 10″ to 30° 55′ 50″ N. It originates at a height of about 7,100 m above mean sea level (amsl) and, its terminus is at 3,922 m above mean sea level (amsl). Numerous small-sized glaciers join the main Gangotri glacier from all sides to form the Gangotri group of glaciers (after Sharma and Owen 1996; Fig. 1a). The main glacier, together with its tributaries, is a compound valley glacier. The total spread of the ice volume is about 39.18 km^3 (Kaul 1999) and the total glacierised area (75 % of total basin area) is about 258.56 km^2 (Naithani et al. 2001). The main glacier drains towards the northwest from the Baghirathi group of peaks. The basin is largely devoid of vegetation and human population.

As a non-glacial basin, the study is conducted in the northern part of the Kosi basin (upper Kosi watershed between 29° 30′ and 29° 55′ N Latitudes and 79° 30′ and 79° 45′ E Longitudes covering 480.15 km^2 area) spreading over the Lesser Himalayan domain and administratively within district Almora, Uttarakhand state.

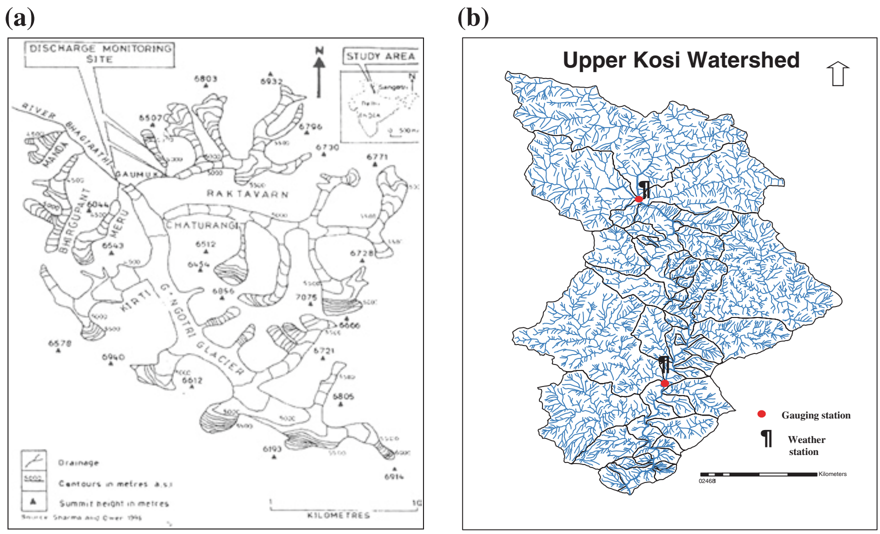

Fig. 1 **a** Glacial watershed. **b** Non-glacial watershed (Upper Kosi)

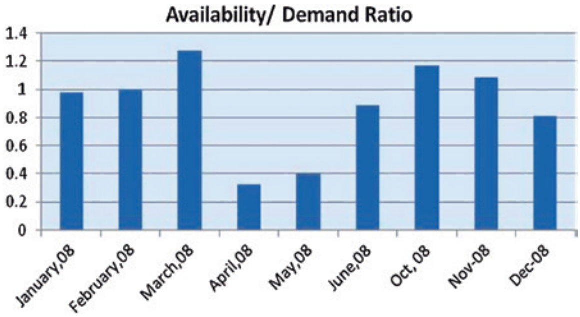

Fig. 2 Water availability demand ratio of Upper Kosi basin

The absolute relief of the catchment ranges between 1,080 m and 2,720 m from the mean sea level (Fig. 1b).

The basin is highly populated and water availability/demand ratio is below 1 in most of the dry months (Fig. 2) indicating severe water stress in non-monsoon months. A gauging station was established for the glacier discharge measurements on the Bhagirathi River, at 500 m downstream of the terminus of Gangotri glacial and for non glacial discharge measurement gauging station was established at Kosi River near Kosi Bridge. Automatic stage level recorder has been installed at gauging station for stage measurement. Discharge measurements were made using the area-velocity method by establishing a rating curve for both watersheds (Water Measurement Manual 1997).

3 Results

Flow pattern of glacial and non-glacial basins are discussed separately in the following sections in terms of daily discharge variations, flow duration curves and ratio of maximum and minimum discharge.

3.1 Rainfall and Meltwater Discharge from Glacial Basin

Daily rainfall was recorded for eleven years (1999–2009). Maximum total rainfall recorded in 2000 with value 306.14 mm and minimum total rainfall was recorded in 2004 having value 106.30 mm. Monthly rainfall for five years indicates that most of the rainfall has occurred in the month of June, July and August corresponding with the summer monsoon season. Average total rainfall over the entire monitoring period was 204.30 mm, which is very low in comparison to other valleys. Overall the Gangotri valleys received scanty rainfall due to its lee side location which forms a rain shadow zone. However, some events of high intensity rainfall were noticed in this area (i.e., 60.55 mm/day in June 2000) (Fig. 3). Such events were responsible for sudden increase in discharge and high concentration of suspended sediment into the river.

Himalayan Rivers along with glaciated catchments have regional importance, and the water from the glacier melt of sustains stream flow in such rivers through

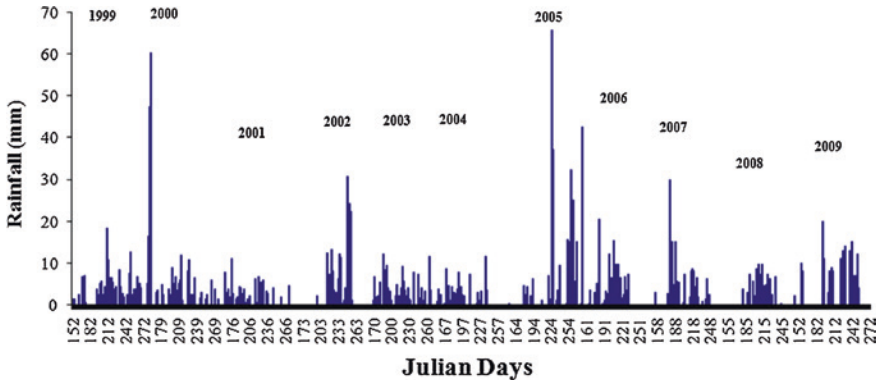

Fig. 3 Daily rainfall in Gomukh

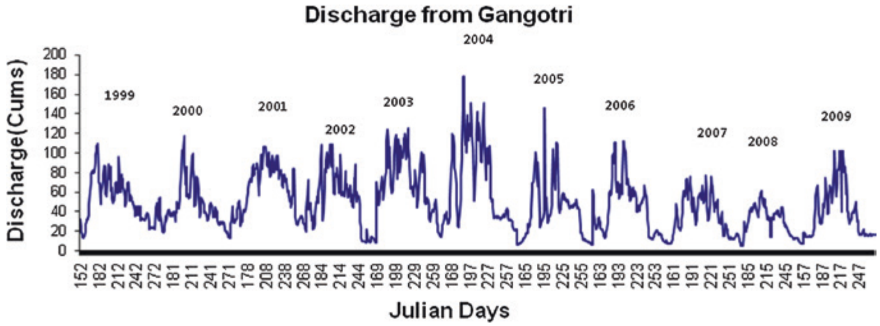

Fig. 4 Discharge pattern of Upper Bhagirathi basin (1 km downstream of Goumukh)

the dry season. Considering the importance of this "Water Tower" of the subcontinent, the study of its water resources becomes relevant in the context of changing climate and socio-physical conditions. Melt water discharge of Gangotri glacier in eleven consecutive years (1999–2009) showed variations on a seasonal scale in terms of Coefficient of Variation (CV) which is ranges from 0.40 to 0.70 during ablation season (June–September) when active melting takes place (Fig. 4). The distribution of mean monthly discharge in the channel showed that it started increasing from the month of June till mid-August and after that decreasing trend was followed in September, maximum and minimum discharge values behaved differently in the beginning of the season. Large variations were noticed in different months. Events related to high flow mostly occurred in the months of July and August confirming that these events were caused by opening up of drainage network and excessive melting of glacier. Analysis of hydrographs for different years indicates that sudden peaks in the stream flow are observed at the monitoring site. Such peaks in the hydrographs are often generated by outburst of water bodies formed in different part of glacier valley caused by rising temperature in late summer. Sudden high rainfall events can also cause rise in stream flow in the glacier basin.

In case of large glacier systems like Gangotri glacier, several discharge peaks can also be generated due to variation in melting rate of various tributary glaciers experiencing different temperature patterns. Though the rainfall is very low in valley, but distribution of rainfall also controls the runoff behaviour from the basin to some extent. Relatively higher runoff in July and August is due to influence of higher temperature in those months in the respective years. In the beginning of season, early rise in the hydrograph in every ablation season (1999–2009) was due to opening of ice jam conduits and their first flushing to downstream in the month of June. Flow duration curves constructed for ablation season (JJAS) indicate gentle slope (Fig. 5).

This indicates influence of glacier storage and release of water from different zones of the glacier which sustain the flow in the stream. The variations in mean daily flow in different months are lower. However, there are significant variations in the mean values of different months. The ratio of minimum and maximum discharge in different months of ablation season indicates high variations in June (Fig. 6). This is mainly

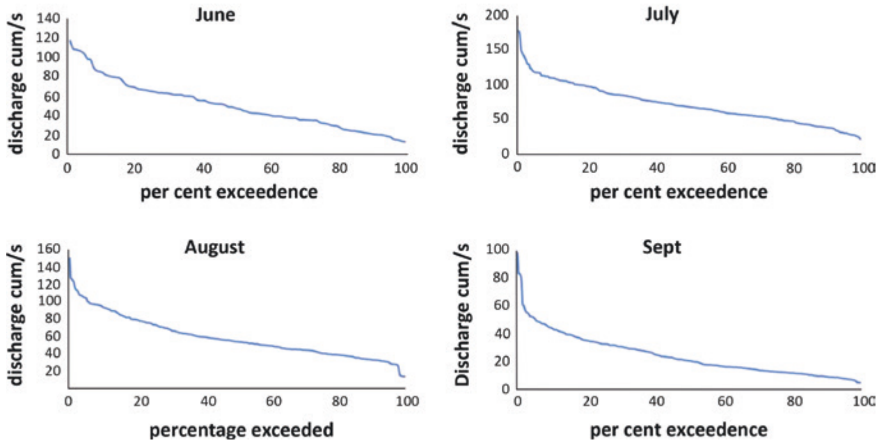

Fig. 5 FDC of glacial basin on Gangotri glacier

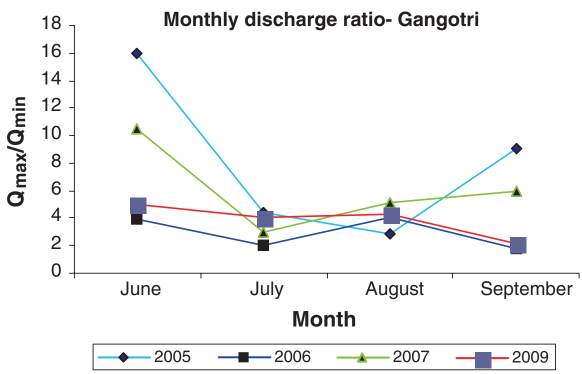

Fig. 6 Ratio of max and min discharge of gangotri basin

due to sudden peaking of discharge possibly due to opening of ice jammed conduits and flash floods in 2006 and 2007. However, the ratio is lower in subsequent monsoon months (July and August). Some increase in ratio in September is mainly due to low value of minimum flow at the end of the season. This is typical behaviour of glacial basins where flow is maintained by constant supply from stored frozen water.

3.2 Rainfall and River Discharge from Non-glacial Basin

The Kosi River is non-glacier river system which originates from forest of Pinath near Kausani (Almora district). The river flow is largely depends on rainfall. The mean rainfall of the basin is 1,400 mm and about 80 % of it is received in four monsoon months. Upper Kosi watershed is targeted by the local govt. agencies as water stressed considering the threat to water availability from the watershed, which is the only source for the area. Hourly rainfall-runoff relationships in monsoon months indicate that, runoff generated due to monsoon rainfall sustained for short duration (Fig. 7). There is average time lag of 1 day between rainfall and runoff for the watershed.

The flow duration curves of Kosi for different monsoon months describe the changing flow pattern (Fig. 8). A large part of the year falls under dry weather and low flow conditions and the flow generated by the rain recedes very fast. Only about 10 % time in the year the high flow conditions are observed. For almost 60 % of the time the river flow is sustained by the base flow.

The rate of increase and decrease of discharge with time (dry and wet season) depends upon type of source, storage characteristics of the aquifer and catchment area. In 2008, the Qmax /Qmin ratio was the highest in June (240.12) and it was maximum in May having a value of 302.06 in 2009. In 2010, this ratio was maximum

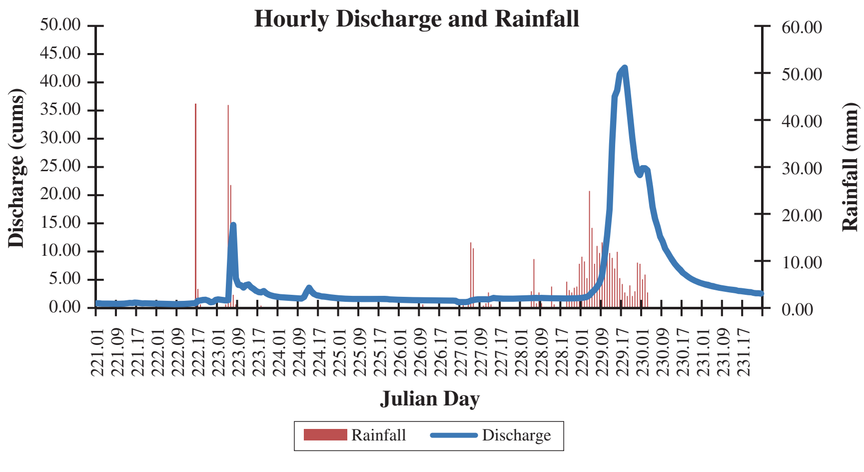

Fig. 7 Hourly discharge and rainfall in monsoon season at Upper Kosi catchment

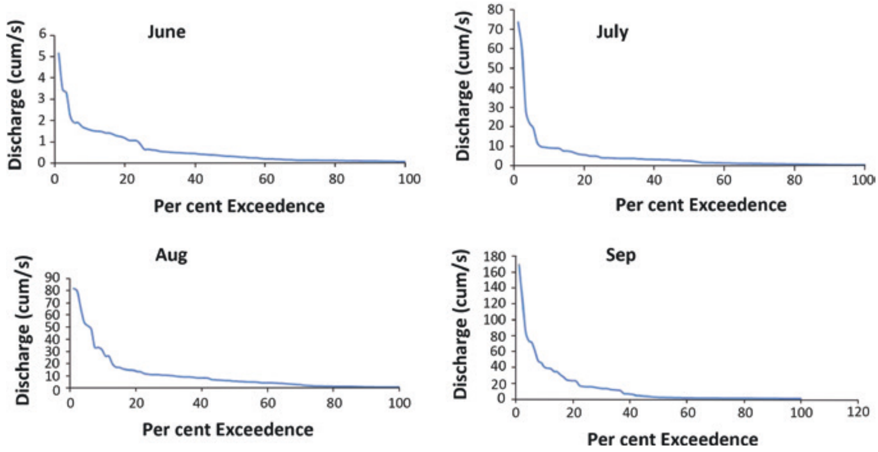

Fig. 8 Flow duration curve for Upper Kosi basin

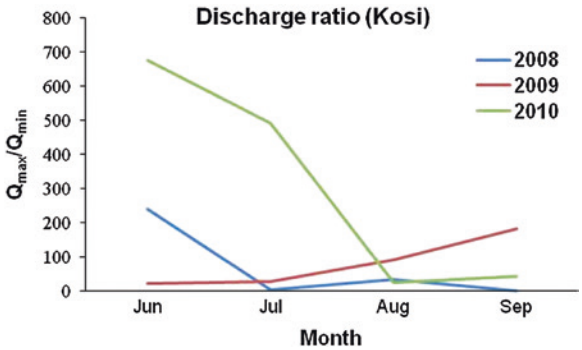

Fig. 9 Ratio of max and min discharge of upper koshi basin

in June (Fig. 9). There is a growing trend in Q_{max}/Q_{min} ratio and low discharge days are increasing, however, longer data may be required to establish the trend. The influence of rainfall is clearly visible in variation of discharge ratios in different years.

3.3 Hydrological Response of Non-glacial Basin

The non-glacial basins are typically modified by the human interventions and facing severe water and resource scarcity. The hydrological responses of different altitudinal zones are also not same except for the decline in stream and spring discharges (Table 1). Lower valleys are densely populated and intensive agriculture is practiced there. Whereas, in middle and uplands the agriculture is mostly rainfed (RF) and

Table 1 Hydrological characteristics of non-glacial basin

Lower transect (below 800 m)	Middle zone (800–1,600 m)	Upper zone (1,600–2,400 m)
Water discharge decreasing (up to 20 %)	Water discharge decreasing (up to 30 %)	Water discharge decreasing (up to 35 %)
Catchment area (15–20 ha) in RF Agri. and multi village	Catchment area (5–12 ha) in civil forest, Agri. and multi village	Catchment area (8–18 ha) in civil forest, one more village and RF
Dense mixed reserve forest	Open Pine forest	Dense mixed forest
Deforestation has limited role in source decline	Deforestation has limited role in source decline	Deforestation has major role in source decline
Flooding, land slide, gulley erosion and slumming in catchment area. Medium slope	Gulley erosion in catchment area with moderate to steep slope	Land slide and gulley erosion with steep slope
Limited grazing pressure on the catchment area	Heavy grazing pressure on the catchment area	Grazing pressure on the catchment area
Catchment area is enough to meet water demand. Large population depends on catchment	Catchment area only sufficient to meet demand at present, if conserved	Catchment area is large to meet demand. Catchment dependence is less

productivity is less. These areas show abandoned common and private lands experiencing heavy soil erosion and nutrient losses. Water retention capacity is reduced due to the action of erosion and deforestation. Most of these areas demand urgent action for rehabilitation and watershed management to sustain water regime.

4 Conclusions and Recommendations

The study highlights the specific features of the hydrologic behavior of a glacial and non-glacial basin. Glacial basins are characterized as high energy landforms with less biotic activities, whereas the non-glacial basins have gentle slopes and more intensive biotic activities. Hydrological responses of the studied basins confirm the role of these characteristics. Glacial basin generates large flow variations on seasonal basis, but the mean daily flow in different months is less variable. The role of frozen storage and difference in time of concentration is significant for maintaining the flow in compound glacier like Gangotri. In case of non-glacial systems, the flow is more precipitation dependent and catchment characteristics play an important role in time of concentration. Headwaters of such rivers have time lag of only few days and flow is not sustained after rains as reflected by the high discharge ratios in case of Kosi. This has serious implications for water management in such water stressed systems. Based on the study some management and adaptation options for such basins are recommended.

1. Water management and conservation during extreme events is a top priority of the glacial watersheds. In the absence of proper planning high intensity rainfall

distributed over a small geographical area (cloud bursts), outburst of glacial (GLOF) and landslide dammed lakes can give rise to floods and associated loss of lives and property in the downstream regions. There is a need of appropriate technologies to harness the non-consumptive potential of water resources in this region. There is still a scope to tap the huge water potential in the rivers which has not been adequately utilized so far for irrigation and power generation, adventure tourism, fish cultivation and other industrial uses.

2. Optimisation of water allocation is needed in non-glacial systems for its efficient utilisation for population, livestock, production of non-agricultural and industrial items, production of energy, improvement of the quality of life and preserving the ecology of the region. One of the major challenges on the way to sustainable management of water is providing equitable access to water, both in terms of quality and quantity.
3. Information sharing mechanism for water management is urgently needed in institutional level. There is lack of well-developed meteorological and river gauging network for improving the knowledge on hydrology, rainfall and sediment transport, etc. throughout the region. A continuous monitoring of hydro-meteorological data will help the planners for their planning and making projections for water management for future.
4. Glacier retreat is a growing concern throughout the Himalayan region. Spatio-temporal monitoring of glacier dynamics and their melting rate is required to improve the designs and operational efficiency of all proposed hydropower and irrigation projects. This knowledge will also help for formulating efficient strategies for conservation, mitigation and adaptations in the downstream.

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