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Research paper

The Himalayan cryosphere: A critical assessment and evaluation of glacial melt fraction in the Bhagirathi basin

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ABSTRACT

The cryosphere constitutes an important subset of the hydrosphere. The Himalayan cryosphere is a significant contributor to the hydrological budget of a large river system such as the Ganges. Basic data on the cryosphere in the Himalaya is inadequate and also has large uncertainties. The data on glacial melt component in the Himalayan rivers of India also shows high variability. The Gangotri glacier which constitutes nearly a fifth of the glacierized area of the Bhagirathi basin represents one of the fastest receding, large valley glaciers in the region which has been surveyed and monitored for over sixty years. The availability of measurement over a long period and relatively small glacier-fed basin for the Bhagirathi river provides suitable constraints for the measurement of the glacial melt fraction in a Himalayan river. Pre- and post-monsoon samples reveal a decreasing trend of depletion of $\delta^{18}O$ in the river water from glacier snout (Gaumukh) to the confluence of the Bhagirathi river with the Alaknanda river near Devprayag. Calculations of existing glacial melt fraction (~30% at Rishikesh) are not consistent with the reported glacial thinning rates. It is contended that the choice of unsuitable end-members in the three component mixing model causes the overestimation of glacial melt component in the river discharge. Careful selection of end members provides results (~11% at Devprayag) that are consistent with the expected thinning rates.

1. Introduction

Frozen waters (snow and ice cover over land and sea, glaciers and ice caps, permafrost and seasonally frozen ground and solid water precipitation) are together termed as cryosphere (Dobrowolski, 1923). Two major facets of the cryosphere concern us. First, it is the storehouse of a major portion of the worlds freshwater in the form of frozen glaciers. Second, the cryosphere has a direct bearing on climate and its fluctuations through its influence on surface energy and moisture fluxes, clouds and precipitation, ocean and atmosphere circulations and hydrology. The two major domains where frozen freshwater is stored are the icecaps of Arctic and Antarctica. Outside these regimes, the Himalayan cryosphere spreads with in the geographic domain of India in an area of ~33,050 km^2 and provides ~8.6 × 10^6 m^3 of water annually (Dyurgerov and Meier, 1997).

In terms of the ice mass and its heat capacity, the cryosphere plays a significant role in the global climate system as it is the second largest storehouse of water after the ocean (Barry, 1987, 2002a). All parts of the cryosphere contribute to short-term climate changes, with permafrost, ice shelves and ice sheets also contributing to longer-term changes including the ice age cycles. Considering its implications on climate and sea level changes, the monitoring and evaluation of cryosphere regions and the climate change effects on the cryosphere are of crucial importance (IPCC, 2013). Such an impact study requires the availability of reliable basic data on cryosphere volumes and their seasonal variability. We critically assess the status of this information for the Himalaya and

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attempt to estimate a realistic glacial melt component in the discharge in the Bhagirathi basin.

2. The Himalayan cryosphere

Glaciers occupy about 10% of the Earth's land surface but hold roughly 77% of its fresh water. More than 96% of glacier ice lies in the Polar Region (Dyurgerov and Meier, 2005). The largest glacial cover outside the polar region ($\sim 116 \times 10^3$ km^2) is in the Indian Himalaya and the surrounding High Mountains of Asia (Dyurgerov, 2001), which together are termed as the 'third pole'.

There are 9575 glaciers spread across the Indian part of the Himalayas (Sangewar and Shukla, 2009), some of which form the perennial source of major rivers. Changes in glaciers are one of the clearest indicators of alterations in regional climate, since they are governed by changes in accumulation and ablation. The difference between accumulation and ablation or the mass balance is crucial to the health of a glacier. The Geological Survey of India has given details about Gangotri, Bandarpunch, Jaundar Bamak, Jhajju Bamak, Tilku, Chipa, Sara Umga Gangstang, Tingal Goh Panchi nala I, Dokriani, Chaurabari and other glaciers of Himalaya (Raina and Srivastava, 2008; Sangewar and Shukla, 2009) in the 'Glacial Atlas of India' besides documenting various aspects of the Himalayan glaciers covering their origin, classification, landforms, snow cover assessments and basin wise inventory.

Since glaciers are strongly controlled by precipitation and the Himalaya depict variability of climate (and weather) across its length, a west to east zonation can form a starting point of analyzing glacier behavior (Fig. 1). The western domain experiences strong winter precipitation (Karakoram and the western Himalayas) while summer monsoon precipitation is intense over central and eastern Himalaya (UNEP, 2012). The westernmost Zone 1 (mainly Afghanistan) has 'westerlies' dominated precipitation and the glaciers grow mainly by winter snow accumulation. In this zone the glacier disintegration is minimal and the retreat rates are slow to neutral. This grades into Zone 2 (Karakoram and western Himalayas) where there is spatial variability on account of merging influences of the summer monsoon and the westerlies, less intense melting and more intense sublimation, relatively less debris cover and high sensitivity to wind and precipitation on account of being in the marginal zone. The central Himalayas located in Zone 3 (India, SW Tibet, western Nepal) have increased and intense melting, higher debris cover, higher proportion of soot effect on ice surfaces and higher retreat rates of the glaciers (Bhambri and Bolch, 2009). The easternmost Zone 4 is dominated by the summer monsoon influence and the glacier growth is mainly by summer snow accumulation. The glacier disintegration and growth of glacial lakes are significantly higher in this zone. The summer monsoon causes an elevated heat pump effect and glaciers are most unstable in this zone. Complexity of the variability with an underlying geographic control has also been recognized elsewhere (Scherler et al., 2011).

2.1. Ice volume

Estimates of the ice volume in the Himalayan cryosphere vary considerably depending on the quality of remote sensed data and the model adopted. To illustrate considering slope dependent ice thickness the volume works out to $\sim$2300 km^3 while it varies between 3600–6500 km^3 considering volume area scaling (Bolch et al., 2012). Ice thickness is an important factor in this context which is mostly lacking for the glaciers in the Indian Himalayan region and only sparsely available for the Himalayan glaciers outside India's geographic boundaries. Gades et al. (2000) reported maximum ice thicknesses of 160 and 450 m for Lirung and Khumbu glaciers in Nepal (mean value $\sim$125 m) while lower 1/3rd of Zuoqiupu glacier in Tibet averages around 125 m (Aizen et al., 2002). In a temporal (2004–2007) IRS LISS III based study, the Indian Space Research Organization (ISRO) mapped a total of 16,049, 6237 and 10,106 glaciers in Indus, Ganges and Brahmaputra basins with the glaciated areas in these basins estimated as 32,246, 18,393 and 20,543 km^2 respectively. These estimates lead to total glaciated area in these three basins to be 71,182 km^2 for 32,392 glaciers (ISRO report, 2010). Earlier a total of 16,117 glaciers constituting a total of 32,182 km^2 area and 3421 km^3 ice volume were estimated for the Ganga, Brahmaputra and Indus basins (Qin, 1999). Considering an area of 40,800 km^2 (22,800 km^2 for the Himalayas and 18,000 km^2 for Karakoram, Bolch et al., 2012) and an average thickness of

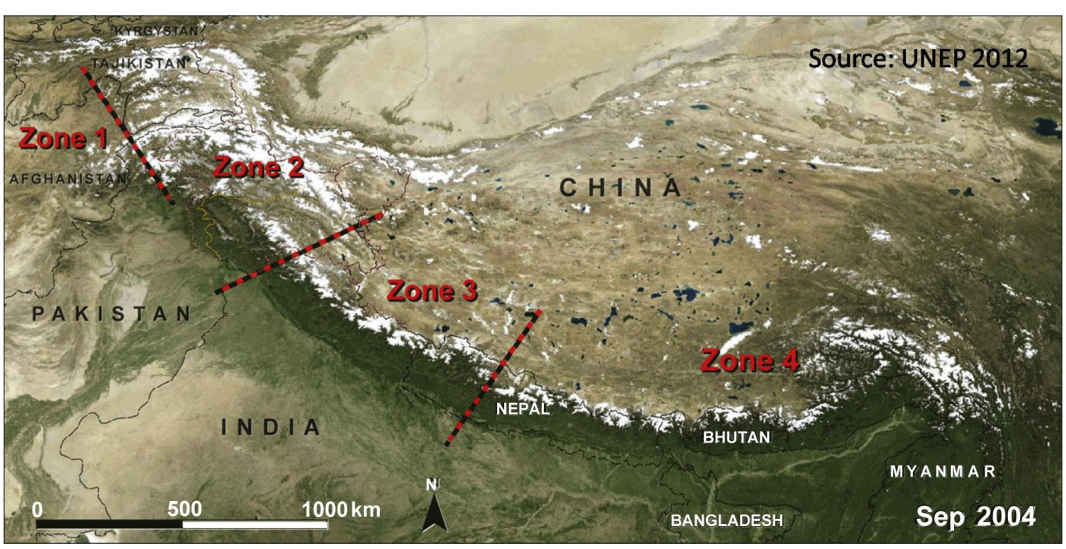

Figure 1. Map showing 4 major climatic zones in Himalayas and adjacent regions (UNEP, 2012). Zone 1–represents mainly Afghanistan, westerlies dominated, with in this zone glaciers grow mainly by winter snow accumulation. Zone 2–this zone includes Karakoram and western Himalaya, both westerlies and summer monsoon. Zone 3–Central Himalaya zone include parts of India, SW Tibet and western Nepal, with in this zone glaciers are highly debris covered and retreat rate is high. Zone 4–easternmost zone, summer monsoon is dominated with in this zone and glaciers are growing by summer snow accumulation and are most unstable.

~125 m (Benn et al., 2012) we estimate the ice volume to be ~5100 km^3 or 4590 km^3 of water. This, however, represents only an approximation.

2.2. Glacial melt contribution

There are three river basins, namely, Indus, Ganga and Brahmaputra from west to east which are influenced by the Himalayan cryosphere. It is logical to assume that the cryosphere-river water interaction as a subset of the hydrologic cycle will follow the geographic Zones 1 to 4 described above. However, this correlation has only limited applicability as the hydrologic cycle is mainly dependent on the precipitation and contribution from the ground water. For example, it is estimated that nearly half of the discharge in the westernmost Indus basin is contributed by glacial melt water, it is ~10% in the central Ganga basin and ~12% in the easternmost Brahmaputra basin (Table 1). Going by the glacier disintegration and their instability (UNEP, 2012), the melt contribution is nearly inverse of that assessed from Zone 1 to Zone 4. Though it may be argued that the glaciated areas in each basin and the annual precipitation may control the contribution, it is seen from Table 1 that the estimated glacial melt proportion cannot be explained even considering these parameters. Estimation of the melt fraction contribution is difficult (Eriksson et al., 2009) and the inadequacy of available data will be demonstrated later.

2.3. Ice velocity

Ice velocities are highly variable across and within the zones/geographic domains. It has been often obtained by dividing the glacier length by an assumed typical ice velocity (e.g. 5 m yr^{-1}) (Raina, 2009). However, the measured values may be significantly higher and variable (Kaab, 2005; Bolch et al., 2008; Quincy et al., 2009). Ice velocity is a significant parameter in assessing the response time of glaciers and an abnormally low value will lead to a long estimation of response time.

2.4. Mass balance of Himalayan glaciers

In a recent study (Kulkarni et al., 2011), an attempt has been made to assess changes in the Himalayan cryosphere using remote sensing techniques. From their studies on the changes in glacial extent, glacial mass balance and seasonal snow cover for 1868 glaciers in 11 basins since 1962 they have estimated the glacial retreat at 16% (overall deglaciation). The monitoring of the seasonal snow cover in 28 river sub-basins in the central and western Himalayas indicated snow retreat even during winters. In the Hindu Kush-Himalayan region a study using MODIS data from 2000 to 2010 shows peak snow cover depletion during February (Gurung et al., 2011). In another study using optical satellite sensor data of the Chenab basin Shukla et al. (2009) inferred that the glacier area has reduced from a total of 110.5 to 96.8 km^2, indicating an overall deglaciation of 13.7 km^2. For differentiation of snow and ice, Normalized Difference Glacier Index (NDGI) and Normalized Difference Snow Ice Index (NDSII) have been proposed (Keshri et al., 2009). Raina and Srivastava (2008) compared the mass balance of two glaciers in Himachal Pradesh, one North facing (Gara glacier) and the other South-facing (Gorgarang glacier). They concluded that a relative excessive winter snow precipitation leads to a positive balance or a reduced negative balance. However a retreating glacier may continue to retreat even under high winter accumulation.

Glaciers globally have been showing a recession since the last ice age (Barry, 2006) and the Himalayan glaciers follow this trend with net negative mass imbalance being 0.5–0.9 m yr^{-1} in Nepal and the western Himalayas (Immerzeel et al., 2010). Annual glacier movements ranging from −80 to +40 m were observed in a satellite imagery based time series data of 8 years (2000–2008) on 286 representative glaciers in an area extending from Karakoram to Bhutan and it indicated that the Karakoram region was an exception in having 58% glaciers advancing while ≥ 65% glaciers were retreating in other regions with highest retreating rates and retreating glaciers in the western Himalaya (Scherler et al., 2011). The role of debris cover is also significant in this context. Identifying the severe lack of observational and measurement data, positive mass balance in the Karakoram region leading to a sea level reduction of the order of −0.01 mm yr^{-1} was indicated in another remote sensed based study (Gardelle et al., 2012).

It is clear that the measurements of the Himalayan cryosphere data can only be carried out in a limited way on account of its vastness, variability and inaccessibility. Thus, the only option is to model this data. Modeling requires well constrained measurements in defined zones which can be then upscaled to the larger areas. One of the most well studied cryosphere domains in the Himalayas is the Gangotri glacier. We will now examine it in some detail and test the validity of the known measurements on the glaciers.

3. Estimation of glacial melt in a data-constrained domain

3.1. Gangotri glacier area

Gangotri group of glaciers is located in the central Himalaya, and originates from the Chaukhamba peaks (7138 m above sea level). It is the source of the river Bhagirathi which is the largest tributary of the Ganges and has an important status in Indian religious culture. The Bhagirathi meets the Alaknanda, the other major river in the area at Devprayag town from where the river assumes the name Ganges. The first documentary record of the snout of the Gangotri glacier is in the form of a sketch by Carl Greisbach of the Geological Survey of India in 1891. A survey map of the Gangotri glacier was prepared later (Auden, 1937) which is generally used as a reference point. The Geological Survey of India continued mapping of the area periodically in 1957, 1971, 1975, 1977 and with gaps till 1996. Thus a record of the Gangotri glacier for over 60 years is available.

There are various possible techniques which can be used for the estimation of glacial melt in river water. These include: (1) Snow Melt Runoff Model: (a) Degree Day Model, (b) Energy Balance Model; (2) Oxygen Isotopes: Hydrograph separation using stable isotopes of oxygen and hydrogen is an important method to characterize the water mixing in a river.

Table 1
Basic parameters of the Indus, the Ganges and the Brahmaputra basins.

Basin characteristics	Nos. of sub-basins	Total area (km^2)	Total no. of glaciers	Total glaciated area (km^2)	Annual precipitation (mm)	Glacial melt contribution
Indus	18	1,005,786	16,097	32,246.43	423	~50%
Ganges	7	990,316	6237	18,392.9	1035	~9–10% (~30% at Rishikesh**)
Brahmaputra	27	525,797	10,106	20,542.75	1071	~12%
Total	52	2,521,899	32,440	71,182.08		

Sources: Eriksson et al., 2009; Immerzeel et al., 2010; **: Maurya et al., 2011.

Table 2
Comparison of published and calculated glacier melt fraction.

Mean annual glacier contribution estimates			
Area/Source	Method used	Published glacier contribution (%)	Source (Schaner et al., 2012)
Muzat, China	Mass and water balance	82.8 (Zongtai, 1989)	0.1
Heihe (Yinglu hydro station), China	Water balance	5 (Zhenniang, 1989)	0.1
Bow River, Banff, Alberta, Canada		1.8 (1952–1993) (Hopkinson and Young, 1998)	15.1
Mass and water balance			
Deoprayag, Ganga River, India	–	28.7 (Jain, 2002)	6.5
Bhakra Dam, Satluj River, India	Water balance	59 (Singh and Jain, 2002)	4.8
Yanamarey, Cordillera Blanca, Peru	Water balance	35 ± 10 (1998–1999) (Mark and Seltzer, 2003)	16.5
Uruashraju, Cordillera Blanca, Peru	Water balance		
Rio Santa, Callejon de Huaylas, Peru	Hydrochemical mixing model		
Yanamarey, cordillera Blanca, Peru	Water balance	58 ± 10 (2001–2004) (Mark et al., 2005)	16.5
Rio Santa, Callejon de Huaylas, Peru	Hydrochemical mixing model		
Pandoh Dam, Beas river, India	Water balance	49.1 (1982–1992) (Kumar et al., 2007)	27.4
Tuotuo River, China	Modified degree day model	32 (1961–2004) (Zhang et al., 2008)	2.5
Tarim Basin, China	–	40.2	8.2
Juggar Basin, China	–	13.5	2.4
Quidam Basin, China	–	12.5	0.1
Hexi Corridor, China	–	13.8	0.1
Quighai Lake, China	–	0.4 (Xu et al., 2009)	3.2
North Saskatchewan River at Edmonton, Alberta, Canada	WATFLOOD, Hydrological model	9.33 (1975–1998) (Comeau et al., 2009)	6.0
Bow River at Calgary, Alberta, Canada	WATFLOOD, Hydrological method	41 (1993–2003)	
Maneri, Bhagirathi river, Uttarakhand		70% (glacier + snow) (Arora et al., 2010)	–
Devprayag/Rishikesh	Hydrograph Separation using stable oxygen isotopes and Electrical conductivity	32% (Maurya et al., 2011)	6.5

In this paper the oxygen isotope method is used. The fundamental assumption is that the liquid (water) and solid (snow) precipitation will distinctly fractionate the light and heavy isotopes of oxygen. Since the precipitation of snow is altitude dependent, snow (and also ice) is likely to contain less amount of heavier (^{18}O) isotope compared to liquid precipitation. The oxygen isotope composition is expressed in the form of a ratio expressed as parts per thousand or parts per mil in reference to a standard composition.

In the context of a Himalayan river it can be assumed that the river discharge comprises three components, namely (1) surface runoff due to summer rainfall, post monsoon interflow and winter snow melt from the catchment area (R); (2) glacier ice melt (I); (3) ground water (G).

Total river discharge (T) at any point in a river channel will be

$$T = I + G + R \tag{1}$$

If total discharge is considered one then the three components can be considered as fraction of 1

$$i + g + r = 1 \tag{2}$$

If the three end members have fixed isotope characteristics and another temperature dependent measurement (such as Electrical Conductivity, EC) is available then the mixing equation in fraction terms (i.e. considering the sum of three components to be one) will allow estimation of glacial melt fraction (e.g. Maurya et al., 2011).

$$i \cdot \delta_I + g \cdot \delta_G + r \cdot \delta_R = \delta_T \tag{3}$$

$$i \cdot E_I + g \cdot E_G + r \cdot E_R = E_T \tag{4}$$

where, i, g and r denote discharge fractions due to snow and ice-melt, ground water and surface runoff.

$$r = \frac{(\delta_T - \delta_I)(E_G - E_I) - (\delta_G - \delta_I)(E_T - E_I)}{(\delta_R - \delta_I)(E_G - E_I) - (\delta_G - \delta_I)(E_R - E_I)} \tag{5}$$

$$g = \frac{(\delta_T - \delta_I)(E_R - E_I) - (\delta_R - \delta_I)(E_T - E_I)}{(\delta_G - \delta_I)(E_R - E_I) - (\delta_R - \delta_I)(E_G - E_I)} \tag{6}$$

By putting the estimated values of r and g in Eq. (2), we can estimate the value of i.

There is also the assumption that $\delta^{18}O$ and EC of the three end members are constant throughout the year excluding the surface runoff component as it varies significantly during the pre- and post-monsoon periods.

In a recent study the upper limits on snow and glacial melt fraction estimates for river discharge were determined (Schaner et al., 2012) using glacier energy balance approach and global hydrology models based on GLIMS and DCW datasets and compared with melt fraction estimates obtained by methods such as water balance, hydrological models (e.g. WATFLOOD), hydrochemical mixing, mass and water balance and modified degree day models. The data indicates significant overestimation (Table 2 of Schaner et al., 2012). Specifically, in the case of the isotope mixing approach errors in estimation are likely to occur if the end-member compositions are not well defined.

3.2. End member variability

The oxygen isotope value of glacier ice melt is reported to be highly variable (Rai et al., 2009) and at Gaumukh it varies from −13.5‰ to −18.5‰. The electrical conductivity (EC) of stream flow changes significantly from pre-monsoon to post-monsoon, e.g. 212 μs/cm during February 2000, 146 μs/cm during June 2000 and 172 μs/cm during September 2000 at Gaumukh (Trivedi et al., 2010). In another study (Pandey et al., 1999), the EC values during pre- and post-monsoon at Gaumukh are reported to be 99 to 68 μs/

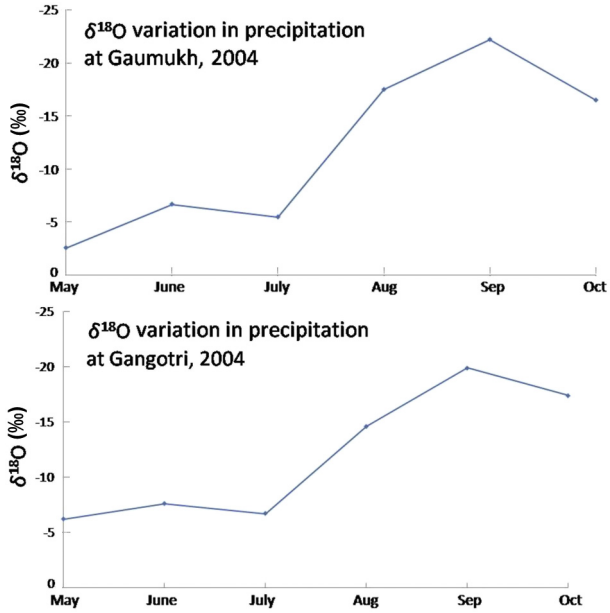

Figure 2. Graph showing variation of $\delta^{18}O$ value from May to October 2004 at Gaumukh and Gangotri (Kumar et al., 2010).

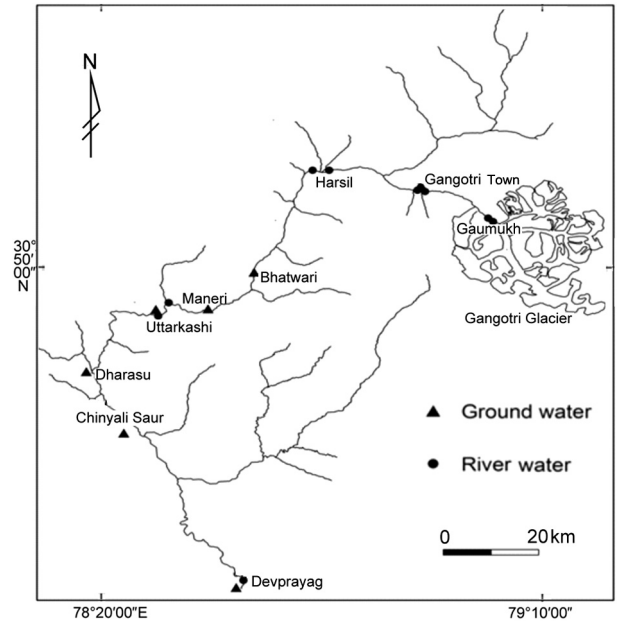

Figure 4. Map showing location of water sampling before and after the confluence of major tributaries along the Bhagirathi river.

cm respectively, while these are 90 to 112 μs/cm at Uttarkashi and 103 to 115 μs/cm at Devprayag for these two sampling periods. Similarly, there is wide variation in the reported ground water oxygen isotope as well as EC values.

The seasonal variation of rain water isotopic composition in Indian rivers was well illustrated by Kumar et al. (2010) in a 3-year study. Within the Bhagirathi basin, the $\delta^{18}O$ values of the rain varied from $\sim -3‰$ to $\sim -25‰$ during May to September 2004. The trend

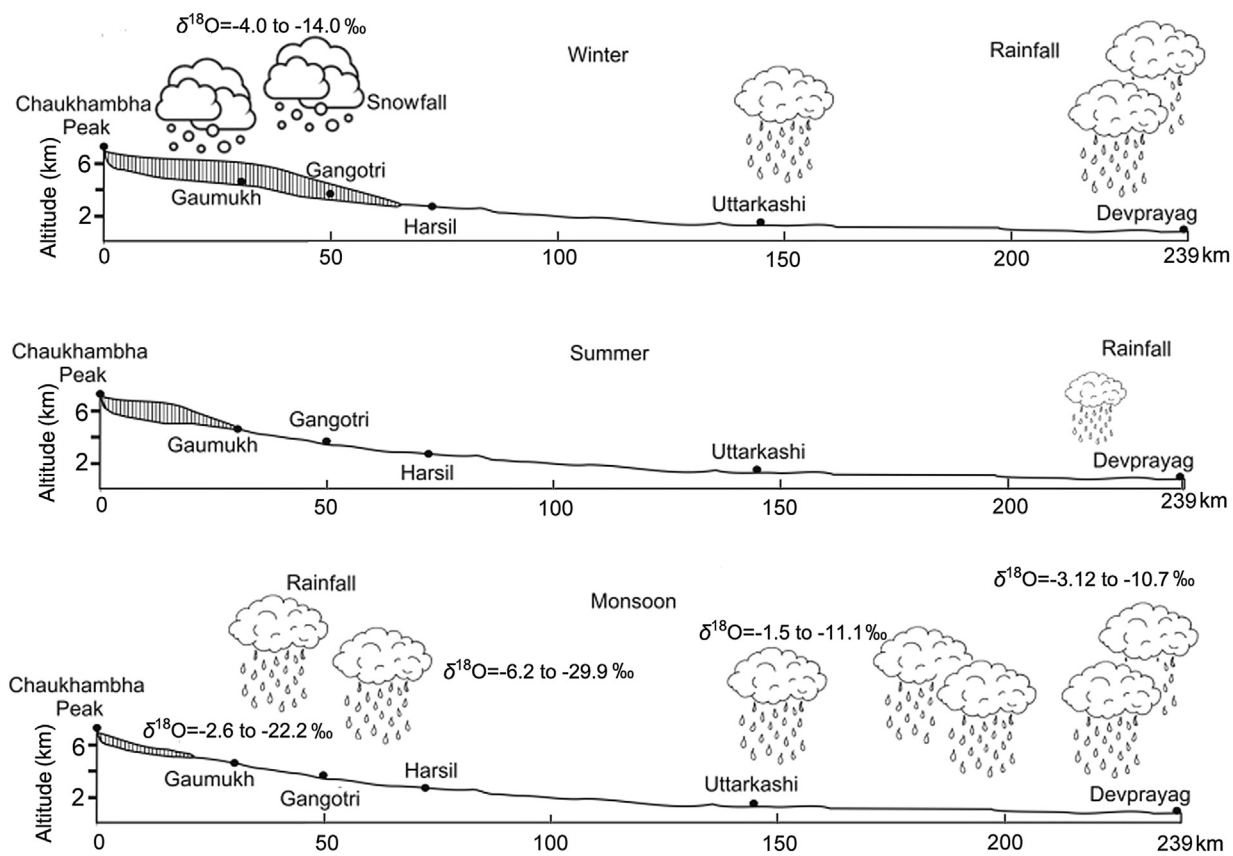

Figure 3. A schematic diagram showing seasonal variability of precipitation with altitude. In this diagram the profile is drawn using digital elevation model on ASTER data and the isotope data is from Rai et al. (2009) and Kumar et al. (2010). Note the ambient condition dependent variability of precipitation as liquid or solid at same locations and more heavy oxygen depleted liquid precipitation during summer at higher altitudes.

Table 3
Selected results of electrical conductivity and oxygen isotopes values of Bhagirathi river from Gaumukh to Devprayag during pre- and post-monsoon.

Location name	Electrical conductivity (μs/cm)		δ^{18}O (‰)	
	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon
Gaumukh	162	55	−13.5	−14.6
At Gangotri from Bhagirathi river before confluence with Kedar Ganga tributary	120.3	62.1	−13.2	−14.2
At Gangotri from Bhagirathi river after confluence with Kedar Ganga tributary	133.6	60.5	−13.1	−14.5
At Harsil from Bhagirathi river before confluence with Kakora Gad and Jalandhari tributaries	155.7	84.2	−12.5	−13.7
At Harsil from Bhagirathi river after confluence with Kakora Gad and Jalandhari Gad tributaries	155.2	81.2	−12.0	−13.2
At Uttarkashi Town, Bhagirathi river	132.3	87.2	−11.4	−12.3
Devprayag, before confluence with Alaknanda river	151.6	86.7	−10.5	−11.4

of variation at Gaumukh and Gangotri was similar (Fig. 2). Reason for this seasonal variability of precipitation, in a terrain with high altitudinal variation, can be understood by the schematic diagram given in Fig. 3. It is evident that higher air temperature during summer causes liquid precipitation of highly ^{18}O depleted water while at same altitude, significantly less depleted snow precipitation takes place when the air temperature is lower during winter. Moderate to heavy rainfall is reported in the upper Ganga basin with the average annual precipitation for the entire basin to be ~1100 mm (Khan et al., 2015). In the pre-monsoon discharge, the surface run-off component will largely be from winter snow melt while in post-monsoon discharge the precipitated rain is likely to constitute the dominant part of the surface run-off. Since the isotopic composition of post-monsoon rain is distinctly different, an assessment based on uniform surface-run off criteria is likely to lead to erroneous calculation. It is, therefore, of great significance to choose the appropriate end-member compositions prior to applying the hydrograph separation equations.

4. Sampling and analysis

Detailed pre- and post-monsoon sampling along the entire course of the Bhagirathi river was carried out. The sample location points are indicated in Fig. 4. At each location more than one sample was collected. Water samples were collected about 1 to 2 m away from the bank of the river and at a depth of around 0.5 to 1 m. Electrical conductivity and total dissolved solids were measured onsite using YSI pro Conductivity/TDS Meter. Separate water samples were collected for oxygen isotope analysis in 15 mL, narrow Tarson bottles, rinsed with ambient water several times before collecting the samples, sealed to avoid evaporation, contamination or mixing with atmosphere. Samples were analyzed by a Finnigan Mat Delta Plus XP continuous flow mass spectrometer at DST-IIT National Stable Isotope Facility at IIT Kharagpur. All isotopic data are reported against SMOW. One set of pre- and post-monsoon samples were also analyzed at the National Center for Antarctic and Ocean Research, Goa.

5. Oxygen isotope and EC data

Pre- and post-monsoon δ^{18}O data and corresponding electrical conductivity values from selected locations from Gaumukh to Devprayag are detailed in Table 3 and plotted in Fig. 5. There is a decrease in δ^{18}O values from Gaumukh to Devprayag (Fig. 5a) and the post-monsoon river water is more depleted in the heavier oxygen isotope. The range of δ^{18}O values for glacial ice varies from −12.9‰ for pre-monsoon to −15.6‰ for post-monsoon. The EC is high during pre-monsoon and low during post-monsoon all along the Bhagirathi river and shows a moderate inverse relation with δ^{18}O values (Fig. 5a and b).

6. Evaluation of existing glacial melt fraction in the Bhagirathi river

At the outset it is interesting to analyze the available glacial melt estimate using oxygen isotopes wherein ~30% of the discharge at Rishikesh was considered to have been by glacial melt (Maurya et al., 2011). Annual water flow of Bhagirathi river at Gaumukh is approximately 1 km^3. At midstream it increases to 4.2 km^3. Further downstream at Devprayag it is 6.3 km^3 (Chakrapani and Saini, 2009). Considering a specific gravity of 0.9 the Bhagirathi discharge in ice equivalent works out to be 6.93 km^3. If we assume the figure of ~30% for glacial melt fraction for the Bhagirathi basin (which is upstream of Rishikesh) then 30% of 6.93 km^3 ice is required to be melted within the Bhagirathi basin. Total glacierized area of the Bhagirathi basin is 755.47 km^2 out of which the area of

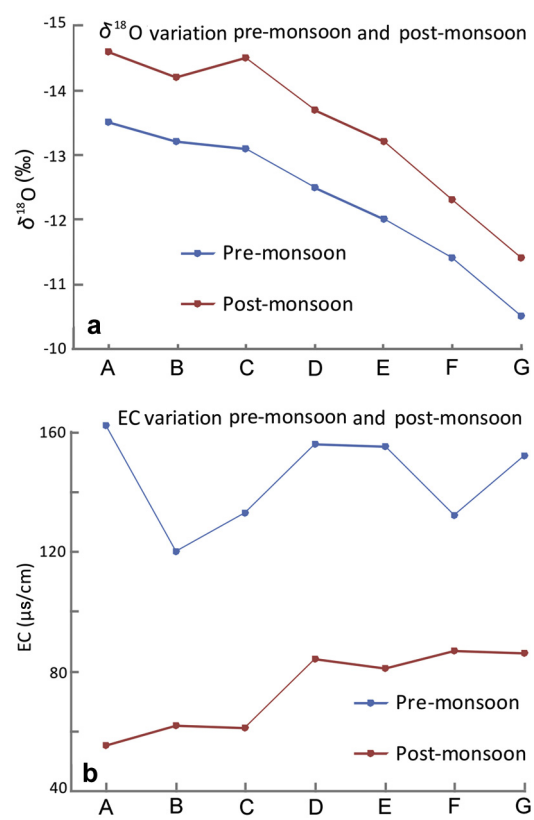

Figure 5. Graph showing variation of (a) δ^{18}O value and (b) electrical conductivity value of Bhagirathi river from Gaumukh to Devprayag during pre-monsoon and post-monsoon period. A–at Gaumukh, B–at Gangotri before the confluence of a tributary, Kedar Ganga, C–at Gangotri town after the confluence of a tributary, Kedar Ganga, D–at Harsil before the confluence of two tributaries namely Kakora gad and Jalandhari gad, E–at Harsil after the confluence of two tributaries namely Kakora gad and Jalandhari gad, F–at Uttarkashi, G–at Devprayag.

Table 4
Selected end member components used for estimating the glacial melt fraction in Bhagirathi basin during pre- and post-monsoon.

End members	$\delta^{18}O$ (‰)	Reference	Electrical conductivity (μs/cm)	References
Glacier ice melt (δ_I)	−15.6	This work	$E_I = 115$	Lambs, 2000
Ground water (δ_G)	−8.6	This work	$E_G = 330$	This work
Surface run off pre-monsoon (δ_R)	−10.7	This work	$E_R = 50$	Maurya et al., 2011
Surface run off post-monsoon (δ_R)	−11.1	This work	$E_R = 50$	Maurya et al., 2011

Gangotri glacier is 143.58 km^2. Thus, 19% of the total ice covered area of the Gangotri is represented by the Gangotri glacier for which detailed measurements of 60 years are available. Using topographic sheets, surveying records and satellite imagery data it has been estimated that the Gangotri glacier has vacated 578,100 m^2 in 61 years (1935–1996) (Srivastava, 2012) which implies an annual retreat of 9477 m^2. If the retreat rate of Gangotri glacier is projected over the entire glacierized area of Bhagirathi Basin, then the annual ice retreat for the Bhagirathi basin works out to be 0.0502 km^2 (0.009477 km^2 × 5.3; multiplication factor of 5.3 is derived by normalizing the Gangotri glacier area over the glacierized area of the entire Bhagirathi basin i.e. (100/19) = 5.3). If the entire 30% glacial melt is attributed only to the average annual retreat area, the annual vertical ice loss in Bhagirathi basin works out (h = volume/area) to 41.2 m (2.06 km^3/0.0502 km^2). However, it will be more rational to consider that the vertical ice loss or thinning took place in the entire ablation area. The total area occupied by the ablation zone in the Gangotri glacier is 92.48 km^2 (64.41% of total glacierized area; Srivastava, 2012). Considering 64% of the entire glacierized area in Bhagirathi basin, the average annual vertical thinning (h = volume/area) works out to 4.26 m (2.06 km^3/483.50 km^2) and if thinning is ascribed to the entire glacierized area (a limiting case of minimum thinning rates) then this number is 2.73 m yr^{-1}. However, the reported maximum annual thinning rate of Himalayan glaciers ranges from 0.32 ± 0.08 to 0.79 ± 0.52 m yr^{-1} (Benn et al., 2012). Highest thinning rates for the Gangotri glacier have been reported as ~1.5 m yr^{-1} (Dong et al., 2013). However, even these are still nearly half of the minimum limited thinning rates estimated using the existing melt fraction data as demonstrated above.

7. End member components

The apparent overestimation of glacial melt fraction can be ascribed to two factors: (1) unsuitable choice of end members; (2) not distinguishing between pre- and post-monsoon characteristics of precipitation.

The present work is based on a three-component mixing model. These are glacial melt, surface runoff and ground water contributions to the Bhagirathi river. Selected end members for three component mixing model calculations are listed in Table 4. Considering that the most depleted value of $\delta^{18}O$ during the pre- and post-monsoon represents glacial ice melt we have chosen ($\delta_I = -15.6$‰). The glacier ice is highly charged with ions due to long time storage and contact with the ground (Lambs, 2000). Following his study we have used the electrical conductivity of ice ($E_I = 115$) as an end member for our calculations.

The surface runoff comprises three main components namely snow melt in winter, rainfall runoff during monsoon and the post-monsoon interflow. Solid precipitation in the Himalayan region occurs in the form of snow during October to March in high altitude regions including at glaciers. Snow melt is the only major component of surface runoff during pre-monsoon period from November to May but during monsoon and post-monsoon period liquid precipitation in the form of rainfall forms the dominant contribution of the surface runoff. The $\delta^{18}O$ value of snow at Bhujwasa near Gaumukh varies generally from −4.0‰ to −14.0‰ (Rai et al., 2009). Average of this $\delta^{18}O$ value of snow melt ($\delta_R = -10.7$‰) is, thus, reasonable as an end member value of surface run off during pre-monsoon period. The electrical conductivity of snowmelt (46.3 μs/cm) is very close to rain value (43.4 μs/cm) (Lambs, 2000). Thus, EC value of surface runoff, $E_T = 50$ μs/cm, is taken as an end member in our calculation. The $\delta^{18}O$ values of rainfall varies significantly (−2.6‰ to −22‰ at Gaumukh in 2004) temporally and spatially as discussed earlier (Fig. 3). As an end member value of $\delta^{18}O$ of surface runoff during post-monsoon, we consider the average value of rain fall from July to September for the two years i.e. during 2004 and 2006 ($\delta_R = -11.1$‰). Since the rainfall oxygen isotope values for the year 2005 are erratic (Kumar et al., 2010) these have been excluded for the calculation of average δ_R.

The EC values of ground water also varies significantly from 147 μs/cm at Gangotri to 562 μs/cm at Devprayag during pre-monsoon and from 152 μs/cm at Gangotri to 564 μs/cm at Devprayag during post-monsoon. Considering that there is no significant change in EC value of ground water during pre- and post-monsoon ground water is recharged either by snowfall or rainfall and both have almost similar EC (Lambs, 2000) we chose an average of the EC value of ground water samples from Gangotri to Devprayag ($E_G = 330$ μs/cm) as an end member for calculation.

8. Conclusions

After giving due consideration to above and using the end members as discussed in the preceding section, our estimations are presented in Table 5. Our estimates indicate glacial melt fraction at the exit of Bhagirathi basin (Devprayag) to be 11% considering pre-monsoon data and 12% considering post-monsoon data. There is a general decreasing depletion of glacial melt component observable downstream from the glacier snout (Table 4). Glacial melt fraction decreases from the snout of the Gangotri glacier to Devprayag during the pre-monsoon and the post-monsoon period, whereas surface run off in the form of snow melt is the major fraction during the pre-monsoon and in the form of rainfall during the post-monsoon period in the Bhagirathi river. Ground water contribution varies significantly from around 35% during pre-monsoon to around 11% during post-monsoon. Our results indicate that ground water contribution is altitude and seasonal dependent being almost negligible at Gangotri during post-monsoon and maximum at Devprayag during pre-monsoon period. Thus, it shows an inverse relationship with the altitude i.e. higher the altitude lower the ground water contribution and lower the altitude higher the contribution of ground water. It is also possible that the ground water recharges mainly from monsoonal rainfall, and during monsoon and post-monsoon period the river discharge is

Table 5
Estimated pre- and post-monsoon glacial melt fraction at selected locations from Gaumukh to Devprayag along the Bhagirathi course.

Location	Glacial melt fraction pre-monsoon (%)	Glacial melt fraction post-monsoon (%)
Gangotri town	57	55
Harsil town	45	52
Uttarkashi	26	29
Devprayag	11	12

dominated by the rainfall. The ground water contribution to river discharge is higher before the onset of monsoon.

Our calculations imply a thinning of $\sim$1.3 m yr^{-1} if thinning is ascribed to the entire glacierized area of the basin which is within the range of reported thinning rates for this basin (Dong et al., 2013). The earlier reported higher values of glacial melt fraction at Rishikesh (e.g. Maurya et al., 2011) are not consistent with the reported thinning rates. Consideration of variability of the isotopic composition of the end-member components and strong seasonal control on the nature of precipitation allows a realistic inference of melt fraction in a three-component mixing model.

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