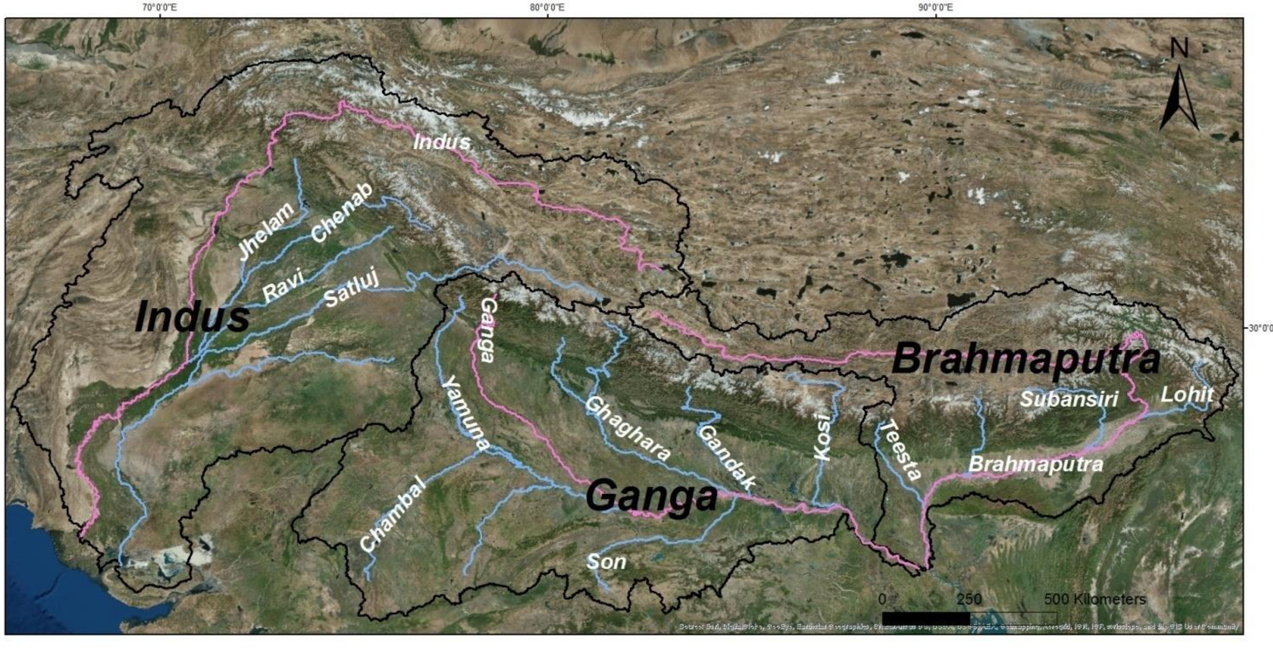
The Water budget of the Himalayan river system–gaps and the strategic significance of Cryosphere and Hydrosphere…….

Dr. Abul Amir Khan

Department of Geology
University of Delhi

Water Tower of Asia

- Himalaya and adjacent mountains- Water tower of Asia
- Source of major Asian rivers- Yellow, Yangtze, Irrawaddy, Mekong Indus, Ganga, Brahamaputra etc
- More than 1.4 billion people depend on water from these basins (Immerzeel et al., 2012)



- Collectively provide close to 50% (320 Km^3) of the total country's utilizable surface water resources (690 Km^3).

- Almost 800 million people live in the catchments of Indus, Ganga and Brahmaputra rivers.

- Hydrological budget – controlled by Precipitation.

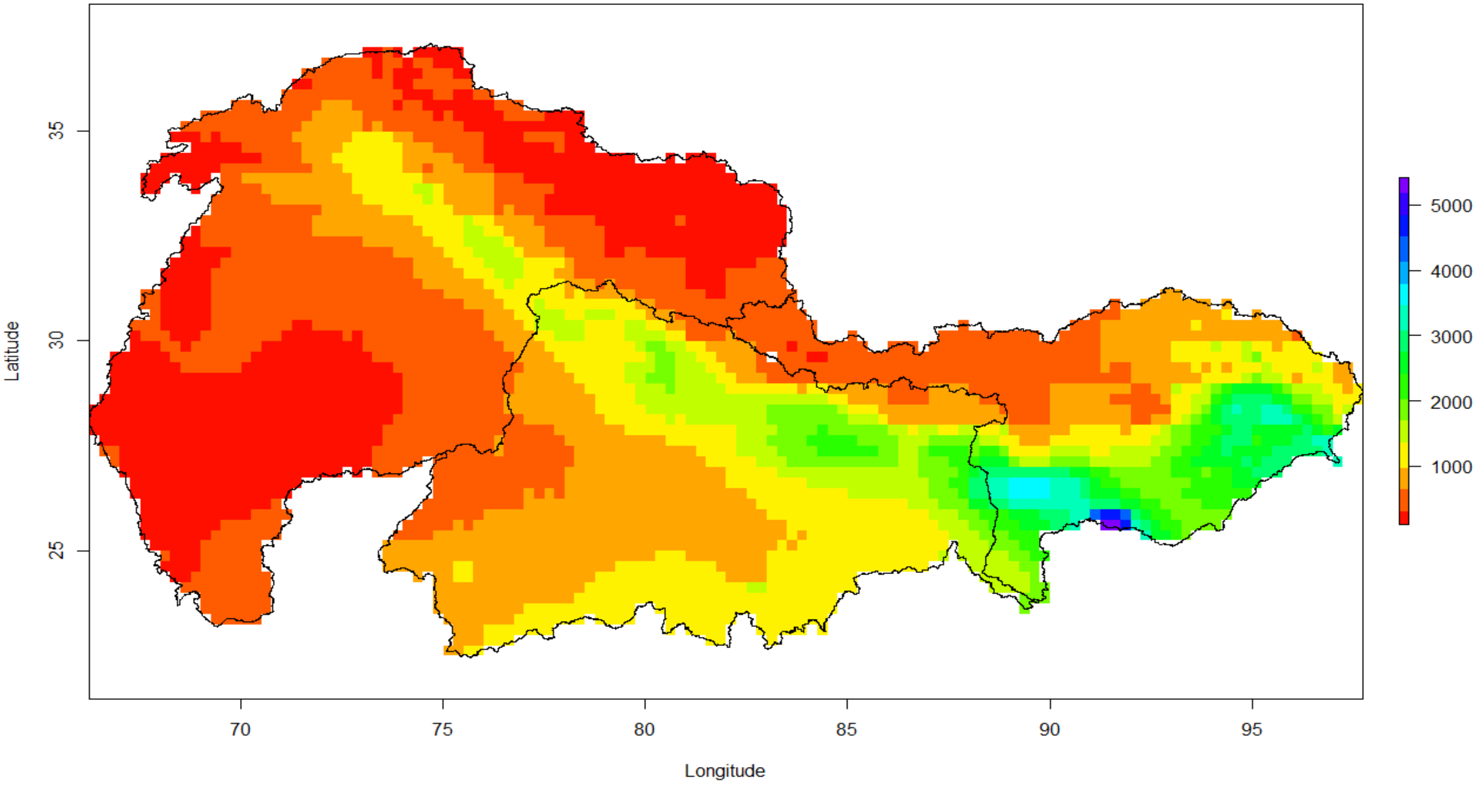
Reported Average Annual Precipitation (mm) of three major Basins

Indus (mm/year)	Ganga (mm/yr)	Brahmaputra (mm/yr)	References
423	1035	1071	Immerzeel et al. (2010)
1097	1051	2589	Jain and Kumar (2012)
405	1118	1145	Kaser et al. (2010)

Variability in the Average Annual precipitation estimates

	Difference	Variability
Indus basin	692 mm	~250%
Ganga basin	83 mm	~100%
Brahmaputra basin	1518 mm	~240%

Indus (mm/yr)	**Ganga (mm/yr)**	**Brahmaputra (mm/yr)**	**References**
423	1035	1071	Immerzeel et al. (2010)
1097	1051	2589	Jain and Kumar (2012)
405	1118	1145	Kaser et al. (2010)
413	**1081**	**1460**	**Khan et al. 2018**



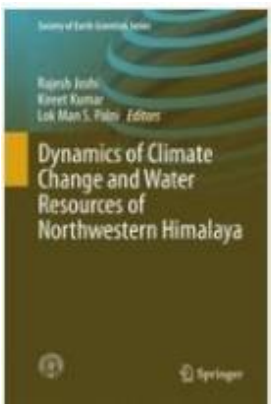
Average annual TRMM derived precipitation map 2001-2010.

Dynamics of Climate Change and Water Resources of Northwestern Himalaya pp 67-84 | Cite as

Critical Evaluation and Assessment of Average Annual Precipitation in The Indus, The Ganges and The Brahmaputra Basins, Northern India

Abul Amir Khan, Naresh C. Pant, Anuj Goswami, Ravish Lal and Rajesh Joshi

Abstract Three major river basins of India which include the Indus, the Ganges and the Brahmaputra contribute more than 50 % of the river discharge of the country. Widely varying average annual precipitations have been reported for these basins. The average annual precipitation is a basic input data for any developmental planning. Low density of rain gauge stations especially in mountainous area, extreme variation in altitudes and large size of these basins forces adaption of remote sensed data for estimation of average annual precipitation. In the present study, 11-years (2000–2010) Tropical Rain Measurement Mission (TRMM) generated radar precipitation raw data has been used for estimating the annual precipi-



A precipitation perspective of the Hydrosphere-cryosphere interaction in the Himalaya

ABUL AMIR KHAN[1], N. C. PANT[1]*, RASIK RAVINDRA[2], APURVA ALOK[1], MANIKA GUPTA[1] & SHIKHA GUPTA[1]

[1]*34, Chhatra Marg, Department of Geology, University of Delhi, Delhi, 110007*

[2]*Ministry of Earth Sciences, Lodhi Road, New Delhi, 110003*

**Correspondence: pantnc@gmail.com*

Abstract: The hydrological budget of the three major Asian rivers, namely the Indus, the Ganga and the Brahmaputra, is controlled by the Indian monsoon and Westerlies but their contribution in these basins are highly variable. Widely varying average annual precipitation has been reported within these basins. A poor network of *in situ* rain gauges, particularly in mountainous regions, inaccessible terrain, high variations in altitude and the significantly large size of basins forces adaption of satellite-based average annual precipitation. We investigate precipitation patterns for these three basins by using satellite-based Tropical Rainfall Measuring Mission (TRMM-3B42) data and compare and validate it with Asian Precipitation Highly Resolved Data Integration Towards Evaluation (APHRODITE) and India Meteorological Department (IMD) interpolated gridded precipitation data. The entire basins as well as basinal areas within the geographic limits of India have been considered. Our study shows that the precipitation broadly follows an east–west and north–south gradient control. The easternmost Brahmaputra Basin has the highest amount of precipitation followed by the Ganga Basin, and the westernmost Indus Basin has the least precipitation; precipitation is highest on the higher elevations than compared to lower elevations of the basins. A seasonal- and elevation-based approach is adapted to estimate snow precipitation and is discussed in terms of overall precipitation.

The hydrosphere refers to all types of water, marine, frozen, river water and groundwater or water under the surface of Earth. Marine water represents the dominant component (over 97%) of hydrosphere on Earth, but the remaining *c.* 2.9% fresh water is of immense significance to mankind as it is essential for human survival. The cryosphere, representing *c.* 2.4% of total water and 75% of fresh water (Kotwicki 2009), constitutes an important subset of the hydrosphere and plays a significant role in the global climate system as it is the second-largest store of water after the ocean (Barry 1987, 2002). It has potential to cause a rise in sea level of 75.6 m with the maximum from the Antarctic ice sheet (68 m) followed by the Greenland ice sheet (7 m), and the remaining 0.6 m from the non-ice-sheet glaciers (Williams & Ferrigno 2012). The cryosphere is also a sensitive indicator of regional climate change (Kang *et al.* 2010), but there is a variability and lack of primary data on glaciers and snow cover, especially in the tropical regions. The Himalayan cryosphere represents a major non-ice-sheet cryosphere domain (Dyurgerov 2001). Field studies in the Himalayas (especially in the Himalayan cryosphere domain) can only be carried out in a limited way on account of its remoteness, vastness, variability and inaccessibility. Remotely sensed data therefore play an important role and have been increasingly used in recent times in this area (e.g. Bookhagen & Burbank 2010; Immerzeel *et al.* 2010; Kulkarni *et al.* 2011; Scherler *et al.* 2011; Bolch *et al.* 2012; Gardelle *et al.* 2012). In the natural hydrological system, precipitation is an important component, especially in the tropics. Glaciers are strongly controlled by precipitation and the Himalaya demonstrates a variability in precipitation across its length (Khan *et al.* 2017). The Himalaya and the adjacent regions act as an orographic barrier and control the distribution of precipitation due to high and variable relief/topography (Andermann *et al.* 2011). The Himalayan mountains and the adjoining Tibetan plateau are considered the water towers for Asia and are the source of major Asian rivers, supporting a population of more than one billion people (Ives & Messerli 1989). In mountainous regions topography affects the regional precipitation pattern through orographic barriers (Roe *et al.* 2003; Roe 2005; Bookhagen & Burbank 2006; Bookhagen & Strecker 2008). The precipitation distribution in mountainous regions can also change significantly within a short distance and over a short time period (Anders *et al.* 2006). The hydrological budget of the high-altitude regions of these major river basins is influenced by rainfall and snowmelt (Bookhagen & Burbank 2010). The three major river basins, namely the Indus, the Ganga and the Brahmaputra (Fig. 1), cover *c.* 50%

From: PANT, N. C., RAVINDRA, R., SRIVASTAVA, D. & THOMPSON, L. G. (eds) *The Himalayan Cryosphere: Past and Present*. Geological Society, London, Special Publications, **462**, https://doi.org/10.1144/SP462.2

Reported Data on Glacial melt

Basin	Glacier melt (%)	References
Indus	26	Immerzeel et al., 2010; Immerzeel and Bierkens, 2012
	44.8	Jianchu et al., 2009
Ganga	3.1	Immerzeel et al., 2010; Immerzeel and Bierkens, 2012
	9.1	Jianchu et al., 2009
Brahmaputra	<10	Immerzeel et al., 2010; Immerzeel and Bierkens, 2012
	12.3	Jianchu et al., 2009

	Difference	Variability
Indus	18.8%	>170%
Ganga	6%	~300%
Brahmaputra	<2.3%	~100%

Over estimation of glacial melt water (Schaner et al., 2012)

Global hydrology model and glacier energy balance

Existing glaciers melt contribution to river discharge are either shown overestimation or simply wrong.

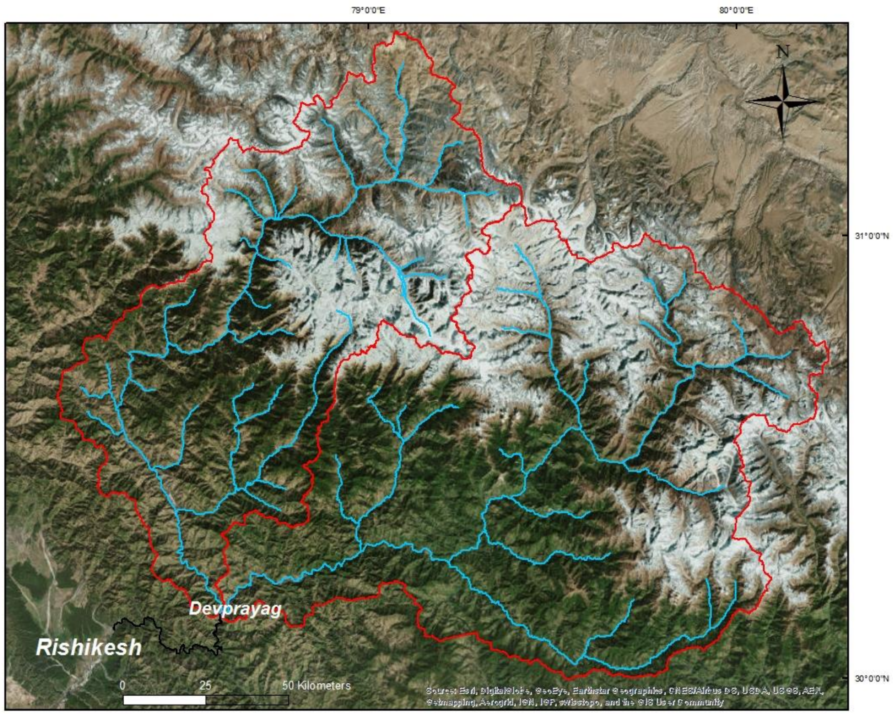
Comparison of published and calculated glacier melt fraction.

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	3.2
		(Xu et al., 2009)	
North Saskatchewan River at Edmonton, Alberta, Canada	WATFLOOD, Hydrological model	9.33 (1975–1998) (Comeau et al., 2009)	6.0
	WATFLOOD, Hydrological method	41 (1993–2003)	
Bow River at Calgary, Alberta, Canada			
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

One sixth of the world's population resides in areas that rely on snow or glacier melt for a major of its water supply (Barnett et al, 2005).

Available estimate for the Upper Ganges

(Maurya et al. 2010) (at Rishikesh)



Total Contribution of glacial ice melt to the stream discharge peaks during summer and monsoon, reaching a maximum value of apprx.40% with an average of 32%.

Bhagirathi basin...

- In this Basin Gangotri glacier is drained.
- One of the Largest and fastest retreating Glacier in Himalaya.
- More than 100 years retreat data available.

Reverse Calculation of ice volume and thinning in Bhagirathi Basin

- Total Glacierzed Area = 755.47km^2
- Area of Gangotri Glacier = 143.58 km^2
- % of Glacierzed Area (of total glacier area) represented by Gangotri Glacier in Bhagirathi Basin = 19 %
- Total Area Vacated by Gangotri (1935-1996) in 61 years = 5,78,100m^2
- Area vacated by Gangotri glacier in one year=9477 m^2
- Annual Areal retreat in Bhagirathi Basin = 9477m^{2}x 5.3 = 0.0502km^2.
- Average Annual flow of Bhagirathi River at Devprayag =6.3km^3
- Bhagirathi discharge in ice equivalent= 6.87km^3
- 30% of Bhagirathi discharge ice equivalent=2.06km^3

Basic data Source: GSI, DST Status Report on Gangotri Glacier and Chakrapani (2009)

- **Annual average vertical Loss,** h = (Volume /area) =2.06km^3/0.0502 m^2= **41.2 m**

- This vertical thinning from the retreated area of the Bhagirathi basin.

- Ablation area of the Gangotri glacier is 92.48 km^2 which is 64% of total glacerized area of Gangotri.

- Considering 64% of the entire glacierized area in Bhagirathi basin, the average annual thinning (h = volume/area) works out to 4.26 m (2.06km^3/483.50 km^2)

- However, the reported maximum annual thinning rate of Himalayan glaciers ranges from 0.32 ±0.08 to 0.79 ± 0.52 m /yr (Benn et al., 2012).

Highest thinning rates for the Gangotri glacier have been reported as ~1.5 m/yr (Dong et al., 2013).

- Thus, existing estimates do not appear to be correct !!!!

Mixing Model:

A three component mixing model using the values of δ^{18} O and electrical conductivity(EC)

Major contributors in stream flow

(1) Surface run off- Snowmelt and rainfall

(2) Glacial ice melt

(3) Ground water discharge

I + G + R = T ……… (1)

I - Ice melt
G - Ground water
R – Surface Runoff
T – Total Discharge

i + g + r = 1 ……. (2)

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

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

Using these Values of g and r, we can calculate the Value of i by putting these Values in Eq. (2).

Glacial Melt Calculation for the Bhagirathi basin end members

- **Glacial Ice end member δ_I =**–15.6‰
- **Ground Water δ_G** =–8.6 ‰
- **Surface run off (Precipitation) δ_R** =–10.7 ‰(Pre-monsoon)
- **Surface run off (Precipitation) δ_R** =–11.1 ‰(Post-monsoon)
- **Glacial Ice E_I** =115 (Lambs, 2000)
- **Ground Water E_G** =330
- **Surface runoff (Precipitation) E_R** =20

Glacial melt Calculation for the Alaknanda basin end members

- **Glacial Ice end member δ_I =** –16.7‰
- **Ground Water δ_G** =–7.8‰
- **Surface run off (Precipitation) δ_R** =–8.21 ‰(Pre-monsoon)
- **Surface run off (Precipitation) δ_R** =–11.1 ‰(Post-monsoon)
- **Glacial Ice E_I** =115 (Lambs, 2000)
- **Ground Water E_G** =300
- **Surface runoff (Precipitation) E_R** =20

Results

Location	Pre-monsoon			Post-monsoon		
	Surface runoff (%)	Ground water (%)	Glacial melt (%)	Surface runoff (%)	Ground water (%)	Glacial melt (%)
Bhagirathi basin	50	39	**11**	70	17	**13**
Aalknanda basin	61	31	**8**	64	26	**10**
Upper Ganga up to Rishikesh	60	30	**10**	65	24	**11**

These estimates closely matches with the reported ice thinning rates of the Himalaya (~1.2 m/year).

Cause of Glacial melt over estimation

Most depleted heavier isotopes value represent glacial Ice

Location	$\delta^{18}O$ (‰)	Sources
Gaumukh, Gangotri Glacier Ice	-18.5	Rai et al., 2009
	-15.0	Rai et al., 2009
	-14.5	Rai et al., 2009
	-15.6	Khan et al., 2017
	-15.9	This work

Ice mean $\delta^{18}O$ = -15.9 ‰

Rain fall represents pseudo glacial melt in the river

Isotopic value of rainfall in the Bhagirathi basin

	Time	$\delta^{18}O$ (‰)
Gomukh	May 2004	-2.6
	Jun 2004	-6.7
	Jul 2004	-5.5
30^0 55' 34" N	Aug 2004	-17.5
$79^0$04' 15" E	Sep 2004	-22.2
	Oct 2004	-16.5
3800 m a.s.l	Jun 2005	-6.4
	Jul 2005	-7.6
	Aug 2005	-17.2
	Sep 2005	-11.8
	May 2006	-30.3
	Jun 2006	-8.4
	Jul 2006	-13.4
	Aug 2006	-15.3
	Sep 2006	-17.6

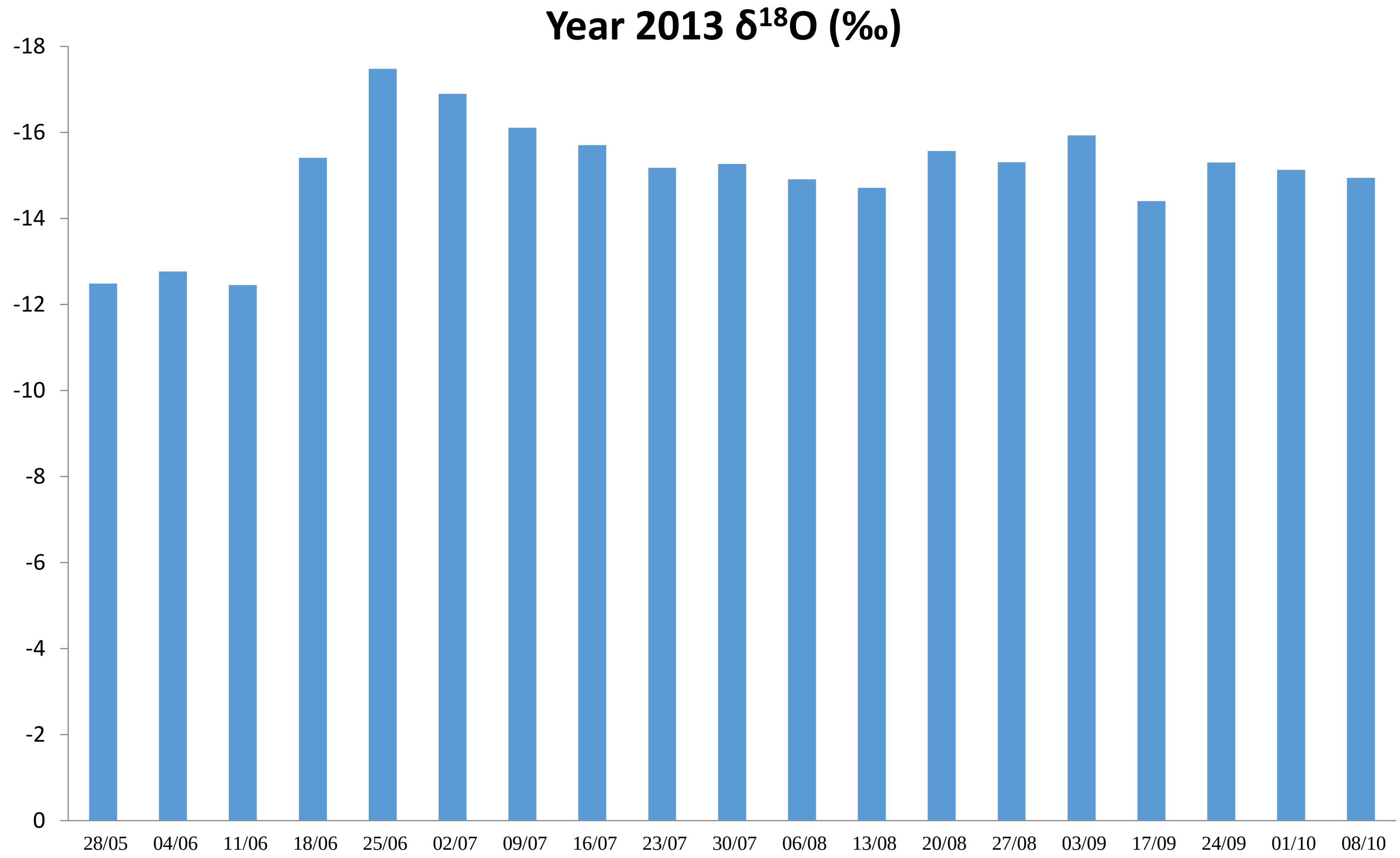
	Time	$\delta^{18}O$ (‰)
	01 Aug 2013	-12.9
	08 Aug 2013	-16.8
Bhojwasa	13 Aug 2013	-30.7
	19 Aug 2013	-19.3
	23 Aug 2013	-15.8
	28 Aug 2013	-16.8
	31 Aug 2013	-16.6
	01 Sep 2013	-16.8
	09 Sep 2013	-3.2
	11 Sep 2013	-16.5
	27 Sep 2013	-15.2
	1 Oct 2013	-16.7

Rainfall mean $\delta^{18}O$ = -18.3‰

Kumar et al., 2010

	Time	$\delta^{18}O$ (‰)
Gangotri	May 2004	-6.2
	Jun 2004	-7.6
	Jul 2004	-6.7
	Aug 2004	-14.6
30^0 59' 48" N	Sep 2004	-19.9
$78^0$56' 25" E	Oct 2004	-17.4
3053 m a.s.l	Jun 2005	-1.8
	Jul 2005	-17.6
	Aug 2005	-9.3
	Sep 2005	-28
	May 2006	-3.1
	Jun 2006	-4.8
	Jul 2006	-9.9
	Aug 2006	-16.3
	Sep 2006	-12.4

$\delta^{18}O$ (‰) value at Bhojwasa from the Bhagirathi river



Geoscience Frontiers 8 (2017) 107–115

HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

GEOSCIENCE FRONTIERS

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

Research paper

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

CrossMark

Abul Amir Khan [a], Naresh Chandra Pant [a,*], Anindaya Sarkar [b], S.K. Tandon [c], Meloth Thamban [d], Mahalinganathan K. [d]

[a] Department of Geology, University of Delhi, New Delhi 11007, India
[b] Department of Geology and Geophysics, Indian Institute of Technology, West Bengal 721302, India
[c] Department of Earth Science, Indian Institute of Technology, Kanpur, Uttar Pradesh 208016, India
[d] Department of Cryosphere Science, National Centre for Antarctic and Ocean Research (NCAOR), Ministry of Earth Sciences, Government of India, Headland Sada, Vasco-da-Gama, Goa 403804, India

A R T I C L E I N F O

Article history:
Received 13 August 2015
Received in revised form
23 November 2015
Accepted 20 December 2015
Available online 23 January 2016

Keywords:
Cryosphere
Glacial melt fraction
Bhagirathi river
Oxygen isotope

A B S T R A C T

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.

Current Status of Himalayan Cryosphere and Adjacent Mountains

Abul Amir Khan*, N C Pant•, Rasik Ravindra•

ABSTRACT

Hindu Kush- Karakoram- Himalaya (HKH) region represents one of the major non-polar cryosphere domains on the Earth. This region feeds three major rivers namely: the Indus, the Ganga and the Brahmaputra and supports a huge population of more than 1 billion people. There is wide variability and uncertainty in data on most aspects of this Cryospheric domain. The behavior of glacial melting in HKH region is highly heterogeneous with the highest negative mass balance in the Eastern Himalaya, relatively less negative mass balance in the western Himalaya with positive mass balance in the Karakoram. The hydrological budget of the higher Himalayan rivers depends on the precipitation (snowfall and rainfall) but the available estimates on snow cover and rainfall are highly variable and in few cases appear to be unacceptable. Reported precipitation variability for the Indus basin is more than 250%, for the Ganga basin it is 100% and for the Brahmaputra basin the variability is more than 240%. The estimate on glacial cover and its volume in the Himalayan-Karakoram regions shows variability of more than 130% and 250% respectively. The available estimates on the glacial melt fraction also show high variability, for example for the Indus basin the variability is ~170%,

*Department of Geology, University of Delhi.
•Corresponding author
•Former Chair, Panikkar Professor, Ministry of Earth Sciences, New Delhi.
Email- pantnc@gmail.com

Springer

http://www.springer.com/978-3-319-57764-7

Science and Geopolitics of The White World
Arctic-Antarctic-Himalaya
Goel, P.S.; Ravindra, R.; Chattopadhyay, S. (Eds.)
2018, XIII, 195 p. 60 illus., 48 illus. in color., Hardcover
ISBN: 978-3-319-57764-7

Thank you…….