Assessment and modelling of various hydrological process in small watershed of the Imphal valley, Manipur

File Number : PDF/2023/001498

Submitted By : Dr. Ningombam Prikash Meetei
[SERB Qualified Unique Identification Document: SQUID-1992-NM-4542]

Submission Date : 09-Aug-2023

PROPOSAL DETAILS

(PDF/2023/001498)

Principal Investigator	Mentor & Host Institution
Dr. Ningombam Prikash Meetei	**Surjeet Singh**
pksangom@gmail.com	ssingh_sagar@yahoo.co.in
Scientist G(Groundwater Hydrology Division)	Scientist G(Ground Water Hydrology Division)
Contact No : +919485263726	**National Institute of Hydrology** Jal vigyan bhawan, roorkee, Uttarakhand-247667
Date of Birth : 02-Feb-1992	
Name of Father/Spouse : N Dhananjoy Meetei	**Contact No.** : +919456134747 **Registrar Email** : dir.nihr@gov.in **No. of PHD Scholars** : 0 **No. Post-Doctoral Fellow** : 0

Details of Post Doctorate

Ph.D. (Applied Geology) [Not yet Awarded. Thesis Submitted On : 08-Jun-2023]

Assessment of Snow and Glacier melt runoff in Pindar River, Central Himalaya, India using isotope and modelling approach

Research Supervisor/Guide & Institution :

Prof. S. Sarangi, Dept of Applied Geology, IIT(ISM), Dhanbad
Dr. Rajeev Saran Ahluwalia, External co-guide, Doon University
Dr. S P Rai, External Co-guide, Banaras Hindu University

Indian Institute of Technology (Indian School of Mines), Dhanbad

Brief details of Thesis work :

The Himalaya has one of the largest concentrations of snow/glacier outside the polar region. It is called third pole because its snow/glacier reserve is the largest fresh water outside the polar region. The Himalaya acts as a great climatic divide, which effects the large system of air and water circulation. Meteorological conditions of the entire Indian sub-continent and central Asian highlands to the north is generally decided by Himalaya. The Himalaya has three major divisions i.e., Outer Himalaya or Siwalik Range, Lesser Himalaya and Greater Himalaya Range. The Greater Himalaya Range is the backbone for snow/glacier because of its height and favorable condition for the deposition of snow/ice. The great Himalayan Range acts as a barrier for the cold continental air moisture source from the north into India as well as for the Indian Summer Monsoon (ISM), which gives all the rain during the monsoon season in India. The Himalayan Region experiences mainly two precipitation seasons in the winter and summer with the westerlies and ISM moisture sources respectively.
In this study an integrated approach was applied to assess the snow/glacier melt runoff in the Pindar River basin, central Himalaya. A detailed study on snow cover mapping in Pindar River basin was carried out using a continuous data set of Moderate Resolution Imaging Spectroradiometer (MODIS) snow products from 2005 to 2016.Snowcover depletion curves (SDC) were also created using snow cover maps. These SDC are being used as input for snowmelt runoff modelling. During the study period, average snow cover area (SCA) achieves a high of ~51.26 to ~53.30 % in February and March and a low of ~9.35 to ~11.34 % in July and August. SCA start to increase from September onwards in the basin as the wind becomes colder due to the monsoon withdrawal. Between December and January, there is a significant difference in SCA between December and January. It ranges from ~33. 90 % to ~48.09 %, with a 15 % difference. In the Pindar River Basin, SCA is found to be ~34.75 % (maximum) in January and ~5.66 % (minimum) in August. Snowmelt runoff modelling was carried out using the SNOWMOD model. The model was calibrated for the period of four years and then it was run to simulate the daily flows for the Pindar River at Karanprayag. The model efficiency was calculated using daily simulated and observed flow levels. The difference of volumes of estimated and observed streamflow were range from -3.49 % to -8.96 % for the simulation period, while R2 ranged between 0.88 and 0.94. Throughout the study period, the model overall efficiency (R2) was 0.88, and the significant difference between estimated and observed streamflow volume (DV) was -7.21% with RMSE value of 0.34. The model has the capability to differentiate the contribution of base flow, rainfall, and snow/glacier melt from the simulated flows. Ther rain events are accountable for all of the high peaks in streamflow, but snowmelt is also responsible for sustaining the high flow. According to the findings, the contribution of snow /glacier melt runoff come out to be ~33.16 %, ~33.91 %,~32.45 %, ~34.01 %, ~33.38 %,~33.20 %,~33.32 %,~33.57 % , ~35.09% and ~31.75 % in the years 2005-2006,2006-2007,2007–2008,2008–2009,2009-2010,2010–2011,2011-2012,2013 2014,2014-2015 and 2015-2016 respectively, with an average of ~33.38 % of snow /glacier melt runoff in the Pindar River at Karanprayag.
Isotopic characteristics of the snow, rainfall and river water was also developed for the Pindar River basin. The Pindar River water samples were collected from March 2017- March 2019. During the summer season, samples of river water were taken daily, but in the winter season, samples of river water are taken weekly. Along the course of the Pindar River, three sites were chosen based on their elevation. These sites are Khati, Nandakeshri and Karanprayag. Hydrograph separation was carried out using isotope technique. The results of hydrograph separation were estimated that snow/glacier melt contribution reaches up to ~79.63% (April). The estimated contribution of snow/glacier melt varies from ~30.83% (July) to ~33.90% (August) throughout the monsoon season. It ranges from ~17. 04 % in December to ~32.02% in March throughout the post-monsoon and winter seasons. The average contribution of snow/glacier melt is ~36.49 % of the total discharge in the Pindar River at the Karanprayag. The present study will help the researcher to expand their knowledge in the field of mountain hydrology. The hydrological model and isotopic approach used in this study will help to understand the variation of flow with the contribution of different components i.e., snow/ glacier melt, rainfall and ground water (baseflow) in the Pindar River basin, so that it can efficiently managed the water resources accordingly.
Keywords: Moderate Resolution Imaging Spectroradiometer (MODIS), Snow Cover Area, SNOWMOD, Isotope Hydrology, Pindar River Basin,Karanprayag.

Technical Details :

Research Area : Earth & Atmospheric Sciences (Earth & Atmospheric Sciences)

Project Summary :

Water is a valuable natural resource. It is a vital component of all living things. Water comes in two basic forms: surface water and ground water. The study of surface water and ground water hydrological processes is critical for a wide range of applications including household, agriculture, industry and other water related work. Water resources are under stress due to rising societal demands. The effects of climate change on various components of the water cycle are critical for sustainable management of these resources. Climate change will affect water resources through altering precipitation, time variability and intensity. Climate change influences water cycle processes in a variety of ways, with complex and dynamic properties (Liu et al., 2014). Increasing the temperature of the region can produce more precipitation, but precipitation changes can cause floods and drought (Dai, 2013). Anthropogenic activities, deforestation, urbanisation have caused significant changes in the region's climatic conditions in recent decades. Natural disasters such as flood, drought and landslides etc. have regularly encounter in the recent years. With the advancement of remote sensing and hydrological modelling tool, it helps the hydrological process and simplify the hydrological systems, forecast hydrological changes, and simulate hydrological effects and create policy for water resource management plans (Mirza et al., 2003; Zhang et al., 2017). To accomplish exact evaluations in the field of hydrological modelling, various hydrological models, such as the SWAT (Soil and Water Assessment Tool), MIKE-SHE, and VIC, have been developed in recent years (Devi et al., 2015). In this study, the SWAT model is used to investigate the hydrological process of the small watershed of the Imphal valley. Imphal valley is one the most populated region in Manipur which is surrounded by hill representing about 10% of the total geographical area of Manipur. Loktak lake, the only floating national park in the world also lies in this region. This research aims to examine the impact of climate change on comprehending the interrelationships between many complex hydrological parameters in the river basin, as well as to provide some scientific support for water resource development.

Objectives :

-
- Assessment of hydrological change in the small watershed of Imphal Valley.
- To assess the potential zone for groundwater recharge.
- Impact of climate change on the hydrological process
- Impact of land used and land cover change on the hydrological process

Keywords :
Climate Change, Hydrological Process, SWAT model, Imphal Valley

Expected Output and Outcome of the proposal :

- Provide the information on impact of climate change and interrelationships between many complex hydrological parameters in the river basin.
- Suggesting the important of groundwater recharge
- Provide the information for modification of the suitable environmental flow assessment
- Provide some scientific support for water resource development.

Reference Details :

S.No	Reference Details
1	**Dr Rajeev Saran Ahluwalia** **Doon University, Dehradun[+8937877774]** raahluwalia05@gmail.com
2	**Prof S Sarangi** **Department of Applied Geology, IIT ISM Dhanbad[+9471173190]** shushanta@iitism.ac.in

Methodology:

The SWAT model will be used to analyse the hydrological processes in the Imphal valley. The model parameters will be created using a GIS platform. ASTER DEM will be used to create the digital elevation model (DEM). A slope map will be created. Meteorological data will be collected from ICAR Lamphapat and other government agencies. SWAT model requires DEM, LULC data, soil data and meteorological data as data input to be set up. Model calibration and validation were performed using observed discharge data. The manual of the SWAT model explains the details of the SWAT model.

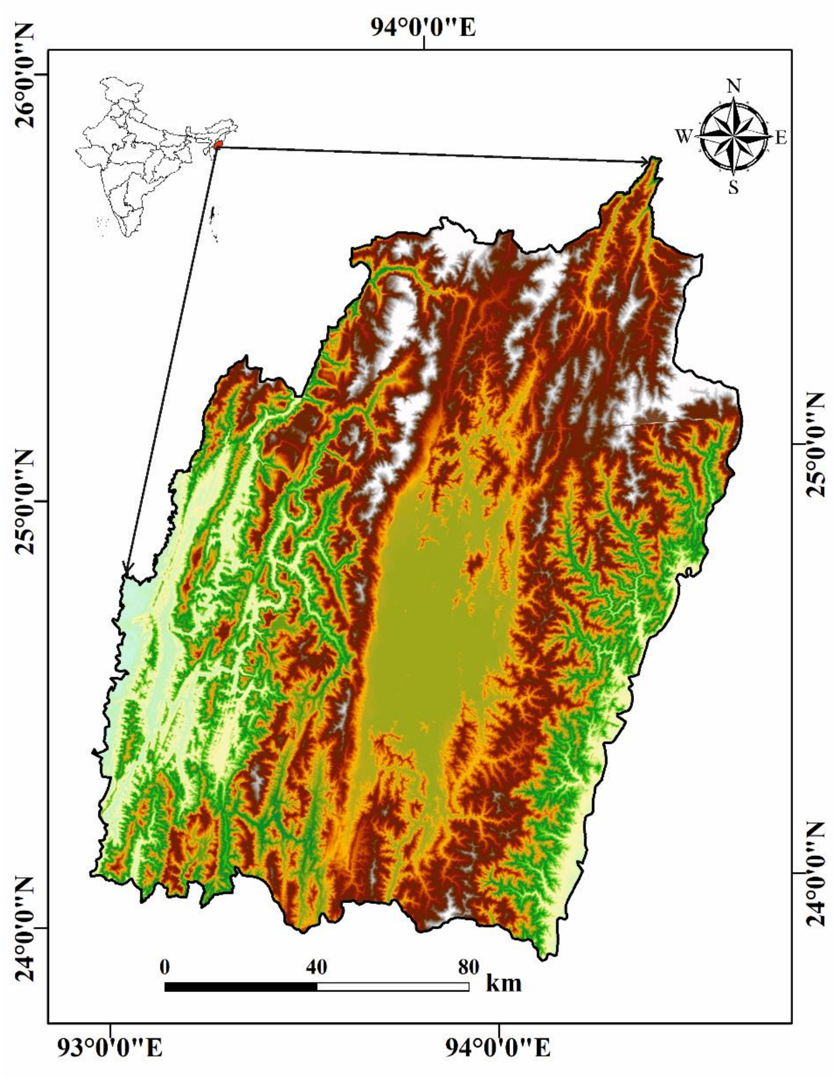

Figure: Geographic location of the study area

Work Plan

The following is a detailed implementation plan and work schedule.

- Field work for ground truthing the remote sensing data.
- Simulation of the model and validation
- Data Interpretation.
- Finalise the report and publication.

Work schedule:

1st Year

- Filed work for ground truthing the remote sensing data, collection of meteorological data from the government agency for validating the hydrological modelling.
- Preparation of the data for simulation of SWAT model.
- Preparation of annual report.

2nd Year

- Field work in around Imphal Valley for validation of data.
- Simulation and validation of the model.
- Preparation of data and short communication for any new finding.
- Compilation of data, finalizing the project report.
- Submission of manuscript to the reputed journal.

PROFORMA FOR BIO-DATA

1. Name and full correspondence address: **Ningombam Prikash Meetei**
Yurembam Mayai Leikai
PO: Langjing, Imphal West
Manipur,795113

2. Email(s) and contact number(s): pksangom@gmail.com ,**+919485263726**

3. Institution: **Department of Applied Geology, Indian Institute of Technology (Indian School of Mines), Dhanbad**

4. Date of Birth: **02/02/1992**

5. Gender (M/F/T): **Male (M)**

6. Category Gen/SC/ST/OBC: **OBC**

7. Whether differently abled (Yes/No): **No**

8. Academic Qualification (Undergraduate Onwards)

	Degree	Year	Subject	University/Institution	% of marks
1.	Bachelor of Science (BSc)	2012	Geology(H), Physics, Mathematics	DM college of Science, Manipur University	62.11%
2.	Master of Science (MSc)	2014	Earth Sciences	Manipur University	65.04%
3.	PhD	2023 (Submitted)	Applied Geology	Indian Institute of Technology (Indian School of Mines), Dhanbad	-

9. Ph.D thesis title, Guide's Name, Institute/Organization/University, Year of Award.
"Assessment of Snow and Glacier melt runoff in Pindar River, Central Himalaya, India using isotope and modelling approach"
Name of the Supervisor's: Prof. S. Sarangi, Dept of Applied Geology, IIT(ISM), Dhanbad
Dr. Rajeev Saran Ahluwalia, External co-guide, Doon University
Dr. S P Rai, External Co-guide, Banaras Hindu University
Year of Award/ submission of thesis:08.06.2023

10. Work experience (in chronological order).

S.No.	Positions held	Name of the Institute	From	To	Pay Scale
1	JRF	Wadia Institute of Himalayan Geology, Dehradun	2017	2019	12000(Fixed)
2	SRF	Wadia Institute of Himalayan Geology, Dehradun	2019	2020	35000 (Fixed)

11. Professional Recognition/ Award/ Prize/ Certificate, Fellowship received by the applicant.

S.No	Name of Award	Awarding Agency	Year
1	JRF	DST	2017
2	SRF	DST	2019

12. Publications *(List of papers published in SCI Journals, in year wise descending order).*

S.No.	Author(s)	Title	Name of Journal	Volume	Page	Year
1	**Meetei,P.N**. ,Ahluwalia, R.S.,Rai,S.P ,Khobragade,S.,Sarangi, S.,Goel,M., &Kumar,S	**Spatio-temporal analysis of snow cover and effect of terrain attributes in the Upper Ganga River Basin, central Himalaya.**	Geocarto International	VOL. 37, NO. 4	1139-1159	2022
2	Ahluwalia, R.S., Rai, S.P., **Meetei, P.N**., Kumar, S., Sarangi, S., Chauhan, P. and Karakoti, I., 2021.	**Spatial-diurnal variability of snow/glacier melt runoff in glacier regime river valley: Central Himalaya, India**	Quaternary International	Volume:585	183-194	2021

13. Detail of patents: **Nil**

S.No	Patent Title	Name of Applicant(s)	Patent No.	Award Date	Agency/Country	Status

14. Books/Reports/Chapters/General articles etc.:**Nil**

S.No	Title	Author's Name	Publisher	Year of Publication

15. Any other Information (maximum 500 words)
    Work as JRF and SRF (2017-2020) in the Centre for Glaciology, Wadia Institute of Himalayan Geology in the DST sponsored project entitled "Understanding of hydrological process of Upper Ganga River basin using isotopic techniques"

Undertaking by the Fellow

I, Ningombam Prikash Meetei , Son/Daughter/Wife of Shri N Dhananjoy Meetei, resident of Yurembam Mayai Leikai, Manipur,795113 agree to undertake the following, If I am offered the SERBN-PDF

`

1. **I shall abide by the rules and regulations of SERB during the entire tenure of the fellowship.**
2. **I shall also abide by the rules, discipline of the institution where I will be implementing my fellowship**
3. **I shall devote full time to research work during the tenure of the fellowship**
4. **I shall prepare the progress report at the end of each year and communicate the same to SERB through the mentor**
5. **I shall send two copies of the consolidated progress report at the end of the fellowship period.**
6. **I further state that I shall have no claim whatsoever for regular/permanent absorption on expiry of the fellowship.**

Date:08.08.2023 **Signature** N. Prikash Meetei

आपो हिष्टा मयोभुवः

राष्ट्रीय जलविज्ञान संस्थान

(जल शक्ति मंत्रालय, जल संसाधन, नदी विकास और गंगा संरक्षण विभाग, के अधीन भारत सरकार की समिति)
जलविज्ञान भवन, रुड़की–247 667 (उत्तराखण्ड) भारत

National Institute of Hydrology

(A Goverment of India Society under Ministry of Jal Shakti, Department of Water Resources, R.D. & G.R
Jalvigyan Bhawan, Roorkee - 247 667, (Uttarakhand) INDIA
(An ISO 9001 : 2015 Certified Organization)

जल शक्ति अभियान

Phone: +91-1332-272108, 272106
Fax : +91-1332-272123, 273976
Web : www.nihroorkee.gov.in

Endorsement Certificate from the Mentor & Host Institute

This is to certify that:

I. The applicant, **Ningombam Prikash Meetei**, will assume full responsibility for implementing the project.

II. The fellowship will start from the date on which the fellow joins University/Institute where he/she implements the fellowship. The mentor will send the joining report to the SERB. SERB will release the funds on receipt of the joining report.

III. The applicant, if selected as SERB-N PDF, will be governed by the rules and regulations of the University/ Institute and will be under administrative control of the University/ Institute for the duration of the Fellowship.

IV. The grant-in-aid by the Science & Engineering Research Board (SERB) will be used to meet the expenditure on the project and for the period for which the project has been sanctioned as indicated in the sanction letter/ order.

V. No administrative or other liability will be attached to the Science & Engineering Research Board (SERB) at the end of the Fellowship.

VI. The University/ Institute will provide basic infrastructure and other required facilities to the fellow for undertaking the research objectives.

VII. The University/ Institute will take into its books all assets received under this sanction and its disposal would be at the discretion of Science & Engineering Research Board (SERB).

VIII. University/ Institute assume to undertake the financial and other management responsibilities of the project.

IX. The University/ Institute shall settle the financial accounts to the SERB as per the prescribed guidelines within three months from the date of termination of the Fellowship.

Dated: 07.08.2023

Signature of the Mentor:

Name & Designation: Dr. Surjeet Singh
Scientist 'G'

डॉ० सुरजीत सिंह / Dr. Surjeet Singh
वैज्ञानिक 'जी' / Scientist 'G'
राष्ट्रीय जल विज्ञान संस्थान
National Institute of Hydrology
रुड़की–247 667 (भारत) / Roorkee-247 667 (INDIA)

Dated: 7/8/23

Signature of the Registrar of University/Head of Institute

Seal of the Institution

डॉ. सुधीर कुमार / Dr. Sudhir Kumar
निदेशक / Director
राष्ट्रीय जलविज्ञान संस्थान
National Institute of Hydrology
रुड़की / Roorkee-247 667

Curriculum vitae

Personal information	*Name*	**Dr. Surjeet Singh**
	Date of Birth:	21.07.1973
	Address:	Scientist-G, Groundwater Hydrology Division, National Institute of Hydrology, Roorkee – 247 667, Uttarakhand, India.
	Phone number:	(+91)-1332-272230 (O); +91 9456134747 (Mobile)
	E-mail:	surjeet.nihr@gov.in; ssingh_sagar@yahoo.co.in

Degrees	*Ph. D in Irrigation & Drainage Engineering (2003)*	G.B. Pant University of Agric. & Tech., Pantnagar, India
	M. Tech in Irrigation & Drainage Engineering(1997)	G.B. Pant University of Agric. & Tech., Pantnagar, India
	B. E. in Civil Engineering (2004)	Kamla Nehru Institute of Technology, Sultanpur, India

	Position & Organisation	Nature of Job	Period
Employment Records	Scientist-G, National Institute of Hydrology, Roorkee	R & D	2023-onwards
	Scientist-F, National Institute of Hydrology, Roorkee	R & D	2018-2023
	Scientist-E, National Institute of Hydrology, Roorkee	R & D	2016-2017
	Scientist-D, National Institute of Hydrology, Roorkee	R & D	2011-2016
	Scientist-C, National Institute of Hydrology, Roorkee	R & D	2002-2011
	Scientist-B, National Institute of Hydrology, Roorkee	R & D	1998-2002

Sponsored Research Projects

Topic	Funding Agency	Year
The Structure and Dynamics of Groundwater Systems in Northwestern India under Past, Present and Future Climates	Ministry of Earth Science, Govt. of India	2017
Peya Jal Suraksha - Development of Six Pilot Riverbank Filtration Demonstrating Schemes in Different Hydrogeological Settings for Sustainable Drinking Water Supply	Ministry of Water Resources, River Development & Ganga Rejuvenation, Govt. of India	2019
Study of river - aquifer interactions and groundwater potential in the upper Ganga basin up to Dabrani	DST, Ministry of Science & Technology under NMSHE	2021
Ganges aquifer management in the context of monsoon runoff conservation for sustainable river ecosystem services – A pilot study	World Bank under the National Hydrology Project.	2022
Future Secular Changes and Remediation of Groundwater Arsenic in the Ganga River Basin	DST-Newton Bhabha-NERC-EPSRC India-UK Water Quality Research Programme	2022

Memberships

- Indian Water Resources Society, Roorkee (India), Fellow Member (FM-317).

- Indian Association of Hydrologists, Roorkee (India), Fellow Member (F-2014-1351).
- Indian Society of Dryland Agriculture (India), Life Member (LM/ISDA/404).
- Indian Association of Soil and Water Conservationists (India), Life Member (LM-2058).

Professional experience

Dr. Surjeet Singh has about 25 years of service experiences in research and development activities. The research areas pursued and emerged as his present areas of interest are largely:

(i) Groundwater flow modeling and management, (ii) Vadose zone modeling, (iii) Rainfall-runoff analysis and modeling, (iv) River-aquifer interaction, (v) Groundwater resources estimation, (vi) Groundwater recharge estimation, (vii) (River)Bank filtration, (viii) Managed Aquifer Recharge, (ix) Water quality indices.

Dr. Surjeet Singh has published 102 publications in refereed journal (Intl. + Natl.); 78 publications in Conferences/Symposia (Intl. + Natl.) ; 29 Project reports; 6 Book chapters; and worked in 15 Sponsored projects.

Sponsored Research Projects (last 5 years)

(i) PI of the Purpose Driven Study entitled "*Ganges aquifer management in the context of monsoon runoff conservation for sustainable river ecosystem services – A pilot study of Sot River Catchment*" sponsored by the MoJS, DoWR, RD&GR under the National Hydrology Project. PI: Dr. Surjeet Singh; Project Cost: Rs. 57.71 Lakhs; Duration: 04 years. (Completed)

(ii) Team Member of the Purpose Driven Study entitled "*Assessment of impacts of groundwater salinity on regional groundwater resources, current and future situation in Mewat, Haryana – Possible remedy and resilience building measures.*" sponsored by the MoJS, DoWR, RD&GR under the National Hydrology Project. PI: Dr. Gopal Krishan; Project Cost: Rs. 65 Lakhs; Duration: 4.5 years. (Completed)

(iii) Co-PI of the Special PDS Study entitled "*Integrated Assessment of the Impacts of Climate Change on the Hydrology of Narmada basin through Hydrological Modelling Approaches*" sponsored by the MoJS, DoWR, RD&GR under the National Hydrology Project. PI: Dr. T. Thomas; Project Cost: Rs. 2.5 Crore; Duration: 05 years. (Ongoing)

(iv) Co-PI of the Purpose Driven Study entitled "*Impact Assessment of the Upcoming Irrigation Projects and Climate Change on the Droughts and Desertification Scenario for Chambal Basin in Western Madhya Pradesh*" sponsored by the MoJS, DoWR, RD&GR under the National Hydrology Project. PI: Dr. T. Thomas; Project Cost: Rs. 44.4 lakh; Duration: 4.5 years. (Ongoing)

(v) Team Member of the Purpose Driven Study entitled "*Hydrological Modelling for Evaluation of Return Flow and Irrigation Planning for Optimal Utilization of Water Resource in the Command of Sanjay Sagar Project in Madhya Pradesh*". sponsored by the MoJS, DoWR, RD&GR under the National Hydrology Project. PI: Dr. R.K. Jaiswal; Project Cost: Rs. 64.36 Lakhs; Duration: 04 years. (Ongoing)

(vi) Team Member of sponsored project entitled "*Capacity development program on site suitability mapping for managed aquifer recharge (MAR) under varying climatic conditions using remote sensing and machine learning-based hydrological modelling tools*" sponsored by the Asia-Pacific Network (APN) for Global Change Research. PI: Nitesh Patidar; Project Cost: Rs. 34.00 Lakhs; Duration: 01 year. (Completed)

(vii) PI of the project on "*Ground Water Investigations of Rana Sugars Limited Buttar Seviyan area of Amritsar District, Punjab*" sponsored by B.R. Ambedkar National Institute of Technology, Jalandhar, Punjab. [CS-226/2020-21/GWHD]" PI: Dr. Surjeet Singh; Project Cost: Rs. 6.49 Lakhs; Duration: 6 Months. (Completed)

(viii) PI of the project on "*Hydrogeological Study to Assess the Impact of Mining Activities in and around the Rampura Agucha Mine Area of Hindustan Zinc Limited in the Bhilwara District, Rajasthan*" sponsored by Hindustan Zinc Limited (HZL), Bhilwara, Rajasthan. [CS-246/2022-23/GWHD]" PI: Dr. Surjeet Singh; Project Cost: Rs. 28.91 Lakhs; Duration: 06 Months. (Completed)

(ix) Co-PI of the project on "*Study of Various Possible Scenarios for Understanding the Long-term Effect of en-route Canal Irrigation for Proposed Mahanadi-Godavari Link*" sponsored by National Water Development Agency (NWDA), Bhubaneswar, Govt. of India. [CS-195/2020-21/WRS]" PI: Dr. M.K. Goel; Project Cost: Rs. 85 Lakhs; Duration: 12 Months. (Completed)

(x) PI of the project on "*System Studies for Proposed Farakka – Sundarban Link Project*" sponsored by National Water Development Agency (NWDA), Bhubaneswar, Govt. of India. [CS-257/2022-23/GWHD]" PI: Dr. Surjeet Singh; Project Cost: Rs. 82.6 Lakhs; Duration: 18 Months. (Ongoing)

(xi) C-PI of the project on "*Hydrogeological Study to Assess the Impact of Dewatering on Groundwater and Its Quality in the Nearby Areas of Rajpura Dariba Mine of Hindustan Zinc Limited*" sponsored by Hindustan Zinc Limited (HZL), Bhilwara, Rajasthan through Euro Smile Facility Management Services Pvt. Ltd., Ghaziabad. [CS-252/2022-23/GWHD]" PI: Dr. Surjeet Singh; Project Cost: Rs. 23.60 Lakhs; Duration: 06 Months. (Ongoing)

Publications
Krishan Gopal, Kumar M., Rao M.S., Garg Rahul, Yadav B.K., Kansal M.L., Singh S., Bradley A., Muste M., Sharma L.M. (2022). Integrated approach for the investigation of groundwater quality through hydrochemistry and water quality index (WQI). Urban Climate (Impact Factor=6.663), Accepted.
G. Krishan, A. Bhagwat, P. Sejwal, B. K. Yadav, M. L. Kansal, A. Bradley, S. Singh, M. Kumar, L. M. Sharma and M. Muste (2022). Assessment of groundwater salinity using principal component analysis (PCA): a case study from Mewat (Nuh), Haryana, India. Environ Monit Assess, (2023) 195:37 https://doi.org/10.1007/s10661-022-10555-1, Online Published.
Mohammed Mainuddin, Donald S. Gaydon, Sreekanth Janardhanan, John M. Kirby, Mohammad A. Mojid, Sumant Kumar, Phil Davies, Surjeet Singh and Dave Penton (2022). Sustainable groundwater use in the Eastern Gangetic Plains requires region-specific solutions. Groundwater for Sustainable Development, Elsevier, 18 (2022) 100798. https://doi.org/10.1016/j.gsd.2022.100798 (Impact Factor=5.213), Online Published.
M. K. Sharma, Mohit Kumar, D. S. Malik, Surjeet Singh, A. K. Patre, Beena Prasad, Babita Sharma, Shekhar Saini, A. K. Shukla and P. C. Das (2022). Assessment of groundwater quality and its controlling processes in Bemetara District of Chhattisgarh State, India. Applied Water Science, Springer (2022) 12:102 (Impact Factor=3.874), Online Published.
Surjeet Singh, Pinki Sharma, Raju Mudhulkar, Biswajit Chakravorty, Ankit Singh and Survey D. Sharma (2021). Assessment of hydrogeochemistry and arsenic contamination in groundwater of Bahraich District, Uttar Pradesh, India. Arabian Journal of Geosciences, Springer (Impact Factor=1.827), Online Published.
Gaurav Singh, A. R. S. Kumar, R. K. Jaiswal, Surjeet Singh and R. M. Singh (2021). Model coupling approach for daily runoff simulation in Hamp Pandariya catchment of Chhattisgarh state in India. Environment, Development and Sustainability, Springer. https://doi.org/10.1007/s10668-021-01949-1 (Impact Factor=3.219).
Sumant Kumar, Manish Kumar, V.K.Chandola, Vinod Kumar, R.K. Saini, Neeraj Pant, Nikul Kumari, Ankur Srivastava, Surjeet Singh, Rajesh Singh, Gopal Krishan, Shashi Indwar, Sudhir Kumar, Brijesh Yadav, N. S. Maurya and Anju Chaudhary (2021). Groundwater quality issues and challenges for drinking and irrigation uses in central Ganga basin dominated with rice-wheat cropping system. Water, MDPI. (Impact Factor=3.103) https://www.mdpi.com/journal/water/sections/hydrogeology.
G. Krishan, A. K. Taloor, N. Sudarsan, P. Bhattacharya, S. Kumar, N. C. Ghosh, S. Singh, A. Sharma, M. S. Rao, S. Mittal, B. S. Sidhu, R. Vasisht and R. Kour (2021). Occurrences of potentially toxic trace metals in groundwater of the state of Punjab in northern India. Groundwater for Sustainable Development, Elsevier. (Impact Factor=) https://doi.org/10.1016/j.gsd.2021.100655 https://authors.elsevier.com/c/1dbh5,rVni2FIW.
Sumant Kumar, S.K. Joshi, Neeraj Pant, Surjeet Singh, B. Chakravorty, Ravi Saini, Vinod Kumar, Ankit Singh, N.C. Ghosh, Abhijit Mukherjee, Prashant Rai and Vijeta Singh (2021). Hydrogeochemical evolution and groundwater recharge processes in arsenic enriched area in central Gangetic plain, India. Applied Geochemistry, Elsevier. (Impact Factor=3.524), 131 (2021) 105044.
Sumant Kumar; Vinod Kumar; Ravi K. Saini; Neeraj Pant; Rajesh Singh; Ashwin Singh; Sudhir Kumar; Surjeet Singh; Brijesh K. Yadav; Gopal Krishan; Ameesha Raj; N.S. Maurya and Manish Kumar (2021). Floodplains Landforms, Clay Deposition and Irrigation Return Flow govern Arsenic Occurrence, Prevalence and Mobilization: A geochemical and isotopic study of the Mid-Gangetic Floodplains. Environmental Research, Elsevier. (Impact Factor=3.524) https://doi.org/10.1016/j.envres.2021.111516, 201 (2021): 111516.
Priyanka Sharma, Surjeet Singh and Survey D. Sharma (2021). Artificial Neural Network Approach for Hydrologic River Flow Time Series Forecasting. Agricultural Research, Springer https://rdcu.be/cnr9Y

https://doi.org/10.1017/s40003-021-00585-5, 11, 465–476.
Gopal Krishan, B. Kumar, N. Sudarsan, M.S. Rao, N.C. Ghosh, A.K. Taloor, Prosun Bhattacharya, Surjeet Singh, C.P. Kumar, Anupma Sharma, S.K. Jain, B.S. Sidhu, Sumant Kumar and Rajesh Vasisht (2021). Isotopes (δ18O, δD and 3H) variations in groundwater with emphasis on salinization in the state of Punjab, India. Science of the Total Environment, Elsevier. (Impact Factor=7.963), Vol. 789, 148051, October 2021.
Gopal Krishan, G. Prasad, Anjali , C.P. Kumar, N. Patidar, B.K. Yadav, M.L. Kansal, S. Singh, L.M. Sharma, A. Bradley and S.K. Verma (2020). Identifying the seasonal variability in source of groundwater salinization using deuterium excess - a case study from Mewat, Haryana, India. Journal of Hydrology: Regional Studies, 31 (2020) 100724, Aug 2020.
Rao, Y.R.S., Vijay, T., Prasad, Y.S. and Surjeet Singh (2020). Development of River Bank Filtration (RBF) Well in Saline Coastal Aquifer. Journal of Water Process Engineering, Elsevier (Impact Factor=3.173 > 3) https://doi.org/10.1016/j.jwpe.2020.101478, Vol.-37 (2020), Oct 2020, 101478.
Gopal Krishan, N.C. Ghosh, C.P. Kumar, Lalit Mohan Sharma, Brijesh Yadav, M.L. Kansal, Surjeet Singh and S.K. Verma (2020). Understanding stable isotope systematics of salinity affected groundwater in Mewat, Haryana, India. Journal of Earth System Science, Springer. https://doi.org/10.1007/s12040-020-1380-6, (2020) 129:109.
Kumar Amrit, S.K. Mishra, R.P. Pandey, S.K. Himanshu and Surjeet Singh (2019). Standardized Precipitation Index based approach to predict environmental flow condition. Ecohydrology.
Biswajit Das, Sanjay Jain, Praveen Thakur and Surjeet Singh (2020). Assessment of Climate change Impact on the Gomti river basin in India under different RCP scenarios. Arabian Journal of Geosciences. https://link.springer.com/article/10.1007/s12517-020-06359-7, 14: 120 (2021).
Biswajit Das, Sanjay Jain, Surjeet Singh and Praveen Thakur (2019). Evaluation of Multisite Performance of SWAT Model in the Gomti River Basin, India. Applied Water Science, Springer. https://doi.org/10.1007/s13201-019-1013-x, (2019) 9:134.
Gopal Krishan, Surjeet Singh, R.J. Thayyan, N.C. Ghosh, S.P. Rai and Manohar Arora (2019). Understanding river-subsurface water interactions in upper Ganga basin, India. International Journal of River basin Management, Taylor & Francis. DOI: 10.1080/15715124.2019.1683853, 18:2, 243-253.
Suman Gurjar, N.C. Ghosh, Sumant Kumar, Anupma Sharma and Surjeet Singh (2018). Process based Integrated Models for Managed Aquifer Recharge and Aquifer Storage Treatment and Recovery. Water Resources Management, Springer. DOI: 10.1007/s11269-018-2108-0.
Surjeet Singh, N.C. Ghosh, Gopal Krishan, Sumant Kumar, Suman Gurjar and M.K. Sharma (2019). Development of Indices for Surface and Ground Water Quality Assessment and Characterization for Indian Conditions. Environmental Monitoring and Assessment, Springer, 191: 182. https://doi.org/10.1007/s10661-019-7276-8 (https://rdcu.be/boezT), Feb., 2019.
Gaurav Singh, Surjeet Singh, A.R.S. Kumar, R.M. Singh, V.K. Chandola and A.K. Nema (2018). Multi criteria based watershed prioritization for effective catchment area treatment plan in Andhiyarkhore catchment in Chhattisgarh, India. CATENA, Elsevier.
G. Krishan, N. Sudarsan, N.C. Ghosh, S. Kumar, S. Singh, A. Sharma, S. Mittal, B.S. Sidhu and R. Vashisth (2021). Concentration of heavy metals in groundwater and heavy metal pollution index in Punjab. e-Journal of Geohydrology, 2(1), 24-33, 2021.
Biswajit Das, Surjeet Singh, S.K. Jain and Praveen Thakur (2021). Prioritization of Sub-Basins of Gomti River for Soil and Water Conservation through Morphometric and LULC Analysis Using Remote Sensing and GIS. J. Indian Society of Remote Sensing https://link.springer.com/article/10.1007/s12524-021-01410-w, 49, 2503–2522 (2021).
M.K. Sharma, Surjeet Singh, Pradeep Kumar, A.K. Patre, Mohit Kumar, Beena Prasad, A.K. Shukla and P.C. Das (2020). Hydrogeochemical Evaluation of Groundwater of Bemetara District, Chhattisgarh. e-Journal of Geohydrology, 1(2), 2020, 82-92.
Surjeet Singh, Sumant Kumar and A. K. Singh (2020). Assessment of Groundwater Quality of Bijnor District, India using Water Quality Index. J. of Water Engg. and Mgt. DOI : https://doi.org/10.47884/jweam.v1i2pp52-60, 2020,1(2): 52-60.
Kumar, S., Kumar, V., Saini, R. K., Kumar, C.P., Raju, M., Singh, S., Singh, O., and Chakravorty, B. (2020). Detection of arsenic in groundwater of Laksar area, Haridwar district. Journal of Indian Water Resources Society.
Gaurav Singh, R.M. Singh, Surjeet Singh, A.R.S. Kumar, R.K. Jaiswal, V.K. Chandola and A.K. Nema (2019). Multi-criteria analytical hierarchical process based decision support system for critical watershed prioritization of Andhiyarkhore catchment. Indian Journal of Soil Conservation, 47(3): 263-272, 2019.
Ashutosh Singh, Surjeet Singh, A.K. Nema and Anshu Gangwar (2019). Physiographic Mapping of Vinayakpur Intermediate Catchment using Remote Sensing and Geographical Information System. Environment & Ecology,

37(3B): 1100-1106, July-September, 2019.
Gopal Krishan, S.K. Chandniha, A.K. Lohani, B.K. Yadav, N.K. Arora, Surjeet Singh, C.P. Kumar, L.M. Sharma and A.K. Bhardwaj (2018). Assessment of Heavy Metals in Relation to Soil Pollution at Mewat, Haryana, India. Current World Environment, 13(3), 2018, 299-306.

Undertaking by the Principal Investigator

To

The Secretary
SERB, New Delhi

Sir

I **Ningombam Prikash Meetei** hereby certify that the research proposal titled "**Assessment and modelling of various hydrological process in small watershed of the Imphal valley, Manipur**" submitted for possible funding by SERB, New Delhi is my original idea and has not been copied/taken verbatim from anyone or from any other sources. I further certify that this proposal has been checked for plagiarism through a plagiarism detection tool i.e. Turnitin approved by the Institute and the contents are original and not copied/taken from any one or many other sources. I am aware of the UGCs Regulations on prevention of Plagiarism i.e. University Grant Commission (Promotion of Academic Integrity and Prevention of Plagiarism in Higher Educational Institutions) Regulation, 2018. I also declare that there are no plagiarism charges established or pending against me in the last five years. If the funding agency notices any plagiarism or any other discrepancies in the above proposal of mine, I would abide by whatsoever action taken against me by SERB, as deemed necessary.

N. Prikash Meetei

N Prikash Meetei
(08.08.2023)
Signature of PI with date

Name / designation

No. B **01639**

BOARD OF SECONDARY EDUCATION, MANIPUR

HIGH SCHOOL LEAVING CERTIFICATE EXAMINATION

Date : 04/06/07

CERTIFIED

that NINGOMBAM PRIKASH MEETEI

Roll No. 9751

son/daughter of Shri (L) N DHANANJOY MEETEI (father)

and Shrimati N INDRANI LEIMA (mother)

born on 02/Feb/1992 duly passed the

High School Leaving Certificate Examination of the Board held

in April.2007 **From** POLE STAR PUBLIC SCHOOL, PATSOI

and was placed in 1st division and secured the following marks

Subjects	Pass Marks	Full Marks	Secured Marks
1. Ae e			32 30
TOTAL	33	100	62
2. ENGLISH	33	100	65
3. MATHEMATICS	33	100	70
4. SCIENCE			
Science Paper I	---	45	30
Science Paper II	---	45	33
Science Paper III	---	45	39
Science-Practical	---	15	15
TOTAL	50	150	117
5. SOCIAL SCIENCE			
Social Science I	---	50	22
Social Science II	---	50	21
Social Science III	---	50	31
TOTAL	50	150	74
Total Without Additional Subject -			388
6. HIGHER MATHEMATICS AND EXCESS MARKS	33	100	64 31
GRAND TOTAL :			419
7. PHYSICAL EDUCATION	33	100	94
8. WORK EXPERIENCE	33	100	96

Controller of Examinations

Compared by

Secretary

Geocarto International

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tgei20

Spatio-temporal analysis of snow cover and effect of terrain attributes in the Upper Ganga River Basin, central Himalaya

Prikash N. Meetei, Rajeev Saran Ahluwalia, S.P. Rai, Suhas Khobragade, Shushanta Sarangi, Manmohan Goel & Sushil Kumar

To cite this article: Prikash N. Meetei, Rajeev Saran Ahluwalia, S.P. Rai, Suhas Khobragade, Shushanta Sarangi, Manmohan Goel & Sushil Kumar (2022) Spatio-temporal analysis of snow cover and effect of terrain attributes in the Upper Ganga River Basin, central Himalaya, Geocarto International, 37:4, 1139-1159, DOI: 10.1080/10106049.2020.1762764

To link to this article: https://doi.org/10.1080/10106049.2020.1762764

Published online: 19 May 2020.

GEOCARTO INTERNATIONAL
2022, VOL. 37, NO. 4, 1139–1159
https://doi.org/10.1080/10106049.2020.1762764

Taylor & Francis
Taylor & Francis Group

Check for updates

Spatio-temporal analysis of snow cover and effect of terrain attributes in the Upper Ganga River Basin, central Himalaya

Prikash N. Meetei[a,d], Rajeev Saran Ahluwalia[a], S.P. Rai[b], Suhas Khobragade[c], Shushanta Sarangi[d], Manmohan Goel[c] and Sushil Kumar[e]

[a]Centre for Glaciology, Wadia Institute of Himalayan Geology, Dehradun, India; [b]Department of Geology, Banaras Hindu University, Varanasi, India; [c]National Institute of Hydrology, Roorkee, India; [d]Department of Applied Geology, Indian Institute of Technology (Indian School of Mines), Dhanbad, India; [e]Wadia Institute of Himalayan Geology, Dehradun, India

ABSTRACT
Continuous monitoring of snow cover area (SCA) in space and time is a vital input to estimate the snow/glacier melt runoff, glacial mass balance and other hydrological studies. The present study aims to find out the spatio-temporal variation of SCA and inter-relationship between snow accumulation and topography in the Upper Ganga River Basin (UGRB) including Bhagirathi, Alaknanda, Mandakini and Pindar River sub-basins, central Himalaya using MODIS Terra (MOD10A2) data. SCA is found ~32.33% to the total basin area of ~18724 km^2 in UGRB. The Average of 12 year shows that Bhagirathi River Basin has maximum SCA~33.25%, whereas Pindar river basin has minimum SCA ~17.50% among these four sub-basins. Maximum rate of change of SCA is found in the Mandakini River Basin. Slope class 20°–30° has more favorable conditions for snow accumulation. North and north-west aspect has higher snow accumulation with maximum positive attribution in January and minimum in July.

ARTICLE HISTORY
Received 28 December 2019
Accepted 12 April 2020

KEYWORDS
Snow cover; elevation; slope; aspect; MODIS; Upper Ganga River Basin

Introduction

The Himalaya has one of the largest concentration of snow/glacier outside the polar region (Bajracharya et al. 2015). It is called third pole because its snow/glacier reserve is the largest fresh water source outside the polar region (Bajracharya and Shrestha 2011). The Himalaya acts as a great climatic divide, which effects the large system of air and water circulation. Meteorological conditions of the entire Indian sub-continent and central Asian highlands to the north is generally decided by Himalaya (Dimri and Dash 2012). The Himalaya has three major divisions i.e., Outer Himalaya or Siwalik Range, Lesser Himalaya and Greater Himalaya Range (DiPietro and Pogue 2004). The Greater Himalaya Range is the backbone for snow/glacier because of its height and favorable condition for the deposition of snow/ice. The great Himalayan Range acts as a barrier for the cold continental air moisture source from the north into India as well as for the Indian Summer

CONTACT Rajeev Saran Ahluwalia raahluwalia05@gmail.com

Monsoon (ISM), which gives all the rain during the monsoon season in India (Dimri and Dash 2012). The Himalayan Region experiences mainly two precipitation seasons in the winter and summer with the westerlies and ISM moisture sources respectively. Due to the low pressure zone in high altitude during the winter, heavy snowfall is precipitated in the Great Himalayan Ranges. At the end of the May, southwest monsoon is active towards the eastern Himalaya with the rising of moisture source in steep high peaks and receive the condition for the condensation to fall as snow and rain. Further, climatic condition for the SCA also vary with respect to the relief and location. It gives the impact on different slope of same range with different rate of change of SCA (Pu et al. 2007; Yaning et al. 2008; Brown and Robinson 2011; Khan et al. 2015; Kour et al. 2016; Azmat et al. 2017; Dai et al. 2017; Fayad et al. 2017; Saavedra et al. 2017; Shukla et al. 2017; Yu et al. 2017; Negi et al. 2018; Shafiq et al. 2019).

SCA also plays vital role for the Himalayan River hydrology as all the major rivers i.e., Ganga, Indus and Brahmaputra originate from the Himalaya and their upper catchment is covered with the snow/glacier throughout the year (Jain et al. 2009). These rivers are mainly fed by the snow/glacier melt runoff (Ahluwalia et al. 2013). These are the lifeline for water security in north Indian states (Rai et al. 2009; Kulkarni and Karyakarte 2014; Gaddam et al. 2020). Total amount of water flowing from the Himalaya to the plains of the Indian Subcontinent is estimated to be about $\sim 8.6*10^6$ m^3 per year (IPCC 2001; Singh and Jain 2002).

Variations in the snow cover influences the energy and water exchange between the land surface and the lower troposphere by regulating the radiation, water and heat flux (Cohen and Rind 1991). SCA variations have been also suggested as the embryonic predictor of the Asian Monsoon in some previous studies (Hahn and Shukla 1976; Dey et al. 1985; Parthasarathy and Yang 1995; Sankar-Rao et al. 1996; Yang 1996). Therefore, study of variation of SCA in the Himalayan region is very important for solving the scientific problems like monsoon prediction, glacier mass balance and melt runoff modelling etc.

Himalayan SCA plays an important role in the hydro-electricity production using runoff. SCA has a direct impact on economic development of India and its society (Kulkarni et al. 2007). It contributes about ~22% and ~17% share on gross domestic product on the hydroelectric power generation and agriculture (Sharma et al. 2014). Accumulation of the SCA in the winter season tends to damage the crop due to freezing and thus, causes food shortage for animals which leads to the death of many animals and causes a huge economic loss. The amount and nature of the seasonal and the monsoonal precipitation in the Himalayan region influences the dynamics of the river flow and thus the distribution of water (Immerzeel et al. 2010; Dimri and Dash 2012).

Therefore, it is essential to set up the SCA information system for the individual basin or other hydrological units, planning region or even entire mountain ranges on a long term perspective. Thus, an attempt was made to carry out the spatio-temporal analysis of SCA and the effect of terrain attributes was observed in the UGRB and its sub-basins i.e., Bhagirathi, Alaknanda, Mandakini and Pindar River Basins using MODIS 8 Day L3 Global 500 m Grid (MOD10A2).

Study area

The Ganga is a major river of north India, emanates from the Gangotri Glacier (~3892 m) as Bhagirathi River. It receives the name Ganga at the confluence of the Bhagirathi and Alaknanda River at Devprayag located in the central Himalaya (Khan et al. 2017). It is the largest river basin in India, extending over the states of Uttarakhand, Uttar Pradesh, Haryana, Himachal Pradesh, Delhi, Bihar, Jharkhand, Rajasthan, Madhya Pradesh, Chhattisgarh and West Bengal. Highly variable and climatic conditions of the UGRB between 29°59′43.32″ N-31°27′33.69″ N latitude and 78°9′14.89″ E-80°14′21.25″ E longitude of UGRB is considered for the present study (Figure 1). Total area of the study basin is ~18724km^2 with the elevation range between ~419 to 7785 m (Figure 1). Drainage area of the basin is constituted with four main sub-basins namely Bhagirathi, Alaknanda, Mandakini, and Pindar River Basin upto Devprayag (Figure 1). The study was also carried out to these sub-basins separately to examine the role of terrain features for the distribution of snow.

The northern part of the study area comes under high elevation, whereas southern part comes under low elevation, and snowfall events never occur here. Therefore, study area was restricted in the hilly area above 500 m. The Bhagirathi River is one of the main tributaries of the Ganga River. It originates from the Gangotri Glacier (~30.20 km), which is one of the largest glacier of the Himalaya. Total area of the Bhagirathi River Basin is ~7717 km^2 with ~238 glaciers (Raina and Srivastava 2008).

Other main tributary is Alaknanda River originates from the Satopanth Glacier. Total area of the Alaknanda River Basin is ~11006 km^2 with ~407 glaciers (Raina and Srivastava 2008). Further, the Mandakini and the Pindar Rivers are the major tributaries of the Alaknanda River. The Mandakini River originates from the Chorabari Glacier at ~3840 amsl and meets with the Alaknanda River at Rudraprayag at ~600 amsl. The Mandakini River Basin is having ~24 glaciers. The Pindar River is also main tributary of the Alaknanda River, geographically in the southern side of the great Himalaya having ~56 glaciers. It is a part of Kumaon Himalayan Region. Total length of the river

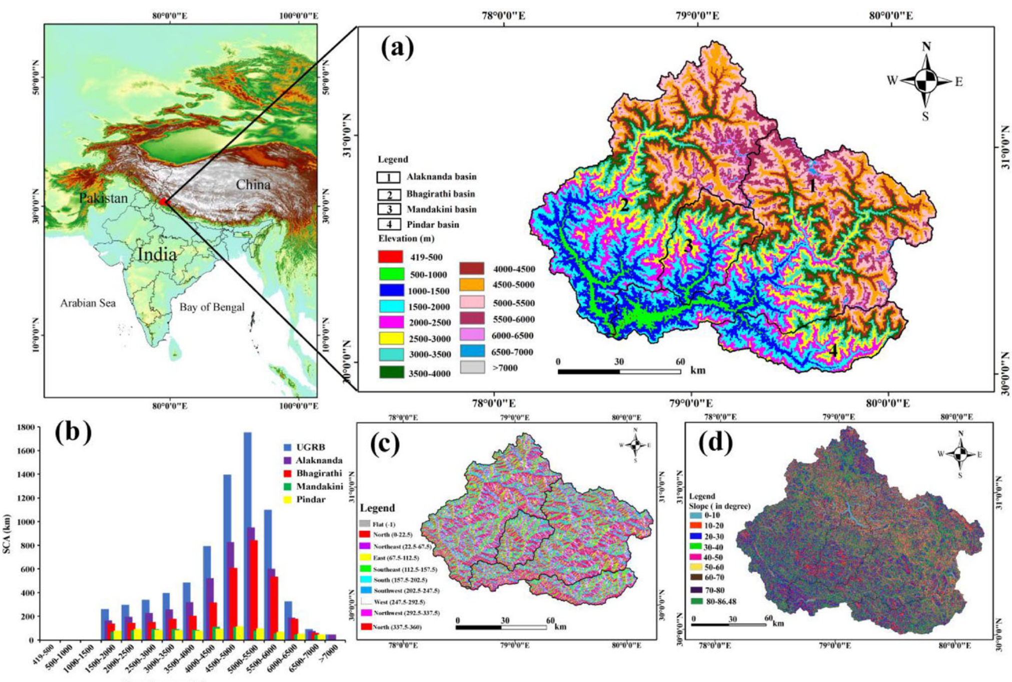

Figure 1. Study area of UGRB upto Devprayag to examine the role of topographical features for snow distribution in central Himalaya. a) shows different elevation zone with its four sub basin, b) area of UGRB and its four subbasin, c) Aspect map and d) Slope map of the region.

is ∼124 km flowing from east to west and drainage area is ∼1860km^2 till the confluence with the Alaknanda River at Karanprayag.

Data used and methodology

SCA derived from satellite data

Monitoring of the SCA on regular basis by traditional mean in the Himalayan Region is very difficult due to unfriendly topography, scanty of the snow gauges and inaccessible terrain. With the advancement of the remote sensing technology, it provides satellite data for the monitoring of SCA with the spatial and temporal resolution in such a rugged terrain. Now a days, various sensors are available which provide high spectral, spatial and temporal resolution. MODIS (Moderate Resolution Imaging Spectroradiometer) Terra and Aqua satellites are considered as an optimum tool to monitor the SCA. MODIS have both regional and global scale for the daily time frequency, multi-spectral capabilities and medium spatial resolution. MODIS data possess the properties of the multi band data set with the moderate spatial and high temporal resolution (Painter et al. 2009; Parajka et al. 2010; Yang et al. 2012). MODIS SCA product has been used to study the spatial temporal variation of SCA in the Himalayan region (Ahluwalia et al. 2013; Kour et al. 2016; Shukla et al. 2017; Singh et al. 2018; Shafiq et al. 2019).

MODIS/Terra SCA8 days L3 global 500 m grid (MOD10A2) contains the data of maximum SCA over 8 day repeated periodically (Hall et al. 2001). The MODIS SCA product is freely downloadable through the Distributed Active Archive Center (DAAC) located at the National Snow and Ice Data Center (NSIDC). MODIS SCA product was downloaded for the period 2005–2016 from the https://search.earthdata.nasa.gov to estimate the SCA and its variability. However, sometimes there is mixing of snow cover and cloud cover in MODIS scenes specially in monsoon period. Several researchers have applied various methods to filter cloud cover pixels from MODIS snow cover product (Gao et al. 2010; Shukla et al. 2017). To reduce such cloud obstruction, multi-sensor and multi-day image combination approach was applied (Gao et al. 2010). Further, the average snow cover on that date was estimated by interpolating linearly the previous and the next available cloud free images (Shukla et al. 2017). MODIS deliver public domain data in raster of the Hierarchical Data Format (HDF) which was converted into an image for visualization using ERDAS Imagine software. The MODIS Snow Data products were in Sinusoidal Projection and re-projected into Universal Transverse Mercator (UTM) projection (zone 44 -WGS84). Normally, there are four 8 day composite dataset for each month in the MOD10A2. Monthly SCA is obtained by taking the average of four 8 day scenes. Annual mean SCA is also obtained by taking the average of 12 months. We name 8-day duration as 8-days of 1 for 1–8 January, 8 days of 9 for 9–16 January, 8 days for 17 for 17–24 January and so on. Likewise, other scenes also name with the Julian days along with the 8-day composite period in each scene. A total of 551 scenes (2005–2016) cloud free images were used for SCA estimation.

Terrain features using digital elevation model (DEM)

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM is used to obtain the various terrain features i.e., elevation zone, slope and aspect maps. This is an imaging instrument on board the Terra Satellite launched in December 1999 as a part of NASA's Earth Observing System (EOS). The instrument records in three bands

Table 1. Detail information about the area of UGRB and its sub basin in different elevation zone, slope and aspect along with the percentage with respect to the total geographical area.

	Elevation ranges	UGRB area in km^2 (% in each zones)	Alaknanda basin area in km^2 (% in each zones)	Bhagirathi basin area in km^2 (% in each zones)	Mandakini basin area in km^2 (% in each zones)	Pindar basin area in km^2 (% in each zones)
Elevation (m)	419–500	4.75 (0.03)	3.25 (0.03)	1.5 (0.02)	–	–
	500–1000	619.75 (3.31)	394.5 (3.58)	225.25 (2.92)	47.25 (2.80)	17.75 (0.95)
	1000–1500	1762 (9.41)	1020 (9.27)	742 (9.61)	200.75 (11.91)	184.5 (9.92)
	1500–2000	2306.75 (12.32)	1317.25(11.9)	989.5 (12.82)	292.5 (17.36)	400.75 (21.5)
	2000–2500	2079 (11.10)	1253.25(11.39)	825.75 (10.70)	316.25 (18.77)	422.5 (22.72)
	2500–3000	1531.25 (8.18)	1010 (9.18)	521.25 (6.75)	230 (13.65)	223 (11.99)
	3000–3500	1282.75 (6.85)	817.25 (7.43)	465.5 (6.03)	179 (10.62)	169.25 (9.10)
	3500–4000	1204.25 (6.43)	767.25 (6.97)	437 (5.66)	120.5 (7.15)	113.25 (6.09)
	4000–4500	1552 (8.29)	972.5 (8.84)	579.5 (7.51)	133 (7.89)	108.75 (5.85)
	4500–5000	2244.5 (11.99)	1278 (11.61)	966.5 (12.52)	96 (5.70)	105.75 (5.69)
	5000–5500	2403.75 (12.84)	1255.5 (11.41)	1148.25 (14.88)	42.75 (2.54)	67.5 (3.63)
	5500–6000	1338.25 (7.15)	701.5 (6.37)	636.75 (8.25)	17 (1.01)	31.5 (1.69)
	6000–6500	330.5 (1.77)	170.75 (1.55)	159.75 (2.07)	6.75 (0.40)	11.75 (0.63)
	6500–7000	58.5 (0.31)	39.25 (0.36)	19.25 (0.25)	3.25(0.19)	3.75 (0.20)
	>7000	6.25 (0.03)	6.25 (0.06)	–	–	–
Slope Classes						
Slopes(°)	0–10	1240.62 (6.63)	692.99 (6.30)	545.82 (7.07)	71.79 (4.26)	75.3 7(4.05)
	10–20	3519.06 (18.79)	2019.93 (18.35)	1498.29 (19.41)	345.27 (20.49)	336.33 (18.08)
	20–30	5586.75 (29.84)	3176.34 (28.86)	2412.93 (31.26)	537.09 (31.87)	584.55 (31.43)
	30–40	4995.61 (26.68)	2920.10 (26.53)	2077.18 (26.91)	446.67 (26.51)	539.42 (29.00)
	40–50	2443.70 (13.05)	1537.05 (13.96)	906.12 (11.74)	217.09 (12.88)	251.35 (13.51)
	50–60	765.58 (4.09)	531.98 (4.83)	232.82 (3.02)	58.12 (3.45)	62.78 (3.38)
	60–70	159.89 (0.85)	118.63 (1.08)	41.01 (0.53)	8.35 (0.50)	10.21 (0.55)
	70–80	12.93 (0.07)	9.44 (0.09)	3.48 (0.05)	0.62 (0.04)	–
	80–86.48	0.12 (0.00)	0.03 (0.00)	0.09 (0.00)	–	–
Aspect Classes						
Aspect	N	2314.96 (12.36)	1345.70 (12.23)	970.44 (12.57)	184.79 (10.97)	197.13 (10.60)
	NE	2359.66 (12.60)	1406.49 (12.78)	953.54 (12.36)	209.81 (12.45)	211.19 (11.35)
	E	2302.98 (12.30)	1347.19 (12.24)	955.68 (12.38)	208.07 (12.35)	241.86 (13.00)
	SE	2315.56 (12.37)	1386.39 (12.60)	927.30 (12.02)	235.91 (14.00)	270.749 (14.56)
	S	2407.60 (12.86)	1426.41 (12.96)	979.94 (12.70)	234.26 (13.90)	227.14 (12.21)
	SW	2466.94 (13.18)	1451.20 (13.18)	1015.69 (13.16)	216.98 (12.88)	239.96 (12.90)
	W	2348.82 (12.54)	1358.54 (12.34)	991.21 (12.84)	205.44 (12.19)	249.94 (13.44)
	NW	2206.87 (11.79)	1284.14 (11.67)	923.57 (11.97)	189.71 (11.26)	222.10 (11.94)

i.e., visible/near infrared (VNIR), shortwave infrared (SWIR) and thermal infrared (TIR) oriented on the nadir and looking backward. Because of its off nadir sensor pointing capability, ASTER collect the stereo pairs necessary to generate high-resolution DEM (Band3N and 3B) and produce 30 m resolution elevation data. Accuracy assessment of the ASTER DEM has been carried out by several researchers under the Himalayan conditions (Jain et al. 2009; Singh et al. 2018) and concluded that the ASTER DEM could be effectively used for the Himalayan regions. The 30 m ASTER DEM was resampled to 500 m to match the resolution of MODIS SCA data.

Elevation is an important component to decide the hydrology, precipitation nature and climate control (Woo and Thorne 2006). The precipitation takes place in term of the snow in higher places in the mountainous region. Therefore, to evaluate the SCA with respect to the elevation, the UGRB is divided into 15 elevation zones from ~419 to ~7785m with the regular interval of 500 m. The UGRB covers the geographical area ~4693.25 km^2 (25.07%) in <2000 m, ~13635.75 km^2 (72.82%) covers in the elevation range of 2000–6000 m, and ~395.25 km^2 (2.11%) covers > 6000 m elevation (Table 1).

Slope of the study area is also classified into 9 classes at 10° regular interval varies from 0 to 86.48° (Figure 1). Slope class 20–30° have maximum geographical area ~5586.75 km^2, whereas minimum is ~0.12 km^2 in 80–86.48°. To evaluate the SCA distribution over aspect classes, aspect map is derived into 8 classes i.e., N, NE, E, SE, S, SW, W, and NW using the ASTER DEM (Figure 1). The study area was distributed almost uniform throughout each aspect class with the highest percentage distribution in the SW and S classes i.e., ~13.18% and ~12.86% respectively and lowest in the NW class i.e., ~11.79%. The sub-basins of UGRB were also classified into different elevation zone, slope and aspect classes and given in Table 1.

Rate of change of SCA with elevation

The nth standard zone for the change of SCA % per meter rise in elevation (Rn) in the snow accumulation period (October to March) and depletion period (April to September) is determined by using the Equation (1) (Kour et al. 2016)

$$R_n = \frac{Sn - Sn - 1}{MEn - MEn - 1} \tag{1}$$

where S_n is SCA (%) for the respective snow accumulation/depletion period pertaining to the nth standard elevation zone, S_{n-1} is the SCA (%) for the respective snow accumulation/depletion period. ME_n is the middle elevation of the nth elevation zone, and ME_{n-1} is the middle elevation of the previous elevation zone.

Results and discussion

SCA variation with elevation bands

SCA was intersected with the classified DEM of 15 elevation zones between 419–500 (zone 1) and > 7000 m (zone 15) for the UGRB. It was observed that the first three elevation zone have almost negligible SCA in the UGRB. The zone 4 (1500–2000) is more sensitive to receive the SCA and limited to few days. It reaches to maximum ~43.07% on 345 day of 2007, however total yearly SCA in this zone is ~6.60%. The SCA received only for few days in this zone and illustrated in Table 2.

More than 30% SCA were estimated on 345 day of the year 2014, 9 day of the years 2007, 2012 and 17 day of the year 2007 in the same elevation zone. The zone 5

Table 2. Distribution of SCA (%) on event basis in zone 4 (1500–2000).

Zone 1500–2000	1-Jan	9-Jan	17-Jan	25-Jan	2-Feb	10-Feb	18-Feb	2-Dec	11-Dec	19-Dec	27-Dec
2005	–	–	21.36	12.9	15.83	–	–	–	–	10.20	–
2006	–	–	–	–	–	–	–	–	14.53	–	–
2007	13.70	34.74	35.86	–	13.12	–	17.50	13.08	43.07	11.01	19.85
2008	–	–	13.03	–	15.86	–	–	–	–	–	–
2009	–	–	–	–	–	25.82	–	–	–	–	–
2010	–	–	–	–	–	–	–	–	–	–	12.58
2011	11.72	25.85	–	–	–	–	–	–	–	–	13.61
2012	10.81	36.12	10.85	–	–	–	–	–	–	–	–
2014	–	–	12.01	–	–	15.06	–	–	34.19	10.21	–
2015	–	–	–	–	–	–	–	–	10.26	18.33	10.52
2016	–	–	20.49	10.56	26.56	–	–	–	–	–	–

(2000–2500) was covered with the snow during 9, 17, 25 and 33 day during all the years with the maximum ~75.78% SCA in 9 day in 2012. All the zones >2500 m elevation is covered with snow on 9, 17, 25, 33 345, 353 and 361 days. It was observed that the elevation zone > 4500 m received more than 60% SCA with maximum~99.97% (33 day of 2016) throughout the year except few days in the summer. This suggests that variation in SCA correlate systematically with the changes in elevation. In the elevation zone 2000–2500, SCA exists till 65 days of the year. Similarly zone 2500–3000, SCA shows decrement after 81 days. The SCA persist till 129 days with 30% area in the zone 3500–4000. It is interesting that the 353 day have more SCA than the 361 day during the year 2005, 2007, 2012, 2014 and 2015. It is also observed that the average ablation of the SCA extent for the elevation upto 3500 m is almost 100% in the UGRB and received snow from the 353 day onwards except few events in the November. The elevation zone 4000–4500 is covered with the snow till 145 day from the January onwards and 297 day to the end of the year. The zone 4500–5000 is covered with snow till 161 day from the January onwards and received snow from 265 day onwards to the end of the year for the most of the years during the study period. The SCA has advancement for 15 days from 4000–4500 to 4500–5000 from 145 day to 161 day. Figures 2 and 3 show mean SCA variation with different elevation zones for 12 years (2005–2016) during the accumulation and ablation/depletion period in the UGRB. There is variation in the curve from year to year in each zones, which can be used to find out the water equivalent in the accumulation and ablation/depletion period. It is observed that the elevation zone 15 has the highest SCA percentage among all other zones during the April to September, if averaged out for the 12 year. While in the month of the January and the February, zone 13, 14 and 15 has less SCA percentage as compared to zone 10, 11 and 12. The elevation zone 13,14 and 15 cover ~2.11% of the basin area lie in the Greater Himalayas and has lower SCA percentage during the January and the February months. This is due to the winter snowfall decreases with the rising altitude in the Great Himalaya Range (Sharma and Ganju 2000; Bhutiyani et al. 2009) but these elevation zones have higher snow percentage in ablation/depletion period due to low temperature and less melting of snow (Figure 3).

SCA with respect to slope and aspect

12 years classified SCA were intersected with the slope map of UGRB and its sub-basins to investigate the impact of slope for the accumulation of snow (Table 3). Maximum SCA is ~25.14% in the 20–30° slope class respective to the total SCA. The SCA is found ~22.62% above 40° class, ~7.72% above 50° class, ~1.64% above 60° class, ~.13% above 70° class, and ~0.0013% above 80°slope. Total SCA is found ~6050 km^2 (32.33%) in the

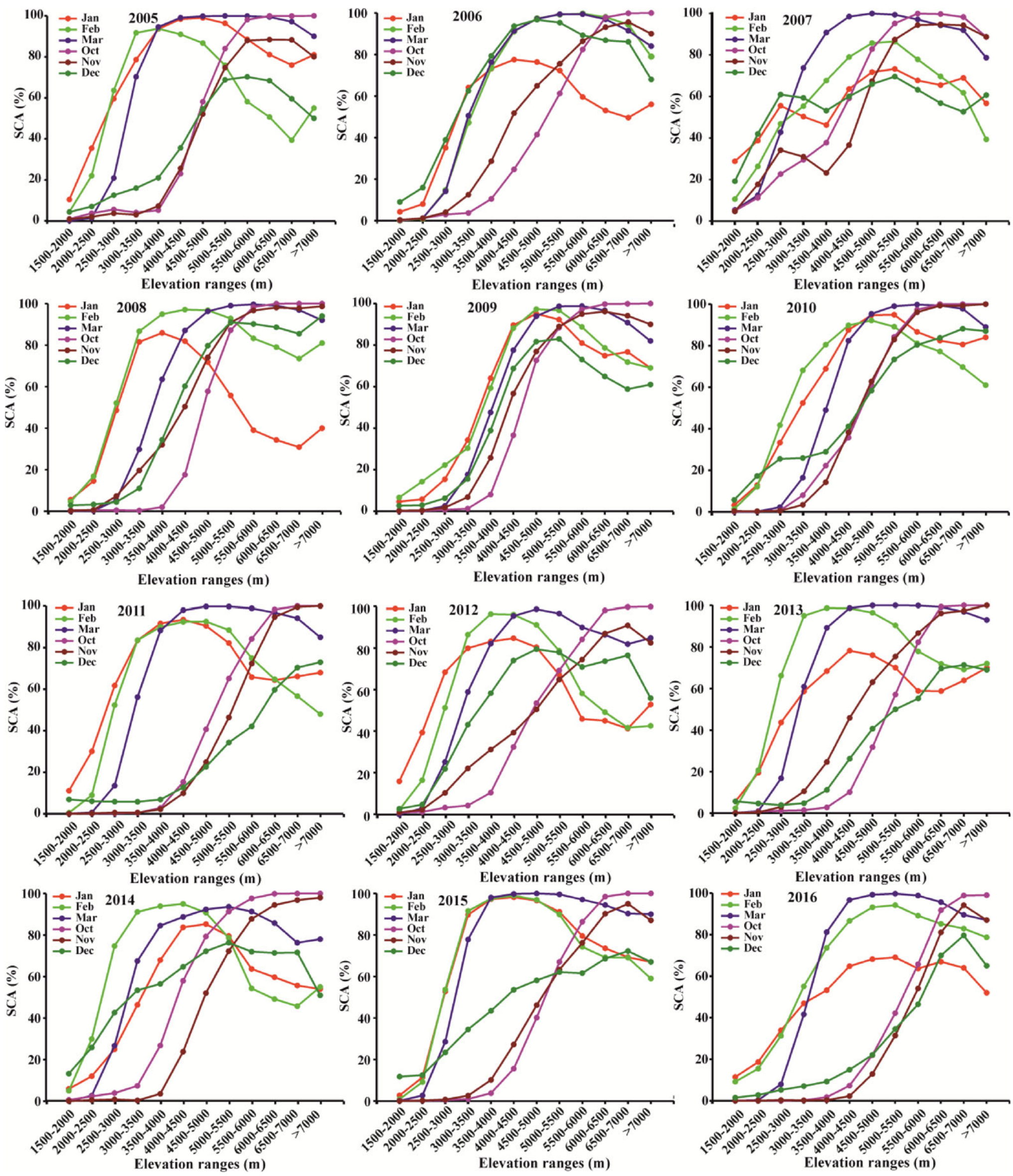

Figure 2. Mean SCA percentage variation in elevation zones 4–15 for 12 years (2005–2016) during October to March (accumulation period) in the UGRB.

UGRB upto Devprayag. The SCA is found maximum in the March (824 km^2) for 0–10° slope class, whereas classes between 10–20° and 40–50°, SCA is observed maximum in the February (1764, 2699, 2696, 1520 km^2), respectively. From 50° onwards, it is found maximum in the March, and minimum is found in the August for all slope classes.

In Bhagirathi River, SCA is found maximum ~26.34% in 20–30° slope class. It is found minimum ~0.002% in 80–86° slope class with least geographical area in this slope class. Total SCA is found ~2566 km^2 with ~33.25% for all the slope classes upto Devprayag respective to the geographical area of the Bhagirathi River Basin. It is ~19.74% beyond 40° slope class with respect to the total SCA.

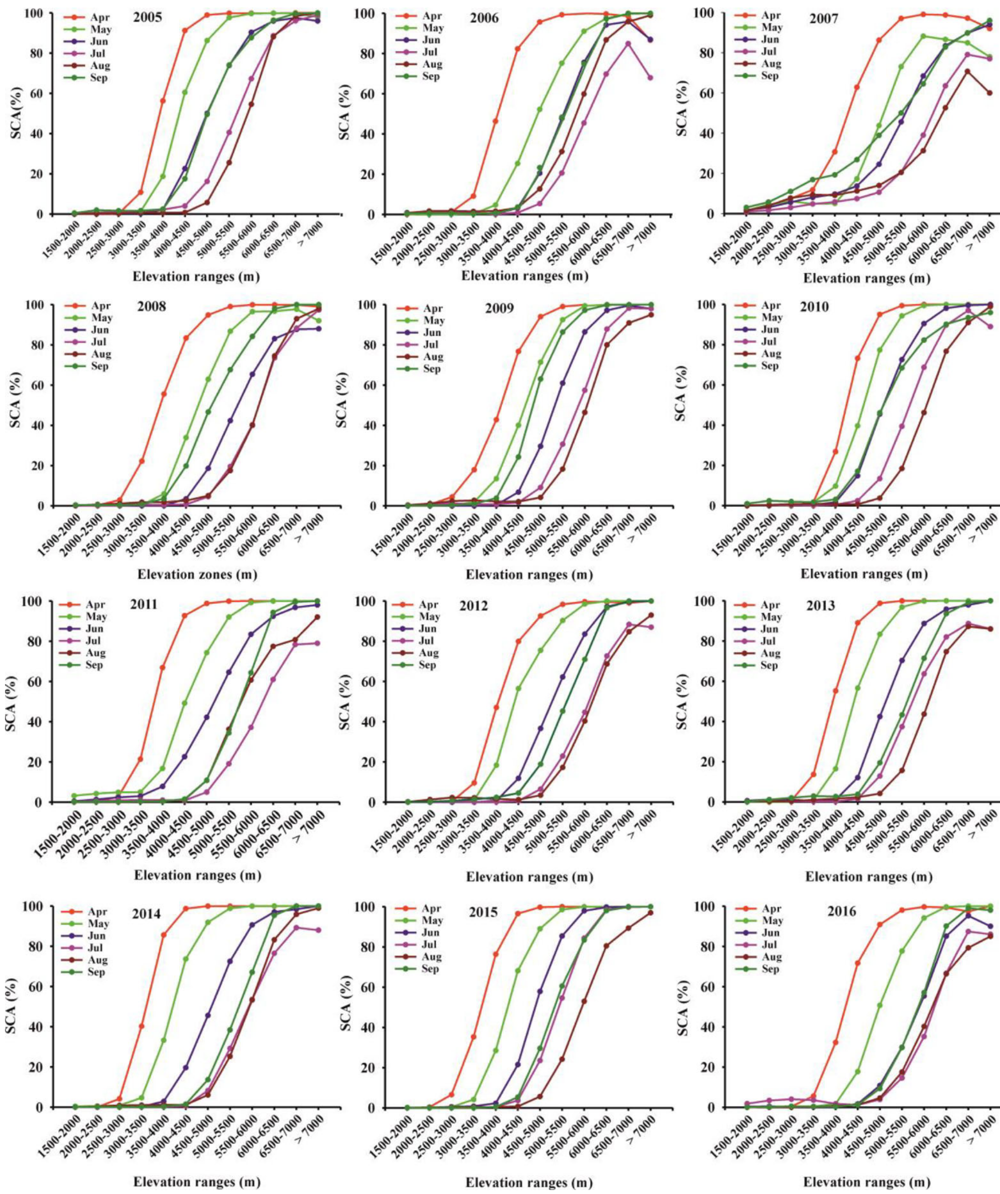

Figure 3. Mean SCA percentage variation in elevation zones 4–15for 12 years (2005–2016) during April to September (ablation/depletion period) in the UGRB.

For the Alaknanda River Basin, maximum SCA is observed ~24.25%, in 20–30° slope class and subsequently 30–40° slope class receive ~24.16%. However, SCA is decreased beyond 40° slope classes and it is estimated ~24.78% with respect to the total SCA. Total SCA is estimated in the Alaknanda River Basin is ~3461 km^2 (~31.45%) for all the slope classes upto Devprayag. The Pindar River Basin was classified into 7 slope classes, having maximum slope ~64.98° with regular interval of 10°. The Pindar River Basin has ~325 km^2 (17.5%) SCA. This is also interesting that the Pindar River Basin has maximum SCA~27.90% in 30–40° slope class rather than 20–30° class. Further, the Mandakini River Basin was classified into 8 slope classes with maximum slope class ~79.59°. The

Table 3. SCA % of the nine slope classes for UGRB and its sub basin are given in table along with maximum, minimum and average annual SCA variation with respect to slope.

	Average of SCA for 12 years (2005–2016) in km					Average of maximum for 12 years (2005–2016) in km					Average of minimum for 12 years (2005–2016) in km				
Slope class (°)	UGRB (SCA% in each slope)	Alaknanda (SCA% in each slope)	Bhagirathi (SCA% in each slope)	Mandakini (SCA% in each slope)	Pindar (SCA% in each slope)	UGRB	Alaknanda	Bhagirathi	Mandakini	Pindar	UGRB	Alaknanda	Bhagirathi	Mandakini	Pindar
0–10	556.46 (9.19)	302.16 (8.73)	251.50 (9.80)	26.36 (8.46)	14.65 (4.50)	828.93	457.52	372.46	92.63	29.61	181.36	90.44	90.37	2.71	3.83
10–20	1118.91 (18.49)	625.79 (18.08)	488.21 (19.03)	62.86 (20.17)	47.02 (14.45)	1838.94	1036.46	800.96	186.05	114.12	300.65	164.38	134.27	8.27	11.91
20–30	1521.41 (25.14)	839.44 (24.25)	675.81 (26.34)	85.58 (27.47)	88.83 (27.30)	2817.43	1570.25	1233.64	217.06	218.58	313.75	172.95	138.79	10.63	21.91
30–40	1485.94 (24.55)	836.46 (24.16)	643.75 (25.09)	75.23 (24.14)	90.80 (27.90)	2806.25	1611.55	1188.12	173.08	222.03	307.07	170.13	134.83	14.01	21.92
40–50	902.35 (14.91)	542.84 (15.68)	356.15 (13.88)	41.90 (13.45)	55.10 (16.93)	1575.72	966.99	612.15	90.67	118.80	257.57	149.68	105.94	11.17	16.85
50–60	368.15 (6.08)	244.79 (7.07)	122.00 (4.75)	15.85 (5.09)	24.77 (7.61)	555.58	379.17	181.41	26.61	45.79	150.23	94.92	54.92	7.00	9.79
60–70	91.03 (1.50)	64.59 (1.87)	26.10 (1.02)	3.62 (1.16)	4.24 (1.30)	126.79	91.93	35.30	5.31	7.59	45.41	30.77	14.35	1.82	2.10
70–80	7.92 (0.13)	5.52 (0.16)	2.37 (0.09)	0.21 (0.07)	–	10.63	7.49	3.16	0.30	–	4.26	2.97	1.25	0.09	–
>80	0.08 (0.00)	0.01 (0.00)	0.07 (0.00)	–	–	0.11	0.02	0.09	–	–	0.02	0.00	0.02	–	–

Mandakini River Basin is covered ∼312 km^2 (∼18.49%) area with SCA. The SCA is found maximum ∼27.47% in 20–30° slope class, whereas minimum ∼0.07% in >70° slope class (Table 3). Relationship between SCA and slope is important as 32–40° slope range is vulnerable to about 75% avalanches occur in the mid latitudinal Himalayan range (Shukla et al. 2017). It is important for avalanche danger forecasting because snow avalanches often form in steep terrain interspersed with rock (Schweizer et al. 2003). Occurrence of ∼60% avalanches is also reported in the slope range of 30–38° in the lower Himalayan range (Sharma and Ganju 2000; Shukla et al. 2017). However, snow accumulate permanently in all the slope classes with varied amount. The SCA is near to zero beyond 60° slope classes for the UGRB and its sub basins. Several studies have been also reported that snow can not retained in high slope terrain (70–90°) (Winstral and Marks 2002; Schmid and Sardemann 2003). Results of the study show that snow accumulation is inversely proportional to the slope and less than 1% snow accumulates above 60° angle.

$$SCA \propto {}^{1}/_{Slope} \tag{2}$$

Bloschl and Kimbauer (1992) have also observed that SCA decreases with slope, specially ≥60° is almost snow free area due to the gravitational effect and wind. The average monthly third order polynomial of SCA of 12 years was analysed in the respective slope class to investigate the dependency of SCA on slope (Figure 4). A high polynomial regression coefficient was obtained for SCA and slope classes throughout the year.

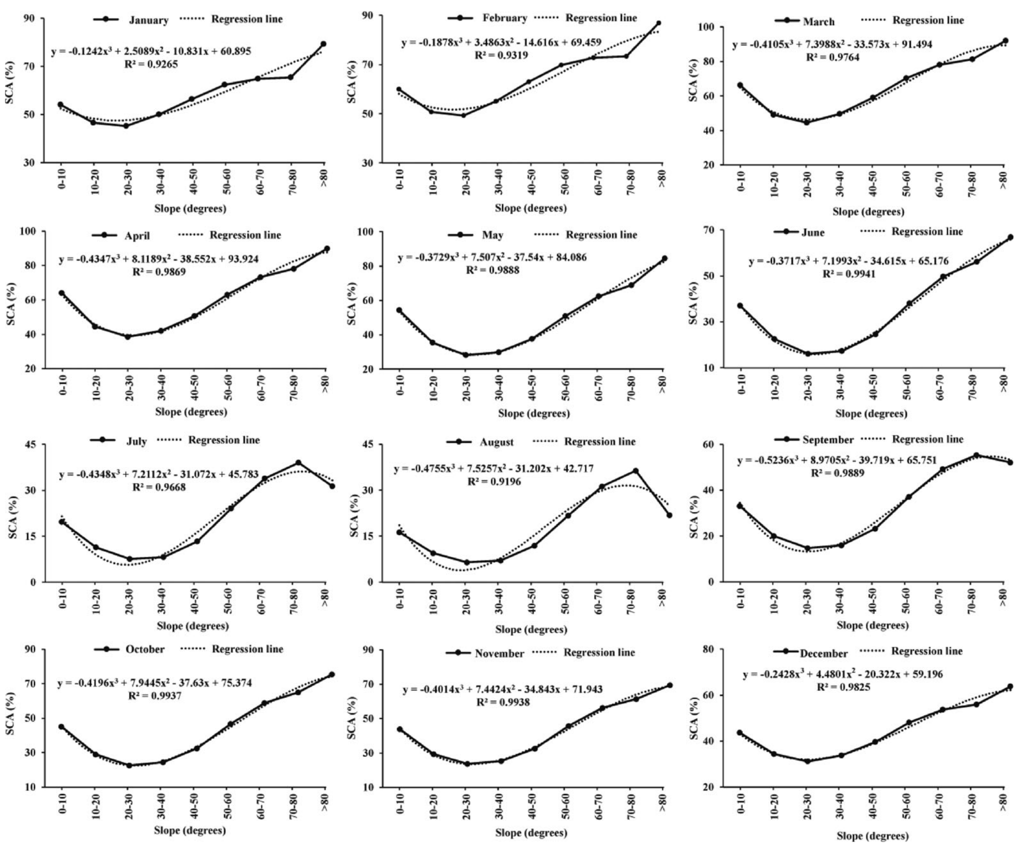

Figure 4. Polynomial regression showing the relationship between monthly average of SCA and Slope.

SCA is also associated with 8 different aspect classes in the study region (Figure 5). It is found to be maximum in the N and NW (~34.11% and ~33.84%), and minimum in the S and SW (~29.87%and ~30.26%). This may be due to varied solar elucidation in these classes. The South facing slope receive sun rays directly, therefore climatic conditions are less favorable in south facing as well as speedy melting of fallen snow (Bahadur 2004; Bhambri et al. 2011). In northern hemisphere, South facing slope receive more solar energy than the north facing slope, thus the latter tends to be more humid and cool (Holland and Steyn 1975). South facing slope receive ~16% more solar radiation than North facing, while the middle and upper portion of slope receive 6% and 8% less solar radiation than the lower part (Méndez-Toribio et al. 2016). Moisture availability differ among the topographic position at the lower portion of slope, larger amount of water and organic matter accumulate (Maidment 1993). Due to the solar illumination and shadowing, aspect have fundamental effect on the snow distribution and its melting (Dexter 1986; Baumgartner and Apfl 1997). Least SCA was observed in the July in all aspect classes. More than 50% area in all aspect classes are covered with SCA during January, February and March except E, SE, S and SW classes during January (Figure 5). Maximum SCA was observed in the February for all aspect classes, while maximum positive

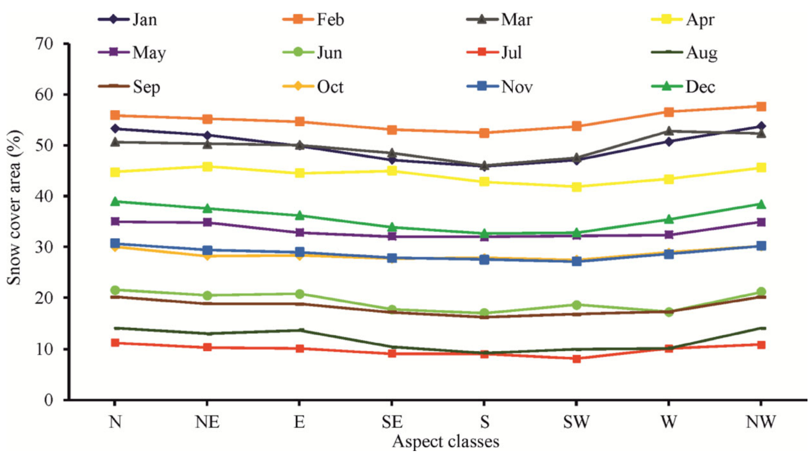

Figure 5. The average of 12 year SCA versus aspect classes shows maximum SCA in N, NE and NW classes.

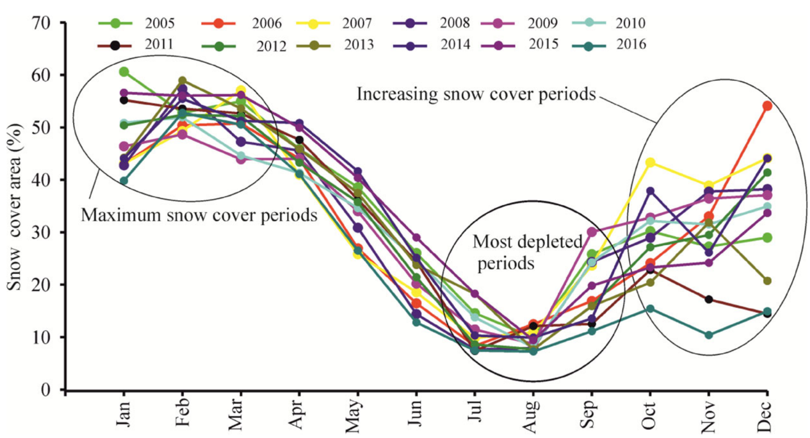

Figure 6. SCA depletion map shows most depleted period between July and September in UGRB.

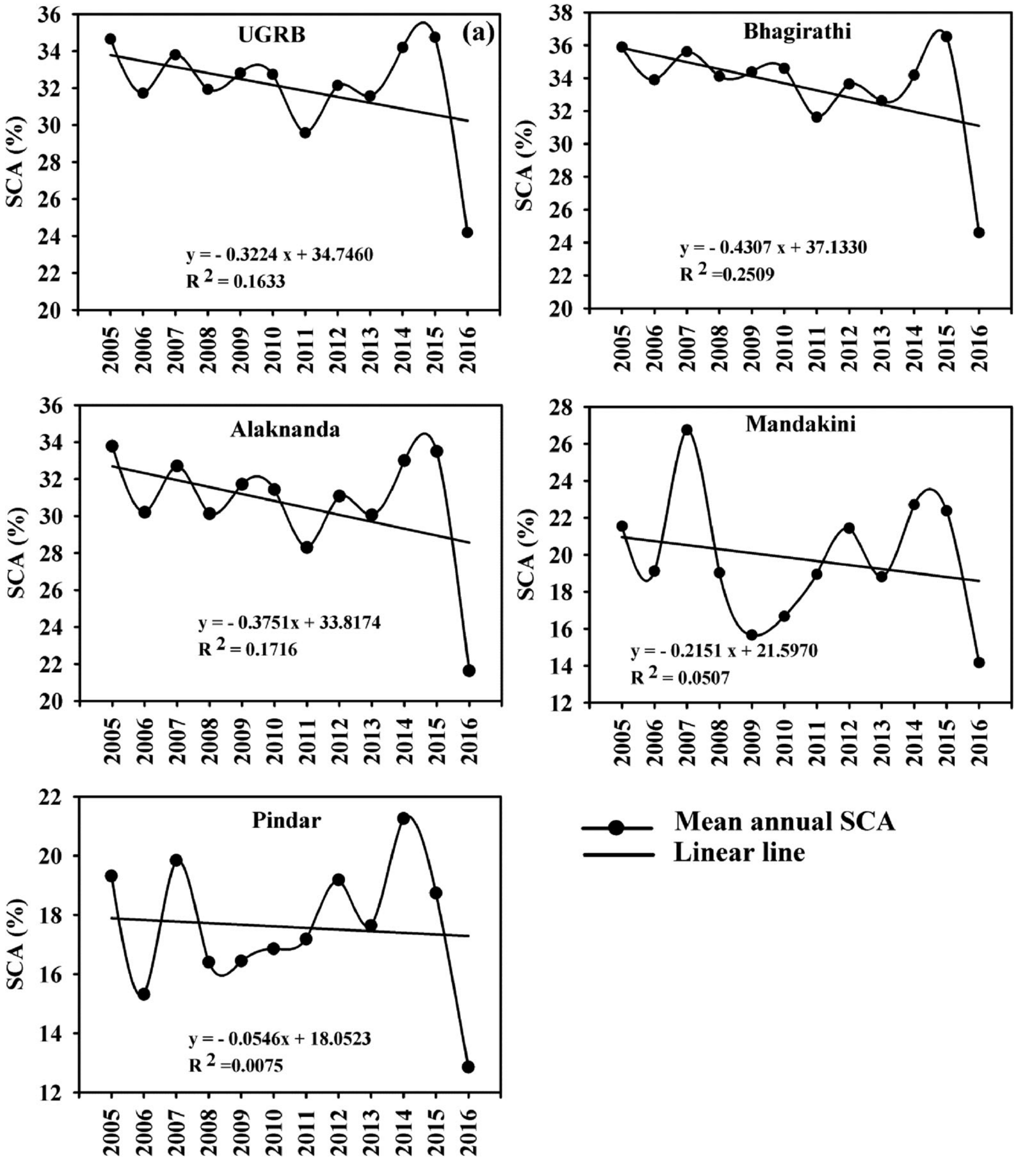

Figure 7. Annual, seasonal, trend analysis of average values of snowfall from 2005–2016 **a)** annual **b)** Premonsoon **c)** Winter **d)** monsoon **e)** Post monsoon.

attribution was found in the January with minimum positive difference in the July. A positive and negative both difference was found in the November as positive difference was observed in N, NE, SE and NW, while it is negative in S, SW and W aspect classes.

Spatio-temporal variation of SCA

A year is divided into four seasons based on the climatic conditions in the basin i.e., winter (January to March), Pre-monsoon (April to June), Monsoon (July to September) and Post-monsoon (October to December) (Rai et al. 2009; Arora et al. 2010). Based on the four seasons, broadly a year was classified into two periods i.e., ablation/depletion and

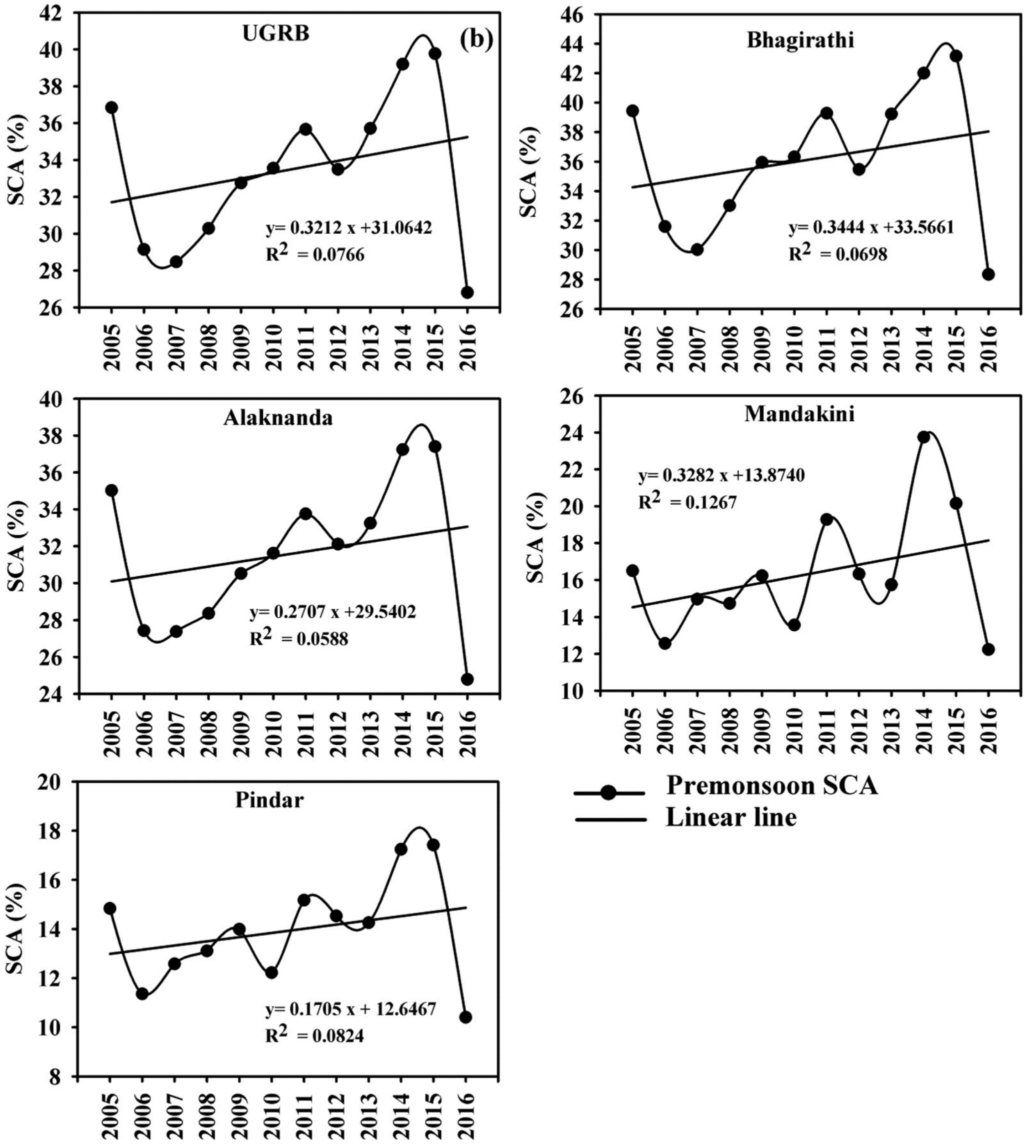

Figure 7. Continued

accumulation period. The ablation/depletion period tends to melting period with rising temperature. Under the Himalayan conditions, April to September is considered the ablation/depletion period, whereas the accumulation period cover October to March with snowfall events and less temperature (Jain et al. 2009, Ahluwalia et al. 2016).

The average SCA reaches to its maximum ~51.26 to~53.30% in the February and March and minimum ~9.35% to ~11.34% in the July and August during the study period (Figure 6). The SCA tends to increase from September (~19.50%) onwards, when wind is colder with the offset of monsoon (Figure 6). There is a large variation in SCA between December and January. It reaches ~33.90% to ~48.09% with the difference of ~15%. Further, January to March is considered the maximum accumulation period, however occurrence of snowfall takes place throughout the year in the greater Himalaya. However,

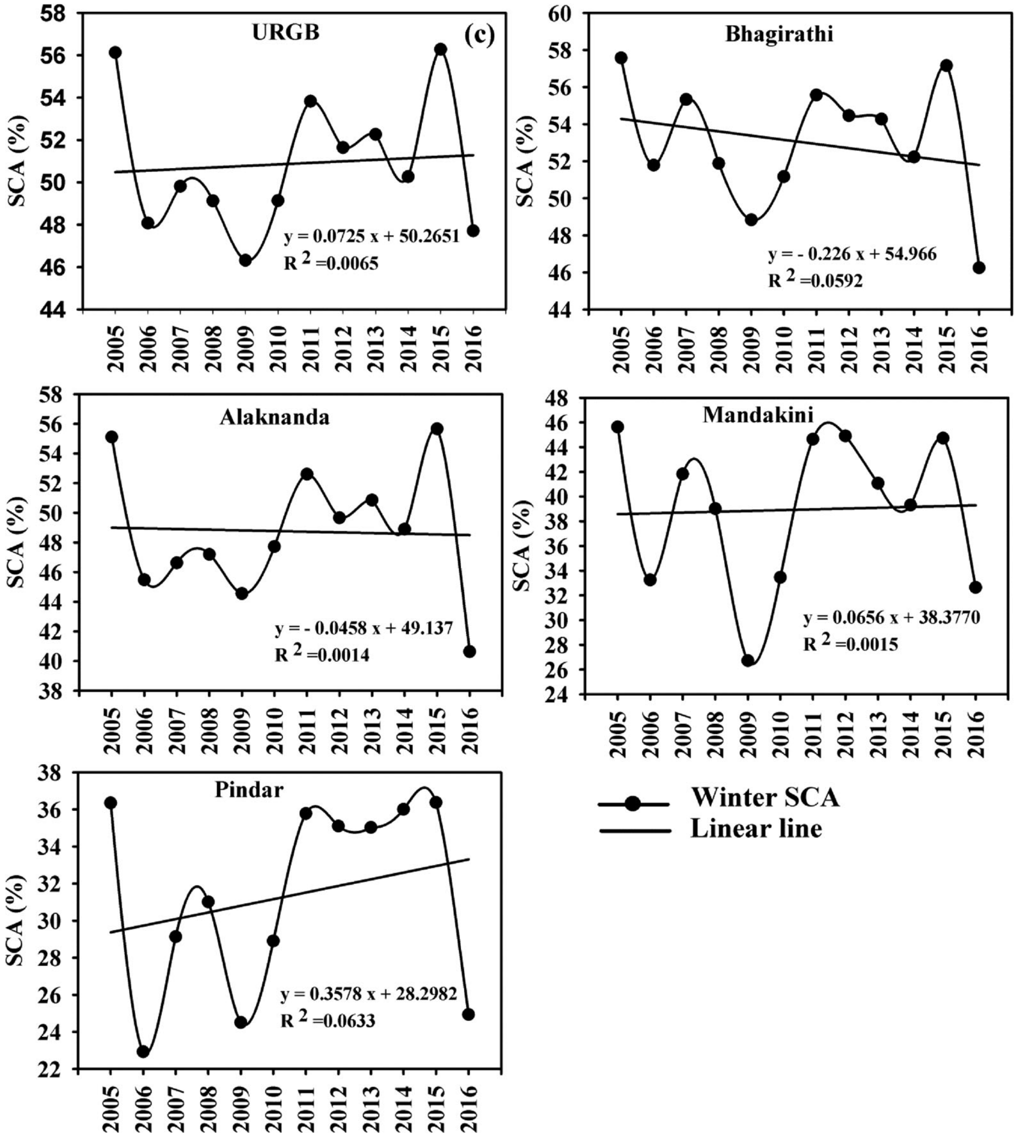

Figure 7. Continued

March is considered as the accumulation month, but in the middle Himalaya, temperature tends to increase and thus, melting of lower reaches snow takes place (Figure 6). During the winter, SCA tends to ∼39.74% in the winter season, whereas ∼26.15%, ∼10.46% and ∼23.65% in the premonsoon, monsoon and post monsoon seasons. However, Bhagirathi River Basin receive 54.05% and 54.09% SCA (almost equal) in the February and March with minimum ∼10.11% SCA in the August.

In Alaknanda River Basin, SCA is found maximum ∼50.74% in the February and minimum∼8.81% in the August. Similarly, it is found maximum in the February and minimum in the August in the Mandakini River Basin. However, SCA is found maximum ∼34.75% in the January and minimum∼5.66% in the August in the Pindar River Basin. This suggests that major portion of the basin remains with snow in the accumulation

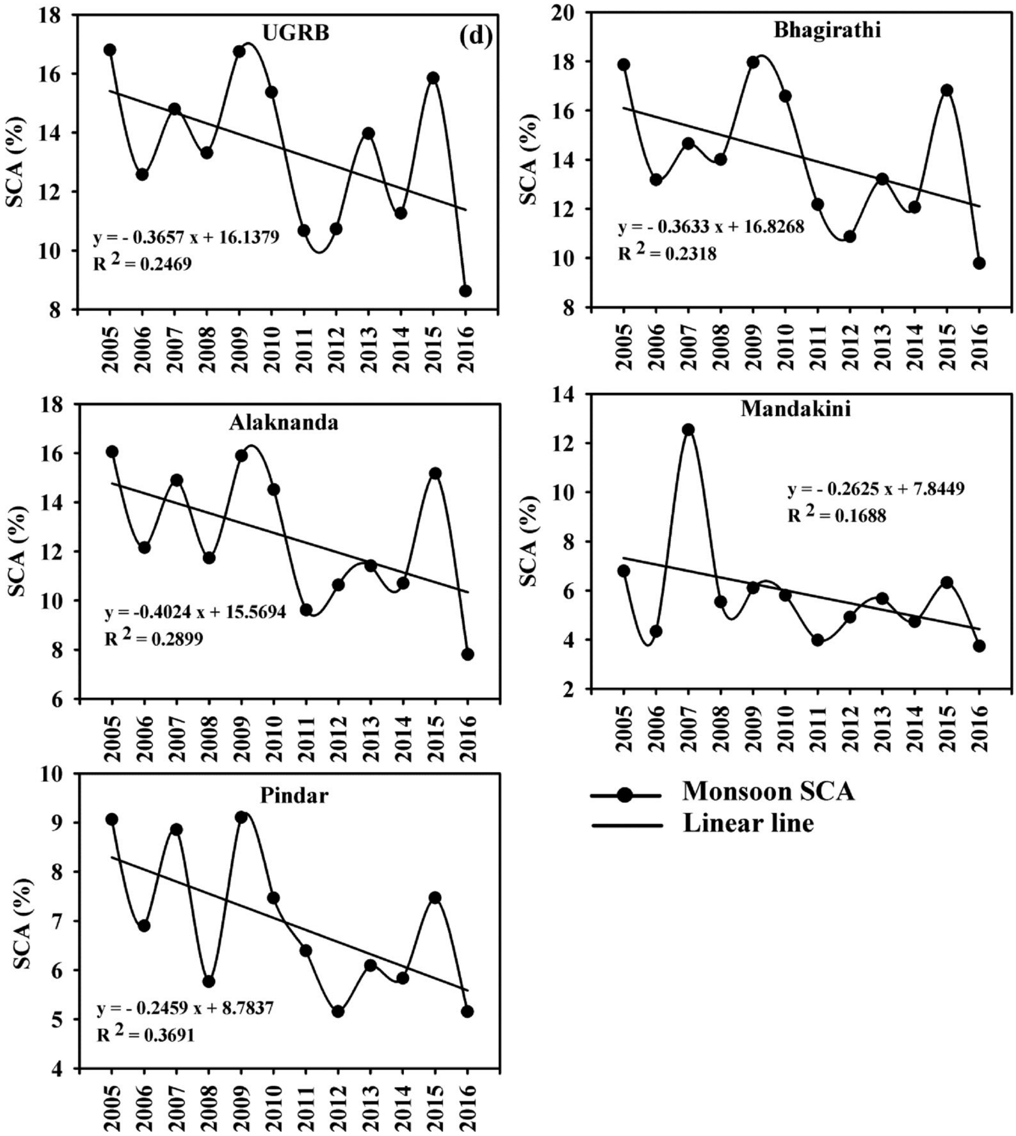

Figure 7. Continued

period and river receive significant proportion of snow melt with the rising temperature in the summer/premonsoon season. Rai et al. (2009) has been reported ∼97% contribution of snow/glacier melt runoff in the greater Himalaya at Gaumukh.

The linear trend analysis of mean annual values show insignificant negative trend for the UGRB and its all four sub-basins (Figure 7(a)). The premonsoon period shows insignificant positive trend for all basins (Figure 7(b)). However, for the winter period, Alaknanda and Bhagirathi river basins show insignificant negative trend but UGRB, Mandakini and Pindar river basins show insignificant positive trend (Figure 7(c)). Further, the monsoon and post monsoon period exhibit negative trend (Figure 7(d, e)) because the snowfall during this period occur only in very high altitude.

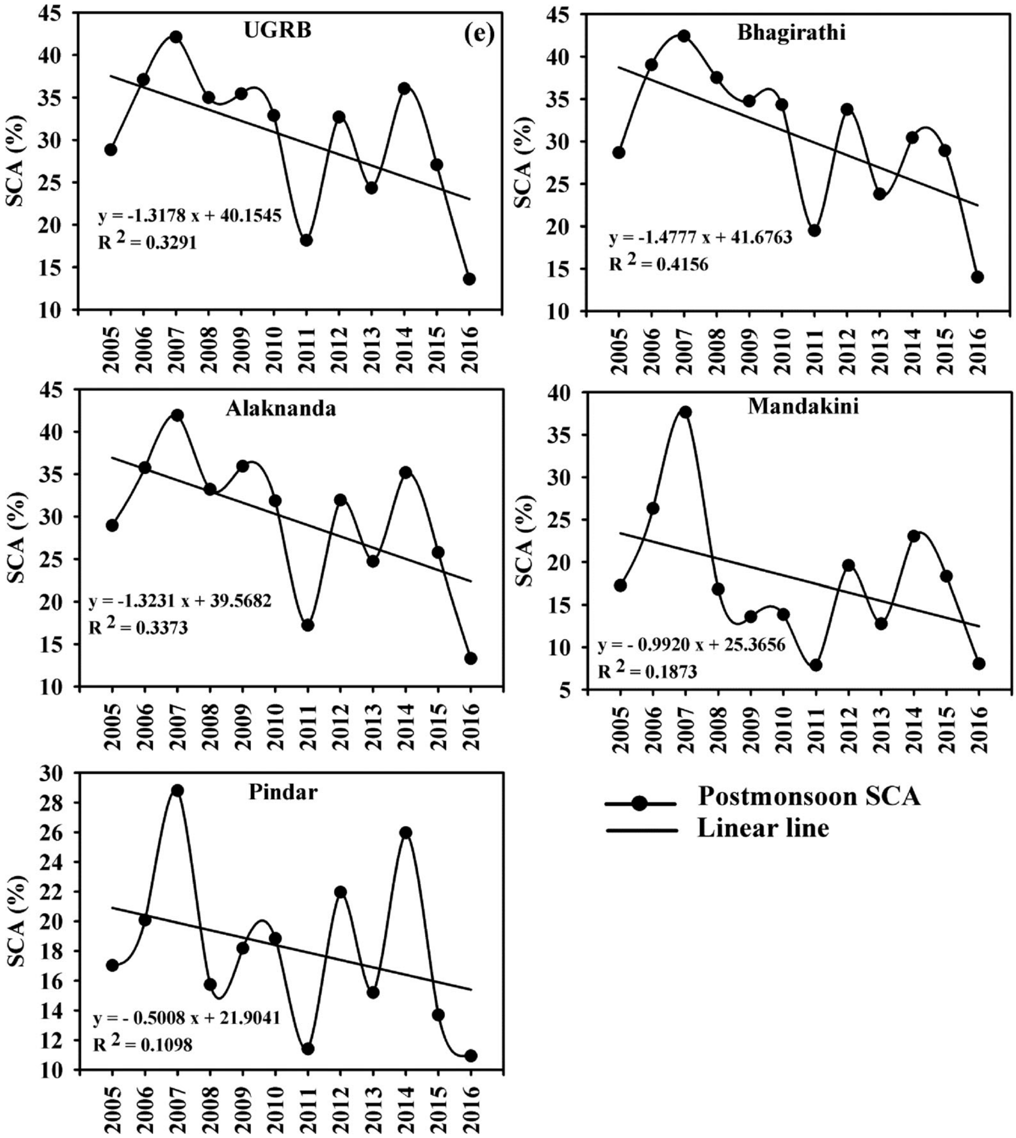

Figure 7. Continued

SCA is increased with elevation, though negative rate of change is found > 5500 m elevation during the accumulation period in the UGRB, however it follows positive rate of change in the ablation period (Table 4). However, annual average of SCA shows positive rate of change in the higher elevation zone in the UGRB. The Bhagirathi River Basin follows different trend with positive rate of change in both period for all elevation. While analyzing the SCA, it is observed that 2005, 2007, 2009, 2014, and 2015 show increasing trend of SCA. However, year 2016 shows most negative trend of SCA during the whole study period from 2005–2016. Ministry of Home Affairs, Government of India also reported that 2005 was the highest snowfall year ever recorded in the last 30 years (Annual Report 2004–2005).

Table 4. Rate of change of SCA % per 100 m during October to March (accumulation) and April to September (ablation/depletion period) for UGRB and its sub basin.

		UGRB (%)		Alaknanda (%)		Bhagirathi (%)		Mandakini (%)		Pindar (%)	
Elevation zones	Elevation ranges (m)	Accumulation Period	Ablation/ depletion period	Accumulation Period	Ablation/ Depletion period	Accumulation Period	Ablation/ Depletion period	Accumulation Period	Ablation/ Depletion period	Accumulation Period	Ablation/ Depletion period
1	419–500	0.00	0.00	0.00	0.00	0.00	0.00	–	–	–	–
2	500–1000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	1000–1500	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	1500–2000	0.45	0.16	0.69	0.06	0.80	0.08	0.63	0.08	0.68	0.14
5	2000–2500	1.13	0.08	1.12	0.08	1.14	0.09	1.40	0.12	1.04	0.09
6	2500–3000	2.90	0.13	2.60	0.11	3.50	0.18	3.71	0.18	2.94	0.17
7	3000–3500	3.18	0.47	3.07	0.44	3.30	0.52	2.59	0.38	1.77	0.26
8	3500–4000	2.40	1.47	2.74	1.47	1.79	1.48	2.38	1.58	3.20	1.72
9	4000–4500	2.54	2.56	2.95	2.68	1.88	2.36	3.25	3.14	3.92	3.31
10	4500–5000	1.96	3.12	2.17	3.16	1.81	3.10	3.61	5.06	3.56	4.59
11	5000–5500	1.09	3.57	0.98	3.72	1.34	3.42	1.27	6.23	1.59	4.80
12	5500–6000	−0.02	3.43	−0.24	3.60	0.20	3.23	−0.90	1.23	−0.10	2.17
13	6000–6500	0.26	2.92	−0.03	2.55	0.60	3.32	−1.34	0.81	−0.42	0.98
14	6500–7000	−0.26	1.08	−0.38	1.05	0.19	1.09	−0.59	0.22	1.31	0.97
15	Gt 7000	−0.53	0.01	−0.51	−0.01	–	–	–	–	–	–

Conclusion

The main objective of the study is to evaluate the spatio-temporal variability of SCA and effect of terrain attributes in the UGRB, central Himalaya. To achieve this aim, MODIS/Terra SCA 8 days L3 global 500 m grid (MOD10A2) and ASTER DEM were used. Annual mean of the SCA was found to be maximum ~34.65%, ~34.19% and ~34.74% in 2005, 2014 and 2015, respectively. A least SCA year was also examined and it was found ~24.18% in the year 2016. Monthly computed average of 12 years SCA is exhibited maximum ~53.30% in the February and minimum ~9.34% in the August. The Mandakini and Pindar River basin receive less SCA as these basin occupy less moderate to higher elevation areas. The amount of snow in extremely steep terrain is limited but not negligible. Accumulation of snow is more in moderately steep terrain. Insignificant SCA accumulation is observed with the slope steeper than 60° degree. This may be due to the gravity induced force and occurrence of snow sliding in higher slope classes. Among all 9 slope classes, SCA is found maximum in 20–30° slope class and minimum in 80–86.14° slope class. Further N and NW classes are found to be maximum SCA among all the 8 aspect classes considered in the study area. Among the terrain features considered in the study, variation in elevation has major influence on snow accumulation. Topography (slope, aspect and topographic position) drives environmental heterogeneity, thus effect of topography on the atmospheric flow field leads to an uneven deposition of snow at small scale. The result obtained from the present investigation can further be improved through other techniques and also by placing the more snow gauge stations. These can further be improved by incorporating the influence of meteorological parameters on SCA.

Acknowledgments

The MODIS data were acquired as part of NASA's Earth-Sun System Division and were archived and distributed by the reverb processing System. RSA and NPM is thankful to the Director, Wadia Institute of Himalayan Geology, Dehradun, India for supporting this research and permission to publish this work. Help extended by the Director, National Institute of Hydrology, Roorkee is also gratefully acknowledged.

Disclosure statement

The authors declare no conflict of interest.

Funding

This study was supported by National Mission for Sustaining the Himalayan Ecosystem (NMSHE) funded by Department of Science and Technology, GoI, New Delhi under the Research Project (Research Project ID number 9).

References

Ahluwalia RS, Rai SP, Gupta AK, Dobhal DP, Tiwari RK, Garg PK, Kesharwani K. 2016. Towards the understanding of the flash flood through isotope approach in Kedarnath valley in June 2013, Central Himalaya, India. Nat Hazards. 82(1):321–332.

Ahluwalia RS, Rai SP, Jain SK, Kumar B, Dobhal DP. 2013. Assessment of snowmelt runoff modelling and isotope analysis: a case study from the western Himalaya India. Ann Glaciol. 54(62):299–304.

Annual Report. 2004–2005. Government of India Ministry of Home Affairs. [accessed 2019 June 26]. https://mha.gov.in/sites/default/files/ar0405-Eng.pdf.

Arora M, Rathore DS, Singh RD, Kumar R, Kumar A. 2010. Estimation of melt contribution to total streamflow in river Bhagirathi and river DhauliGanga at Loharinag Pala and TapovanVishnugad project sites. JWARP. 02(07):636–643.

Azmat M, Liaqat UW, Qamar MU, Awan UK. 2017. Impacts of changing climate and snow cover on the flow regime of Jhelum River, Western Himalayas. Reg Environ Change. 17(3):813–825.

Bahadur J. 2004. Himalayan snow and glaciers: associated environmental problems, progress, and prospects (No. 7). New Delhi: Concept Publishing Company.

Bajracharya SR, Shrestha BR. 2011. The status of glaciers in the Hindu Kush-Himalayan region. Kathmandu, Nepal: International Centre for Integrated Mountain Development (ICIMOD).

Bajracharya SR, Maharjan SB, Shrestha F, Guo W, Liu S, Immerzeel W, Shrestha B. 2015. The glaciers of the Hindu Kush Himalayas: current status and observed changes from the 1980s to 2010. Int J Water Resour Dev. 31(2):161–173.

Baumgartner MF, Apfl GM. 1997. Remote sensing, geographic information systems and snowmelt runoff models—an integrated. In Remote sensing and geographic information systems for design and operation of water resources systems. Oxfordshire (UK): IAHS Publication; p. 73.

Bhambri R, Bolch T, Chaujar RK, Kulshreshtha SC. 2011. Glacier changes in the Garhwal Himalaya, India, from 1968 to 2006 based on remote sensing. J Glaciol. 57(203):543–556.

Bhutiyani MR, Kale VS, Pawar NJ. 2009. Climate change and the precipitation variations in the northwestern Himalaya: 1866–2006. Int J Climatol. 30(4):535–548.

Bloschl G, Kimbauer R. 1992. An analysis of snow cover patterns in a small alpine catchment. Hydrol Process. 6(1):99–109.

Brown RD, Robinson DA. 2011. Northern Hemisphere spring snow cover variability and change over 1922–2010 including an assessment of uncertainty. Cryosphere. 5(1):219–229.

Cohen J, Rind D. 1991. The effect of snow cover on the climate. J Climate. 4(7):689–706.

Dai L, Che T, Ding Y, Hao X. 2017. Evaluation of snow cover and snow depth on the Qinghai-Tibetan Plateau derived from passive microwave remote sensing. Cryosphere. 11(4):1–16.

Dexter LR. 1986. Aspect and elevation effects on the structure of the seasonal snow cover in Colorado [Ph.D. thesis]. University of Colorado.

Dey B, Kathuria SN, Kumar OB. 1985. Himalayan summer snow cover and withdrawal of the Indian summer monsoon. J Climate Appl Meteor. 24(8):865–868.

Dimri AP, Dash SK. 2012. Wintertime climatic trends in the western Himalayas. Clim Change. 111(3-4): 775–800.

DiPietro JA, Pogue KR. 2004. Tectonostratigraphic subdivisions of the Himalaya: A view from the west. Tectonics. 23(5):1–23..

Fayad A, Gascoin S, Faour G, Fanise P, Drapeau L, Somma J, Fadel A, Al Bitar A, Escadafal R. 2017. Snow observations in Mount Lebanon (2011–2016). Earth Syst Sci Data. 9(2):573–587.

Gaddam VK, Kulkarni AV, Gupta AK. 2020. Assessment of the Baspa basin glaciers mass budget using different remote sensing methods and modeling techniques. Geocarto Int. 35(3):296–221.

Gao Y, Xie H, Yao T, Xue C. 2010. Integrated assessment on multi-temporal and multi-sensor combinations for reducing cloud obscuration of MODIS snow cover products of the Pacific Northwest USA. Remote Sens Environ. 114(8):1662–1675.

Hahn DG, Shukla J. 1976. An apparent relationship between Eurasian snow cover and Indian monsoon rainfall. J Atmos Sci. 33(12):2461–2462.

Hall DK, Foster JL, Salomonson VV, Klein AG, Chien JYL. 2001. Development of a technique to assess snow-cover mapping errors from space. IEEE Trans Geosci Remote Sens. 39(2):432–438.

Holland PG, Steyn DG. 1975. Vegetational responses to latitudinal variations in slope angle and aspect. J Biogeogr. 2(3):179–183.

Immerzeel WW, Van Beek LP, Bierkens MF. 2010. Climate change will affect the Asian water towers. Science. 328(5984):1382–1385.

IPCC. 2001. Third assessment report. Summary for policymakers-2001.

Jain SK, Goswami A, Saraf AK. 2009. Role of elevation and aspect in snow distribution in Western Himalaya. Water Resour Manage. 23(1):71–83.

Khan AA, Pant NC, Goswami A, Lal R, Joshi R. 2015. Critical evaluation and assessment of average annual precipitation in the Indus, the Ganges and the Brahmaputra basins, Northern India. In: Dynamics of climate change and water resources of Northwestern Himalaya. Cham: Springer; p. 67–84.

Khan AA, Pant NC, Sarkar A, Tandon SK, Thamban M, Mahalinganathan K. 2017. The Himalayan cryosphere: A critical assessment and evaluation of glacial melt fraction in the Bhagirathi basin. Geosci Front. 8(1):107–115.

Kour R, Patel N, Krishna AP. 2016. Effects of terrain attributes on snow-cover dynamics in parts of Chenab basin, western Himalayas. Hydrol Sci J. 61(10):1–1876.

Kulkarni AV, Karyakarte Y. 2014. Observed changes in Himalayan glaciers. Curr Sci. 106(2):237–244.

Kulkarni AV, Bahuguna IM, Rathore BP, Singh SK, Randhawa SS, Sood RK, Dhar S. 2007. Glacial retreat in Himalaya using Indian remote sensing satellite data. Curr Sci. 92(1):69–74.

Maidment DR. 1993. Handbook of hydrology. Vol. 9780070. New York: McGraw-Hill; p. 397323.

Méndez-Toribio M, Meave JA, Zermeño-Hernández I, Ibarra-Manríquez G. 2016. Effects of slope aspect and topographic position on environmental variables, disturbance regime and tree community attributes in a seasonal tropical dry forest. J Veg Sci. 27(6):1094–1103.

Negi HS, Shekhar MS, Gusain HS, Ganju A. 2018. Winter climate and snow cover variability over northwest Himalaya. In: Science and geopolitics of the white world. Cham: Springer; p. 127–142.

Painter TH, Rittger K, McKenzie C, Slaughter P, Davis RE, Dozier J. 2009. Retrieval of subpixel snow covered area, grain size, and albedo from MODIS. Remote Sens Environ. 113(4):868–879.

Parajka J, Pepe M, Rampini A, Rossi S, Blöschl G. 2010. A regional snow-line method for estimating snow cover from MODIS during cloud cover. J Hydrol. 381(3–4):203–212.

Parthasarathy B, Yang S. 1995. Relationships between regional Indian summer monsoon rainfall and Eurasian snow cover. Adv Atmos Sci. 12(2):143–150.

Pu Z, Xu L, Salomonson VV. 2007. MODIS/Terra observed seasonal variations of snow cover over the Tibetan Plateau. Geophys Res Lett. 34(6):1–6.

Rai SP, Kumar B, Singh P. 2009. Estimation of contribution of southwest monsoon rain to Bhagirathi River near Gaumukh, western Himalayas, India, using oxygen-18 isotope. Curr Sci. 97(2):240–245.

Raina VK, Srivastava D. 2008. Glacier atlas of India. India: Geological Society of India; p. 316.

Saavedra FA, Kampf SK, Fassnacht SR, Sibold JS. 2017. A snow climatology of the Andes Mountains from MODIS snow cover data. Int J Climatol. 37(3):1526–1539.

Sankar-Rao M, Lau KM, Yang S. 1996. On the relationship between Eurasian snow cover and the Asian summer monsoon. Int J Climatol. 16(6):605–616.

Schmid UG, Sardemann S. 2003. High-frequency avalanches: release area characteristics and run-out distances. Cold Reg Sci Technol. 37(3):439–451.

Schweizer J, Bruce Jamieson J, Schneebeli M. 2003. Snow avalanche formation. Rev Geophys. 41(4):1–25.

Shafiq MU, Ahmed P, Islam ZU, Joshi PK, Bhat WA. 2019. Snow cover area change and its relations with climatic variability in Kashmir Himalayas, India. Geocarto Int. 34(6):688.

Sharma SS, Ganju A. 2000. Complexities of avalanche forecasting in western Himalaya - an overview. Cold Reg Sci Technol. 31(2):95–102.

Sharma V, Mishra VD, Joshi PK. 2014. Topographic controls on spatio-temporal snow cover distribution in Northwest Himalaya. Int J Remote Sens. 35(9):3036–3056.

Shukla S, Kansal ML, Jain SK. 2017. Snow cover area variability assessment in the upper part of the Satluj river basin in India. Geocarto Int. 32(11):1285–1306.

Singh DK, Gusain HS, Mishra V, Gupta N, 2018. Snow cover variability in North-West Himalaya during last decade. Arab J Geosci. 11(19):579.

Singh P, Jain SK. 2002. Snow and glacier melt in the Satluj River at Bhakra Dam in the western Himalayan region. Hydrological Sciences Journal. 47(1):93106.

Winstral A, Marks D. 2002. Simulating wind fields and snow redistribution using terrain-based parameters to model snow accumulation and melt over a semi-arid mountain catchment. Hydrol Process. 16(18):3585–3603.

Woo MK, Thorne R. 2006. Snowmelt contribution to discharge from a large mountainous catchment in subarctic Canada. Hydrol Process. 20(10):2129–2139.

Yang C, Zhao Z, Ni J, Ren X, Wang Q. 2012. Temporal and spatial analysis of changes in snow cover in western Sichuan based on MODIS images. Sci China Earth Sci. 55(8):1329–1335.

Yang S. 1996. ENSO–snow–monsoon associations and seasonal–interannual predictions. Int J Climatol. 16(2):125–134.

Yaning C, Changchun XU, Yapeng C, Zhongqin L, Zhonghe P. 2008. Response of snow cover to climate change in the periphery mountains of Tarim river basin, China, over the past four decades. Ann Glaciol. 49:166–172.

Yu L, Liu T, Zhang S. 2017. Temporal and spatial changes in snow cover and the corresponding radiative forcing analysis in Siberia from the 1970s to the 2010s. Adv Meteorol. 2017:1–11.

Sl. No. G-802

OFFICE OF THE DEEPUTY COMMISSIONER ★ IMPHAL WEST MANIPUR ★ सत्यमेव जयते

Annexure

FORM OF CERTIFICATE TO BE PRODUCED BY OTHER BACKWARD CLASSES APPLYING FOR APPOINTMENT TO POSTS UNDER THE GOVERNMENT OF INDIA

This is to certify that Shri/Smt./Kumari NINGOMBAM PRIKASH MEETEI son/daughter of (L). N. DHANANJOY MEETEI of village/town YUREMBAM MAYAI LEIKAI in District/Division PATSOI in the State/Union Territory MANIPUR belongs to the MEETEI community which is recognised as a backward class under the Government of India, Ministry of Social Justice and Empowerment's Resolution No. ______ dated ______ *. Shri/Smt./Kumari NINGOMBAM PRIKASH MEETEI and /or his/her family ordinarily reside(s) in the IMPHAL WEST District/Division of the MANIPUR State/Union Territory. This is also to certify that he/she does not belong to the persons/sections (Creamy Layer) mentioned in Column 3 of the Schedule to the Government of India, Department of Personnel & Training O.M. No. 36012/22/93-Estt. (SCT) dated 8.9.1993**.

District Magistrate
Deputy Commissioner etc.

Addl. District Magistrate.
Imphal West District,
Manipur.

Dated: 13/1/2018

Sub-Deputy Collector
Imphal West Patsoi
Seal

Sub-Divisional Magistrate
Patsoi, Imphal West District
Manipur

*- The authority issuing the certificate may have to mention the details of Resolution of Government of India, in which the caste of the candidate is mentioned as OBC.

**- As amended from time to time.

Note:- The term "Ordinarily" used here will have the same meaning as in Section 20 of the Representation of the People Act, 1950.

Quaternary International 585 (2021) 183–194

Contents lists available at ScienceDirect

Quaternary International

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

Spatial-diurnal variability of snow/glacier melt runoff in glacier regime river valley: Central Himalaya, India

Rajeev S. Ahluwalia [a,*], S.P. Rai [b], Prikash N. Meetei [a,c], Sushil Kumar [d], Shushanta Sarangi [c], Pankaj Chauhan [d], Indira Karakoti [a]

[a] Centre for Glaciology, WIHG, Dehradun, 248001, India
[b] Deptt of Geology, Banaras Hindu University, Banaras, 248001, India
[c] Deptt of Applied Geology, Indian Institute of Technology (ISM), Dhanbad, 826004, India
[d] Wadia Institute of Himalayan Geology, Dehradun, 248001, India

ARTICLE INFO

Keywords:
Spatial-diurnal variation
Stable isotope
Snow/glacier melt runoff
Groundwater
Bhagirathi river

ABSTRACT

Spatial-diurnal variability in the snow/glacier melt isotope signature and their influence on hydrograph separation based on mixing model received less attention. We present isotope data from a high elevation catchment (glacierized area: 286 km^2) in the central Himalaya (India) and investigated the spatial-diurnal variability of snow/glacier meltwater along with inferences of groundwater dynamics. Isotope signature variation in streamflow was small during the study period. We applied a two-component mixing model using oxygen-18 and electrical conductivity. Hydrograph separation (snow/glacier meltwater and groundwater) was carried out for Bhagirathi River at three sites i.e., Gaumukh, Bhojbasa, and Gangotri, during the ablation period of 2014 (September). The Bhagirathi River is a major tributary of river Ganga, originate from Gangotri Glacier (~30 km), the largest glacier in central Himalaya. The electrical conductivity of the river is measured in-situ and varies from 10 μS/cm to 100 μS/cm. The river water isotope signature of oxygen was ranged from −15.53‰ to −14.32‰ from Gaumukh to Gangotri, snow samples were ranged from - 17.63‰ to - 15.86‰ collected at Gaumukh. Groundwater samples were varied from −8.53‰ to-7.57‰ from Gaumukh to Gangotri. River water signature is close to snow/glacier melt runoff signature, reveal that the snow/glacier melt runoff contribution is higher in river flow. Average fractions of snow/glacier melt runoff were estimated ~82% to~76%, whereas groundwater was estimated ~18% to ~24%. The results of this study reveal the necessity of a multiple sampling approaches to characterize the snow/glacier melt and the importance of groundwater dynamics in catchments with snow/glacial runoff regime.

1. Introduction

Most of the rivers in the world originate from the places in the high mountainous region, where a huge amount of freshwater is stored in the form of snow and glacier (Barnett et al., 2005; Kaser et al., 2010; Ahluwalia et al., 2013; Rai et al., 2019). Three major river system namely Ganga, Brahmaputra and Indus emanate from such high altitude snow/glacier covered region in Himalaya and fed by snow/glacier melt runoff (Rai et al., 2009; Maurya et al., 2011; Kulkarni and Karyakarte, 2014; Gaddam et al., 2018). Rising demand for freshwater, industrial and societal development always depend on these Himalayan rivers (Jain et al., 2007). Snow/glacier mass loss may impact freshwater supply on the socio-economic structure of the people living in downstream (Jain et al., 2010; Ahluwalia et al., 2015). Therefore, accurate quantification of snow/glacier melt runoff contribution on microscale basin in extreme high altitude valley becomes necessary to investigate the origin of water to understand the stream flow generation in a glacierized catchment under the scope of changing climate. Among them, the Ganga River system originate from central Himalaya and travel around Gangasagar by traversing a distance of 2525 km from five states. Food and water for nearly half of the population in the country come from the Ganga River system and contribute ~ 25% of the country's gross water (Singh et al., 2005; Arora et al., 2010). Therefore, an attempt was made to assess the spatial diurnal variability of snow/glacier melt runoff and inferences of dynamics of groundwater in the Bhagirathi River.

In the recent past, many studies have been carried out covering the

* Corresponding author.
E-mail address: raahluwalia05@gmail.com (R.S. Ahluwalia).

https://doi.org/10.1016/j.quaint.2021.01.003
Received 10 June 2020; Received in revised form 30 December 2020; Accepted 6 January 2021
Available online 12 January 2021

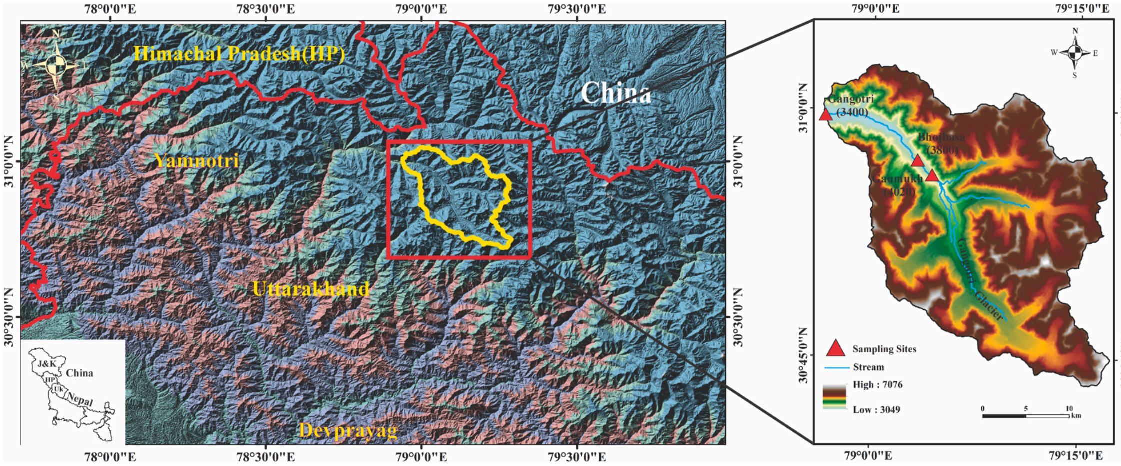

Fig. 1. Study area of the headwater region of the Bhagirathi River, a major tributary of the Ganga River, for the spatial diurnal variability of the source water.

different aspects of Geology, Glaciology and Geomorphology in the Ganga River system. The water chemistry of headwater of the Ganga River has been investigated by Pandey et al., (1999), Ahmad and Hasnain (2001), Chakrapani (2005), Singh et al. (2012), Kumar et al. (2009), Trivedi et al. (2010). Tangri (2000) made an attempt to study the basic drainage network and associated geomorphological aspects of the Bhagirathi River basin. The water balance/modeling aspects of the stream-flow in the Bhagirathi River at Devprayag has been attempted by Singh et al. (1994). Singh et al. (2005) have made an attempt to study the diurnal variation in discharge and suspended sediment concentration near Gaumukh. Maurya et al. (2011) and Khan et al. (2017) have estimated the average snow/glacier melt contribution in the Ganga River downstream at Devprayag and Rishikesh by adopting isotope approach. However, spatial-diurnal variability in isotope signature of the source water and their contribution to the river could not receive much attention.

The stable isotope characteristics of the Himalayan rivers have been studied by Ramesh and Sarin. (1992), Dalai et al. (2002), Rai et al. (2009), Rai et al. (2016), Khan et al., 2017, Ala-Aho et al. (2018). Carbon isotope composition have been studied to understand the source of dissolved inorganic carbon (Chakrapani and Veizer., 2005). The correlation of electrical conductivity and stable isotope $\delta^{18}O$ in the Bhagirathi River was also studied by (Lamb, 2000).

In order to carry out the study, isotope signature ($\delta^{18}O$ and δD) of snow/glacier melt runoff, groundwater and river water were analyzed on the spatial-diurnal basis. Further, an attempt was also made to assess the relationship of d-excess and electrical conductivity of river discharge to different source water.

2. Study area

The study was conducted in the head water region of the Bhagirathi River basin, a sub-basin of the Ganga River system, for the spatial diurnal variability of snow/glacier melt runoff at Gaumukh, Bhojbasa, and Gangotri. Upper reaches of the river basin remain under snow cover throughout the year. Cluster of many glaciers and the main Gangotri Glacier (length: 30 km) forms the trunk part of the system. This is known as Gangotri Glacier system. The major glacier tributaries of the Gangotri Glacier system are Raktvarn Glacier (area: 45.34 km^2), Chaturangi Glacier (area: 72.91 km^2), Kirti Glacier (area: 31.28 km^2), Swachand Glacier (area: 16.71 km^2), Ghanohim Glacier (area: 12.97 km^2), Meru Glacier (area: 6.11 km^2), Maindi Glacier (area: 4.76 km^2) (Naithani et al., 2001).

The study area lies between 30°43′20.90″ N and 31°2′44.93″ N latitude and longitude between 78°56′18.59″ E and 79°17′18.26″ E covering the area of 691 km^2 up to Gangotri near the temple site, with an elevation range between 3049 and 7076 amsl at Chaokhamba peak, central Himalaya (Fig. 1).

The study area receives the average seasonal (May–October) precipitation was ~427 mm. From June to September, precipitation occurred more than ~85% of the days (Singh et al., 2007). The mean monthly temperature from May to October is reported 8.9, 10.3, 11.7, 10.8, 8.0, and 5.3 °C respectively by Singh et al., 2007). July is the warmest month. The study area experience winter from October onwards characterized by the occurrence of snowfall at higher altitudes. An important source of moisture for precipitation during winter is western disturbance originates from the Caspian sea (Rai et al., 2009; Lambs et al., 2005., Meetei et al., 2020). The winter season is followed

Fig. 2. Field photographs during the diurnalcollection of river water sample in the highaltitude Bhagirathi Rivervalley.

Table 1
Diurnal Isotope signature of river water at Gaumukh, Bhojbasa, and Gangotri along with the snow/glacier melt water and groundwater.

S no	Gaumukh						Bhojbasa						Gangotri						Snow/Glacier melt				Groundwater			
	Date	Time	$\delta^{18}O$	δD	EC	d-ex.	Date	Time	$\delta^{18}O$	δD	EC	d-ex	Date	Time	$\delta^{18}O$	δD	EC	d-ex.	$\delta^{18}O$	δD	EC	d-ex.	$\delta^{18}O$	δD	EC	d-ex.
	9/14/2014	9.00	−15.3	−107.2	90	15	9/15/2014	10.00	−14.9	−104.7	80	14	9/21/2014	8.00	−15.3	−104.9	90	17	−16.9	−117	30	18	−8.4	−56.1	190	11
	9/14/2014	6.00	−15.4	−105.8	90	17	9/20/2014	8.00	−14.7	−103.6	90	14	9/21/2014	9.00	−14.5	−100.2	70	16	−15.9	−113.2	30	14	−8	−53.3	180	11
	9/15/2014	10.00	−15.1	−103.4	60	17	9/20/2014	9.00	−15	−105.7	70	14	9/21/2014	1.00	−14.9	−100.9	70	18	−15.9	−111.5	10	15	−7.6	−49.8	180	11
	9/16/2014	8.00	−14.9	−103.8	50	15	9/20/2014	10.00	−15	−107.1	80	13	9/21/2014	6.00	−14.8	−102.2	80	16	−17.1	−121.3	30	15	−8.1	−53.6	240	12
	9/16/2014	9.00	−15.2	−105.5	80	16	9/20/2014	11.00	−15.1	−105.2	90	16	9/22/2014	9.00	−14.9	−101.3	90	18	−17.6	−124.1	10	17	−8.1	−55.2	290	10
	9/16/2014	10.00	−15.3	−107.5	80	15	9/20/2014	12.00	−15.1	−104.9	80	16	9/22/2014	6.00	−14.8	−102.5	80	16	−15.9	−112	10	15	−8.3	−54.9	280	12
	9/16/2014	11.00	−15.1	−99.52	60	21	9/20/2014	1.00	−15.2	−107.1	90	14	9/23/2014	7.00	−15	−102.8	80	17	−17.4	−121.7	40	17	−8.5	−57.7	760	11
	9/16/2014	12.00	−14.9	−105.2	70	14	9/20/2014	2.00	−15	−105.4	80	14	9/23/2014	8.00	−14.9	−101.6	70	18	−16.2	−113.4	30	16	−9.1	−61.4	280	11
	9/16/2014	1.00	−15.3	−107	80	15	9/20/2014	3.00	−14.9	−106.2	70	13	9/23/2014	9.00	−14.9	−104	80	16	−16.8	−116.6	20	18	−8.7	−58.7	290	11
	9/16/2014	2.00	−15.1	−103.6	70	17	9/20/2014	4.00	−15.2	−106.6	70	15	9/23/2014	10.00	−14.3	−101	90	14	−16.7	−118.5	40	15	−8.9	−62.1	510	9
	9/16/2014	3.00	−15	−105.3	80	15	9/20/2014	5.00	−15.1	−105.2	60	15	9/23/2014	11.00	−14.7	−102.1	80	16	−16.9	−119.7	20	15	−9.1	−60.8	380	12
	9/16/2014	4.00	−15	−101.5	50	18	9/20/2014	6.00	−15	−103.6	50	17	9/23/2014	12.00	−15	−103.3	80	17					−9	−63.1	300	9
	9/16/2014	5.00	−15.1	−104.5	80	16	9/20/2014	7.00	−15	−102.9	50	17	9/23/2014	1.00	−14.5	−100.8	90	15					−9.2	−63.4	150	10
	9/16/2014	6.00	−15.2	−105.1	80	16	9/20/2014	8.00	−15.1	−104.3	40	17	9/23/2014	2.00	−14.7	−103.3	90	14					−8.6	−56.9	350	12
	9/16/2014	7.00	−14.9	−103.4	50	16	9/20/2014	9.00	−14.9	−104.2	40	15	9/23/2014	3.00	−14.8	−104.8	80	13					−8.4	−54.6	220	12
	9/16/2014	8.00	−15.2	−103.9	90	17	9/20/2014	10.00	−15.2	−105.9	70	16	9/23/2014	4.00	−14.7	−103.8	70	14								
	9/16/2014	9.00	−15.2	−101.4	70	20	9/20/2014	11.00	−14.5	−103.9	70	12	9/23/2014	5.00	−14.9	−103.6	60	15								

(*continued on next page*)

Table 1 (*continued*)

S no	Gaumukh						Bhojbasa						Gangotri						Snow/Glacier melt				Groundwater			
	Date	Time	$\delta^{18}O$	δD	EC	d-ex.	Date	Time	$\delta^{18}O$	δD	EC	d-ex	Date	Time	$\delta^{18}O$	δD	EC	d-ex.	$\delta^{18}O$	δD	EC	d-ex.	$\delta^{18}O$	δD	EC	d-ex.
	9/16/2014	10.00	−15.4	−108.7	10	15	9/21/2014	8.00	−15.1	−105.7	70	15	9/23/2014	6.00	−14.7	−102.1	60	16								
	9/17/2014	8.00	−15.4	−107.3	90	16	9/21/2014	9.00	−15.2	−105.7	70	16	9/23/2014	7.00	−14.8	−102.3	50	16								
	9/17/2014	9.00	−15.5	−107.1	90	17	9/21/2014	10.00	−15.2	−104.1	70	17	9/23/2014	8.00	−14.6	−101.8	40	15								
	9/17/2014	10.00	−15.1	−106	100	15	9/21/2014	11.00	−15.1	−104.1	70	17	9/23/2014	9.00	−14.8	−101.4	70	17								
	9/17/2014	11.00	−15.3	−107.4	90	15	9/21/2014	12.00	−15.2	−105.3	70	17	9/23/2014	10.00	−14.8	−102.1	70	16								
	9/17/2014	12.00	−15.4	−106.1	100	17	9/21/2014	1.00	−15.1	−105	70	16	9/23/2014	11.00	−15	−103.1	70	17								
	9/17/2014	1.00	−15.4	−105.7	90	17	9/21/2014	2.00	−15.2	−104.6	70	17	9/23/2014	12.00	−14.8	−103.9	70	14								
	9/17/2014	2.00	−15.2	−105.4	70	16	9/21/2014	3.00	−15	−104.2	80	16	9/24/2014	8.00	−14.8	−102.7	70	16								
	9/17/2014	3.00	−15.1	−105	30	16	9/21/2014	4.00	−15	−103.8	80	16	9/24/2014	9.00	−14.6	−102.1	60	14								
	9/17/2014	4.00	−15.1	−102.3	40	18							9/24/2014	10.00	−14.9	−103.6	70	15								
	9/17/2014	5.00	−15.3	−105.7	50	17							9/24/2014	11.00	−14.9	−103.7	80	16								
	9/17/2014	6.00	−15.1	−105.3	50	15							9/24/2014	12.00	−14.7	−102.8	80	15								
	9/18/2014	9.00	−15.3	−106.7	50	16							9/24/2014	1.00	−14.8	−103.3	80	15								
	9/18/2014	1.00	−15.1	−106.7	50	14																				
	9/19/2014	9.00	−15.1	−104.2	90	17																				
	9/19/2014	1.00	−15.4	−107.9	80	15																				
	9/19/2014	6.00	−15.4	−106.1	70	17																				
		9.00	−15.3	−106.5	80	16																				

(*continued on next page*)

Table 1 (*continued*)

S no	Gaumukh						Bhojbasa						Gangotri						Snow/Glacier melt				Groundwater			
	Date	Time	$\delta^{18}O$	δD	EC	d-ex.	Date	Time	$\delta^{18}O$	δD	EC	d-ex	Date	Time	$\delta^{18}O$	δD	EC	d-ex.	$\delta^{18}O$	δD	EC	d-ex.	$\delta^{18}O$	δD	EC	d-ex.
	9/20/2014																									
	9/20/2014	1.00	−15.2	−106.8	90	15																				
	9/20/2014	6.00	−15.2	−106.2	80	15																				
	9/21/2014	9.00	−15	−106.2	100	14																				
	9/21/2014	1.00	−15.4	−107.2	80	16																				

by the pre-monsoon season (April to June). The monsoon season sets usually by July and extend up to September.

The high altitude Ganga River basin is comprised of young immature mountains of the central Himalaya. The basin have glacial valleys in the higher reaches and deep river gorges in the lower parts. The Gangotri Glacier does not occupy the entire section of the valley but has longitudinal valleys along its sides between its lateral moraine and the valley walls. At some places, alluvial deposits have covered the glacial deposits and even affected their shapes. There are large depressions partially or fully filled up between the oldest preserved moraines and the valley walls at the confluence of large tributaries with the main glacier. These are Tapoban at the confluence of Meru glacier and Brahmpuri at the confluence of Kirti Bamak, etc. Besides these, there are a number of small and large lakes over the glacier. These lakes are being filled up by debris from surface moraines and some of the dried contain varve like accumulations of clays and association (Tangri, 2000).

3. Methodology

3.1. Samples collection and analysis

A total of 121 samples of river water, snow/glacier meltwater along with groundwater were collected for isotope analysis in the study area (Fig. 2). Samples were collected at three sites on an hourly basis at Gaumukh (Site I-4020 a.m.s.l), Bhojbasa (Site II-3800 a.m.s.l) and Gangotri (Site III-3400 a.m.s.l) in the ablation period (September) 2014. Groundwater samples were collected from the springs along the hill slope close to the river. Snow/glacier samples were collected to the upstream of the river at different altitudes varying between 4000a.m.s.l to 4500a.m.s.l. Snow/glacier samples were collected in zip-lock polybags and kept in a cold and dark place.

Water samples were collected in pre-cleaned Tarson ~20 ml polypropylene bottles for stable isotope ($\delta^{18}O$ and δD) measurement. The bottles were rinsed thoroughly with sample water at the sample site, filled with respective water sample tightly capped to prevent evaporation and exchange with atmospheric moisture and transferred to the laboratory for isotope analyses.

The oxygen and deuterium ($\delta\ ^{18}O$ & δD) isotope measurement was carried out using a Dual Inlet Isotope Ratio Mass Spectrometer (GV Instruments, UK) with an automatic sample preparation unit. For ($\delta\ ^{18}O$ & δD), 400 μl water sample was taken and hokkobeads were used as the catalyst. Along with each batch of samples, secondary standards developed with reference to primary standards (i.e. V-SMOW, SLAP, GISP) and final δ values were calculated using a triple-point calibration equation. The overall precision, based on ten points of repeated measurement of each sample, was within ±0.1‰ for $\delta\ ^{18}O$ and ±1‰ for δD. Isotopic ratio is reported in the d notation (as ½) relative to the Vienna-Standard Mean Ocean Water (V-SMOW):

$$\delta = \left[\left(\frac{Rsa}{Rst}\right) - 1\right] \times 1000 \quad (1)$$

where R is the ratio of $^{18}O/^{16}O$ or $^{2}H/^{1}H$ for water samples and standard water sample.

3.2. Isotope approach

The role of snow/glacier meltwater and groundwater (baseflow) water can be derived in river water by solving the mass-balance equations for water and tracer fluxes. To estimate the contribution of runoff components, the following two components balance equation was used:

$$Q_t = Q_{sm} + Q_{gw} \quad (2)$$

Similarly, the isotopic balance equation can be written as

$$\delta_t Q_t = \delta_{sm} Q_{sm} + \delta gw Q_{gw} \quad (3)$$

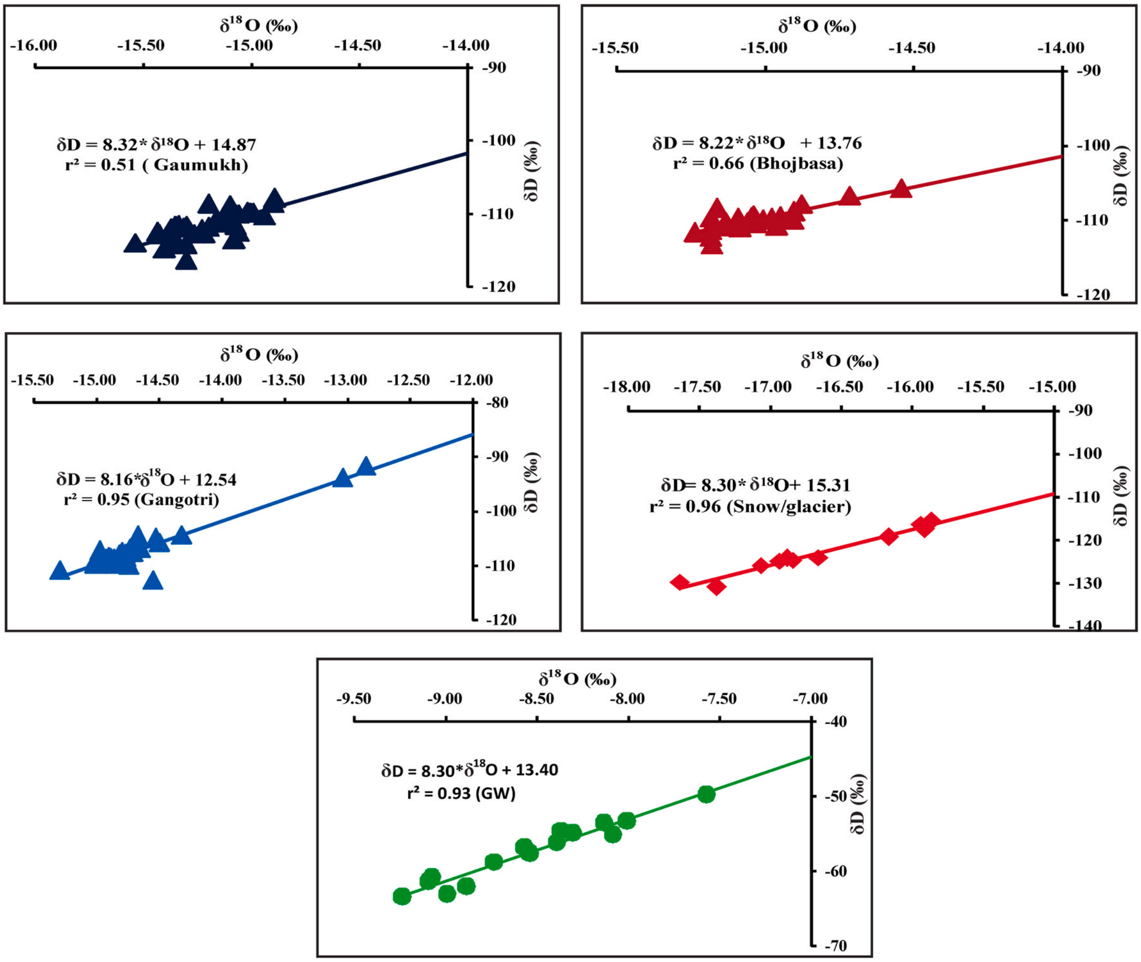

Fig. 3. Isotope composition ($\delta^{18}O$ &δD) in snow/glacier meltwater, groundwater, river water samples at Gaumukh, Bhojbasa, and Gangotri.

Solving equations (2) and (3), runoff components may be separated out. Where Q is the runoff component, and subscripts t, sm, and r represent river discharge, snow/glacier meltwater, and gw stands for groundwater. However, isotope model requires some assumptions as a) The isotope content of the different components are distinguishable from each other b) Snow/glacier meltwater maintain a constant isotope content c) Groundwater and vadose water will be taken as a single unit (Rai et al., 2009; Ahluwalia et al., 2013).

4. Results and discussion

4.1. Isotope composition of $\delta^{18}O$ and δD of groundwater, snow/glacier and river water

In this study, spatial diurnal variability of $\delta^{18}O$ and δD in high altitude Bhagirathi River basin is presented and discussed. Spatially distributed isotope signature of $\delta^{18}O$ and δD in groundwater and river water is presented in Table 1 $\delta^{18}O$ of fifteen groundwater/spring samples range from −9.23‰ to −7.57‰, while δD range from −63.43‰ to −49.82‰ VSMOW. The average value of $\delta^{18}O$ and δD signatures are −8.53‰ and −57.45‰ respectively. The best fit regression line of groundwater is $\delta D = 8.30 * \delta^{18}O + 13.40$ with correlation coefficient $r^2 = 0.93$.

Snow/glacier isotope signature vary from −17.63‰ to −15.86‰ with the average −16.66‰ and −117.18‰. Meteoric water line (MWL) was developed for the Bhagirathi River Basin i.e., $\delta D = 8.30 * \delta^{18}O + 15.31$, $r^2 = 0.96$, n = 11 using snow/glacier meltwater samples (Fig. 3). Snow/glacier melt is more depleted because they incorporate higher

Table 2
$\delta^{18}O$ signature of snow/glacier meltwater studies in different part of Himalaya by other authors.

Location	Altitude	$\delta^{18}O$	Investigators
Rohtang	3748	−18.1	Pande et al. (2000)
Barrlacha La	4650	−15.9	
Thanglang La	5210	−24.7	
Zozila	3540	−12.2	
Khardung la	5629	−17.2	
Khardung la	5649	−15.3	
Dokriani	4836	−11 to −15.2	Nijampurkar et al. (2002)
Chhota Shigri	4100–4600	−6 to −11	Nijampurkar and Rao. (1993)
Changme Khanfu		−12 to −17	
Gaumukh	4000	−13.37 to −18.5	Rai et al. (2009)
Gaumukh	4000–4500	−16.93	Present Study
		−15.94	
		−15.86	
		−17.07	
		−17.63	
		−15.91	
		−17.37	
		−16.16	
		−16.84	
		−16.66	
		−16.88	

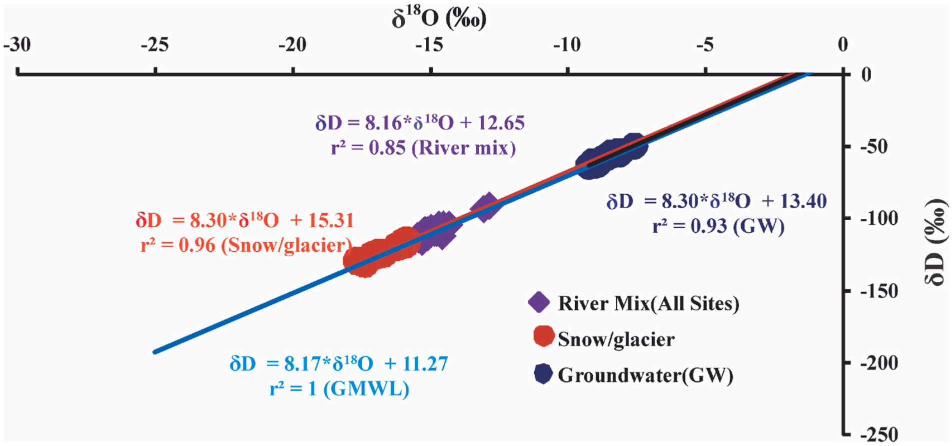

Fig. 4. Isotope composition of $\delta^{18}O$ &δD and comparison of local precipitation (snow/glacier) meteoric water line with global meteoric water line (GMWL).

altitude snow, which is isotopically light, due to the fractionation (Moser and Stichler, 1980). $\delta^{18}O$ and δD isotope of snow/glacier meltwater reported in other studies were also examined and compared with the present study (Table 2). Both slope and intercept of the MWL is higher than $\delta D = 8.17 *\delta^{18}O + 11.27$ (GMWL). However, MWL slope is little higher but intercepts difference is high between MWL and GMWL. It indicates that moisture source of precipitation in this region originate from the western disturbance of the Mediterranean Sea (Kumar, 2010)).

As the river was spatially and diurnally monitored at three locations namely Gaumukh (site 1), Bhojbasa (site 2) and Gangotri (site 3), the isotope signature of $\delta^{18}O$ ranging from −15.53‰ to −14.89‰ and −107.53‰ to −99.52‰ for δD at Gaumukh with the average of −15.19‰ and −105.38‰ respectively. The best fit regression line was $\delta D = 8.32*\delta^{18}O + 14.87$ with correlation coefficient $r^2 = 0.51$. At Bhojbasa, river isotope signature for $\delta^{18}O$ and δD vary from −15.19‰ to −14.71‰ and −107.11‰ to −102.92‰ with the average of −15.03‰ and −104.9 ‰ respectively. The best fit regression line was $\delta D = 8.22 *\delta^{18}O + 13.76$ with correlation coefficient $r^2 = 0.66$. Isotope signature of river water at Gangotri vary from −15.29‰ to −14.32‰ and −104.89‰–100.21‰ with the average of −14.7‰ and −102.59‰ for $\delta^{18}O$ and δD respectively. The best fit line show $\delta D = 8.16*\delta^{18}O + 12.54$ with correlation coefficient $r^2 = 0.95$. The best fit regression line relationship between δD and $\delta^{18}O$ for the Bhagirathi River Basin is established and found $\delta D = 8.16*\delta^{18}O + 12.65$, $r^2 = 0.85$, $n = 95$ from Gaumukh to Gangotri (18 km) as shown in Fig. 4. The similarity in slope with GMWL also indicate that river water did not suffer much kinetic fractionation up to Gangotri (Fig. 4). The intercept of MWL of snow/glacier meltwater and regression line of river water for Gaumukh, Bhojbasa, and Gangotri approaches to each other. This indicates a significant contribution of snow/glacier meltwater in the Bhagirathi River.

As river flows down from higher altitude to lower altitude, catchment area of low altitude is increased. Several springs as groundwater meet the river and forms enriched isotope signature (Ahluwalia et al., 2013). However, enrichment order of river water is small in high mountainous region (Table 1). This small variation in isotope also indicate that the area between Gaumukh to Gangotri generates groundwater, which sustains the river flow during the lean flow period (Rai et al., 2016).

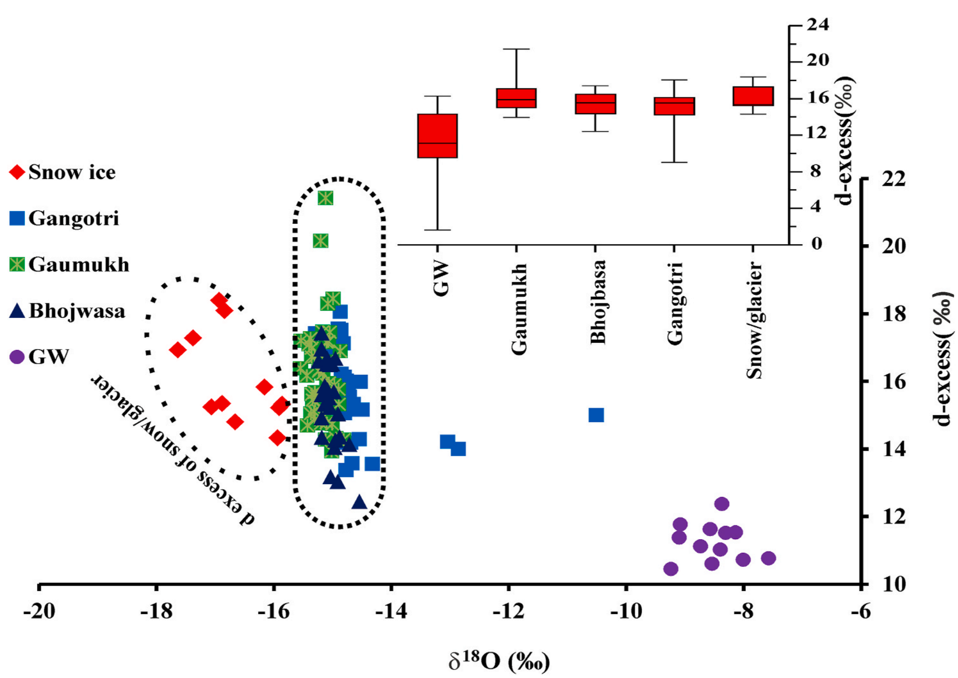

Fig. 5. Variation in d-excess with isotope signature $\delta^{18}O$ of river water at Gaumukh, Bhojbasa, and Gangotri along with the snow/glacier meltwater and groundwater.

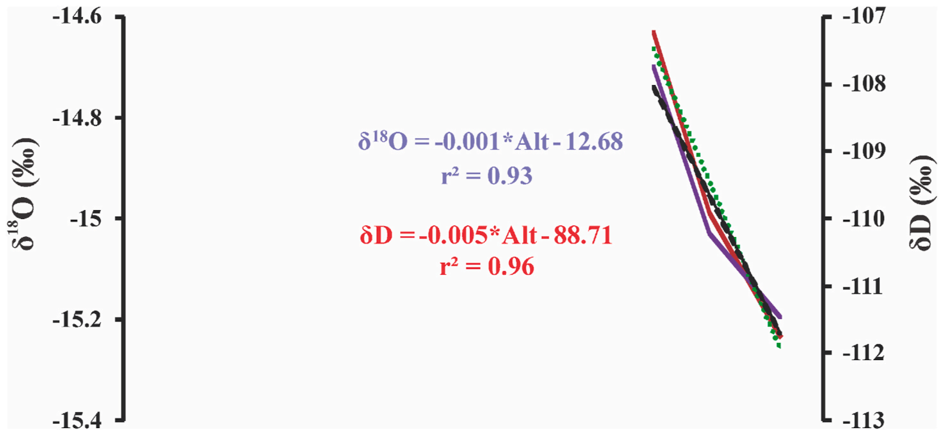

Fig. 6. Altitude versus $\delta^{18}O$ and δD at the offset of monsoon intheriver water.

4.2. D-excess characteristics

The deuterium excess (d) is defined as the intercept of the global meteoric water line (GMWL) as d = δD-8*$\delta^{18}O$ (Dansgaard, 1964). D-excess of the river water goes up to 21‰ at Gaumukh similar to the westerly (22‰) suggesting about the dominant source of moisture in the study area (Karim and Veizer, 2002). It gives an idea about the initial condition that is prevailed during precipitation processes i.e. source, mixing of vapor sources (Rai et al., 2013). Globally, it is near to 10‰ due to slower diffusion of $H^2{}_{18}O$ relative to $H^2{}_{16}O$ than $HD_{16}O$ relative to $H^2{}_{16}O$ for meteoric water during evaporation (Cappa et al., 2003). Though d-excess varies for region to region as in the Great Lakes Region, it is over 10‰ due to recycled water input (Koster et al., 1993; Gat et al., 1994; Machavaram and Krishnamurthy, 1995). In this high altitude valley of the Bhagirathi River, d-excess ranges from 14 to 21‰ at Gaumukh, 12–17‰ at Bhojbasa and 13–17‰ at Gangotri, which indicate about the westerly as main source of moisture.

Fig. 5 shows spatial changes in $\delta^{18}O$ and d-excess alongwith the variation in snow/glacier and groundwater signature. Higher d-excess was noticed at Gaumukh and Bhojbasa (Fig. 5 inset). The relatively decreased d-excess of river water from Gaumukh to Gangotri may be generally basin induced evaporative enrichment of different sources (Yuan and Miyamoto, 2008). The d-excess suggests that high altitude region is dominated by winter snow precipitation. The d-excess of groundwater vary from 2‰ to 16‰ with the maximum value near to the 16‰ (Fig. 5). This is close to the westerly moisture source in the study area.

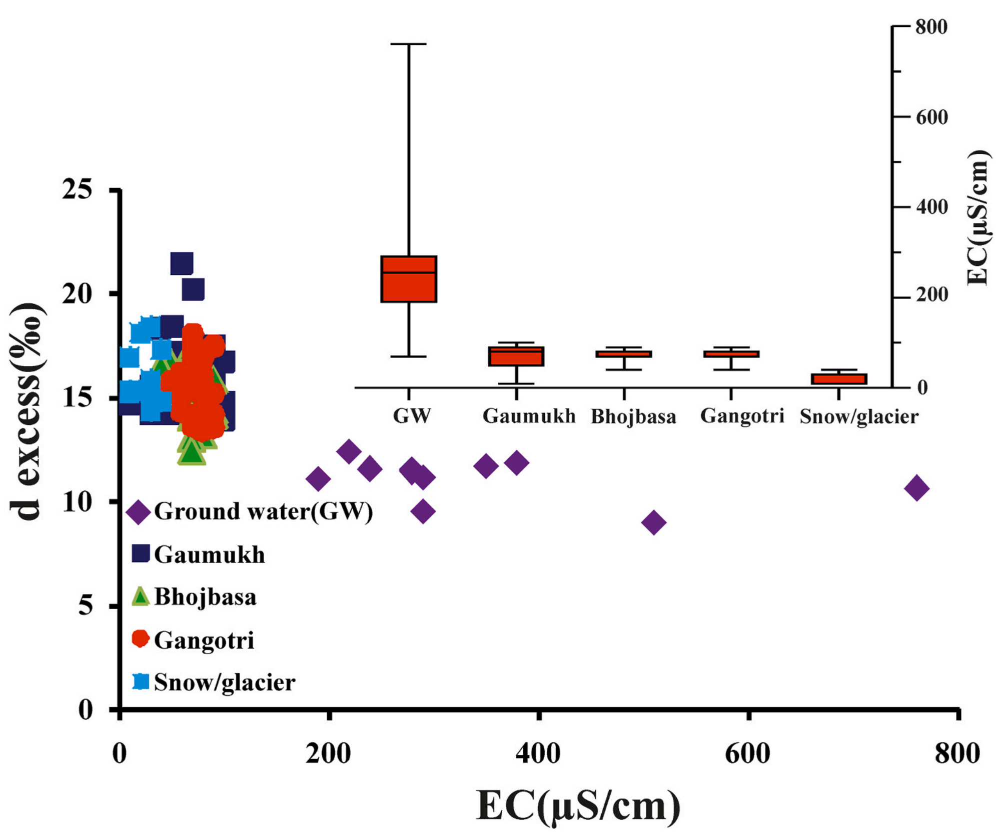

Fig. 7. d-excess versus electrical conductivity variation in the river water with snow/glaciermelt and groundwater.

Table 3a
Diurnal contribution of snow/glacier meltwater and groundwater using $\delta^{18}O$.

Sr no	Gaumukh			Bhojbasa			Gangotri		
	Date	Snow/glacier melt	Ground water	Date	Snow/glacier melt	Ground water	Date	Snow/glacier melt	Ground water
1	9/14/2014	84	16	9/15/2014	78	22	9/21/, 2014	83	17
2	9/14/2014	84	16	9/20/2014	79	21	9/21/2014	74	26
3	9/15/2014	85	15	9/20/2014	80	20	9/21/2014	78	22
4	9/16/2014	80	20	9/20/2014	81	19	9/21/2014	77	23
5	9/16/2014	78	22	9/20/2014	81	19	9/22/2014	78	22
6	9/16/2014	85	15	9/20/2014	82	18	9/22/2014	77	23
7	9/16/2014	86	14	9/20/2014	79	21	9/23/2014	79	21
8	9/16/2014	81	19	9/20/2014	78	22	9/23/2014	78	22
9	9/16/2014	83	17	9/20/2014	82	18	9/23/2014	79	21
10	9/16/2014	84	16	9/20/2014	80	20	9/23/2014	71	29
11	9/16/2014	84	16	9/20/2014	80	20	9/23/2014	76	24
12	9/16/2014	82	18	9/20/2014	79	21	9/23/2014	80	20
13	9/16/2014	80	20	9/20/2014	81	19	9/23/2014	73	27
14	9/16/2014	81	19	9/20/2014	78	22	9/23/2014	76	24
15	9/16/2014	83	17	9/20/2014	82	18	9/23/2014	77	23
16	9/16/2014	80	20	9/20/2014	74	26	9/23/2014	76	24
17	9/16/2014	83	17	9/20/2014	81	19	9/23/2014	78	22
18	9/16/2014	81	19	9/21/2014	82	18	9/23/2014	76	24
19	9/17/2014	82	18	9/21/2014	82	18	9/23/2014	77	23
20	9/17/2014	83	17	9/21/2014	81	19	9/23/2014	75	25
21	9/17/2014	81	19	9/21/2014	82	18	9/23/2014	77	23
22	9/17/2014	81	19	9/21/2014	80	20	9/23/2014	77	23
23	9/17/2014	84	16	9/21/2014	82	18	9/23/2014	80	20
24	9/17/2014	84	16	9/21/2014	79	21	9/23/2014	77	23
25	9/17/2014	83	17	9/21/2014	76	24	9/24/2014	77	23
26	9/17/2014	82	18	9/21/2014	80	20	9/24/2014	78	22
27	9/17/2014	81	19				9/24/2014	74	26
28	9/17/2014	80	20				9/24/2014	78	22
29	9/17/2014	84	16				9/24/2014	79	21
30	9/18/2014	79	21				9/24/2014	77	24
31	9/18/2014	83	17						
32	9/19/2014	81	19						
33	9/19/2014	80	20						
34	9/19/2014	79	21						
35	9/20/2014	80	20						
36	9/20/2014	82	18						
37	9/20/2014	78	22						
38	9/21/2014	82	18						
39	9/21/2014	82	18						

4.3. Altitude effect in the river water

During the orographical upliftment of the air masses, cooling takes place and subsequently, precipitate heavier isotopes. Thus, isotope signature of source water is depleted with increase in altitude. Depending on the precipitation history, topography, degree of cooling, and precipitable moisture left altitude effect on δ^{18}Oin mid latitude ranges between 0.15‰ and 0.30 ‰ per 100 meter gain in altitude (IAEA Report). Fig. 6 shows the relationship between altitude and δ^{18}O-δD of river water. δ^{18}O-δD signature of river water show correlation $r^2 = 0.96$ as a function of altitude. The linear fit is good and δ^{18}O depleted by −0.10‰ and δD depleted by −0.50‰ between ~3400 amsl and ~4020 amsl per 100 m. Fritz., 1981 have reported the signature −0.23‰ for δ^{18}O and −1.8‰ for δD per 100 m altitudinal increment for the Chimbo River that originate from the Andes. Garzione et al. (2000) estimated the altitude effect of 0.11‰ for δ^{18}O isotopein Nepal. Ramesh and Sarin. (1992) have also reported −0.19‰ for δ^{18}O and −1.6‰ for δDper 100 m increase in altitude for Ganga River. Wen et al. (2012) have also reported a lapse rate of 0.36%/100 m for river water in the southern Himalaya. Rai and Purushothaman (2014) also reported thealtitudinal effect ranges from −0.10‰to 0.50‰ per 100 m in the Bhagirathi River.

4.4. Relationship between electrical conductivityand d-excess

Analysis of electrical conductivity with d-excess is carried out from Gaumukh to Gangotri. Electrical conductivity varies from ~10 to ~100 μS/cm at Gaumukh, and ~40 and ~90 μS/cm at Bhojbasa and Gangotri for the river water. The electrical conductivity of snow/glacier varies from ~10 to ~40 μS/cm,whereas, it varies between ~80 μS/cm and ~760 μS/cm for groundwater. High electrical conductivity indicate solute concentration and a longer contact period between the water and bedrock or sediments at the bed. Fig. 7 shows a significant relationship between electrical conductivity and d-excess of river water. River water with high d-excess tends to have less electrical conductivity. In high altitude region, river water is featured with low electrical conductivity because of fresh runoff with high d-excess, while high electrical conductivity is induced because of the mixing of different sources of water towards the downstream and as a result of different sediment concentration in the upstream and downstream (Fig. 7 inset) (Yuan and Miyamoto, 2008). The mixing of water is reflected in the variation of electrical conductivity and d-excess (Fig. 7). The electrical conductivity of snow/glacier is closed to the river water at all three sites i.e. Gaumukh, Bhojbasa, and Gangotri. This also lead to conclude that river water is mainly contributed by snow/glacier melt runoff in high altitude river valley.

4.5. Spatial-diurnal variability of snow/glacier melt and groundwater in the Bhagirathi River

Spatial diurnal variability is carried out to estimate the contribution of snow/glacier melt runoff and groundwater in the Bhagirathi River using two box mixing model. The purpose of the study is to estimate the spatial diurnal variation of snow/glacier melt and groundwater in high altitude region of the Bhagirathi River using δ^{18}O and δD isotope

Table 3b
Diurnal contribution of snow/glacier melt water and groundwater using δD at Gaumukh, Bhojbasa, and Gangotri, central Himalaya.

Sr no	Gaumukh			Bhojbasa			Gangotri		
	Date	Snow/glacier melt	Ground water	Date	Snow/glacier melt	Ground water	Date	Snow/glacier melt	Ground water
1	9/14/2014	83	17	9/15/2014	79	21	9/21/ 2014	79	21
2	9/14/2014	81	19	9/20/2014	77	23	9/21/2014	72	28
3	9/15/2014	77	23	9/20/2014	81	19	9/21/2014	73	27
4	9/16/2014	78	12	9/20/2014	83	17	9/21/2014	75	25
5	9/16/2014	80	20	9/20/2014	80	20	9/22/2014	73	27
6	9/16/2014	84	16	9/20/2014	79	21	9/22/2014	75	25
7	9/16/2014	70	30	9/20/2014	83	27	9/23/2014	76	24
8	9/16/2014	80	20	9/20/2014	80	20	9/23/2014	74	26
9	9/16/2014	83	17	9/20/2014	82	18	9/23/2014	78	22
10	9/16/2014	77	23	9/20/2014	82	18	9/23/2014	73	27
11	9/16/2014	80	20	9/20/2014	80	20	9/23/2014	75	25
12	9/16/2014	74	26	9/20/2014	77	23	9/23/2014	77	23
13	9/16/2014	79	21	9/20/2014	76	24	9/23/2014	73	27
14	9/16/2014	80	20	9/20/2014	78	22	9/23/2014	77	23
15	9/16/2014	77	23	9/20/2014	81	19	9/23/2014	79	21
16	9/16/2014	78	22	9/20/2014	78	22	9/23/2014	78	22
17	9/16/2014	74	26	9/20/2014	81	19	9/23/2014	77	23
18	9/16/2014	86	14	9/21/2014	81	19	9/23/2014	75	25
19	9/17/2014	83	17	9/21/2014	78	22	9/23/2014	75	25
20	9/17/2014	83	17	9/21/2014	81	19	9/23/2014	74	26
21	9/17/2014	81	19	9/21/2014	78	22	9/23/2014	74	26
22	9/17/2014	84	16	9/21/2014	78	22	9/23/2014	75	25
23	9/17/2014	81	19	9/21/2014	80	20	9/23/2014	76	24
24	9/17/2014	81	19	9/21/2014	80	20	9/23/2014	78	22
25	9/17/2014	80	20	9/21/2014	79	21	9/24/2014	76	24
26	9/17/2014	75	25	9/21/2014	78	22	9/24/2014	75	25
27	9/17/2014	81	19				9/24/2014	77	23
28	9/17/2014	80	20				9/24/2014	77	23
29	9/17/2014	82	18				9/24/2014	76	24
30	9/18/2014	82	18				9/24/2014	77	23
31	9/18/2014	78	22						
32	9/19/2014	84	16						
33	9/19/2014	81	19						
34	9/19/2014	82	18						
35	9/20/2014	83	17						
36	9/20/2014	82	18						
37	9/20/2014	82	18						
38	9/21/2014	82	18						
39	9/21/2014	83	17						

(Table 3a,b). To estimate the different components, $\delta^{18}O$ and δD of groundwater is taken as the average of all groundwater samples collected during the study period, which is −8.53‰. The average of all snow/glacier samples is taken as representative $\delta^{18}O$ of snow/glacier i.e., −16.66‰. Using two box mixing model, snow/glacier melt runoff goes to ~84% and groundwater contributes ~16% in the river on 14th September. On 16th September, snow/glacier melt runoff varies from ~86% to ~78%, whereas groundwater contribution varies from ~22% to ~14% at Gaumukh. Snow/glacier melt runoff varies from ~84% to ~80% and groundwater from ~20% tõ16% at Gaumukhon 17th September. The average of snow/glacier melt runoff is also computed with ~82% and groundwater is being contributed ~18% using $\delta^{18}O$ at Gaumukh.

At Bhojbasa, river water samples were collected from 15th to 21stSeptember. On 20th September, snow/glacier melt runoff varies from ~82% to ~74%, whereas groundwater varies from ~26% to ~18%. On 21st September, these components vary from ~82% to ~76% and ~24%–~18%, respectively for snow/glacier melt runoff and groundwater. On average, snow/glacier melt runoff contribution is ~80% and groundwater contribution is ~20% at Bhojbasa about 6 km downstream from Gaumukh (Fig. 8). Site III- Gangotri (~20 km downstream of Gaumukh), river water sampling was carried out during 12–23 September 2014. The diurnal river water sample was collected on 23rd September from 7AM to 12AM. Snow/glacier melt runoff varies from ~80% to ~71% and groundwater contribution varies from ~29% to ~20% (Table 3a). δD is also used to estimate the contribution of snow/glacier melt runoff and groundwater at above three sites. δD is taken as the average of all groundwater and snow/glacier melt signature (Table 1) i.e., −57.49‰ and −117.18‰, respectively. It gives the average snow/glacier melt contribution ~80%, ~79%, and ~76% and groundwater contribution is ~20%, ~21%, and ~24% at Gaumukh, Bhojbasa, and Gangotri, respectively (Table 3b). However $\delta^{18}O$ and δD are linearly related to each other, but estimation of different component was carried out by both isotopes to check the accuracy of the data. Results from both $\delta^{18}O$ and δD isotopes perform very well and corroborate to each other.

Diurnal variation of these components at above three sites i.e., Gaumukh, Bhojbasa, and Gangotri indicate that the contribution of snow/glacier melt runoff comes more in late hours. This may be the result of rising temperature during day time and melting takes place due to heat transfer into snow/glacier. Gangotri Glacier is ~30 km long and runoff from snow/glacier takes some lag time, which reaches to river in late hours (Singh et al., 2011; Sharma et al., 2019). Another interesting finding is that in such a small basin up to Gangotri, there is a significant variation of snow/glacier melt runoff and groundwater contribution between Gaumukh-Bhojbasa and Gangotri. Snow/glacier melt runoff is decreased, whereas the contribution of groundwater is increased from Gaumukh to Bhojbasa, which is only ~6 km away from Gaumukh. This is similar to Gangotri site, which is ~20 km downstream from Gaumukh and ~14 km from Bhojbasa.

5. Conclusion

Isotope approach for the estimation of the spatial diurnal

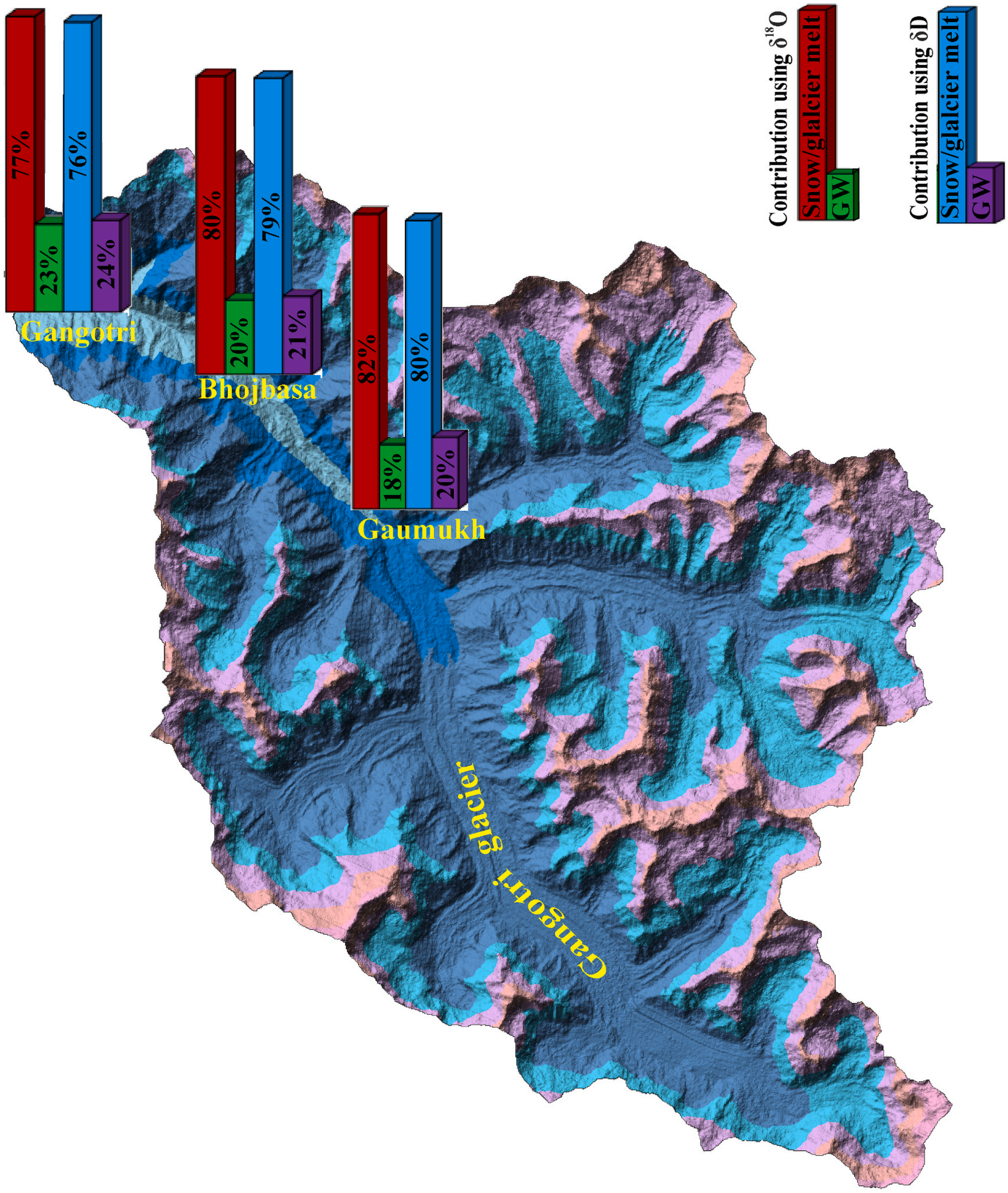

Fig. 8. Estimation of average contribution of snow/glacier melt runoff and groundwater (GW) in the high altitude Bhagirathi River valley at Gaumukh, Bhojbasa, and Gangotri, central Himalaya.

contribution of snow/glacier melt runoff in high altitude river valley shows good outcome despite the little available data. On the basis of $\delta^{18}O$ and δDsignature of river water samples and GMWL, it was observed that river water did not suffer much evaporation. The river water in the Bhagirathi River basin is separated into snow/glacier meltwater and groundwater during the non-rainy season using a two-component mixing model. Stable isotope characteristics and the relationship of river water, snow/glacier meltwater, and groundwater show that river water is close to the average of a snow/glacier melt runoff. The average contribution of snow/glacier melt runoff in river water is~82%–~76% and groundwater contribution is ~18%–~24% from Gaumukh to Gangotri by using both $\delta^{18}O$ and δD isotopes. It is found that Bhagirathi River is snow/glacier dependent river. However, the contribution of groundwater is also important, which increases from Gaumukh to Gangotri in this high altitude region. An important finding of the study is also that estimation of different components suggests meaningful outcomes that may be used as the basis of long term study. Other river basins of the Himalaya should also be investigated to guide the sustainable water resource policy.

Declaration of competing interest

The authors declare no conflict of interest for the submitted manuscript titled "**Spatial-diurnal variability of snow/glacier melt runoff in glacier regime river valley: Central Himalaya, India**".

Acknowledgment

The authors are thankful to the Director, Wadia Institute of Himalayan Geology (WIHG) for providing all the necessary help, support, and encouragement to carry out this work. Mr. Akhilesh Gairola, STA for helping during the field work is also acknowledged.

References

Ahluwalia, R.S., Rai, S.P., Jain, S.K., Kumar, B., Dobhal, D.P., 2013. Assessment of snowmelt runoff modelling and isotope analysis: a case study from the western Himalaya, India. Ann. Glaciol. 54 (62), 299–304.

Ahluwalia, R.S., Rai, S.P., Jain, S.K., Dobhal, D.P., Kumar, A., 2015. Estimation of snow/glacier melt contribution in the upper part of the Beas River basin, Himachal Pradesh, using conventional and SNOWMOD modeling approach. Journal of Water and Climate Change 6 (4), 880–890.

Ahmad, S., Hasnain, S.I., 2001. Snow and stream-water chemistry of the Ganga headwater basin, Garhwal Himalaya, India. Hydrol. Sci. J. 46 (1), 103–111.

Ala-Aho, P., Soulsby, C., Pokrovsky, O.S., Kirpotin, S.N., Karlsson, J., Serikova, S., Vorobyev, S.N., Manasypov, R.M., Loiko, S., Tetzlaff, D., 2018. Using stable isotopes to assess surface water source dynamics and hydrological connectivity in a high-latitude wetland and permafrost influenced landscape. J. Hydrol. 556, 279–293.

Arora, M., Rathore, D.S., Singh, R.D., Kumar, R., Kumar, A., 2010. Estimation of melt contribution to total streamflow in river Bhagirathi and river DhauliGanga at loharinag pala and tapovan vishnugad project sites. J. Water Resour. Protect. 2 (7), 636.

Barnett, T.P., Adam, J.C., Lettenmaier, D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438 (7066), 303.

Cappa, C.D., Hendricks, M.B., DePaolo, D.J., Cohen, R.C., 2003. Isotopic fractionation of water during evaporation. J. Geophys. Res.: Atmosphere 108 (D16).

Chakrapani, G.J., 2005. Major and trace element geochemistry in upper Ganga River in the Himalayas, India. Environ. Geol. 48 (2), 189–201.

Chakrapani, G.J., Veizer, J., 2005. Dissolved inorganic carbon isotopic compositions in the Upstream Ganga river in the Himalayas. Curr. Sci. 89 (3), 553–556.

Dalai, T.K., Bhattacharya, S.K., Krishnaswami, S., 2002. Stable isotopes in the source waters of the Yamuna and its tributaries: seasonal and altitudinal variations and relation to major cations. Hydrol. Process. 16 (17), 3345–3364.

Dansgaard, W., 1964. Stable isotopes in precipitation. Tellus 16 (4), 436–468.

Fritz, P., 1981. In: Gat, J.R., Gonfiantini, G. (Eds.), Stable Isotope Hydrology, vol. 210. IAEA Tach. Rep.Ser., pp. 177–201

Gaddam, V.K., Kulkarni, A.V., Gupta, A.K., 2018. Assessment of snow-glacier melt and rainfall contribution to stream runoff in Baspa Basin, Indian Himalaya. Environ. Monit. Assess. 190 (3), 154.

Garzione, C.N., Quade, J., DeCelles, P.G., English, N.B., 2000. Predicting paleoelevation of Tibet and the Himalaya from δ18O vs. altitude gradients in meteoric water across the Nepal Himalaya. Earth Planet Sci. Lett. 183 (1–2), 215–229.

Gat, J.R., Bowser, C.J., Kendall, C., 1994. The contribution of evaporation from the Great Lakes to the continental atmosphere: estimate based on stable isotope data. Geophys. Res. Lett. 21 (7), 557–560.

IAEA Report http://www/naweb.iaea.org/napc/ih/documents/userupdate/descrip tion/precip5.html.

Jain, S.K., Agarwal, P.K., Singh, V.P., 2007. Hydrology and Water Resources of India, vol. 57. Springer Science & Business Media.

Jain, S.K., Goswami, A., Saraf, A.K., 2010. Assessment of snowmelt runoff using remote sensing and effect of climate change on runoff. Water Resour. Manag. 24 (9), 1763–1777.

Karim, A., Veizer, J., 2002. Water balance of the Indus River Basin and moisture source in the Karakoram and western Himalayas: implications from hydrogen and oxygen isotopes in river water. J. Geophys. Res.: Atmosphere 107 (D18). ACH-9.

Kaser, G., Großhauser, M., Marzeion, B., 2010. Contribution potential of glaciers to water availability in different climate regimes. Proc. Natl. Acad. Sci. Unit. States Am. 107 (47), 20223–20227..

Khan, A.A., Pant, N.C., Sarkar, A., Tandon, S.K., Thamban, M., Mahalinganathan, K., 2017. The Himalayan cryosphere: a critical assessment and evaluation of glacial melt fraction in the Bhagirathi basin. Geoscience Frontiers 8 (1), 107–115.

Koster, R.D., de Valpine, D.P., Jouzel, J., 1993. Continental water recycling and H218O concentrations. Geophys. Res. Lett. 20 (20), 2215–2218.

Kulkarni, A.V., Karyakarte, Y., 2014. Observed changes in Himalayan glaciers. Curr. Sci. 237–244.

Kumar, 2010. Isotopic characterstic of indian Precipitation. Water Resour. Res. https://doi.org/10.1029/2009WR00008532.

Kumar, K., Miral, M.S., Joshi, S., Pant, N., Joshi, V., Joshi, L.M., 2009. Solute dynamics of meltwater of Gangotri Glacier, garhwal Himalaya, India. Environ. Geol. 58 (6), 1151–1159.

Lamb, L, 2000. Correlation of conductivity and stable isotope 18O for the assessment of water origin in river system. Chem. Geol. 164 (1–2), 161–170.

Lambs, L., Balakrishna, K., Brunet, F., Probst, J.L., 2005. Oxygen and hydrogen isotopic composition of major Indian rivers: a first global assessment. Hydrol. Process.: Int. J. 19 (17), 3345–3355.

Machavaram, M.V., Krishnamurthy, R.V., 1995. Earth surface evaporative process: a case study from the Great Lakes region of the United States based on deuterium excess in precipitation. Geochem. Cosmochim. Acta 59 (20), 4279–4283.

Maurya, A.S., Shah, M., Deshpande, R.D., Bhardwaj, R.M., Prasad, A., Gupta, S.K., 2011. Hydrograph separation and precipitation source identification using stable water isotopes and conductivity: river Ganga at Himalayan foothills. Hydrol. Process. 25 (10), 1521–1530.

Meetei, P.N., Ahluwalia, R.S., Rai, S.P., Khobragade, S., Sarangi, S., Goel, M., Kumar, S., 2020. Spatio-temporal analysis of snow cover and effect of terrain attributes in the Upper Ganga River Basin, central Himalaya. Geocarto Int. 1–7. https://doi.org/10.1080/10106049.2020.1762764. Apr.

Moser, H., Stichler, W., 1980. Environmental isotopes in ice and snow. In: Handbook of Environmental Isotope Geochemistry, vol. 1.

Nijampurkar, V., Rao, K., Sarin, M., Gergan, J., 2002. Isotopic study on Dokriani Bamak glacier, central Himalaya: implications for climatic changes and ice dynamics. J. Glaciol. 48 (160), 81–86.

Nijampurkar, V.N., Rao, D.K., 1993. Ice Dynamics and Climatic Studies on Himalayan Glaciers Based on Stable and Radioactive Isotopes, vol. 218. IAHS Publications-Publications of the International Association of Hydrological Sciences, pp. 355–370.

Pandey, S.K., Singh, A.K., Hasnain, S.I., 1999. Weathering and geochemical processes controlling solute acquisition in Ganga headwater–Bhagirathi river, Garhwal Himalaya, India. Aquat. Geochem. 5 (4), 357–379.

Pande, K., Padia, J.T., Ramesh, R., Sharma, K.K., 2000. Stable isotope systematics of surface water bodies in the Himalayan and Trans-Himalayan (Kashmir) region. Journal of Earth System Science 109 (1), 109–115.

Ramesh, R., Sarin, M.M., 1992. Stable isotope study of the Ganga (Ganges) river system. J. Hydrol. 139 (1–4), 49–62.

Rai, S.P., Kumar, B., Singh, P., 2009. Estimation of contribution of southwest monsoon rain to Bhagirathi River near Gaumukh, western Himalayas, India, using oxygen-18 isotope. Curr. Sci. 240–245.

Rai, S.P., Thayyen, R.J., Purushothaman, P., Kumar, B., 2016. Isotopic characteristics of cryospheric waters in parts of Western Himalayas, India. Environmental Earth Sciences 75 (7), 600.

Rai, S.P, Purushothaman, P, 2014. Stable Isotopic composition of precipitation in the River bhagirathi Basin and identification of source vapour. Environ. Earth Sci. 71, 4835–4847.

Rai, S.P., Singh, D., Jacob, N., Rawat, Y.S., Arora, M., 2019. Identifying contribution of snowmelt and glacier melt to the Bhagirathi River (Upper Ganga) near snout of the Gangotri Glacier using environmental isotopes. Catena 173, 339–351.

Singh, P., Jain, S.K., Kumar, N., Singh, U.K., 1994. Snow and Glacier Contribution in the Ganga River at Devprayag. CS (AR)-132. National Institute of Hydrology, Roorkee, India and suspended.

Singh, P., Kumar, A., Kishore, N., 2011. Meltwater storage and delaying characteristics of Gangotri Glacier (Indian Himalayas) during ablation season. Hydrol. Process. 25 (2), 159–166.

Singh, P., Haritashya, U.K., Ramasastri, K.S., Kumar, N., 2005. Diurnal variations in discharge sediment concentration, including runoff-delaying characteristics, of the Gangotri Glacier in the Garhwal Himalayas. Hydrol. Process.: Int. J. 19 (7), 1445–1457.

Singh, P., Haritashya, U.K., Kumar, N., 2007. Meteorological study for Gangotri Glacier and its comparison with other high altitude meteorological stations in central Himalayan region. Nord. Hydrol 38 (1), 59–77.

Sharma, M.K., Thayyen, R.J., Jain, C.K., Arora, M., Lal, S., 2019. Assessment of system characteristics of Gangotri glacier headwater stream. Sci. Total Environ. 662, 842–851.

Singh, V.B., Ramanathan, A.L., Pottakkal, J.G., Sharma, P., Linda, A., Azam, M.F., Chatterjee, C., 2012. Chemical characterisation of meltwater draining from Gangotri glacier, Garhwal Himalaya, India. Journal of earth system science 121 (3), 625–636.

Tangri, A.K., 2000. Integration of Remote Sensing Data with Conventional Methodologies in Snow Melt Runoff Modeling in Bhagirathi River Basin, UP Himalayas. Remote Sensing Application Centre, Lucknow, p. 601.

Trivedi, S., Gopal, K., Singh, J., 2010. Hydro-geochemical attributes of the meltwater emerging from Gangotri glacier, Uttaranchal. J. Geol. Soc. India 76 (2), 105–110.

Wen, R., Tian, L., Weng, Y., Liu, Z., Zhao, Z., 2012. The altitude effect of δ 18 O in precipitation and river water in the Southern Himalayas. Chin. Sci. Bull. 57 (14), 1693–1698.

Yuan, F., Miyamoto, S., 2008. Characteristics of oxygen-18 and deuterium composition in waters from the Pecos River in American Southwest. Chem. Geol. 255 (1–2), 220–230.

INDIAN INSTITUTE OF TECHNOLOGY
(INDIAN SCHOOL OF MINES), DHANBAD
Office of the Dean (Academic)

No- TSN/18DP000351/AGL/Acad

Date: 23.06.2023

Thesis Submission Notification

Mr. Ningombam Prikash Meetei, having admission no. **18DP000351**, registered as **Part Time Research Scholar** in the dept. of **Applied Geology** has submitted the soft copy of thesis as per the details given below:

Sl No	Particulars	Details
1.	Name & address of the Research Scholar as per her/his Ph.D registration form	**Ningombam Prikash Meetei** **Yurembam Mayai Leikai, P.O. - Langjing, Imphal West Manipur, Pin - 795113**
2.	Ph.D admission no. with date	**18DP000351 dt 11.05.2017**
3.	Full Time/Part Time/External Research Scholar	**Part Time Research Scholar**
4.	Title of the Thesis	**ASSESSMENT OF SNOW AND GLACIER MELT RUNOFF IN PINDAR RIVER, CENTRAL HIMALAYA, INDIA USING ISOTOPE AND MODELLING APPROACH**
5.	Name of the Supervisor & Department	**Prof. S. Sarangi, Dept. of Applied Geology, IIT(ISM), Dhanbad**
6.	Name of Co-Supervisor, if any.	**NA**
7.	Name of External Co-Supervisor(s), if any.	**1. Dr. Rajeev Saran Ahluwalia, External Co-guide, Doon University** **2. Dr. S. P. Rai, External Co-guide, Banaras Hindu University**
8.	Courses cleared by the Scholar as advised by DSC (if applicable)	**1. GLC51121 Petroleum Geology and Petroleum Geochemistry** **2. HSC61153 Research and Technical Communication** **3. GLC52124 Micropaleontology in hydrocarbon exploration and Coal bed methane and Gas Hydrate Exploration** **4. GLC72101 Research Methodology**
9.	Date of submission of thesis along with all the required documents & annexures	**08.06.2023**

23/06/2023

AR (Academic-PG)

Copy to:
: Mr. Ningombam Prikash Meetei, Part Time Research Scholar
: Prof. S. Sarangi, Supervisor, Dept. of Applied Geology, IIT(ISM), Dhanbad
: HOD (AGL)
: Dean (SW)/ DR (SW)/AR (SW)
: CDC
: DPGC (Convener)

INDIAN INSTITUTE OF TECHNOLOGY
(INDIAN SCHOOL OF MINES), DHANBAD
Office of the Dean (Academic)

No- TSN/18DP000351/AGL/Acad

Date: 23.06.2023

Thesis Submission Notification

Mr. Ningombam Prikash Meetei, having admission no. **18DP000351**, registered as **Part Time Research Scholar** in the dept. of **Applied Geology** has submitted the soft copy of thesis as per the details given below:

Sl No	Particulars	Details
1.	Name & address of the Research Scholar as per her/his Ph.D registration form	**Ningombam Prikash Meetei** **Yurembam Mayai Leikai, P.O. - Langjing, Imphal West** **Manipur, Pin - 795113**
2.	Ph.D admission no. with date	**18DP000351 dt 11.05.2017**
3.	Full Time/Part Time/External Research Scholar	**Part Time Research Scholar**
4.	Title of the Thesis	**ASSESSMENT OF SNOW AND GLACIER MELT RUNOFF IN PINDAR RIVER, CENTRAL HIMALAYA, INDIA USING ISOTOPE AND MODELLING APPROACH**
5.	Name of the Supervisor & Department	**Prof. S. Sarangi, Dept. of Applied Geology, IIT(ISM), Dhanbad**
6.	Name of Co-Supervisor, if any.	**NA**
7.	Name of External Co-Supervisor(s), if any.	**1. Dr. Rajeev Saran Ahluwalia, External Co-guide, Doon University** **2. Dr. S. P. Rai, External Co-guide, Banaras Hindu University**
8.	Courses cleared by the Scholar as advised by DSC (if applicable)	**1. GLC51121 Petroleum Geology and Petroleum Geochemistry** **2. HSC61153 Research and Technical Communication** **3. GLC52124 Micropaleontology in hydrocarbon exploration and Coal bed methane and Gas Hydrate Exploration** **4. GLC72101 Research Methodology**
9.	Date of submission of thesis along with all the required documents & annexures	**08.06.2023**

23/06/2023

AR (Academic-PG)

Copy to:
: Mr. Ningombam Prikash Meetei, Part Time Research Scholar
: Prof. S. Sarangi, Supervisor, Dept. of Applied Geology, IIT(ISM), Dhanbad
: HOD (AGL)
: Dean (SW)/ DR (SW)/AR (SW)
: CDC
: DPGC (Convener)