B. TECH. PROJECT REPORT

On

Runoff modeling of debris-covered Gangotri Glacier System, Himalaya using ERA5 data since 1979

By

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DEPARTMENT OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

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Runoff modeling of debris-covered Gangotri Glacier System, Himalaya using ERA5 data since 1979

A PROJECT REPORT

Submitted in partial fulfillment of the

requirements for the award of the degrees

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in

CIVIL ENGINEERING

Submitted by:
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(Associate Professor, Civil Engineering)

DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY INDORE
November 2022

CANDIDATE'S DECLARATION

I hereby declare that the project entitled "**Runoff modeling of debris-covered Gangotri Glacier System, Himalaya using ERA5 data since 1979**" submitted in partial fulfillment for the award of the degree of Bachelor of Technology in 'Civil Engineering' completed under the supervision of Dr. Mohd. Farooq Azam, Associate Professor, Civil Engineering, IIT Indore is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere

Rhitvan
24/11/22

Signature and name of the student(s) with date

CERTIFICATE by BTP Guide(s)

It is certified that the above statement made by the students is correct to the best of my knowledge.

Mohd. Farooq Azam
24/11/2022
Associate Professor, Department of Civil Engineering, IIT Indore
Signature of BTP Guide(s) with dates and their designation

Preface

This report on "**Runoff modeling of debris-covered glaciers in Gangotri Glacier System, Himalaya using ERA5 data since 1979**" is prepared under the guidance of Dr. Mohd. Farooq Azam.

Through this project, I have explained the concept of calculation of snow melt, ice melt and total Runoff of Gangotri Glacier System using a simplified runoff model, including a temperature-index and accumulation module.

Graphs and Figures have been used to vividly describe the observations. I have tried to the best of my abilities and knowledge to explain the content in a lucid manner.

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Acknowledgement

I wish to thank Dr. Mohd. Farooq Azam for his kind support, expertise and valuable guidance. He provided a perfect environment for critical thinking and research acumen and was always available for discussions, doubt clearance and guidance at every part of the project. He has constantly motivated me to take the project to its very culmination.

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Without their support, this report would not have been possible.

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Abstract

The present study describes the hydrological characteristics of the Gangotri Glacier System, which is one of the largest glacier systems in the Bhagirathi Basin, located in the Garhwal range of the central Himalaya in the Uttarakhand state of India. Snow melt, ice melt and rainfall-runoff were reconstructed over 1979–2020 for the Gangotri Glacier catchment (India) applying a glacio-hydrological model. The model was calibrated against available geodetic MBs over the period 2006-2014. Model validation was done using field-observed runoff for the period 1999–2000. The mean annual catchment-wide runoff is 12.94 m^3/s over 1979–2020. Snow melt contribution was the maximum with a value of 33%, while debris covered ice melt, rainfall and clean ice melt contributed 31%, 21% and 15%, respectively to the total runoff over this period. The whole Gangotri Glacier System shows the maximum annual runoff of 15.65 $m^3 s^{-1}$ in the year 1994 and the minimum annual runoff of 10.26 $m^3 s^{-1}$ in the year 1989. The model is most sensitive to the threshold temperature for melt.

Keywords: Himalayan glaciers, Debris cover, MB, Hydrology Ice-melt runoff, Snow-melt runoff.

Table of Contents

List of Figures

List of Tables

Introduction

The Himalayan region - The Third pole — is the origin of several perennial river systems in south Asia such as Indus, Ganga and Brahmaputra and provides a continuous fresh water supply for over a billion people, which is used for drinking, hydropower generation, agriculture, sanitation and other purposes (Azam et al., 2021). All the major south Asian rivers originate in the Himalayan and their upper catchments are covered with snow and glaciers. Consequently, there are increasing concerns about the effect of global warming on Himalayan river hydrology, and specifically on the different hydrologic components (glacier melt runoff, snowmelt runoff, and total streamflow). The fourth assessment report of IPCC (IPCC 2007) indicated an unambiguous warming of global climate causing melting over the northern latitudes and snow cover is projected to shrink. In order to understand the impact of climate change, estimation of runoff from glacierized basins is crucial. Hence, hydrological study of Himalayan glaciers has become inevitable in the country due to their importance in water resources, hydroelectric power generation, irrigation and drinking water supply.

Due to the harsh climatic conditions, low oxygen level, and steep terrain of the Himalaya, it becomes difficult to investigate the field observations hence the *in situ* observations (Mass Balances as well as Runoff) have only been observed for a short period and on a few small glaciers (Azam et al., 2018). However, due to advancement of satellite missions and remote sensing methods, it has become possible to work at a regional scale using geodetic method to estimate the glacier mass balances (MBs) (Bolch et al., 2019), but the uncertainty associated with the sensors and inability to estimate the seasonal variations of glacier MB and Runoff limit its applicability to understand the glacier-climate relationship (Vincent et al., 2018). Due to the scarcity of *in situ* MB and runoff observations in the Himalaya, modeling approaches have been used to understand the MB and runoff variabilities with climatic parameters.

These models range from simple temperature-index (T-index) to complex surface energy balance (SEB) models (Hock and Holmgren, 2005; Srivastava and Azam, 2022a). The SEB models are limited in the Himalaya because of the need for extensive input data such as long wave radiation, sensible heat flux etc. (Azam et al., 2014a). On the other hand, the T-index models often require only the temperature data (Hock, 2003). Therefore, despite the simple computation of the T-index models, they have been applied widely to the Himalayan glaciers to reconstruct the long-term glacier MBs and runoffs (Srivastava and Azam, 2022b).

For the present study, we have selected Gangotri Glacier System (Gangotri and its fragmented tributary glaciers - Chaturangi, Raktavaran and Meru glaciers) as it is one of the biggest glaciers in India and has already been studied (Bhattacharya et al., 2016; Hussain et al., 2022). The quantification of different hydrologic components was done using the Glacio-hydrological model to understand the relative contribution of different hydrologic components to the total river runoff between 1979 to 2020.

The seasonal and annual glacier-wide MBs were modeled by a recent study (Hussain et al., 2022). The major objectives of this study are (1) to estimate the runoff for glacierized and non-glacierized areas of the Gangotri Glacier catchment and, (2) estimate the contribution of snow and glacier ice melt and (3) to check the sensitivity of the modeled runoff for different model parameters.

Study Area

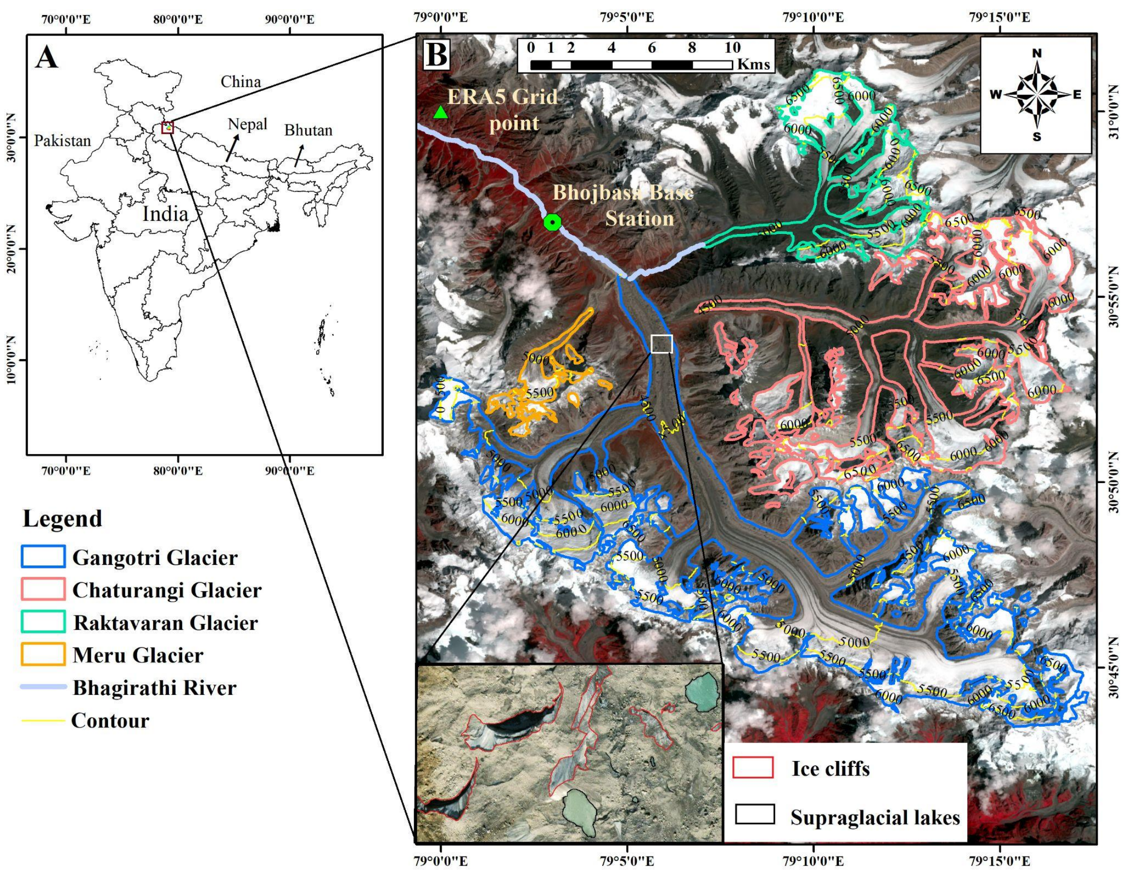


Figure 1. (A) Panel shows the location of the Gangotri Glacier System, India. (B) Panel shows all four glaciers Gangotri (blue), Chaturangi (red), Raktavaran (green) and Meru (yellow) on Landsat eight image of 13th September 2017, and the inset (left bottom of B) shows the enlarged view of ice cliffs (red outlines) and supra-glacial lakes (black outlines) on the surface of Gangotri Glacier (Figure from Hussain et al., 2022).

The Gangotri Glacier System is located in the Uttarkashi district of Uttarakhand and lies within longitude 78.99°–79.29° E and latitude 30.72° –31.02° N. The north-west facing Gangotri Glacier System is a valley type glacier originating in the Chaukhamba group of peaks. Numerous smaller glaciers join the main stream of the main glacier to form the Gangotri group of glaciers. The Gangotri Glacier System (Gnagotri and its fragmented tributaries) covers an area of 252 km^2, with the main trunk of Gangotri Glacier being ~32 km long and 1–3 km wide.

It is one of the most sacred shrines in India, with immense religious significance. Being the main source of the river Ganga, it attracts thousands of pilgrims every year. The Gangotri glacier is a vital source of freshwater storage and water supply, especially during the summer season for a large human population living downstream.

Meru, Chaturangi and Raktavarna glaciers were tributary glaciers of the main Gangotri Glacier and got fragmented in the past (Hussain et al., 2022). All four glaciers of the Gangotri Glacier System are heavily debris-covered. Gangotri Glacier has highest debris cover and numerous ice cliffs and glacial lakes that act as melting hotspots.

Data Generation and Bias-Correction

Daily temperature and precipitation data was acquired from ERA5 (https://cds.climate.copernicus.eu) to determine the annual and seasonal MBs and runoff of Gangotri Glacier System since 1979. The ERA5 reanalysis temperature and precipitation data were downloaded at the nearest grid point (~8 km) to the Bhojbasa Base Camp (3,800 m a.s.l.) (Figure 1).

The mean monthly temperature data from May 2006 to April 2007 from an Automatic Weather Station (AWS) at Bhojbasa Base Camp was used for bias correction of raw ERA5 temperature data. Raw ERA5 mean monthly temperature exhibited a high correlation (R^2= 0.88) with AWS temperature. In situ precipitation data was available only for the summer months (May-October) over 2000–2003 (Singh et al., 2006) and utilized for bias correction of the raw ERA5 precipitation data. ERA5 precipitation data also showed high correlation ($R^2 = 0.85$).with the available mean monthly precipitation data.

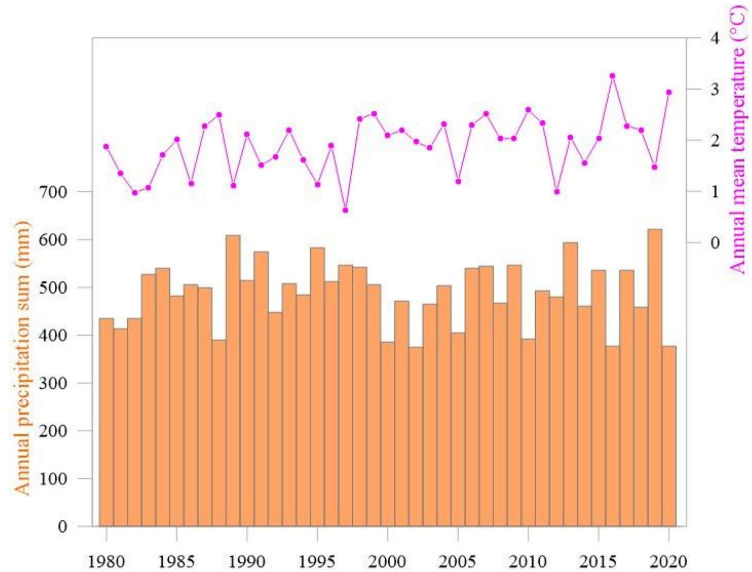


Figure 2. Series of annual mean temperature and annual precipitation sums from bias-corrected ERA5 data set (1979–2020).

Methodology

The required forcing data for the runoff model is snow ablation, ice ablation, rain, and debris ablation for each 50-m altitudinal range. The model starts on 1st November of a year and calculates glacier MB and runoff for each elevation range of 50 m at daily time-step (Figure 3) for a full hydrological year (until 31th October of the following year), taking into account the glacier surface state (snow, bare ice or debris) and using the corresponding degree-day factor (DDF).

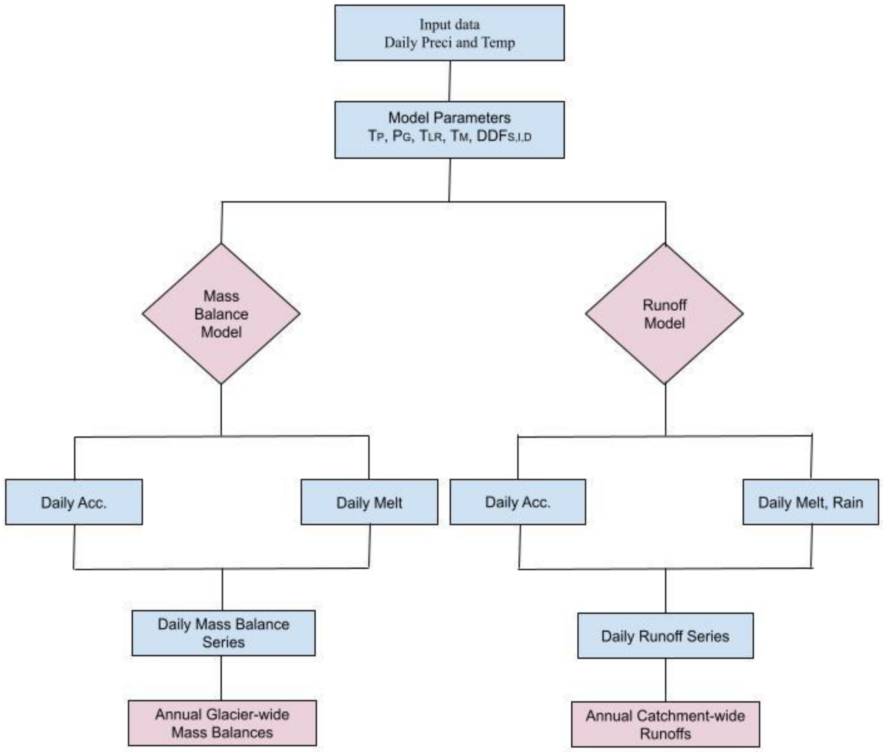


Figure 3. Glacial-Hydrological Model Structure.

Each component of runoff was computed for each elevation zone separately and then output from all the zones was integrated to provide the total runoff from the basin. Details of the methodology adopted for estimating different components of streamflow are discussed below.

1) Surface runoff from glacierized area:-

The surface runoff generated from the glacierized part of the basin can be categorized in four parts, namely: (a) snow melt runoff; (b) runoff due to clean-ice ablation; (c) runoff due to debris covered ice ablation; and (d) runoff generated from the rain falling over the glacierized area.

Snow melt runoff at a given elevation, Q_{sg} over the glacierized area is computed as:

$Q_{sg(given\ elevation)} = a_s * A_g$

where, a_s and A_g are snow ablation and glacierized area at a given elevation, respectively.

Total Snow melt over glacierized area Q_{sg}=$\sum Q_{sg(given\ elevation)}$

Clean ice ablation melt runoff at a given elevation, Q_{cig} over the glacierized area is computed as:

$Q_{cig(given\ elevation)} = a_{ci} * A_{cig}$

Total clean ice ablation over glacierized area Q_{cig}=$\sum Q_{cig(given\ elevation)}$

where, a_{ci} and A_{cig} are clean ice ablation and clean ice area at a given elevation, respectively.

Debris melt runoff at a given elevation, Q_{dg} over the glacierized area is computed as:

$Q_{dg(given\ elevation)} = a_d * A_{dg}$

where, a_d and A_{dg} are debris ablation and debris area at a given elevation, respectively.

Total debris melt over glacierized area Q_{dg}=$\sum Q_{dg(given\ elevation)}$

Rainfall runoff at a given elevation, Q_{rg} over the glacierized area is computed as:

$Q_{rg(given\ elevation)} = r * A_g$

where, r and A_g are rainfall and glacierized area at a given elevation, respectively.

Total rainfall runoff glacierized area Q_{rg}=$\sum Q_{rg(given\ elevation)}$

Total runoff over glacierized area: $Q_g = Q_{sg} + Q_{cig} + Q_{dg} + Q_{rg}$

2) Surface runoff from non-glacierized area:-

The source of surface runoff from the glacier-free area is either rainfall or snow. As for the melt runoff computations, runoff from glacier free area was also computed for each zone using:

Snow melt runoff at a given elevation, Q_{sng} over the non- glacierized area is computed as:

$$Q_{sng(given\ elevation)} = a_s * A_{sng}$$

where, a_s and A_{sng} are snow ablation and non-glacierized area at a given elevation, respectively.

Total Snow melt over non-glacierized area Q_{sng}=$\sum Q_{sng(given\ elevation)}$

Rainfall runoff at a given elevation, Q_{rng} over the glacierized area is computed as:

$$Q_{rng(given\ elevation)} = r * A_{ng}$$

where, r and A_{ng} are rainfall and non-glacierized area at a given elevation, respectively.

Total rainfall runoff over non-glacierized area Q_{rng}=$\sum Q_{rng(given\ elevation)}$

As total catchment area (A_c) and total glacierized area (A_g) at each elevation is available, total non glacierized area(A_{ng}) at each elevation is calculated as:-

$A_{ng} = A_c - A_g$

Total runoff over non-glacierized area: $Q_{ng} = Q_{sng} + Q_{rng}$

The resulting daily runoff, Q, at the catchment outlet is computed using the following equation:-

$Q = Q_g + Q_{ng}$

Model Parameters

As the in-situ Degree Day Factor (DDF) for snow, ice, and debris-cover are not available for Gangotri Glacier System, these were taken as 6.1, 7.7 and 4.8 mm $d^{-1}°C^{-1}$, respectively, from the Dokriani Bamak Glacier located in the same basin (Azam and Srivastava, 2020) . The T_p is taken as 0.7 °C from (Jennings et al., 2018). The temperature is extrapolated at different altitudinal ranges using the monthly LRs developed on the Dokriani Bamak Glacier catchment (Azam and Srivastava, 2020). All the model parameters are listed in Table 1.

Table 1 : List of Model Parameters used for MB-runoff modeling.

Threshold temp for Melt (°C)*	0
Threshold temp for snow/rain (°C)	0.7
Precipitation Gradient (m km^{-1})*	46
Altitude of Base Camp (m)	3800
DDF for Debris (mm $d^{-1}°C^{-1}$)	4.8
DDF for Ice (mm $d^{-1}°C^{-1}$)	7.7
DDF for snow (mm $d^{-1}°C^{-1}$)	6.1

*Calibrated Parameters

Model Calibration

The precipitation distribution in the complex Himalayan terrain is poorly known because of very limited in situ observations (Azam et al., 2021), hence the suitable selection of P_g for precipitation distribution on the glaciers is always challenging in the mountainous region (Bolch et al., 2019). Another critical parameter is T_M, for which the MB models are very sensitive (Engelhardt et al., 2017; Azam and Srivastava, 2020). Further, studies suggest that sometimes melting does not even happen at an air temperature of >0°C (Hock, 2003) however, some T-index model studies suggest that the calibrated TM can be negative at the daily time step (Azam and Srivastava, 2020).

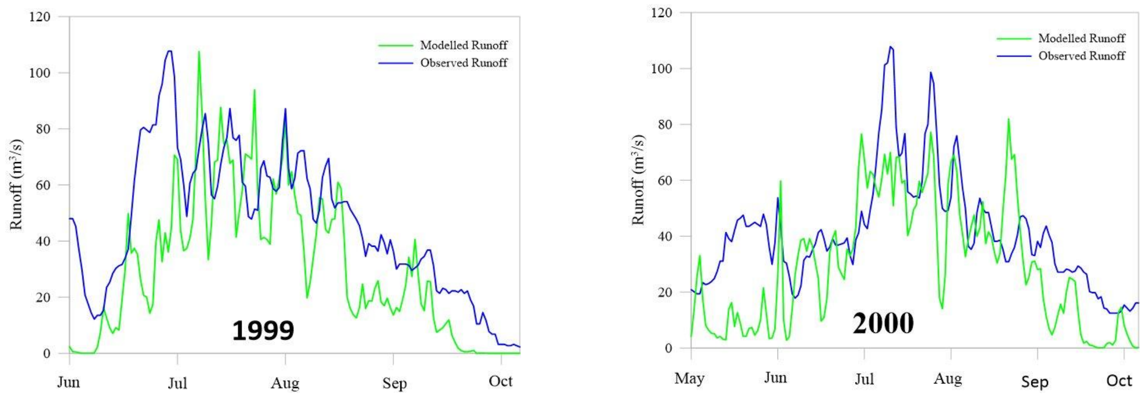
The model was calibrated in a previous study (Hussain et al., 2022) and the value of calibrated parameters, T_M and P_g was 0°C and 46% km^{-1} respectively.

The same calibrated model was used in this study to develop the runoff.

Model Validation

The model is validated against available data sets for year 1999 and 2000 on Gangotri Glacier System using (Kumar, 2002), where modeled daily runoffs for 1999 and 2000 have been compared to observed runoffs at discharge site (Gaumukh) for summer season. The agreement is good with the value of correlation coefficient (R^2) equal to 0.79 and 0.78 for 1999 and 2000, respectively (Figure 4).

A.



B.

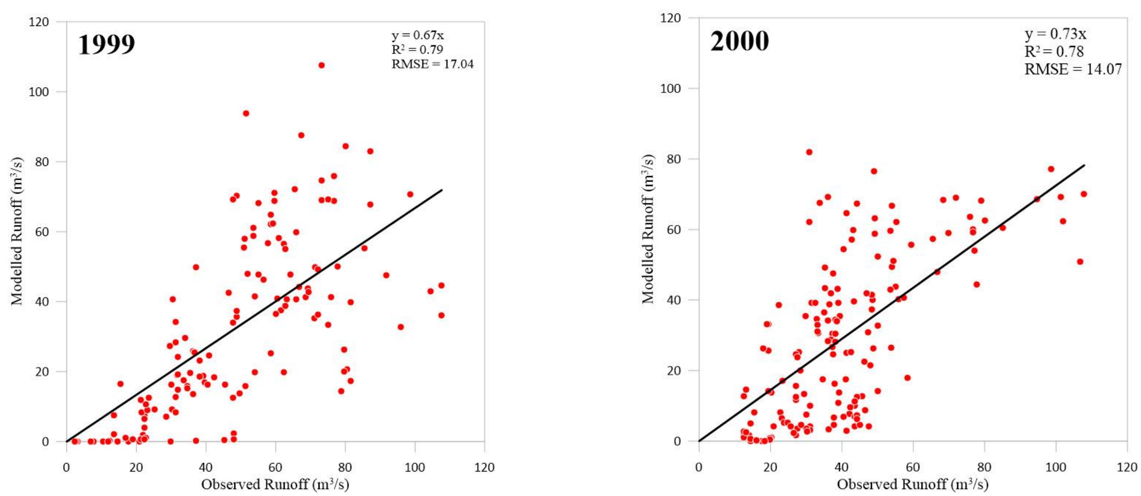


Figure 4. (A) Comparison between modeled and observed hydrographs during the summer monsoon months when the runoff measurements are available (1999–2000) and (B) correlation between modeled and observed mean daily runoffs over the same period.

Model Sensitivity

Model sensitivity (S) for each parameter was evaluated, one-by-one, by re-running the model with a new set of each parameter while keeping all the other parameters unchanged. These sensitivities were estimated by calculating the annual catchment-wide runoff averaged over the period 1979–2020 following:

$$\frac{dBa}{d\mu} = \frac{B_a(\mu_H) - B_a(\mu_L)}{2}$$

Where B_a is the average annual runoff for the period 1979-2020 and μ_H and μ_L are the highest and lowest values of parameters, respectively.

The runoff model is most sensitive to T_M with sensitivity of 0.52 m^3/s. The similar sensitivities were also found on the other Himalayan glaciers: runoff was most sensitive to T_M with the sensitivities of -0.20 m^3/s for the Dokriani Bamak Glacier and -0.29 m^3/s for the Chhota Shigri Glacier (Azam et al., 2019; Azam and Srivastava, 2020). The runoff showed almost the same sensitivity (0.51 m^3/s) to DDF_I, due to the assumption of the lower debris-covered area with melting hotspots (ice cliffs and supra glacial lakes) on Gangotri Glacier to be similar to clean ice.

Results

The modeled runoffs from the catchment are negligible during the winter season (November to April). The summer runoffs (May to October) with a mean value of 25.51 m^3/s are responsible for the total annual runoffs due to higher summer temperatures. Figure 5 represents the seasonal hydrographs of snow-melt runoff, debris-melt runoff, ice-melt runoff, rainfall runoff and total runoff. In early summers the runoff is mainly generated by snow melt which starts in April and peaks in July with a value of 25.86 m^3/s. As maximum snow has already melted out till July there is a sharp decrease in snow melt whereas ice melt and debris melt progressively increase and reach their maximum in August with a mean value of 13 m^3/s and 18 m^3/s respectively. The major rainfall contribution comes between June and September peaking in July with a monthly value of 13.38 m^3/s. The total monthly runoff peaks in July with a value of 62.6 m^3/s from a combination of high snow melt, significant debris melt and maximum rainfall runoff (Figure 5).

The maximum share of 33% to total catchment runoff comes from snow melt with almost equal contribution of 31% from debris melt as the large area of Gangotri Glacier system is covered by debris, followed by 15% and 21% contribution from ice melt and rain respectively (Figure 5-Donut Plot).

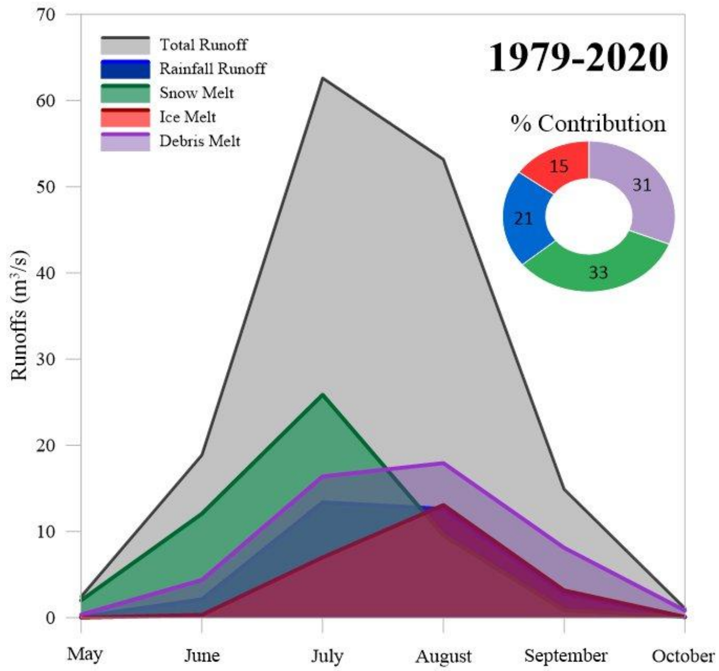


Figure 5. Mean monthly hydrographs of total runoff and different hydrologic components (snow melt, ice melt, debris melt, rainfall runoff)) and the donut chart (inset) shows the percent of annual runoff contribution of each hydrological component

The modeled MBs from a previous study are shown here using the same model (Hussain et al., 2022). The modeled mean glacier-wide MB was −0.27 m w.e.a^{-1} over 1979-2020 (Hussain et al., 2022). The Gangotri Glacier System showed a continuous but moderate mass loss from 1979 to 2020, except for 1989 when the MB was slightly positive with a value of 0.06 m w.e.a^{-1}**.** Over the whole modeling period, the mean annual runoff is 12.94 m^3/s . The annual mean runoffs show a large inter-annual variability with highest and lowest being 15.64 m^3/s for the hydrological year 1994/95 and 10.26 m^3/s for the hydrological year 1989/90 respectively (Figure 6). The more negative MBs are often associated with increased runoff at catchment outlet or vice versa. Hydrological year 1989/1990 is associated with the highest value of MB in agreement with the minimum value of runoff. Though the hydrological year 1994/1995 is not associated with the least MB value but the rainfall contribution is maximum hence the runoff value is maximum.

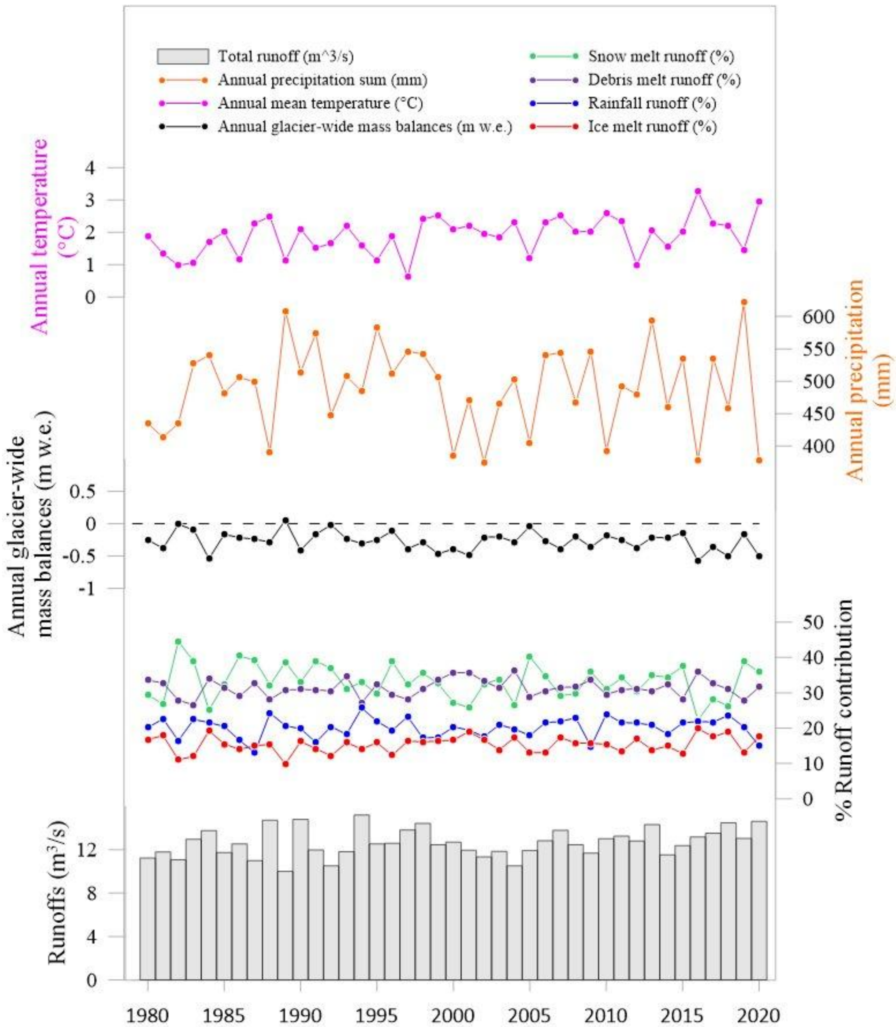


Figure 6. Annual total runoff, snow melt, ice melt, debris melt and rainfall-induced runoff as well as annual precipitation and annual mean temperature, and modelled annual glacier-wide MBs for Gangotri Glacier System over 1979-2020.

Mean monthly catchment-wide temperatures are the highest during July-August in agreement with the highest catchment runoffs with values of 62.60 m^3/s and 53.17 m^3/s respectively (Figure 7).

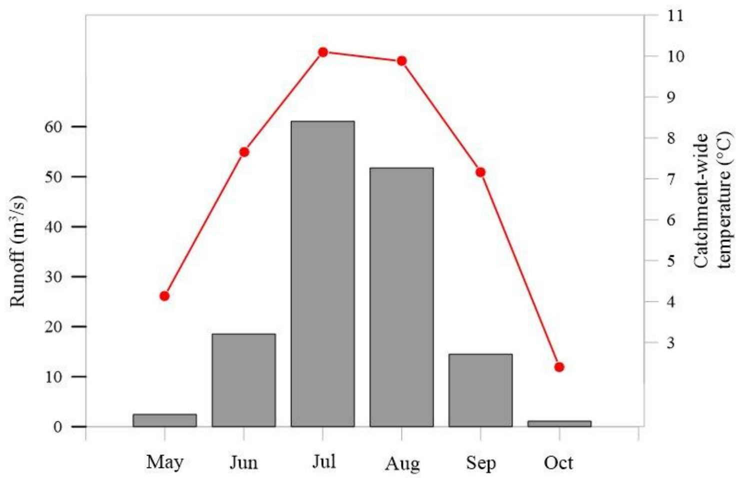


Figure 7. Mean monthly runoff and monthly mean temperature during summer (May - Oct) for Gangotri Glacier System over 1979-2020.

The model was run several times while changing successive total precipitation to discern the precipitation amount needed to compensate for a 1 °C change in temperature. An increase of 45% in precipitation is required to offset the change in catchment runoff resulting from a 1 °C increase in temperature.

Conclusions

The runoffs of Gangotri Glacier System were reconstructed using the glacio- hydrological model over 1979–2020. Most of the model parameters were taken from the nearby Dokriani Bamak Glacier except T_M and P_g , which were derived by calibrating the modeled MB of the Gangotri Glacier System with the available geodetic MB from Bhattacharya et al., 2016 over 2006–2014 (Hussain et al., 2022). The same calibrated model was used to reconstruct the snow and ice melt runoffs as well as total runoff in this study.

The mean annual runoff is 12.94 m^3/s . The study has provided information on the contribution of different hydrological components and seasonal distribution of runoff for the first time. Snow melt and debris melt contributes to 33% and 31% to total mean annual runoff followed by a share of 21% and 15% from rain and ice melt, respectively The maximum mean monthly discharge was recorded in July with value of 62.60 m^3/s because of maximum snow melt, high debris melt and ice melt and maximum rainfall runoff.

Our study showed that a simple glacio-hydrological model can be applied to simulate the runoffs of large debris-covered glaciers and also understand the relative contribution of different hydrologic components to the total river runoff.

References

1. Singh, P., Haritashya, U.K., Kumar, N. and Singh, Y., 2006. Hydrological characteristics of the Gangotri glacier, central Himalayas, India. *Journal of Hydrology*, *327*(1-2), pp.55-67. https://doi.org/10.1016/j.jhydrol.2005.11.060

2. KIREET KUMAR , M. S. MIRAL , V. JOSHI & Y. S. PANDA (2002) Discharge and suspended sediment in the meltwater of Gangotri Glacier, Garhwal Himalaya, India, Hydrological Sciences Journal, 47:4, 611-619. http://dx.doi.org/10.1080/02626660209492963

3. Azam, M.F. and Srivastava, S., 2020. MB and runoff modeling of partially debris-covered Dokriani Glacier in monsoon-dominated Himalaya using ERA5 data since 1979. *Journal of Hydrology*, *590*, p.125432. https://doi.org/10.1016/j.jhydrol.2020.125432

4. Azam, M.F., Wagnon, P., Vincent, C., Ramanathan, A.L., Kumar, N., Srivastava, S., Pottakkal, J.G. and Chevallier, P., 2019. Snow and ice melt contributions in a highly glacierized catchment of Chhota Shigri Glacier (India) over the last five decades. *Journal of Hydrology*, *574*, pp.760-773. https://doi.org/10.1016/j.jhydrol.2019.04.075

5. Hussain, M.A., Azam, M.F., Srivastava, S. and Vinze, P., Positive mass budgets of high-altitude and debris-covered fragmented tributary glaciers in Gangotri Glacier System, Himalaya. *Frontiers in Earth Science*, p.2082. https://doi.org/10.3389/feart.2022.978836

6. Jennings, K.S., Winchell, T.S., Livneh, B., and Molotch, N.P. (2018). Spatial variation of the 767 rain–snow temperature threshold across the Northern Hemisphere. Nature Communications 768 9(1), 1148. https://doi.org/10.1038/s41467-018-03629-7

7. Mukherjee, K., Bhattacharya, A., Pieczonka, T., Ghosh, S., Bolch, T., 2018. Glacier mass budget and climate reanalysis data indicate a climatic shift around 2000 in LahaulSpiti, western Himalaya. Clim. Change 148 (1–2), 219–233. https://doi.org/10.1007/s10584-018-2185-3

8. Azam, M.F., Wagnon, P., Vincent, C., Ramanathan, A.L., Favier, V., Mandal, A., Pottakkal, J.G., 2014b. Processes governing the MB of Chhota Shigri Glacier (western Himalaya, India) assessed by point-scale surface energy balance measurements. Cryosphere 8 (6), 2195–2217. https://doi.org/10.5194/tc-8-2195-201

9. Singh, P., Haritashya, U. K., Kumar, N., and Singh, Y. (2006). Hydrological characteristics of the Gangotri Glacier, central himalayas, India. J. Hydrology 327 (1–2), 55–67. https://doi.org/10.1016/j.jhydrol.2005.11.060

10. Bhattacharya, A., Bolch, T., Mukherjee, K., Pieczonka, T., Kropáček, J., and Buchroithner, M. F. (2016). Overall recession and mass budget of Gangotri Glacier, Garhwal Himalayas, from 1965 to 2015 using remote sensing data. J. Glaciol. 62 (236), 1115–1133. https://doi.org/10.1017/jog.2016.96

11. Bolch, T., Shea, J.M., Liu, S., Azam, F.M., Gao, Y., Gruber, S., Immerzeel, W.W., Kulkarni, A., Li, H., Tahir, A.A., Zhang, G., 2019. Status and change of the cryosphere in the Extended Hindu Kush Himalaya Region. In: The Hindu Kush Himalaya Assessment. Springer, Cham, pp. 209–255. https://doi.org/10.1007/978-3-319-92288-1_7

12. Vincent, C., Soruco, A., Azam, M. F., Basantes-Serrano, R., Jackson, M., Kjøllmoen, B., et al. (2018). A nonlinear statistical model for extracting a climatic signal from glacier MB measurements. J. Geophys. Res. Earth Surf. 123 (9), 2228–2242. https://doi.org/10.1029/2018JF004702

13. Engelhardt, M., Ramanathan, Al., Eidhammer, T., Kumar, P., Landgren, O., Mandal, A., et al. (2017). Modelling 60 years of glacier MB and runoff for Chhota Shigri Glacier, western Himalaya, northern India. J. Glaciol. 63 (240), 618–628. https://doi.org/10.1017/jog.2017.29

14. Brun, F., Wagnon, P., Berthier, E., Shea, J. M., Berthier, W. W., Kraaijenbrink, P. D. A., et al. (2018). Ice cliff contribution to the tongue-wide ablation of Changri Nup Glacier, Nepal, central Himalaya. Cryosphere 12 (11), 3439–3457. https://doi.org/10.5194/tc12-3439-2018

15. Azam, M. F., Kargel, J. S., Shea, J. M., Nepal, S., Haritashya, U. K., Srivastava, S., et al. (2021). Glaciohydrology of the himalaya-karakoram. Science 373 (6557), eabf3668. https://doi.org/10.1126/science.abf3668

16. Hock, R. (2003). Temperature index melt modelling in mountain areas. J. Hydrology 282 (1–4), 104–115. https://doi.org/10.1016/S0022-1694(03)00257-9

17. Srivastava, S., and Azam, M. F. (2022a). Functioning of glacierized catchments in monsoon and alpine regimes of Himalaya. J. Hydrology 609, 127671. https://doi.org/10.1016/j.jhydrol.2022.127671

18. Srivastava, S., and Azam, M. F. (2022b). Mass- and energy-balance modeling and sublimation losses on Dokriani Bamak and Chhota Shigri glaciers in Himalaya since 1979. Front. Water 4, 874240. https://doi.org/10.3389/frwa. 2022.874240

19. Hock, R. (2003). Temperature index melt modelling in mountain areas. J. Hydrology 282 (1–4), 104–115. https://doi.org/10.1016/S0022-1694(03)00257-9

20. Hock, R., and Holmgren, B. (2005). A distributed surface energy-balance model for complex topography and its application to Storglaciären, Sweden. J. Glaciol. 51 (172), 25–36. https://doi.org/10.3189/172756505781829566

21. Azam, M. F., Wagnon, P., Vincent, C., Ramanathan, A. L., Linda, A., and Singh, V. B. (2014a). Reconstruction of the annual MB of Chhota Shigri Glacier, western Himalaya, India, since 1969. Ann. Glaciol. 55 (66), 69–80. https://doi.org/10.3189/ 2014AoG66A104

22. Azam, M. F., Wagnon, P., Berthier, E., Vincent, C., Fujita, K., and Kargel, J. S. (2018). Review of the status and mass changes of Himalayan-Karakoram glaciers. J. Glaciol. 64 (243), 61–74. https://doi.org/10.1017/jog.2017.86