B. TECH. PROJECT REPORT

On

Long Term Mass Balance Reconstruction of Bara Shigri Glacier, Western Himalaya, India

By

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Long Term Mass Balance Reconstruction of Bara Shigri Glacier, Western Himalaya, India.

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

of
BACHELOR OF TECHNOLOGY
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CIVIL ENGINEERING

Submitted by:
ANDRALI NEERAJ

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(ASSOCIATE PROFFESSOR, DEPT. OF CIVIL ENGINEERING)

INDIAN INSTITUTE OF TECHNOLOGY INDORE
NOVEMBER 2022

CANDIDATE'S DECLARATION

I hereby declare that the project entitled **"Long Term Mass Balance Reconstruction of Bara Shigri Glacier "** 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,** IIT Indore is an authentic work.

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

Afzal Ali
Neeraj
25/11/22

Signature and name of the student 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/our knowledge.

Mohd. Farooq Azam

Signature of BTP Guide(s) with dates and their designation

Preface

This report on **"Long term Mass balance reconstruction of Bara Shigri Glacier"** is prepared under the guidance of Dr. Mohd. Farooq Azam.

Through this report I have tried to give a detailed explanation of the mass balance model of Bara Shigri Glacier using a temperature index model. I have also discussed how this glacier behaves in different climatic conditions.

I have tried to the best of my abilities and knowledge to explain the content in a simple manner. I have also added graphs, figures and tables to make this report more illustrative.

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Acknowledgements

I would like to thank Dr. Mohd. Farooq Azam for his tremendous support and guidance. He was very approachable and has always motivated me to move forward during this period.

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Abstract

This study presents the reconstruction of long-term mass balance of Bara Shigri Glacier, Western Himalaya, India using a simple temperature – index (T – index) model over the period of 1950 to 2018. The main inputs, temperature, and precipitation, are taken from ERA5 and are bias corrected against the available in – situ temperature and precipitation data from the automatic weather station (AWS) on Chhota Shigri Glacier.

The model output is calibrated against the available geodetic mass balance and validated with the Equilibrium line altitude (ELA) for Bara Shigri Glacier. Bara Shigri Glacier shows the mean mass balance of -0.32 ± 0.23 m w.e.a^{-1} over 1950 – 2018. Bara Shigri Glacier's tongue is covered by thick debris having several supra – glacial lakes and ice cliffs (considered as melting hotspots) therefore, despite the presence of thick debris, we consider the melting over this area as of a clean glacier. The modelled mean ELA is estimated as 5100 m w.e.a^{-1}.Modelled MBs are most sensitive to the threshold temperature for melt.

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1. INTRODUCTION:

In the 21st Century, climate change is one of the most important topic. Glaciers consist of about 10% of earth's land and hold almost 77% of its freshwater and around 96% of this lies in the polar regions. Other than the polar regions, the Himalayas have the largest glacier cover and termed as the "Third Pole." The glaciers in the Himalayan region are an important source of freshwater for the Indian rivers. The Himalayan glaciers are the source of several perennial river systems in south Asia, including the Indus, Ganga and Brahmaputra, providing a continuous supply of fresh water used for drinking, hydropower production, agriculture, sanitation etc.

Systematic study of glacier mass balance (MB) can help us to indicate climate variability. Monitoring the glacier is an important research area now-a-days as it will help us to assess the future water availability, but it is difficult to investigate the field observations in the Himalaya due to its harsh climatic conditions, steep terrain, low oxygen level and hence in situ observations of mass balances have only been observed for short periods of time and for small glaciers (Azam et al., 2018). Since satellite missions and remote sensing have advanced, geodetic methods have been used to monitor the glaciers, but the uncertainties associated with sensors, and the inability to estimate seasonal and annual mass balance, their applicability to understanding the glacier-climate relationship is limited. Due to this scarcity of in-situ MB and the limitations with the remote sensing method, modelling approaches have been used to understand the response of glacier against the climate change.

The applicability of simple T-index model is common in the Himalayan glaciers because of its simple computations and a smaller number of data requirement. The present study is an attempt to reconstruct the long time series of mass balance of Bara Shigri Glacier by applying simple T– index model, including with the accumulation module. The objectives of this study are to test the applicability of the T-index model to Bara Shigri Glacier, modelling the long term annual and seasonal MB series for Bara Shigri Glacier and to understand the model sensitivity to different model parameters used.

2. STUDY AREA:

Bara Shigri Glacier (32.1647° N, 77.6876° E) is a non-surging glacier located in Lahul and Spiti valley, Pir Panjal range, Himachal Pradesh, India. It lies approximately 18 km East from the Chhota Shigri glacier. It feeds the Chandra River, one of the tributaries of the Indus River system. This glacier extends from 3900 to 6300 m a.s.l. with a length of ~26 km. Bara Shigri glacier has a total area of 143.5 km^2 making it one of the largest glaciers in India.

The debris covered surface i.e. upto 4900 m a.sl of Bara Shigri Glacier also consist of ice cliffs and supra – glacial lakes, which acts as the melting hotspots. The debris layer is highly heterogeneous, ranging from silts measuring a few millimeters to big boulders sometimes exceeding several meters.(Azam et al., 2014)

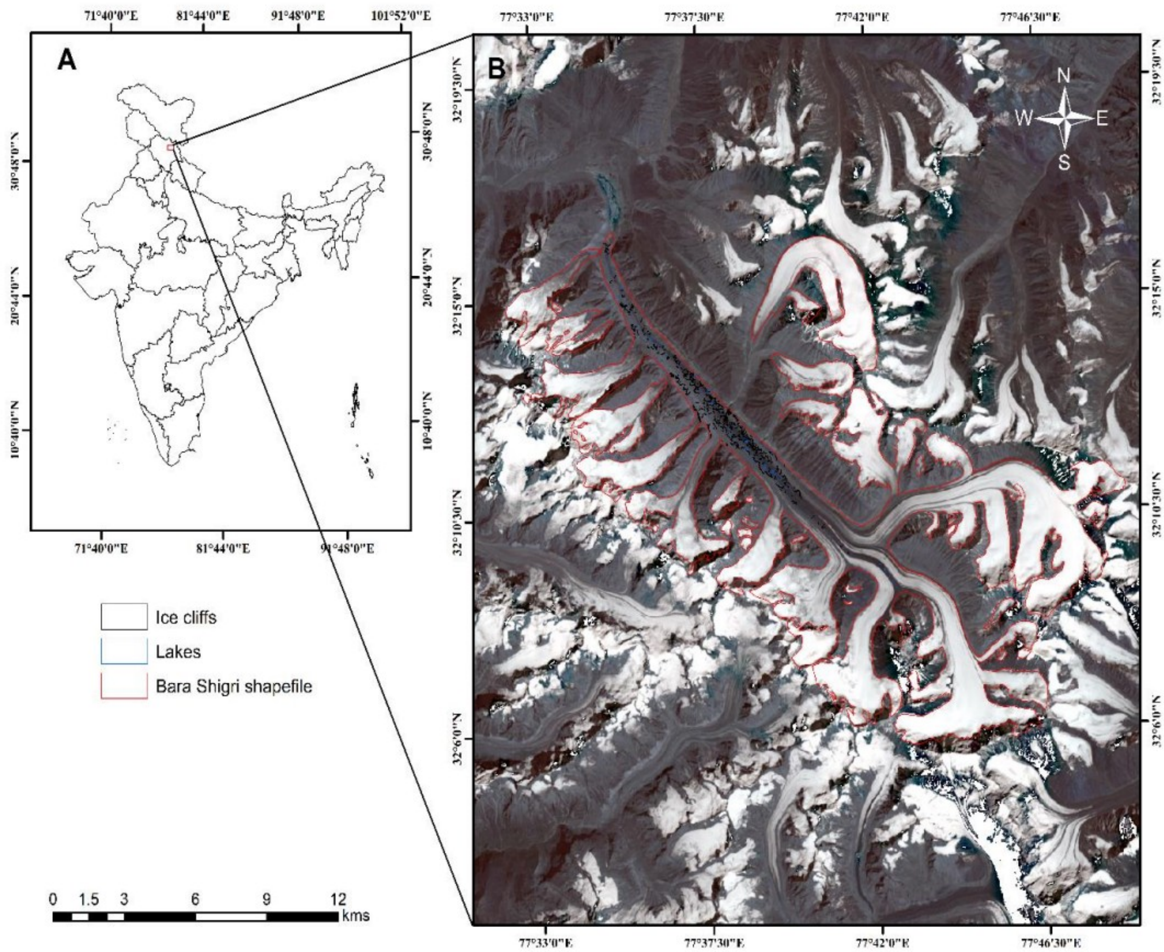

Figure 1: Study site of Bara Shigri glacier, showing delineated ice cliffs and lakes Black dots represent ice cliffs and blue dots represent lakes.

3. DATA GENERATION:

The daily temperature (pressure level) and precipitation data from 1950 to 2018 was acquired from the ERA5 (https://cds.climate.copernicus.eu/) to determine the annual and seasonal MBs of Bara Shigri Glacier. The ERA5 reanalysis temperature and precipitation data were downloaded at the nearest grid point (77.5E, 32.25N) to the Bara Shigri Glacier at 0.25˚ x 0.25˚ resolution. Reanalysis ERA5 data (precipitation and temperature) were bias corrected with the help of available in- situ data, which is discussed in the section below.

4. Bias - Correction:

The daily AWS mean temperature (from August 2009 to September 2019) from the high camp (4863 m) and the daily AWS precipitation (from July 2012 to September 2020) from the base camp (3850) of Chhota Shigri Glacier was used to bias correct the reanalysis ERA5 data. We have calculated the monthly correction factors for temperature as well as for the precipitation with the help of available in-situ and ERA5 reanalysis data over the same period and the same correction factors were applied to whole period.

The monthly correction factors are listed in Table 1.

TABLE 1: Monthly Temperature and Precipitation factors for bias

MONTH	TEMPERATURE FACTORS	PRECIPITATION FACTORS
January	1.17	0.61
February	1.18	0.62
March	1.28	0.59
April	1.43	0.46
May	2.15	0.26
June	0.46	-0.39
July	0.86	3.34
August	0.84	2.14
September	0.27	-0.27
October	1.73	0.44
November	1.32	0.49
December	1.16	0.52

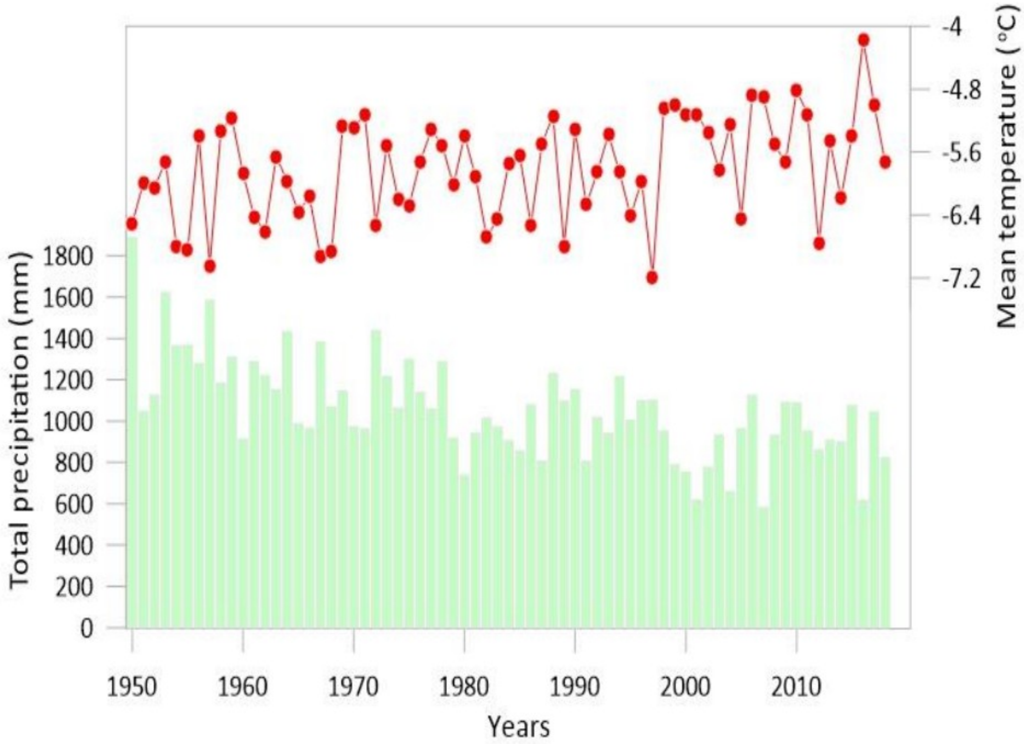

Figure 2: Annual temperature and precipitation

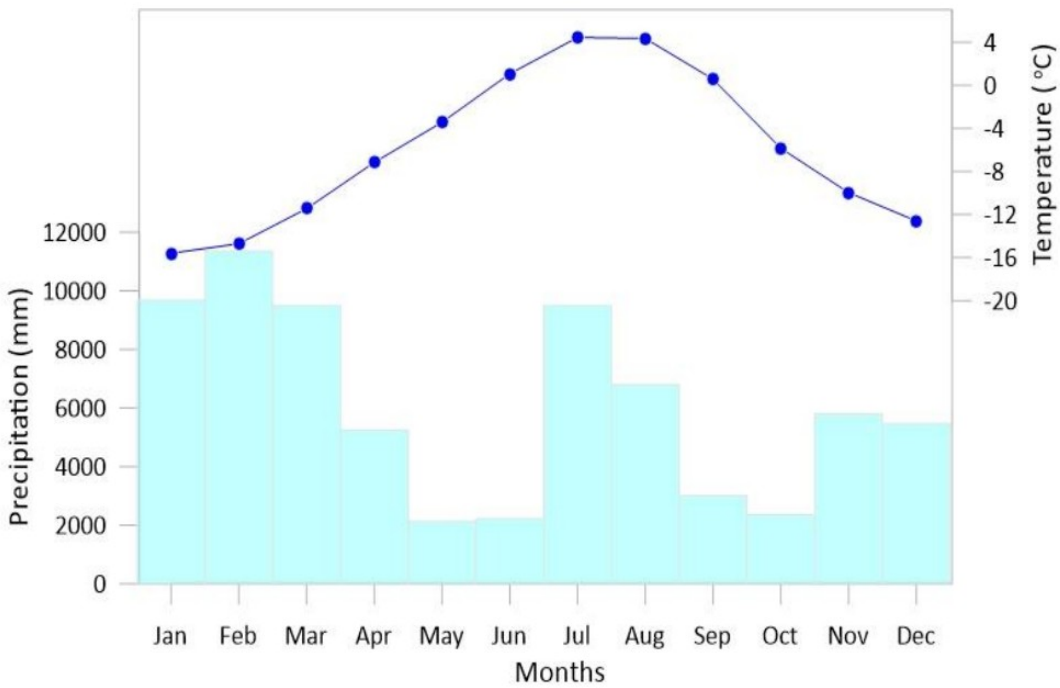

Figure 3: Monthly Temperature and precipitation

5. MODEL PARAMETRES:

The in situ DDF for snow, ice and debris cover are not available for Bara Shigri Glacier and were taken as 3.34, 8.63 and 5.28 mm $d^{-1}{}^{o}C^{-1}$ respectively, which were used on the Chhota Shigri Glacier located ~18 km East of Bara Shigri Glacier (Azam and Srivastava 2020).

Temperature is extrapolated at different altitudinal ranges using the monthly LRs of Chhota Shigri Glacier. Monthly LRs vary with the highest monthly LR being 0.0074^{o}C km^{-1} in June and the lowest monthly LR is 0.0044^{o} C km^{-1} in January. All the model parameters used are listed in the TABLE 2.

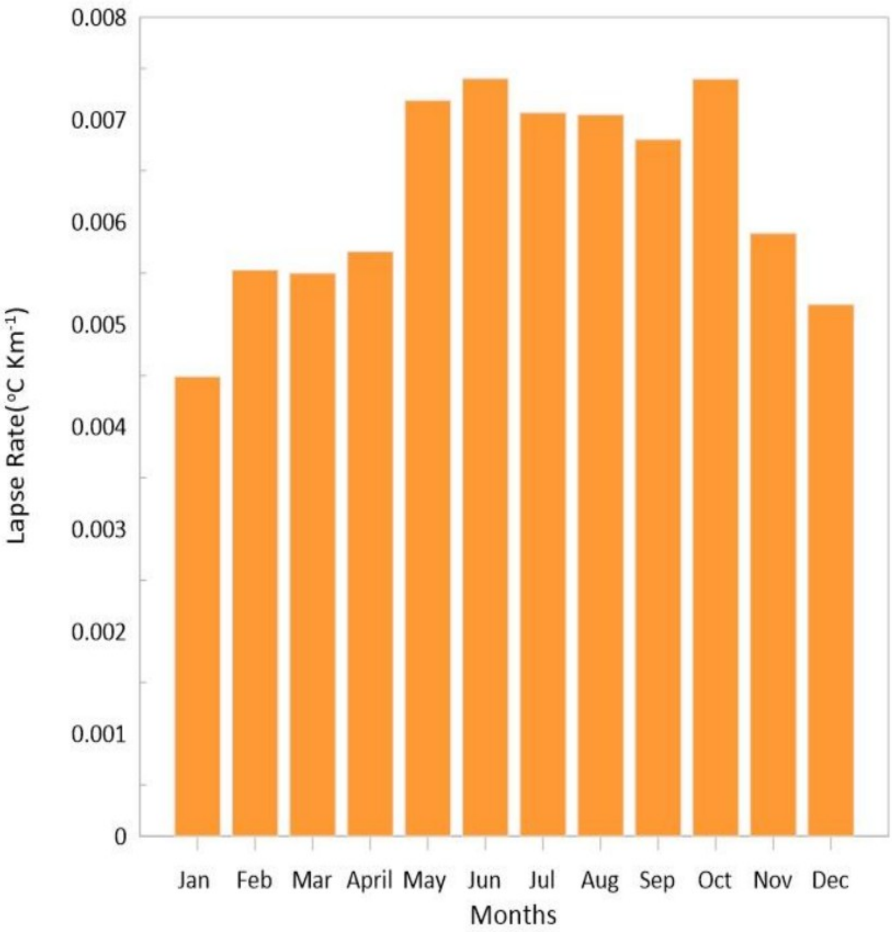

Figure 4: Monthly Temperature Lapse Rates

TABLE 2: Model parameters of Bara Shigri glacier. (* denotes the calibrated values)

Model Parameters	Value
Threshold temp for Melt (°C)*	-1.2
Threshold temp for PPT (°C)	1.1
Precipitation Gradient (m km-1)*	35.7
Lapse Rate for temp	
Altitude of Base Camp(m)	3850
DDF for Debris (mm d-1 °C-1)	3.34
DDF for Ice (mm d-1 °C-1)	8.63
DDF for snow (mm d-1°C-1)	5.28
Altitude of high Camp(m)	4863

6. METHODOLOGY:

The Bara Shigri Glacier's annual and seasonal MB is reconstructed, using a Temperature-index model. The model is built using bias corrected ERA5 daily precipitation and temperature data from 1950 to 2018. (Azam et al.2014) The model runs on a daily time scale and estimates daily accumulation and ablation for each 50-m altitudinal range over the course of a hydrological year, which is from the 31st of September to 1st of October.

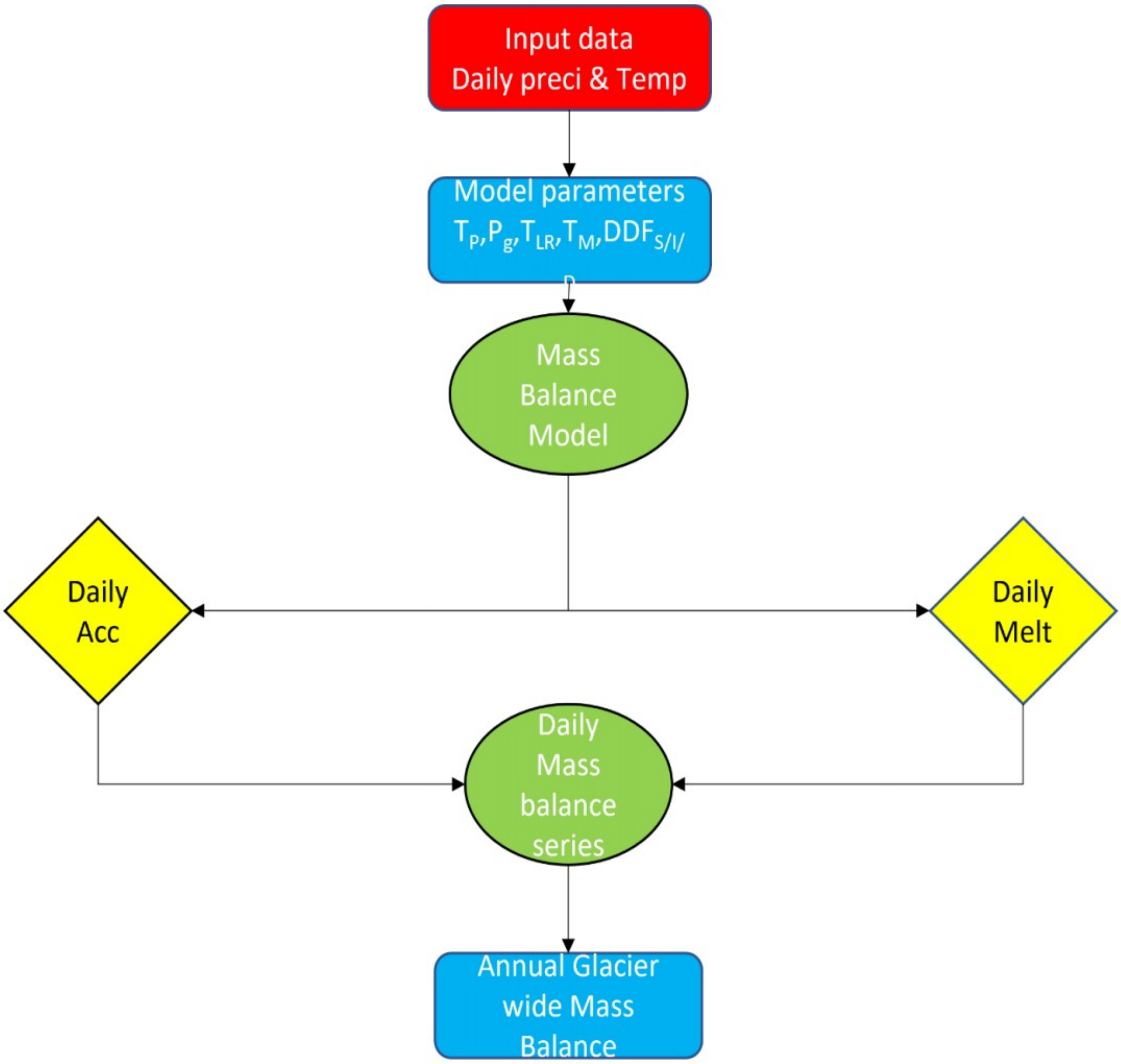

Fig 5: Flow chart of mass balance

In this model, for each 50-m altitudinal range, the daily temperature is extrapolated by applying the the temperature lapse rate (LR).

$$T = T_i - LR \times \Delta H$$

T Calculated temperature at different altitudinal range

T_i Temperature at Barashigri

LR Lapse rate

ΔH Altitude of the base/high camp – altitude of the band

The same way precipitation will be extrapolated at each 50 m altitudinal range by applying altitudinal Precipitation gradient

$$P = P_i + P_g \times \Delta H$$

P Calculated precipitation at different altitudinal range

P_i precipitation at Bara Shigri

P_g precipitation gradient

ΔH Altitude of the base/high camp – altitude of the band

The daily snow accumulation (A_a) is estimated by using the threshold temperature for rain (T_p) and the daily snow ablation (A_b) is estimated by using the threshold temperature for melt (T_m).

Accumulation happens when $T<T_p$

Daily snow accumulation at each altitudinal range is computed by:

$$Aa = \begin{cases} P & : \quad T \leq T_p \\ 0 & : \quad T > T_p \end{cases}$$

P Daily precipitation (mm)

T Temperature extrapolated at each altitudinal range

T_p Threshold temperature for precipitation

Ablation happens when $T>T_m$

Daily snow ablations at each altitudinal range are computed by:

$$Ab = \begin{cases} DDF_{D/I/S} \times (T - T_M) & : T > T_M \\ 0 & : T \geq T_M \end{cases}$$

DDF_D Degree-day factor (mm d^{-1} $^{o}C^{-1}$) for debris-covered ice (D)

DDF_I Degree-day factor (mm d^{-1} $^{o}C^{-1}$) for ice (I)

DDF_S Degree-day factor (mm d^{-1} $^{o}C^{-1}$) for snow (S)

T Temperature extrapolated at each altitudinal range

T_M Threshold temperature for melt

The daily mean altitudinal mass balance (b_i) of Bara Shigri Glacier at each 50-m altitudinal range is computed by using the daily snow Accumulation(A) and daily snow ablation (M)

$$b_i = A\,a - Ab$$

Using the above formula, we have calculated the daily mass balance as

((Daily snow accumulation with precipitation gradient – daily snow ablation) * surface area) – ((Debris with cliffs and lakes ablation * Debris area) + (Ice ablation *clean ice area)) Where, Debris area and surface area are extracted from the glacier hypsometry (see figure 6)

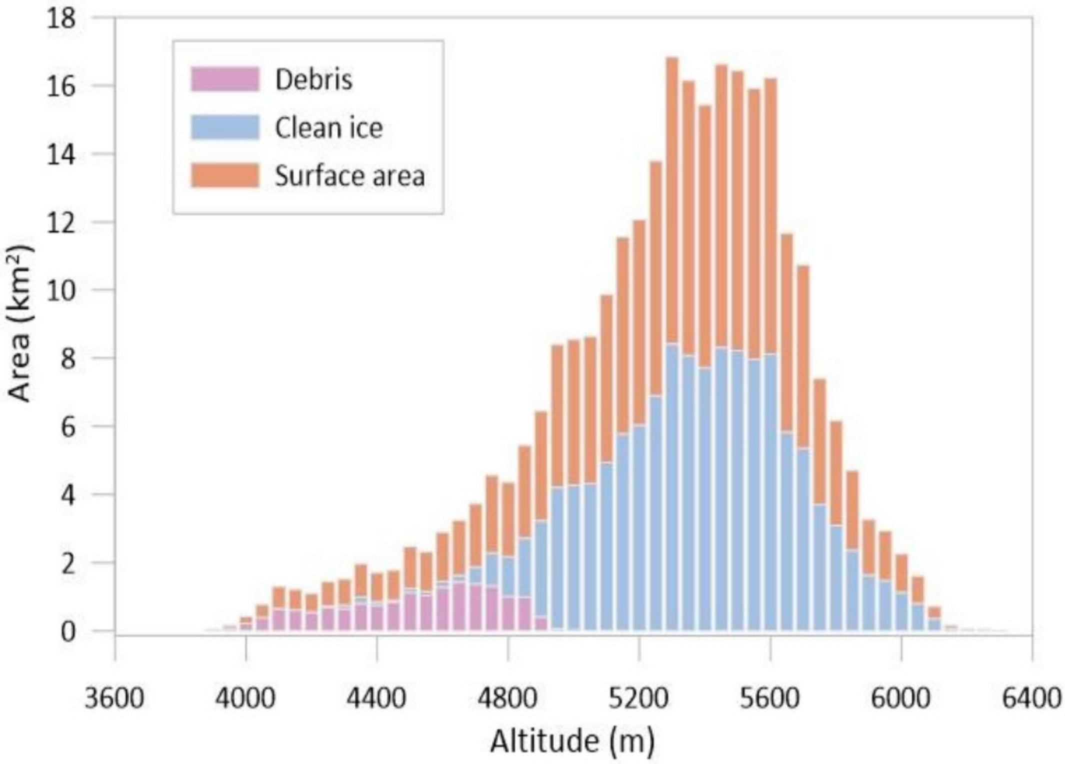

Figure 6: Hypsometry of debris, clean ice and surface area

Now, the Glacier-Wide mass balance is calculated as:

$$B_a = \sum b_i \ (a_i / A_T)$$

Where,

B_a Glacier-wide mass balance

b_i Altitudinal mass balance at each altitude

a_i Area for each altitude

A_T Total glacier area

6.1. CALIBRATION:

For calibration Tm and Pg are chosen as the calibrating parameters and are varied to fit the model output with the observed geodetic MB data. The geodetic MB value was extracted from (Shean et al.) for Bara Shigri Glacier from 2000 to 2018 which was found to be -0.61 m w.e.a^{-1}.

The Tm was altered between -5 and 5°C and the Pg was altered between 0% km^{-1} and 100% km^{-1}. Tm and Pg was given as the input and RMSE and the annual mass balance was given as the output. (Hussain et al. 2022) Monte Carlo simulations were performed for a 1000 runs where the goal was to minimize the root mean square error (RMSE) between modelled and available geodetic Mass Balance from 2000 to 2018 for Bara Shigri Glacier. After 1000 simulations the best of the top 10 results were selected keeping in mind the least value of RMSE. The results of the simulation are given in the table 3.

Sno.	RMSE	Tm	Pg	Avg. AMB 2000-2018
1	0.34	-1.2	35.7	-0.60

TABLE 3: Selected monte carlo simulation result (for 1000 runs)

6.2 . VALIDATION:

The model is validated against the available ELA (equilibrium line altitude) values found out by Remote sensing methods (Pandey et al.), present for 9 nonconsecutive years from 1980 to 2007 and the modeled ELA.

A scatter plot between the observed ELA and the modelled ELA was plotted and a fit curve was drawn between them. The agreement between modeled and the available ELA shows a good correlation. The RMSE value for both the modelled and observed ELA is 154.25 and the correlation coefficient R^2 is found to be 0. 99.The plot for which can be found in figure 7.

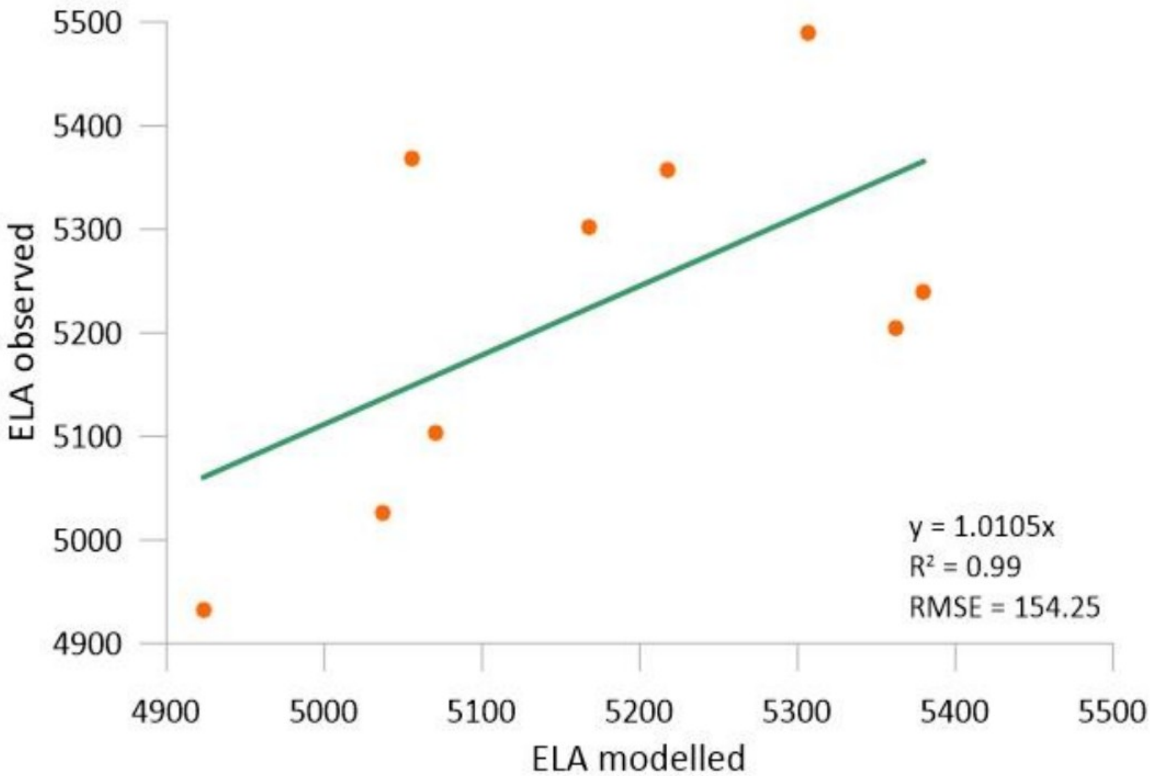

Fig 7: Observed ELA vs Modelled ELA

6.3 . UNCERTAINTY ESTIMATION:

Every model parameter i.e., Threshold temperature for melt, Threshold temperature for PPT, Precipitation Gradient, DDF for debris, DDF for ice and DDF for snow has been altered one at a time, within a 10% range (Hussain et al. 2022) of its calibrated value to estimate the uncertainties in the parameters used. While estimating the uncertainty of one parameter, all the other parameters must be kept constant.

The total uncertainty in Bara Shigri glacier is calculated by summing up all the parametric uncertainties by applying the error propagation rule. The parametric uncertainties calculated are -0.001, -0.0001, -0.004, 0, 0.035, 0.012. The overall uncertainty for the model mass balance is estimated to be ±0.23m w.e.a^{-1} for Bara Shigri Glacier.

7. RESULTS:

7.1 Debris, ice-cliffs and lakes:

Bara Shigri Glacier has number of ice cliffs and lakes present in near to its snout. The percentages of which are 2.6% of ice cliffs with respect to the debris and 0.5% of lakes with respect to the debris.

The total area of the ice cliffs present on the glacier is 0.4km^2 and the total debris area present on the glacier is 16.1 km^2. Lakes have the least area on the glacier out of ice cliffs and debris which is 0.09 km^2. Below the altitude of ~ 5000m i.e from 3900m to 4900m we have applied the degree day factor (DDF) for ice which is 8.63 m d^{-1} ^{o}C^{-1}

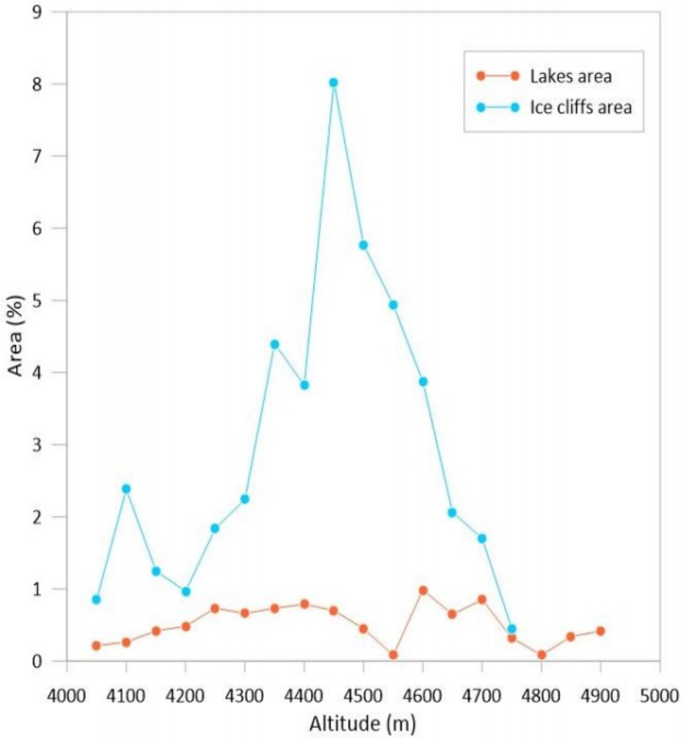

Fig 8: Altitude vs area percentage of lakes and ice cliffs

7.2 ALTITUDNAL MASS BALANCE:

The altitudinal mass balance for Bara Shigri Glacier is depicted in Figure 9.

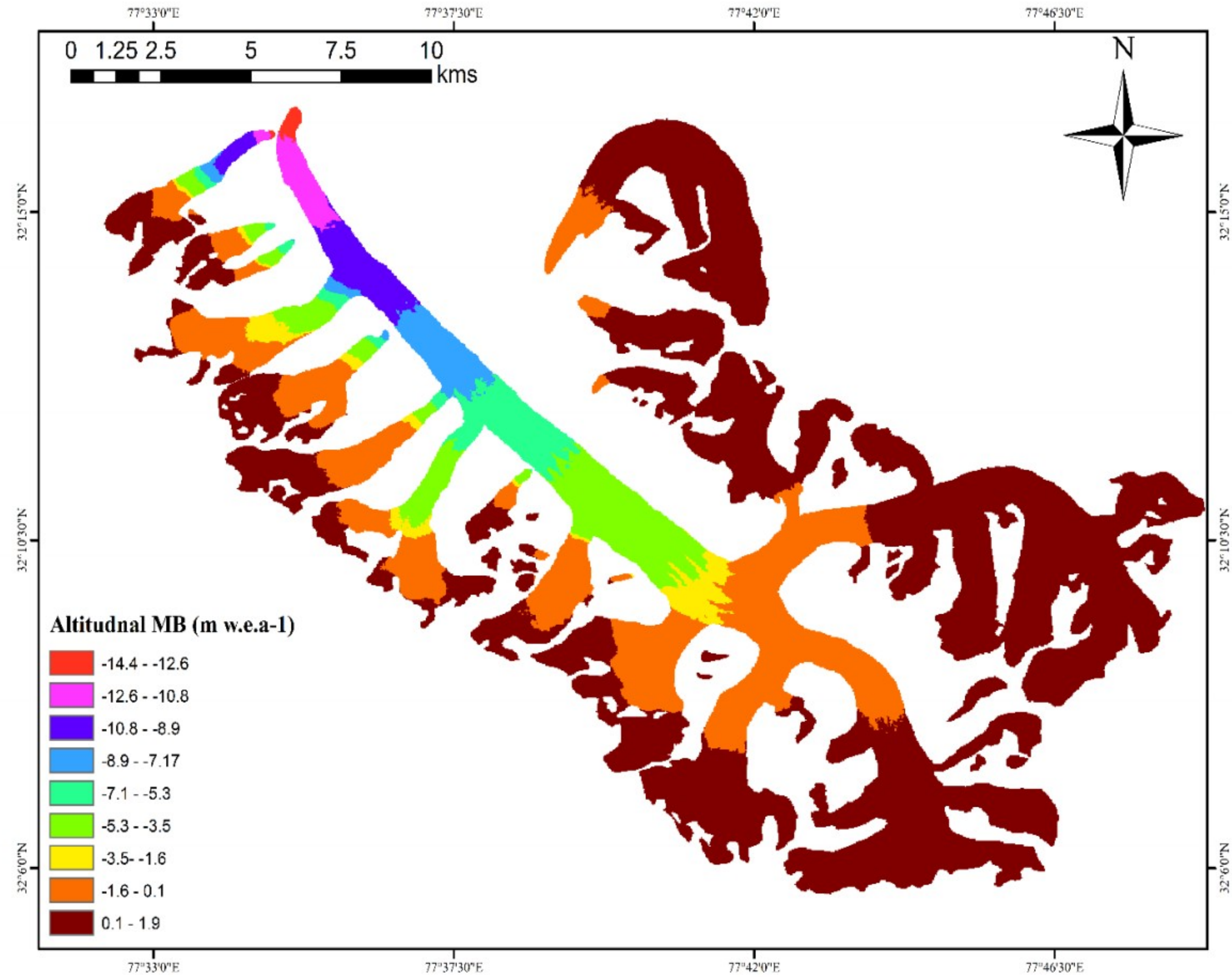

Fig 9: Altitudinal mass balance

7.3 GLACIER WIDE ANNUAL AND SEASONAL MASS BALANCE:

The Mean annual mass balance for Bara Shigri Glacier is -0.32 ± 0.23 m w.e.a^{-1}. The annual mass balance for this glacier has been calculated every year from 1950 to 2018 from 1st of October to 30th of September. The Maximum annual mass balance is 0.6 m w.e.a^{-1}. This has been recorded in the year 1964 and the minimum annual mass balance has been found to be -1.2 m w.e.a^{-1} which was recorded in the year 2001.The mean winter mass balance for Bara Shigri Glacier is 0.89 m w.e.a^{-1}. The winter mass balance for this glacier has been calculated every year form 1950-2018 form the 1st of October to the 31st of march. The Maximum winter mass balance recorded is 1.5 m w.e.a^{-1}. This has been the case in the year 1973 and the minimum winter mass balance has been found to be 0.3 which was recorded in the year 2018. Similarly, the summer mass balance for the year 1950 – 2018 is found to be -1.19. The summer mass balance is calculated every year from 1st of April to 30th of September. The maximum and minimum summer balances are found to be -0.4 and -1.7 respectively in the years 1990 and 2007.

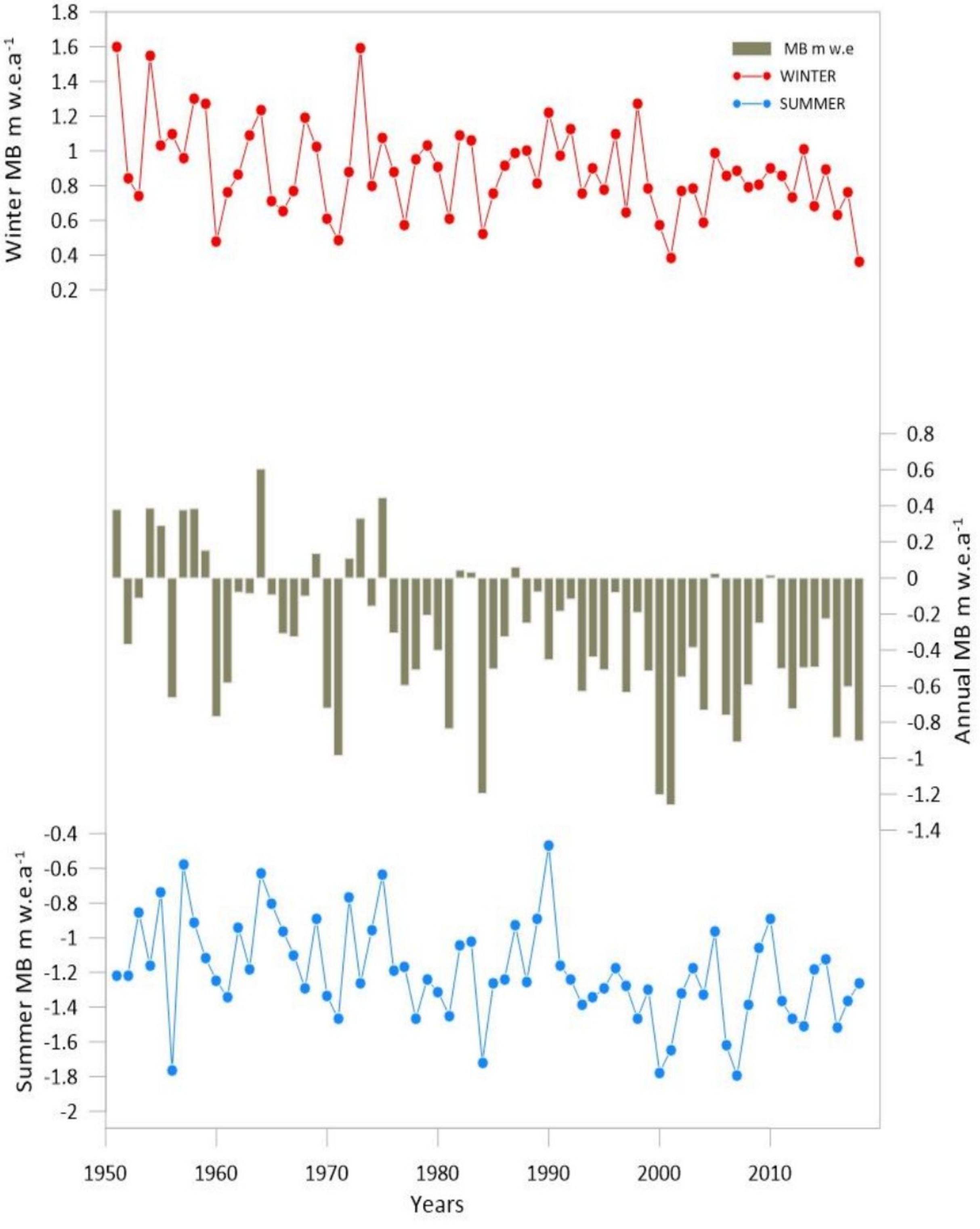

Figure 10: Annual, Summer and Winter Mass Balances

7.4 GLACIER WIDE DECADAL MASS BALANCE:

If we talk about the decadal wise mass balances of annual, summer and winter then the maximum decadal mass balance has been recorded in the very 1st decade i.e., 1951-1960 which is 0.005 m w.e.a^{-1}. The minimum decadal Mass Balance has been recorded in the last decade of the study i.e., 2011-2018 which is found to be -0.6 m w.e.a^{-1}. Similarly, the maximum winter mass balance on the decadal scale is 1.08 m w.e.a^{-1} and is observed in the decade 1951-1960. The minimum winter mass balance has been observed to be 0.7 in the decade 2011-2018.Similarly, the maximum summer mass balance on the decadal scale is -1.04 m w.e.a^{-1} and is observed in the decade 1961-1970. The minimum summer mass balance has been observed to be -1.3 in the decade 2011-2018.

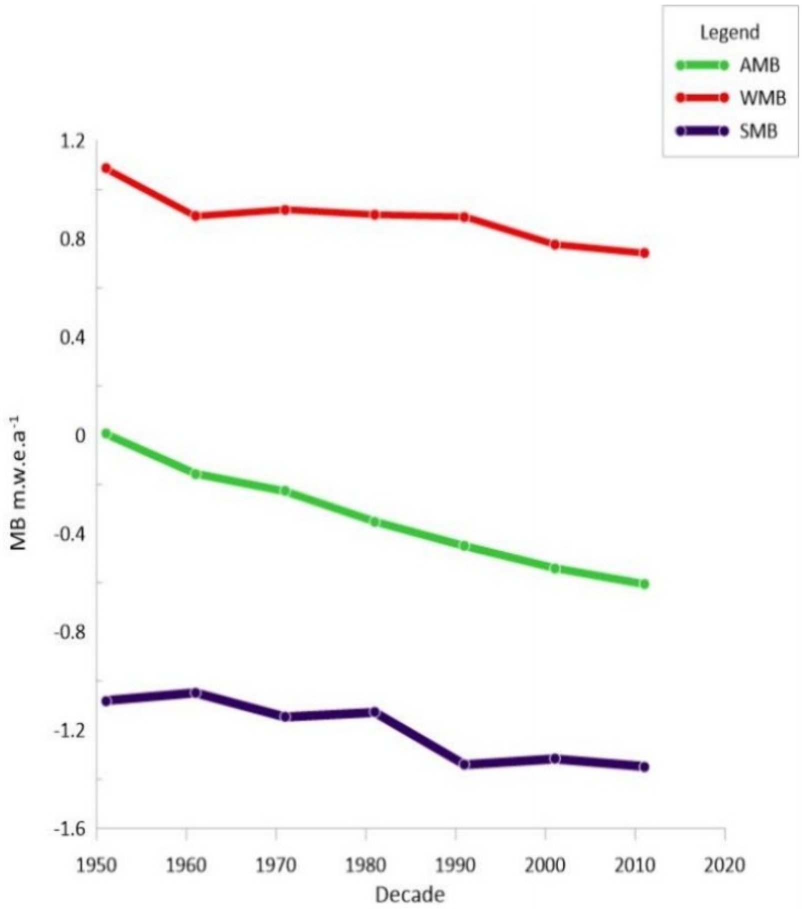

Fig 11: Decadal mass balance

8. DISCUSSION:

8.1 Assumption of DDF for the ice cliffs and supra-glacial lakes region

Figure 12 shows us the altitude where the presence of debris, cliffs and lakes are present.

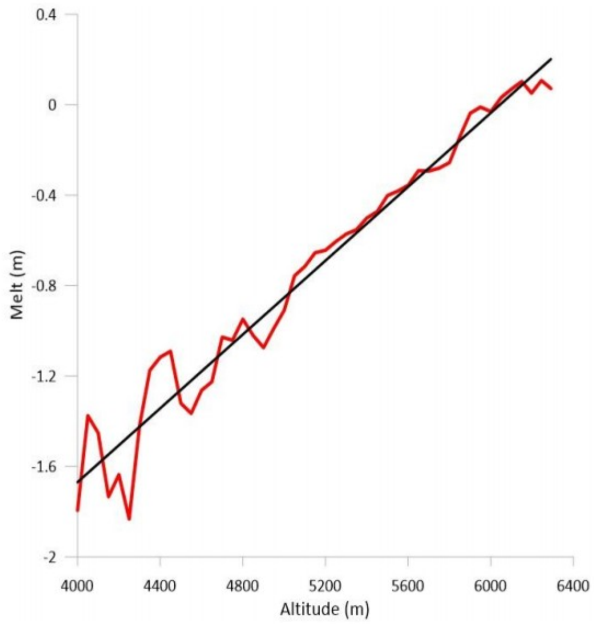

Fig 12: Melt vs Altitude

As shown in the plot the more ablation is occurring on the altitudes below 5000m. The reason for this can be the presence of ice cliffs and lakes as they act as a catalyst in the process of melting the snow. We have assumed that the whole glacier is behaving as clean ice.

Therefore, where ever there is ice cliffs and lakes DDF for ice has been applied in the model.

8.2 Decadal mass balance:

As discussed in the results the annual mass balance from 1950 to 2018 is -0.32 m w.e.a^{-1}. During this whole period the maximum mass balance is found to be 0.6 in the year 1964 the reason for this accumulation is the low temperature of -5.9 supported with high precipitation of 1433mm in the year 1964.

If we see the trend of the decadal mass balance in Figure 11, we can see that decade by decade there has been more melting in the Bara Shigri glacier. Increased temperature due to global warming can be a strong reason to support this result.

9. CONCLUSION:

The annual and seasonal mass balance model of Bara shigri glacier has been constructed by using a simple temperature index model from 1950 to 2018. The main input parameters for a temperature index model are temperature and precipitation. Hourly temperature and precipitation data from 1950 to 2018 has been extracted from ERA5 reanalysis data from the nearest grid point to Bara Shigri glacier.

The extracted raw data has been bias corrected with the available field data from Chhota shigri glacier. The model was calibrated against the geodetic mass balance values from shean et.al (2020) study to get the suitable threshold temperature for melt and the precipitation gradient.

The mean mass balance for Barashigri glacier is found to be -0.3 ± 0.23 m. w.e.a^{-1}.

After the calibration to find if the modelled value is reliable, we have validated the model. For validation ELA (equilibrium line altitude) of barashigri glacier for 9 years was taken from literature. The validation between modelled ELA and the remote sensing ELA showed a very high correlation i.e $R^2 = 0.999$ and an RMSE of 158 which shows that our modelled mass balance is reliable.

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