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REMOTE SENSING BASED ACCUMULATION AREA RATIO METHOD FOR GLACIER MASS BALANCE OF CHHOTA SHIGRI GLACIER

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ABSTRACT

Glaciers are considered as the fresh source of water that depicts non uniform change in their area and volume either spatially or temporally. This paper focus on Accumulation Area Ratio (AAR) technique for monitoring changes in glacier mass balance with the help of Remote Sensing. This study establishes a mathematical model among the actual mass balance , total glacier extent and accumulation area collected in between 2002-2010 on Chhota Shigri Glacier, which result as a linear relationship.

The various zones of glaciers for satellite images between 1997-2010 are mapped and zone of accumulation calculated using NDSI and Band ratio techniques which is used to calculate AAR and further mass balance of glaciers. The actual and satellite derived mass balance are comparable and shows good correlation. The value of AAR ranges between 0.29 to 0.72. The mass balance also ranges in between -1.38 m weq and 0.284 mweq. This study also compares the glacier mass balance generated through the regression model equation calculated over an individual glacier to the mass balance calculated through generalized equation over a large area.

Keywords: AAR, NDSI, GMB

I. INTRODUCTION

Glaciers are one of the major landforms which constitute the frozen form of water on earth. These glaciers are the main reservoirs of water usually found at high altitude, so any change in the shape and size of glaciers directly affects the hydrology of low lying areas. Glacier sensitivity is one of major parameter which establishes the relationship between change in climate, glacier volume and rise in sea level[1]. Change in glacier volumes results in the change in length of the glacier and its mass balance. As per the latest report published in 2011 by the International Centre for Integrated Mountain Development (ICIMOD), Glaciers of central and eastern Himalayas are appear to be shrinking due to loss in glacier extend and mass balance.The melt water of these glaciers and snowmelt from seasonal snow cover provides water to major rivers like Ganga, Indus and Brahmaputra, which meets the water requirement of the people for industries, agriculture and domestic purpose in hot, dry and summer season[2]. So, in order to maintain the sustainability of the glacier, which is a vulnerable source of fresh water and for the sake of water security of India, it is important to monitor and assess the health or state of the glacier periodically. Glacier mass balance is assumed to be one of best indicator that depicts the health of the glacier. It basically helps in estimation of the volumetric changes that occur over a period of time.

The mass balance of glaciers is estimated by Glaciological method which includes weekly measurement of ablation stakes and fixed date measurement of net accumulation[3] . But it has limitations that it seems to be very difficult to go to such a rough and mountainous region to collect information every time in difficult weather and terrain conditions. It also involves intense manual labour and there are difficulties in maintaining a well monitored network. The inaccessible terrains and the harsh climate prevailing in the Himalayas makes the task of data collection very difficult[4]. therefore, space based monitoring has been found to be feasible and useful alternative to study and understand the changes in the Himalayan snow and glacier covers which in turn help in studying long term change in mass balance of glaciers. **LaChapelle** **[5]** proposed the use of aerial photography as an index for the glacier mass budget, and the equilibrium-line altitude (ELA), a variable observable without direct access to the glacier, is recognized as a valuable climate proxy[6]**.** One of the satellite based approach to estimate the glacier mass balance is, Accumulation Area Ratio method (AAR). The Accumulation Area ratio is the ratio of the accumulation area to the total area of the glacier[7].

$$AAR = \frac{AccumulationArea}{TotalGlacierArea} \quad 1$$

Based on the studies till now it is found that with the increase in the AAR ratio there occurs changes in annual and net mass balance[8].This relationship suggests that change in glacier mass balance can be measured only if the change in the accumulation area of a glacier is estimated. Kulkarni[12] used field data for Tipra Bank, Gara, Gor-Garang and Neh-Nar Glaciers collected from various unpublished reports of the Geological Survey of India (GSI) and Raina and others (1977), for Kolahoi and Shishram Glaciers from Kaul (1986)**,** and for Chhota Shigri Glacier from Kulkarni[12] to estimate the common AAR value representing zero mass balance for western Himalayan glaciers. This work suggests an AAR value of 0.44 for these glaciers, corresponding to a zero mass balance.

II. LITERATURE REVIEW:-AAR BASED GLACIER MASS BALANCE

Bamber and Rivera[9] classified remote sensing based GMB method under three classes namely component approach, proxy measures of mass balance and geodetic approach. The AAR method comes under proxy measures of mass balance. To estimate the glacier mass balance by AAR, accumulation and ablation area needs to be mapped. The accumulation and ablation zones of the glacier can be mapped by applying various techniques on optical remote sensing data. Remote sensing data in multi-spectral mode, can be used to determine the end of summer snowline by differentiation between (wet) snow and ice[10] which in turn determinate accumulation and ablation area. Excluding the influence of superimposed ice on the net m.b., the transient snowline altitude (SLA) at the end of the ablation season is a reasonable proxy for the ELA and can, therefore, be used to determine the AAR of the glacier[9].

Kulkarni**[12]** has used field-based estimates of mass balance and AAR available from 1977-78 to 1982-83 and 1976-77 to 1983-84 for Gara and Gor-Garang Glaciers, located in catchment of Sutlej River, to develop the regression analysis between specific mass balance and AAR. This suggests a high correlation coefficient, i.e. 0.88 and 0.96 with AAR values of 0.47 and 0.43, representing zero mass balance for Gara and Gor-Garang Glaciers, respectively. The same relation was along with remote sensing based Landsat data to find AAR in Gara Glacier. For Gara Glacier, AAR values for 1986-87 and 1987-88 are 0.57 and 0.16 respectively[12].

Kulkarni[11] used AAR method for monitoring of glacial mass balance in the Baspa basin using relation of AAR and specific glacier mass balance of Gara and Gor-Garang Glaciers developed by Kulkarni[12]. However, the extrapolation of this AAR relation to other glaciers not sampled on the field is problematic because this relationship is different from one glacier to another and other uncertainties associated with this method of measuring glacier mass balance from space[13].

Based on the above discussion it is clear that AAR method has been extensively in many areas of world for GMB studies, but in case of India, the basic field observed relation of AAR is for Gara and Gor-Garang glaciers, which is used in many glaciers of India[2]. But in last decade there has been continuous field monitoring of Chhota Shigri glacier, which has given continuous observed data on GMB from 2004 onwards[14]. Therefore, the main objective of this work is to use the recent field observations along with time series of remote sensing data to find GMB of Chhota Shigri glacier by AAR method. This work also indents to quantify accuracy and errors of remote sensing based AAR method for study area.

III. STUDY AREA

The Glaciers of Western Himalayas contribute a large fraction of area to the total area of the glaciers found worldwide. Chotta Shigri glacier is one of long term monitored glacier. Most of the Scientists and Organisation have done lot of work on this glacier. In 2002 Commission of cryospheric science, previously named as International Commission of Snow and Ice selected this glacier as one of the benchmark in whole Hindu-Kush-Himalayas[15]. Chotta Shigri glacier is a valley type glacier which extends over 32.19^0 - 32.28^0N latitude and 77.48^0 - 77.55^0E longitude. The glacier is located in the Chandra River basin in Lahual and Spiti valley of Himachal Pradesh in western Himalayas. The length of glacier is about 9km which covers mainly with ice, debris, snow and debris covered with ice. The glacier covers around 15.8 km^2 with height varying from appox. 4050m – 6263m (m.a.s.l). The glacier is oriented roughly north-south in its ablation area and has a variety of orientations in accumulation area[16].The snout position of glacier is found to be at 32^0 16’ 13.5’’N and 77^0 31’49.4’’E at an altitude of 4108meters (26 September, 2012). It is influenced by the Asian monsoon in the summer and mid latitude westerlies in winter[16]. The alternate variation in the climate makes this glacier as one of main area of research. The annual cycle for this glacier is from October-April for accumulation and from May-September for ablation. The region show high melting during the month of July- September which is considered as right time to study the changes in shape, length, mass and volume of glacier.

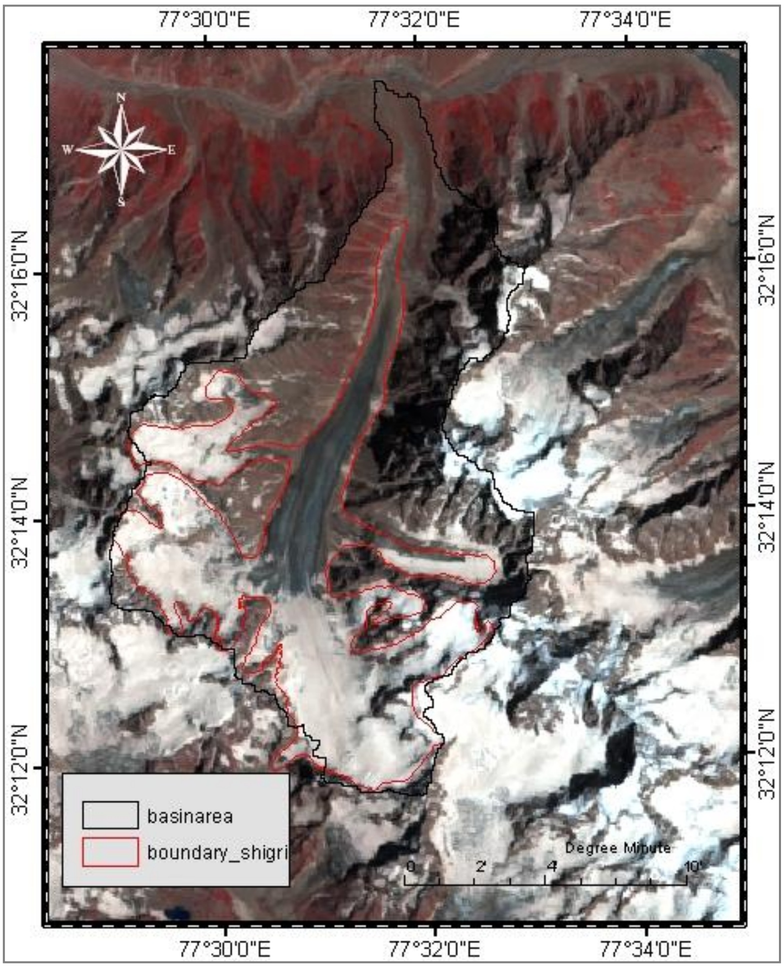

Fig1.The Chhota Shigri Glacier in Lahual and Spiti district of Himachal Pradesh in the satellite image of IRS-1C LISS-III (24 m) on 25Aug 2005.

3.1 Data Used

To study such changes there is need to generate a time series of glacier by collecting satellite scenes from different sensor passing over this region in the month of August. The main criteria needed to be fulfilled while selecting scene under study is that the images should be cloud free and area should not come under the shadow. In total 8 scenes are selected for our study from Satellite Landsat, Resourcesat-1, IRS-1C, IRS-1D. Two images of the study area as 17 August 1997 and 5 September 1998 were taken from sensor LISS-III under IRS-1C and one scene of 20 August 2008 from sensor LISS-III under IRS-1D. From Landsat TM, two scenes have been selected13 August 2009 and 16 August 2010. From Landsat ETM, only one scene for 25August 2000 have selected. These scenes are downloaded free from NASA website. From IRS –P6 (Resourcesat-1) two scenes of 23 August 2005 and 18August 2006 under LISS-III have been taken for study.

Table1: Gives the Detailed Information About the Date, Satellite, Sensor and Data Source of the Dataset Used in the Study.

DATE	SENSOR	SATELLITE	DATA SOURCE
17 August 1997	LISS III	IRS-1C	NRSC
05 September 1998	LISS III	IRS-1C	NRSC
25 August 2000	ETM	LANDSAT	USGS
23 August 2005	LISS-III	IRS-P6	NRSC
18 August 2006	LISS-III	IRS-P6	NRSC
20 August 2008	LISS-III	IRS-1D	NRSC
13 August 2009	TM	LANDSAT	USGS
16 August 2010	TM	LANDSAT	USGS

3.2 Radiometric Calibration

Digital sensor record intensity of electromagnetic radiation of Earth Surface as Digital number (DN value) which in turn depends on the radiometric resolution of sensor[17]. In general LISS III, TM, ETM has radiometric resolution of 7 bit so it can store DN values in the range of 0-255. But the spectral signature of the Earth surface is not measured by the DN values. As spectral signature of the surface depends mainly on location of sun, viewing geometry of the satellite at moment the image has taken, and earth to sun distance[18]. So it is necessary to convert all the DN values to radiance and reflectance.

3.2.1 Conversion of DN (digital number) value to Radiance:-

Digital numbers are converted into at sensor radiance with the help of respective sensor parameters present in the header file of the data. The general equation is as:-

$$Lsensor = \frac{Lmax - Lmin}{Qcalmax - Qcalmin} * (Qcal - Qcalmin) + Lmin \qquad 2$$

Where,

Lsensor = Spectral radiance at sensor level [(W/m^2/sr/µm)]

Lmax = maximum detected spectral radiance [(W/m^2/sr/ µm)]

Lmin = minimum detected spectral radiance [(W/m^2/sr/ µm)]

Qcal = digital number for analysed scene

Qcalmax = maximum possible DN value (for dataset used, It is 255)

Qcalmin = minimum possible DN value (for dataset used, It is 0)

The value for Lmin and Lmax is different for different band for different satellite. These value are generally present in the header or leader file of the data.

3.2.2 Conversion of At-Sensor Radiance to Reflectance:-

The At-Sensor Radiance is further converted to Top of Atmospheric Reflectance which can be evaluated as per formula given as

$$TOA = \frac{\pi * Lsensor * d^2}{E_{sun} * Cos\ \theta} \qquad 3$$

Where

TOA = Top of Atmospheric Reflectance [unitless]

Lsensor = Spectral Radiance at Sensor Level [(W/m^2/sr/µm)]

d = Earth sun distance[astronomical unit]

E_{sun} = Mean Exoatmospheric solar irradiance[(W/m^2/ µm)]

θ = Solar zenith angle.(degrees)

The cosine of solar zenith angle is equal to sine of sun elevation angle which is always given in the header file of the sensor.[19] Another ancillary information obtained through their header files is tabulated in Table1.

Table1: The Ancillary Information Present in the Header Files of the Data Used, Which Help in the Conversion from Radiance at Sensor to Reflectance.[18][19]

Date of Pass	Satellite and Sensor	Bands and wavelength in micrometers	Row/ Path	E_{sun} in W/m^2/sr	Sun Elevation Angle	Julian Day	Eath to Sun Distance
17 Aug 1997 5 Sept 1998	IRS-1C (LISS-III)	B2 (green) - 0.52-0.59 B3 (Red)- 0.62-0.68 B4 (NIR)- 0.77-0.86 B5(SWIR) – 1.55-1.70	95/48	1851.1 1583.8 1102.5 240.40	65.23 60.23	229 248	1.0121 1.007751
28Aug 2000	LANDSAT (ETM)	B1(blue) 0.45-0.51 B2(green) 0.51-0.60 B3(red) 0.61-0.69 B4 (VNIR) 0.76-0.90 B5 (SWIR) 1.55-1.75 B6 (TIR) 10.40-12.5 B7(SWIR) 2.09-2.35 B8(PAN) 0.52-0.90	147/38	1969 1840 1551 1044 22.5 ------ 82.07 1368.0	58.33	241	1.009475
23 Aug 2005 18 Aug 2006	IRS-P6 LISS-III	B2 (green) - 0.52-0.59 B3 (Red)- 0.62-0.68 B4 (NIR)- 0.77-0.86 B5(SWIR) – 1.55-1.70	95/48	1849.5 1553 1092 240.40	63.48 64.57	235 230	1.010401 1.0119

20 Aug 2008	IRS-1D LISS-III	B2 (green) - 0.52-0.59 B3 (Red)- 0.62-0.68 B4 (NIR)- 0.77-0.86 B5(SWIR) – 1.55-1.70	95/48	1852.2 1577.3 1096.7 240.60	42.441	233	1.01128
13 Aug 2009 16 Aug 2010	LANDSAT TM	B1(blue) 0.45-0.51 B2(green) 0.51-0.60 B3(red) 0.61-0.69 B4 (VNIR) 0.76-0.90 B5 (SWIR) 1.55-1.75 B6 (TIR) 10.40-12.5 B7(SWIR) 2.09-2.35	147/38	1957 1826 1554 1036 215 ----- 80.67	60.94 60.648	225 228	1.01286 1.01229

IV. METHODOLOGY

After radiometric calibration of the scene the next step is to find the extend of the glacier and corresponding indices which help in the distinguishing the zones of glaciers i.e. accumulation and ablation zone. The extend of glacier is marked with the help of digitising the boundary of glacier through mosaiced and georeferenced toposheets, consisting of toposheet numbers 52 H/7 , 52H/8, 52H/11 and 52H/12. The area approximately comes to be 15.8Km^2 – 16Km^2. This boundary now then used to subset area of study in the satellite images. Various kind of techniques like NDSI, TM, NDSTI have been applied on the radiometrically subsetted images which clearly mapped the different parts of glaciers when an appropriate threshold applied on it. After applying threshold accumulation area is estimated which results in the evaluation of Accumulation Area Ratio and finally annual mass balance. The overall methodology has been shown in the fig 2. given below

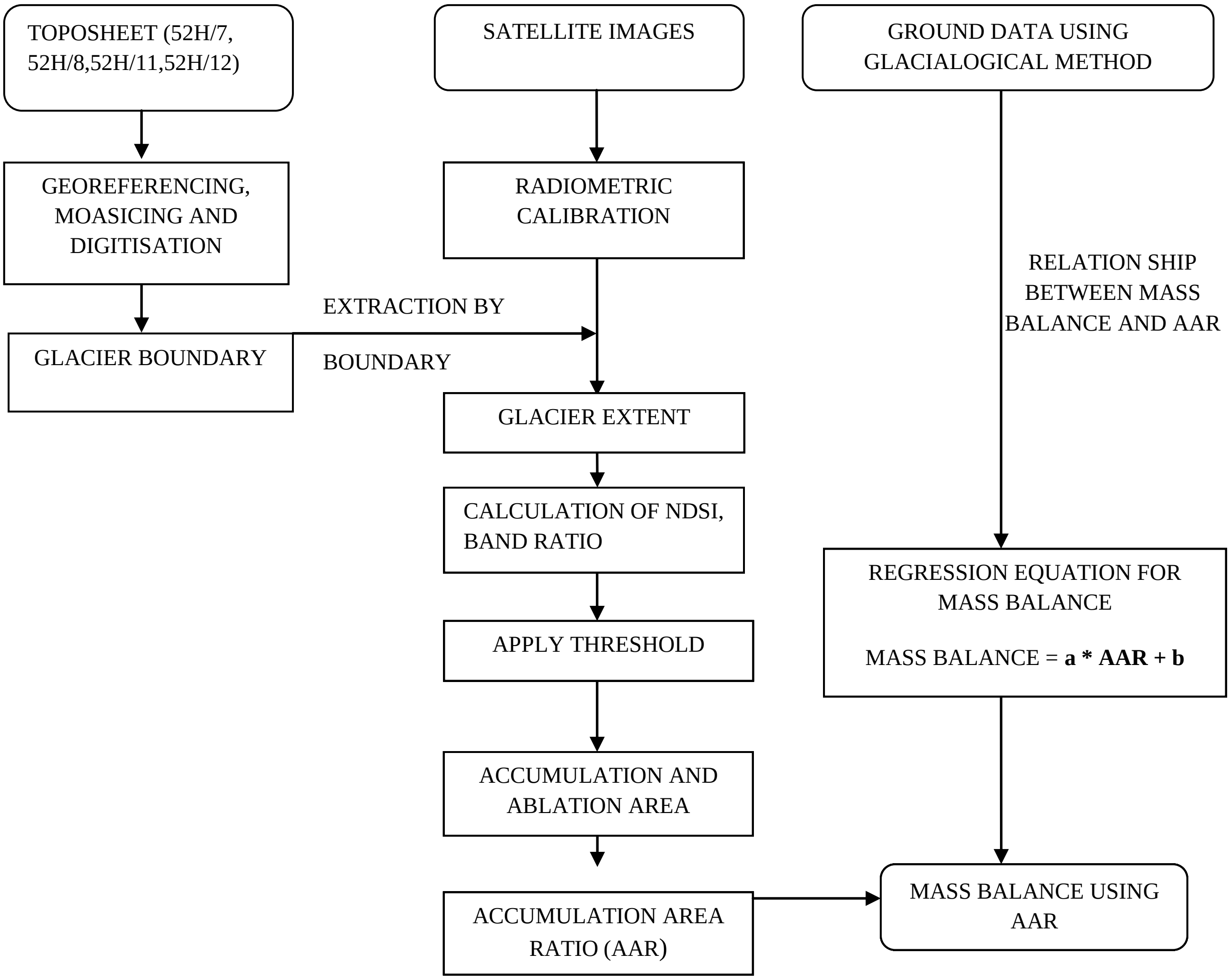

Fig. 2: Overall Methodology for Estimating the Mass Balance Using AAR Method

V. MAPPING TECHNIQUES

The major difficulties in monitoring and mapping the glaciers zones in the Himalayas region is mountain shadow and intense cloud cover in the visible and infrared region. Because of these reasons combination of digital and visual interpretation is needed[20]. But there are some automated techniques which overcome the effect of Shadowing and cloud covering. These papers generally focus on generally two techniques NDSI and TM Ratio.

5.1 NDSI

Normalized Difference Snow Index is found to be very effective in mapping of snow and non snow cover area. This algorithm uses the reflectance values of snow. Generally the snow show very reflectance in visible region and appear white in colour while in SWIR region it has very low reflectance and generally appear black. Due to this notion, NDSI is proved to a useful index for discriminating snow and clouds as cloud show even high reflectance in SWIR region[20]. It also have been proved that NDSI values can be used to identify snow or non-snow pixels under mountain shadow region to some extend and under any orientation i.e. it is independent of illumination condition[21]. NDSI is generally estimated using the Equation.[22]

$$NDSI = \frac{GREEN\ REFLECTANCE - SWIR\ REFLECTANCE}{GREEN\ REFLECTANCE + SWIR\ REFLECTANCE} \quad 4$$

Generally value of NDSI range from -1 to 1. Using corresponding bands in different sensors, NDSI value is determined. Based on the visual interpretation and their respective NDSI values appropriate threshold is applied which automatically delineate the accumulation and ablation zones of glaciers. Since due to the topographic effect sometimes manual delineation need to be done on this automated techniques. The range of threshold applied on the dataset to discriminate zones is between 0.4 to 0.8.

5.2 Band Ratio

Band ratio is also one of the semi automated techniques used for glacier mapping. The ratio of NIR/SWIR have been shown to be effective in discriminating ice and snow faces particularly in shadow area[23]. Paul (2001) concluded that NIR/SWIR (TM4/TM5) ratio techniques are appropriate for clean ice glacier mapping. In case of LISS the band3 (NIR) and band4 (SWIR) is used while in case of Landsat TM and ETM band4 (NIR) and band5(SWIR) is used. This ratio was evaluated mostly on DN values and generally threshold of 1-2 is applied. But this study has evaluated the ratio based on reflectance of their respective band used.

$$BAND\ RATIO = \frac{NIR\ BAND\ REFLECTANCE}{SWIR\ BAND\ REFLECTANCE} \quad 5$$

On applying appropriate range of threshold on band ratio, accumulation and ablation areas get separated. Selection of threshold value is one of crucial job because a small variation lead to under or over estimation of snow cover. Threshold may also varies from one satellite sensor to another [24][25].

These mapping techniques give us time series of accumulation and ablation areas when applied on the available dataset. Once accumulation areas are determined, AAR can be calculated using eq.1 which help in the estimation of mass balance.

VI. RELATIONSHIP BETWEEN AAR AND MASS BALANCE

Based on the field investigation, specific mass balance between year 2002-2010 is estimated by [16]; JNU-SAC, 2008 ; JNU- IFCPAR, 2009,2010 which is reported in Himalayan Glaciology Technical Report as “STATUS REPORT ON CHHOTA SHIGRI GLACIER” (HIMACHAL PRADESH) is shown in table 2 [14]. The study uses this data and establish a mathematical model between Specific mass balance and AAR as a regression equation of 0.0386*AAR – 2.5000 with R^2 =0.95 as in fig3. This mathematical model then use the AAR derived from the dataset used for the study. This model help in the validation of the remote sensing based derived AAR and mass balance with the ground data.

Table 2 shows the ground data e from period (2002-2010).

S.NO	YEARS	AAR VALUE (%)	MASS BALANCE (m weq)
1	2003	31	-1.4
2	2004	31	-1.2
3	2005	74	0.1
4	2006	29	-1.4
5	2007	36	-1.3
6	2008	37	-0.93
7	2009	63	0.13
8	2010	70	0.33

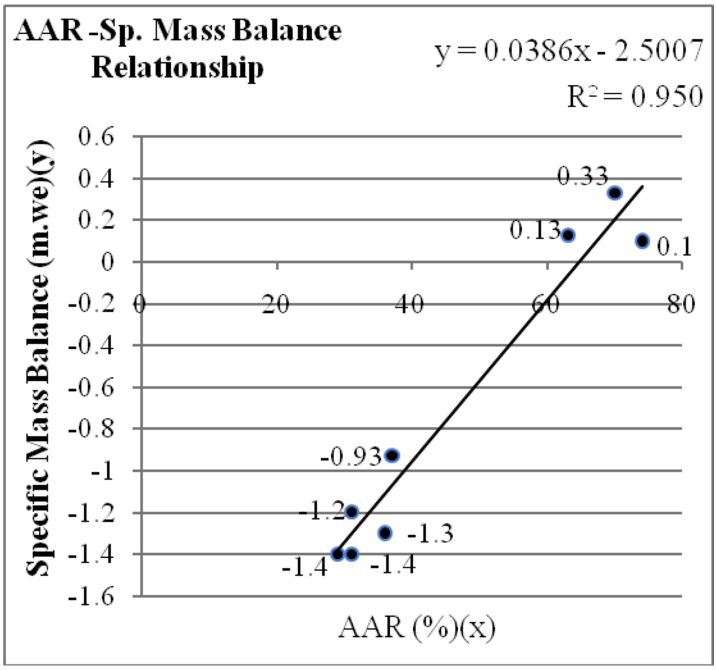

Fig3 Mathematical Model Derived from the Relationship Between Mass Balance and AAR with y=0.0386*x – 2.5007 with Coefficient of Correlation is 0.95.

VII. RESULTS AND DISCUSSIONS

This mathematical model is regional model. This model validates the AAR and mass balance over only Chhota Shigri glacier. The accumulation and ablation areas obtained from the mapping of satellite images using two different techniques of NDSI and BAND RATIO are approximately equal as that obtained from ground investigation. AAR also range from 0.3 to 0.7 which is also relatively similar to data obtained from field. The mass balance so evaluated from this method is comparable and shows good correlation with the mass balance calculated on ground. The mass balance of 2005, 2009 and 2010 showing positive mass balance while 1998, 1997 2000, 2006, 2008 showing negative mass balance thus good result of using this mathematical model. As per the results year 2006 shows highest glacier mass balance loss of -1.384 m. weq, while studies depict glacier gain of mass balance in 2010 is 0.25 m. weq The table 4 and table5 shows the results that come out of the study. The table 3 and 4 are obtained from two mapping techniques NDSI and band ratio. The threshold values of NDSI for separating accumulation and ablation zones are in the range of 0.4-0.8. And for band ratio, though sensors are different and their reflectance is also different so, range is variable. The average mass balance so calculated from 2005 to 2010 for given dataset is -0.354 m weq for field data. It is -0.40995 m weq with NDSI techniques and -0.3898 m weq with band ratio. The percentage difference between the calculated mass balance and actual mass balance is ± 30 % which is a little more towards higher side. This percentage error is further being reduced if some more pixel based classification technique can be applied. The RMSE error for NDSI is found to be around 0.040 m weq while for Band Ratio it is found to be 0.060772 and found to be acceptable. The requirement of the model is based on availability of cloud free satellite image and field data. The main advantage of this method is that mathematical model of a specific glacier can be estimated and annual mass balance can be obtained without performing any field work over and over again.

Table 3: Glacier Mass Balance Calculated through AAR Method by Applying Suitable Threshold on the Band Ratio Separating Accumulation and Ablation Areas

Date of Scene	Threshold (NDSI range)	Ablation Area(km^2)	Accumulation Area(km^2)	AAR (%)	Mass Calculated (m weq)	Mass Observed (m weq)
17Aug1997	0.58	6.23	9.57	60.5	-0.163	Nil
05Sep1998	0.6	7.14	8.66	54.8	-0.384	Nil
25Aug2000	0.83	10.78	5.02	31.7	-1.27	Nil
25Aug2005	0.6	5.23	10.57	67	0.0862	0.1
18 Aug2006	0.65	11.23	4.58	28.9	-1.384	-1.4
20Aug2008	0.41	5.91	9.89	37	-1.0718	-0.93
13Aug2009	0.7	5.32	10.48	66.5	0.07	0.13
16Aug2010	0.8	4.54	11.26	71	0.25	0.33

Table 4: Mass Balance Calculated through AAR Method by Applying Suitable Threshold on NDSI Separating Accumulation and Ablation Areas

Date of Scene	Threshold (Band Ratio)	Ablation Area(km^2)	Accumulation Area(km^2)	AAR (%)	Mass Calculated (m.weq)	Mass Observed (m.weq)
17Aug1997	5.8	6.26	9.54	60.3	-0.172	Nil
05Sep1998	6.0	7.27	8.53	54	-0.42	nil
25Aug2000	13.0	10.87	4.93	31.2	-1.295	nil
25Aug2005	4.7	5.06	10.74	68	0.12	0.1
18Aug2006	4.6	11.20	4.60	29	-1.380	-1.4
20Aug2008	8.5	6.0	9.8	38	-1.0332	-0.93
13Aug2009	9	5.33	10.47	66.2	0.06	0.13
16Aug2010	8	4.52	11.28	72.2	0.284	0.33

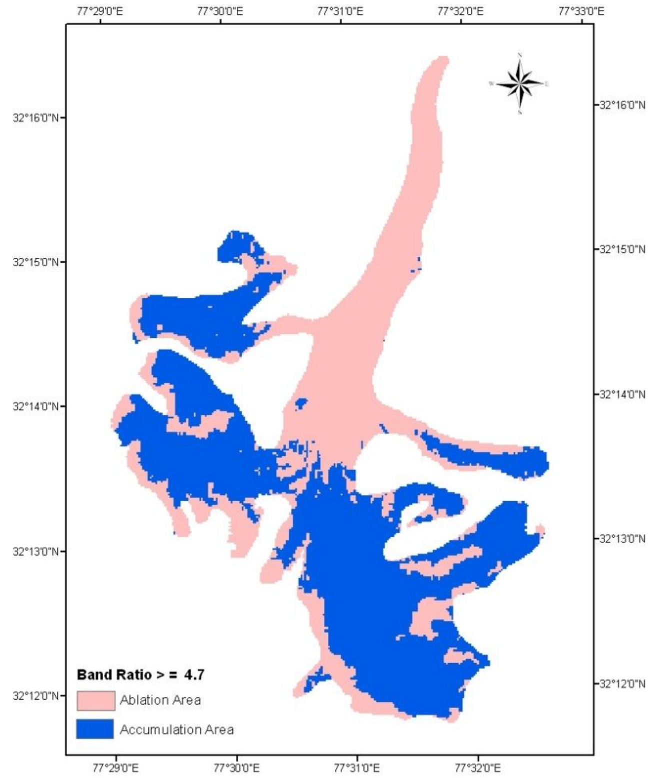

Fig4.a. Separation of Accumulation and Ablation area of glacier by applying threshold of 4.7 on Band ratio map of 25 Aug 2005

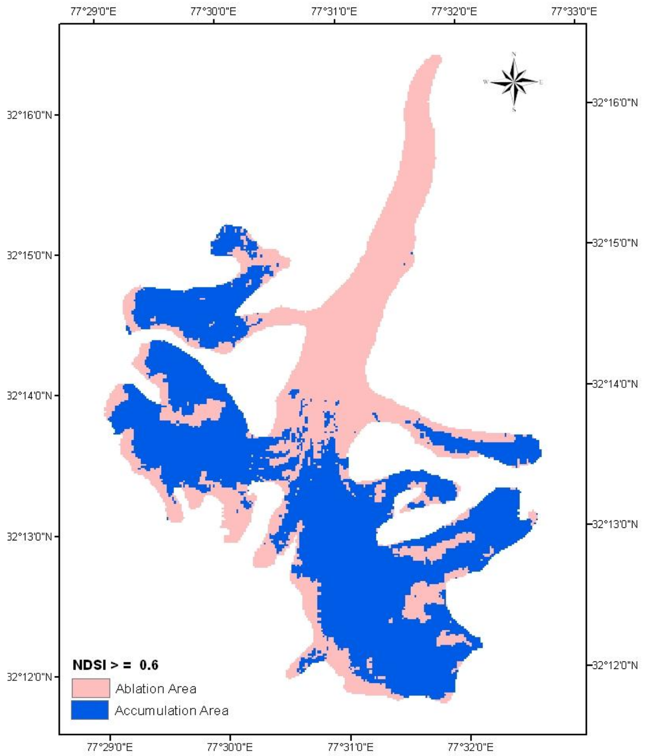

Fig4.b. Separation of Accumulation and Ablation area of glacier by applying threshold of 0.6 on NDSI map of 25 Aug 2005

VIII. ADVANTAGES AND LIMITATIONS OF AAR METHOD

Taking into consideration the remote areas, rugged topography, harsh climate of the glaciers, AAR method is proved to be better to do such mass balance studies with the help of remote sensing. If the field data for AAR and mass balance of glacier for few years are available, then mass balance for the subsequent years for same glacier can be calculated i.e continuous monitoring of the glacier without field visit. But if there is lack of field data, this technique may needs some other parameters like elevation (ELA), depth of the glacier, density along with the AAR to estimate glacier mass balance.

The reliability of this technique also depends on the data availability. Optical data usually suffers from high cloud cover and shadows over such kind of snow covered topography. Since glacier study can be carried over a particular period of an year (mainly last week of August and 1st week of September), only such satellite data can be prove to be useful which frequently passes through this region at that period of year. Medium to high resolution SAR data in high incidence angles can overcome limitation of cloud cover during this time period.

IX. CONCLUSIONS

The mass balance estimation done by the AAR technique using remotely sensed data can directly estimate the total loss or total gain in the glacier. The positive value shows net annual gain in the mass balance while negative value shows the net loss in mass balance. It has been concluded from the relationship that the increase in the AAR ratio, causes increase in mass balance. Higher the value of AAR, more positive will be mass balance. Optical data because of their high resolution proved to useful to distinguish the accumulation and ablation zones of glacier by applying appropriate threshold value on NDSI and Band Ratio. Accumulation and ablation areas evaluated through both the techniques are almost equal showing that both technique of mapping is appropriate for such studies. But in visual interpretation band ratio clearly separate the snow accumulated areas and ablation areas. The mathematical model of $y = 0.0386 * x – 2.5007$ for chhota shigri can be considered to give better result and can be further used for study. Similar kind of study can be carried out with other monitored glacier also so as to reduce the risk of staying such remote areas.

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