

**GEOSPATIAL MODELLING OF GLACIERS HEALTH AND LINKAGES
WITH HYDROLOGY AND CLIMATE CHANGE USING REMOTE
SENSING, GIS AND SEASONAL SENSITIVITY CHARACTERISTICS**

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**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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Sensing, GIS and Seasonal Sensitivity Characteristics**

by

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DEPARTMENT OF CIVIL ENGINEERING

Submitted

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CERTIFICATE

This is to certify that the thesis entitled “**Geospatial Modelling of Glaciers Health and Linkages with Hydrology and Climate Change using Remote Sensing, GIS and Seasonal Sensitivity Characteristics**” submitted by **Ms. Swati Tak** to Indian Institute of Technology Delhi for the award of **Doctor of Philosophy** is a record of bonafide research work conducted by her. She carried out her research work under my supervision for the submission of this thesis, which to the best of my knowledge has reached the required standard.

This Ph.D. thesis is original and has not been presented elsewhere for the award of any degree.

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The initiation of this thesis has been a challenging process, right from the beginning in the year 2015, with the introduction to building performance simulation in a research.

The objective of this research was to investigate the glacier mass balance, runoff, and sensitivity analysis. However, the final goal of the research has been climate change aspect for the Parbati region. Even though the research started out with a tool and developed the application for it as a secondary objective, the study has been a success. It has highlighted interesting aspects about the investigation of glacier under future weather projections and proven that the generic platform for sensitivity analysis is working for this research.

I also express gratitude to my host institution “Indian Institute of Technology Delhi (IIT DELHI)” for giving me this opportunity to conduct my research on the topic “Geospatial Modeling of Glaciers Health and Linkages with Hydrology and Climate Change using Remote Sensing, GIS and Seasonal Sensitivity Characteristics”.

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Abstract

There is an increasing interest in glacier studies worldwide as glaciers are considered as the most sensitive indicators of climate change and several model studies show that the climate change due to global warming will result in significant melting of earth's glaciers and thereby a significant rise in the global sea level. There is a lack of knowledge on the mass balance of several glaciers and the hydrological response of the glacierized catchment and its sensitivity in a changing climate because many glacierized regions of the world including Himalayan region remain either unsampled or poorly sampled, and the direct field measurements for continuous monitoring of glaciers on a large scale or in complex harsh terrain are costly, time consuming and difficult. Further, the appropriate models incorporating glacio-hydrological processes and its time varying behavior are very limited. Glaciers and seasonal snow cover play vital role in the hydrology of mountainous catchments and river basins originating from the glaciated region.

The studies on Himalayan glaciers are very limited. The Himalayan glaciers are very sensitive to climate change and influence the hydrology of several rivers in Indus, Ganga and Brahmaputra systems. The glacier retreat may have greater ramifications on water, food and energy security. The glaciological processes and the dynamics of glaciers and snow mass are also sensitive to climate change as small fluctuations can sometimes lead to rapid retreat or surge in the glacial extent which may cause devastating flood, glacier lake outburst flood and snow avalanche that may affect life, property and infrastructure adversely on the downstream.

In the present study, an integrated geospatial glacial hydrological model is developed to improve the understanding of accumulation and ablation processes, to quantify the mass balance of glaciers and to assess the glacial health, to simulate the glacier and snow melt and runoff from the glacierized catchment and to carry out hydrological sensitivity using multitemporal multispectral satellite imageries. The remote sensing based integrated glacial hydrological model consists of the advance-retreat glacial model, glacial hydrological model that incorporates the glacial climate model and a seasonal sensitivity characteristic based methodological framework for hydrological sensitivity. The glacial hydrological model utilizes a conceptual water balance model based on high resolution remote sensing and a temperature-based

degree day method for glacier and snow melt and rainfall runoff simulation in a glacierized mountainous catchment. The developed model has been applied to the glacierized Parbati basin located in the Western Himalayan region of India, which is also a part of the Beas and Indus river systems. The remote sensing data utilized in the present study includes LANDSAT and MODIS satellite images for 19 years from 1998 to 2016. The multispectral data utilized in the study includes Landsat 5 and 7 images for the years 1998-2002 and 2009-2011, MOD10A2 images for the years 2003-2007 and 2012, and Landsat 8 OLI images for the years 2013-2016. The processing of multispectral satellite imageries, generation of digital database and mapping of glacial and snow cover extents were carried out with Arc-Info GIS and ERDAS Imagine software.

The geomorphological mapping, the spatial distribution of glaciers and snow cover, the glacial health and the advance-retreat process were examined from the multispectral satellite imageries at 8 days' time interval for the period from 1998 to 2016. The accumulation area was obtained using the FCC, NDSI and band ratio techniques. A spatial raster model was used to compute NDSI and the band ratio of satellite images was carried out pixel by pixel as a raster model using the reflectance values of NIR and SWIR bands. The prevailing glaciological processes were investigated and the mass balance of the Parbati glacier was carried out for 19 years from 1998 to 2016. The glacier-snowmelt runoff, rainfall runoff and total runoff for the Parbati river basin was obtained using the developed hydrological model for 17 years from 2000-2016. The hydrological sensitivity was investigated under changing climate based on the 16 years of climatic and satellite data for the period 2000-2015. The sensitivity of total runoff was computed for two different scenarios of changing climate. The first scenario represents the temperature rise by 1 °K and the increase in precipitation by 10%, whereas the second scenario represents the temperature rise by 4 °K and the increase in precipitation by 10%. A distributed approach has been considered to account the effect of variations in temperature and precipitation on the total runoff.

The study shows that the Parbati glacier spreads over 425.318 sq km and more than 50% of the area is accumulation area. The Parbati glacier is not in equilibrium and its behavioural response changes year to year characterized with high rate of mass loss and retreat. The value of AAR varies between 0.33 and 0.67 with an average value of

0.55 indicating a negative mass loss. The mean specific mass loss is -0.48 ± 0.11 m.w.e. and the total mass loss is 3.95 Gt., indicating strong influence of climate change and effect on river flows and water availability. The maximum snow cover area is found to be 1640 km², whereas the minimum snow cover area is 1100 km², indicating a difference of 49%. The snow cover is predominantly in the elevation zone of 4000-6000 m. The total runoff obtained is in agreement with the observed discharge of the Parbati river showing value of r^2 equal to 0.85. The peak total runoff occurs in July month with a value of 132.83 cumecs and the lowest total runoff is observed during December month with a value of 30.13 cumecs. The basin receives about 55% of total runoff during the ablation period (May-September).

The rainfall is the largest contributor to the runoff during most months particularly monsoon months; however, the melt runoff also contributes significantly. The melt runoff hydrograph is observed to be a unimodal with a peak in July, whereas the rainfall runoff and total runoff hydrographs are found to be bimodal having peaks in March and August months for rainfall runoff and in March and July months for total runoff. The contribution from the melt runoff is significant. However, rainfall is the largest contributor. The Parbati basin is vulnerable to the climate change because of high retreat of the Parbati glacier, which may influence water availability and environmental flows in the region. There is a strong influence of climate change parameters, namely, temperature and precipitation on the glacier mass loss and the total runoff from the glacierized Parbati basin, indicating a major concern of global warming on the streamflow, water availability and livelihood in the western Himalayan region. The summer temperature and the winter precipitation are the two important factors that hold the mass balance in the region. The peak runoffs are significantly different under changing climate scenarios. The low runoffs are also altered substantially in changed scenarios of climate. The peak runoff reduces by more than 15% under changing climate because of reduction in snow cover areas due to rise in temperature and the loss is not fully compensated by the increased rainfall. The glacier retreat will greatly affect the runoff and the water availability for drinking water supply, irrigation and hydropower in the region. This will have strong influence on the hydrology, water resources and environment of Beas river basin and the Indus system.

Indian Himalaya is losing ice, usually expressed as loss of glacier mass. Rates of mass loss for Himalayan glaciers are rapidly increasing and shrinking glaciers are often the most visible indicators of mountain ecology for the changing climate. Retreating of the glaciers gives rise to the total discharge and affect the water flow regime, which brings the attention to the changing climate.

A key investigation of this research is to run the simulation for a series of varying weather and climatic conditions, and implications of local changing climate on the hydrology of the glacierized catchment through the sensitivity analysis. The sensitivity is presented to understand the changes in runoff under changing climate. There is alarming rise of temperature and decrease of precipitation which continuously show the negative mass balance of the Parbati glacier.

The limitation of the present study is primarily due to inadequate network for temperature, precipitation and discharge measurements, and modeling uncertainties. The study would be very helpful in better management of water resources and evolving strategic plans to secure water, food and energy, and addressing flood disaster in mountainous areas and western Himalayan region in particular. It would be also helpful in the studies of hydrological and avalanche dynamics and glacial hazards, and determining the response of glaciers to global warming and climatic changes and in identifying the plausible reasons causing aberration in glacier response as it may also be affected by the presence of debris and human behavior.

सार

दुनिया भर में ग्लेशियर के अध्ययन में रुचि बढ़ रही है क्योंकि ग्लेशियरों को जलवायु परिवर्तन के सबसे संवेदनशील संकेतक के रूप में माना जाता है और कई मॉडल अध्ययनों से पता चलता है कि ग्लोबल वार्मिंग के कारण जलवायु परिवर्तन से पृथ्वी के ग्लेशियरों के पिघलने का महत्वपूर्ण परिणाम होगा और इससे वैश्विक स्तर पर महत्वपूर्ण वृद्धि होगी। समुद्र का स्तर। कई हिमनदों के द्रव्यमान संतुलन और हिमनदीकृत जलग्रहण की हाइड्रोलॉजिकल प्रतिक्रिया और बदलती जलवायु में इसकी संवेदनशीलता के बारे में ज्ञान की कमी है क्योंकि हिमालयी क्षेत्र सहित दुनिया के कई हिमनदीकृत क्षेत्र या तो बिना नमूने वाले या खराब नमूने वाले रहते हैं, और प्रत्यक्ष क्षेत्र मापन बड़े पैमाने पर या जटिल कठोर इलाकों में ग्लेशियरों की निरंतर निगरानी के लिए महंगा, समय लगता है और मुश्किल है। इसके अलावा, उपयुक्त मॉडल जिसमें ग्लेशियो-हाइड्रोलॉजिकल प्रक्रियाएं शामिल हैं और इसका समय अलग-अलग हैव्यवहार बहुत सीमित है। ग्लेशियर और मौसमी हिम आवरण पर्वतीय कैचमेंट और नदी नालों के जल विज्ञान में महत्वपूर्ण भूमिका निभाते हैं। हिमालय के ग्लेशियरों पर अध्ययन बहुत सीमित हैं। हिमालय के ग्लेशियर जलवायु परिवर्तन के लिए बहुत संवेदनशील हैं और सिंधु, गंगा और ब्रह्मपुत्र प्रणालियों में कई नदियों के जल विज्ञान को प्रभावित करते हैं। ग्लेशियर पीछे हटने से पानी, भोजन और ऊर्जा सुरक्षा पर अधिक प्रभाव पड़ सकता है। ग्लेशियर की प्रक्रियाएं और हिमनद और हिमपात की गतिशीलता भी जलवायु परिवर्तन के प्रति संवेदनशील हैं क्योंकि छोटे उतार-चढ़ाव कभी-कभी ग्लेशियल सीमा में तेजी से पीछे हटने या बढ़ने का कारण बन सकते हैं जो विनाशकारी बाढ़, ग्लेशियर के प्रकोप बाढ़ और बर्फ हिमस्खलन का कारण बन सकते हैं जो जीवन को प्रभावित कर सकते हैं। संपत्ति और बुनियादी ढांचे में गिरावट पर प्रतिकूल प्रभाव। वर्तमान अध्ययन में, ग्लेशियरों के द्रव्यमान संतुलन को निर्धारित करने और ग्लेशियर और हिमपात पिघल और ग्लेशियर कैचमेंट से अपवाह को दूर करने के लिए, ग्लेशियरों के बड़े संतुलन को निर्धारित करने और संचय प्रक्रियाओं की समझ में सुधार करने के लिए एक एकीकृत भू-स्थानिक हिमनदीय हाइड्रोलॉजिकल मॉडल विकसित किया गया है। और मल्टीटेम्पोरल मल्टीस्पेक्ट्रल सैटेलाइट इमेजियों का उपयोग करके हाइड्रोलॉजिकल संवेदनशीलता को पूरा करने के लिए। सुदूर संवेदी आधारित एकीकृत हिमनदीय जलविभाजक मॉडल में एडवांस रिट्रीट ग्लेशियल मॉडल, ग्लेशियल हाइड्रोलॉजिकल मॉडल शामिल हैं, जो हिमनद जलवायु मॉडल और हाइड्रोलॉजिकल संवेदनशीलता के लिए एक मौसमी संवेदनशीलता विशेषता आधारित पद्धतिगत ढांचा शामिल है। ग्लेशियल हाइड्रोलॉजिकल मॉडल उच्च संकल्प रिमोट सेंसिंग पर आधारित एक वैचारिक जल α बैलेंस मॉडल और ग्लेशियर में बर्फ पिघल और वर्षा अपवाह सिमुलेशन के लिए एक तापमान आधारित डिग्री दिन पद्धति

का उपयोग करता है। विकसित मॉडल को भारत के पश्चिमी हिमालयी क्षेत्र में स्थित ग्लेशियर पारबती बेसिन पर लागू किया गया है, जो ब्यास और सिंधु नदी प्रणालियों का भी एक हिस्सा है। वर्तमान अध्ययन में उपयोग किए गए रिमोट सेंसिंग डेटा में 1998 से 2016 तक 19 साल के लिए LANDSAT और MODIS उपग्रह चित्र शामिल हैं। अध्ययन में उपयोग किए गए मल्टीस्पेक्ट्रल डेटा में 1998-2002 और 2009-2011 के लिए लैंडसैट 5 और 7 छवियां, MOD10A2 छवियां शामिल हैं। वर्ष 2003-2007 और 2012, और 2013-2016 के लिए लैंडसैट 2003 ओएलआई चित्र। मल्टीस्पेक्ट्रल सैटेलाइट इमेजरीज की प्रोसेसिंग, डिजिटल डेटाबेस का निर्माण और ग्लेशियल और स्नो कवर एक्सटेंशन्स की मैपिंग को आर्क-इंफो जीआईएस और ईआरडीएस इमेज सॉफ्टवेयर के साथ किया गया। 1998 से 2016 की अवधि के लिए 8 दिनों के अंतराल पर भू-आकृति विज्ञान मानचित्रण, हिमनदों और हिम आवरणों का स्थानिक वितरण, हिमस्खलन स्वास्थ्य और अग्रिम-वापसी प्रक्रिया की जांच मल्टीस्पेक्ट्रल उपग्रह इमेजियों से की गई। एफसीसी, एनडीएसआई और बैंड अनुपात तकनीक। एनडीएसआई की गणना करने के लिए एक स्थानिक रेखापुंज मॉडल का उपयोग किया गया था और उपग्रह चित्रों के बैंड अनुपात को पिक्सेल द्वारा पिक्सेल के रूप में एनआईआर और एसडब्ल्यूआईआर बैंड के प्रतिबिंबित मूल्यों का उपयोग करके किया गया था। प्रचलित ग्लेशियोलॉजिकल प्रक्रियाओं की जांच की गई और 1998 से 2016 तक 19 वर्षों के लिए पारबती ग्लेशियर का द्रव्यमान संतुलन किया गया। पारबती नदी बेसिन के लिए ग्लेशियर-स्नोमेल्ट अपवाह, वर्षा अपवाह और कुल अपवाह को 17 के लिए विकसित हाइड्रोलॉजिकल मॉडल का उपयोग करके प्राप्त किया गया था। वर्ष 2000- 2016 तक। वर्ष 2000-2015 की जलवायु और उपग्रह डेटा के 16 वर्षों के आधार पर बदलती जलवायु के तहत जल विज्ञान संवेदनशीलता की जांच की गई। कुल अपवाह की संवेदनशीलता बदलती जलवायु के दो अलग-अलग परिदृश्यों के लिए गणना की गई थी। पहला परिदृश्य 1 ठीक है द्वारा तापमान वृद्धि और 10% से वर्षा में वृद्धि का प्रतिनिधित्व करता है , जबकि दूसरा परिदृश्य 4 ठीक है द्वारा तापमान वृद्धि और 10% से वर्षा में वृद्धि का प्रतिनिधित्व करता है । कुल अपवाह पर तापमान और वर्षा में भिन्नता के प्रभाव को ध्यान में रखते हुए एक वितरित दृष्टिकोण पर विचार किया गया है। अध्ययन से पता चलता है कि पारबती ग्लेशियर 425.318 वर्ग किमी में फैला है और 50% से अधिक क्षेत्र संचय क्षेत्र है। पारबती ग्लेशियर संतुलन में नहीं है और इसकी व्यवहारिक प्रतिक्रिया साल-दर-साल बदलती रहती है, जिसमें बड़े पैमाने पर नुकसान और पीछे हटने की उच्च दर होती है। AAR का मान 0.33 और 0.67 के बीच भिन्न होता है, जिसका औसत मान 0.55 होता है जो एक नकारात्मक द्रव्यमान हानि का संकेत देता है। औसत विशिष्ट जन हानि -0.48 विशिष्ट 0.11 mwe है । और कुल जन हानि 3.95 Gt है, जो जलवायु परिवर्तन के मजबूत प्रभाव और नदी के प्रवाह और जल की उपलब्धता पर प्रभाव को दर्शाता है। अधिकतम बर्फ कवर क्षेत्र 1640 किमी² पाया जाता

है, जबकि न्यूनतम बर्फ कवर क्षेत्र 1100 किमी² है, जो 49% के अंतर को दर्शाता है। बर्फ का आवरण मुख्य रूप से 4000-6000 मीटर की ऊंचाई वाले क्षेत्र में है। प्राप्त कुल अपवाह पारबती नदी के अवलोकनित निर्वहन के साथ है, जो कि आर 2 का मान 0.85 के बराबर है। शिखर कुल अपवाह 132.83 क्यूमेक्स के मूल्य के साथ जुलाई महीने में होता है और दिसंबर के दौरान सबसे कम कुल अपवाह 30.13 क्यूमेक्स के मूल्य के साथ देखा गया है। बेसिन को अपस्फीति अवधि (मई-सितंबर) के दौरान कुल अपवाह का लगभग 55% प्राप्त होता है। अधिकांश महीनों विशेषकर मानसून के महीनों में अपवाह के लिए वर्षा का सबसे बड़ा योगदान होता है; हालाँकि, पिघला हुआ अपवाह भी महत्वपूर्ण योगदान देता है। पिघले हुए अपवाह हाइड्रोग्राफ को जुलाई में एक शिखर के साथ एक असमान के रूप में देखा जाता है, जबकि वर्षा अपवाह और कुल अपवाह हाइड्रोग्राफ को मार्च अप और अगस्त के महीनों में वर्षा अपवाह के लिए चोटियों और मार्च में और जुलाई में कुल अपवाह के लिए पाया जाता है। पिघले अपवाह से योगदान महत्वपूर्ण है। हालाँकि, वर्षा का सबसे बड़ा योगदान है। पारबती ग्लेशियर के उच्च पीछे हटने के कारण पारबती बेसिन जलवायु परिवर्तन की चपेट में है, जो इस क्षेत्र में पानी की उपलब्धता और पर्यावरणीय प्रवाह को प्रभावित कर सकता है। ग्लेशियर जन हानि और ग्लेशियर पारबती बेसिन से कुल अपवाह पर जलवायु परिवर्तन मापदंडों, अर्थात्, तापमान और वर्षा का एक मजबूत प्रभाव है, जो पश्चिमी हिमालय क्षेत्र में जलप्रवाह, जल उपलब्धता और आजीविका पर ग्लोबल वार्मिंग की एक प्रमुख चिंता का संकेत देता है। गर्मियों का तापमान और सर्दियों की बारिश दो महत्वपूर्ण कारक हैं जो इस क्षेत्र में बड़े पैमाने पर संतुलन रखते हैं। बदलते जलवायु परिदृश्य के तहत शिखर अपवाह काफी भिन्न होते हैं। जलवायु के परिवर्तित परिदृश्यों में कम अपवाह को भी काफी हद तक बदल दिया जाता है। बदलते जलवायु के तहत चोटी के अपवाह में 15% से अधिक की कमी होती है क्योंकि तापमान में वृद्धि के कारण बर्फ के आवरण क्षेत्रों में कमी होती है और नुकसान की भरपाई पूरी तरह से बढ़ी हुई वर्षा से नहीं होती है। ग्लेशियर पीछे हटने से क्षेत्र में पीने के पानी की आपूर्ति, सिंचाई और जल विद्युत के लिए अपवाह और पानी की उपलब्धता पर काफी असर पड़ेगा। इससे ब्यास नदी बेसिन के जल विज्ञान, जल संसाधनों और पर्यावरण और सिंधु प्रणाली पर मजबूत प्रभाव पड़ेगा। viii भारतीय हिमालय बर्फ खो रहा है, जिसे आमतौर पर ग्लेशियर द्रव्यमान के नुकसान के रूप में व्यक्त किया जाता है। हिमालय के ग्लेशियरों के लिए बड़े पैमाने पर नुकसान की दर तेजी से बढ़ रही है और बदलते जलवायु के लिए सिकुड़ते ग्लेशियर अक्सर पहाड़ पारिस्थितिकी के सबसे दृश्यमान संकेतक हैं। ग्लेशियरों का पीछे हटना कुल निर्वहन को जन्म देता है और जल प्रवाह शासन को प्रभावित करता है, जो बदलते जलवायु की ओर ध्यान दिलाता है। इस शोध की एक प्रमुख जाँच अलग-अलग मौसम और जलवायु परिस्थितियों की एक श्रृंखला के लिए सिमुलेशन को चलाना है, और संवेदनशीलता विश्लेषण के माध्यम से ग्लेशियर के जलग्रहण पर स्थानीय

परिवर्तनशील जलवायु के निहितार्थ हैं। बदलती जलवायु के तहत अपवाह में परिवर्तन को समझने के लिए संवेदनशीलता प्रस्तुत की जाती है। तापमान का खतरनाक वृद्धि और वर्षा में कमी है जो लगातार पारबती ग्लेशियर के नकारात्मक द्रव्यमान को दर्शाता है। वर्तमान अध्ययन की सीमा मुख्य रूप से तापमान, वर्षा और निर्वहन माप और मॉडलिंग अनिश्चितताओं के लिए अपर्याप्त नेटवर्क के कारण है। अध्ययन जल संसाधनों के बेहतर प्रबंधन और पानी, भोजन और ऊर्जा को सुरक्षित करने के लिए रणनीतिक योजनाओं को विकसित करने और विशेष रूप से पर्वतीय क्षेत्रों और पश्चिमी हिमालयी क्षेत्र में बाढ़ आपदा को दूर करने में बहुत मददगार होगा। यह हाइड्रोलॉजिकल और हिमस्खलन की गतिशीलता और हिमनदी खतरों के अध्ययन में भी सहायक होगा, और ग्लेशियरों की ग्लोबल वार्मिंग और जलवायु परिवर्तन की प्रतिक्रिया का निर्धारण करेगा और प्रशंसनीय कारणों की पहचान करके ग्लेशियर की प्रतिक्रिया में विपथन पैदा करेगा क्योंकि यह भी प्रभावित हो सकता है। मलबे और मानव व्यवहार ।

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NOTATIONS

a	accumulation (due to mainly snow precipitation)
b	ablation (defined here negative due to melting)
a_r	accumulation rate
a	summer ablation
b_r	ablation rate
b_s	summer mass balance
A	Minimum seasonal degree day ($^{\circ}\text{C}$)
C	rate of glacier melt from both iceberg calving and melting across E
	Evaporation (water, snow and ice)
D	Depression constant
Q	Runoff
P_{av}	average seasonal rainfall in the region(m)
R	Runoff calculated from discharge data
T	Temperature
P	Precipitation
E	Evapotranspiration
CI	consistency Index
RI	Random Index
M	Monthly Precipitation
MT	Monthly Temperature
B_A	basin area without snow/glacial cover (m^2) Parbati region
B_m	specific mass balance
B_n	Net balance of the glacier
M_s	winter melt snow area (m)
S_w	snow region in winter (m^2)

W_a	winter snow
W_s	winter snowfall in the Parbati region (m) W_s summer accumulation
R_1	Runoff coefficient for glacierized area
R_2	Runoff coefficient for non-glacierized area
R_3	Runoff coefficient for seasonal snow cover area
S_s	seasonal snow cover (m^2)
T_{ab}	total annual ablation
T_{ac}	total annual accumulation
A_{gl}	Average glacier surface
A_{mb}	Annual mass balance
A_{term}	terminus area
P_{snow}	rate of snow addition
T_{avg}	elevation on the glacier surface
T_{lapse}	lapse rate
CRI	Consistency Ratio Index
GM _{OC}	Glacier Model Out-come
α	constants values for a study basin by analysis of the depression curves
β	constants values for a study basin by analysis of the depression curves
Q_i	Above equation Initial discharge in the basin
Q_p	Discharge after the precipitation in 'n' days in the basin
R_c	Runoff coefficient of the basin
pptn	precipitation
w.e.	water equivalent
S_{p+1}	Snowmelt for day 'n+1' in the basin
ΔTWS	Collected Water or change in Terrestrial Water Storage

LIST OF ACRONYMS

AAR	Area Accumulation Ratio
ARGM	Advance Retreat Glacial Model
BBMB	Bhakra Beas Management Board
BGR	Blue Green Red
DDF	Degree Day Factor
DEM	Digital Elevation Model
DMA	Decision Making Algorithm
ETM+	Thematic Mapper PlusImageries
EVA	Eigen Vector Algorithm
ELA	Equilibrium Line Altitude
FCC	False Color Composites
GCM	Glacial Climate Model
GER	Glacial Erosion Rates
GHM	Glacial Hydrological Model
GIS	Geographical Information System
GLIMS	Global Land Ice Measurements from Space
GM	Glacier Monitoring
GRR	Glacier Retreat Rates
GCS	Geographic Coordinate System
GSI	Geological Survey of India
GTN-G	Global Terrestrial Network for Glaciers
IGB	Indus Ganga andBrahmaputra
IHR	Indian Himalayas region
IPCC	Intergovernmental Panel on Climate Change

NDSI	Normalized Difference Snow Index
RGI	Randolph Glacier Inventory
RS	Remote Sensing
SA	South Asia
SOI	Survey of India
SRMP	Snowmelt-Runoff Model for the Parbati region
SS	Seasonal Snow
SSC	Seasonal Sensitivity Characteristics
TIRS	Thermal Infrared Sensor
TMI	Thematic Mapper Imageries
UNFCCC	United Nations Framework Convention on Climate Change
WGMS	World Glacier Monitoring Service
WHR	Western Himalayan Region
WST	World Surface Temperature

“A glacier is a large permanent mass of ice, consisting mainly of re-crystallization of snow and rock debris that accumulate in and moves slowly outwards or downwards due to the stress of their sheer mass under the effect of gravity”.

Will Harrison, Glaciologist