

**GLACIER RETREAT STUDY AND MELT MODELING IN
DUDH KOSI RIVER BASIN USING
REMOTE SENSING AND GIS TECHNIQUES**

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REMOTE SENSING AND GIS TECHNIQUES**

by

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Submitted

In fulfilment of the requirements of the degree of Doctor of Philosophy

to the



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Dedicated to
My Family

CERTIFICATE

This is to certify that the thesis entitled “**Glacier Retreat Study and Melt Modeling in Dudh Kosi River Basin Using Remote Sensing and GIS Techniques**”, being submitted by **Mrs. Fahimah Shad S. V** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a Bonafide record of the research work carried out by her under our supervision and guidance. The thesis work, in our opinion, has reached the requisite standard, fulfilling the requirements for the degree of Doctor of Philosophy.

The results contained in this thesis have not been submitted, in full or in part, to any other University or Institute for the award of any degree or diploma.

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ABSTRACT

The glacier retreat is a trending subject of discussion nowadays among researchers. The emergence of remote sensing and GIS techniques opened a new world for glaciologists and researchers to study inaccessible glaciers due to the lack of sufficient data. This study employed these advanced techniques to understand and comprehensively analyse the statics of glaciers in the selected basin of the Central Himalayas. This research work consists of four sections. The first section deals with monitoring glacier changes over a long period of 45 years. In the second part of this research, we tried to understand the factors affecting these glacier changes, which include morphological, topographical, and climatic factors. The third part differentiates the small and large glacier characteristics and their difference in retreat behaviors. Last, the fourth section deals with the modeling of glacier melting and mass changes using an Energy balance (EB) approach, where the findings from the first, second, and third sections are incorporated into the model used. This part also quantifies the runoff derived from snow and glacier melt estimated using the EB model. The entire research is conducted on the glaciers in the Dudh Kosi river basin of the Central Himalayan region.

Initially, we tried to capture the retreat characteristics of each glacier in the river basin over 45 years, from 1975 to 2020. By utilizing the remote sensing data, a multi-temporal approach is employed for examining the glacier changes at an interval of 4 years. The glacier changes were quantified by taking the percentage area losses, terminus retreat, changes in glacier elevations and mass balance, and finally, the shifting of Equilibrium altitudes. The analysis results show that all selected glaciers were retreating from 1975 to 2020, irrespective of their size, orientation, position, etc. The highest reduction in area is observed predominantly for smaller glaciers with greater than 70% loss, and minimal area losses were observed for larger glaciers with a magnitude of less than 10%. Glacier surface elevation change and mass balance followed

the same trend as the prevailing climate change, with substantial changes from the 2000-2020 period. An increase in elevation change from 0.35 m/a in 1975-2000 to 0.55 m/a in the 2000-2020 period is observed. Similarly, the mass balance decreased from -0.285 m.w.e /a during the 1975-2000 period to -0.54 m.w.e/a in the 2000-2020. Faster retreating of glaciers is observed after 2000 compared to the period before 2000, which is a clear indication of climate-glacier interaction.

The influence of morphological, topographical, and climate parameters on the above-determined glacier retreat is analyzed next. The factors considered include the debris cover, glacier size and shape, glacier elevation, slope, aspect, etc., determined using well-established methods applied to remote sensing data. The potential relationships between the selected factors and the glacier changes are assessed by regression analysis. The results show that the debris cover significantly influenced area losses with an R-value of -0.56, followed by glacier elevation with an R-value of -0.42, and glacier shape. The glacier size and slope have the most minor influence on area losses in the case of selected glaciers. However, the glacier slope considerably influences ELA shifting, with an R-value of 0.48, indicating higher shifting rates with steeper glacier slopes. Similarly, the slope possesses a perfect positive correlation with elevation change, with an R-value of 0.49. Glacier shapes influence the glacier retreat statistics, with large, compacted glaciers showing less area losses than smaller elongated glaciers.

The present study investigated the behavioral differences between small and larger glaciers in retreat by repeating the same analysis on the glaciers separated into two clusters of sizes less than 5 km² and greater than 5 km². The influence of topographical parameters on the retreat characteristics of these clusters is analyzed. It is observed that larger glaciers are mainly observed at higher elevations with similar responses to each topographical and morphological parameter. However, smaller glaciers show considerable variations in their characteristics within the cluster. Debris cover is predominantly observed for the glaciers with steeper slopes, followed

by gentle slopes, particularly with larger glaciers. This is mainly due to the occurrence of avalanches driven by the topography.

Estimating snow and glacier ice melt is crucial today since the enhanced melting induced by climate change accelerates the glacier retreat. The Himalayan glaciers, especially, are undergoing severe retreats. In this study, an Energy Balance model is used to estimate snow and ice melting. Additionally, this study tried to capture the difference in melt from debris-free and debris-covered regions of the glacier by applying the model at a point scale and a glacier scale. The mass changes are estimated at an hourly resolution, including melting, refreezing, and sublimation processes. This enabled us to understand the spatial and temporal patterns of melting, refreezing, and mass changes. The input data required for running the model are collected from satellite, metrological, and hydrological data. The results show a large seasonal melting trend, with the magnitude of melting higher during the monsoon season and lesser during the pre and post-monsoon seasons. For the selected region, melting from clean ice pixels was higher since more than 80% of the pixels were covered with clean ice pixels and the least from debris-covered ice pixels. The snow melt was least during winter, which increased towards the pre-monsoon season, and peaks during monsoon; after that, it decreased in the post-monsoon period, falling to very little to zero during the beginning of the following winter. The melt from debris-free pixels was higher than debris debris-covered pixels, with the melt reducing as the debris thickness increased towards the terminus. With the model, glacier surface height change is observed, and it shows a positive height change at the higher altitudes where the accumulation dominates, and the surface height change is negative in the lower ablation region, showing a net reduction of glacier mass. Similarly, the depth of refreezing was higher at higher altitudes, and it reduced down-glacier owing to the increased temperature. The runoff simulated from the glacier melt model in this study produced an R^2 value of 0.856 and NSE of 0.765 with the field-measured discharge.

अमूर्त

ग्लेशियरों का पीछे हटना आजकल शोधकर्ताओं के बीच चर्चा का विषय बना हुआ है। रिमोट सेंसिंग और जीआईएस तकनीकों के उद्भव ने ग्लेशियोलॉजिस्ट और शोधकर्ताओं के लिए पर्याप्त डेटा की कमी के कारण दुर्गम ग्लेशियरों का अध्ययन करने के लिए एक नई दुनिया खोल दी है। इस अध्ययन में मध्य हिमालय के चयनित बेसिन में ग्लेशियरों की स्थैतिकता को समझने और व्यापक रूप से विश्लेषण करने के लिए इन उन्नत तकनीकों का इस्तेमाल किया गया। इस शोध कार्य में चार खंड शामिल हैं। पहला खंड 45 वर्षों की लंबी अवधि में ग्लेशियर परिवर्तनों की निगरानी से संबंधित है। इस शोध के दूसरे भाग में, हमने इन ग्लेशियर परिवर्तनों को प्रभावित करने वाले कारकों को समझने की कोशिश की, जिसमें रूपात्मक, स्थलाकृतिक और जलवायु कारक शामिल हैं। तीसरा भाग छोटे और बड़े ग्लेशियर की विशेषताओं और उनके पीछे हटने के व्यवहार में अंतर को अलग करता है। अंत में, चौथा खंड ऊर्जा संतुलन (ईबी) दृष्टिकोण का उपयोग करके ग्लेशियर पिघलने और द्रव्यमान परिवर्तनों के मॉडलिंग से संबंधित है, जहां पहले, दूसरे और तीसरे खंड के निष्कर्षों को इस्तेमाल किए गए मॉडल में शामिल किया गया है। यह भाग ईबी मॉडल का उपयोग करके अनुमानित बर्फ और ग्लेशियर पिघलने से प्राप्त अपवाह को भी मापता है। संपूर्ण शोध मध्य हिमालयी क्षेत्र के दूध कोसी नदी बेसिन के ग्लेशियरों पर किया गया है।

प्रारंभ में, हमने 1975 से 2020 तक, 45 वर्षों में नदी बेसिन में प्रत्येक ग्लेशियर की पीछे हटने की विशेषताओं को पकड़ने की कोशिश की। रिमोट सेंसिंग डेटा का उपयोग करके, 4 साल के अंतराल पर ग्लेशियर परिवर्तनों की जांच के लिए एक बहु-कालिक दृष्टिकोण का इस्तेमाल किया जाता है। ग्लेशियर में होने वाले परिवर्तनों को प्रतिशत क्षेत्र हानि, टर्मिनस पीछे हटना, ग्लेशियर की ऊंचाई और द्रव्यमान संतुलन में परिवर्तन और अंत में, संतुलन ऊंचाई में बदलाव के द्वारा मापा गया। विश्लेषण के परिणाम बताते हैं कि सभी चयनित ग्लेशियर 1975 से 2020 तक पीछे हट रहे थे, चाहे उनका आकार, अभिविन्यास, स्थिति आदि कुछ भी हो। क्षेत्र में सबसे अधिक कमी मुख्य रूप से 70% से अधिक हानि वाले छोटे ग्लेशियरों के लिए देखी गई है 1975-2000 में ऊंचाई में 0.35 मीटर प्रति वर्ष से 2000-2020 की अवधि में 0.55 मीटर प्रति वर्ष तक की वृद्धि देखी गई है। इसी तरह, द्रव्यमान संतुलन 1975-2000 की अवधि के दौरान -0.285 m.w.e/a से घटकर 2000-2020 में -0.54 m.w.e/a हो गया। 2000 से पहले की अवधि की तुलना में 2000 के बाद ग्लेशियरों का तेजी से पीछे हटना देखा गया है, जो जलवायु-ग्लेशियर संपर्क का एक स्पष्ट संकेत है।

इसके बाद ऊपर निर्धारित ग्लेशियर पीछे हटने पर रूपात्मक, स्थलाकृतिक और जलवायु मापदंडों के प्रभाव का विश्लेषण किया जाता है। विचार किए गए कारकों में मलबे का आवरण, ग्लेशियर का आकार और आकृति, ग्लेशियर

की ऊँचाई, ढलान, पहलू आदि शामिल हैं, जिन्हें रिमोट सेंसिंग डेटा पर लागू अच्छी तरह से स्थापित विधियों का उपयोग करके निर्धारित किया जाता है। चयनित कारकों और ग्लेशियर परिवर्तनों के बीच संभावित संबंधों का मूल्यांकन प्रतिगमन विश्लेषण द्वारा किया जाता है। परिणाम दिखाते हैं कि मलबे के आवरण ने -0.56 के आर-मान के साथ क्षेत्र के नुकसान को महत्वपूर्ण रूप से प्रभावित किया, इसके बाद ग्लेशियर की ऊँचाई -0.42 के आर-मान के साथ और ग्लेशियर के आकार को प्रभावित किया। चयनित ग्लेशियरों के मामले में ग्लेशियर के आकार और ढलान का क्षेत्र के नुकसान पर सबसे कम प्रभाव पड़ता है। हालाँकि, ग्लेशियर का ढलान ELA शिप्टिंग को काफी प्रभावित करता है, जिसका R-मान 0.48 है, जो अधिक खड़ी ग्लेशियर ढलानों के साथ उच्च शिप्टिंग दरों को दर्शाता है। इसी तरह, ढलान में ऊँचाई परिवर्तन के साथ एक पूर्ण सकारात्मक सहसंबंध होता है, जिसका R-मान 0.49 है। ग्लेशियर के आकार ग्लेशियर पीछे हटने के आँकड़ों को प्रभावित करते हैं, बड़े, संकुचित ग्लेशियर छोटे लम्बे ग्लेशियरों की तुलना में कम क्षेत्र के नुकसान दिखाते हैं।

वर्तमान अध्ययन में 5 किमी² से कम और 5 किमी² से अधिक आकार के दो समूहों में विभाजित ग्लेशियरों पर एक ही विश्लेषण को दोहराकर पीछे हटने वाले छोटे और बड़े ग्लेशियरों के बीच व्यवहारगत अंतर की जांच की गई है। इन समूहों की पीछे हटने की विशेषताओं पर स्थलाकृतिक मापदंडों के प्रभाव का विश्लेषण किया गया है। यह देखा गया है कि बड़े ग्लेशियर मुख्य रूप से प्रत्येक स्थलाकृतिक और आकारिकी पैरामीटर के समान प्रतिक्रियाओं के साथ अधिक ऊँचाई पर देखे जाते हैं। हालाँकि, छोटे ग्लेशियर समूह के भीतर अपनी विशेषताओं में काफी भिन्नता दिखाते हैं। मलबे का आवरण मुख्य रूप से अधिक ढलान वाले ग्लेशियरों के लिए देखा जाता है, इसके बाद धीमी ढलान होती है, खासकर बड़े ग्लेशियरों के साथ। यह मुख्य रूप से स्थलाकृति द्वारा संचालित हिमस्खलन की घटना के कारण होता है।

आज बर्फ और ग्लेशियर की बर्फ पिघलने का अनुमान लगाना बहुत ज़रूरी है क्योंकि जलवायु परिवर्तन के कारण बढ़ी हुई पिघलन ग्लेशियर के पीछे हटने को तेज़ करती है। हिमालय के ग्लेशियर, खास तौर पर, गंभीर रूप से पीछे हट रहे हैं। इस अध्ययन में, बर्फ और बर्फ पिघलने का अनुमान लगाने के लिए ऊर्जा संतुलन मॉडल का उपयोग किया जाता है। इसके अतिरिक्त, इस अध्ययन ने ग्लेशियर के मलबे से मुक्त और मलबे से ढके क्षेत्रों से पिघलने में अंतर को एक बिंदु पैमाने और एक ग्लेशियर पैमाने पर मॉडल लागू करके पकड़ने की कोशिश की। पिघलने, फिर से जमने और ऊर्ध्वपातन प्रक्रियाओं सहित द्रव्यमान परिवर्तनों का अनुमान प्रति घंटे के रिज़ॉल्यूशन पर लगाया जाता है। इससे हमें पिघलने, फिर से जमने और द्रव्यमान परिवर्तनों के स्थानिक और लौकिक पैटर्न को समझने में मदद मिली। मॉडल को चलाने के लिए आवश्यक इनपुट डेटा उपग्रह, मेट्रोलॉजिकल और हाइड्रोलॉजिकल डेटा से एकत्र किए जाते हैं। परिणाम एक बड़ी मौसमी पिघलने की प्रवृत्ति दिखाते हैं, जिसमें मानसून के मौसम के दौरान पिघलने की मात्रा अधिक होती है और मानसून से पहले और बाद के मौसमों के दौरान कम होती है। चयनित क्षेत्र के लिए, साफ बर्फ पिक्सल से पिघलना अधिक था क्योंकि 80% से अधिक पिक्सल साफ बर्फ पिक्सल से ढके हुए थे और मलबे से ढके बर्फ पिक्सल से सबसे कम थे। सर्दियों के दौरान बर्फ पिघलना सबसे कम था, जो मानसून-पूर्व मौसम की ओर बढ़ गया, और मानसून के दौरान चरम पर था; उसके बाद, मानसून के बाद की अवधि में यह कम हो गया, और

अगली सर्दियों की शुरुआत में बहुत कम या शून्य हो गया। मलबे से मुक्त पिक्सेल से पिघलना मलबे से ढके पिक्सेल की तुलना में अधिक था, मलबे की मोटाई टर्मिनस की ओर बढ़ने के साथ पिघलना कम हो गया। मॉडल के साथ, ग्लेशियर की सतह की ऊंचाई में परिवर्तन देखा जाता है, और यह उच्च ऊंचाई पर एक सकारात्मक ऊंचाई परिवर्तन दिखाता है जहां संचय हावी है, और सतह की ऊंचाई में परिवर्तन निचले अपघटन क्षेत्र में नकारात्मक है, जो ग्लेशियर द्रव्यमान में शुद्ध कमी दर्शाता है। इसी तरह, उच्च ऊंचाई पर फिर से जमने की गहराई अधिक थी, और तापमान में वृद्धि के कारण यह नीचे ग्लेशियर में कम हो गई। इस अध्ययन में ग्लेशियर पिघल मॉडल से अनुकरण किए गए अपवाह ने क्षेत्र-मापा निर्वहन के साथ 0.856 का R2 मान और 0.765 का NSE उत्पन्न किया।

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LIST OF ABBREVIATIONS

GIS	Geographical Information System
FCC	False Color Composite
RGI	Randolph Glacier Inventory
DEM	Digital Elevation Model
DKB	Dudh Kosi River Basin
GDEM	Global Digital Elevation Model
KH-9	Key Hole-9
SRTM	Shuttle Radar Topographic Mission
RS	Remote Sensing
IR	Infrared
TIR	Thermal infrared
NIR	Near-infrared
SWIR	Shortwave infrared
SAR	Synthetic aperture radar
LST	Land surface temperature
TIRS	Thermal infrared sensor
TLR	Temperature Lapse Rate
MODIS	Moderate resolution imaging spectroradiometer
SCA	Snow Cover Area
NDSI	Normalised Difference Snow Index
OLI	Operational Land Imager
CNW	West Changri Nup
EB	Energy Balance
EBM	Energy Balance Model
DEB	Debris Energy Balance
SEB	Surface Energy Balance
SWE	Snow Water Equivalent
EMS	Electro Magnetic Spectrum
EDA	Ensemble of Data Assimilations

HMA	High Mountain Asia
NDVI	Normalised Difference snow index
ELA	Equilibrium Line Altitude
MB	Mass Balance