

**COMPREHENSIVE LANDSLIDE ANALYSIS USING
GEOSPATIAL DATA: EXAMINING CONDITIONING
FACTORS, SCALING RELATIONSHIPS, AND
SUSCEPTIBILITY MAPPING UTILIZING CLOUD
COMPUTING AND MACHINE LEARNING**

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**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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by

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Submitted

In fulfillment of the requirements for the degree of **Doctor of Philosophy**

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CERTIFICATE

This is to certify that the thesis, entitled “**Comprehensive Landslide Analysis using Geospatial Data: Examining Conditioning Factors, Scaling Relationships, and Susceptibility Mapping Utilizing Cloud Computing and Machine Learning**” being submitted by Mrs. Saloni Jain to the Indian Institute of Technology, Delhi, for the award of Doctor of Philosophy, is a record of bonafide research work carried out by him under my supervision. The thesis work, in our opinion, has reached the standard, fulfilling the requirements for the said degree. Further, we certify that this submission is Mrs. Saloni’s work and that, to the best of our knowledge and belief, it contains no material previously published or written by another person which, to a substantial extent, has been accepted for the award of any other degree or diploma of any University or Institute, except where due acknowledgment has been made in the text.

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A handwritten signature in blue ink, consisting of a stylized 'S' followed by the name 'Saloni'.

Saloni Jain

ABSTRACT

According to a study by the GSI, about 12.6 percent of India's total land mass falls under the landslide-prone hazardous zone. However, data availability and quality still need to be addressed, which results in the underrepresentation of landslide-prone areas and less robust predictions. Landslides represent a significant natural hazard with potentially devastating consequences for human populations and infrastructure. This study advances knowledge regarding landslides, their behavior, and associated factors, with implications for effective management, risk reduction, and resilience-building in landslide-prone regions. The study investigates various aspects of landslide dynamics and their underlying drivers through a multidisciplinary approach combining field investigations, remote sensing analysis, and machine learning techniques.

One key focus of the study is investigating the impact of landslide size and settings on the scaling relationship, providing valuable insights into the beginning and characteristics of landslides of different magnitudes. The study enhances our understanding of landslide scaling by examining a combination of log normal and power law distributions, contributing to improved landslide modeling and risk assessment methodologies. Furthermore, empirical analysis using machine learning algorithms identifies key precondition factors influencing landslide sizes, such as Normalized Difference Vegetation Index (NDVI), soil depth, and Height Above Nearest Drainage (HAND), providing actionable insights for landslide mitigation strategies.

Constructing a landslide inventory using Sentinel-2 satellite imagery from 2015 to 2021 offers a comprehensive understanding of landslide distribution and extent over time. This inventory is a valuable resource for land management and risk assessment, enabling stakeholders to identify high-risk areas and prioritize mitigation efforts effectively. A detailed study of successive landslide

movements and triggering factors also enhances our understanding of landslide succession processes. The analysis reveals that landslides at low HAND and steep slopes are more vulnerable to reactivation, while sites with high and moderate slopes are more conducive to recovery. Moreover, the study conducts triggering factor analysis and prepares Event Duration (ED) and Interevent Duration (ID) curves, providing valuable insights into the temporal patterns of landslide occurrence.

Integrating spatial-temporal clustering techniques in landslide susceptibility mapping further improves the accuracy of identifying landslide-prone areas. By leveraging advanced clustering algorithms, the study enhances the precision of landslide susceptibility maps, supporting informed decision-making for land-use planning, infrastructure development, and disaster risk reduction efforts. These findings underline the importance of considering spatial and temporal dynamics in landslide susceptibility assessment, particularly in regions vulnerable to recurrent landslide events.

In conclusion, this study contributes significantly to the advancement of understanding regarding landslide behavior and risk assessment. The study offers valuable insights into the factors affecting landslide occurrence, evolution, and spatial distribution by integrating field observations, remote sensing analysis, and machine learning techniques. These insights have practical implications for landslide management, risk reduction, and resilience-building efforts, ultimately enhancing the capacity of communities and stakeholders to mitigate the impacts of landslides and build more resilient landscapes in landslide-prone regions.

सार

GSI के एक अध्ययन के अनुसार, भारत के कुल भूमि क्षेत्र का लगभग 12.6 प्रतिशत भूस्खलन-प्रवण खतरनाक क्षेत्र के अंतर्गत आता है। हालांकि, डेटा उपलब्धता और गुणवत्ता को अभी भी संबोधित करने की आवश्यकता है, जिसके परिणामस्वरूप भूस्खलन-प्रवण क्षेत्रों का कम प्रतिनिधित्व और कम मजबूत भविष्यवाणियाँ होती हैं। भूस्खलन एक महत्वपूर्ण प्राकृतिक आपदा का प्रतिनिधित्व करता है जो मानव जनसंख्या और बुनियादी ढांचे के लिए विनाशकारी परिणाम दे सकता है। यह अध्ययन भूस्खलन, उनके व्यवहार और संबंधित कारकों के बारे में ज्ञान को बढ़ाता है, जिसका प्रभावी प्रबंधन, जोखिम में कमी और भूस्खलन-प्रवण क्षेत्रों में सहनशीलता निर्माण के लिए महत्वपूर्ण है। यह अध्ययन एक बहुआयामी दृष्टिकोण का उपयोग करके भूस्खलन की गतिशीलता और उनके अंतर्निहित चालकों के विभिन्न पहलुओं की जांच करता है जिसमें क्षेत्रीय जांच, रिमोट सेंसिंग विश्लेषण और मशीन लर्निंग तकनीकें शामिल हैं।

अध्ययन का एक प्रमुख ध्यान भूस्खलन के आकार और सेटिंग्स के प्रभाव की जांच करना है, जो विभिन्न परिमाणों के भूस्खलनों की शुरुआत और विशेषताओं के बारे में मूल्यवान अंतर्दृष्टि प्रदान करता है। यह अध्ययन लॉग नॉर्मल और पावर लॉ वितरण के संयोजन की जांच करके भूस्खलन स्केलिंग को समझने में वृद्धि करता है, जो भूस्खलन मॉडलिंग और जोखिम मूल्यांकन पद्धतियों में सुधार में योगदान देता है। इसके अलावा, मशीन लर्निंग एल्गोरिदम का उपयोग करके अनुभवजन्य विश्लेषण मुख्य पूर्वनिर्धारित कारकों की पहचान करता है जो भूस्खलन के आकार को प्रभावित करते हैं, जैसे कि नॉर्मलाइज्ड डिफरेंस वेजिटेशन इंडेक्स (NDVI), मृदा गहराई, और निकटतम ड्रेनेज (HAND) से ऊँचाई, जो भूस्खलन शमन रणनीतियों के लिए क्रियाशील अंतर्दृष्टि प्रदान करता है।

2015 से 2021 तक सेंटिनल-2 उपग्रह इमेजरी का उपयोग करके एक भूस्खलन सूची का निर्माण भूस्खलन वितरण और विस्तार की व्यापक समझ प्रदान करता है। यह सूची भूमि प्रबंधन और जोखिम मूल्यांकन के लिए एक मूल्यवान संसाधन है, जिससे हितधारकों को उच्च-जोखिम वाले क्षेत्रों की पहचान करने और प्रभावी ढंग से शमन प्रयासों को प्राथमिकता देने में सक्षम बनाता है। लगातार भूस्खलन आंदोलनों और ट्रिगरिंग कारकों का विस्तृत अध्ययन भी भूस्खलन उत्तराधिकार प्रक्रियाओं की हमारी समझ को बढ़ाता है। विश्लेषण से पता चलता है कि कम HAND और तीव्र ढलानों पर भूस्खलन पुनः सक्रियण के लिए अधिक संवेदनशील होते हैं, जबकि उच्च और मध्यम ढलानों वाले स्थल पुनर्प्राप्ति के लिए अधिक अनुकूल होते हैं। इसके अलावा, अध्ययन ट्रिगरिंग फैक्टर विश्लेषण करता है और इवेंट ड्यूरेशन (ED) और इंटरइवेंट ड्यूरेशन (ID) वक्र तैयार करता है, जो भूस्खलन घटनाओं के अस्थायी पैटर्न के बारे में मूल्यवान अंतर्दृष्टि प्रदान करता है।

भूस्खलन संवेदनशीलता मानचित्रण में स्थानिक-सामयिक क्लस्टरिंग तकनीकों का एकीकरण भूस्खलन-प्रवण क्षेत्रों की पहचान की सटीकता में और सुधार करता है। उन्नत क्लस्टरिंग एल्गोरिदम का लाभ उठाकर, अध्ययन भूस्खलन संवेदनशीलता मानचित्रों की सटीकता को बढ़ाता है, जिससे भूमि-उपयोग योजना, बुनियादी ढांचा विकास, और आपदा जोखिम में कमी के प्रयासों के लिए सूचित निर्णय लेने में समर्थन मिलता है। ये निष्कर्ष भूस्खलन संवेदनशीलता मूल्यांकन में स्थानिक और अस्थायी गतिशीलता पर विचार करने के महत्व को रेखांकित करते हैं, विशेष रूप से उन क्षेत्रों में जो आवर्ती भूस्खलन घटनाओं के लिए संवेदनशील हैं।

अंत में, यह अध्ययन भूस्खलन व्यवहार और जोखिम मूल्यांकन के बारे में समझ के विकास में महत्वपूर्ण योगदान देता है। यह अध्ययन क्षेत्रीय अवलोकनों, रिमोट सेंसिंग विश्लेषण, और मशीन लर्निंग तकनीकों को एकीकृत करके

भूस्खलन घटना, विकास और स्थानिक वितरण को प्रभावित करने वाले कारकों के बारे में मूल्यवान अंतर्दृष्टि प्रदान करता है। ये अंतर्दृष्टि भूस्खलन प्रबंधन, जोखिम में कमी, और सहनशीलता निर्माण के प्रयासों के लिए व्यावहारिक निहितार्थ रखती हैं, अंततः भूस्खलन-प्रवण क्षेत्रों में समुदायों और हितधारकों की भूस्खलन के प्रभावों को कम करने और अधिक सहनशील परिदृश्य बनाने की क्षमता को बढ़ाती हैं।

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