

**A NEW SOIL EROSION SEVERITY MAP FOR INDIA USING
GEOSPATIAL MODELING AND MACHINE LEARNING**

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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 LATE FATHER

CERTIFICATE

This is to certify that the thesis entitled “**A New Soil Erosion Severity Map for India using Geospatial Modeling and Machine Learning**”, being submitted by **Mr. Ravi Raj**, to the **Indian Institute of Technology Delhi** for the award of the degree of ‘**Doctor of Philosophy**’ in the Department of Civil Engineering is a record bonafide research work carried out by him under our supervision and guidance. The thesis work, in our opinion, has reached the requisite standards fulfilling the requirement for the Degree of **Doctor of Philosophy**.

The material contained in the thesis is original and has not been submitted in part or full to any other University or Institute for the award of any other degree or diploma.

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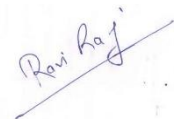
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A handwritten signature in blue ink that reads "Ravi Raj". The signature is written in a cursive style and is underlined with a single horizontal line.

(Ravi Raj)

ABSTRACT

Soil erosion is a critical agricultural and environmental problem as it poses threats to agricultural productivity, soil fertility, and hydrological processes on a large scale, affecting 751 million hectares globally through water erosion. Considering the substantial reliance of the Indian economy on agriculture, the significance of erosion is amplified. The escalating demand of the unplanned growing population is generating scenarios wherein forests and grasslands undergo alterations, exposing the uppermost fertile soil layer rainfall intensity and runoff induced erosion. Approximately half of the total geographical area of India is susceptible to the erosion induced by water. This thesis encompasses the political boundary of India, despite having some initial estimates of soil loss, no national-scale estimates of soil erosion are available for India. There is a need for comprehensive soil erosion assessments on a national scale. Estimating and monitoring erosion over an extended period for a large region is both expensive and time-consuming. Various methods, such as empirical, mathematical, and GIS (Geographic Information System)-based models, are employed to calculate soil loss, each having its inherent limitations. The Revised Universal Soil Loss Equation (RUSLE) model stands out globally for its precision in estimating soil loss over larger areas. In this thesis, soil loss was assessed using the RUSLE-based algorithm, encompassing all five of its factors. Notably, there is a lack of national-scale estimates for all five RUSLE-factors contributing to soil loss—rainfall erosivity, soil erodibility, slope length and steepness, cover management and agricultural support practices—across India. The importance of contributing factors like rainfall intensity, soil properties, LULC, and agricultural practices on the soil erosion process in Indian condition was also using the Random Forest algorithm in machine learning (ML). Hence, in this thesis all these factors were modeled and mapped over the

study region specifically the factors associated with rainfall intensity and soil properties with feature importance analysis of these factors using ML.

Rainfall erosivity is a measure of the erosive force of rainfall which represents the potential of rain to cause soil erosion. A large proportion of the total eroded soil in India is due to erosion by water, and rainfall erosivity is one of the major components. The current assessments of rainfall erosivity in India are however largely based on rain-gauge recordings and surveys which hinders its estimation and understanding over large areas. Growing availability of remotely sensed gridded precipitation datasets presents an unprecedented opportunity to study long-term rainfall erosivity over varied terrains and address some of the limitations of point data-based estimations. In this thesis, multiple national and global gridded precipitation datasets were utilized to develop a high-resolution rainfall erosivity factor (R-factor) map to highlight areas prone to rainfall-induced erosion. Further, a large selection of empirical equations from literature were employed for estimating rainfall erosivity to provide a comparative analysis of these commonly adopted methods. The calculated rainfall erosivity is also compared with alternative methods to estimate R-factor such as Fournier Index (FI) and Modified Fournier Index (MFI). It was observed that MFI is highly correlated with rainfall erosivity, and an equation was finally proposed to estimate R-factor using MFI.

The soil erodibility factor, denoted by the K-factor, is an essential component of RUSLE. Although previous studies have assessed soil erodibility in India, they have been limited to small scales such as watersheds or districts. A national-scale assessment of soil erodibility doesn't exist and is critical to developing a systematic understanding of soil erosion over India. In this study, we estimated soil erodibility factors over India using RUSLE Nomograph and Environmental Policy Integrated Climate (EPIC) model approaches at a high resolution of 250 m. Our results showed

that the K-factor estimated using the Nomograph approach was more accurate than the observed soil erodibility factors. Additionally, we developed erodibility indices such as CR (Clay Ratio), MCR (Modified Clay Ratio), and CLOM (Critical Level of Organic Matter) to assess their sensitivity with respect to soil erodibility factors. Finally, we created a susceptibility to erosion map over India using CLOM index classification. The national average soil erodibility factor for India is estimated to be 0.028 t-ha-h/ha/MJ/mm. Histosols soil type is the least susceptible to erosion, while the Xerosols soil type is most susceptible among the prevalent soil classes in India.

Likewise, the topographic factor which is also called slope-length and steepness factor was estimated using digital elevation model with the help of Terrain Analysis module while cover management and support practices factors were estimated with the help of land use / land cover datasets. This thesis estimates the yearly Potential Soil Loss (PSL) by multiplying all these five factors throughout India at a composite spatial resolution of 250 meters and explores its variability considering districts, soil texture, soil type, land use and land cover, and basins. Further, the Sediment Delivery Ratio (SDR) and Specific Sediment Yield (SSY) were mapped to assess the actual soil loss reaching downstream pixels across the national boundary. Additionally, a novel erosion-severity classification system has been introduced and implemented for understanding the extent and severity of erosion. Rainfall erosivity (R-factor) emerges as the most crucial feature in estimating soil erosion in Indian conditions. Additionally, when the combined impact was assessed, rainfall intensity, combined with the topographic factor, demonstrated the highest influence on soil erosion.

This thesis presents detailed discussions on the key contributing factors, including rainfall intensity, soil properties, topography, land use/land cover, and agricultural practices, that contribute to soil erosion in India. It also claims itself as the first comprehensive national-scale

assessment of rainfall erosivity, soil erodibility, soil erosion, and sediment yield mapping across India. This study enhances our understanding of rainfall-induced erosion, driven by both rainfall and runoff, providing a crucial resource for experts engaged in soil conservation and erosion management planning.

शोध प्रबंध का शीर्षक: भू-स्थानिक मॉडलिंग और मशीन लर्निंग का उपयोग करके भारत के लिए एक नया मृदा कटाव गंभीरता मानचित्र

छात्र का नाम: रवि राज

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सार

मृदा क्षरण एक गंभीर कृषि और पर्यावरणीय समस्या है क्योंकि यह बड़े पैमाने पर कृषि उत्पादकता, मिट्टी की उर्वरता और जल विज्ञान प्रक्रियाओं के लिए खतरा पैदा करता है, जिससे जल क्षरण के माध्यम से वैश्विक स्तर पर 751 मिलियन हेक्टेयर भूमि प्रभावित होती है। कृषि पर भारतीय अर्थव्यवस्था की पर्याप्त निर्भरता को ध्यान में रखते हुए, क्षरण का महत्व बढ़ जाता है। अनियोजित बढ़ती जनसंख्या की बढ़ती मांग ऐसे परिदृश्य उत्पन्न कर रही है जिसमें जंगलों और घास के मैदानों में परिवर्तन हो रहा है, जिससे ऊपरी उपजाऊ मिट्टी की परत में वर्षा की तीव्रता और अपवाह प्रेरित कटाव उजागर हो रहा है। भारत के कुल भौगोलिक क्षेत्र का लगभग आधा हिस्सा पानी से होने वाले कटाव के प्रति संवेदनशील है। यह थीसिस भारत की राजनीतिक सीमा को शामिल करती है, मिट्टी के नुकसान के कुछ प्रारंभिक अनुमान होने के बावजूद, भारत के लिए मिट्टी के कटाव का कोई राष्ट्रीय स्तर का अनुमान उपलब्ध नहीं है। राष्ट्रीय स्तर पर व्यापक मृदा क्षरण आकलन की आवश्यकता है। किसी बड़े क्षेत्र के लिए विस्तारित अवधि में कटाव का अनुमान लगाना और उसकी निगरानी करना महंगा और समय लेने वाला दोनों है। मिट्टी के नुकसान की गणना के लिए अनुभवजन्य, गणितीय और जीआईएस (भौगोलिक सूचना प्रणाली)-आधारित मॉडल जैसे विभिन्न तरीकों को नियोजित किया जाता है, जिनमें से प्रत्येक की अपनी अंतर्निहित सीमाएं होती हैं। संशोधित सार्वभौमिक मृदा हानि समीकरण (आरयूएसएलई) मॉडल बड़े क्षेत्रों में मिट्टी के नुकसान का अनुमान लगाने में अपनी सटीकता के लिए विश्व स्तर पर खड़ा है। इस थीसिस में, RUSLE-आधारित एल्गोरिदम का उपयोग करके, इसके सभी

पांच कारकों को शामिल करते हुए, मिट्टी के नुकसान का आकलन किया गया था। विशेष रूप से, भारत भर में मिट्टी के नुकसान में योगदान देने वाले सभी पांच आरयूएसएलई-कारकों - वर्षा क्षरण, मिट्टी की कटाव, ढलान की लंबाई और ढलान, कवर प्रबंधन और कृषि सहायता प्रथाओं - के लिए राष्ट्रीय स्तर के अनुमानों की कमी है। भारतीय परिस्थितियों में मृदा अपरदन प्रक्रिया पर वर्षा की तीव्रता, मृदा गुण, एल्यूमिनीय और कृषि पद्धतियों जैसे योगदान कारकों का महत्व भी मशीन लर्निंग (एमएल) में रैंडम फ़ॉरेस्ट एल्गोरिदम का उपयोग करके किया गया था। इसलिए, इस थीसिस में, इन सभी कारकों को अध्ययन क्षेत्र में मॉडल किया गया और मैप किया गया, विशेष रूप से, वर्षा की तीव्रता और मृदा गुणों से जुड़े कारकों, एमएल का उपयोग करके सभी योगदान कारकों के फ़ीचर महत्व विश्लेषण के साथ।

वर्षा क्षरणशीलता वर्षा की क्षरणकारी शक्ति का एक माप है जो वर्षा द्वारा मृदा क्षरण पैदा करने की क्षमता को दर्शाती है। भारत में कुल क्षरित मिट्टी का एक बड़ा हिस्सा पानी के क्षरण के कारण है, और वर्षा क्षरण प्रमुख घटकों में से एक है। हालाँकि, भारत में वर्षा कटाव का वर्तमान आकलन काफी हद तक वर्षा-गेज रिकॉर्डिंग और सर्वेक्षणों पर आधारित है जो बड़े क्षेत्रों में इसके अनुमान और समझ में बाधा डालता है। दूर से संवेदित ग्रिडयुक्त वर्षा डेटासेट की बढ़ती उपलब्धता विभिन्न इलाकों में दीर्घकालिक वर्षा क्षरण का अध्ययन करने और बिंदु डेटा-आधारित अनुमानों की कुछ सीमाओं को संबोधित करने का एक अभूतपूर्व अवसर प्रस्तुत करती है। इस थीसिस में, वर्षा-प्रेरित कटाव की संभावना वाले क्षेत्रों को उजागर करने के लिए एक उच्च-रिज़ॉल्यूशन वर्षा कटाव कारक (आर-फैक्टर) मानचित्र विकसित करने के लिए कई राष्ट्रीय और वैश्विक ग्रिड वर्षा डेटासेट का उपयोग किया गया था। इसके अलावा, आमतौर पर अपनाई जाने वाली इन विधियों का तुलनात्मक विश्लेषण प्रदान करने के लिए वर्षा कटाव का अनुमान लगाने के लिए साहित्य से अनुभवजन्य समीकरणों का एक बड़ा चयन नियोजित किया गया था। गणना की गई वर्षा कटाव की तुलना आर-कारक का अनुमान लगाने के वैकल्पिक तरीकों जैसे कि फोरनियर इंडेक्स (एफआई) और संशोधित

फोरनियर इंडेक्स (एमएफआई) से भी की जाती है। यह देखा गया कि एमएफआई वर्षा क्षरण के साथ अत्यधिक सहसंबद्ध है, और अंततः एमएफआई का उपयोग करके आर-कारक का अनुमान लगाने के लिए एक समीकरण प्रस्तावित किया गया था।

मिट्टी का कटाव कारक, जिसे K-फैक्टर द्वारा दर्शाया जाता है, RUSLE का एक अनिवार्य घटक है। हालाँकि पिछले अध्ययनों ने भारत में मिट्टी के कटाव का आकलन किया है, लेकिन वे जलक्षेत्रों या जिलों जैसे छोटे पैमाने तक ही सीमित रहे हैं। मिट्टी के कटाव का राष्ट्रीय स्तर पर मूल्यांकन मौजूद नहीं है और यह भारत में मिट्टी के कटाव की व्यवस्थित समझ विकसित करने के लिए महत्वपूर्ण है। इस अध्ययन में, हमने 250 मीटर के उच्च रिज़ॉल्यूशन पर आरयूएसएलई नॉमोग्राफ और पर्यावरण नीति एकीकृत जलवायु (ईपीआईसी) मॉडल दृष्टिकोण का उपयोग करके भारत में मिट्टी के कटाव कारकों का अनुमान लगाया। हमारे परिणामों से पता चला कि नोमोग्राफ दृष्टिकोण का उपयोग करके अनुमानित के-कारक, देखे गए मिट्टी के कटाव कारकों की तुलना में अधिक सटीक था। इसके अतिरिक्त, हमने मिट्टी के क्षरण कारकों के संबंध में उनकी संवेदनशीलता का आकलन करने के लिए सीआर (मिट्टी अनुपात), एमसीआर (संशोधित मिट्टी अनुपात), और सीएलओएम (कार्बनिक पदार्थ का महत्वपूर्ण स्तर) जैसे क्षरण सूचकांक विकसित किए हैं। अंत में, हमने सीएलओएम सूचकांक वर्गीकरण का उपयोग करके भारत में कटाव के प्रति संवेदनशीलता मानचित्र तैयार किया। भारत के लिए राष्ट्रीय औसत मृदा अपरदन कारक $0.028 \text{ t-ha-h/ha/MJ/mm}$ अनुमानित है। हिस्टोसोल्स मिट्टी का प्रकार कटाव के प्रति सबसे कम संवेदनशील है, जबकि भारत में प्रचलित मिट्टी वर्गों में ज़ेरोसोल्स मिट्टी का प्रकार सबसे अधिक संवेदनशील है।

इसी तरह, स्थलाकृतिक कारक जिसे ढलान-लंबाई और ढलान कारक भी कहा जाता है, का अनुमान टेरन विश्लेषण मॉड्यूल की मदद से डिजिटल उन्नयन मॉडल का उपयोग करके किया गया था, जबकि कवर प्रबंधन और समर्थन प्रथाओं के कारकों का अनुमान भूमि उपयोग / भूमि कवर डेटासेट की मदद से लगाया

गया था। यह थीसिस पूरे भारत में इन सभी पांच कारकों को 250 मीटर के समग्र स्थानिक रिज़ॉल्यूशन पर गुणा करके वार्षिक संभावित मिट्टी के नुकसान (पीएसएल) का अनुमान लगाती है और जिलों, मिट्टी की बनावट, मिट्टी के प्रकार, भूमि उपयोग और भूमि कवर, और बेसिन पर विचार करते हुए इसकी परिवर्तनशीलता का पता लगाती है। इसके अलावा, राष्ट्रीय सीमा के पार डाउनस्ट्रीम पिक्सल तक पहुंचने वाली वास्तविक मिट्टी की हानि का आकलन करने के लिए तलछट वितरण अनुपात (एसडीआर) और विशिष्ट तलछट उपज (एसएसवाई) को मैप किया गया था। इसके अतिरिक्त, क्षरण की सीमा और गंभीरता को समझने के लिए एक नवीन क्षरण-गंभीरता वर्गीकरण प्रणाली शुरू और कार्यान्वित की गई है। भारतीय परिस्थितियों में मृदा अपरदन का अनुमान लगाने में वर्षा क्षरणशीलता (आर-फैक्टर) सबसे महत्वपूर्ण विशेषता के रूप में उभर कर सामने आती है। इसके अतिरिक्त, जब संयुक्त प्रभाव का आकलन किया गया, तो वर्षा की तीव्रता, स्थलाकृतिक कारक के साथ मिलकर मृदा अपरदन पर सबसे अधिक प्रभाव प्रदर्शित करती है।

यह थीसिस वर्षा की तीव्रता, मिट्टी के गुण, स्थलाकृति, भूमि उपयोग/भूमि आवरण और कृषि प्रथाओं सहित प्रमुख योगदान कारकों पर विस्तृत चर्चा प्रस्तुत करती है, जो भारत में मिट्टी के कटाव में योगदान करते हैं। यह पूरे भारत में वर्षा क्षरण, मृदा क्षरण, मृदा क्षरण और तलछट उपज मानचित्रण का पहला व्यापक राष्ट्रीय स्तर का आकलन करने का भी दावा करता है। यह अध्ययन वर्षा और अपवाह दोनों से प्रेरित वर्षा-प्रेरित कटाव के बारे में हमारी समझ को बढ़ाता है, जो मृदा संरक्षण और कटाव प्रबंधन योजना में लगे विशेषज्ञों के लिए एक महत्वपूर्ण संसाधन प्रदान करता है।

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LIST OF ABBREVIATIONS

FI: Fournier Index

MFI: Modified Fournier Index

USLE: Universal Soil Loss Equation

RUSLE: Revised Universal Soil Loss Equation

IMDAA: Indian Monsoon Data Assimilation and Analysis

IMD: India meteorology Department

CHIRPS: Climate Hazards Group InfraRed Precipitation with Station data

NCMRWF: National Centre for Medium Range Weather Forecasting

NMM: National Monsoon Mission

4DVAR: Four-Dimensional Variational Assimilation Scheme

HadISST2: Hadley Centre Ice and Sea Surface Temperature dataset version 2

FEWS NET: Famine Early Warning Systems Network

TMPA 3B42: Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis

TARCAT: TAMSAT African Rainfall Climatology And Time series

NOAA: National Oceanic and Atmospheric Administration

GPCC: Global Precipitation Climatology Centre

PSL: Potential soil loss

LULC: Land use/land cover

SDR: Sediment Delivery Ratio

SSY: Specific Sediment Yield

CSWCRTI: Centre Soil and Water Conservation, Research and Training Institute

NBBS and LUP: National Bureau of Soil Survey and Land Use Planning

GIS: Geographic information system

GASEMT: Global Applications of Soil Erosion Modelling Tracker

SDC: Sediment Transport Capacity

InVEST: Integrated Valuation of Environmental Services and Trade-offs

IREDD: Indian Rainfall Erosivity Dataset

ISED: Indian Soil Erodibility Dataset

CWC: Center Water Commission

CR: Clay Ratio

MCR: Modified Clay Ratio

CLOM: Critical Level of Organic Matter

NRSC, ISRO: National Remote Sensing Center, Indian Remote Sensing Organization

DEM: Digital elevation models

MERIT: Multi-Error-Removed Improved-Terrain

GloSEM: Global soil erosion modeling

t/ha/yr: Tons/hectare/year

ML: Machine Learning