Review Article

Enhancing Soil Degradation Assessment through the Integration of GIS and RS: A Comprehensive Review

ABSTRACT

GIS and RS are powerful tools that play a crucial role in natural resource management, especially when it comes to assessing soil degradation. Soil degradation is a long-standing global problem, and to understand the role of GIS and RS in addressing it, data from secondary sources were collected and analyzed. Several researchers have utilized GIS and RS, integrated with the Universal Soil Loss Equation (USLE), to assess soil degradation. Their findings reveal that soil erosion, triggered primarily by water, is a critical form of land degradation. This erosion significantly reduces the potential capacity of the soil, posing threats to economic growth, environmental resources, and social assets. Furthermore, the severity of soil erosion varies across different regions of the country. Despite the valuable insights gained through studies using GIS and RS for soil degradation assessment, their contributions are not yet widely recognized by government organizations, NGOs, policymakers, decision-makers, environmentalists, and researchers. This lack of recognition hinders the attention and action that could be directed towards mitigating soil degradation. To address this issue, this paper aims to comprehensively review the contributions of GIS and RS in assessing soil degradation. By doing so, it seeks to raise awareness among key stakeholders and foster greater attention and support for tackling this critical environmental challenge.

Keywords: Geographic Information System, Remote Sensing, Soil degradation, Soil loss

1. INTRODUCTION

Geographic Information System (GIS) and Remote Sensing (RS) are crucial tools in the management of natural resources. Soil erosion is the process that deteriorates the quality, functionality, and environmental services, particularly concerning soil resources (1). The integration of GIS and RS with the Universal Soil Loss Equation (USLE) allows for the estimation of soil loss, as evidenced by studies (2, 3).

This widespread erosion results in on-site effects on the land itself and off-site effects in other areas. Erosion agents like water (56%) and wind (28%) remove the top fertile soil, leading to low crop yields (4). The annual yield collected is only one to three percent, while the population continues to grow at a rate of 3.3%, exacerbating food insecurity and poverty levels (5).

The agricultural sector, particularly in India, heavily relies on soil resources, supporting farmers' livelihoods and contributing 20.19% of the country's GDP. Soil degradation, primarily caused by human activities, poses a significant challenge, with soil erosion being a major contributor. Scholars have emphasized that anthropogenic factors account for approximately 60-80% of soil erosion and land degradation (6, 1, 3).

The concept of Soil Sustainability (SS) as an assessment of the ability of soils to withstand different degradation processes while maintaining their fertility capacities. This measure serves as an indicator of soil quality, reflecting their capacity to support ecosystem and social services by effectively carrying out their functions and adapting to external influences. Ultimately, this framework plays a crucial role in determining the management priorities for various soil zones (8, 9, 10, 11).

However, there are several challenges, including a lack of utilization of modern technology tools like GIS and RS. Many community-based participatory watershed management activities do not fully employ GIS and RS due to the complexity of watershed attributes and the difficulties in manual delineation.

Nevertheless, some researchers have successfully used GIS and RS tools, integrated with erosion models like USLE or RUSLE (Revised Universal Soil Loss Equation), to assess soil degradation in various regions of India. These technical tools offer numerous benefits, such as examining watershed characteristics and delineation, identifying eroded areas, estimating soil loss, prioritizing severity areas, and assessing land use land cover change (12, 13, 14, 15, 2, 16, 17, 18, 19).

Moreover, GIS and RS play a crucial role in developing strategic plans and recommending appropriate mitigation measures like soil and water conservation (20, 21,3, 22). However, there is a lack of centralized documentation and dissemination of the research findings, hindering the effective use of GIS and RS in sustainable natural resource management in India.

To address these challenges, this paper aims to review the significant contributions of GIS and RS in assessing soil degradation.

1.1 Objective

1.1.1 General objective

To review the contribution of GIS and RS for soil degradation assessment

1.1.2 Specific objectives

- To assess and discuss the role of GIS and RS for watershed delineation;
- To identify and discuss how GIS and RS can estimate the amount of soil loss couple with USLE or RUSLE; To clarify and discuss the contributions of GIS and RS for identifying soil erosion hotspot area;
- To assess and discuss the contributions of GIS and RS for identifying causes of soil erosion
- To give awareness on how GIS and RS are playing for assessing the consequences of soil erosion.

1.2 Significant of this review paper

This review aims to highlight the significant contributions of GIS and RS in various aspects of natural resource management, particularly in addressing soil degradation issues. It seeks to raise awareness about the multiple roles of GIS and RS, such as watershed delineation, predicting soil loss, identifying erosion severity levels, prioritizing erosion hotspots, and developing appropriate soil and water conservation measures. The information presented in this review is intended to benefit governmental organizations, NGOs, policymakers, decision-makers, and environmentalists by demonstrating the advantages of using GIS and RS for effective resource management. Additionally, researchers interested in studying the role of GIS and RS in soil degradation and related fields can utilize this review as secondary data for their detailed investigations.

2. APPROCHES USED

To achieve the intended objectives, relevant information was gathered from secondary sources. The process involved the following steps: First, articles related to the topic were downloaded from Google Scholar. Second, these downloaded articles were carefully read, and a purposive method was employed to select those specifically focused on GIS and RS assessments related to watershed delineation, soil loss estimation, identification and prioritization of areas for intervention, and the causes and consequences of soil erosion.

The information collected from each article was then synthesized by reviewing their key findings. Whenever possible, a thorough discussion was conducted for each finding. Finally, the discussed concepts were presented in the form of tables, figures, and narratives to effectively communicate the outcomes of the review.

3. BRIEF HISTORY OF GEOGRAPHIC INFORMATION SYSTEM AND REMOTE SENSING

GIS is a computerized software designed to store, retrieve, manipulate, analyze, and visualize geographically referenced datasets (23, 24). It finds applications in diverse fields. GIS is capable of handling two fundamental types of data: geospatial data, which define the location of features or objects on the ground, and attribute data, which describe the characteristics of these features (25). GIS data is typically represented and stored in either vector or raster formats.

In a vector data structure, geospatial data is represented as points, lines, or polygons. For example, features like fire rings or campsites are stored as points, trails or streams as lines, and forests or recreation opportunity classes as polygons. On the other hand, a raster data structure represents geospatial data in a regular grid of cells, where attributes apply to the entire cell. Raster data provides continuous coverage of an area, such as a Digital Elevation Model showing slope, aspect, and elevation in a grid for a specific region. GIS has the unique ability to link spatial and attribute data, enabling manipulation and analysis of relationships between them (25).

Remote sensing, on the other hand, is the art and science of acquiring information about objects, areas, or phenomena without direct physical contact with the subjects under investigation. The concept of remote sensing dates back to the 1820s, with the term itself gaining popularity in the 1960s when the first earth resource satellite, Landsat-1, was launched in 1972. Since then, remote sensing has significantly evolved, and numerous satellites are now used for various applications, including natural resource management, particularly for assessing soil erosion, a major trigger of land degradation.

Remote sensing involves measuring electromagnetic radiation (reflected or emitted) from the Earth's surface using air-borne or space-borne sensors. These measurements are used to collect data in a given area and monitor changes in land use and land-cover patterns over time. Remotely collected data, often stored as image data in the form of aerial photographs or satellite images, can be combined and analyzed using GIS to represent real-world features. While remote sensing data can be processed and interpreted independently, optimal results are achieved when these measurements are linked to ground or surface measurements and observations (26).

The integration of GIS and remote sensing is highly valuable, especially in erosion mapping, validation of mapping methods, and qualitative and quantitative erosion assessment. Remotely sensed data, particularly satellite imagery, provides repeatable measurements over large areas with necessary spatial and temporal resolution. These data can extract new or more accurate information, making it possible to detect eroded areas, determine their spatial extent, and assess erosion factors like vegetation cover, slope, or soil type. These parameters are often used as input factors in soil erosion models like the Universal Soil Loss Equation (USLE). Optical satellite systems, which operate in the visible, near-infrared, shortwave infrared, and thermal infrared parts of the electromagnetic spectrum, are commonly used in erosion research

In summary, the relationship between GIS and remote sensing is highly synergistic, as GIS utilizes remote sensing data for analyzing and reporting information, particularly for assessing soil degradation.

4. CONTRIBUTION OF GIS AND RS FOR DEGRADATION ASSESSMENT

The combined use of GIS and RS has proven to be invaluable in natural resource management, particularly in soil and water conservation practices and assessing soil erosion rates in India (27).

To support the assessment of soil degradation, erosion mapping, and qualitative and quantitative erosion assessments, various spatial data sources can be utilized. These include topographic sheets, soil type information, land use maps, field surveys, climate reports, laser scanning data, aerial photographs, and satellite imagery. Among these sources, remotely sensed data, particularly satellite imagery, stands out as it offers repeatable measurements over large areas with desirable spatial and temporal resolution. Several researchers have utilized various types of Landsat imagery satellites to assess soil degradation.

Satellite imagery allows for the extraction of watershed boundaries, detection of degraded areas, and examination of soil erosion factors such as vegetation cover, topography, and soil type. While some researchers have successfully conducted watershed delineations using GIS and RS techniques, there remains a lack of comprehensive documentation on these efforts in India.

On the other hand, there are numerous available assessments concerning soil loss estimation, identification of erosion hotspot areas, and the factors causing soil erosion. These issues, along with others related to soil degradation and erosion, are further discussed in detail in the following sections.

4.1 Contribution of GIS and RS in watershed delineation

A watershed is defined as a geographical area where rainfall runoff is collected and drained through a common confluence point. It encompasses both environmental resources, such as land, water, soil, wildlife, and vegetation, as well as socio-economic elements, including people, their farming systems, economic status, and cultural aspects. From a hydrological perspective, its definition is directly linked to the runoff and drainage systems (28).

Watershed management is an ancient practice dating back to around 5000 years, originating with the advent of agriculture. In modern times, GIS and RS play a crucial role in watershed delineation, becoming the cornerstone for sustainable natural resource management, particularly in reducing soil erosion. Through GIS and RS, soil erosion-prone areas can be identified based on estimated soil loss, and appropriate soil and water conservation structures can be designed while considering cost efficiency (13, 29, 30).

While it is possible to implement soil erosion mitigation measures without watershed delineation, the effectiveness and impact of such measures may not be substantial without a comprehensive understanding of the watershed's characteristics and dynamics. Watershed delineation in community-based participatory watershed management planning is a crucial step taken by the Indian government to reduce soil erosion through soil and water conservation measures. This process can be accomplished through manual methods, such as digitizing from topographic maps, or automatically using Digital Elevation Models (DEMs) through electronic means. While manual methods are still commonly used, they may be less accurate and time-consuming compared to DEM-based approaches, which make use of GIS and RS technologies.

The use of GIS and RS in watershed delineation offers significant advantages, particularly in large-scale watersheds. These technologies enable efficient and accurate identification of basic watershed attributes, such as drainage patterns, topography, land use types, soil types, degraded land, and soil erosion (12, 13). Researchers have successfully demonstrated the potential of GIS and RS in watershed delineation, as shown in case studies of micro watersheds like Ocholo and Chille (13). In these studies, data collected from zonal regions and satellite images were utilized to identify land use types and assess the extent of degraded land in the watersheds.

In other assessments, GIS and RS were employed to analyze the Agula watershed and its sub-watershed in the Eastern Tigray region. These studies examined various morphometric parameters, geometry, drainage texture, and relief characteristics of the watershed, which are essential for planning, managing, and decision-making related to soil erosion control (22). Similar findings were reported in the Chelekot micro-watershed, highlighting the importance of GIS and RS in understanding terrain parameters and assisting decision-makers in designing appropriate soil and water conservation structures (12).

Despite the clear benefits of using GIS and RS in watershed delineation and conservation planning, there are challenges in its widespread adoption. These challenges include a lack of knowledge on how to use GIS and RS, limited access to necessary components like hardware, software, data, and skilled personnel, and financial constraints.

In conclusion, adopting GIS and RS for watershed delineation instead of manual methods offers more efficiency, reliability, and speed, depending on the computer's processing capacity. By employing these advanced techniques, India can enhance its efforts in reducing soil erosion and ensuring sustainable natural resource management.

The critical issue of declining groundwater levels in the Arkavathi sub-watershed, comprising urbanized areas like Bangalore rural and Bangalore urban. The aim is to identify the potential zones for groundwater extraction and augmentation through an effective management approach. Various factors, such as geomorphology, geology, soil, drainage density, lineament density, slope, land use, and rainfall variation, were analyzed using satellite images and real-time data in a GIS environment. The Analytical Hierarchy Process (AHP), a Multi-Criteria Decision Making (MCDM) method, was used to determine the weights for each factor. The resulting Ground Water Potential zone (GWP) map was divided into five classes: Very good, Good, Moderate, Poor, and Very poor. The study's accuracy was confirmed by validating the GWP map with data from 14 pumping wells collected by the Central Ground Water Board (CGWB). The findings can aid local and government authorities in identifying suitable zones for exploring new groundwater wells while ensuring sustainability (31).

A combination of the Revised Universal Soil Loss Equation (RUSLE) with Remote Sensing (RS) and Geographic Information System (GIS) to evaluate soil erosion in the lower Sutlej River basin in Punjab, India. They divided the basin into 14 sub-watersheds and collected data on rainfall, soil characteristics, topography, and land use. By overlaying these datasets, they determined the average annual soil loss for each sub-watershed (32).

The results indicated that the average annual soil loss ranged from 1.26 to 25 tonnes per hectare (t ha^{-1}), with a total estimated soil loss of 2,441,639 tonnes. Most of the area (approximately 94.4%) experienced very slight erosion (0–5 t ha^{-1} year^{-1}), while about 4.7% faced slight erosion (5–10 t ha^{-1} year^{-1}). A small portion (0.11%, 9.38 km^2) had very severe soil loss (>25 t ha^{-1} year^{-1}).

Based on the calculated average annual soil loss for each sub-watershed, the researchers prioritized implementation of soil and water conservation measures. Sub-watershed WS8 received the highest priority due to the highest estimated soil loss (323.5 t ha^{-1} year^{-1}), followed by WS9 (303.8 t ha^{-1} year^{-1}). Conversely, WS2 was given the lowest priority as it experienced the lowest soil loss (122.02 t ha^{-1} year^{-1}).

4.2 Application of GIS techniques for facilitating erosion estimation

The RUSLE soil loss model in combination with RS and GIS technologies to assess soil erosion potential and prioritize conservation efforts in Northeastern Maysan Governorate, southern Iraq. The results indicated varying levels of soil loss, with the northern and northeastern parts of the sub-watersheds being more susceptible due to steep slopes and mountainous terrain. High-priority conservation plans are needed in these areas, although implementation may be challenging. On the other hand, sub-watersheds with lower soil loss, like SW-01, SW-03, SW-05, and SW-06, are given lower priority for conservation efforts. The factors R (rainfall) and LS (slope length and steepness) were found to have the most significant impact on soil erosion compared to other components (33).

Table 1: Use of Software in GIS Modelling

Author	Software used	Model used
Alkhoury *et al*. (2019) (34)	ArcGIS	Revised Universal Soil Loss Equation (RUSLE)
Bhattarai *et al*. (2015) (35)	ArcGIS, ERDAS Imagine, ENVI, ILWIS, GRASS GIS	Various models reviewed
Chen and Wu (2015) (36)	ArcGIS, ENVI, IDRISI	Revised Universal Soil Loss Equation (RUSLE)
Chen *et al*. (2014) (37)	ArcGIS	Revised Universal Soil Loss Equation (RUSLE)
Chormanski and Kozak (2018) (38)	ERDAS Imagine, ArcGIS	Slope stability model and sediment transport model
Das and Kar (2019) (39)	ArcGIS, ERDAS Imagine	Revised Universal Soil Loss Equation (RUSLE)

Ghorbanzadeh *et al*. (2016) (40)	ArcGIS	Revised Universal Soil Loss Equation (RUSLE)
He and He (2016) (41)	ArcGIS	Analytical Hierarchy Process (AHP) and Weighted Sum Model (WSM)
Huang *et al*. (2021) (42)	ArcGIS	Revised Universal Soil Loss Equation (RUSLE)
Javadi *et al*. (2019) (43)	Not applicable	Not applicable
Ji *et al*. (2016) (44)	ArcGIS	Revised Universal Soil Loss Equation (RUSLE)
Khaledian *et al*. (2021) (45)	Not mentioned	Not applicable
Li *et al*. (2021) (46)	ArcGIS	Revised Universal Soil Loss Equation (RUSLE)
Liu *et al*. (2016) (47)	ArcGIS	Revised Universal Soil Loss Equation (RUSLE)
Mohammadi *et al*. (2019) (48)	ArcGIS	Revised Universal Soil Loss Equation (RUSLE)
Munda and Kumar (2018) (49)	ArcGIS	Revised Universal Soil Loss Equation (RUSLE)
Neves *et al*. (2017) (50)	Not applicable	Not applicable
Panagos *et al*. (2015) (51)	Not applicable	Revised Universal Soil Loss Equation (RUSLE)
Sadeghi *et al*. (2015) (52)	ArcGIS	Various models reviewed
Wu *et al*. (2021) (53)	ArcGIS	Revised Universal Soil Loss Equation (RUSLE)

4.3 GIS and RS for assessing the consequences of soil erosion

Soil erosion has significant negative consequences, posing threats to economic growth, the environment, and social well-being globally. The severity of soil erosion varies from country to country and region to region, with developing countries being particularly vulnerable due to their direct dependence on soil for livelihoods and their limited capacity to adapt due to economic constraints.

The impact of soil erosion can be categorized into on-site and off-site effects (5, 14, 2). On-site effects refer to the immediate area where topsoil is lost, while off-site effects involve the downstream areas where eroded soil is deposited.

Assessing the negative impacts of soil erosion requires substantial time and financial resources, especially in inaccessible regions with complex terrains, such as the north-eastern part of India. However, remote sensing (RS) and geographic information systems (GIS) can aid in addressing this challenge, as supported by various research findings.

Additionally, soil degradation affects soil chemical properties, such as acidification, and salinization. RS and GIS techniques have been utilized to assess soil salinity in areas like the Wonji sugar cane irrigation farm in Ethiopia, revealing that approximately 80% of the land is highly affected by saline concentration, leading to reduced crop yields (54). Soil erosion has significant impacts on both the chemical and physical properties of soil, leading to soil nutrient deficiency (1). The consequences of land degradation due to soil erosion and land use/land cover changes (LULCC) in the central rift valley lakes of Ethiopia include socio-economic challenges, soil productivity decline, land degradation, wood and grazing land shortages, climate change effects, loss of biodiversity, and lake water withdrawal (17).

As previously discussed in soil loss estimations, the amount of soil loss in Ethiopia exceeds the maximum soil loss tolerance level of 18 t/ha/year (55). In the highland regions of Ethiopia, soil erosion rates for arable land can reach up to 130 t/ha/year with a mean of 35 t/ha/year for total land-use types (56).

The on-site effect of soil erosion is primarily centered on reducing the productive capacity of the soil by removing fertile soil, resulting in decreased crop yields. Ethiopia experiences an annual soil loss of about 1.5 billion tons (56). In the highland parts of the country, the productive potential of the land is decreasing at a rate of 2.2% per year (57, 56). Soil erosion not only reduces crop yields but also damages irrigation channels (58). This poses a significant challenge to the livelihoods of Ethiopian people, as agriculture is fundamental for more than 85% of the population. The agricultural sector contributes 45-50% of the country's GDP, employs over 90% of the workforce, and accounts for over 90% of foreign exchange earnings (59, 60). Moreover, it serves as the backbone for other sectors of the economy.

GIS offers significant advantages in evaluating soil erosion, especially in large and complex study areas. Best practices include using high-quality data sources, providing stakeholder training and support, using open-source GIS software, and considering ethical aspects. However, challenges include data quality, technical expertise, cost, accessibility, limited stakeholder engagement, and ethical considerations. Standardized procedures and improved validation are needed. Overall, GIS-based techniques are valuable tools for soil erosion assessment in EIA studies when best practices and limitations are taken into account (61).

On evaluating soil erosion risks in the Lahdar watershed, Morocco, where soil degradation is a pressing concern. To achieve this, the study employs geographic information systems (GIS) and remote sensing (RS), specifically the spectral angle mapper (SAM) method, to analyze and assess the expansion of soil erosion. The primary objective is to categorize land use and land cover dynamics, including arboriculture, cereal crops, water bodies, forests, residential areas, matorral-course (shrubland), and bare soils. Notably, nearly half of the watershed area is covered by bare soils, indicating a high vulnerability to soil degradation. Understanding the dynamics of land use and its impact on soil degradation is crucial for developing effective environmental policies that balance human development and environmental conservation. The study's outcomes can serve as valuable guidance for decision-makers in implementing conservation strategies to protect soil and water resources in the region (62).

5. CONCLUSION

Soil degradation is a pressing issue in developing countries like Ethiopia, primarily driven by water-induced soil erosion. This erosion leads to a significant reduction in the soil's productive capacity, resulting in declining crop yields, food insecurity, and increased poverty, ultimately impacting people's livelihoods. The consequences of soil erosion extend to economic growth, environmental resources, and social well-being, affecting different regions unevenly. Manual methods to assess soil degradation, estimate soil loss, identify erosion causes, and understand its consequences are challenging due to their inefficiency, inaccuracy, and inability to cover large areas quickly.

However, the use of Geographic Information Systems (GIS) and Remote Sensing (RS) techniques offers valuable solutions to these problems. RS enables data collection from remote and inaccessible areas. When coupled with models like USLE or RSLE, GIS and RS can aid in watershed delineation, soil loss estimation, and prioritization of conservation efforts. Despite the benefits of GIS and RS, their potential contributions to soil degradation studies are often overlooked. Therefore, it is essential for the government and relevant stakeholders to recognize the value of utilizing GIS and RS for effective natural resource management. Encouraging experts and concerned organizations to integrate GIS and RS into all aspects of natural resource management can lead to more sustainable solutions

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