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GIS assessment of soil erosion in Uzbekistan's rainfed mountain lands

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Abstract. This study investigates soil erosion and land degradation in the mountainous regions of the Parkent district in Uzbekistan using Geographic Information System (GIS) technologies. The research aims to analyze the extent and severity of soil degradation while examining related factors such as vegetation loss and changes in land use patterns. Advanced spatial analysis techniques and high-resolution remote sensing data were employed to conduct a detailed assessment of environmental transformations within the region. The analysis identifies critical degradation hotspots, revealing the influence of topographical diversity, climatic variations, and human activities, including overgrazing and unsustainable land-use practices. Predictive models were developed to evaluate the future risks associated with soil erosion, offering significant insights into the dynamics of soil fertility and its implications for agricultural productivity. These findings serve as a valuable resource for developing soil conservation strategies and promoting sustainable agricultural practices tailored to mitigate erosion. Furthermore, this research highlights the potential of GIS technologies as an indispensable tool for monitoring, visualizing, and addressing land degradation issues. By harnessing the advanced analytical capabilities of GIS, this research lays a strong foundation for designing precise intervention measures, improving the efficiency of land management strategies, and reinforcing long-term environmental sustainability in mountainous regions that are particularly vulnerable to soil erosion.

1 Introduction

Globally, the application of geoinformation system (GIS) technologies has revolutionized the way soil properties are analyzed, assessed, and managed. These systems are integral to modern agricultural practices, enabling detailed evaluations of soil quality, land degradation, and productivity enhancement. Research efforts in this field prioritize the use of cutting-edge computational tools to interpret soil research findings, monitor degradation processes, and establish robust information systems for soil condition assessments. Additionally, digital soil mapping is recognized as a vital component of sustainable land management strategies. In Uzbekistan, the integration of GIS technologies into agriculture reflects the nation's

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commitment to digital transformation. The Presidential Decree No. PK-4699, issued on April 28, 2019, emphasizes the importance of leveraging GIS for the rapid development of agriculture and the broader implementation of e-governance systems. This directive underscores the country's strategic focus on modernizing agricultural practices through advanced geoinformation tools [1].

Rainfed farming constitutes a significant portion of Uzbekistan's agricultural framework, with over 2.1 million hectares of land deemed suitable for this purpose. However, only 757.3 thousand hectares of this land are currently utilized for cultivation. Rainfed soils in Uzbekistan primarily consist of brown and serozem types, which are valued for their high fertility due to their moisture retention capacity, abundant humus content, and dynamic biological activity. These soils are geographically distributed based on elevation, ranging from 1,000–1,200 meters in the northern regions, such as the Tashkent area, to 1,800–1,900 meters in the southern parts, including the Surkhandarya region. These areas feature diverse topographical and climatic conditions, which shape the spatial characteristics of rainfed soils. In some regions, rainfed soils form extensive belts, while in others, they appear as narrow strips along mountainous terrains [2][3][4].

The mountainous landscapes of Uzbekistan, which are part of the Tien Shan and Alay mountain systems, are integral to the nation's geographical and ecological diversity. These mountain ranges, extending into Kyrgyzstan and Tajikistan, include notable sub-ranges such as Chatkal, Kurama, Piskom, and Ugom in the Tashkent region, all part of the Tien Shan system. Additionally, the Turkestan, Zarafshan, and Hisar mountains, situated in the eastern and southern parts of Uzbekistan, belong to the Alay system. These regions exhibit distinct geomorphological features that significantly influence soil formation and degradation processes [2].

One of the most pervasive challenges affecting soil health in these mountainous areas is erosion. Erosion, a natural process exacerbated by human activities, represents a major form of land degradation. In mountainous terrains, the relief plays a critical role in shaping erosion dynamics. Factors such as slope exposure, soil morphometric parameters, and vegetation distribution significantly impact the patterns and intensity of erosion. For instance, the slope's orientation affects the distribution of surface moisture and heat, influencing water runoff rates and the removal of nutrients from the soil. This underscores the importance of conducting targeted research to map erosion-prone areas and develop strategies for mitigating its effects. Three-dimensional mapping of soil erosion levels in mountainous rainfed farming regions is a key research priority to address these challenges effectively [5].

The use of GIS technologies in preserving and restoring soil fertility has gained substantial attention in recent years. GIS enables comprehensive analysis of degraded lands, providing insights into factors limiting soil productivity and offering solutions to improve soil properties. By integrating data from modern software and hardware systems, GIS tools facilitate the assessment of complex environmental variables and the prediction of adverse conditions caused by varying degrees of soil erosion. These capabilities are crucial for designing effective soil restoration strategies and implementing sustainable management practices.

Rainfed farming systems, which depend entirely on precipitation, are particularly vulnerable to climatic variability. The productivity of rainfed crops such as grains fluctuates significantly with rainfall patterns. In dry years, crop yields typically range between 3 to 5 centners per hectare, whereas in periods of increased precipitation, productivity can rise to 8–10 centners per hectare. One of the most effective strategies for maximizing water retention in rainfed agricultural systems is the application of clean fallows. This method plays a critical role in preserving soil moisture, reducing weed proliferation, and ultimately enhancing overall soil quality. On average, fallow fields are capable of storing 720–800 cubic meters of water per hectare by the time the planting season begins for autumn crops. During years of abundant rainfall, this water accumulation can further increase, reaching 1,000–1,200 cubic meters per hectare, ensuring better moisture availability for crops and improving agricultural sustainability. Such measures are vital for maintaining soil productivity and ensuring the sustainability of rainfed agricultural systems [6].

Despite their high fertility, rainfed soils in Uzbekistan are increasingly threatened by unsustainable land-use practices, such as overgrazing, deforestation, and improper agricultural techniques. These activities accelerate soil degradation and erosion, diminishing the land's capacity to support agricultural productivity. Addressing these issues requires a multifaceted approach that combines advanced technologies, such as GIS, with policy interventions and community engagement. GIS technologies, in particular, offer a powerful platform for identifying erosion hotspots, analyzing contributing factors, and designing targeted conservation measures.

2 Materials and methods

The rainfed lands analyzed in this study are located in the central regions of the Soqoqsoy basin, characterized by sharply varying terrain on the right and left banks. These regions, positioned at altitudes ranging from 900 to 1,200 meters above sea level, are predominantly characterized by dark serozem soils, which have developed on silty and sandy loess deposits. The area receives an annual precipitation of 956 to 1,150 millimeters, with a substantial fraction of this rainfall—approximately 345 to 364 millimeters—concentrated within the March to May period, making it a crucial phase for soil moisture replenishment and agricultural productivity. This period, characterized by high erosion risk, coincides with plowing and limited soil vegetation cover, which typically does not exceed 20–30%. As a result, the upper soil layers of pastures and rainfed lands are highly susceptible to erosion.

The topography of the study area includes slopes ranging from 20° to over 25°, with a distinct relief gradient. The eastern sections of the region are defined by the Chatkal ridge valley, where the soil-forming layer comprises poorly developed fine-grained sedimentary rocks. Elevations here range between 1,500 and 1,800 meters. The dominant soil types include brown soils formed on heavy sandy loess and skeletal deposits. These soils support various land uses, including rainfed farming, horticulture, viticulture, and, to a lesser extent, pasture-based animal husbandry. The geology, diverse soil-forming materials, uneven relief, and lack of anti-erosion measures collectively contribute to the formation of soils with varying degrees of erosion.

Rainfed farming in these regions relies solely on moisture retained in the soil from precipitation. Therefore, crops are typically cultivated only in areas receiving an average annual rainfall of at least 200 millimeters. The classification of rainfed lands in the study area is based on their moisture availability: high-moisture zones, primarily found in highland areas where brown and dark serozem soils dominate; moderate-moisture regions, which are typically mid-elevation zones consisting of typical serozem soils; and low-moisture areas, primarily located in the lowlands, where light serozem soils prevail [7].

To conduct this research, satellite data were obtained from Landsat 5 TM (Thematic Mapper) and Landsat 8 OLI (Operational Land Imager) via the United States Geological Survey (USGS) Earth Explorer platform. These datasets offer a spatial resolution of 30 meters, ensuring adequate detail for analyzing the study area. Google Earth Pro was utilized for preliminary image processing and visual interpretation, while ground-based observations were incorporated to enhance the accuracy of validation procedures.

To analyze the collected data, advanced geospatial techniques were applied. The study employed ArcGIS 10.6 for data preprocessing, including boundary delineation, coordinate system definition, and image subsetting to ensure precise analysis within the study's geographical scope. Land classification was carried out using supervised classification methods in combination with the maximum likelihood algorithm, a well-established technique in remote sensing. Additionally, the Land Cover Change Index (LCCI) algorithm was implemented, as it has been widely recognized for its effectiveness in evaluating changes in land cover using Landsat satellite imagery [8].

Soil types were categorized based on slope exposure and other topographic parameters. The classification steps involved creating detailed 3D maps to visualize the spatial distribution of eroded soils. These maps incorporated Sentinel-2 and Landsat-8 imagery, enabling researchers to assess erosion levels and their impacts on agricultural productivity. By identifying specific zones with varying erosion intensities, this methodology facilitated the development of targeted conservation strategies and practical recommendations for sustainable land use.

The research methodology also included field surveys to measure and verify soil characteristics. Key parameters such as slope gradient, humus content, and nutrient distribution were assessed to validate satellite data and refine the classification process. The field surveys provided critical insights into the morphogenetic features of rainfed soils and their susceptibility to erosion under different climatic and topographic conditions.

The comprehensive integration of GIS and remote sensing data, coupled with field observations, allowed for a robust analysis of the study area’s soil conditions. This approach ensured that the research outputs were both accurate and actionable, providing a scientific basis for the effective management of rainfed agricultural systems and the mitigation of erosion in the Soqoqsoy basin.

3 Results and discussion

The Parkent district, located along the northern slopes of the eastern Tien Shan Mountain range, forms a key part of eastern Tashkent and serves as a significant area for analyzing land cover transformations and soil erosion patterns [9]. This research utilized remotely sensed imagery to evaluate land cover changes and propose measures for improving soil and land management. The parent materials of rainfed brown soils in the district include proluvial-deluvial, eluvial, and deluvial deposits, along with fine granular particles and coarse rock fragments. These materials, often formed under geomorphological conditions of strongly folded mountain slopes at low to medium altitudes, provide the foundation for soils developed in deluvial loess clays and sands. Sparse juniper forests commonly cover these steep slopes, offering limited protection against erosion [10].

Research activities were conducted in specific base massifs within the Chatkal mountain range, where serozem and brown soils coexist. The results of these studies have contributed to the development of a comprehensive electronic database, which is supported by advanced geoinformation technologies. This database is designed to evaluate the condition of eroded soils and formulate effective strategies for their sustainable utilization in rainfed agriculture. A thorough analysis was conducted on the genesis, evolution, and fertility attributes of eroded dark serozems, alongside an assessment of ecological and genetic changes in the land. The study primarily focused on rainfed agricultural areas within the Chatkal range, where varying levels of erosion severity were observed. The implementation of vertical zoning techniques provided a structured approach for categorizing soil characteristics in the affected regions.

This research aimed to investigate the morphogenetic, agrophysical, and agrochemical properties of rainfed soils, offering insights into how erosion influences these attributes. Additionally, the study sought to generate high-resolution 3D maps of eroded soil landscapes by employing state-of-the-art geoinformation systems and satellite datasets acquired from Sentinel-2 and Landsat-8. The ultimate objective was to provide practical recommendations for optimizing the use of rainfed farmlands, drawing on insights derived from the generated 3D maps.

Fig. 1. Spatial image of rainfed cropland areas of the Soqoq region of Parkent district.

The soils of the studied region exhibited substantial variability in their humus and nutrient content, reflecting differences in soil formation processes and environmental conditions. Mountain brown soils exhibited a notably higher humus content compared to dark serozem soils. This difference is largely attributed to the humification process, which prevails over mineralization in moderately humid and warm high-altitude environments. Such climatic conditions enhance organic matter accumulation, leading to an increase in humus levels. The highest concentrations of humus and nitrogen were detected in unwashed and slightly washed soils, particularly in watershed areas and lower slopes. In contrast, soils located on steeper slopes, where erosion is more intense, displayed significantly lower reserves of humus and nitrogen due to the removal of the fertile topsoil layer, which is essential for root growth and nutrient cycling. The depletion caused by erosion processes highlights the critical influence of slope orientation and terrain characteristics on soil fertility [11].

Regarding total phosphorus and potassium levels, variations across the soil profile were relatively minimal. These nutrients were found to accumulate primarily in the upper layers, driven by biological activity. However, despite similar total concentrations across different soil types, their mobile forms displayed notable differences. Mountain brown soils contained higher levels of mobile phosphorus and potassium, which play a crucial role in enhancing plant growth and maintaining soil fertility. By contrast, mountain brown carbonate soils showed lower levels of mobile nutrients, largely due to the sparse vegetation cover, which limits the organic matter necessary for nutrient mobilization. This dynamic highlight the role of vegetation in maintaining soil fertility (Table 1).

The study area's dark serozem soils were primarily distributed along the mountain slopes of the Western Chatkal ridges, at elevations ranging from 450 to 900 meters above sea level. As elevation increased, these soils transitioned into brown carbonate soils, illustrating the interplay between altitude, soil type, and nutrient availability.

Table 1. Changes in morphological parameters of rainfed dark serozems depending on the degree of erosion. Tashkent region, Parkent district, Soqoq.

Soil section number degree of soil erosion	Slope level	Humus layer thickness, (A+B1+B2)	The upper limit of carbonates, cm		Gypsum accumulation limit, cm	Arable layer color
			in the form of mold	in the form of clods or white pores		
Dark serozem soil formed on a loess bed is distributed in undulating asperity.						
Uneroded soil in the upper watershed of the slope	$0,5^0$	83	52	63	low from 2 m.	umber color
Upper part of the slope, less eroded soil	around $2,5^0$	75	26	75	low from 2 m	dust color
The first middle part of the slope, moderately eroded	$7,5^0$	45		from above, on the surface	absent	dust color, gives a pale-yellow color
The second middle part of the slope, strongly eroded	9^0	42		from above, on the surface	absent	pale yellow color, gives a dust color
The lower flat part of the slope. Soil accumulated as a result of erosion.	less than 1^0	90-105	30-42	90-105	absent	umber color

The research conducted in the Western Chatkal mountain system identified three distinct subtypes of brown soils: brown carbonate eroded soils, brown typical soils, and brown decalcified soils. These subtypes were distinguished based on their chemical composition and development characteristics. A key feature of mountain brown soils is the presence of carbonate in their mineral content. The degree of carbonation and the extent of carbonate accumulation are influenced by the stage of soil formation. In carbonate soils, these factors are primarily determined by the depth at which carbonates are located, while in typical and alkalized soils, the process is affected by the degree of soil wetting due to atmospheric precipitation.

Brown decalcified soils are typically found above the regions dominated by brown soils. These decalcified soils transition into brown typical soils at lower altitudes, which eventually change into brown carbonate soils. The composition and structure of these soils differ due to the varying proportions of fine particles and skeletal material, with the dominance of fine particles becoming more evident in the decalcified zones.

In dark serozem soils, as well as in mountain brown carbonate, typical, and dealkalized soils, the gypsum (SO4) content is generally low, while the carbonate (CO2) content varies with elevation. The erosion of the upper soil layers often exposes deeper, less alkaline layers. This process results in an increased carbonate concentration near the surface. Additionally, as erosion progresses, the carbonate layer tends to rise, which can affect the soil's boiling point when exposed to acids. These patterns are reflected in Table 2, which highlights the morphological parameters of brown carbonate soils in relation to their degree of erosion.

Table 2. Changes in morphological parameters of brown carbonate soils depending on the degree of erosion. Tashkent region, Parkent district, Soqoq.

Soil section number degree of soil erosion	Slope level, in degrees	Humus layer thickness, (A+B+B)	The upper limit of carbonates, cm		Gypsum accumulation limit	Upper layer color
			in the form of mold	in the form of pores		
Weakly eroded soil, northern exposure	7^0	47-78	8	20-42	-	Light brown
Weakly eroded soil, northern exposure	10^0	37-78	10	16-37	-	Pale dust color
Moderately eroded soil, southern exposure	17^0	40	From soil surface		-	Gives pale dust color
Strongly eroded soil, southern exposure	22^0	33	From soil surface		-	Gives pale dust color

The increase in soil erosion directly correlates with a rise in carbonate concentration and a sharp decline in humus levels. This inverse relationship is a key characteristic of eroded soils. A reduced humus-to-carbonate ratio increases the soil's vulnerability to dusting and further erosion. These changes are not uniform across the landscape but vary significantly depending on the topography and morphological features of the soil. Variations can be observed in the cross-sectional structure of both eroded and accumulated soils, including differences in the thickness, color, and composition of the humic layer, the depth at which carbonate concretions and mycelia accumulate, and the skeletal structure of the soil.

Such distinctions are particularly evident in the rainfed lands of the Western Chatkal mountain system, where they provide valuable insights for accurate soil assessments. These findings facilitate the effective zoning and mapping of areas prone to erosion, such as the Soqoqsoy region in the Parkent district of Tashkent. These maps are crucial for identifying high-risk areas and implementing targeted conservation measures.

In practical terms, the effective use of rainfed agricultural lands in the Soqoq region can yield substantial economic benefits. Using GIS-based forecasts, it was estimated that 654.56 tons of land could be harvested annually, generating an income of 1 billion 7 million 712 thousand soums for local farmers (Table 3). These projections underscore the potential for sustainable land management practices to mitigate erosion impacts and enhance agricultural productivity.

Table 3. Economic Efficiency of Rainfed Croplands Using 3D Maps

Region name	Total area of the region (ha)	Total arable cropland in the region (ha)	Average yield (tons)	Income from the harvest (thousand sums)
Soqoq	5180	761	654,56	1007 712,61
Nomdanak	6114	1673	1 439,00	2215 378,71

4 Conclusions

The integration of advanced 3D mapping technologies presents substantial opportunities for combating soil degradation and improving agricultural sustainability. These maps allow for precise identification of areas affected by erosion, enabling the efficient utilization of degraded lands while helping to meet the rising food demands of the population. Furthermore, they play a crucial role in reinforcing the feed supply for livestock farming and enhancing overall soil structure, ensuring long-term land productivity.

This advanced geospatial mapping system provides rapid access to detailed soil information, including structural characteristics and topographical variations influenced by slope exposure, particularly in mountainous regions prone to erosion. Such insights are essential for assessing the extent of soil degradation and its direct impact on land productivity. The research findings, along with the generated cartographic materials, contribute to improving soil conditions, evaluating water-resistant aggregates, and mitigating erosion-related issues. This methodology supports the restoration of soil fertility, guiding the selection of appropriate crops based on erosion severity and slope orientation in rainfed farming systems.

The outcomes of this study, including detailed maps and scientific analyses, provide a solid foundation for decision-making in land management. These findings support measures aimed at enhancing rainfed agricultural productivity while also facilitating strategic land allocation for non-agricultural uses. Collectively, these efforts contribute to economic stability, strengthen the sustainability of the agricultural sector, and reinforce both environmental resilience and food security for the population.

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