CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2024; 34 (4): 0223-0233
DOI: 10.59440/ceer/193151
Original Research Article

ENGINEERING STUDY OF EROSION TO PROTECT THE GOMETSERI ALAZANI AND PIRIKITI ALAZANI CATCHMENT AREA (KAKHETI REGION, AKHMETA MUNICIPALITY, TUSHETI)

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Abstract

Soil erosion is a global environmental issue that reduces soil productivity, affects water quality, leads to sediment deposition, and increases the likelihood of agricultural land degradation. Combating erosion requires both quantitative and qualitative assessment of potential soil erosion on specific sites, along with knowledge of local terrain, soil types, land use systems, and management practices. From a theoretical and practical point of view, erosion processes are widespread and dangerous in Georgia, especially in mountainous areas. Slopes that have not been eroded or have not formed ravines are rare. Intensive landslides and mudslides are also observed here. Changes in factors associated with erosion are of interest, including the impact of climate change and human activity on components of erosional geosystems, especially on soil cover. Modern geoinformation systems (GIS) provide qualitatively new opportunities for research, modelling and optimization of the use of erosion-prone lands. Despite its wide application in many spheres of human activity, its potential in erosion research has not yet been fully realized. This article discusses about the Gometseri Alazani and Pirikiti Alazani (Akhmeta Municipality, Tusheti) catchment areas. The erosion-landslide processes developed in the research area are studied using the Revised Universal Soil Loss Equation (RUSLE). Erosion-vulnerable areas have been identified, where it is necessary to carry out additional engineering protection measures.

Keywords: soil erosion, land degradation, rivers catchment, RUSLE, GIS

1. INTRODUCTION

The study of soil erosion by water is an integral part of current research in the fields of agriculture, ecology, and natural resource management. This issue attracts the attention of researchers and practitioners due to its wide-ranging consequences, including the loss of fertile soil layers, ecosystem

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degradation, threats to food security, economic losses, and social problems, as well as potential impacts on biodiversity and the need for the development of sustainable soil erosion management strategies [1]. Current research on soil erosion aims to identify the main factors contributing to its development and to develop effective strategies for prevention and management of this process. Analysis of the soil cover structure, topographic characteristics, climatic conditions, and anthropogenic impacts allows us to assess soil resistance to erosion and determine optimal measures to contain it, including methods for assessing soil erosion potential and analysing the influence of geomorphological factors [2,3].

Engineering erosion control structures such as terraces, barriers, drainage systems, and protective vegetation are important elements in combating soil erosion by water [4]. Their use is based on the principles of hydrotechnics, geomorphology, and ecology, aimed at strengthening the soil cover, reducing water flow velocity, and minimizing erosion processes [5].

It is important to note that soil erosion by water is closely related to the dynamics of natural processes such as rainfall, wind activity, terrain slope, and soil cover characteristics [6]. Multifactor analysis of these processes requires the use of modern methods and tools, including geographic information systems (GIS), modelling, remote sensing, and analytical techniques [7,8].

Integration of the Revised Universal Soil Loss Equation (RUSLE) method with geographic information systems (GIS) provides spatial modelling and analysis of soil losses due to erosion by water based on a multifactorial approach, which forms the basis for the design of engineering erosion control structures to reduce water flow velocity and minimize the impact of erosion processes on soil [9,10].

2. STUDY AREA

Tusheti is situated beyond the Main Ridge of the Caucasus, on its Northern slope, exhibiting elevations ranging from 1650 to 4493 meters above sea level (Fig.1). Encompassing an area of approximately 896 square kilometres, the region assumes the configuration of an irregular pentahedral depression, characterized by a southern-eastern axis stretching 40 km in length and 25 km in width [11]. The prevailing climate is cold and falls within the Alpine Climatic Zone. The mean annual temperature stands at 5°C, with temperatures in July averaging around 13-15°C. Annual precipitation levels range from 450 to 900 mm, predominantly in the form of snowfall [12].

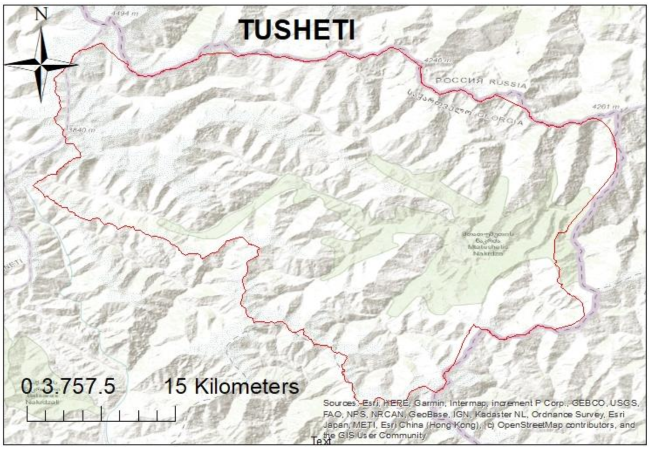

Fig. 1. Tusheti - Gometseri Alazani and Pirikiti Alazani Catchment Area

Tusheti is geographically delineated by Dagestan to the east, Pshav-Khevsureti to the west, Chechnya-Ingushetia to the north, and Eastern Kaheti to the south. It is demarcated by watershed high ridges characterized by elevations ranging from 3000 to 4500 meters above sea level. Notably, the northern ridge stands out for its imposing peaks, including Tebulo Mount (4492 m), Komito (4261 m), Dano Mount (4174 m), and Diklosmta (4285 m), collectively forming the Tusheti Alp, which serves as a natural boundary separating it from Chechnya-Ingushetia. The interior of Tusheti is marked by a network of ravines, with Pirikiti Kedi being prominent, originating from the sources of the Amugo and both Alazani rivers and extending southeast ward, effectively partitioning Tusheti into Pirikiti Gorge to the north and Gometseri Gorge to the south. Narrow trails traverse Pirikiti Gorge, facilitating passage between the two gorges, notably including the routes of Larovani (3317 m) from Larovani Gorge to the source of the Alazani River and Nakle-Kholi (2903 m).

The entirety of this rugged terrain is characterized by an extensive network of ravines, originating from the lofty mountain peaks, and channelling swiftly into the two primary rivers of Tusheti – the Gometseri Alazani and Pirikiti Alazani. The Gometseri Alazani originates from Borbalo Mountain (3134 m) and cascades eastward with considerable velocity. It receives the tributaries of Ortskali at the village of Gogrula and Chanchakhovani Tskali at the village of Khakhabo. Meanwhile, the Pirikiti Alazani emerges from Amugo Mountain (3839 m), augmented by the waters of Larovani Tskali at the ancient site of Hegho, before veering northeastward in tandem with the Gometsari Alazani. Along its course, it is supplemented by the tributaries originating from the Tusheti Alp, including Hashaki Tskali, Katsi Tskali, Dano Tskali, Kvavlo Tskali, among others. The convergence of these two Alazanis occurs at the village of Shenako, forming a single expansive river that extends beyond the confines of Tusheti into the territory of Dagestan, where it is recognized as the 'Andis Koisu'. Eventually, merging with the 'Avarias Koisu', it ultimately discharges into the Caspian Sea as the 'River Sulaki'. The entire expanse of Tusheti lies within the watershed of these two Alazani rivers and is geographically partitioned into four distinct gorges: Pirikiti Gorge, Gometseri Gorge, Chagma, and Chanchakhovani [13].

In the municipality of Tusheti, the highly fragmented relief and the wide distribution of rocks unstable to denudation processes, together with the local climatic and meteorological conditions, lead to the wide spread of erosion and gravity denudation processes.

The part of Tusheti, compared to other regions of Georgia, has been studied fragmentarily in this respect. This may be due to the difficult accessibility of the research area on the one hand and the small number of inhabitants on the other hand.

Water erosion poses a significant challenge to Tusheti, primarily due to its mountainous terrain and abundant precipitation. Situated in a high-altitude zone with steep slopes and river valleys, the region experiences rapid runoff of rainwater and snowmelt, leading to extensive soil erosion from hilltops and slopes and resulting in avalanches and landslides. This presents a threat to both residential settlements and agriculture, the primary source of sustenance for the local population [14].

The scale of negative manifestations of erosive processes is especially large in relation to highways and riverbanks. Banks and the roads passing through them on the stretches of hundreds of meters every year, during floods and torrents, become the object of the so-called lateral erosion produced by the water flows. The scale of negative manifestations of erosive processes is especially large in relation to highways and riverbanks. Banks and the roads passing through them on stretches of hundreds of meters every year, during floods and torrents, become the object of the so-called lateral erosion produced by the water flows. In some cases, especially on the lower slopes (Tusheti highland terrain), anthropogenic impact also causes significant erosion of the slope, the main source of which is unregulated runoff.

Furthermore, intense water runoff contributes to the pollution of water sources and rivers, deteriorating the quality of drinking water and adversely affecting the region's ecosystems. Combating water erosion requires a comprehensive approach, including the implementation of sustainable land management practices, soil conservation strategies, the construction of erosion control structures, as well as community education on soil and water conservation methods and practices. Only through such measures can the impact of water erosion be mitigated, and sustainable development be ensured in Tusheti.

Kakheti, both within Georgia and the Caucasus, belongs to one of the difficult regions in terms of the scale of development of debris flow events, the frequency of recurrence, the economic damage caused and the risk of danger. All geomorphological units, except plain terrain, are damaged by debris flow processes or are in the danger zone. More than half of the territory is classified as very high and high danger risk category (with a coefficient of 0.6-0.9). Debris flow is typical for massifs built with clays of Jurassic age, to which the main watershed range of the Caucasus belongs in Akhmeta municipality, and on the contrary, massifs built with shales of the Alazni basin. In addition to the geological features, significant slopes, frequent hydrographic network and atmospheric precipitations in the form of rains contribute to debris flows. According to the solid composition, the debris flows are stony and muddy. Almost all the left tributaries of Alazni river in Akhmet municipality are floodplain, and 80 debris flow watercourses are recorded in Mtatusheti. The rivers should be mentioned separately. The relief of the Alazni gorge of Tusheti is the gorge of Mozartaindurta-Etelta village, which is located 2000 m above sea level. The area bears traces of the Pleistocene glaciation in the form of tributary troughs, which have been largely erased by the influence of modern denudation processes. The valley is carved out of rocks that are quite unstable to erosion processes - jurassic clays, due to which a rather frequent network of gullies and pits is formed on the slopes. Due to the significant inclination of the slopes, landslides, rockfalls and other gravitational processes are frequent, examples of which are the landslides developed on the slopes near the villages of Etelta and Sagirta.

3. METHODOLOGY

Modelling the water erosion process of the soil cover is a rather difficult and unsolved problem. One of the most important tasks of soil erosion research is the evaluation of soil erosion hazards. In order to solve this issue, it is necessary to develop and implement methods for identifying the most sensitive areas to erosion processes and to analyse them qualitatively and quantitatively in order to further apply anti-erosion measures.

From the point of view of erosion, those soils are considered vulnerable, where the combination of natural-climatic conditions (climate, topography, soil-forming and bedrock, sediments) create favourable conditions for the formation of water-borne soil erosion.

Currently, there are several models for evaluating the degree of water erosion of the soil cover, among which we would highlight: WEPP (Water Erosion Prediction Project), USLE (Universal Soil Loss), RUSLE (Revised Universal Soil Loss Equation) and MUSLE (Modified Universal Soil Loss Equation). Each model has its own qualitative characteristics and can be used in different conditions and situations. However, their applications in large of the most listed models, hard-to-reach and poorly studied areas, such as the area of the Tusheti, remains a real problem due to the partial absence and quality of the necessary data for carrying out a full-scale study.

Additionally, most of the listed software tools that fully implement this kind of modelling are trial versions whose methods and algorithms require further analysis and performance evaluation.

The effectiveness of the practical use of these models is largely determined by the availability of initial information, therefore, in the development of modern models of soil water erosion, the first task is to create a model that requires the minimum available data.

MUSLE (Modified Universal Soil Loss Equation) is also used in the practice of modelling and assessment, which requires much more accurate and extensive information, which at the current stage of our research we do not fully possess. However, at the next stage of our scientific project, when we collect more theoretical, practical and field research data to assess and predict erosion processes in the pilot area, we will conduct a comparative analysis of the factors considered in each of the above-mentioned models for assessing soil loss in places. The main characteristics of these models will be studied when applied in the conditions of the mountainous region of Tusheti. At the same time, during the study, the main advantages and disadvantages of each of the models will be identified, the most optimal options for using a particular model in certain conditions will be summarized.

According to the above mentioned, the objective of this study is to evaluate, predict and analyse water erosion using GIS environment for the Revised Universal Soil Loss Equation (RUSLE) in the territory of Tusheti.

The Revised Universal Soil Loss Equation (RUSLE) is a mathematical model developed in 1980 in the USA. It represents an improved version of the Universal Soil Loss Equation (USLE) and was created to enhance the accuracy and applicability of the USLE model for estimating soil loss due to erosion. RUSLE is one of the most widely used tools for analysing erosion processes and assessing erosion risks on agricultural and other land areas. The method considers various factors influencing erosion, such as slope steepness, soil type, vegetation density, rainfall intensity, and land use practices. The availability of the mentioned factors caused us to give preference to RUSLE for our modelling.

The RUSLE model is used to predict soil loss in different regions and helps to identify areas most susceptible to erosion, making it possible to develop appropriate soil conservation and restoration measures. It is a very useful tool for soil science and land management, supporting to reduce the negative effects of erosion and maintain soil fertility. However, it should be noted that RUSLE focuses on larger-scale estimates of soil loss without considering erosion estimates at smaller scale conditions such as individual fields or plots of land. However, this limitation does not in any way interfere with our planned research, since it does not apply to those large-scale mountainous areas, considering the extensive catchment areas, where erosion processes may occur, which may lead to the formation of mudflow and landslide centres.

Back to the RUSLE, given model is a mathematical expression based on five main factors that determine the intensity of water-erosion processes given equation is represented as follows (3.1):

$$A = R \times K \times LS \times C \times P \tag{3.1}$$

where:

A represents the soil loss due to erosion on a specific land area (in tons per hectare per year);

R - the rainfall erosivity factor, which accounts for the amount and intensity of rainfall;

K - the soil erodibility factor, reflecting the susceptibility of a particular soil type to erosion;

LS - the slope length and steepness factor, considering the combined effects of slope length and steepness;

C - the cover and management factor, describing the degree of ground cover by vegetation or other protective materials;

P - the support practice factor, accounting for the impact of land management practices on erosion levels.

The calculation of the rainfall intensity factor (R) using geographic information systems (GIS) involves integrating climatic data and conducting spatial analysis of precipitation. Initially, data on rainfall are collected from diverse sources, including meteorological stations, and then utilized to generate a raster layer where each cell denotes precipitation values for a specific region.

Subsequently, interpolation techniques such as kriging or inverse distance weighting (IDW) are employed to fill spatial gaps and achieve a smoother precipitation distribution across the entire area. This step is crucial for maintaining data continuity and minimizing distortions in analysis outcomes.

The range of R values is contingent upon the climatic conditions prevailing in the region and may span from zero to several hundred or even thousand millimetres per year. For instance, in arid or semi-arid locales, R values tend to be minimal, whereas regions characterized by high humidity and heavy rainfall typically exhibit significantly higher R values.

The determination of the soil erodibility factor (K) using geographic information systems (GIS) involves an intricate process of integrating soil data and conducting spatial analysis. Initially, comprehensive data on soil characteristics are collected from various sources, including soil surveys and remote sensing imagery. These data are then utilized to create a soil database, where each soil type is characterized based on parameters such as texture, structure, organic matter content, and permeability.

Subsequently, spatial analysis techniques are employed to assess the spatial distribution of different soil types across the study area. This involves overlaying soil maps with other relevant spatial datasets to identify the spatial variability of soil erodibility. Methods such as soil erodibility indices and fuzzy logic modelling can be utilized to quantify the erodibility of different soil types based on their inherent properties. The next step involves assigning erodibility values to each soil type based on its susceptibility to erosion. This can be achieved through expert knowledge, empirical relationships, or statistical analyses. The resulting soil erodibility map represents the spatial distribution of K values across the study area, which can then be integrated into erosion modelling frameworks [2].

The range of values for K varies depending on the soil characteristics and can range from low to high erodibility. Soils with high clay content, poor structure, and low permeability are typically associated with higher K values, indicating greater susceptibility to erosion. Conversely, soils with sandy texture, good structure, and high organic matter content tend to have lower K values, indicating lower susceptibility to erosion.

The computation of **the slope length and steepness factor (LS)** via geographic information systems (GIS) involves the amalgamation of terrain data and spatial analysis. Initially, data pertaining to the terrain characteristics such as slope gradient and length are gathered from digital elevation models (DEMs) and topographic maps. These data are then utilized to generate a raster layer representing the slope gradient and length for the study area [11].

Following this, spatial analysis techniques such as slope analysis and hydrological modelling are applied to delineate the spatial distribution of slope lengths and steepness across the study region. This process involves assessing the slope length and steepness for each cell in the raster layer, considering the terrain morphology.

The resulting slope length and steepness raster layer provides valuable information on the variability of terrain steepness and slope lengths across the study area. This data can then be integrated into erosion models (RUSLE) to assess its impact on soil erosion. The LS factor is crucial in determining the erosive power of runoff on sloping terrain, with higher LS values indicating increased susceptibility to erosion. Conversely, lower LS values signify reduced erosion risk, particularly in areas with flatter terrain and shorter slopes.

The determination of the cover and management factor (C) utilizing geographic information systems (GIS) involves integrating land cover data, including the Normalized Difference Vegetation Index (NDVI), along with management practices through spatial analysis. Initially, data on land cover, including NDVI values derived from satellite imagery, are collected from various sources. These data depict the extent and type of vegetation cover across the study area.

Subsequently, the NDVI values are processed and analysed spatially to delineate the distribution of vegetation cover. The NDVI serves as a key indicator of vegetation density and health, with higher values indicating denser and healthier vegetation cover, while lower values signify sparse or absent vegetation.

Additionally, information on land management practices, such as conservation tillage, contour plowing, and terracing, is collected and integrated into the analysis. This enables the assessment of the effectiveness of various management practices in reducing soil erosion and maintaining ground cover.

The resulting cover and management factor map provides insights into the spatial variability of ground cover and management practices across the landscape, integrating both NDVI-derived vegetation data and information on land management practices. This information is essential for erosion modelling and soil conservation planning, as areas with higher NDVI values and effective management practices typically exhibit lower erosion rates, while areas with lower NDVI values and poor management practices are more susceptible to erosion [14].

The determination of the support practice factor (P) using geographic information systems (GIS) involves the integration of data on land management practices and erosion control measures with spatial analysis. Initially, information on various support practices such as contour farming, terracing, grassed waterways, and other conservation practices is collected from field surveys or existing databases.

Once collected, this data is processed and analysed spatially to delineate the distribution of support practices across the study area. GIS tools are utilized to overlay this information with other relevant spatial datasets, such as soil maps and land cover data, to assess the effectiveness of support practices in reducing soil erosion and sediment transport [7].

The resulting support practice factor map provides insights into the spatial variability of erosion control measures and their impact on soil erosion. This information is crucial for erosion modeling and soil conservation planning, as areas with effective support practices are typically associated with lower erosion rates, while areas lacking such practices may be more susceptible to erosion.

Integration of the support practice factor with other factors such as slope, land cover, and soil erodibility allow for a comprehensive assessment of erosion risk and the development of targeted conservation strategies to mitigate soil erosion and protect valuable land resources.

4. FINAL CONCLUSIONS

- Based on the analysis of the digital elevation model (DEM), it has been determined that the total watershed area of the Gomeceri Alazani and Pirikiti Alazani rivers is 93578.63 hectares. Further analysis of surface runoff revealed the hydrographic network of these rivers and their tributaries, which was classified into 5 levels according to the Strahler method, with a total length of 117.4 kilometres (Fig. 2).

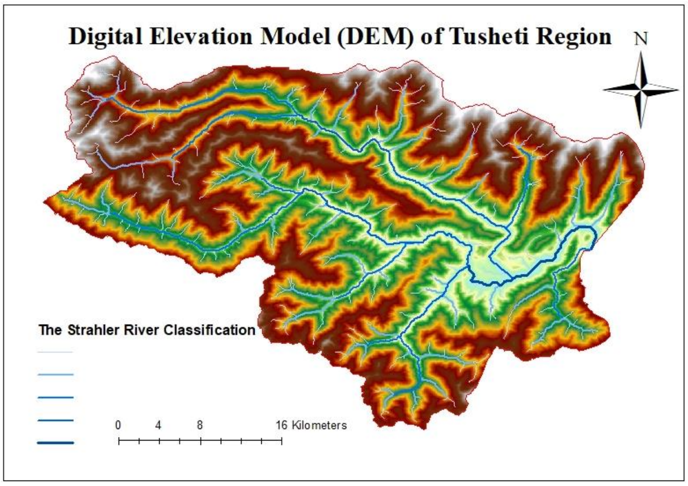

Fig. 2. Digital elevation model (DEM) - Gometseri Alazani and Pirikiti Alazani Catchment Area

- Upon analysing the topographic factor LS, which represents the erosion potential of the terrain, it was determined that the minimum value is significantly low, while the maximum value reaches as high as 458.608. This maximum value is predominantly observed in mountainous and foothill regions. These findings suggest a considerable variability in erosion potential across different landscapes, indicating that topographic features play a crucial role in influencing soil erosion processes in the studied area. The pronounced LS values in the elevated regions underscore the heightened risk of erosion in these areas, necessitating targeted soil conservation measures (Fig.3).

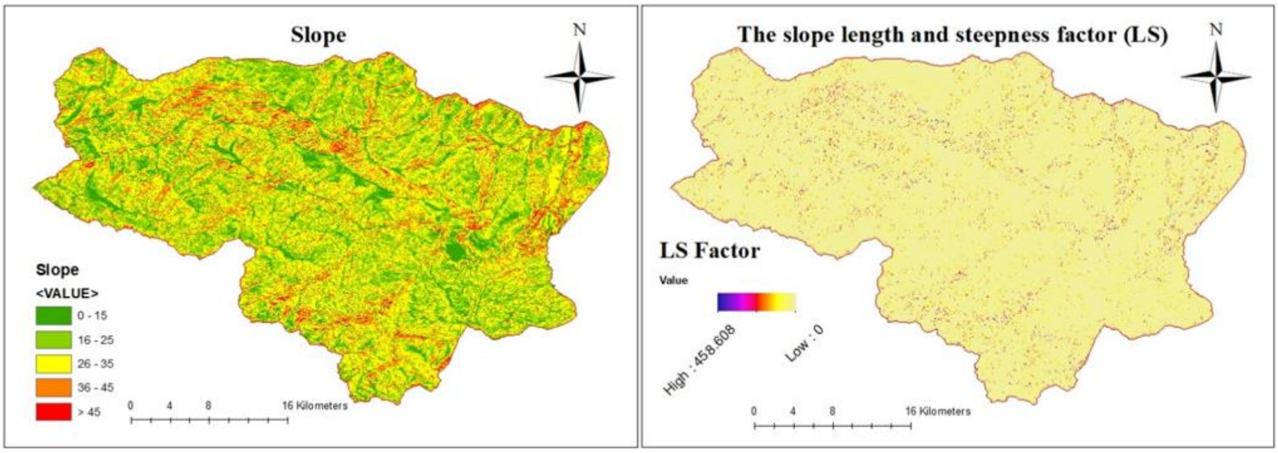

Fig. 3. Slope and Slope Length and Steepness factor (LS)

- As evident from the analysis of the obtained results, the maximum erosional potential (R-factor) of atmospheric precipitation is 301.695 MJ×mm/(ha×h) and is predominantly observed in highland regions, whereas it diminishes towards plains and lowlands. The minimum value recorded is 274.193 MJ×mm/(ha×h). The average R-factor value for the watershed basin is estimated at 279.96 MJ×mm/(ha×h) (Fig. 4).

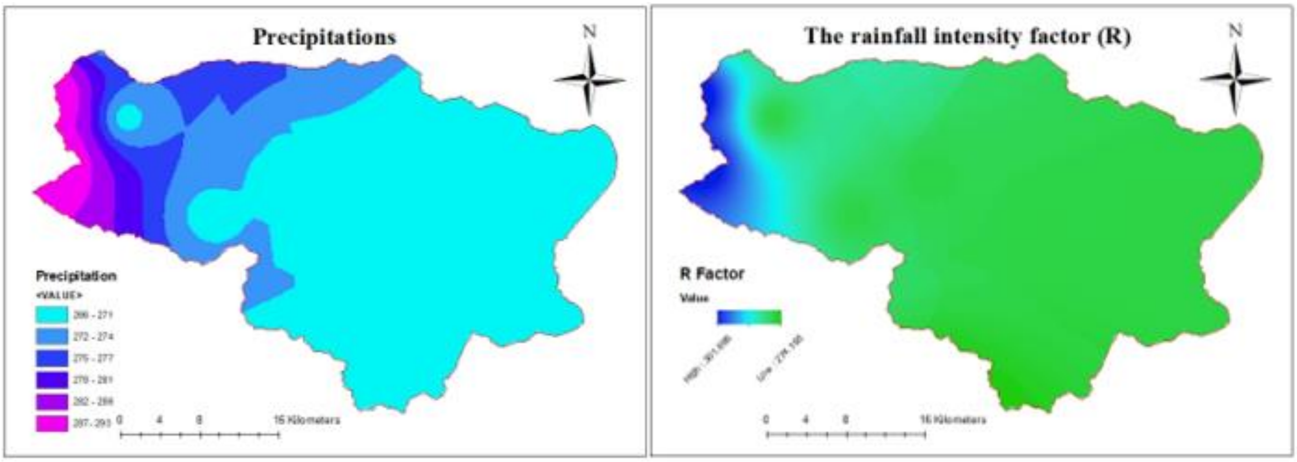

Fig. 4. Precipitations and the Rainfall Intensity Factor (R)

- The cover-management factor (C) ranges from 0.242 to 0.825. Given that the C factor values span from 0 to 1, with 0 representing very strong cover effects and well-protected soil, it can be inferred that a significant portion of the river basin area is susceptible to water erosion (Fig. 5).

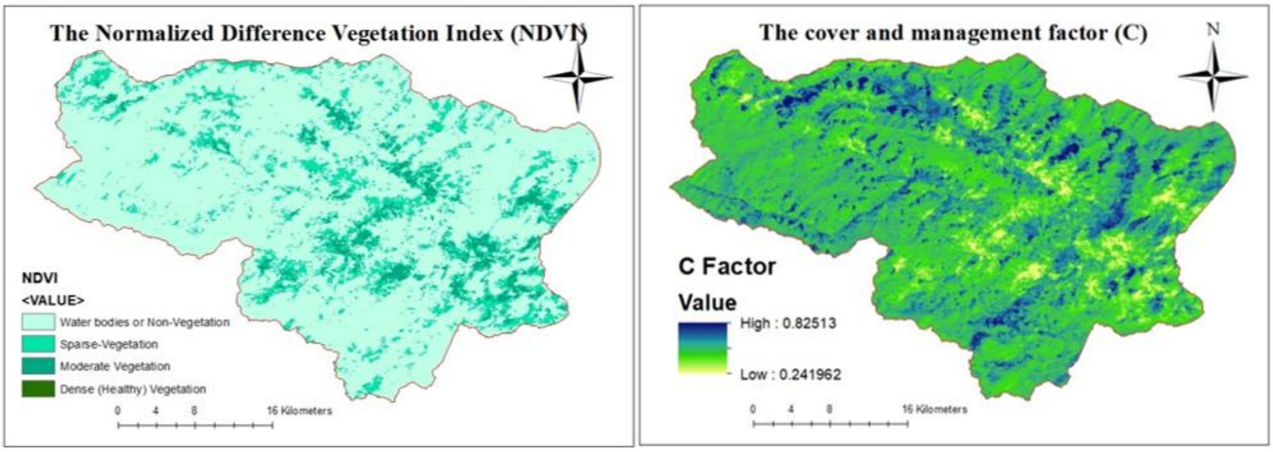

Fig. 5. The Normalized Difference Vegetation Index (NDVI) and The Cover and Management Factor (C)

- Upon scrutiny of the soil data within the Gometseri Alazani and Pirikiti Alazani Catchment Area, classified in accordance with the FAO (Food and Agriculture Organization of the United Nations) standards, it was discerned that two predominant soil types prevail (I-Be-2c and I-Bh-U-2c). Correspondingly, the erodibility factor K for these soils is determined as 0.0184 (Fig. 6).
- The factor of support practice (P) exhibits variability ranging from 0.55 to 1 contingent upon slope inclination and agricultural practices. Findings highlight that even within areas characterized by extensive development and current implementation of erosion control measures, the P factor remains at 0.55, whereas an ideal manmade erosion control facility would entail a P factor of 0 (Fig.6).

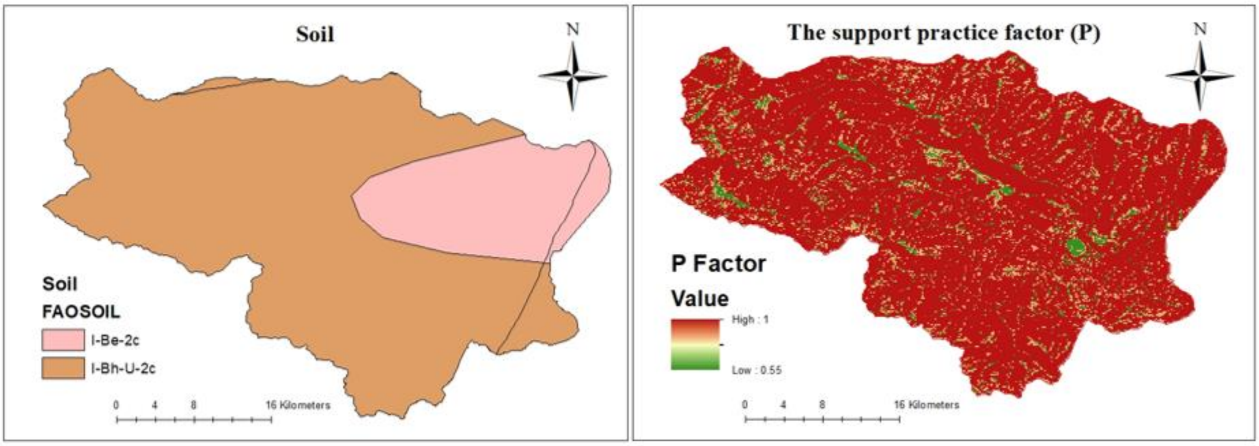

Fig. 6. Soil and the Support Practice Factor (P)

- Taking into account the values of the coefficients obtained, utilizing Formula (3.1) and GIS software, we calculated the magnitude of the long-term average annual soil loss (tons per hectare per year) (Fig. 7).

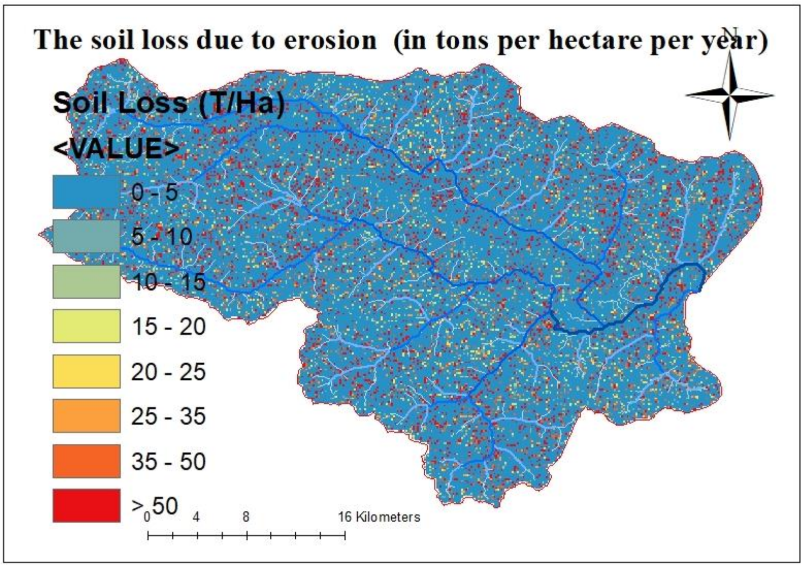

Fig. 7. The Soil Loss

Based on the analysis of the obtained data, we have concluded that channel erosion predominantly prevails in the watersheds of the Gometsari Alazani and Pirikiti Alazani rivers. This is attributed to the high flow velocity and significant slopes, which contribute to active channel incision. Their tributaries are particularly prone to erosion, necessitating the development and implementation of a comprehensive set of measures to mitigate erosional processes.

In these areas, the implementation of the following erosion control measures is necessary:

1. Bank stabilization structures: Utilization of gabion structures, geotextiles, and vegetative bank stabilization to stabilize riverbanks and prevent further erosion.
2. Flow regulation engineering structures: Construction of weirs and spillways to reduce flow velocity, thereby mitigating erosional processes.
3. Terracing on slopes: The construction and systematic implementation of terracing systems on steep inclines serve as an essential erosion control measure by substantially attenuating surface runoff velocities, thus minimizing the potential for soil displacement and degradation.
4. Channel stabilization: The employment of engineered concrete and stone revetments in geotechnically vulnerable sections of riverine channels is a critical intervention for the stabilization of these channels, effectively mitigating fluvial erosion processes.
5. Construction of water retention systems: Building reservoirs and detention basins to regulate water flow and reduce erosional impact.

These measures will help reduce flow velocity, decrease soil erosion, and prevent further landscape degradation. Regular monitoring of watershed conditions is also essential for timely detection and mitigation of erosional processes.

ADDITIONAL INFORMATION

The presented research has been conducted in the framework of the ongoing Grant Project #FR-23-9448 entitled "Engineering study of debris flow centre areas in the mountainous regions of Georgia" funded by the Shota Rustaveli National Science Foundation of Georgia.

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