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Research Article

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Analysis of the intensity of erosive processes and state of vegetation cover in the zone of influence of the Kolubara Mining Basin

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Abstract: Ensuring the quality protection of geospatial elements entails environmental control, a task unattainable without precise measurement results. This article aims to conduct a spatio-temporal analysis of soil degradation and vegetation status within the influence zone of the Kolubara Mining Basin in Serbia. Remote sensing is employed to assess vulnerability to erosion using the erosion potential method. A geographic information system environment is utilized to generate an erosion map, illustrating erosive processes across different time periods, particularly comparing the present situation (2022) to 1983. Results indicate that observed areas are experiencing erosion due to changes in land use. Furthermore, this study investigates the use of the normalized difference vegetation index to monitor vegetation cover changes from 1992 to 2022. The objective is to demonstrate that these methods effectively depict degradation levels and vegetation status in the area. This comprehensive overview provides insights into the changes occurring across the analyzed years. Such insights are crucial for informing future efforts to restore the region to its natural state prior to lignite mining.

Keywords: land use, remote sensing, erosion potential method, NDVI, Kolubara MB, Serbia

1 Introduction

A prerequisite for the seamless advancement of modern society hinges upon the sustainable management and utilization of natural resources. As humanity becomes increasingly consumer centric, the demands placed upon resources burgeon each day. Nonrenewable natural resources are being depleted at an alarming rate, far outpacing the time it took to form. It should be emphasized that the stability and strength of a country depend on the wealth of its natural resources, which consequently constitute national wealth. Soil, as a natural resource, is slowly formed and rapidly destroyed by degradation processes. Knowing this fact, society should strive to preserve land as a resource and improve it as much as possible for future generations [1].

Land degradation refers to the erosion or deterioration of the intrinsic functionality and potential worth of land, typically resulting in its diminished capacity to support various ecosystems or human activities [2]. The most common form of environmental degradation is soil erosion. We are witnessing that the loss of this natural resource precisely causes significant ecological and socioeconomic problems [3–5]. The complex process of soil erosion is caused by the physical and chemical properties of the soil type itself, topography, vegetation cover, and human factors [6,7]. The factors influencing the degradation process are highly dynamic and vary over time and space, necessitating a multidisciplinary approach and the use of modern methods and techniques in research. To date, numerous soil erosion models have been developed to assess soil erosion, with the ultimate goal of finding measures to prevent it. Depending on the research goals and data availability, a specific model is chosen for application, all with the aim of assessing the impact of soil erosion on the quality of various environmental elements [8]. In addition to the model, it is important to highlight the significance of methods for assessing soil loss resulting from erosion and sediment transport. Without the aforementioned information, planning soil erosion

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protection measures is not feasible. Remote sensing methods play a crucial role in studying various environmental elements [9,10]. For over 40 years, remote sensing has been employed for continuous monitoring of the Earth's surface, ensuring ongoing analysis of changes in vegetation cover [11]. The application of remote sensing methods is indispensable in various scientific research endeavors today, and the results have broad applications. Remote sensing methods aid in the identification, evaluation, and detection of various objects utilizing remote sensing sensors [12]. By processing satellite imagery, we acquire data on soil cover and evaluate vegetation conditions.

The erosion potential model (EPM) has been applied in many countries and has consistently provided reliable results for assessing the severity of soil erosion, estimating average annual soil loss due to water and sedimentation, as well as implementing runoff regulation and erosion control measures [13]. Bezak et al. evaluated the applicability of the EPM and its modified version for the estimation of the gross and net erosion rates at a global scale [14]. EPM was most frequently applied in the Mediterranean region (e.g., countries of the former Yugoslavia, North Africa, Italy, Greece) [15–19], although applications in other climates (e.g., Brazil, Iran, Nepal) can also be found [20–24].

The reliability of results obtained through geographic information system (GIS), as per Thieken et al. and Vogt et al. [25,26], is strongly influenced by the level of detail and accuracy of the input data (topographic, land-use, and soil-data sources).

In Serbia, numerous authors have studied changes in soil erosion using the EPM in various research areas [8,27–33]. Lakicevic and Srdjevic [34] analyzed the relationship between socioeconomic conditions and erosion processes in small watersheds. They concluded that over time, the conversion of agricultural land to other uses leads to a reduction in the intensity of erosion processes and sediment production in the area. Milanović et al. investigated land degradation analysis of the mine-impacted zone of Kolubara in Serbia for two different periods [30].

In forestry, information obtained through remote sensing finds extensive application [35–38]. Essentially, this method entails collecting data about objects without physical contact and from significant distances. The acquired data are then processed within GIS. In contemporary times, natural vegetation has undergone significant changes primarily due to human influence, continuously altering its natural arrangement. Therefore, prioritizing the preservation of vegetation and its thorough monitoring is essential for studying and protecting the area. Deforestation in modern times can be attributed to imperfections prevailing in planning and legal ownership relations [39], a phenomenon evident in the analyzed area. When ownership of the forest is unclear, when ownership cannot be readily transferred, when property use does not exclude others, or when private rights are not protected, it leads to emergence of imperfections in both market and forest management [40,41]. Illegal logging and various corrupt activities are among the most common causes that lead to the decline of forested areas [42,43].

In the Republic of Serbia, soil erosion ranks among the most significant forms of degradation, with approximately 80% of the territory having the potential for erosive processes of varying intensity. Of particular concern is the fact that over 35% of the territory south of the Sava and Danube rivers in the Republic of Serbia is affected by more severe categories of erosion [29,44–46]. In large mining basins like the Kolubara Mining Basin (Kolubara MB), conflicts between lignite exploitation and environmental protection are evident. The intensive surface exploitation of lignite in the Kolubara MB since 1952 has led to a significant shift in land use and the transformation of rural areas into industrial and urban zones [30]. This article addresses the significant degradation of land resources within the investigation area influenced by the Kolubara MB, as well as the analysis of the state of forest vegetation. The research time frame extends from 1983 to the present (2022), comparing the past situation to the current one. In addition to surface mines, the analysis also encompasses a broader area directly influenced by them, which was not previously studied.

Given the significance and complexity of forest conservation and sustainable forest management [47–49], efforts have been directed toward assessing the potential use of the normalized difference vegetation index [50]. NDVI is one of the most frequently employed vegetation indices, offering a simple and clear graphical indicator suitable for remote sensing analysis without constraints [51]. It is noteworthy that the NDVI is widely acknowledged as one of the most effective methods for reliably, swiftly, and easily identifying vegetation cover and evaluating its condition. Its ease of application has established it as a prevalent index for discerning green plant canopies in multispectral images through remote sensing techniques [52–54]. Another benefit of utilizing the NDVI index in vegetation cover analysis is its capacity to facilitate comparisons between images obtained at different time intervals [55].

Satellite images from the Landsat 5 and Landsat 8 satellite missions were utilized in this research. Changes in vegetation cover were detected for four analyzed time periods: 1992, 2002, 2011, and 2022, with a particular emphasis on areas covered by forest vegetation. The results of remote sensing for monitoring forest areas were analyzed using QGIS software in this article.

The primary objective of this study is to perform a spatiotemporal analysis of soil degradation and the status of forest vegetation within the Kolubara MB influence area. By generating a soil erosion map, erosive processes were depicted across different time periods. A key concern highlighted is the alteration in land use. The relatively favorable condition of forest vegetation over various time spans is largely attributed to the area's classification as having low erosion rates. Including additional factors such as NDVI and other indicators significantly enhances our ability to gain valuable insights into how vegetation arrangements protect the soil from erosive processes.

Changes in vegetation cover are analyzed over time and enhancements to the local vegetation management system are suggested, particularly focusing on forest vegetation in the zone influenced by the Kolubara MB entails employing more precise methods for assessing changes in forest areas. The study utilized the NDVI, widely acknowledged as a highly effective tool for classifying and evaluating various types of land cover in extensive and remote areas [56].

2 Methods

2.1 Study area

The study was conducted within the influence zone of the Kolubara MB. Intensive development of both mining and industrial activities occurred in the second half of the twentieth century. The Kolubara MB is located 60 km southwest of Belgrade and covers an area of about 600 km^2. The zone of influence of Kolubara MB is a spatial entity separated based on lignite exploitation (black or black-brown sedimentary rock of organic origin that has the ability to burn). The total area of the influence zone of the analyzed area is 301.29 km^2 (Figure 1). The area is characterized by slightly undulating alluvial plains along the Kolubara River and its tributaries, including the Tamnava, Peštan, and Turija. The basin is divided into eastern and western parts, with the eastern portion fully explored and the western part receiving increased attention in recent years [57]. Active exploitation primarily occurs within the municipality of Lazarevac, with lesser activity in the municipalities of Lajkovac and Ub. The area's abundant natural resources, with lignite coal being the most significant, coupled with favorable physical and geographical conditions, have contributed to its development. However, the exploitation of coal and the subsequent industrialization have had detrimental effects on the environment, resulting in the degradation of the area. Over time, lignite exploitation has led to land surface occupation, the transition of agricultural populations to the mining and industrial sectors, and a general sensitivity in the ecological system. Under the influence of expanding mining activities and intensive lignite exploitation in several open fields, populations resettle both within settlements and neighboring areas gravitating toward the Kolubara MB. Sociodemographic processes further exacerbate the already disadvantaged status of natural resources in the Kolubara MB's zone of influence, ultimately resulting in deforestation, water and land pollution, and additional land occupation for residential buildings or infrastructure construction.

The development of space within lignite basins has been discussed by authors from surrounding countries [58–60]. Lignite, a fossil fuel, represents one of the most important resources for electricity production in the Republic of Serbia through combustion in thermal power plants. According to the Energy Sector Development Strategy of the Republic of Serbia for the period up to 2025 with projections up to 2030, and supported by professional literature, coal, particularly lignite of low carbonation degree, is Serbia's largest geological energy resource [61]. Coal accounts for about 88% of electricity production, with the potential for energy production from remaining reserves (such as rivers, smaller coal mines, and oil shale) estimated at a maximum of 10% [62].

2.2 Methodology for erosion assessment

The development of erosive processes is influenced by the shape and character of the relief of a space [63]. The relief was analyzed in this study using a digital terrain model (DTM) with a resolution of 100 m.

Soil degradation processes in this study are examined through erosion potential methods. This method is notable for its high degree of reliability in determining erosion intensity and calculating the production and transmission of erosion deposits [64]. It falls within the category of regional methods and is classified as a semi-quantitative method in the literature [65]. The utilization of the EPM in a GIS environment is one of the main reasons for its extensive application in the Republic of Serbia [66–68].

$$W_{\text{god}} = T \cdot H_{\text{god}} \cdot \pi \cdot \sqrt{Z^3} \cdot A \ [\text{m}^3/\text{god}], \tag{1}$$

where W_{god} is annual yields of erosive material, T is the temperature coefficient, H_{god} is average yearly precipitation (mm), π is the Ludolf number (Archimedes' constant) – 3.14159, Z is the erosion coefficient, and A is the area (km^2).

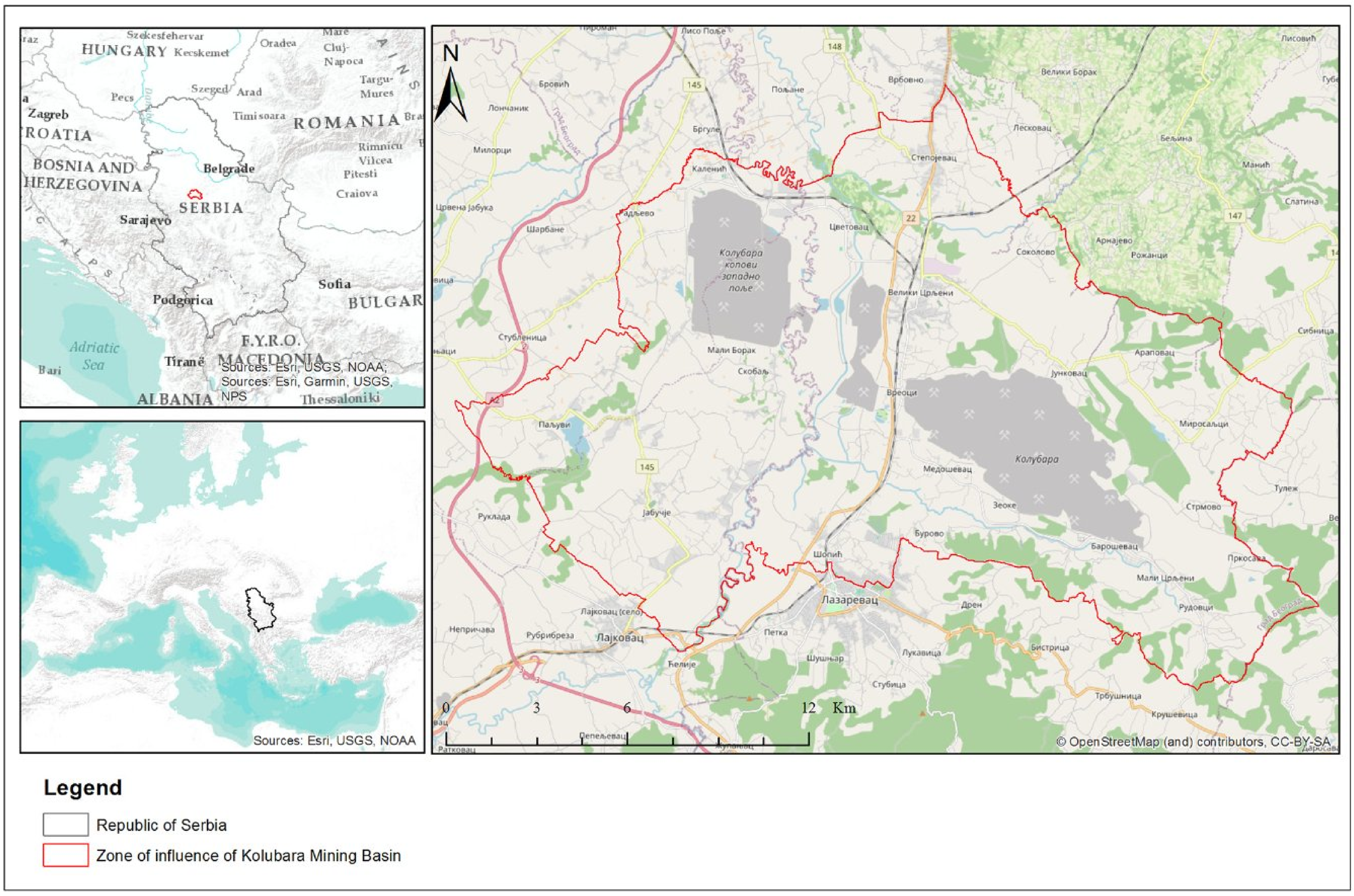


Figure 1: Geographical position of the zone of influence of Kolubara MB.

The EPM relies on analytically processing data concerning all factors influencing erosion. Quantitative erosion coefficient values are employed to differentiate erosion intensity across various categories [69]. As erosion is a spatial phenomenon, it is mapped based on the classification and the analytically calculated erosion coefficient (*Z*), which is independent of climatic characteristics but rather influenced by soil attributes, vegetation cover, relief, and observable erosion. The erosion coefficient is derived from the following expression [67]:

$$Z = Y \cdot X_a \cdot (\phi + \sqrt{I_{sr}}), \quad (2)$$

where Z is the erosion coefficient; Y is the soil erosion resistance coefficient; X is the soil protection coefficient against weathering and erosion; ϕ is the numerous equivalent of visible and clearly expressed erosion processes; and I_{sr} is the mean drop of the surface for which the erosion coefficient is calculated.

Through analysis of the coefficient *Z*, erosion processes were categorized according to Gavrilović as present in Table 1. Typically, values range from 0.1 to 1.5 or higher, indicating areas ranging from slight erosion to those significantly affected by soil degradation. Exceptions may occur where values exceed or fall below these specified limits [67].

The soil erosion resistance coefficient can vary from 0.25 (applicable to bare and erosive substrates) to 2.0 (pertaining to sandy and loose soils). The basin management coefficient is determined by land use in the studied area, ranging from 1.0 for entirely bare soil to 0.05 for well-structured forests. The coefficient ϕ signifies the numerical representation of visible and pronounced erosion processes, with values ranging from 1.0 (indicating areas with severe erosion) to 0.1 (representing areas without visible signs of erosion).

To analyze the fundamental physical–geographical parameters of the zone of influence, topographic maps from the Military Geographical Institute at a scale of 1:25,000 were utilized, alongside DTM data with a resolution of 100 m, derived from scanned topographic maps. The geological foundation was examined using a scanned basic geological map of the SFRY at a scale of 1:100,000 (published by the Federal Geological Institute) from 1970 (Figure 2), along with a pedological map of the SR of Serbia at a scale of 1:50,000 (published by the Institute for Soil Studies, Belgrade - Topčider) from 1966 (Figure 3). The land use map was compiled based on the CORINE Land Cover database and recent orthophotos

Table 1: Classification category of erosion by erosion coefficient *Z* [67]

Erosion category	Qualitative name of erosion category	Type of the ruling erosion	Range of values of coefficient *Z*	Mean value of coefficient *Z*
I	Excessive erosion- deep erosion process	Depht	>1.51	1.25
		Mixed	1.21–1.50	
		Surface	1.01–1.20	
II	Heavy erosion-milder than excessive erosion	Depht	0.91–1.00	0.85
		Mixed	0.81–0.90	
		Surface	0.71–0.80	
III	Medium erosion	Depht	0.61–0.70	0.55
		Mixed	0.51–0.60	
		Surface	0.41–0.50	
IV	Slight erosion	Depht	0.31–0.40	0.30
		Mixed	0.25–0.30	
		Surface	0.20–0.24	
V	Very slight erosion	Traces of erosion	0.01–0.19	0.01

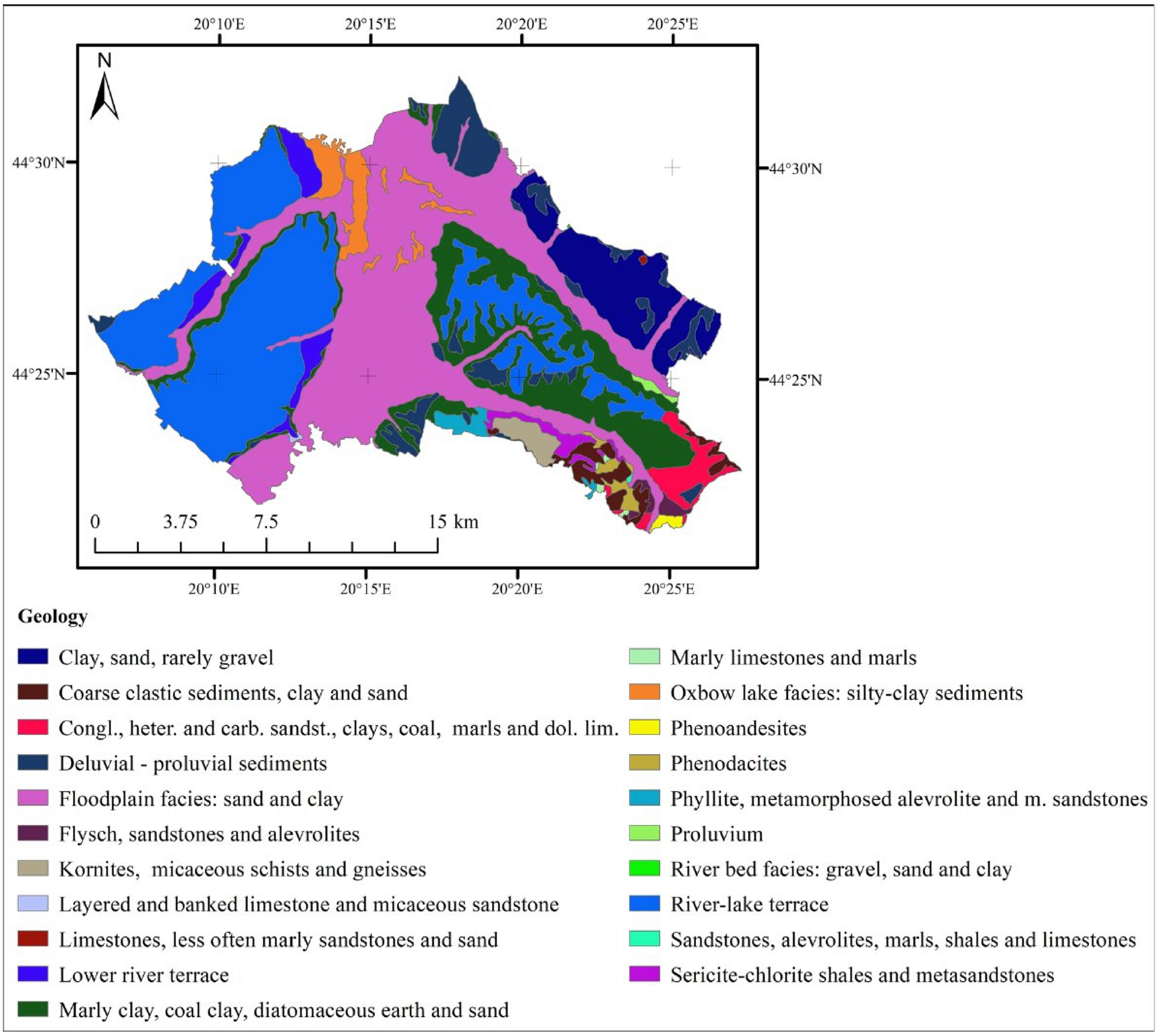


Figure 2: Geological map of the zone of the influence of Kolubara MB.

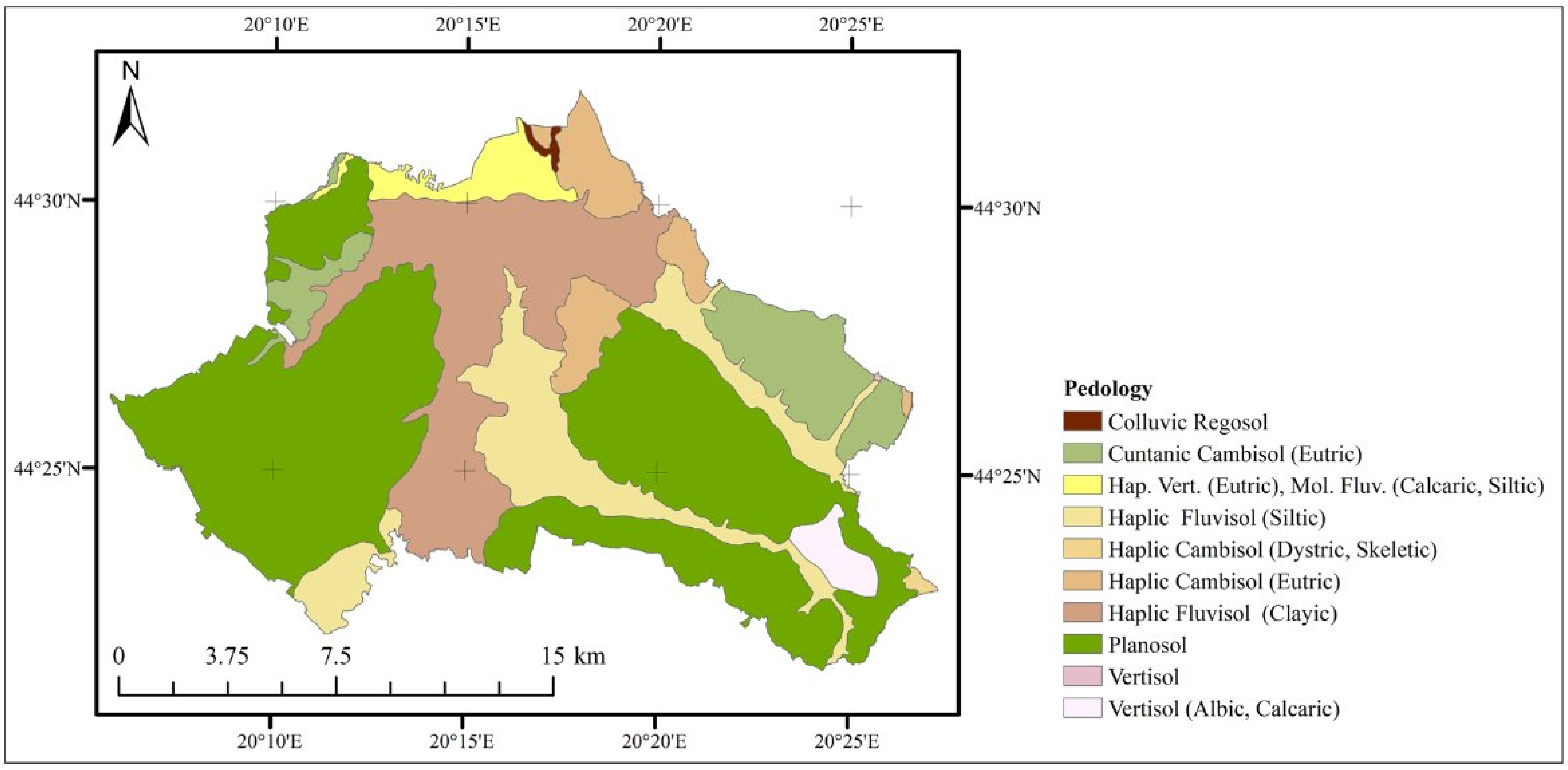


Figure 3: Pedological map of the influence zone of Kolubara MB.

(Figure 4). The mean slope of terrain I_{sr} was derived from DEM and expressed in the form of a raster database (Figure 5).

Analysis and processing of all input data and various databases were carried out using the QGIS program. Continuing with the work, Figure 6 depicts a schematic representation of the input data utilized for calculating the erosion coefficient using GIS.

For precise determination of the soil erosion resistance coefficient (Y), a comprehensive understanding of the geological and pedological conditions in the research area is essential. Given the diverse thickness of the soil layer, especially on steep slopes, a thorough examination of the pedological and geological substrate is crucial. Only through detailed analysis can coefficient values be differentiated for specific spatial units.

The basin management coefficient (X_a), in conjunction with the coefficient representing visible and clearly expressed erosion processes (ϕ), is determined by segregating areas with similar characteristics. X_a values are formatted as

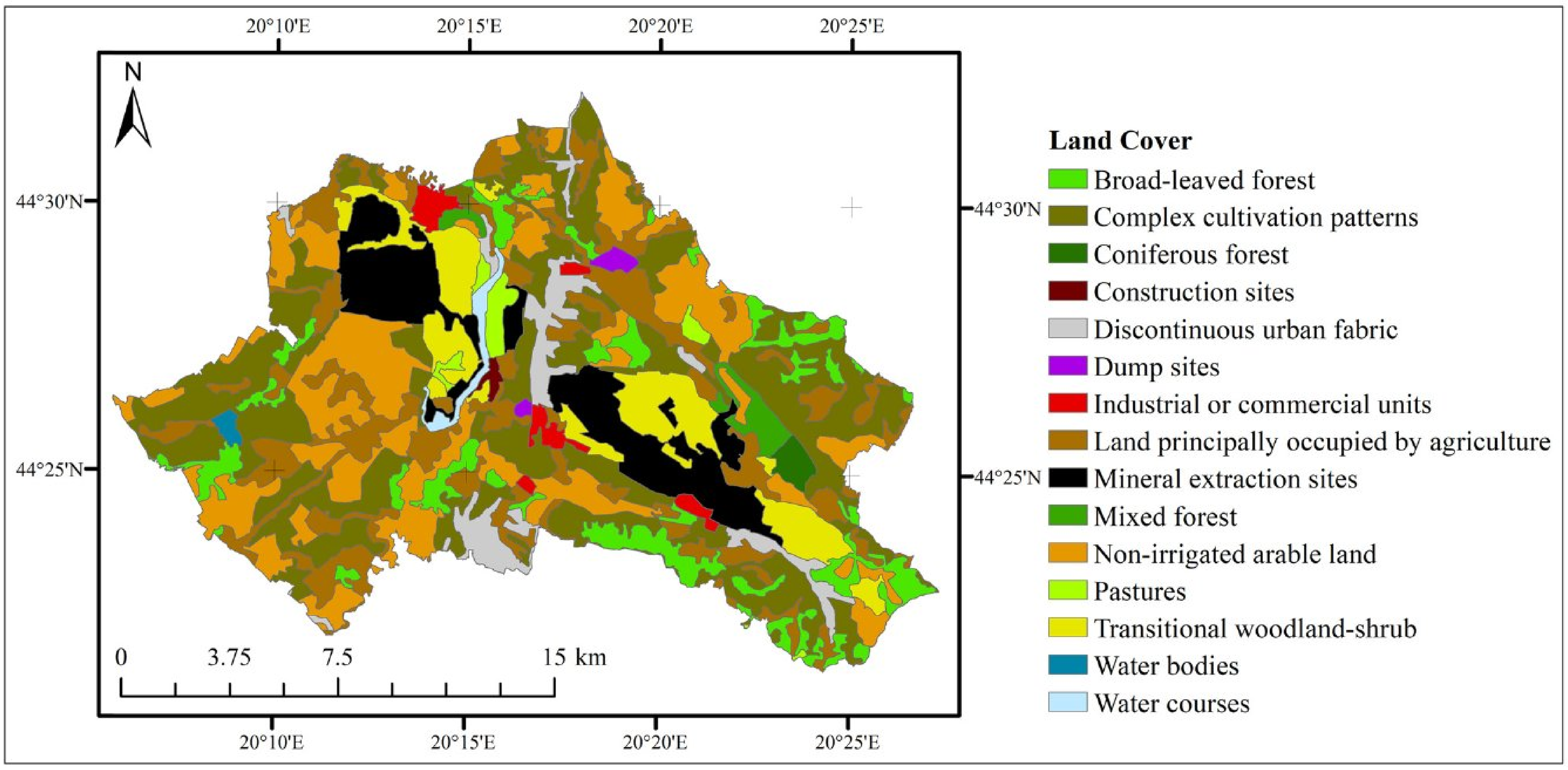


Figure 4: Map of land use in the zone of the influence of Kolubara MB.

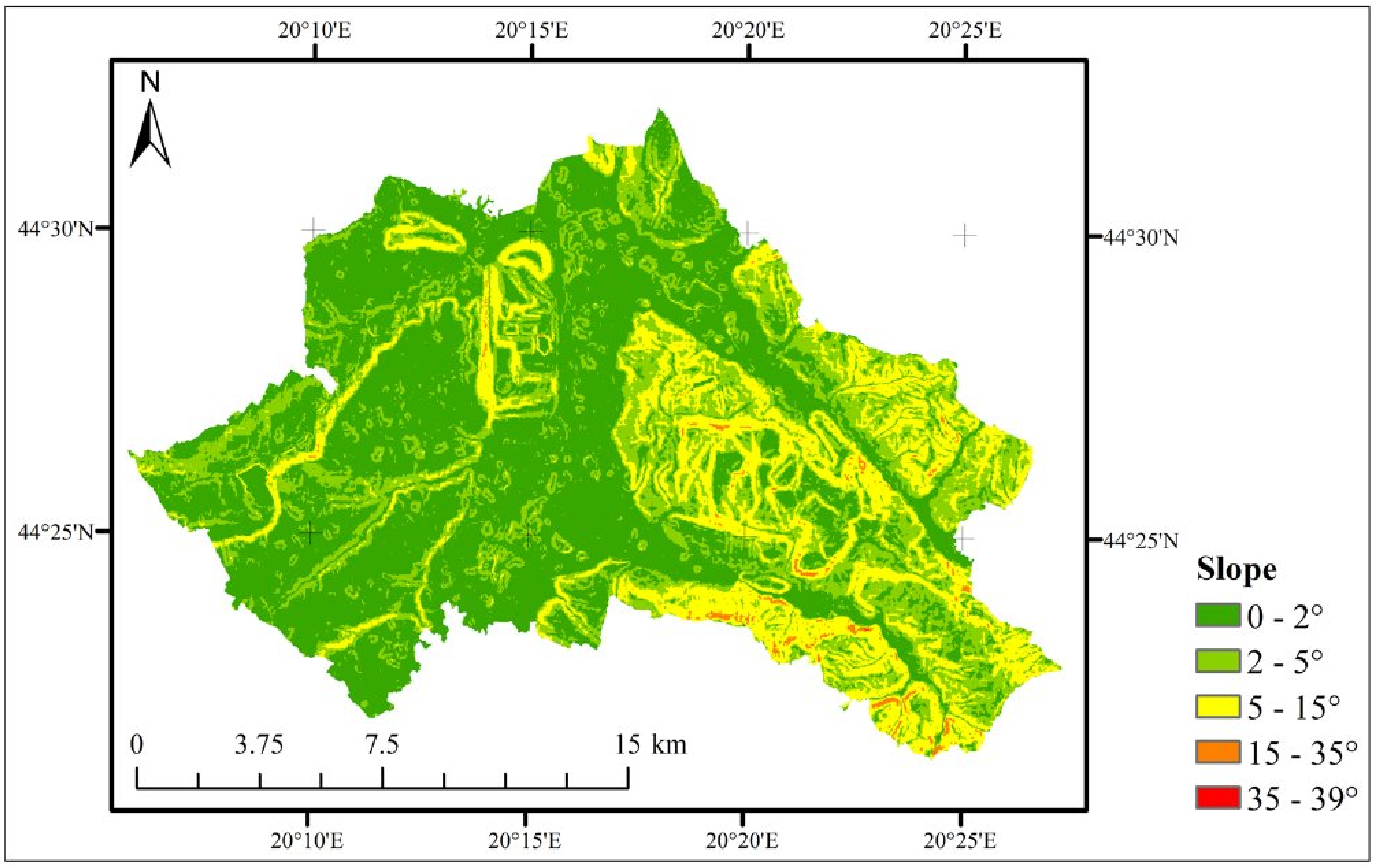


Figure 5: Map of the slope of the terrain in the zone of the influence zone of Kolubara MB.

attributes assigned to the modified Corine base for the examined area. Using this framework, areas consisting of discontinuous urban fabric, industrial and commercial units, and watercourses (hereafter referred to as the mask area) were excluded from the calculation of erosion processes. The coefficient value for visible and clearly expressed erosion processes (ϕ) is established based on orthophotos and the percentage participation of specific land use classes. The average slope I_{sr} of the study area is calculated and depicted using the DEM as a raster database.

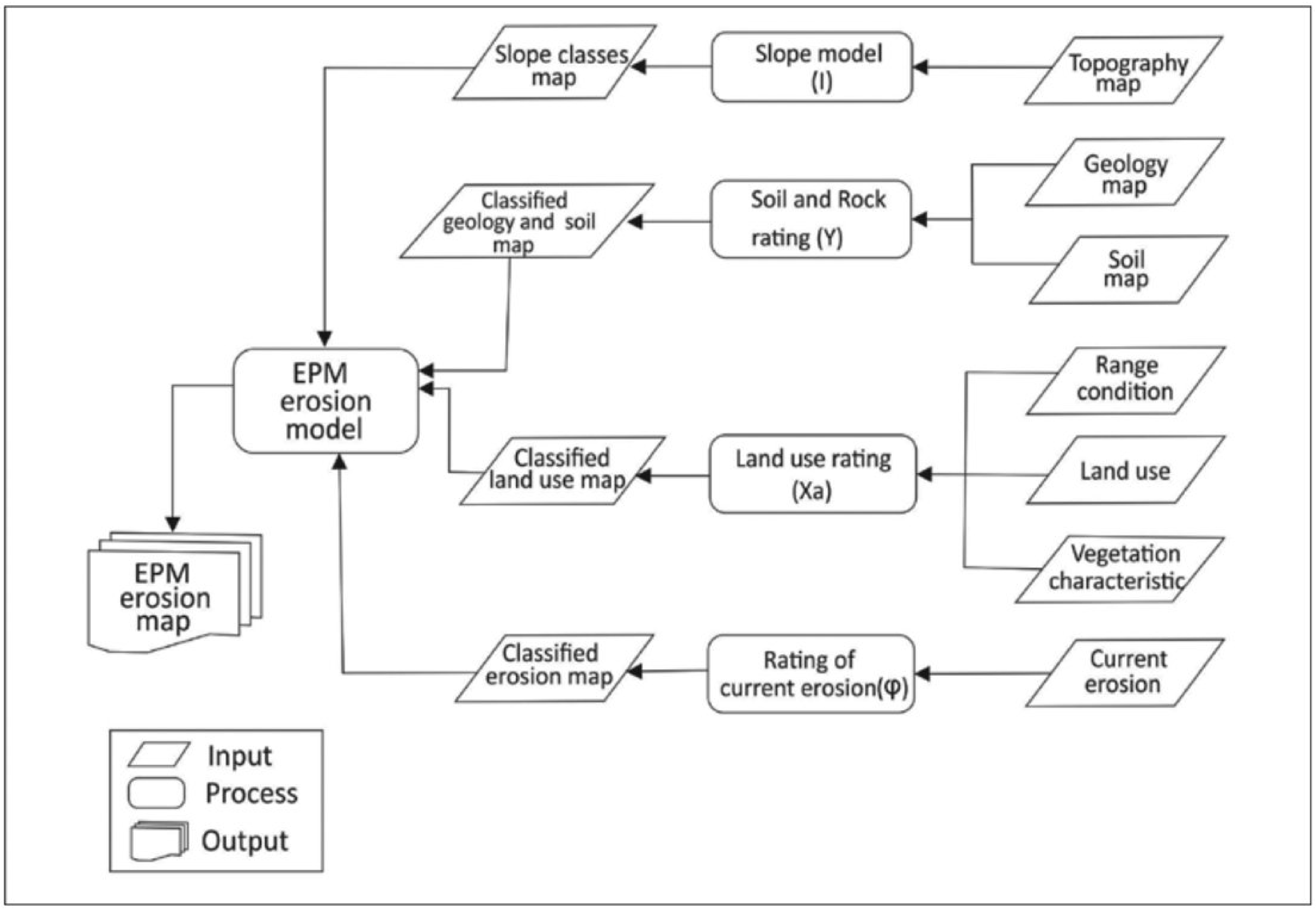


Figure 6: Application of the Erosion Potential Method with the Geographic Information System (GIS) [70].

2.3 Methodology for vegetation assessment

Quantitative methods, analysis and synthesis techniques, classification, and other methodologies utilized in the research, aligned with the research objectives, are essential for deriving valid results from the remote sensing method employed. The interpretation and the analysis of space rely on the utilization of multispectral images obtained through remote sensing, which encompass diverse spectral channels. These channels are amalgamated to create various composite images, thereby enhancing the discernibility of specific features. This process facilitates the acquisition of dependable information, especially concerning ground objects such as vegetation.

Over time, a plethora of algorithms have been developed with the aim of accurately determining the biophysical characteristics of vegetation, utilizing various multispectral approaches, spectral channels, and so on. The NDVI stands out as one of the earliest analytical tools employed in remote sensing, driven by the necessity to simplify the complex multispectral array of satellite images. Today, the NDVI remains the most widely utilized algorithm for vegetation assessment. Given the ubiquity of visible and near-infrared channels in multispectral sensors, the NDVI enjoys popularity and extensive application. Numerous studies have attested to the reliability of vegetation analysis using the NDVI. Its primary function is to generate a dataset reflecting the health status of vegetation, predicated on the disparity between the infrared and red spectral ranges. Scores within the range of −1 to +1 are assigned, with higher values indicative of healthier vegetation. A defining characteristic of the NDVI is its emphasis on both the vegetation cover within the surveyed area and the condition of that cover itself [71,72].

During the preparation of this article, it was not feasible to compare and verify the data between the results obtained through the application of the NDVI and the national forest inventories due to the absence of a standardized procedure for earlier years. Records were sporadically compiled, with assessments conducted approximately every 20 years: in 1961, 1979, and 2003–2006. Only since 2007 has there been an official annual census of forests, where forest areas are aggregated at the municipal level without delineating their spatial distribution [73].

NDVI data (Table 2) for the Kolubara MB zone of influence were derived from LANDSAT 5 Thematic Mapper (TM) satellite images captured on 1992 (July 30, 1992), 2002 (June 24, 2002), 2011 (July 19, 2011), and LANDSAT 8 TM for 2022 (July 1, 2022) (www.usgs.gov). The downloaded images exhibit minimal cloud cover (10–20%). Atmospheric corrections were unnecessary since the downloaded images were obtained under clear weather conditions. Given the consistency of the input data and the continuity of Landsat satellites in monitoring the research area's surface, these images, with a resolution of approximately 30 m, were integrated with panchromatic images (with a resolution of 15 m) to ensure optimal accuracy. Consequently, the other channels were adjusted based on the panchromatic channel to enhance image resolution, following the methodology outlined by Jovanović et al. and Jovanović and Milanović [72,74].

The NDVI is grounded on the principle that chlorophyll pigments in plant leaves absorb radiation within the 0.4–0.7 μm range of visible light (during photosynthesis), while the structure of plant leaves reflects radiation in the near-infrared range (0.7–1.1 μm). NDVI values range between −1 (clear/deep water bodies, bare) and +1 (dense forests) [11]. In addition, essential transformations were implemented, primarily involving the visible red and infrared portions of the satellite image spectrum during the application of the NDVI.

Table 2: Band designations for the Landsat 5 and Landsat 8 satellites (Source: https://landsat.gsfc.nasa.gov/satellites/landsat-8/)

Band No.	Landsat 5		Landsat 8	
	Bandwidth	**Resolution (m)**	**Bandwidth**	**Resolution (m)**
1	0.45–0.52	30	0.43–0.45	30
2	0.52–0.60	30	0.45–0.51	30
3	0.63–0.69	30	0.53–0.59	30
4	0.76–0.90	30	0.64–0.67	30
5	1.55–1.75	30	0.85–0.88	30
6	10.40–12.50	120	1.57–1.65	30
7	2.08–2.35	30	2.11–2.29	30
8	—	—	0.50–0.68	15
9	—	—	1.36–1.38	30
10	—	—	10.6–11.19	100
11	—	—	11.5–12.51	100

Satellite images are processed in GISs to calculate the NDVI index using the following formula:

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED})/(\mathrm{NIR} + \mathrm{RED})$$

where NIR is the near-infrared channel, and RED is the red channel from the visible part of the spectrum [75,76]. For Landsat 5, NDVI = (Band 4 – Band 3)/(Band 4 + Band 3). For Landsat 8, NDVI = (Band 5 – Band 4)/(Band 5 + Band 4) (Table 2).

After applying the equation, the analysis and photo-interpretation of the observed elements, processes, and phenomena detected in the images were commenced using the QGIS software.

When analyzing the results obtained using the NDVI, the following intervals are important: dense vegetation canopies typically yield positive values (0.3–0.8); snow fields or clouds typically yield negative values in this index; and water surfaces exhibit very low reflectance in both spectral ranges, resulting in low positive or even negative NDVI values; soils generally exhibit near-infrared reflectance slightly higher than red, leading to very low positive NDVI values (0.1–0.2); barren surfaces such as rocks, sand, and snow typically yield very low NDVI values (0.1 and below); shrubs and lawns typically yield moderate values (0.2–0.3); and high NDVI values (0.6–0.8) are indicative of temperate and tropical forests [77,78]. Negative values can also occur when calculating the NDVI. Therefore, the range from 0 to −0.3 signifies arable agricultural regions lacking vegetation. Coniferous forests typically exhibit NDVI values above 0.5, mixed forests range between 0.35 and 0.5, whereas broadleaf deciduous forests typically show values ranging from 0.3 to 0.4 [79,80].

A schematic representation of work process is illustrated in Figure 7.

3 Results and discussion

Over time, a new ecosystem has emerged in the researched area as a result of mining activities, significantly altering the natural environment. Segments of natural vegetation have persisted alongside rivers and streams, mainly in the form of swamps, meadows, or smaller forest complexes. Areas for cultivation were obtained by clearing forest habitats, while vegetation on active surface mines was completely removed due to mining activities.

Initially, maps were digitized, and specific values were assigned to the elements, respectively. Subsequently, the data were converted into a raster format with a resolution of 100 m, where the attribute values of Y and X_a served as criteria for the conversion into a raster base. This raster

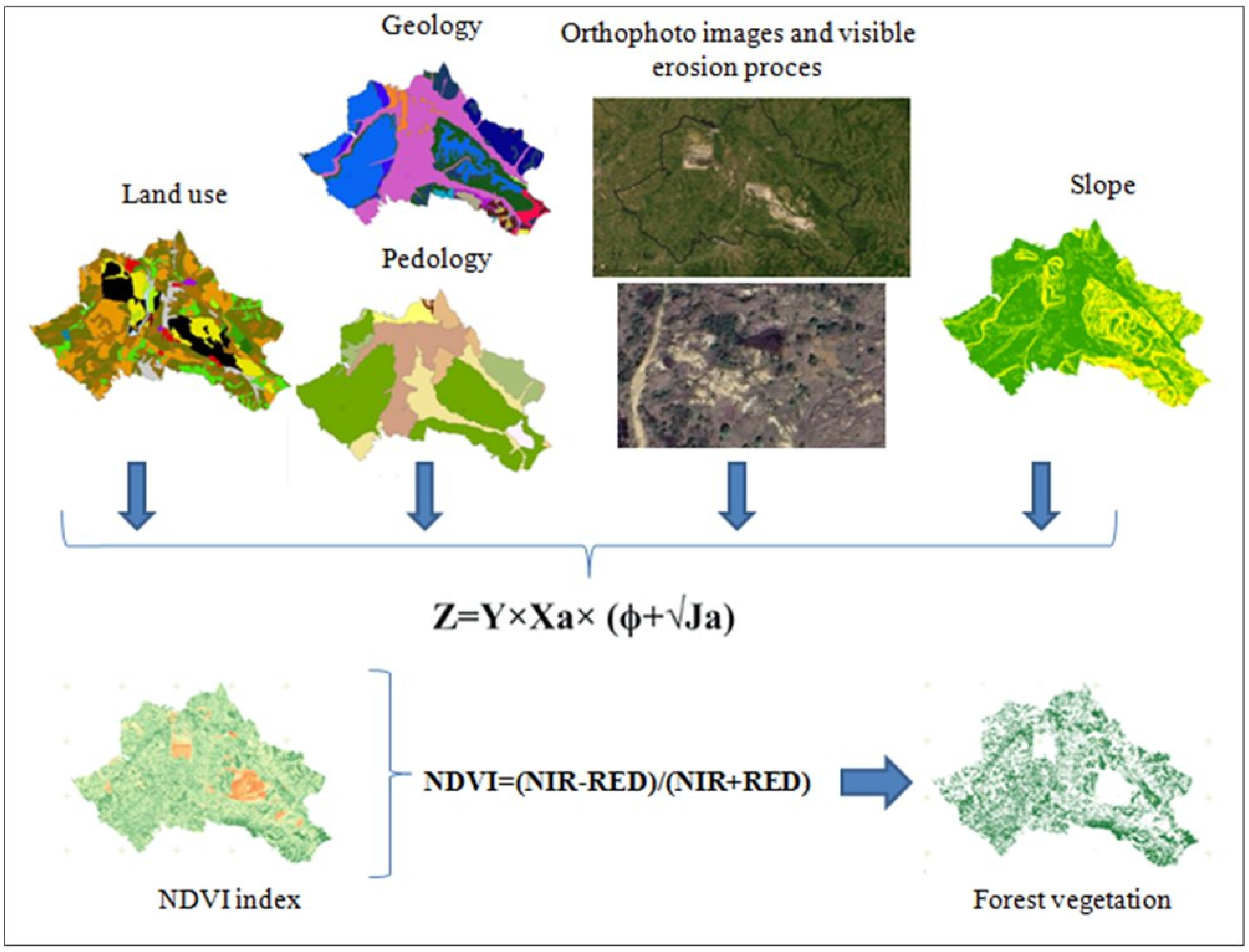
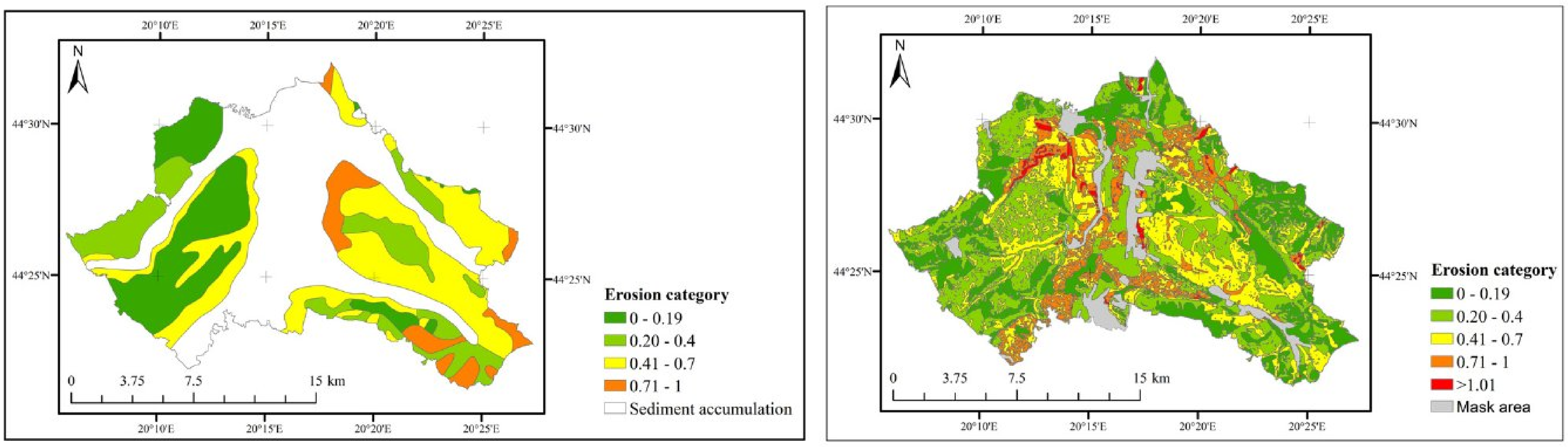


Figure 7: Schematic representation of the procedures carried out for this study.



(a) (b)

Figure 8: Erosion processes in the area of the influence zone of Kolubara MB (a) 1983 and (b) the current state (2022).

format is well suited for computing the erosion coefficient *Z*, as per the aforementioned formula. Consequently, each pixel on the map is assigned a specific value for the erosion coefficient *Z*. By categorizing the numerical values of the raster into defined classes, an erosion map is generated (Figure 8). This map illustrates the spatial distribution of erosive processes, providing a closer examination of their intensity and characteristics. In the influence zone of Kolubara MB, erosion manifests in various forms across the area. Table 3 presents the prevalence and the intensity of erosion in the studied region. Based on the current erosion processes (2022), the investigated area can be classified using the EPM as exhibiting weak erosion, with an average erosion coefficient of $Z = 0.37$.

Table 3: Representation of erosion categories in the area of the influence zone of MB Kolubara in 1983 and currently (2022)

Erosion category	Qualitative name of erosion category	1983		2022	
		km^2	%	km^2	%
I	Excessive erosion-deep erosion process	0	0	5.25	1.89
II	Heavy erosion-milder from excessive erosion	17.56	5.83	31.38	11.31
III	Medium erosion	76.99	25.56	70.85	25.54
IV	Slight erosion	40.03	13.28	103.75	37.40
V	Very slight erosion	51.28	17.02	66.18	23.86
VI	Accumulation of sediment	115.43	38.31	0	0
	Mask area	0	0	23.88	0
In total		301.29	100	301.29	100
Mean value of erosion coefficient in the area of influence zone of Kolubara MB		$Z_{sr} = 0.23$		$Z_{sr} = 0.37$	

The observed situation in 2022 indicate that the category of excessive erosion covers an area of 5.25 km², equivalent to 1.89% of the total studied area. Strong erosion is observed on 31.38 km², accounting for 11.31% of the total area. Based on the spatial distribution, these two categories are concentrated in the central parts of the research area, likely influenced by ongoing intensive mining activities and resultant soil bareness. The middle category of erosion intensity occupies 70.85 km², accounting for 25.54% of the area, while weak erosion is the most prevalent category, covering 103.5 km², or 37.40%. Very weak erosion occupies 66.18 km², representing 23.86% of the total area. According to the spatial arrangement, medium, weak, and very weak erosion are evident along the perimeters of surface mines and settlements not currently directly affected by mining operations. It's notable that weak erosion is observable in former open surface mine areas where, due to effective technical and biological reclamation efforts, the soil has become stable and is gradually reverting to its natural state. The analysis excludes built-up areas such as settlements and industrial facilities, comprising a total area of 23.88 km^2 (masked area).

To quantify the observed changes in erosion intensity within the researched area using GIS, the area was digitized based on the existing Erosion Map from 1983 [44]. The erosion map of the Republic of Serbia was created over 40 years ago, with work commencing in 1966 and extensive field research completed by 1971. The existence of this map is valuable as it enables comparisons and monitoring of changes in relation to the current state (2022) obtained through the application of the EPM (Figure 8).

The situation in 1983 is such that it is the average mean value of the erosion coefficient (Z_{sr}) is lower compared to the current situation (2022), amounting to $Z_{sr} = 0.23$ (indicating weak erosion). In contrast to the present condition, the sediment accumulation category is most prevalent on the 1983 map along the major watercourses of the researched area: Kolubara, Kladnica, Peštan, and Turija. Currently, this area is affected by excessive, strong, and medium erosion categories. There was no excessive erosion category in the 1983 data. According to the 1983 data, strong erosion covers an area of 1.56 km^2 or 5.83%. Medium erosion is evident on a surface area of 76.99 km^2, representing 25.56% (similar to the current situation). Weak erosion encompasses an area of 40.03 km^2, accounting for 13.28%, while very weak erosion occupies 51.28 km^2 or 17.02%.

According to the study by Milanović et al., similar values of the coefficient Z were obtained. Specifically, for the year 2001, it was 0.215, while for 2011, the value stood at 0.212. These results align with the previous study, confirming that the studied area, despite evident spatial degradation, is subject to weak erosion [30]. The study mentioned is the sole source against which the obtained results for the study area can be compared, taking into account differences in the research areas. The application of EPM using the NDVI is being carried out for the first time in the Kolubara MB influence zone. Hence, the studied area presents an interesting subject for further, more detailed investigation.

The results obtained indicate that the observed area has been undergoing erosion during the analyzed time period, primarily due to shifts in land use. Dominant anthropogenic activities such as mining, industrialization, and agriculture have contributed to this erosion. Conversely, deliberate exploitation planning and efforts to ensure ecosystem sustainability through appropriate protective measures have aided in maintaining stability. Therefore, future expansion of open-pit mines necessitates meticulous planning, integrating sustainable conservation measures. This includes prioritizing afforestation efforts in previously exploited mining areas, alongside implementing standard mitigation strategies.

To conduct an analysis of vegetation cover, researchers must examine both the visible and infrared parts of the sunlight spectrum. Chlorophyll, the pigment in plant leaves, absorbs visible light (0.4–0.7 μm) and utilizes it for the process of photosynthesis. Conversely, plant leaves reflect infrared light (0.7–1.1 μm). Therefore, very low NDVI values (0.1 and below) correspond to barren surfaces such as rock, sand, and snow. Moderate values (0.2–0.3) represent shrubs and grasslands, while high values (0.6–0.8) indicate temperate and tropical rainforests [81–83].

The NDVI, presented as a raster layer, was computed for the Kolubara MB's zone of influence utilizing LANDSAT 5 and LANDSAT 8 satellite images from 1992, 2002, 2011, and 2022. Through software processing and amalgamation of individual spectral channels, a comprehensive spatial analysis was conducted across various time periods with the aim of showing changes over a 10-year interval.

Utilizing the NDVI, even the slightest changes were detected in the time-varying images of the researched area. Negative and slightly positive values of the index were observed in the central parts of the research area beginning in 1992. Spatial arrangement of different NDVI values by year is shown in Figure 9.

The coefficients derived from applying the formula for calculating the NDVI index can be categorized based on types of vegetation, with this process relying on various factors such as the geographical latitude of the analyzed area, the altitude of locations where specific vegetation is present, and so forth.

After reviewing the available literature, it was determined that there are multiple methods for categorizing the NDVI. By using the results obtained and field observations, researchers establish threshold values. A widely used approach is to employ the scale of positive NDVI values recommended by NASE (Earth Observatory of NASA). This article focuses on analyzing changes in areas covered by forest vegetation. Spatial distribution of forest vegetation by year is shown in Figure 10.

After processing satellite images from each analyzed period, it was determined (as shown in Table 4) that in 1992, forested areas occupied 110.79 km^2 or 36.82%. By 2002, forests covered 88.03 km^2 or 29.26%, while in 2011, they occupied 99.21 km^2 or 32.98%. By 2022, they covered 97.62 km^2 or 32.45% of the total analyzed area. From the data, we can infer that the forested areas have not experienced significant changes over the observed time periods, indicating a positive approach toward their preservation and management.

The issue of recultivation of degraded areas in Serbia is legally defined by the Law on Mining and Geological Exploration [84]. Article 153 addresses recultivation, emphasizing that operators of mining activities must fully recultivate the land during and after completion of exploitation works, and no later than 1 year following the completion of mining activities. This recultivation must adhere to the technical and biological reclamation project specified in the main or supplementary mining project documents.

Establishing a national system for quality control inspection of land recultivation and reclamation sites, along with providing training on the management of restored lands, is imperative [85]. The process involves two key components: technical recultivation and biological recultivation and reclamation.

Development plans for exploitation in the research area are accompanied by reclamation efforts, suggesting that the environmental condition postexploitation will likely be more favorable than it currently stands. According to available internal reports, initial afforestation efforts in this area

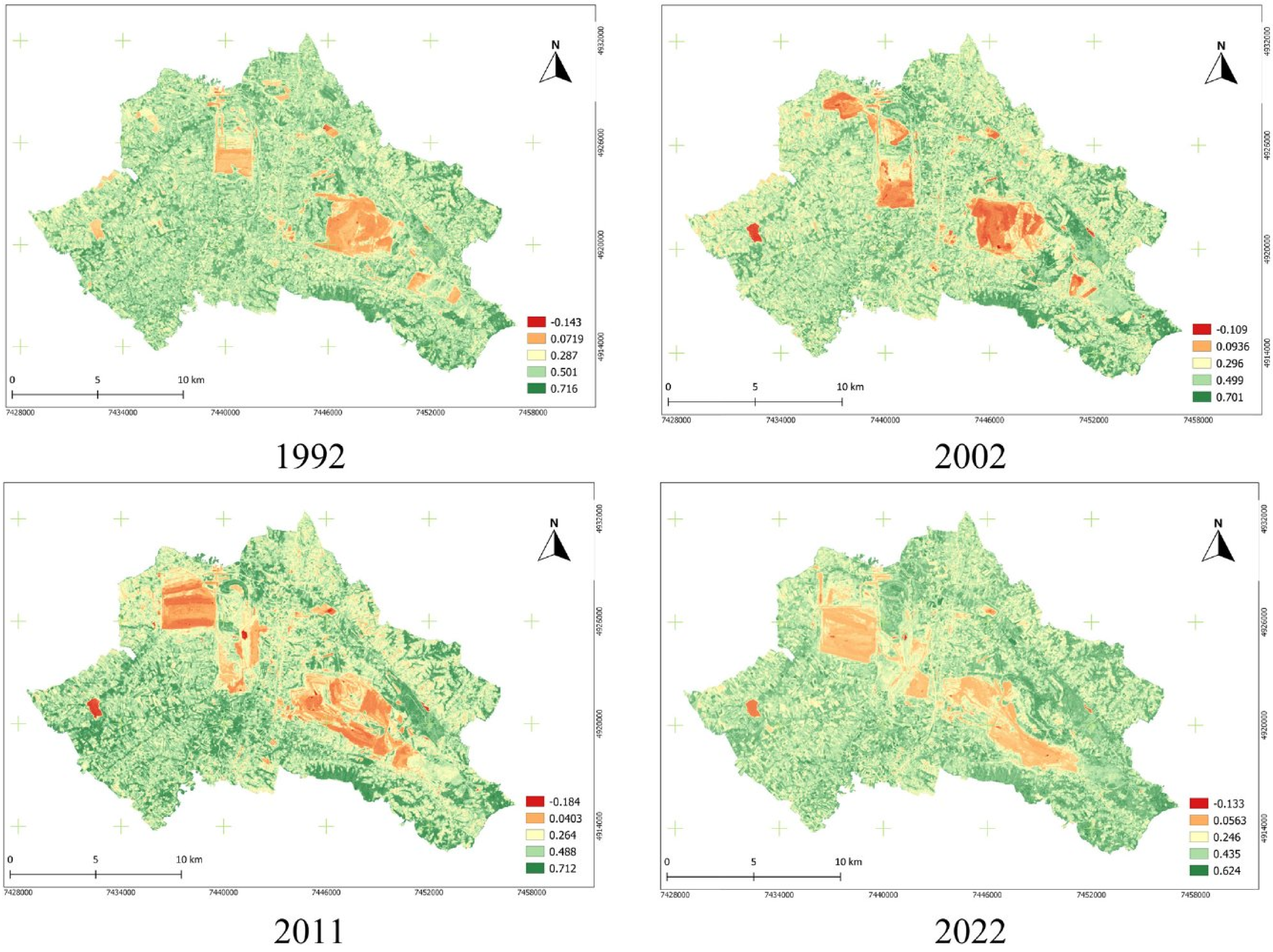


Figure 9: Spatial arrangement of different NDVI index values by year.

occurred between 1957 and 1959, followed by another initiative in 1969, which involved establishing acacia monocultures covering a total area of 110 hectares. Based on previous ecological, phytocenological, and pedological research on the deposol, the afforestation process began with specific contractor projects conducted by the Belgrade Institute of Forestry in 1977 [86].

Following a successful forest reclamation process, exceptional forest ecosystems have been established, encompassing multifunctional aquatic and grassland ecosystems. Over time, this contributes significantly to the natural adaptation and development of biodiversity, which is now richer compared to the pre-exploitation period. The lands managed by Kolubara MB and the forests within this economic unit are crucial for enhancing the environment and meeting various needs of the inhabitants of Lazarevac, including protection, recreation, education, production, and others.

During the mentioned period, the approach was such that no prior tests conducted on the quality and productivity of the substrate, which is now a mandatory requirement for any consideration and undertaking of work on the area's reclamation. Depending on the microecological conditions of the soil deposits, the selection of species for afforestation includes both conifers and deciduous trees. The selected species often have modest requirements in terms of plant assimilation and possess a well-developed root system. Black and white pine occupy the largest areas, whereas deciduous trees such as linden, alder, elm, and birch constitute a significantly smaller percentage of the total forested area.

Part of the planned activities in afforesting degraded areas involves establishing fast-growing plantations with the long-term goal of attaining adequate biomass. According to current estimates, this biomass could potentially replace up to 20% of fossil fuels (specifically lignite coal).

In addition to preserving the forest culture in this area, these efforts contribute to the restoration of degraded land and mitigate aeolian erosion on the ground, which has been stripped bare due to exploitation consequences. The forests of the economic unit MB Kolubara do not constitute a single entity but are composed of mutually distant units,

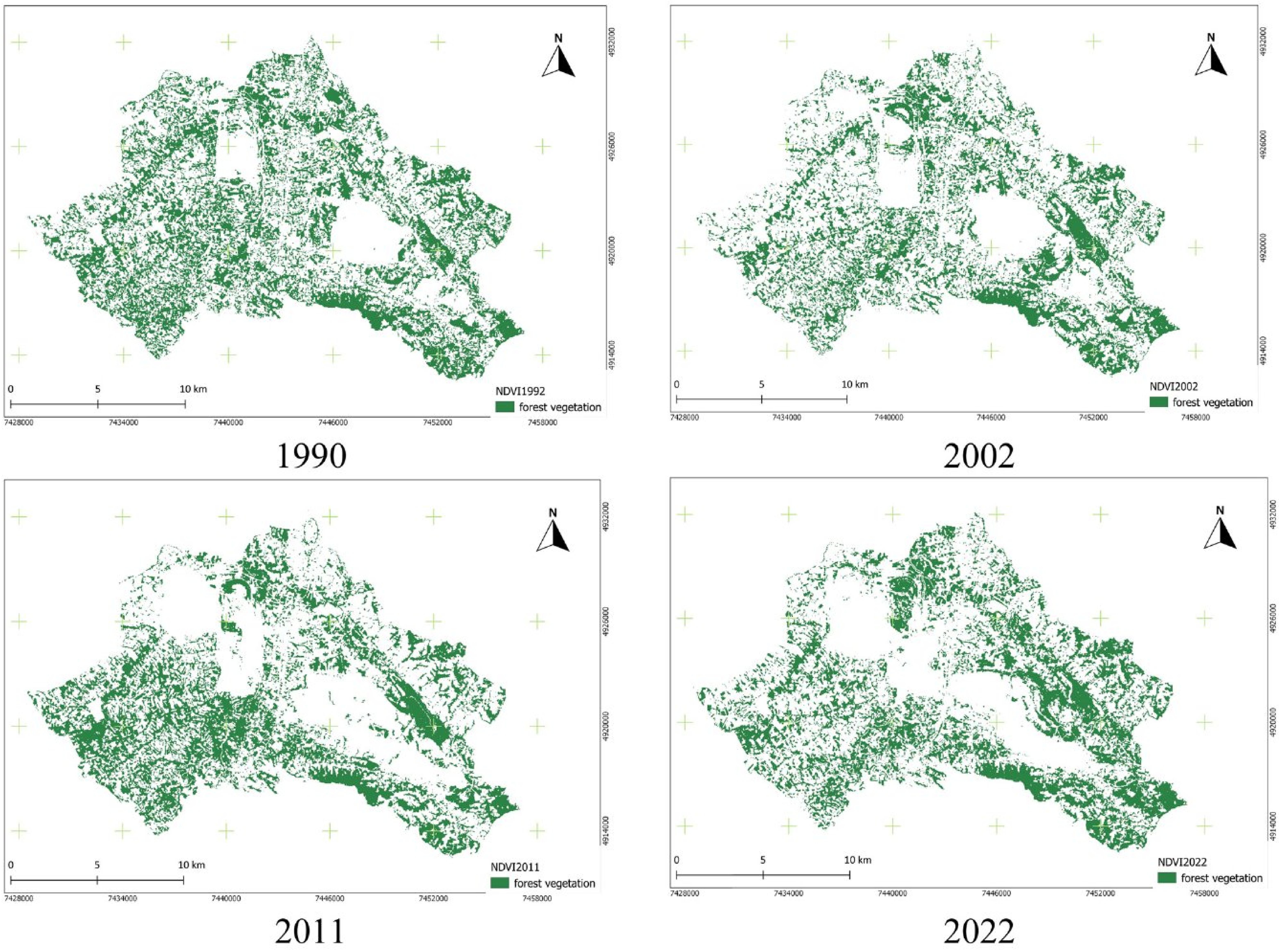

1990
2002
2011
2022

Figure 10: Spatial distribution of forest vegetation by year.

Table 4: Areas under forests in the zone of influence of Kolubara MB

Year	Areas under forests (km^2)	%
1992	110.79	36.82
2002	88.03	29.26
2011	99.21	32.98
2022	97.62	32.45

significantly hindering the preservation and management of these forests. Figure 11 depicts the state on the ground: the advancement of mining operations employing suitable mechanization, alongside traces of the terrain's previous vegetative cover.

The NDVI finds practical application as it can be computed annually for analysis. Unlike official statistical data, which only represent tall vegetation, the utilization of the NDVI provides insights into all types of vegetation cover (pastures, shrubby vegetation, meadows, etc.). It demonstrates excellent precision and is suitable for small spatial units, such as 25 m^2. This is particularly significant considering that in the Republic of Serbia, private forest areas are widespread and encompass almost half of the total forest area in the country. It is noteworthy that the average private farm in Serbia is about 5 hectares [87].

To mitigate the effects of erosive processes and enhance protection measures, improving the data inventory is essential, starting with ensuring its accuracy and precision. In addition, enhancing the spatial resolution of the layers is necessary to acquire more detailed information.

The information obtained from this research can serve as a valuable resource in the future for planning, decision-making, or informing stakeholders [88]. It is easy to identify areas that require special attention or prioritization in the near future to mitigate resulting processes and protect the population and employees.

In the researched area, it is crucial to conduct a detailed assessment of erosive processes using both remote detection methods and direct terrain surveys. This approach is essential because only through it can

Figure 11: Presentation on the progress of mining operations in the investigated terrain (Source: https://www.eps.rs/lat/kolubara/Stranice/Baner2-FOTOGRAFIJE/galerija.aspx? folder = Galerija%2fGalerija, downloaded on May 15, 2024).

protection measures be specified and long-term soil loss prevented.

It is necessary to conduct additional research to validate the obtained results. For this purpose, it would be beneficial to perform precise LIDAR measurements.

Measures such as afforestation, precise land use definition, and timely informing of stakeholders and the local population about terrain dangers would significantly reduce the consequences of erosive processes.

Numerous possibilities and examples exist for efficiently utilizing reclaimed areas of lignite mines worldwide [89–93].

The limitations of this study primarily concern the study area, specifically the dynamic nature of surface mines whose spatial dimensions change annually. Not selectively disposal of overburden creates tailings landfills that can render layers biologically inactive over time. Over time, clay-sandy soils form on the surface, originating from deeper layers before lignite coal exploitation, resulting in surface washing and the onset of gully erosion. After a period of time, these areas may be re-excavated, where former landfills turn into open pits, thereby postponing the reclamation process until mining activities cease. Therefore, future research results should consider these real situations that occur in such areas. Many years can pass between the period of the former landfill and the reactivation of the surface mine. Often, nature itself begins to regenerate, fostering meadow and forest plant species whose root systems aid in controlling erosive processes.

4 Conclusion

Soil, a natural resource, is formed under the influence of both biotic and abiotic factors. Human activities significantly accelerate changes compared to previous periods. Erosion processes stand out as the most significant factor in soil degradation, leading to a series of negative consequences. Over time, numerous erosion assessment methods have been developed to accurately gauge erosion intensity and propose degradation mitigation measures. GIS plays an invaluable role in this regard, facilitating the analysis and display of crucial spatial data. The EPM is applicable to surfaces of varying sizes, offering the advantage of not requiring a large number of input parameters.

By establishing an integrated geospatial database system, it enables us to promptly access all the necessary information for long-term environmental management. With this approach in the Kolubara MB, monitoring the reclamation and rehabilitation of mining spatial entities becomes more accessible.

To this day, remote sensing finds wide application in agriculture and forestry, encompassing tasks such as monitoring crop development, tracking seasonal changes, analyzing vegetation status, and assessing phenomena such as floods, forest fires, as well as air and water pollution [94,30].

The utilization of remote sensing techniques for studying vegetation cover holds significant importance, particularly for comprehensive and intricate analysis and data collection. A meticulous approach is vital to mitigate improper land use and reduce harmful anthropogenic impacts. This study entails the examination of vegetation status and alterations in forested regions through the utilization of Landsat 5 and Landsat 8 imagery. Within forestry, GISs find extensive application for planning, management, and enhancing the efficiency of felling and planting operations. It is necessary to conduct more detailed field research and verify the results obtained from this study.

Revitalization and recultivation processes are currently underway in areas where mining operations have concluded. Recultivation primarily involves afforestation, with a smaller portion of the surface allocated for agricultural crops. Commonly employed species for afforestation include black and white pine, acacia, poplar, oak, maple, linden, birch, among others. The attained outcomes are deemed satisfactory, although there exists potential for further enhancement in this domain. Obstructive factors frequently entail unresolved property-legal disputes and the reoccurrence of portions of the recultivated space being subjected to various forms of surface exploitation.

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