Remote Sensing and Nuclear Techniques for Soil Erosion Research in Forest Areas: Case Study of the Crveni Potok Catchment

Soil erosion is a major environmental issue causing both on-site land degradation and off-site impacts such as sediment deposition in the watercourses. Although basically a natural process driven by climate change, soil characteristics, and topography, it can be accelerated by improper land management (Kosmas et al., 1996; Poesen 2018; Rodrigo-Comino et al., 2020; Rodrigues et al., 2021). Accelerated soil erosion and associated land degradation represent a threat not only to environmental ecosystem functions but also to socio-economic development at regional and global scales.

Undisturbed forests are generally characterized by low susceptibility to erosion. The management practices such as timber harvesting result in a decrease in evapotranspiration, increased subsurface flow, and soil compaction, increasing soil erosion and impacting forest ecosystem functioning (Yoho 1980; Romeo et al., 2020). Forest degradation by soil erosion can further affect forest services by reducing water availability, nutrients, and organic matter (FAO (Food and Agriculture Organization of the United Nations) 2011). The forest-related operation may particularly trigger the initialization of gully erosion, an important land degradation process causing on-site and off-site environmental effects such as sedimentation of eroded soils down the catchment area and consequent siltation of water bodies. Notwithstanding the adverse impacts of gully erosion on forest services, the research addressing gullies on forest land is still limited (Strunk 2003; James et al., 2007; Parkner et al., 2007).

The methods for identifying areas susceptible to soil erosion based on land use, soil quality, topography, and other factors developed in recent decades have shown acceptable results (Alewell et al., 2019; Dimotta 2019). A wide variety of methods including physical, empirical, statistical, and process-based models, have been used by many researchers to predict soil erosion worldwide (Dimotta 2019). However, some of these methods require high-density sampling, which is sometimes not feasible due to the inaccessibility of some areas and limited resources. The conception and development of remote sensing techniques have contributed to significant improvements in analyzing forest areas' conditions, by providing accurate 3D spatial data relating to both the forest stands and characteristics of the underlying terrain (Andersen et al., 2006; Gao et al., 2020). As a cost-effective approach to survey large and inaccessible areas, remote sensing has also found its application in soil erosion studies, by detecting areas at the risk of extensive soil erosion (Xu H. et al., 2019), their mapping (Arabameri et al., 2019) and linking to the controlling factors (Garosi et al., 2018). One of the typical remote sensing products is the digital elevation model (DEM), used for geometric corrections of remotely sensed data and terrain modeling, and as such, essential input in soil erosion research and soil erosion modeling. Common remote sensing methods for obtaining DEM surfaces are satellite interferometry, photogrammetry, and light detection and ranging (LiDAR). Those models represent the Earth's surface that contains height points of terrain, vegetation, and manmade objects. For soil erosion research, especially in the forest areas, models that are suitable for extracting terrain surface and representing a bare Earth are of great importance. The quality of the DEM directly impacts secondary products, including slope, slope length, and slope steepness, which reliability is vital for soil erosion estimations (Romshoo et al., 2021). Because topography is one of the most critical variables in soil erosion, DEMs with high spatial resolution and precision are essential (Garosi et al., 2018). High-resolution DEMs are particularly useful for smaller areas that need to be analyzed in more detail.

The concerns for problems of accelerated soil erosion and its associated impacts on forest ecosystems generated the need for reliable quantitative data on the extent of soil erosion for establishing effective soil conservation and forest management. Traditional monitoring for obtaining erosion rates, particularly erosion plots, faces numerous problems in terms of costs and representativeness of the results. The nuclear techniques, i.e., the use of fallout radionuclides (FRNs) for soil erosion assessment, possess some advantages as compared to traditional methods, such as cost-effectiveness and the possibility to derive information on soil erosion rates at a sampling retrospectively based on a single site visit (Walling et al., 2006; Mabit et al., 2008; Mabit et al., 2014). Cesium-137 is by far the most widely used radionuclide in soil erosion and sedimentation research due to its high affinity for fine soil particles, its relatively long half-life, and its relative ease of measurement (Ritchie and Mc Henry 1990; Walling and Quine 1993). Cesium-137 is an artificial radionuclide (fission product) with a half-life of 30.2 years released in the atmosphere after nuclear tests and accidental events at nuclear facilities. Most 137Cs is retained in the organic layer in forest soils, and downward migration and leaching of 137Cs in the forest floor are very slow (Rafferty et al., 2000). Soil erosion processes could be considered responsible for any subsequent redistribution of 137Cs within the landscape, making it an effective tracer of erosion and sedimentation processes. Over the years, many empirical and theoretical models have been developed for cultivated and uncultivated lands to derive estimates of rates of soil loss and soil redistribution from measurements of the increase or decrease in the soil 137Cs inventory, relative to a local reference inventory, such as models developed by Walling et al., 2006 - Proportional Model, Mass Balance Model I, II and III, Profile Distribution Model and Diffusion and Migration Model, by Arata et al. (2016a), Arata et al. (2016b) - Modelling Deposition and Erosion Rates with RadioNuclides (MODERN), by Soto and Navas (2004), Soto and Navas (2008), etc.

The integration of remote sensing and soil erosion models has proven to be an effective tool for mapping erosion-prone areas for the development of sustainable conservation plans (Prasannakumar et al., 2011; El Jazouli et al., 2017; Almasalmeh et al., 2022). However, to the authors' best knowledge, this is the first study to apply the approach combining remote sensing and nuclear techniques in soil erosion research so far. The main objectives of this study were to: 1) to identify the erosion-prone areas using remote sensing in Crveni potok catchment; 2) to evaluate and compare the efficiency of different remote sensing methods, instruments, and software for analyses of morphometric and morphologic features of gullies identified in the investigated area; 3) to quantify the soil erosion rates using nuclear techniques and 4) to recommend site-specific forest management practices measures for reducing erosion and protecting the entire catchment area, including the forest areas and the village of Malča which is directly endangered by torrential floods and suspended sediment load.

2 Study Area

The study area covers the Crveni potok River Basin, located in Eastern Serbia, in the border area of the mountainous system of Carpatho-Balkanides, which spreads through several countries, including neighboring Bulgaria and Romania (Figure 1). The Crveni potok is the biggest tributary of the Malčanska River, which belongs to the Nišava River system and the Black Sea drainage basin. The Crveni potok River Basin is primarily hilly, covers about 8 km2, and is elongated in the meridian direction. The basin altitude ranges from 284 m at the confluence of the Crveni potok River and the Malčanska River, to the 729 m at the northern watershed.

Figure 1

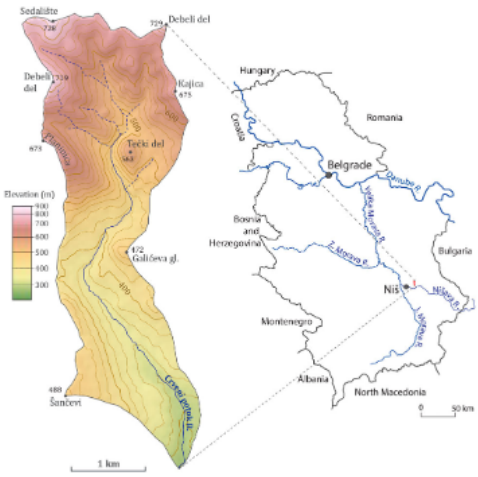

FIGURE 1. The Crveni potok River Basin and its geographical location in Serbia.

The main geographical factors of soil erosion in the Crveni potok Basin are physical characteristics of the soil, relatively large slope of the terrain, intensive rainfalls in late spring and late autumn, physical characteristics of the parent material, and vegetation. The complex geological structure of the river basin generates a variety of geomorphological forms, including the surface erosion ones. Soils in the Crveni potok River Basin result from several pedogenetic factors, but it seems that the most important is the geological composition in this small area (Group of Authors 1979). Sandstone, conglomerate, and siltstone are type of parent material that is susceptible to mechanical disintegration, well-drained, and thus water erosion-prone. On the other hand, small particles in the parent material make the soil more clayey and less prone to erosion.

The northern areas of the basin are covered by haplic cambisol (eutric) formed on red sandstone (Figure 2). This soil is loamy, well-drained, medium-deep to deep, and erosion-prone. Limestone areas are characterized by mollic leptosol formed on limestone, which is loamy and clayey, moderately drained, shallow or medium-deep, less erosion-prone compared to soils formed on red sandstone. Southern parts of the basin are covered mostly by different types of vertisols on lacustrine deposits, poorly drained, shallow to medium-deep. Clay particles reduce soil erodibility. The southwestern part of the basin is covered by leptic calcisol on marl, which is clayey and shallow (Nikodijević 1979). At the furthermost downstream sector, along the Crveni potok River, there is a small area covered by recent haplic fluvisol which consists of gravel, sand, loam, and clay, of shallow depth. Steeper slopes cause water to move faster and increase soil erodibility. The most erosion-prone area of the Crveni potok River Basin, the northern part, is characterized by large slopes. Terrain slope values (based on DEM 30 m) are in general over 10°, often over 20°, and even over 25° (Figure 2). In the middle and downstream parts of the river basin, slope values are mostly under 10°.

Figure 2

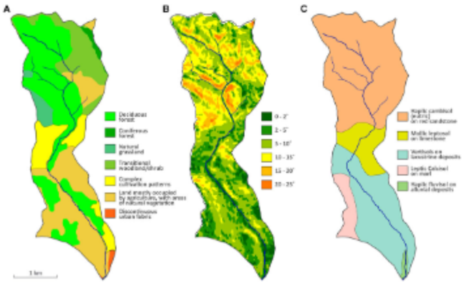

FIGURE 2. (A) Land Cover (B) slope and (C) soil map of the Crveni potok River Basin.

During the summer and early autumn, all flows in the Crveni potok River drainage basin dries up, but during short periods of intensive precipitations, flows are torrential and characterized by huge oscillations of the runoff and the suspended sediment load. Water soil erosion is mainly related to extreme meteorological and hydrological events during which the water flow and the transport of eroded material increase significantly during a relatively short period, while water soil erosion is weak in some years.

The Crveni potok River Basin is located in an area characterized by a temperate continental climate. Precipitation and temperature are the most important climate elements that influence soil erosion intensity. The predicted average annual precipitation is between 632 mm in the lower parts of the river basin and 861 mm in the highest parts of the river basin (Đokić 2015). The largest amount of precipitation occurs during June, May, and April, and the smallest amount during February, January, and August. According to Živković (2009), we can assume that the average annual temperature in the basin is between 8.8 and 10.9°C, depending on the altitude. Temperature rise in early spring often leads to fast snow cover melting and intense water soil erosion, especially if snow melting coincides with rainfalls.

The vegetation cover (Figure 2) includes forest, transitional woodland/shrub, natural grassland, and agricultural land (Copernicus 2018). The northern, higher areas of the basin, which are the focus of this study, are covered with forest and transitional woodland/shrub vegetation. Deciduous forest dominates, while planted coniferous forest (Scots pine - Pinus sylvestris) spread out in a small area at the basin foremost northeast. Different tree species are heavily mixed in a deciduous forest, with oak dominating. The edificatory species is the Balkan sessile oak (Quercus delechampii). Other noticeable species are hornbeam

(Carpinus), hawthorn (Crataegus), and hazel bush (Corylus). Full strength forest areas, which consist of old, tall, thick trees are very rare, as the result of unplanned deforestation. Weak vegetation of low ecological value is common in this area. Vegetation of shrubs is partially developed from the stumps. Transitional woodland/shrub consists of herbaceous vegetation and dispersed solitary adult trees. The sparse canopy of degraded Balkan sessile oak and the relatively large distance between the trees do not significantly reduce and slow down the erosion process. Also, young sessile oak trees have an axial root that provides poorer protection against soil erosion than the older trees with a laterally branched root system.

It is noticeable that many oak trees are affected by epiphytes and lichens (Evernia prunastri), which reduce the life potential of the trees by absorbing moisture from the air and reducing dissimilation and decreasing the wood volume growth. The tree bark is often moist, which favors the development of fungi and the spread of lichens. With pathogenic bacteria and fungi development, the vascular cambium of woody vegetation is exposed to necrosis and rapid decay. Significant forest areas are heavily damaged by freezing rain or the snow weight, especially peripheral parts covered by Scots pine forest. The pine trees have an elevated, sparse canopy and high branching, and grow in acidic edaphic soil conditions. However, such stands do not significantly prevent erosion of the solum, especially in inclined positions, due to the axial root system. A smaller area of deciduous forest covers the middle part of the basin, as well as downstream and lower altitude areas. In the middle and particularly downstream parts of the Crveni potok River Basin, there are significant areas used for agricultural production, mainly wheat, corn, clover, sunflower, orchards, and vineyards. Agricultural production is extensive and implies small fields, modest labor inputs, farm mechanization, and fertilizers. Also, agricultural production is constantly declining caused by the depopulation of rural areas. Many fields are not cultivated for years and are completely abandoned.

The upstream area of the Crveni potok River Basin is characterized by intense surface water soil erosion, which is manifested primarily through gully erosion. Gully erosion represents the removal of the soil along drainage lines by surface water runoff. The gullies have formed a huge and dense network. The gully depth ranges from a few dozens of centimeters to several meters, occasionally up to 8 m, while the length is from a few meters to several hundred meters.

Materials and Methods- Digital Elevation Model

In this study, freely available DEMs with horizontal resolutions from 1 arc-second (30 m) (SRTM) to 12.5 m (ALOS PALSAR RT1) were used. Furthermore, terrain/surface models based on airborne laser scanning created by the Republic Geodetic Authority of Serbia (Republički geodetski zavod - RGZ) in 10 m grid were used, as well as a digital surface model in a 3 m grid created by Military Geographical Institute (Vojnogeografski institut - VGI) (Stanojević et al., 2022). The photogrammetric data acquisition of the second one is conducted by an ADS80 airborne sensor from Leica Geosystems that provides multiple stereo coverage. This system captures objects from different angles and allows a pairing of identical points of stereo pairs and applying Semi-Global Matching (SGM) principle developed by Hirschmüller (Hirschmuller 2008; Hirschmuller and Bucher 2010). Using this algorithm, multi-image matching resulted in a dense point cloud that was later used for deriving of Digital surface model (DSM) of a 3 m grid.

Even though VGI SGM DEM has a higher resolution than ALOS PALSAR for the watershed delineation of Crveni potok river, the ALOS PALSAR 12,5 m model was used for hydrological modeling. The drawback of VGI DSM for watershed delineation was the presence of artificial structures and vegetation canopy that led to errors in river networks, watershed boundaries, and drainage directions. The only way of using of DSMs for watershed delineation is with a previous thorough examination of barriers represented by linear vegetation, built-up structures, and river embankments and their elimination by flattening them (Đorđević et al., 2016). The next step of watershed extraction was making hydrologically correct DEM. It was obtained by removing pits from the model using the flooding approach. That way, all sinks were eliminated, thus creating conditions to compute flow directions.

Tools used for watershed extraction was TauDEM (Terrain Analysis Using Digital Elevation Models). Those open-source algorithms work as a plug-in for ArcGIS and QGIS. Despite other software packages being able to do watershed delineation, like ArcHydro, HEC-GeoHMS, and PCRaster, TauDEM was chosen because it offers the D-infinity method, which provides improved computation of flow directions and watershed delineation (Zhang and Chu 2015). The D-infinity method defines flow direction as an angle in radians toward the steepest downward slope, unlike the D8 method, which determines the flow direction in eight discrete horizontal angles toward one of the adjacent cells (Tarboton 1997).