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Effects of Erosion Control Works: Case Study—Grdelica Gorge, the South Morava River (Serbia)

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Abstract: The aim of this research was to analyse the changes in the soil erosion intensity caused by erosion control works (ECW) in Grdelica Gorge (The South Morava River) in the period between 1953 and 2016. For the purpose of quantifying the erosion intensity changes, the erosion potential model (EPM) was used to calculate the annual gross erosion (W), sediment transport (G), and erosion coefficient (Z) in the study area. As a result of the performed technical and biotechnical erosion control works, there was a general decreasing trend in the intensity of soil erosion processes in the last 63 years. The specific annual gross erosion in Grdelica Gorge was 1920.34 $m^3/km^{-2}/year^{-1}$ in 1953, while in 2016 it was 492.42 $m^3/km^{-2}/year^{-1}$. The specific sediment transport was 1421.05 $m^3/km^{-2}/year^{-1}$ in 1953 and 364.39 $m^3/km^{-2}/year^{-1}$ in 2016. Due to the changes in the intensity of erosion processes, the specific annual gross erosion in the study area decreased by 1427.92 $m^3/km^{-2}/year^{-1}$ and the specific sediment transport by 1056.66 $m^3/km^{-2}/year^{-1}$. The value of the erosion coefficient was reduced from Z = 0.84 in 1953 to Z = 0.32 in 2016. The results show that there is a significant correlation between the soil erosion intensity (erosion coefficient) and ECW (biotechnical works) performed in Grdelica Gorge. The permanent control of erosion processes in Grdelica Gorge is very important for torrential flood prevention and protection of two very important traffic routes (Belgrade-Skopje-Athens railway and motorway—Corridor X), as well as settlements, local roads, and other facilities in this area. Furthermore, these results are the basis for future water management projects, soil and environmental protection, spatial planning, agriculture, and other human activities.

Keywords: soil erosion; erosion potential model (EPM); erosion coefficient; erosion control works; the South Morava River; Serbia

1. Introduction

Soil erosion is one of the most significant forms of land degradation in the Republic of Serbia. It is present on the whole territory, with 86% of its area with some potential for soil erosion. The categories of severe soil erosion account for 35% of the territory of Serbia south from the Sava and the Danube Rivers [1–3]. The South Morava River Basin, but particularly Grdelica Gorge with the greatest number of torrential floods, is one of the areas most endangered by soil erosion and torrential floods in Serbia [4].

A large number of previous studies show that intensive rainfalls [5–10], topography [11–16], vegetation type [17–20], land use [21–25], and land management [26–31] are the main factors that determinate the rates of soil erosion. The studies of natural conditions in the South Morava River Basin (Grdelica Gorge) uniformly show that this area is predisposed to intensive soil erosion [2,32]. Furthermore, extreme forest exploitation and destruction in Grdelica Gorge have resulted in extremely intensive erosion processes and frequent striking torrential floods causing disastrous damage, including taking human lives.

In the mid-1950s, Grdelica Gorge belonged to the areas most endangered by erosion in Europe. Two major international routes (Belgrade-Skopje-Athens railway and motorway—Corridor X), situated in South Morava Valley, were often interrupted by torrential floods, which escalated after the Second World War when these interruptions lasted up to 15 days. The Law on Erosion and Torrent Control that was passed in 1954 [33] recognized Grdelica Gorge as an important erosive area, giving it an urgent priority for the performance of erosion control works. Corridor X is now one of the most important traffic routes running through Serbia. It has a great international importance, connecting Salzburg and Thessaloniki (total length of 2360 km). Its section through Serbia is 835 km long, and it runs for 26.6 km in Grdelica Gorge.

Grdelica Gorge is particularly important since there are 137 torrential streams, direct tributaries of the South Morava River, registered on the small area of 26.6 km in length [34]. The first erosion control works in Serbia started in Grdelica Gorge before the end of the 19th century, with the organized erosion control works being performed at the beginning of the 20th century and large-scale erosion control works (ECW) after the Second World War. By the end of the 1980s, numerous erosion control works had been performed in Serbia including the South Morava River Basin, which resulted in evident reduction of soil erosion intensity and stabilization of the flow regime in the river basins [9,17,27,28,35]. In this research, the performed ECW and their effects on the state of erosion were studied through a comparative analysis of the circumstances in 1953 and 2016 with the aim of upgrading the methods of soil erosion and torrential flood control. In this period, various erosion control works and protection measures, together with a significant scope of torrent control works, were performed in Grdelica Gorge.

Although the processes of erosion in Grdelica Gorge have shown a calming tendency over the past 40–50 years, there is still a great potential of erosion, as well as a danger of the erosion being intensified due to the unplanned and uncontrolled exploitation of forests and degradation of vegetation cover, inadequate land use, and the construction of roads and other structures. Soil protection against erosion requires implementation of various methods and structures of torrent control. Properly designed and performed erosion control works can decrease the intensity of soil erosion. In this respect, bioengineering and technical works have different effects. Biotechnical works (afforestation, grassing, and orchard establishment on terraces) are performed on watershed slopes. On the other hand, technical works can be longitudinal or transversal. Longitudinal works protect stream banks against erosion and sloughing, while transversal works prevent the erosion of torrent beds and retain the sediment (primarily the bedload) [17,34].

The main aim of this research was to determine spatial and temporal changes in the soil erosion intensity and determine the effects of erosion control works on the annual gross erosion, sediment transport, and spatial distribution of soil erosion in Grdelica Gorge. The results of the research confirmed the significance of the effects of erosion control works, land use and land cover changes (LULCC) on the gross erosion rate and the mitigation of the intensity of soil erosion and sediment transport. In addition to its direct significance for the study area, the study of the erosion intensity changes in the function of erosion control works also has a wider practical and theoretical significance, because it was performed in one of the most representative torrential flood areas in Serbia and Southeastern Europe.

2. Materials and Methods

2.1. Study Area

Grdelica Gorge is a part of the South Morava River, located in the southeastern part of Serbia (Figure 1). It covers an area of 430.44 km^2 (403.06 km^2 of which is under torrential watersheds).

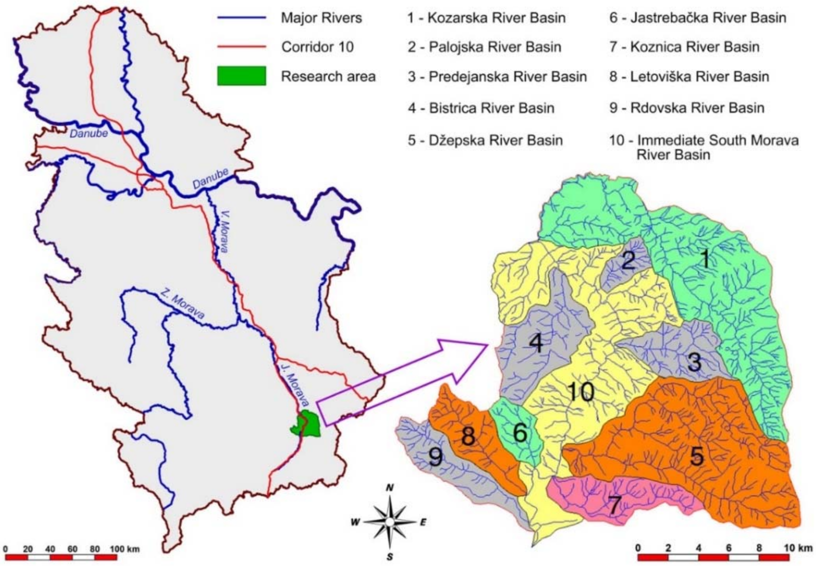
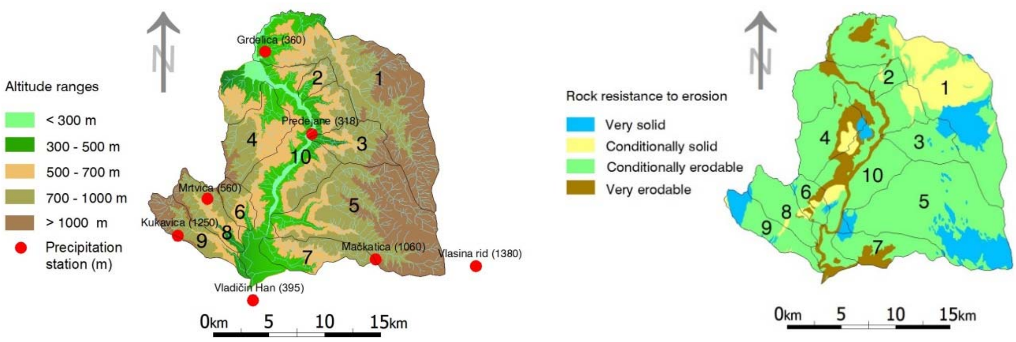


Figure 1. Study area: Grdelica Gorge in The South Morava River Basin, Serbia.

According to the topographic analysis, the highest point is at 1638 m (Mt. Čemernik) and the lowest at 253 m (Grdelica). The average elevation of Grdelica Gorge is 789.57 m, while the average slope amounts to 14.8° and the perimeter to 99.57 km. The analysis of hypsometric characteristics of Grdelica Gorge shows that 20.66% (88.94 km^2) is located between 250 and 500 m, 53.98% (232.35 km^2) between 500 and 1000 m and 25.36% (109.14 km^2) above 1000 m. Grdelica Gorge is characterrized by steep slopes which make it highly prone to intensive soil erosion processes. Slope angles up to 10° account for 32.17% of its territory and dominate in the South Morava Valley. The slope angles between 10 and 25° which cover 59.62% are very important for the high potential of soil erosion. Slope angles greater than 25° cover 8.21% of the total area (Figure 2a). Vertical dissection of relief, terrain slopes, and the number of torrential floods clearly show that the area is highly endangered by excessive soil erosion.



(**a**) (**b**)

Figure 2. (**a**) Hypsometric map with the position of the precipitation stations; (**b**) Map of the rock resistance to erosion.

The bedrock is predominantly composed of Palaeozoic crystalline shales, micashists, gneisses, orthogneisses, chloritoshists, quartz shales, etc. There are also granitoid and dacitic-andesitic rocks and tuffs, Paleogene and Neogene complexes, and quaternary sediments. The represented types of bedrock are grouped according to the resistance to erosion processes in 4 categories: very solid rocks (granite and dacite); conditionally solid rocks (gneiss, metamorphic granites, limestone with sandstone and slate); conditionally erodable rocks (sericite chloritoshists, Permian red sandstone, micashists and volcanic tuffs); very erodable rocks (conglomerates, sandstone, marl, gravel, sand, clay, eluvium, deluvium) [36]. According to the resistance to erosion processes (Figure 2b), the areas potentially endangered by erosion cover 90% of the area, with the conditionally solid rocks, very erodible rocks, and conditionally erodable rocks occupying 10.47%, 9.78%, and 71.85% of the surface area, respectively [37].

From the aspect of the development of erosion processes, the soils of the weaker structure are represented: dystric cambisol 83.04%, eutric cambisol 8.42%, ranker 1.95%, regosol 1.90%, calcocambisol 1.68%, vertisol 0.92%, and fluvisol 2.09% [38]. The high share of oak forests led to the formation of acid humus which together with the bedrock affected the stability of soil aggregates.

Analysing the annual rainfall amounts in Grdelica Gorge for the period 1961–2015, it can be concluded that the study area has a continental rainfall regime which is characterized by the maximum rainfall in spring and at the beginning of summer and the minimum rainfall in winter. The average annual rainfall in Grdelica Gorge for the period 1961–2015 amounted to 770.3 mm. Based on the rainfall data from 7 rain gauge stations (Table 1), the greatest quantity of precipitation falls in the warmer part of the year, i.e., in June (11.42% of the annual sum), May (11.16%) and April (9.25%), and the smallest in February (7.04%). The amount of rainfall in the growing period was 417.5 mm (54.20% of the annual rainfall). The average decrease in precipitation in the period from 1991 to 2015 compared to the period 1961–1990 in this area was 51.7 mm per year or 6.7%. There was a characteristic decrease in the rainfall in the last decade, which further affected the change in the precipitation pattern, its spatial distribution, intensity, seasonal distribution (especially during the growing period), etc.

Table 1. Precipitation stations in the study area.

No.	Precipitation Station	Coordinates		Elevation m a.s.l.
		X	Y	
1.	Predejane	7593085	4743847	318
2.	Grdelica	7588902	4751199	360
3.	Vladičin Han	7587822	4728966	395
4.	Mrtvica	7583614	4738172	560
5.	Mačkatica	7598693	4732815	1060
6.	Kukavica	7580930	4734437	1250
7.	Vlasina Rid	7607783	4732042	1380

There is a series of South Morava data on the average discharge that present the properties of the water regime and the water level of the discharge area. In the South Morava River Basin, the frequency Qmax > Qmaxmean is most prominent at the end of spring—in the first half of June, then at the beginning of summer—the last decade of June and at the beginning of July [39]. The mean long-term discharge of the South Morava River (1946–2006) was 24.7 m^3s^{-1} at Grdelica and 18.8 m^3s^{-1} near Vladičin Han [32]. In this sector, the South Morava River has 137 torrential tributaries of different types and categories, from very small watershed areas below 1 km^2 (gullies) to torrential rivers with the watershed area over 90 km^2. The density of the hydrographic network is 0.64 $km \cdot km^{-2}$. The immediate basin of the South Morava River has a large number of torrential tributaries (torrential streams, wadies, ravines, and gullies) concentrated in intercatchments from several tens of hectares to 3.6 km^2 in size. The average fall of torrential tributaries ranges from 6 to 38%.

2.2. Methodology

It is known that many empirical equations for the intensity of soil erosion and sediment transport cannot be easily applied in different countries, despite many efforts to make truly 'universal' models. Inadequate application of globally recognized methods is most often characterized by insufficiently precise monitoring of all the parameters included in them or by the complete lack of the parameters. Therefore a lot of countries or regions have developed their own research methodology, i.e., specialized models that incorporate data of available parameter monitoring and thus reflect the state and intensity of soil erosion. Although they have received only limited attention in the international literature, some of the methods have received scientific verification at the regional level. They are based on the scoring system and are known in the literature as scoring models [40].

One of the most widely accepted and applied empirical models in Serbia and the Balkan region, East and Central Europe, is the Erosion Potential Model (EPM), also known as Gavrilović method [41]. Numerous studies across Europe and the world have confirmed the scientific verification of the EPM model and its modifications [42]. Taking into account 11 methods and models, De Vente and Poesen [40], concluded that the EPM model was most quantitative of all the regional methods and models they analysed. Studies of different authors in the alpine basins [43–45], on the territory of the former Yugoslavia [46–52], and lately in Serbia [9,28,38] and Greece [53–55] have shown that the results obtained by this model are very reliable and acceptable in professional and scientific practice.

The Erosion Potential Model (EPM), which is used to evaluate soil erosion and investigate its spatial distribution, is calculated by Equation (1):

$$\mathrm{W} = \mathrm{T}\cdot\mathrm{H}\cdot\pi\cdot\sqrt{\mathrm{Z}^3}\cdot\mathrm{F} \tag{1}$$

where, W is the total annual erosion (m^3/year), T is the temperature coefficient, H is the mean annual precipitation (mm), Z is the erosion coefficient, and F is the basin area (km^2)

The temperature coefficient (T) is calculated by Equation (2):

$$\mathrm{T} = \sqrt{\frac{\mathrm{t}}{10} + 0.1} \tag{2}$$

The soil erosion coefficient (Z) can be calculated from the following Equation (3):

$$\mathrm{Z} = \mathrm{Y}\cdot\mathrm{X}\cdot(\varphi + \sqrt{\mathrm{I}_{av}}) \tag{3}$$

where, X is the soil protection coefficient, Y is the coefficient of soil resistance, φ is the erosion and stream network development coefficient, I is the average slope of the watershed (%). The values of coeficient X, Y, and φ are shown in the Table 2.

The erosion coefficient (Z) ranges from 0.01 (areas not affected) to 1.5 (areas with excessive erosion) (Table 3). Y is the soil erodibility coefficient, which depends on the geology and soil. X is the soil protection coefficient which reflects the type of land use (crop or natural vegetation). φ is erosion and stream network developed coefficient that includes type and extent of erosion (Table 2).

Table 2. Descriptive variables used in the erosion coefficient (Z) by EPM model.

Coefficient of Soil Resistance	**Y**
Fine sediments and soils without erosion resistance	0.80–1.00
Sediments, moraines, clay and other rock with low resistance	0.60–0.80
Weak rock, schistose, stabilised	0.50–0.60
Rock with moderate erosion resistance	0.30–0.50
Hard rock, erosion resistant	0.10–0.30
Coefficient of Soil Protection	**X**
Areas without vegetation cover	0.08–1.00
Damaged pasture and cultivated land	0.06–0.80
Damaged forest and bushes, pasture	0.04–0.06
Coniferous forest with little grove, scarce bushes, bushy prairie	0.20–0.40
Thin forest with grove	0.05–0.20
Mixed and dense forest	0.05–0.20
Coefficient of Erosion and Stream Network Development	**φ**
Whole watershed affected by erosion	0.90–1.00
50–80% of watershed area affected by surface erosion and landslides	0.80–0.90
Erosion in rivers, gullies and alluvial deposits, karstic erosion	0.60–0.70
Erosion in waterways on 20–50% of the watershed area	0.30–0.50
Little erosion on watershed	0.10–0.20

Table 3. Classification of erosion coefficient (Z) and specific annual gross erosion (W_0).

Erosion Category	Erosion Intensity	Range of Z	Range of W_0 (m^3/km^2/Year)
I	Excessive erosion	1.01–1.50	>3000
II	Intensive erosion	0.71–1.00	1200–3000
III	Medium erosion	0.41–0.70	800–1200
IV	Weak erosion	0.21–0.40	400–800
V	Very weak erosion	0.01–0.20	100–400

Precipitation (P) data were obtained from 7 precipitation stations for the period between 1961 and 2015, and Temperature (T) data from 4 temperature stations for the period from 1961 to 2015 [56]. The coefficient of soil resistance (Y) was obtained on the basis of a 1:100,000 geological maps. The coefficient of soil protection (X) and the coefficient of the type and extent of erosion (φ) were obtained according to orthophotos and satellite imagery, CORINE Land Cover 2012 database and the field recognition of the state of erosion for 2016. The structure of surface areas was determined by applying homogeneous plots, within which productive and unproductive areas were differentiated (productive areas: forests, meadows and pastures, arable land, orchards, and unproductive areas: settlements and barren land). The method of processing the land use data was harmonized for both time periods. The morphometric attributes and slope were derived from a topographic map, scale 1:25,000 and a Digital Elevation Model (DEM) with a cell size of 25 m × 25 m.

Having calculated the total annual soil erosion rates, we calculated the sediment delivery ratio, which is needed for the actual sediment yield calculation. Gavrilovic [41] suggested the following equation for the determination of the sediment delivery ratio:

$$R_u = \frac{(O \cdot D)^{0.5}}{0.25 \cdot (L + 10)} \quad (4)$$

where O is perimeter of watershed (km), D is average diferences of elevation of the watershed (km) and L is length of the watershed (km).

Finally, the actual sediment transport (G) was calculated as:

$$G_{year} = W_{year} \cdot R_u \; (m^3/year) \tag{5}$$

Based on EPM methodology, the mapping procedure requires investigations and computations to determine and map the surfaces with the same quantitative erosion category. In this study, GIS was successfully integrated with the EPM model aiming to determine the surfaces with the same quantitative erosion category, but also to define the soil erosion coefficient (Z) for each erosion polygon. In order to quantify the erosion intensity changes, map overlapping of Grdelica Gorge was done with the soil erosion maps from 1953 and the recent state of erosion in 2016. Digitalization of these two maps showing the area affected by different categories of erosion enables us to determine these changes in the last 63 years. Data and model implementation, digitalization, and mapping were done in the Geomedia 6.0 Intergraf.

3. Results

3.1. Analisys of Perfomed Erosion Control Works (ECW) in the Study Area

3.1.1. Transverse Structures in Torrential Streams (Check dams, Sills, and Submerged Sills)

In the first phase of the erosion control works in Grdelica Gorge, technical structures were constructed in the beds of torrential streams: check dams and sills for sediment storage and bed regulation in the areas where watercourses and roads cross. The structures were made of stone masonry, and rustic dry stone masonry check dams were made in gullies. In the period after 1955, priority was given to the protection of settlements and the regulation of lower watercourses through settlements.

Transverse structures built in torrential stream channels generally have multiple effects. When considering the final effect of individual structures, all the positive effects (sediment retention, reduction in the riverbed fall, and stabilization) should be counterbalanced with the cost of such structures and their possible negative effects [35,57]. Of course, in some cases, these criteria are not applicable because the importance of the structures to be protected from torrential floods (roads, settlements, commercial buildings, etc.) outweighs the price of the dam to be built. This means that the importance of the structure that is protected by a dam or some other transverse structure should be introduced as another criterion.

3.1.2. Biological and Biotechnical Works

In the period from 1955 to 1966, anti-erosion agrotechnics was introduced into the agricultural production of the hilly-mountainous part of the area. The regular afforestation with dense pit planting was accompanied with the application of biotechnical works with the aim of preventing the rapid runoff down the slope and thus creates favourable conditions for the growth of seedlings and establishment of a favourable stand canopy. Afforestation was performed on bench terraces, contour ditches, and terraces (Figure 3 and Table 4). Gullies were restored using rustical dams, and sometimes wattling or sills in dry stone.

Biotechnical works included afforestation and grassing of barren land and establishment of orchards on terraced slopes (mild slopes). The species used for afforestation included Austrian pine, Scots pine, walnut, locust, chestnut, Turkish hazel, American ash etc. Grassing and pasture reclamation was carried out using a mixture of grass whose cover ensured the protection of slopes. In the early phases of bench terraces, planting was carried out in one or two rows, which resulted in very dense planting (even 4 seedlings per meter). This method of planting was dismissed because of the low survival rate and poor growth of seedlings and replaced with the one-row planting at a distance of 75 and 100 cm. Planting was carried out in pits. Live wattling was also successfully used (Krpejski potok).

(**a**) (**b**)

Figure 3. Contour ditches and afforestation of bare land: (**a**) 1953 [58]; (**b**) 2016 (photo: S. Braunović).

Biotechnical works were carried out on the slopes of the basin in order to check erosion or to reduce its intensity, to achieve a certain volume of plant production and finally to preserve and improve the environment. In other words, technical works carried out in the hydrographic network of watercourses can solve acute problems, while biological works permanently solve the problem of erosion on the slopes of a basin. The establishment of a vegetation cover creates unfavourable conditions for the development of erosion processes. The degree of the reduction in the erosion intensity depends on the type of vegetation, its density and age. The best protection against erosion is provided by a forest with a dense crown cover. Of course, this does not mean that the entire basin should be forested, only the parts where the high slope inclination does not allow the crop cultivation. Regarding agricultural crops, perennials are favoured on steeper slopes and row crops on the mildest slopes. The selection of crops and the method of planting or sowing were adapted to the conditions in the field with the tendency to ensure maximum soil protection, i.e., to reduce the erosion intensity to the limits of normal erosion. Finally, the establishment of the vegetation cover leads to the protection and improvement of the environment. Vegetation improves the quality of soil, water, and air, and thus helps create better living conditions for people and animals.

The technical works carried in 19 watersheds of torrential tributaries in Grdelica Gorge included: 11,282.6 m of wattling, 11,822 m of terraces, 68,000 m of bench terraces, 9500 m of horizontal walls and 5145 m^3 of check dams of dry laid masonry, 93.43 ha of orchards, and 35.4 ha of reclaimed pastures.

Table 4. Data on the works performed in the direct tributaries of the South Morava in the Grdelica Gorge region in the period from 1947 to 1977 [59,60].

Torrential Watershed	Regulations–Trenches			Transverse Structures			Biological Works	
	Length (km)	Ditch (m^3)	Wall (m^3)	Number of Structures	Ditch (m^3)	Wall (m^3)	Afforestation (ha)	Grassing (ha)
GrdelicaGorge 58 tributaries	5.96	70,405	37,389	1087	55,472	65,087	1041.2	1210.5

3.2. Land Use before and after ECW

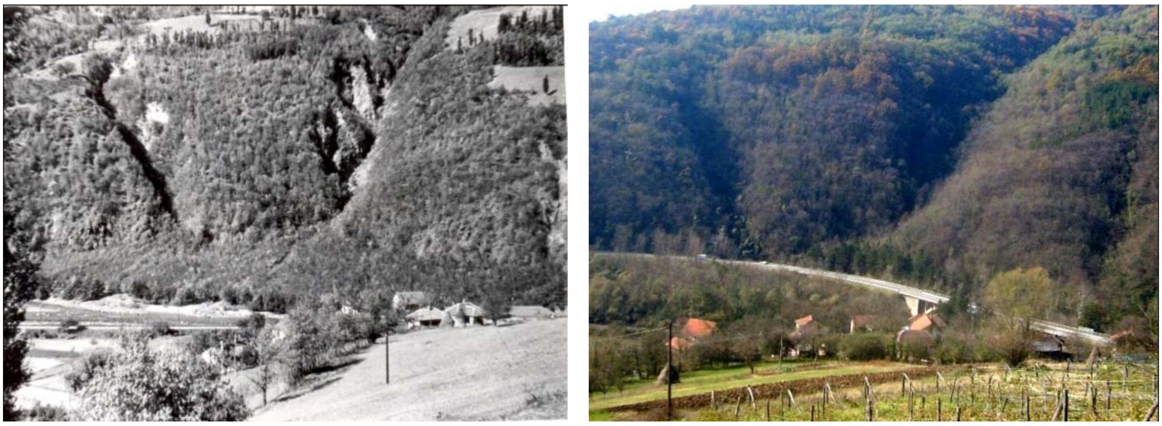
According to the data from 1953, productive areas occupied 75.27% and unproductive more than 24.73% of the total research area. Forests, whose protective role was reduced to a minimum, accounted for 33.19% and mainly included low leaf forage forests and coppice forage forests of oak and Turkey oak. Agricultural land accounted for 181.12 km^2 (42.0%), 82.5% of which was arable. Ploughland occupied 33.23% of the area, or 78% of the arable land.

A particular problem was their equal distribution in the valley of the South Morava and in the hilly mountainous region and the same method of cultivation being applied both on the steep and on the mild slopes. The smallest percentage of arable land was covered with orchards (6.28 km^2), i.e., 3.5% of arable or 1.5% of the total area. The barren land formed by deforestation in the zones of watersheds and by planting along slope lines or under the influence of natural characteristics accounted for as much as 22.4% of the area of Grdelica Gorge (Table 5, Figure 4a).

Table 5. Land use in Grdelica Gorge in 1953 [38] and 2016.

Year	1953		2016		Change	
Land Use	**Area km^2**	**%**	**Area km^2**	**%**	**Area km^2**	**%**
Forests	142.87	33.19	236.6	54.97	93.73	21.77
Meadows and pastures	31.81	7.39	107.73	25.02	75.92	17.64
Ploughlands	143.03	33.23	40.25	9.35	−102.78	−23.88
Orchards	6.28	1.46	1.96	0.46	−4.32	−1.00
Barren land	96.33	22.38	1.06	0.25	−95.27	−22.13
Settlements	10.12	2.35	42.84	9.95	32.72	7.60
Total	430.44	100	430.44	100	0	0

According to the map data from 2016, 55% of Grdelica Gorge area is forestland, 0.57% of which are degraded forests. Meadows and pastures account for 25% of the area, composed of small surface areas near settlements or abandoned weed-covered ploughlands. Ploughlands are less represented (9.35%) and they are located not only along the South Morava but also at higher altitudes, as part of houseyards. These areas are fragmented and scattered. Planting is mostly done along the contour and the ploughland on steep slopes arse abandoned. Thus, from the aspect of erosion, there is currently no danger. Orchards account for 1.96% of the area. The remaining parts of the area (10.2%) are unproductive areas: settlements (9.95%) and barren land which now occupy only 0.25% of the Grdelica Gorge area (Table 5, Figure 4b).



(**a**) (**b**)

Figure 4. Land use change of Zla Dolina: (**a**) 1953 [58]; (**b**) 2016 (photo: S. Braunović).

3.3. Spatial Distribution of Erosion Coefficient (Z), Specific Annual Gross Erosion (W) and Specific Sediment Transport (G) before and after the Conducted ECW

Based on the Erosion map of Grdelica Gorge made before the erosion control works were conducted (1953), it was found that there were erosion processes of all categories of destructiveness, from weak surface erosion on mild slopes to excessive surface and deep erosion on the terrains with expressed configuration. According to the value of the mean erosion coefficient Z_{mean} = 0.84, the Grdelica Gorge area was endangered in the study period (1953) by intensive erosion processes (Table 6, Figure 5a).

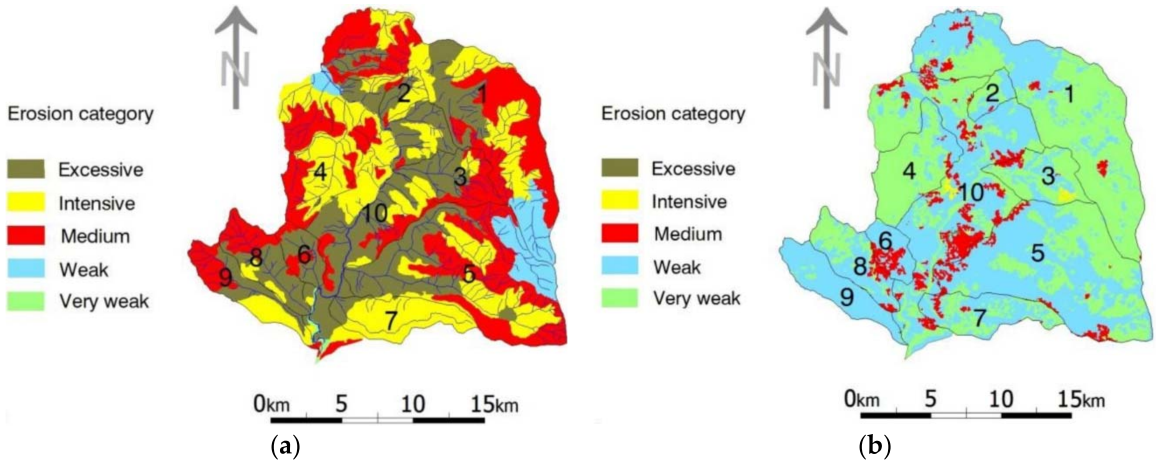


Figure 5. Soil erosion maps: (**a**) in 1953 [38]; (**b**) in 2016 year.

The highest erosion coefficients were registered for the basins of the Jastrebačka River (Z_{mean} = 1.06), the Palojska River (Z_{mean} = 1.02), the Letoviška River, and parts of the immediate basin of the South Morava with a value of Z_{mean} = 0.96.

According to 2016 Erosion map (Figure 5b), 93.64% of the Grdelica Gorge territory was affected by soil erosion of different intensity (403.06 km^2). The processes of excessive and intensive erosion (categories I and II) are present in the immediate South Morava Basin. The most frequent are the processes of weak, very weak, and medium erosion (categories IV, V, and III). The values of the erosion coefficient range from Z_{mean} = 0.21 in the watershed of the Bistrička River to Z_{mean} = 0.42 in the immediate South Morava Basin (Table 6).

Table 6. Surface areas according to the intensity of soil erosion in 1953 [38] and 2016.

1953								
No.	**River Basin**	**Area (km^2)**	**Erosion Category**					**Zmean**
			I	**II**	**III**	**IV**	**V**	
			Excessive Erosion	**Intensive Erosion**	**Medium Erosion**	**Weak Erosion**	**Very Weak Erosion**	
1	Kozarska River	101.00	19.63	26.31	45.43	0.00	9.63	0.72
2	Palojska River	6.87	3.12	3.43	0.32	0.00	0.00	1.02
3	Predejanska River	19.58	9.55	2.62	7.41	0.00	0.00	0.93
4	Bistrička River	29.18	0.18	18.53	10.47	0.00	0.00	0.74
5	Džepska River	91.88	25.00	21.44	35.01	10.43	0.00	0.75
6	Jastrebačka River	9.84	7.18	0.00	2.66	0.00	0.00	1.06
7	Koznica River	21.57	2.64	18.62	0.31	0.00	0.00	0.89
8	Letoviška River	19.60	10.52	1.95	7.13	0.00	0.00	0.96
9	Rdovska River	19.36	7.19	5.59	6.58	0.00	0.00	0.90
10	Immediate South Morava Basin	111.56	52.18	34.54	20.68	2.68	1.91	0.96
Total	**km^2**	430.44	137.19	133.03	135.56	13.11	11.54	0.84
	%	100.00	31.9	30.9	31.5	3.0	3.7	

Table 6. *Cont.*

2016								
No	River Basin	Area (km^2)	Erosion Category					Zmean
			I	II	III	IV	V	
			Excessive Erosion	Intensive Erosion	Medium Erosion	Weak Erosion	Very Weak Erosion	
1	Kozarska River	101.00		3.05	9.75	38.76	45.44	0.27
2	Palojska River	6.87			0.58	2.80	2.51	0.29
3	Predejanska River	19.58		2.13	1.36	8.53	6.56	0.26
4	Bistrička River	29.18			0.41	14.08	13.27	0.21
5	Džepska River	91.88			17.53	56.07	17.85	0.33
6	Jastrebačka River	9.84			3.83	5.48	0.11	0.42
7	Koznica River	21.57			4.88	9.43	5.37	0.31
8	Letoviška River	19.60			7.55	7.54	3.90	0.43
9	Rdovska River	19.36			1.91	12.90	4.05	0.30
10	Immediate South Morava Basin	111.56	1.68	11.86	22.8	54.8	7.4	0.42
Total	**km^2**	430.44	1.68	17.04	70.6	210.39	106.46	0.32
	%	100.00	0.42	4.23	17.52	52.20	26.41	

According to the values of the mean erosion coefficient (Z_{mean} = 0.32) calculated for Grdelica Gorge in 2016, the processes of weak erosion (category IV) remained. These changes were primarily caused by the 'elimination' of the areas endangered by excessive erosion and their redistribution into the lower categories. The specific annual gross erosion in Grdelica Gorge was 1,920.34 $m^3/km^{-2}/year^{-1}$ in 1953, while in 2016 it amounted to 492.42 $m^3/km^{-2}/year^{-1}$. The specific sediment transport was 1,421.05 $m^3/km^{-2}/year^{-1}$ in 1953, while it amounted to 364.39 $m^3/km^{-2}/year^{-1}$ in 2016.

4. Discussion

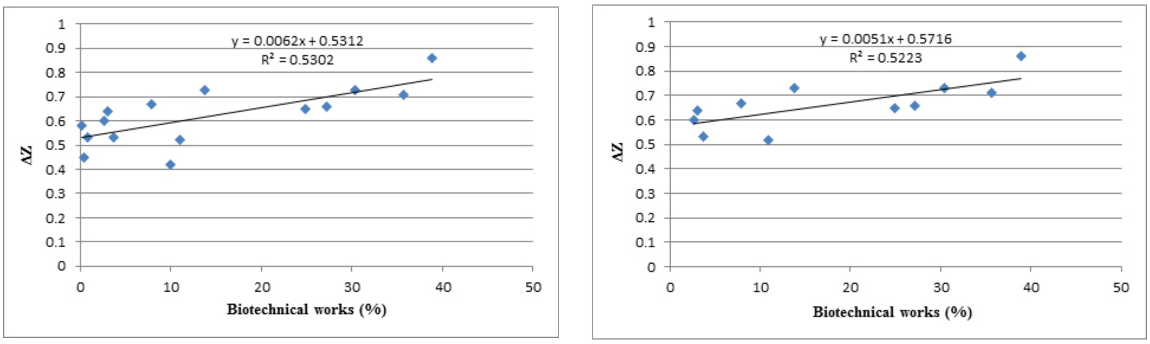
As a result of the technical and biotechnical erosion control works performed in the torrential watershed s of Grdelica Gorge, there has been a general tendency of a decrease in the intensity of soil erosion processes, gross erosion, and sediment transport in the last 63 years (1953–2016). Biotechnical control works have changed the land use in Grdelica Gorge which has had an impact on the distribution and intensity of erosion processes. Prior to the implementation of the erosion control design, forests accounted for 33.19% of the basin, grass (pastures and meadows) covered 7.39%, ploughland 33.23%, orchards 1.46%, and barren land 22.38% of the study area. At the end of 2016, more than half of the study area was under forests (54.97%), 25.02% was grassed, while ploughland, orchards, and barren land covered 9.35%, 0.46%, and 0.25% of the basin area, respectively.

In Serbia, the measured data on the sediment transport in torrential watercourses is insufficient (except in some scientific-research studies). The Republic Hydrometeorological Service of Serbia performs measurements of suspended sediment concentration and sediment transport only on large alluvial watercourses. There is a similar situation in the world because the performance of these measurements entails great difficulties.

Land use changes caused a decrease in the intensity of soil erosion processes in the study area. The differences were determined by comparing the state of erosion processes in two different time periods: in the early 1950s and in 2016. The specific annual gross erosion in Grdelica Gorge was 1,920.34 $m^3/km^{-2}/year^{-1}$ in 1953, while it was 492.42 $m^3/km^{-2}/year^{-1}$ in 2016. Besides, the specific sediment transport was 1,421.05 $m^3/km^{-2}/year^{-1}$ in 1953 compared to 2016 when it was 364.39 $m^3/km^{-2}/year^{-1}$. In other words, due to the changes in the intensity of erosion processes, the specific annual gross erosion in the study area decreased by 1,427.92 $m^3/km^{-2}/year^{-1}$ and the specific sediment transport by 1,056.66 $m^3/km^{-2}/year^{-1}$. The value of the erosion coefficient was reduced from Z = 0.84 in 1953 to Z = 0.32 in 2016. The data gathered while mapping the soil erosion intensity and presented on the Erosion map for 2016 (Figure 5) reveal a decreasing tendency for soil erosion categories I, II, and III (excessive, intensive, and medium erosion) and an increasing one for categories IV and V (weak and very weak). Namely, the category of excessive erosion affected 31.9% of Grdelica Gorge in 1953 and only 0.42% in 2016. Intensive erosion was reduced from 30.9% to only 4.23%. It is very important to note that the performed erosion control works have reduced the area affected by excessive and intensive erosion processes.

Forest cover plays a very important role in the reduction of soil erosion intensity with multiple favourable effects [19,61,62]. Therefore, it has been widely considered as the most effective biotechnical measure [9,63]. The results point to a significant correlation coefficient r (Pearson) between the soil erosion intensity (erosion coefficient) and the erosion control works (biotechnical works, mainly afforestation and grassing) performed in Grdelica Gorge. As can be seen from the obtained regression dependences, the erosion intensities have decreased (which is manifested by the reduction in the value of the erosion coefficient—Z for the amount of ΔZ) with an increase in the percentage of the afforested area of the river basin, i.e, the performed biological works.

Statistical analysis was carried out on the basis of the results of the research that included the first 9 basins (Table 7) and 6 smaller basins (they are all direct tributaries of the South Morava) from the large area of the 'Immediate River Basin' where extensive biotechnical works, above all afforestation, were performed (basins 10–15, Table 7). We studied the dependence of the decrease in the erosion intensity measured over the value of the reduced erosion coefficient—ΔZ on the percentage of the conducted biological works in relation to the total surface area of the basin. The first analysis included all 15 basins, while the second one included the basins with an area of less than 20 km^2 (Figure 6).



(**a**) (**b**)

Figure 6. Pearson's correlation coefficient between the soil erosion intensity (erosion coefficient) and the erosion control works performed for: (**a**) all 15 watersheds; (**b**) for the watersheds with the area smaller than 20 km^2.

In both cases, a significant dependence of the decreasing intensity of soil erosion and the percentage of biological works carried out (related to the surface area of the basin) was confirmed. For all basins, there is a Pearson's correlation coefficient r = 0.728, while in the case of the basins with area smaller than 20.0 km^2, the coefficient of correlation was r = 0.755. This result is unsurprising if we know that biological works directly change the way land is used, which consequently reduces the intensity of erosion. This is especially true for afforestation. It is well-known that forests are the type of vegetation that provides the best protection against soil erosion. When it comes to smaller basins in mountainous areas, the impact of the percentage of biological works on the decrease in the intensity of erosion is even greater because afforestation is the predominant form of biological work performed on these terrains and it gives the best results in the control of erosion. This was confirmed by our research.

Table 7. Changes in the percentage of the forest area after ECW in Grdelica Gorge.

No.	River Basin	F (km^2)	Forest Area				Biotechnical Works		Zmean		ΔZ
			1953		2016						
			km^2	%	km^2	%	ha	%	1953	2010	
1	Kozarska River	101.0	55.61	55.06	56.06	55.50	44.70	0.44	0.72	0.27	0.45
2	Palojska River	6.87	4.04	58.86	4.98	72.55	94.40	13.74	1.02	0.29	0.73
3	Predejanska River	19.68	9.15	46.49	10.70	54.37	155.00	7.88	0.93	0.26	0.67
4	Bistrička River	29.18	20.97	71.87	21.20	72.64	22.50	0.77	0.74	0.21	0.53
5	Džepska River	91.88	40.78	44.38	49.91	54.32	912.70	9.93	0.75	0.33	0.42
6	Jastrebačka River	9.84	3.16	32.11	3.45	35.10	29.40	2.99	1.06	0.42	0.64
7	Koznica River	21.57	7.70	35.70	7.74	35.89	4.20	0.19	0.89	0.31	0.58
8	Letoviška River	19.60	8.45	43.11	9.17	46.81	72.40	3.70	0.96	0.43	0.53
9	Rdovska River	19.36	10.26	53.01	10.77	55.63	51.00	2.63	0.90	0.30	0.60
Immediate South Morava River Basin											
10	Krpejski potok	2.60	0.57	21.92	1.50	57.62	92.80	35.69	1.04	0.33	0.71
11	Bujica Mlakačka	0.71	0.06	8.03	0.28	38.82	21.56	30.36	1.22	0.49	0.73
12	Zle doline	0.36	0.13	36.00	0.27	75.00	14.00	38.89	1.13	0.27	0.86
13	Goli čukar	0.42	0.00	0.00	0.05	10.95	4.60	10.95	0.95	0.43	0.52
14	Kamilja luka	0.39	0.07	17.95	0.18	45.13	10.60	27.18	1.05	0.39	0.66
15	Kalimanska River	16.04	5.44	33.91	9.44	58.84	399.8	24.92	0.93	0.28	0.65

In Serbia, the Kalimanska River (left tributary of the South Morava) has been one of the most dangerous torrents. It had several torrential floods (1929, 1946, 1948, and 1951) that brought huge damage to the town of Vladičin Han and the international railway Belgrade-Skopje-Athens. The torrential flood in summer 1929 destroyed a few hundred houses in the town of Vladičin Han and interrupted the railway traffic for more than 10 days. The first technical documentation on erosion and torrent control in the watershed of the Kalimanska River was prepared in 1923 and the projects started in 1927. The most intensive undertakings were carried out in the period between the end of the World War II and the mid 1970s. The specific sediment transport in that period was 2494.45 $m^3km^{-2}year^{-1}$, calculated according to the EPM method for the hydrological conditions in the basin as in 1929 [64]. As a result of very extensive erosion control works (ECW), the situation in the basin is completely different. The erosion intensity in the basin has been significantly reduced. As a result, the sediment transport has been significantly reduced. In the period from 1981 to 1985, sediment transport measurements were made in the Kalimanska River. The specific sediment transport was 27.94 $m^3km^{-2}year^{-1}$ [65]. This is confirmed by the great positive effect of the performed ECW in the Kalimanska River Basin.

Another example relates to the effect of erosion control works in the Repinska River Basin, the left tributary of the South Morava River, 7 km upstream from Vladičin Han, which means outside the Grdelica Gorge. The area of the basin is 7.82 km^2. Before ECWs, the erosion was strong with Z = 0.90. Flood waves of the Repinske River threatened the international railway and the Belgrade-Skopje-Athens road. The specific average annual sediment transport was 2273.00 $m^3km^{-2}year^{-1}$. The ECW began in the early 1960s. In addition to biological works, a downstream regulation and 7 check dams were built. After the works carried out in the period from 1981 to 1985, the measurement of sediment transport in the Repinska River was performed. The specific mean annual sediment transport was 49.92 $m^3km^{-2}year^{-1}$ [66]. The obtained results of the sediment transport clearly point to the importance of ECWs for controlling erosion processes in the basin and reducing the sediment transport.

Hence, this research examined the effectiveness of the conducted erosion control works, as well as the applied methodology used in Serbia. The results of the research conducted in the area of Grdelica Gorge confirmed the significance of the effects of erosion control works on the reduction of the erosion intensity and consequently in the sediment production and transport. Different species of forest trees were used for afforestation. The best results were achieved with Austrian and Scots pines established on bench terraces, which was expected, bearing in mind the poor conditions for the growth of plants on these terrains [38]. It should be noted that at the beginning of the erosion control works in Grdelica Gorge (in the early 1950s), pit planting was applied as the simplest method of afforestation. The survival rates were catastrophic. The reasons lay in extremely poor conditions of the barren land that was to be afforested: very steep slopes, very shallow or no soil, high temperatures and small amounts of precipitation during the growing period. Therefore, further afforestation was carried out with the preliminary preparation of the terrain with appropriate biotechnical works: the establishment of different types of terraces, contour ditches, contour walls in dry stone, and most often bench terraces. These works created better microclimatic conditions for the growth of the plants and increased the afforestation success above 90%. Later in the 1980s, when container seedlings were first used in afforestation, the plant survival rate was even higher, and the planting could be done during the entire growing period, which increased the efficiency of the works.

A major contribution to the development of scientific and professional approaches to the assessment of the state of erosion in the basin, sediment production and transport, defining the layout of the dams in torrential streams and their effects in the area of Grdelica Gorge was given by the Faculty of Forestry, University of Belgrade. These studies began in the early 1950s and they are still ongoing. A significant contribution was provided by the Institute for Forestry in Belgrade, whose research during the 1950s (practically after the first failures of the afforestation in Grdelica Gorge) helped study the success of afforestation applying different methods of terrain preparation and propose different methods of terrain preparation (various types of terraces, contour trenches, bench terraces, dry walls against the terrain sloughing, etc.) in different site conditions. These proposals were then applied in the field and the success of afforestation was above 90%. For the purpose of these investigations, the Institute established several experimental field points for the afforestation applying different methods of preliminary terrain preparation [67].

A very important segment of all investment projects, including erosion control works, is the maintenance of the constructed structures. This applies both to the technical (building) and the biological and biotechnical constructions. In the course of time, technical structures (check dams and regulations) are prone to various types of damage caused by flood waves. The damage should be repaired immediately because the next flood wave could demolish the structure completely. In the period before the early 1990s, Serbia had a serious state-owned erosion and torrent control service. There were specialized companies for erosion and torrent control which were responsible for the maintenance of all erosion control structures. Technical structures were timely repaired, and the new plantations established on the barren land were tended in the first years, and if necessary, thinned or restocked. All these works were financed by the state. With the break-up of the SFR Yugoslavia and subsequent wars, the UN sanctions and the great economic crisis, very small (symbolic) financial investments were assigned to the protection against erosion and torrential floods and the maintenance of the structures was almost completely neglected. Consequently, there is now a great number of damaged structures in the field and trees growing on tops of many dam overflows, which in case of a flood wave would cause the water to flood over the dam wing, thus endangering the whole structure.

By the end of the 1960s, afforestation was carried out by dense planting with the application of 12,000 or even more seedlings per hectare. This way, very dense monocultures were established without the necessary tending measures being subsequently carried out. Since thinnings have not been carried out at all, there are very dense forests now. They provide good protection of soil against erosion, but their productive capacities are small. The trees are very thin with small diameter increases, and as such, they are not resistant to wind throws and snow breaks and get easily infested by various plant pathogens and insects. Besides the damage caused by snow breaks, these cultures are often affected by fires. Consequently, the further survival of these cultures has been threatened and they call for urgent reconstruction with the application of thinning.

In the whole area of southeastern Serbia, but above all in Grdelica Gorge, there were numerous examples of successful orchard establishment on barren land (basins of the Palojska River, Mlakačka Valley, Katić Valley, etc.) with the aim of protecting soil against erosion and producing fruit at the same time. The most commonly grown fruit included plums, apples, pears, and in later phases currants and raspberries. Orchards were established on terraces or contour trenches and erosion was successfully checked with regular yields attained in the first years. Unfortunately, these orchards were not maintained, that is, they were not properly managed. These are now overmatured dying trees that cannot produce any fruit. The surfaces are grass and weed covered with the emergence of young brush. The degradation of these orchards was due to several reasons: migration of the population into towns, lack of roads (until recently) to bring the fruit to the market, etc. In other words, an integral approach to solving the problem of soil erosion and creating favourable conditions for the improvement of living conditions of the population was lacking.

The situation was similar with newly-established artificial meadows. Due to the migration of the population into the cities, they were practically abandoned and covered in weed. Consequently, significant crop areas do not provide any (or small) yields although substantial financial funds have been invested in their establishment. It is comforting that they at least protect the soil against erosion, but their production function has been lost.

Having in mind the characteristics of soil erosion processes and torrential floods, the best and most successful method of protection is prevention. The prevention consists of permanent control of erosion and torrential processes in the basin which is achieved by an integral river basin management system [9,68,69]. The changes in the intensity of erosion in the function of the performed erosion control works, the experience, the scope and the type of the works, the choice of technology, and the species for afforestation of the eroded land have a wider practical and theoretical significance for the improvement of methods for controlling water erosion and torrential floods because this is one of the most representative torrential areas in the Republic of Serbia and Southeast Europe. The period from 1952 to 1978 was a period of great expansion and a large volume of work that resulted in unhindered traffic flow in the area. The success and the quality of these works were proved by experts who came from developed countries of Europe and the United States to see the volume of the work. Proof of the great significance of these works and the high opinion of the competences of our experts was the Workshop of the Working Group for Watershed Management that took place in the center of Grdelica Gorge—a small town of Predejane in 1958. This group still operates within the Food and Agriculture Organization (FAO) as one of the most important organization of the UN.

5. Conclusions

In the area of Grdelica Gorge, from the early 1950s until the early 1990s, large-scale works on the protection against erosion and torrential floods were carried out. They enabled the unhindered traffic flow on two European traffic routes: the Belgrade-Skopje-Athens railway and motorway. The research showed that these works resulted in the significant reduction of the intensity of soil erosion, sediment production, and transport, which consequently reduced the possibility of torrential floods, all of which contributed to the unhindered flow of traffic through the two above-mentioned international traffic routes.

Many years of work have shown that only a combination of technical, biological, and biotechnical works gives desired results in controlling the erosion processes and sediment transport and thus reduce the risk of torrential floods. Technical works solve the acute problems in the protection against torrential floods and sediments, while biological and biotechnical works offer permanent solutions to the problems of soil erosion and torrential floods in the basin. The results of the study showed a significant dependence of the decreasing erosion intensity (i.e., reducing the value of the erosion coefficient—Z) on the extent of the afforestation of barren land and other biotechnical works in the basin. This can be seen from the presented regressions and coefficients of correlation and determination.

Erosion is a natural phenomenon that has caused environmental and economic consequences in the Eastern Europe and Balkan Peninsula. Hence, the European Commission's Soil Thematic Strategy has defined soil erosion as a significant problem and monitored soil erosion in Europe. In the 21st century, the erosion rate is expected to increase due to global warming and anthropogenic activities, such as land use and land cover changes (LULCC), which are associated with a more powerful hydrological cycle characterized by a higher magnitude of rainfall and more frequent occurrences of heavy rainfalls [70]. The analysis of rainfall and extremes in Serbia has shown that the frequency of heavy rainfall has generally increased [71]. The annual amount of precipitation has not changed significantly, but the pluviometric regime has changed, which can have a significant impact on the vegetation. This is very dangerous because linear erosion forms are particularly affected by this scenario. Vegetation changes with the changes in the precipitation regime, which can reactivate the existing liner erosion forms due to the high erosion potential present there. Because of this, it is necessary to conduct constant prevention and control of the intensity of erosion.

Although there are now no problems with erosion and torrential floods in Grdelica Gorge, it should be kept in mind that there are still 137 torrential streams. With the weather extremes (in the form of heavy showers) occurring more and more often, we must be cautious and continue with erosion control works. A new highway that connects the north and the south of Europe will be completed through Grdelica Gorge this year. This section should be studied because it has certainly disturbed the natural balance and necessary work and measures should be taken.

A great problem not only in the area of Grdelica Gorge area but also in the whole of Serbia is that the maintenance of the constructed erosion control structures and the tending of newly-established (forest and agricultural) plantations was practically neglected with the onset of the economic crisis due to the breakup of the SFR Yugoslavia in 1991 and all the other problems that struck Serbia by the end of the 20th century. This may lead to serious problems which should be addressed as soon as possible. This implies restoration of damaged technical facilities, restocking of thinned forests, and other measures of forest tending and orchard restoration.

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