water

MDPI

Article

Spatial and Temporal Variability of Bank Erosion during the Period 1930–2016: Case Study—Kolubara River Basin (Serbia)

Slavoljub Dragićević [1,*], Mirjana Pripužić [2], Nenad Živković [1], Ivan Novković [1], Stanimir Kostadinov [3], Marko Langović [1], Boban Milojković [4] and Zoran Čvorović [5]

1 Faculty of Geography, University of Belgrade, 11000 Belgrade, Serbia; jatepo3@gmail.com (N.Ž.); novkovic.ivan@gmail.com (I.N.); mlangovic@gef.bg.ac.rs (M.L.)
2 Department of Applied Mathematics and Computer Science, University of Applied Sciences "Vern", 10000 Zagreb, Croatia; mirjanaroks@gmail.com
3 Faculty of Forestry, University of Belgrade, 11000 Belgrade, Serbia; stanimir.kostadinov@sfb.bg.ac.rs
4 The Academy of Criminalistic and Police Studies, 11000 Belgrade, Serbia; boban.milojkovic@kpa.edu.rs
5 Faculty of Security, University of Belgrade, 11000 Belgrade, Serbia; zcvorovic996@gmail.com
* Correspondence: dragicevicslavoljub@gmail.com or sasa@gef.bg.ac.rs; Tel.: +381-602-244-542

Received: 3 July 2017; Accepted: 27 September 2017; Published: 29 September 2017

Abstract: The fluvial process is characterized by an intense meandering riverbed. The aim of this study was to perform a reconstruction of the lateral migration of a 15 km length of an active meandering river during the period 1930–2016. River morphological changes were analyzed and quantified from cadastral maps and aerial photographs as well as by geodetic survey and GIS. Hydrological characteristics and extreme hydrological events were evaluated in relation to bank erosion rate. The rate of bank erosion was markedly different from the long-term studied meanders, just like in the short-term period. During the 87 years of observation (from 1930 to 2016), the length of the Kolubara River was enlarged by 3.44 km. The average migration rate of the Kolubara River for monitored meanders in the period 1930–2010 was 1.9 m·year^{-1}, while in the period 2010–2016, the average migration rate was 3.3 m·year^{-1}. The rate of bank erosion was more intensive across the entire short-term period than during the longer period, and the maximum annual rate of bank erosion during the period 2010–2016 varied between 0.3 and 11.5 m. It is very likely that in the period from 2010, frequent discharge variations and rapid change of its extreme values caused more intensive bank erosion. These research results will be valuable for river channel management, engineering (soft and hard engineering), and planning purposes (predicting changes in river channel form) in the Kolubara River Basin.

Keywords: channel migration; riverbank erosion and accretion; bank-full discharge; Kolubara River

1. Introduction

Lateral channel migration and the stability of rivers are of particular interest from geomorphic, engineering, and ecological points of view. Active meandering rivers are one of the most dynamic and sensitive elements of the landscape [1], and the causes of the rate of riverbank erosion are various, complex, and usually the result of interaction between natural processes and human activities.

The natural factors that can determinate the intensity of bank erosion are numerous. A large number of previous studies have demonstrated that tectonic and geomorphologic characteristics of the river basin, channel geometry, bank material composition (cohesiveness of the materials, etc.), flow characteristics (variability of river discharge and water level, etc.), and vegetation are the main natural factors that affect bank erosion [2–6]. Furthermore, the increasing extent of human activities (regulation, etc.) and climate change may also have notable effects on river systems. However, bank erosion is a complex process and the interaction of numerous factors can determine changes in the river course, bank erosion intensity, sediment regime and the environmental and land use [7–12]. In this study, an analysis was conducted to investigate the effects of different variables on the intensity of the Kolubara riverbank erosion.

Bank erosion and lateral channel migration are the most important geomorphologic processes in the alluvial plain in the southern part of the Pannonian Basin [13–16] and Eastern Carpathians [17–21]. Bank erosion in the Serbian territory is one of the most dynamic and sensitive geomorphologic processes which are currently not being performed for the whole territory, as fluvial and geomorphologic studies in post-Yugoslavian countries are quite rare. Therefore, there are only a few results of bank erosion intensity and the consequences of changes in river course for different rivers in Serbia have been presented, without any short-term period analysis [22–26].

Previous research has shown that the lower part of the Kolubara River is highly mobile, with a sequence of changes that were analyzed from historical maps and aerial photographs [27,28]. River channel changes such as intensive bank erosion and accretion, lateral channel migration, and cut-offs dominate the geomorphologic-hydrological processes in the lower part of the Kolubara River Basin, which can be connected to natural processes and human activity. The lower part of the Kolubara River (as an alluvial river) responds to valley-slope deformation caused by the sinking of active tectonics in various ways, depending on the rate and amount of lateral migration and bank erosion. A map of the active tectonic movements of the Kolubara's basin shows that almost the whole area of the lower part of the Kolubara valley is slowly sinking under tectonic movements [27,29] of the southern part of the Pannonian Basin [3,4,30–32]. It is well known that the discharge represents the main active force for river bed modeling [19,33–35]. The Kolubara River has the highest coefficient of discharge variation in comparison to other larger river basins in Serbia, and has a misbalanced ratio between high and low waters [36]. The Kolubara River has an unfavorable water regime, which is reflected in the excessiveness of water runoff, with floods that are sudden, expressive, and short-term [37,38]. Thus, hydrological characteristics and extreme hydrological events were also evaluated in relation to bank erosion. The human influences on the hydrological network in the study area have been intensive since 1959, when huge regulation works were constructed in the lower part of the Kolubara River Basin by diverting the Kolubara channel into the right tributary of the Pestan channel [24,26]. Lateral channel migration has caused serious socio-economic and environmental consequences due to losses of arable land, land use changes, and flood hazards, as well as economic loss due to the reduction of agricultural production [25].

The fluvial process in this section is characterized by an intense meandering riverbed and the basic idea was to perform a reconstruction of channel changes on a 15 km reach of one such active meandering river during the period 1930–2010 (long-term bank erosion), as well as to show and analyze the recent state and the results of monitoring on the most endangered riverbanks (short-term active bank erosion in six of the most endangered meanders) for six years (2010–2016). The bank-line migration was measured by overlay analysis of the bank lines of several successive periods from 1930 to 2010, according to the date of the cadastral maps and aerial photographs (1930–1959; 1959–1981; 1981–2010), geodetic survey and using the unmanned aerial vehicle Sense Fly eBee in the period 2010–2016. By comparing the data from different periods, we determined the morphological changes in the course of the Kolubara River over the 87-year period. Thus, we reconstructed the lateral evolution of these meanders since 1930, quantified their recent mobility in the few last years, and determined the causes of bank erosion.

The aims of this paper were to (1) quantify the spatial and temporal variability of lateral channel migration in the analyzed sector of the Kolubara River and determine similarities and differences, (2) determine causes and consequences, and (3) assess the relationship between the hydrological characteristics (the mean and bank-full discharge, frequency and magnitude of peak flows and flood events) and the rate of bank erosion. Aside from its fundamental significance, the results of this research are applicable in the field of water resource management—and hydro-technical work—as well as in different aspects of the protection and promotion of the environment (particularly within the concept of sustainable development). In addition, the results form the basis for finding adequate solutions for the rehabilitation of endangered riverbanks, the kind of solutions (soft and hard engineering) that can be applied to stop lateral erosion, and predict changes in river channel form and their consequences in the study area. A better understanding of river channel migration in this area will be of great importance for practical issues such as predicting channel migration rates for river engineering and planning purposes, soil and water management, and land use changes.

2. Study Area

The Kolubara River Basin is situated in the western part of Serbia, has a flow length of 86.4 km and basin surface of 3638.5 km^2, and is classified as a middle-sized river within the territory of Serbia (88,361 km^2). It is the last large tributary of the Sava River and confluences with it 30 km from Belgrade. In this study, we analyzed the lower part of the Kolubara River (about 15 km length), between the confluences of the Turija and Tamnava Rivers, which is the area where bank erosion and lateral migration processes are the most intensive (Figure 1).

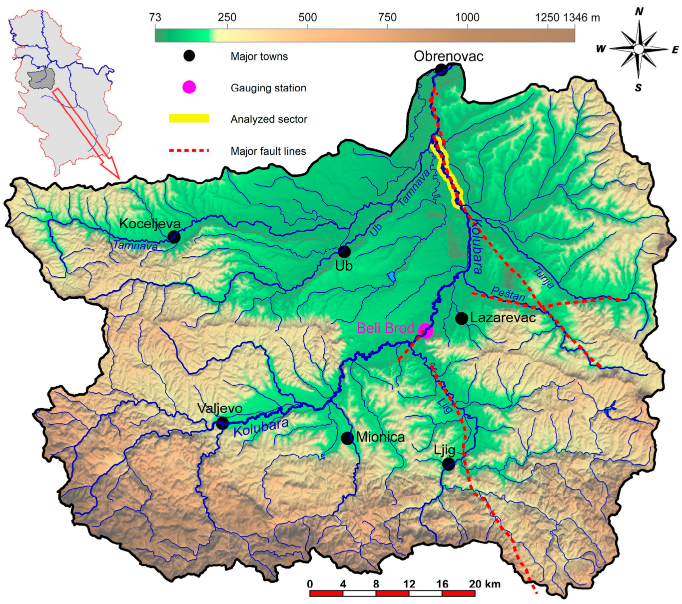


Figure 1. Study area: the Kolubara River Basin in Serbia.

The Kolubara River flows through different landscapes, and this diversity is reflected in the relief, geologic structure, and age of some parts of the basin, and in the geotectonic complexity of the terrain through which the river flows. The drainage basin consists of Mesozoic and Cenozoic igneous and sedimentary rocks and Palaeozoic metamorphic rocks [25,39]. The drainage basin is open towards the north, the highest point is at 1346 m and the lowest has an altitude of 73 m. The average altitude of the Kolubara River Basin is small (272 m) and the average slope is 6.1°.

By analyzing the amount of annual rainfall in the Kolubara River Basin in the period 1959–2010, it can be concluded that the Kolubara River Basin has a continental-pluviometric regime, which is characterized by maximum rainfall at the beginning of summer and a minimum rainfall in the winter [40–42]. The average annual rainfall in the Kolubara River Basin was 809 mm for the period 1959–2010 [36].

The Kolubara River has the highest coefficient of monthly flow variation in comparison to other larger river basins in Serbia, with a very misbalanced ratio between high and low waters. The mean discharge of the Kolubara River for the period 1959–2016 was 16.1 $m^3 \cdot s^{-1}$ (recorded at the Beli Brod gauging station). The largest mean annual discharge during the observation period was in the 1970s at 39 $m^3 \cdot s^{-1}$, while the 1990s had the lowest with a mean annual discharge of 4.9 $m^3 \cdot s^{-1}$. The lowest value of annual maximum discharge was approximately 25 $m^3 \cdot s^{-1}$, and the river flows of 100- and 1000-year return periods were 740 and 960 $m^3 \cdot s^{-1}$, respectively [38]. In 2014, the absolute highest daily discharge at the Beli Brod gauging station was recorded at 954 $m^3 \cdot s^{-1}$ [43].

Tectonic movements have had a huge impact on the genesis and morphological evolution of the hydrological network of the Kolubara River Basin, while fluvial erosion and human impact have influenced the present form of the network. To understand the lateral migration of the study area, the geomorphological characteristics were analyzed in detail. The influences of the natural factors on the rate of channel migration, lateral erosion and accumulation in the lower parts of the Kolubara river valley have been fully explained in previous research described in References [26,28]. The tectonic characteristics of this area, or more precisely the major fault lines, have influenced the orientation of the hydrological network in the Kolubara River Basin. The fault lines extend diagonally and follow the right bank of the Kolubara River (Figure 1). A map of the active tectonic movements of the Kolubara River Basin shows that almost the whole area of the lower part of the Kolubara valley is slowly sinking under tectonic movements [29,37]. This has caused the eastward channel migration of the Kolubara River and its tributaries, and is indicated by a large number of abandoned riverbeds and cut-off meanders. In the area of the lower part of the Kolubara valley, there are 89 fossil fluvial forms: the left river bank has 64, and the right bank 25. The average Kolubara channel slope is 1.27 $m \cdot km^{-1}$ while in the analyzed area, the average channel slope is 0.51 $m \cdot km^{-1}$, which causes slow water drainage, river meandering, sediment deposition, etc.

Additionally, many other natural factors were presented that were favorable for the intense bank erosion of the Kolubara River. The Kolubara River channel has a width of 25–35 m, riverbank height varies from 5 to 7 m and are unprotected by vegetation as the near-bank vegetation is poorly represented. The study area is characterized by agricultural production and an agricultural population as agricultural land comprises 75% of the total area. The agricultural land structure is suitable, with uncultivated (fallow) land accounting for only 4.5% with cultivated land at 95.5% (which is 72.2% of the total area). Cultivated land is mostly arable land (92.4%), orchards (5.1%), and, to a lesser extent, meadows.

Aside from natural factors, the human influences on the Kolubara's hydrological network have been intensive. In the Kolubara River Basin, there is a large open pit of lignite, and the Kolubara River separates the mining basin into two parts: eastern and western. Surface mining of coal in the Kolubara lignite basin began in 1952, and regulation works on the Kolubara River and its tributaries began in 1959/60 with the aim of opening new mining fields. To facilitate the lignite extraction in 1959, the Kolubara River was diverted into the Pestan River (its right tributary) [24,26]. Following this first phase, during 1976, 1981 and 2000, new regulation works to divert the Kolubara riverbed and its tributaries were undertaken [26]. The meandering riverbeds influenced the evolution of the riverbanks, where the process of undermining and the concave river bank collapsing were the most significant. The lack of riverbank defense strategy has resulted in significant river bank movement in history.

3. Materials and Methods

Numerous approaches to studying bank erosion processes have been developed for spatial and temporal extent [44]. Some are concerned with the direct measurement of bank retreat processes, while others focus on inferring bank erosion processes from large spatial scale assessments of channel change, typically in laterally migrating rivers [45,46].

In recent years, there has been an increase in the use of aerial photographs in fluvial process studies, especially to provide a means to assess past river bank erosion rates [47–52]. The history of river channel migration can be described using sequential aerial photographs or over longer timescales, historical maps. In this study, we used cadastral maps from 1930, a series of aerial photographs from 1959 and 1981, and orthophoto images from 2010 to determine the area of the Kolubara River bank erosion and lateral migration. Each aerial photograph (from 1981) was scanned so that every pixel on each photograph represented a ground area value of 1 × 1 m. For this study, a total of 43 GCPs (ground control points) were used to georeference the three aerial photographs. At the end of the georeferencing process, the residual error of each GCP did not exceed six meters. The highest residual for a ground control point was 5.91 m and the lowest was 0.27 m. The RMS error (Root Mean Square error) of the GeoTIFFs ranged from 2.14 to 3.94 m. Using the GeoMedia Professional GIS software, we digitized the Kolubara shorelines (both left and right) in each observed period. Aerial photographs, orthophoto images, and cadastral maps that were used in this study were from the Gauss-Krüger projection and World Geodetic System 1984. The shorelines were already determined from the cadastral maps from 1930, and were easily digitized, but we had to define and delineate the stream channel line on the aerial photographs and orthophoto images. There are many methods to denote channel boundaries; some of them use the limits of vegetation or changes in vegetation type [53]. In this study, we applied the method proposed by Gurnell [54] and Winterbottom [55]. The channel banks were easily detected since the Kolubara River banks are mostly arable land, with non-vegetated (or grass only) parts. For the purpose of consistency, one person carried out all of the digitizing; furthermore, the two digitized channel boundary lines were processed using GeoMedia Professional software tools to generate a channel centerline, which was used to calculate the channel length and channel migration rate [56–60].

In this study, we also calculated the rate of bank erosion and accretion. To calculate the erosion and accretion separately for each side of the river, we copied the digitized left shoreline from each period into a new GIS layer and repeated the process for the right shoreline. Using GeoMedia Professional tools, we created polygons that represented the difference between the two positions in each period of study, and a polygon between the first and last period, which represented the erosion and accretion during the observed period. Comparing the left bank from 1930 to 1959, the erosion polygons were positioned on the left side of the shoreline from 1930, and the accretion polygons were positioned on the right side of the 1930 shoreline. To assess erosion and accretion of the right bank, we applied the same process with one change: the polygons to the left of the 1930 shoreline represented accretion and polygons, the right of the 1930 shoreline represented erosion. The same method was used for the left and right shoreline in 1959, 1981 and 2010, respectfully.

Based on the results related to longer-term bank erosion (1930–2010), we selected six of the most endangered meanders where the intensity of bank erosion and lateral channel migration was the most intensive. Thus, for the short-term period analysis (2010–2016), we monitored six of the most endangered meanders with geodetic survey and using the unmanned aerial vehicle SenseFly eBee (with 5 cm resolution). The data obtained by monitoring the meander position were used for determining the annual bank erosion rate. Loss of soil due to bank erosion was calculated by superimposing the bank lines during the assessment year on those of the previous year in the GIS platform.

It is very likely that, in the period from 2010, frequent discharge variations and rapid change of its extreme values caused more intensive bank collapse. Many authors [61–65] have shown that changes in the frequency and magnitude of peak flows and flood events are an essential part of the historic dynamics of river channels where flood events lead to a considerable increase in bank erosion.

During flood events, the bank line in the active meander can be eroded for several meters; therefore, changes in river hydrology (e.g., changes in the stage or in the frequency of floods due to environmental changes) can significantly alter the long-term tendencies in channel migration. This was proven in May 2014 after the flood wave passed. The range of erosion rates increases as the average monthly discharges and average yearly discharges increase.

To recognize the hydrological changes of the river from 1959 to 2016, hydrological parameters that determine channel form were analyzed. Long-term and short-term changes in the water discharge and the modification of the annual water regime were determined. The dataset of 1959–2016 was split into three periods according to the dates of available aerial photographs: 1959–1981; 1982–2010;

and 2010–2016, thus allowing the hydrological factors underlying the morphological changes to be identified. Long and short-term daily hydrological data for the studied section were taken from the Beli Brod gauging station [43]. The bank-full discharge value (105.14 $m^3 \cdot s^{-1}$ with 1.12 year probability) was calculated using the Chezy-Maning formula [66], and cross-section profiles were obtained by geodetic survey.

To establish a connection between the dynamics of the riverbank movements and occurrence of high discharges in the Kolubara River, we found a strong existing connection exists. The analysis included three sets of variables: average annual riverbank movement, ABE ($m \cdot year^{-1}$); the mean annual discharge, Q_y ($m^3 \cdot s^{-1}$); and the average number of days per year with discharge exceeding a selected threshold. In this case, we examined the thresholds of 80, 90, 100 and 105 $m^3 \cdot s^{-1}$. The most appropriate threshold was of 90 $m^3 \cdot s^{-1}$, or the number of days during the year with a discharge greater than 90 $m^3 \cdot s^{-1}$. This is a discharge of 15 $m^3 \cdot s^{-1}$ less than the required (or 86% of its value). When it emerges, the water level in the river is only 0.5 m lower than the upper edge of the minor riverbed, which does not reduce the effect of high water on the eroding process.

4. Results

4.1. Long-Term Bank Erosion (1930–2010)

The bank erosion process influences river morphology changes. By monitoring this process in the most endangered areas (river meanders), we collected data which helped us determine the spatial and temporal variability of riverbank erosion and accretion in the study area. The length of the Kolubara River in the study area was 11.56 km in 1930, 12.89 km in 1959, 14.25 km in 1981, 14.63 km in 2010, and 15 km in 2016. During the 87 years of observation (from 1930 to 2016), the length of Kolubara River was enlarged by 3.44 km (Figure 2).

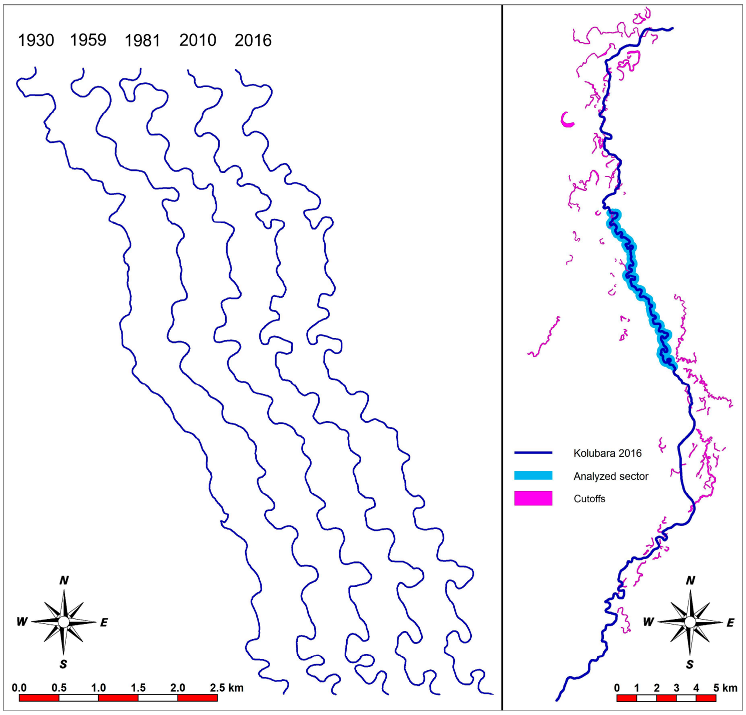


Figure 2. Successive channel planform changes for period 1930–2016 along the study area.

The most intensive change of the Kolubara River occurred during the period 1959–1981, when the riverbed extended by 1.36 km (an average of 62 $m \cdot year^{-1}$) in the study area. During the period 1930–1959, the length of the riverbed of the Kolubara increased by 45.9 m per year (1.33 km), during the period from 1981 to 2010, only 0.01 m·year^{-1}. However, it is important to note that during 2006, the Kolubara River cut the neck of the meander near the confluence of the Tamnava River, which caused the river course to the east. In this way, the length of Kolubara River is shorter by 1.12 km [27]. This would last for the period 1981–2010 with an increase in length of 1.51 m·year^{-1}, or an average of 52.1 m·year^{-1}. This shows that the process of fluvial erosion is still dominant, and that this sector is still characterized by a high intensity of fluvial erosion.

A comparison of the cadastral maps from 1930 with the aerial photographs from 1959 revealed that the Kolubara channel migrated 38.9 m (20.3 m to the left and 18.6 m to the right). During this period, the average lateral migration rate of the Kolubara River was 1.34 m·year^{-1}. Comparing the aerial photographs from 1959 and 1981, we calculated that the Kolubara channel migrated for 32.2 m, which means 18.4 m to the left and 13.8 m to the right. The average migration rate of the Kolubara River during this period was 1.46 m·year^{-1}. The analysis of the last observation period was undertaken using the aerial photographs from 1981 and orthophoto images from 2010 (Figure 3). During this period, the Kolubara channel migrated by 28.9 m, 13.1 m to the left and 15.8 m to the right, with an average migration rate of 0.99 m·year^{-1}.

The analysis of erosion and accretion plots of the Kolubara River banks showed that the total area of erosion from 1930 to 2010 was 124.2 ha (1.242 km^2), of which 63.4 ha was on the left bank and 60.8 ha on the right bank. The accretion area from 1930 to 2010 was 65.6 ha on the left bank and 71.9 ha on the right, which meant that the total area of bank accretion was 137.5 ha or 1.375 km^2 (Table 1). The erosion process was stronger by 26.6% in the period between 1959 and 1981 when compared to the period of 1930–1959. In the last period of observation (from 1981 to 2010), the erosion process stabilized, and the average annual erosion rate was 36.8% lower than in the previous period. The accretion annual rate in the period between 1959 and 1981 was higher by 37.5% when compared to the period 1930–1959. In the last period of observation, the accretion annual rate was 31.5% lower than the period 1959–1981.

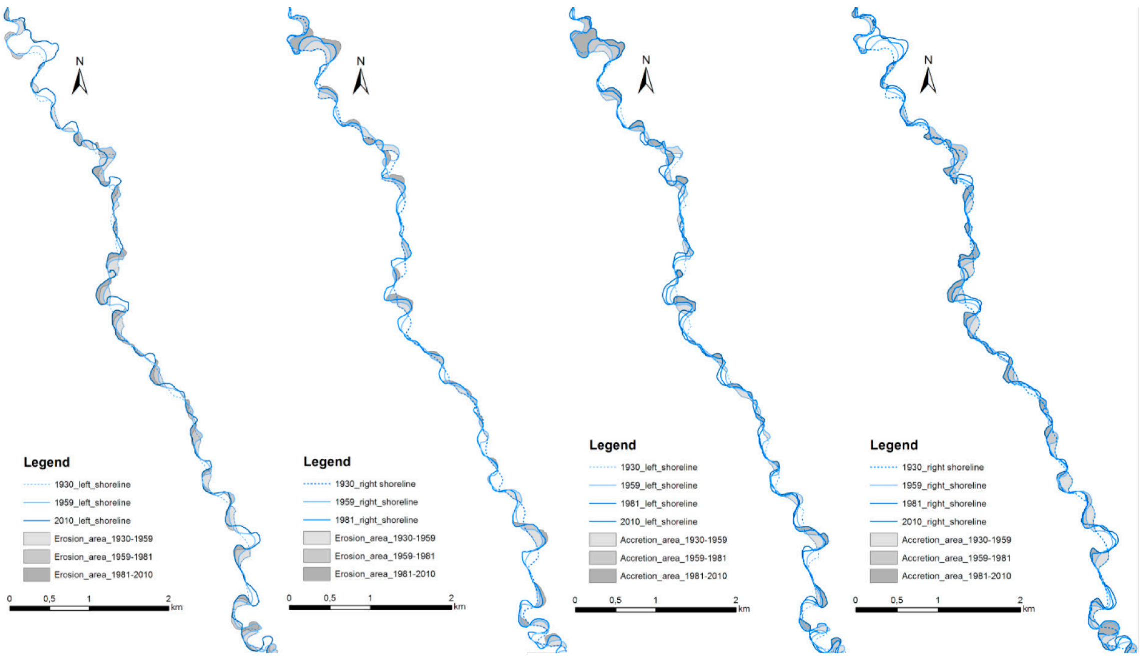


Figure 3. Bank erosion and accretion between 1930 and 2010.

Table 1. Area of riverbank erosion and accretion of the Kolubara River from 1930 to 2010.

Time Span	Area of Erosion (ha)			Area of Accretion (ha)		
	Left Bank	Right Bank	Total	Left Bank	Right Bank	Total
1930–1959	23.3	22.2	45.5	22.8	24.4	47.2
1959–1981	24.0	19.1	43.1	16.4	25.5	41.9
1981–2010	16.1	19.5	35.6	26.4	22.0	48.4
Total (1930–2010)	63.4	60.8	124.2	65.6	71.9	137.5

In our analysis, we identified 96 erosion plots on the left and 95 erosion plots on the right banks of the Kolubara River. The total area of left bank erosion plots was 63.4 ha and the total area of right bank erosion plots was 60.8 ha. On the left bank, there were no erosion plots larger than 3 ha, while on the right bank, three erosion plots were larger than 3 ha. In contrast, there are 24 erosion plots smaller than 0.1 ha on the left bank and 31 on the right bank (Table 2).

The total area of accretion plots was 137.5 ha. There were 95 accretion plots with an area of 65.6 ha on the left bank and 95 with the area of 71.9 ha on the right bank. On the left bank, there was an accretion plot with an area of 7 ha and one with the area of 3.8 ha. Two accretion plots on the right bank were larger than 3 ha (3.2 and 3.6 ha). There were 23 accretion plots smaller than 0.1 ha on the left bank and 21 on the right bank (Table 3).

Table 2. Distribution of the bank erosion.

	Areas of Left Bank Erosion (ha)								Areas of Right Bank Erosion (ha)							
	<0.1	0.1–0.5	0.5–1	1–2	2–3	3–4	>4	Total	<0.1	0.1–0.5	0.5–1	1–2	2–3	3–4	>4	Total
1930–1959																
Number of plots	2	6	7	9	1	0	0	**25**	5	6	4	8	1	1	0	**25**
Total area (ha)	0.07	1.3	5.4	14	2.5	0	0	**23.3**	0.1	1.2	3	12	2.2	3.7	0	**22.2**
(%) of total	0.3	5.6	23.2	60.1	10.8	0	0	**100**	0.5	5.4	13.5	54.1	9.9	16.6	0	**100**
1959–1981																
Number of plots	3	9	8	7	2	0	0	**29**	6	11	6	5	0	1	0	**29**
Total area (ha)	0.2	2.5	6.2	10.5	4.6	0	0	**24.0**	0.02	3.2	4.7	7.4	0	3.8	0	**19.1**
(%) of total	0.8	10.4	25.8	43.8	19.2	0	0	**100**	0.1	16.7	24.6	38.7	0.	19.9	0	**100**
1981–2010																
Number of plots	19	10	8	5	0	0	0	**42**	20	7	7	6	0	1	0	**41**
Total area (ha)	0.3	3	5.6	7.2	0	0	0	**16.1**	0.5	1.9	5.3	8.1	0	3.7	0	**19.5**
(%) of total	1.9	18.6	34.8	44.7	0	0	0	**100**	2.6	9.7	27.2	41.5	0	19.0	0	**100**

Table 3. Distribution of the accretion plots.

	Areas of Left Bank Accretion (ha)								Areas of Right Bank Accretion (ha)							
	<0.1	0.1–0.5	0.5–1	1–2	2–3	3–4	>4	Total	<0.1	0.1–0.5	0.5–1	1–2	2–3	3–4	>4	Total
1930–1959																
Number of plots	6	4	6	6	3	0	0	**25**	7	5	4	7	4	0	0	**27**
Total area (ha)	0.2	1.3	4.6	10.4	6.3	0	0	**22.8**	0.2	1.5	3.1	9.6	0.1	0	0	**24.4**
(%) of total	0.9	5.7	20.2	45.6	27.6	0	0	**100**	0.8	6.2	12.7	39.3	41	0	0	**100**
1959–1981																
Number of plots	4	12	8	3	0	1	0	**28**	3	10	3	10	2	1	0	**29**
Total area (ha)	0.09	2.4	5.4	4.7	0	3.8	0	**16.4**	0.05	2.8	2.6	12.6	4.2	3.2	0	**25.5**
(%) of total	0.6	14.6	32.9	28.7	0	23.2	0	**100**	0.2	11	10.3	49.4	16.5	12.6	0	**100**
1981–2010																
Number of plots	13	11	10	7	0	0	1	**42**	11	12	9	5	1	1	0	**39**
Total area (ha)	0.3	2.1	7.2	98	0	0	0.07	**26.4**	0.2	3.1	6	7	2.1	3.6	0	**22.0**
(%) of total	1.1	8	27.3	37.1	0	0	26.5	**100**	0.9	14.1	27.3	31.8	9.5	16.4	0	**100**

Therefore, the analysis showed that the largest changes in the morphology of the Kolubara riverbed occurred in the period 1959–1981. During this period, the most intense lateral migration occurred, which allowed the formation of a number of cut-off meanders, loss of land, etc. Furthermore, during this period, the regulation works to prepare the site for lignite exploitation in the Kolubara lignite basin were performed, which meant that the Kolubara riverbed was diverted into the Pestan riverbed tributary in the research section.

However, it is also important to determine whether the weather changes in the natural conditions intensified fluvial erosion during this period. Detailed analysis of climatic and hydrological conditions in Kolubara River Basin showed whether the intensification of natural activity in the research period caused the intensification of fluvial erosion (bank erosion). Mathematical calculations showed that the mean annual discharge in the observed period (1959–2016) decreased by an average intensity of 0.37 $m^3 \cdot s^{-1}$ (−2.3%) per decade, or a total loss per trend line of 2.11 $m^3 \cdot s^{-1}$ (−13.2%/58 years) (Figure 4). However, the trend of the mean annual discharge changes was not statistically significant and the tendency of decreasing discharges could be considered irrelevant by the Man Kendall test.

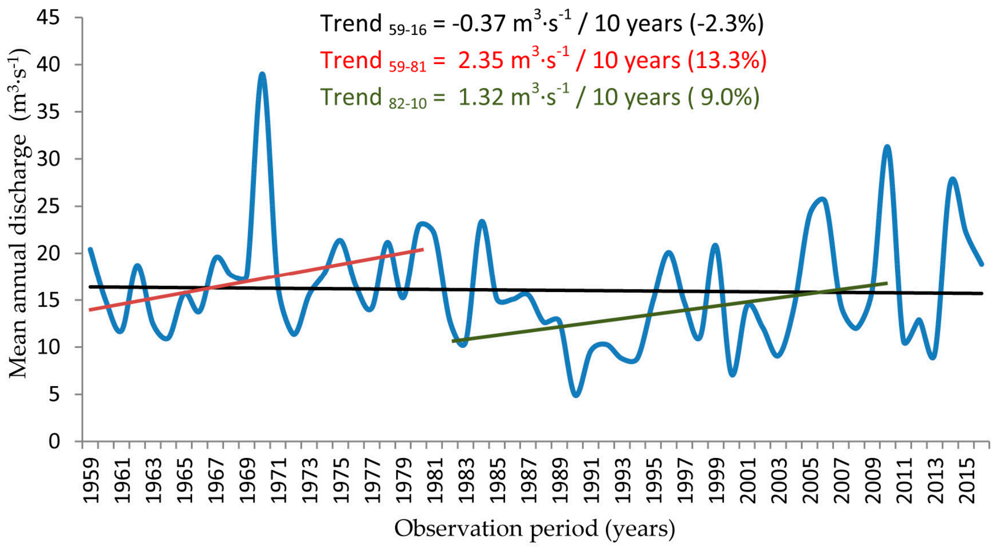


Figure 4. Trend of the mean annual discharge of the Kolubara River measured at the Beli Brod gauging station in the periods of 1959–2016, 1959–1981, and 1982–2010.

By dividing the observed period into two parts (1959–1981 and 1982–2010), the difference in discharge trends were significant. The first period had more waters and the trend of increasing discharge was 2.35 $m^3 \cdot s^{-1}$ (13.3%) per decade, or a total increase per trend line of 5.16 $m^3 \cdot s^{-1}$ (29.1%/23 years). The second period was dryer: only six years had discharges above the average value. During this period, the trend of increasing discharge was 1.32 $m^3 \cdot s^{-1}$ (9%) per decade, or a total increase per trend line of 3.70 $m^3 \cdot s^{-1}$ (25.3%/29 years). In the period 1959–1981, there was significantly more water than in the period 1982–2010, so the trend line (1959–2016) decreased overall. The variations of annual discharges of the second period were more significant when compared to the first period, and the extreme values occurred more often. In most cases, the mean annual discharge was in the range of usual fluctuations, which indicated that nothing unusual happened with the mean annual discharge in the period from 1959 to 2016.

In most cases, the maximal monthly discharge during the period 1959–2010 appeared in June, May, and April, and this period may be characterized as the most vulnerable for bank erosion. All of the above-mentioned indicated that more intensive fluvial erosion at the beginning of the research period could not be the result of natural changes, i.e., changes in precipitation and hydrological changes. Although there were certain trends, they were not intensive or statistically significant to be the only cause of the researched process. In the period between 1959 and 1981 (after diverting the Kolubara into the Pestan riverbed), the Kolubara riverbed moved by 1.46 m per year. In comparison with the results with those from the first observation period (1930–1959), when the average annual riverbank movement was 1.34 m, it could be concluded that when the regulation works on the Kolubara River flow began, fluvial erosion became more intensive. However, the reasons for this ratio could be the extreme hydrological conditions of the 1970s when the highest mean annual discharge was 39 $m^3 \cdot s^{-1}$ and there were many days of high waters, very high waters, and extremely high waters. Since the bank-full discharge in the researched sector was 105.14 $m^3 \cdot s^{-1}$, it is important to point out that in 1970s, there were 48, 42, and 38 days with a daily discharge higher than 80, 90, and 100 $m^3 \cdot s^{-1}$, respectively. In the same year, there were only 22 days with little water, without very little water, and extreme little water. Thus, river bank movement should be researched as a result of both natural conditions and human impact which occurred at that time.

4.2. Short-Term Active Bank Erosion (2010–2016)

Based on the results relating to long-term bank erosion (1930–2010), we selected the six most endangered meanders (locations) where the intensity of bank erosion and lateral channel migration were the most intensive. In the period 2010–2016, we monitored bank erosion and calculated the rate of migration and the rate of land loss carried away by the Kolubara River. The changes to the Kolubara River banks on the monitored meanders in the period 2010–2016 are presented in Table 4.

Table 4. Bank erosion rate in the period 2010–2016.

Bank Erosion	2010–2012	2012–2013	2013–2014	2014–2016	Max. Bank Erosion (m) 2010–2016	Average Bank Erosion 2010–2016 ($m \cdot Year^{-1}$)	Max. Bank Erosion (m) 1930–2010	Average Bank Erosion 1930–2010 ($m \cdot Year^{-1}$)
Meander 1	7.1	0.3	11.5	9.4	28.3	4.72	221.0	2.76
Meander 2	3.8	0.6	6.0	7.7	18.1	3.02	108.5	1.36
Meander 3	5.7	2.6	6.9	7.9	23.1	3.85	133.7	1.67
Meander 4	6.1	0.3	3.2	6.0	15.6	2.60	180.0	2.25
Meander 5	4.2	0.3	4.8	7.2	16.5	2.75	71.9	0.90
Meander 6	6.2	0.7	2.2	6.8	15.9	2.65	203.6	2.55
Average ($m \cdot year^{-1}$)	2.8	0.8	5.8	3.8	-	3.3	-	1.9

The long-term rate of bank erosion was markedly different at the studied meanders, just like in the short-term period. In 1930 and 2010, bank erosion was the most intensive on meanders 1, 6, and 4. The maximum annual rate of bank erosion during the studied period 2010–2016 varied between 0.3 and 11.5 m. It was the highest in meander 1 (28.3 m) during the whole monitoring period (as a long-term analysis) than in meander 3 (23.1 m), meander 2 (18.1 m), etc. The largest bank erosion in one year was observed in 2014, and the least in 2013. Across the entire short-term period, the rate of bank erosion was more intensive than in the longer period. The average migration rate of the Kolubara River for monitored meanders between 1930 and 2010 was 1.9 $m \cdot year^{-1}$, while between 2010 and 2016 the average migration rate was 3.3 $m \cdot year^{-1}$. In meander 1, the average rate of bank erosion was 2.76 $m \cdot year^{-1}$ between 1930 and 2010, while in the last period (2010–2016) it increased by 4.72 $m \cdot year^{-1}$. In meanders 2, 3 and 4 the average increased to almost double of the previous period (Figure 5).

Analysis of the erosion plots of the monitored six meanders on the Kolubara River banks obtained the results shown in Table 5. The largest erosion plots in 1930 and 1959 were those on meander 1, with areas of 3.7 ha and 3.8 ha, respectively, and represented 16.6% of all erosion plots in 1930 and 19.9% of all erosion plots in 1959. The total area of erosion plots on meander 1 was 9.5 ha, and on meanders 2, 3, 4, 5, and 6, the total area of erosion plots was 3.2 ha, 2.1 ha, 4.0 ha, 0.8 ha, and 4.9 ha, respectively. Thus, the designated site over 80 years (1930–2010) is missing 24.5 ha, while in the period of six years, it permanently lost 1.18 ha. On meander 1 during the monitored period, it lost 0.41 ha of arable land from the river banks. During the same period on meander 2, it lost an area of 0.14 ha, on the meander 3 it lost 0.13, while on meanders 4, 5, and 6 the land loss was 0.17, 0.12, and 0.21 ha, respectively (Table 5).

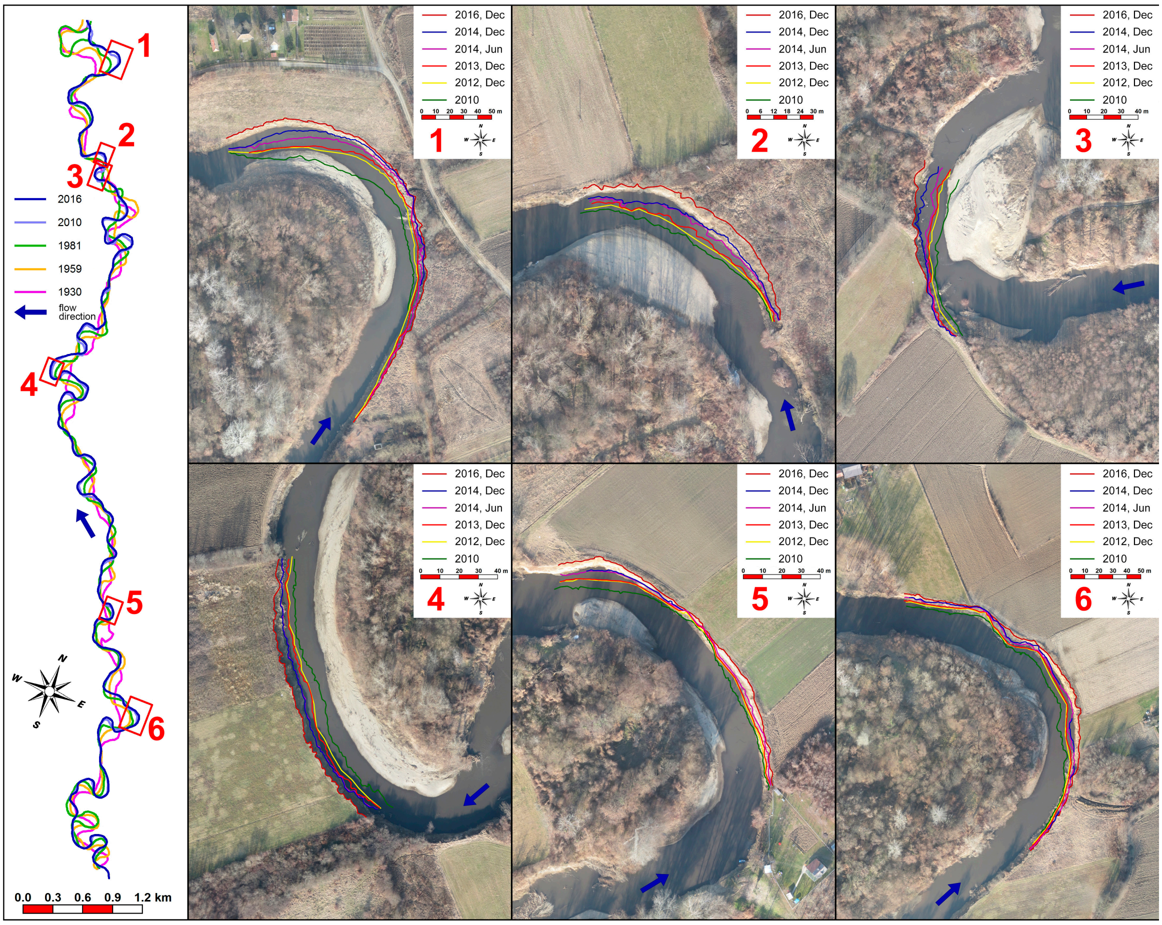


Figure 5. Bank erosion on six meanders in between 2010 and 2016.

Table 5. Erosion plots (land loss) in monitored meanders.

Erosion Plot (ha)	Long-Term Period				Short-Term Period				
	1930–1959	1959–1981	1981–2010	Total	2010–2012	2012–2013	2013–2014	2014–2016	Total
Location 1	3.7	3.8	2.0	9.5	0.1308	0.0458	0.0887	0.14076	0.4159
Location 2	2.0	0.2	1.0	3.2	0.0209	0.0127	0.0299	0.04057	0.1389
Location 3	0.4	0.9	0.8	2.1	0.0391	0.0168	0.0160	0.04209	0.1279
Location 4	1.0	1.0	2.0	4.0	0.0549	0.0157	0.0374	0.03986	0.1697
Location 5	0.3	0.2	0.3	0.8	0.0372	0.0070	0.0282	0.03008	0.1209
Location 6	2.0	2.0	0.9	4.9	0.0679	0.0194	0.0488	0.05933	0.2108

5. Discussion

What could be the reason for the increase in intensity of bank erosion over the last six years? Previous results have shown that a strong correlation exists between the Kolubara riverbed and the suspended sediment concentration and water discharge [36]. All of the Kolubara River water discharges near and over 100 $m^3 \cdot s^{-1}$ in the researched section had critical levels, and it was shown that the largest suspended sediment concentration appeared at the very peak of the incoming flood wave, and together with its passing, came to an outstanding non-linear decrease in their values. Bank-full discharge has been identified as an important parameter for studying river morphology, sediment transport, flood dynamics, and their ecological impacts [67–69]. Additionally, bank erosion is highly influenced by water discharge variability, especially bank-full discharge.

An extreme rate of bank erosion occurred in 2014 after the flood wave passed. The results showed that the land loss during 2014 was three times bigger than in 2013. The flood wave in May 2014 (duration four days) caused a bank erosion rate of 7.1 m on meander 1 and lost 0.25 ha across all six locations, which was 30.3% of land loss in the four years of observation (2010–2014).

To quantify the relationship between discharge and the average bank erosion rate, the discharge value is often used as a threshold corresponding to the flow filled with minor riverbed (bank-full discharge). The value of the bank-full discharge on the analyzed sector of the Kolubara River was 105.14 $m^3 \cdot s^{-1}$. The probability of occurrence of this discharge each year is 88%, which corresponds to a return period of 1.12 years. In comparison to the rivers of similar morphometric and hydrological characteristics, Kolubara is at a disadvantage. This means that almost annually, the water will leave the river bed and flood the alluvial zone; however, it is common that the threshold has a return period between 1.5 and 2 years.

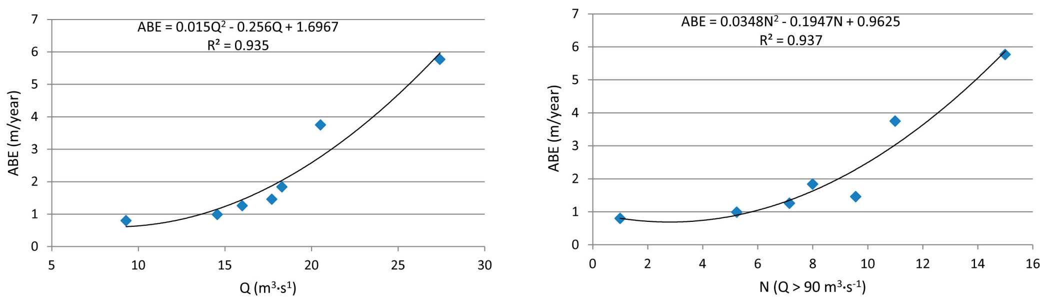
Since we had orthophotos from 1959, 1981, 2010, and geodetic survey for 2012, 2013, 2014, and 2016, we divided the corresponding data into the following series: 1959–2010 (A), 1959–1981 (B), 1982–2010 (C), 2010–2012 (D), 2013 (E), 2014 (F), and 2015–2016 (G) (Table 6).

Table 6. The relationship between the mean annual discharge (Q_y), the number of days per year with the discharge exceeding a selected threshold of 90 $m^3 \cdot s^{-1}$ (N), and average annual river bank erosion rate (ABE).

Analyzed Parameters	1959–2010	1959–1981	1982–2010	2010–2012	2013	2014	2015–2016	Coeff. Correl.		
Q_y ($m^3 \cdot s^{-1}$)	16.0	17.7	14.6	18.3	9.3	27.4	20.5	0.96	-	-
N (Q > 90 $m^3 \cdot s^{-1}$)	7.2	9.6	5.2	8.0	1.0	15.0	11.0		0.83	0.92
ABE ($m \cdot year^{-1}$)	1.26	1.46	0.99	1.84	0.80	5.77	3.75	-		-

Since all three are completely independent variables and have a high correlation among themselves (coeff. correl.), we developed a forecasting model where we could use for Y (the dependent variable) any of the given variables. When it comes to the average movement of the riverbanks (ABE), the models are as follows:

Both models (Figure 6) have their practical uses, although they must consider the small number of observations (7). Our results revealed that the annual bank erosion rate increased exponentially by increasing the mean annual discharge (adj. R^2 = 0.935). Analysis of the first graph (Figure 6a) indicated that the intensity of riverbank movement remained in the range of one meter per year when the mean annual discharge did not exceed the value of the average annual water (16 $m^3 \cdot s^{-1}$). With further increase of the mean annual discharge, erosion progressed faster, and when the discharge as greater than 20 $m^3 \cdot s^{-1}$, it reached a value of more than three meters. This discharge had an occurrence probability of 24% (an empirical value), which meant that it occurred approximately once in every four years. Unfortunately, between that value and the largest one in a series (27 $m^3 \cdot s^{-1}$), there was no measurement of bank movements, so we had to rely on the theoretical estimates.



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

Figure 6. Estimation of average annual riverbank erosion ABE ($m \cdot year^{-1}$) using the mean annual discharge ($m^3 \cdot s^{-1}$) (**a**) and the number of annual discharges which exceed the value of 90 $m^3 \cdot s^{-1}$ (N) (**b**).

According to another dependence (Figure 6b), the riverbank will move up to one meter per year if a daily discharge of 90 $m^3 \cdot s^{-1}$ or more occurs no more than five times per year. With higher frequency, riverbanks become more erodible, and a case from 2014 showed that this threshold may exceed 15 times and thereby move the riverbank almost six meters. Comparing these two dependencies, one can conclude that the second might be more practical. The first reason is that the mean annual discharge only indirectly applies to frequent water, like bank-full discharge and that extrapolations are actualize very rare (only the 1970s and 2010 in the whole series). On the other hand, the number of overcoming bank-full discharge are data that directly affects the vulnerability of riverbanks. Although the maximum value observed in the series was 15 (2014), the number of occurrences over the threshold for 58 years is five.

If we accept the previous models as relevant, it would mean that river banks movement can be estimated through the characteristic waters of that river. In this case (example of model 6a), the displacement limit of one meter per year would correspond to the average annual discharge, while increase of the mean annual discharge by 25% would initiate bank erosion process which would be three times more intensive. It seems that these results (displacement 1–3 m per year) reflect the real state of the Kolubara River, where its discharges vary from minimal to those that occur once every four years. For the extreme values of the discharge (period of overcoming is more than five years), the reliability of the estimation of river banks movement decreases and we are not sure if it would always follow the presented theoretical curve. In that case, the annual distribution of discharges, i.e., the frequency of high waters, would be very important. This is indicated by the second model (Figure 6b), when a bank-full discharge occurs 1 to 10 times a year, causing the riverbed movement from 1 to 2 m and only after that the intensity of bank erosion process rapidly increases. If such trends would be proved on other profiles of the Kolubara River (Slovac, Drazevac, Obrenovac, it is not real to expect the same on the tributaries), then this model could be applied to river basins with similar hydrological characteristics.

Considering that the consequences of river banks movement in the territory of Serbia are very serious, especially in the river basins similar to the Kolubara River Basin, where settlements are located along the river and they are unprotected, and the land is very fertile, investing in the monitoring of this process and an adequate reaction is much cheaper than the repair of damages and the loss of material goods. So, a better understanding of the water discharge impact on the river channel migration is of great importance for the assessment of economic consequences which can be analyzed through the loss of land (reduction of arable land) and loss of the amount of agricultural production. Also, the results of this study could be a warning for future anthropogenic activities on the Kolubara River system, since new changes in the hydrographical network were planned in this area. Four new mining fields are planned, and if that plan realizes, the hydrographic network will be changed again, resulting in the appearance of new problems in the river basin. That is why our numerical models, although with a small number of data, can be of great use to the upstream and downstream sectors of the Kolubara River, which are also vulnerable to floods and to which the bank erosion assessment can be applied.

6. Conclusions

The Kolubara River represents a dynamic river system with distinct lateral instability and bank erosion. The results of this study showed that the mean annual discharge in the observed period (1959–2016) decreased by 0.37 $m^3 \cdot s^{-1}$ (-2.3%) per decade, or that a total loss per trend line is 2.11 $m^3 \cdot s^{-1}$ ($-13.2\%/58$ years). On the other hand, the measurements during the short-term period of observation (from 2010) showed that frequent discharge variations and the rapid change of its extreme values caused more intensive bank erosion than in the long-term period of observation.

On the basis of the observed hydrological and morphological changes, a simple channel development model can be outlined. In the long-time period, the decrease in water discharge initiates channel narrowing, and meanders reach their maximum sustainable length at the given discharge level. As rapid floods with high discharge become more abundant, owing to climate change, future lateral migration and soil loss will be more intensive, similar to previous short-time periods. Short-duration and strong-destruction are the main features of bank erosion during these periods. One of the key factors that affect the evolution of a river channel is the frequency of water discharge greater than 90 $m^3 \cdot s^{-1}$ and bank-full discharge (105.14 $m^3 \cdot s^{-1}$), as the magnitude of flood events. A high rate of bank erosion and loss of land was measured at all of the studied meanders in 2014 when an extreme flood occurred. Consequently, changes in the characteristic stages and frequency of floods since 2010 can highly influence the long-term tendencies of channel migration. Therefore, it is important to define correct river bank protection measures. Extreme hydrological events are characteristic of most rivers in Serbia (and in the region) [70], so timely measures to protect river banks can be widely applied.

Based on the established intensity of bank erosion and its recent state, adequate solutions for the rehabilitation of endangered riverbanks were found, as well as the type of solutions (soft and hard engineering) that can be applied to stop lateral erosion. Changes in river channel form and their consequences in the study area can also be predicted. In the case of the Kolubara River, with the curvature of the river route and a large number of active meanders, there are two possible solutions: the full retention of the existing river channel with construction of the bank revetment along the endangered river banks, or a partial adjustment of the existing channel, i.e., by performing a cross-section of the sharpest curvatures. In the case of large meanders with long concave riverbanks, the rational solution is to cut off curves and excavate a new riverbed. This solution has advantages (according to economic criteria) due to the lower prices of works and the hydraulic characteristics of the watercourse. Furthermore, other softer engineering solutions may also be considered.

An integrated Kolubara River Basin management plan, with the proper selection of land use and organization of erosion control works, would bring a balanced runoff regime of the river. Furthermore, the flood peaks and flood risks would be diminished, as would risks of collapsing riverbanks. These activities have an influence on the enhancement of the basin's hydrological condition in terms of flood risks diminishing, destructive water effects, and it would be a process that could lead to a permanent solution for soil erosion, floods and riverbank erosion in the lower part of the Kolubara River.

Acknowledgments: This paper is part of the project "The Research on Climate Change Influences on Environment: Influence Monitoring, Adaptation and Mitigation" (43007), subproject No. 9: "Torrential Floods Frequency, Soil and Water Degradation as the Consequence of Global Changes," financed by Ministry of Education, Science and Technological Development of the Republic of Serbia as part of the Integrated and Interdisciplinary Researches program for the period from 2011 to 2017.

Author Contributions: Slavoljub Dragićević and Nenad Živković conceived the study, made the statistical analysis and interpretation of the data, and wrote the manuscript. Mirjana Roksandić and Ivan Novković performed GIS and numerical analysis. Stanimir Kostadinov also performed part of the numerical analysis and contributed to the revision of the paper. Marko Langović, Boban Milojković, and Zoran Čvorović performed the field measurements. All authors were involved in the language improvements of the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hooke, J.M. Spatial variability, mechanisms and propagation of change in an active meandering river. *Geomorphology* **2007**, *84*, 277–296. [CrossRef]
2. Knighton, D. *Fluvial Forms and Processes—A New Perspective*, 1st ed.; Arnold: London, UK, 1998; p. 383. ISBN 034066313.
3. Petrovszki, J.; Székely, B.; Timár, G. A systematic overview of the coincidences of river sinuosity changes and tectonically active structures in the Pannonian Basin. *Glob. Planet. Chang.* **2012**, *98–99*, 109–121. [CrossRef]
4. Petrovszki, J.; Timár, G.; Molnár, G. Is sinuosity a function of slope and bankfull discharge?—A case study of the meandering rivers in the Pannonian Basin. *Hydrol. Earth Syst. Sci. Discuss.* **2014**, *11*, 12271–12290. [CrossRef]
5. Blanka, V.; Kiss, T. Effect of different water stages on bank erosion, case study of river Hernad, Hungary. *Carpathian J. Earth Environ. Sci.* **2011**, *6*, 101–108.

6. Zaimes, G.N.; Schultz, R.C.; Isenhart, T.M. Stream bank erosion adjacent to riparian forest buffers, row-crop fields, and continuously-grazed pastures along Bear Creek in central Iowa. *J. Soil Water Conserv.* **2004**, *59*, 19–27.
7. Surian, N.; Rinaldi, M. Morphological response to river engineering and management in alluvial channels in Italy. *Geomorphology* **2003**, *50*, 307–326. [CrossRef]
8. James, L.A.; Marcus, W.A. The human role in changing fluvial systems: Retrospect, inventory and prospect. *Geomorphology* **2006**, *79*, 152–171. [CrossRef]
9. Hooke, J.M. Human impacts on fluvial systems in the Mediterranean region. *Geomorphology* **2006**, *79*, 311–335. [CrossRef]
10. Kiss, T.; Fiala, K.; Sipos, G. Alterations of channel parameters in response to river regulation works since 1840 on the Lower Tisza River (Hungary). *Geomorphology* **2008**, *98*, 96–110. [CrossRef]
11. Vandenberghe, J.; de Moor, J.J.W.; Spanjaard, G. Natural change and human impact in a present-day fluvial catchment: The Geul River, Southern Netherlands. *Geomorphology* **2012**, *159*, 1–14. [CrossRef]
12. Kiss, T.; Blanka, V. River channel response to climate- and human-induced hydrological changes: Case study on the meandering Hernád River, Hungary. *Geomorphology* **2012**, *175–176*, 115–125. [CrossRef]
13. Popov, D.; Marković, S.; Štrbac, D. Generations of meanders in Serbian part of Tisa valley. *J. Geogr. Inst. Cvijic* **2008**, *58*, 29–42. [CrossRef]
14. Dragićević, S.; Tošić, R.; Stepić, M.; Živković, N.; Novković, I. Consequences of the River Bank Erosion in the Southern Part of the Pannonian Basin: Case study—Serbia and the Republic of Srpska. *Forum Geogr.* **2013**, *12*, 5–15. [CrossRef]
15. Tošić, R.; Lovrić, N.; Dragićević, S. Land use changes caused by bank erosion along the lower part of the Bosna River from 2001 to 2013. *Bull. Serbian Geogr. Soc.* **2014**, *94*, 49–58. [CrossRef]
16. Lovric, N.; Tosic, R. Assessment of bank erosion, accretion and lateral channel migration using remote sensing and GIS: Case study—Lower part of the Bosna River. *Quaest. Geogr.* **2016**, *35*, 81–92. [CrossRef]
17. Rădoane, M.; Rădoane, N.; Dumitriu, D. Geomorphological evolution of longitudinal river profiles in the Carpathians. *Geomorphology* **2003**, *50*, 293–306. [CrossRef]
18. Rădoane, M.; Pandi, G.; Rădoane, N. Contemporary bed elevation changes from the eastern Carpathians. *Carpathian J. Earth Environ. Sci.* **2010**, *5*, 49–60.
19. Rădoane, M.; Obreja, F.; Cristea, I.; Mihailă, D. Changes in the channel-bed level of the eastern Carpathian rivers: Climatic vs. human control over the last 50 years. *Geomorphology* **2013**, *193*, 91–111. [CrossRef]
20. Floriou, I. Types of riverbed along the lower course of the Buzau River. *Forum Geogr.* **2011**, *10*, 91–98. [CrossRef]
21. Perşoiu, I.; Rădoane, M. Spatial and temporal controls on historical channel responses—Study of an atypical case: Someşu Mic River, Romania. *Earth Surf. Process. Landf.* **2011**, *36*, 1391–1409. [CrossRef]
22. Petkovic, S.; Petkovic-Obratov, D. Harmonization of the engineering and environmental objectives of the river management—Case study of the Južna Morava river. *Bull. Fac. For.* **2001**, *92*, 125–148. [CrossRef]
23. Petkovic, S.; Malesev, M.; Krunic, B.; Damjanovic, V. River management based on harmonization of principal goals of river training. *Water Sanit. Technol.* **2013**, *43*, 17–24.
24. Dragicevic, S.; Zivkovic, N.; Roksandic, M.; Kostadinov, S.; Novkovic, I.; Tosic, R.; Stepic, M.; Dragicevic, M.; Blagojevic, B. Land use changes and environmental problems caused by bank erosion: A case study of the Kolubara River Basin in Serbia. In *Environmental Land Use Planning*, 1st ed.; Appiah-Opoku, S., Ed.; InTech: Rijeka, Croatia, 2012; pp. 3–20. ISBN 978-953-51-0832-0. [CrossRef]
25. Dragicevic, S.; Stojanovic, Z.; Manic, E.; Roksandic, M.; Stepic, M.; Zivkovic, N.; Zlatic, M.; Kostadinov, S. Economic consequences of bank erosion in the lower part of the Kolubara River Basin, Serbia. *Environ. Eng. Manag. J.* **2017**, *16*, 381–390.
26. Roksandic, M.; Dragicevic, S.; Zivkovic, N.; Kostadinov, S.; Zlatic, M.; Martinovic, M. Bank erosion as a factor of soil loss and land use changes in the Kolubara River Basin, Serbia. *Afr. J. Agric. Res.* **2011**, *6*, 6604–6608. [CrossRef]
27. Dragićević, S.; Živković, N.; Kostadinov, S. Changes of hydrological system in the lower course of the Kolubara River. In *Floods, Morphological Processes, Erosion, Sediment Transport and Sedimentation, Proceedings of the XXIV Conference of the Danubian Countries on the Hydrological Forecasting and Hydrological Bases of Water Management, Bled, Slovenia, 2–4 June 2008*; Mitja, B., Mojca, Š., Eds.; Slovenian National Committee for the IHP UNESCO: Ljubljana, Slovenia, 2008; Volume 5, p. 186. ISBN 978-961-91090-3-8.

28. Dragićević, S.; Živković, N.; Roksandić, M.; Luković, J.; Kostadinov, S. *Recent State, Intensity and Consequences of Degradation of the Riverbanks of Kolubara in the Territory of Obrenovac Municipality*, 1st ed.; Faculty of Geography, University of Belgrade: Beograd, Serbia, 2015; p. 266. ISBN 978-86-6283-028-9. (In Serbian with Summary in English)
29. Manojlović, P.; Dragićević, S.; Mustafić, S. The basic morphometric characteristics of Serbian relief. *Bull. Serbian Geogr. Soc.* **2004**, *84*, 11–20. [CrossRef]
30. Bada, G.; Horváth, F.; Dövényi, P.; Szafián, P.; Windhoffer, G.; Cloetingh, S. Present-day stress field and tectonic inversion in the Pannonian basin. *Glob. Planet. Chang.* **2007**, *58*, 165–180. [CrossRef]
31. Ćalić, J.; Gaudenyi, T.; Milošević, M.V.; Štrbac, D.; Milivojević, M. Geomorphometrical method for delineation of plains—Case study of the South-Eastern (Serbian) segment of the Pannonian Plain. *Carpathian J. Earth Environ. Sci.* **2012**, *7*, 239–248.
32. Ćalić, J.; Milošević, V.M.; Gaudenyi, T.; Štrbac, D.; Milivojević, M. Pannonian Plain as a morphostructural unit of Serbia. *Bull. Serbian Geogr. Soc.* **2012**, *92*, 47–70. [CrossRef]
33. Živković, N.; Dragićević, S.; Ristić, R.; Novković, I.; Djurdjić, S.; Luković, J.; Živković, L.; Jovanović, S. Effects of vegetation on runoff in small river basins in Serbia. *Fresenius Environ. Bull.* **2015**, *24*, 2082–2089.
34. Kasvi, E.; Laamanen, L.; Lotsari, E.; Alho, P. Flow patterns and morphological changes in a sandy meander bend during a flood—Spatially and temporally intensive ADCP measurement approach. *Water* **2017**, *9*, 106. [CrossRef]
35. Gu, L.; Zhang, S.; He, L.; Chen, D.; Blanckaert, K.; Ottevanger, W.; Zhang, Y. Modeling flow pattern and evolution of meandering channels with a nonlinear model. *Water* **2016**, *8*, 418. [CrossRef]
36. Dragićević, S.; Živković, N.; Novković, I.; Petrović, A.; Tošić, R.; Milevski, I. Hydrological and suspended sediment regime in the Kolubara River during the extreme year of 2014. *Revista de Geomorfologie* **2016**, *18*, 26–38.
37. Dragićević, S. *Dominant Processes of Erosion in the Kolubara River Basin*, 1st ed.; Faculty of Geography, University of Belgrade: Belgrad, Serbia, 2007; p. 245. ISBN 978-86-82657-63-7. (In Serbian with Summary in English)
38. Dragićević, S.; Ristić, R.; Živković, N.; Kostadinov, S.; Tošić, R.; Novković, I.; Borisavljević, A.; Radić, Z. Floods in Serbia in 2010–Case study: The Kolubara and Pcinja River Basins. In *Geomorphological Impacts of Extreme Weather: Case Studies from Central and Eastern Europe*, 1st ed.; Loczy, D., Ed.; Springer: Dordrecht, The Netherlands, 2013; pp. 155–170. ISBN 978-94-007-6301-2. [CrossRef]
39. Dragicevic, S.; Carevic, I.; Kostadinov, S.; Novkovic, I.; Abolmasov, B.; Milojkovic, B.; Simic, D. Landslide susceptibility zonation in the Kolubara River Basin (western Serbia)—Analisys of input data. *Carpathian J. Earth Environ. Sci.* **2012**, *7*, 37–47.
40. Dragićević, S. Pluviometric regime and its influence on erosive process in the Kolubara River Basin. *Bull. Serbian Geogr. Soc.* **2001**, *80*, 27–36, (In Serbian with Summary in English).
41. Burić, D.; Stanojević, G.; Luković, J.; Gavrilović, L.; Živković, N. Climate change and river discharge: Case study Kolubara river, Beli Brod hydrological gauge. *Bull. Serbian Geogr. Soc.* **2012**, *92*, 123–134. [CrossRef]
42. Petrović, A.; Dragićević, S.; Radić, B.P.; Milanović Pešić, A.Z. Historical torrential flood events in the Kolubara River Basin. *Nat. Hazards* **2015**, *79*, 537–547. [CrossRef]
43. Republic Hydrometeorological Service of Serbia (RHMOS). *Meteorological and Hydrological Annual Reports—Precipitation and Surface Water*; RHMOS: Belgrade, Serbia, 2014.
44. Lawler, D.M. The measurement of river bank erosion and lateral channel change: A review. *Earth Surf. Process. Landf.* **1993**, *18*, 777–821. [CrossRef]
45. Grove, J.R.; Croke, J.; Thompson, C. Quantifying different riverbank erosion processes during an extreme flood event. *Earth Surf. Process. Landf.* **2013**, *38*, 1393–1406. [CrossRef]
46. Yang, C.; Cai, X.; Wang, X.; Yan, R.; Zhang, T.; Zhang, Q.; Lu, X. Remotely sensed trajectory analysis of channel migration in Lower Jingjiang reach during the period of 1983–2013. *Remote Sens.* **2015**, *7*, 16241–16256. [CrossRef]
47. Hughes, M.L.; McDowell, P.F.; Marcus, A.W. Accuracy assessment of georectified aerial photographs: Implications for measuring lateral channel movement in a GIS. *Geomorphology* **2006**, *74*, 1–16. [CrossRef]
48. Ayalew, L. Analyzing the effects of historical and recent floods on channel pattern and the environment in the Lower Omo basin of Ethiopia using satellite images and GIS. *Environ. Geol.* **2009**, *58*, 1713–1726. [CrossRef]

49. Nicoll, T.J.; Hickin, E.J. Planform geometry and channel migration of confined meandering rivers on the Canadian prairies. *Geomorphology* **2010**, *116*, 37–47. [CrossRef]
50. De Rose, R.C.; Basher, L.R. Measurement of river bank and cliff erosion from sequential LIDAR and historical aerial photography. *Geomorphology* **2011**, *126*, 132–147. [CrossRef]
51. Yao, Z.; Ta, W.; Jia, X.; Xiao, J. Bank erosion and accretion along the Ningxia—Inner Mongolia reaches of the Yellow River from 1958 to 2008. *Geomorphology* **2011**, *127*, 99–106. [CrossRef]
52. Prosdocimi, M.; Sofia, G.; Dalla Fontana, G.; Tarolli, P. Bank erosion in agricultural drainage networks: New challenges from structure-from-motion photogrammetry for post-event analysis. *Earth Surf. Process. Landf.* **2015**, *40*, 1891–1906. [CrossRef]
53. Richard, G.A.; Julien, P.Y.; Baird, D.C. Statistical analysis of lateral migration of the Rio Grande, New Mexico. *Geomorphology* **2005**, *71*, 139–155. [CrossRef]
54. Gurnell, A.M. Channel change on the River Dee meanders, 1946–1992, from the analysis of air photographs. *Regul. Rivers Res. Manag.* **1997**, *13*, 13–26. [CrossRef]
55. Winterbottom, S.J.; Gilvear, D.J. A GIS-based approach to mapping probabilities of river bank erosion: Regulated River Tummel, Scotland. *Regul. Rivers Res. Manag.* **2000**, *16*, 127–140. [CrossRef]
56. Hooke, J.M. An analysis of the processes of river bank erosion. *J. Hydrol.* **1979**, *42*, 39–62. [CrossRef]
57. Hooke, J.M. Magnitude and distribution of rates of river bank erosion. *Earth Surf. Process. Landf.* **1980**, *5*, 143–157. [CrossRef]
58. Hudson, P.F.; Kesel, R.H. Channel migration and meander-bend curvature in the lower Mississippi River prior to major human modification. *Geology* **2000**, *28*, 531–534. [CrossRef]
59. Mount, N.; Louis, J. Estimation and propagation of error in measurements of river channel movement from aerial imagery. *Earth Surf. Process. Landf.* **2005**, *30*, 635–643. [CrossRef]
60. Simon, A.; Castro, J.; Rinaldi, M. Channel form and adjustment: Characterization, measurement, interpretation and analysis. In *Tools in Fluvial Geomorphology*, 2nd ed.; Kondolf, G.M., Piégay, H., Eds.; John Wiley & Sons, Ltd.: Chichester, UK, 2016; pp. 237–259.
61. Hooke, J.M. Temporal variations in fluvial processes on an active meandering river over a 20-year period. *Geomorphology* **2008**, *100*, 3–13. [CrossRef]
62. Couper, P.R.; Maddock, I.P. Subaerial river bank erosion processes and their interaction with other bank erosion mechanisms on the River Arrow, Warwickshire, UK. *Earth Surf. Process. Landf.* **2001**, *26*, 631–646. [CrossRef]
63. Stover, S.C.; Montgomery, D.R. Channel change and flooding, Skokomish River, Washington. *J. Hydrol.* **2001**, *243*, 272–286. [CrossRef]
64. Carroll, R.W.H.; Warwick, J.J.; James, A.I.; Miller, J.R. Modeling erosion and overbank deposition during extreme flood conditions on the Carson River, Nevada. *J. Hydrol.* **2004**, *297*, 1–21. [CrossRef]
65. Rusnák, M.; Lehotské, M. Time-focused investigation of river channel morphological changes due to extreme floods. *Zeitschrift für Geomorphologie* **2014**, *58*, 251–266. [CrossRef]
66. Jevtić, L. *Inženjerski Priručnik za Rešavanje Problema iz Oblasti Bujičnih Tokova*; Izdavačko Informativni Centar Studenata (ICS): Beograd, Serbia, 1978; p. 396. (In Serbian)
67. Williams, G.P. Bankfull discharge of rivers. *Water Resour. Res.* **1978**, *14*, 1141–1154. [CrossRef]
68. Navratil, O.; Albert, M.B.; Hérouin, E.; Gresillon, J.M. Determination of bankfull discharge magnitude and frequency: Comparison of methods on 16 gravel-bed river reaches. *Earth Surf. Process. Landf.* **2006**, *31*, 1345–1363. [CrossRef]
69. Roşca, S.; Bilaşco, Ş.; Petrea, D.; Fodorean, I.; Vescan, I. Bankfull discharge and stream power influence on the Niraj River morphology. *Carpathian J. Earth Environ. Sci.* **2015**, *10*, 133–146.
70. Blöschl, G.; Hall, J.; Parajka, J.; Perdigão, R.; Merz, B.; Arheimer, B.; Aronica, G.; Bilibashi, A.; Bonacci, O.; Borga, M.; et al. Changing climate shifts timing of European floods. *Science* **2017**, *357*, 588–590. [CrossRef] [PubMed]