OPEN ACCESS
Water Economics and Policy, (2024) 2450003 (24 pages)

DOI: 10.1142/S2382624X24500036

Assessment of the Economic Consequences of Riverbank Erosion: The Case of the South Morava River, Serbia

Marko Langović[*,‡], Svetlana Popović[†], Slavoljub Dragićević[*], Žaklina Stojanović[†] and Emilija Manić[†]

[*]*Department of Physical Geography*
Faculty of Geography, University of Belgrade
Studentski trg 3/3, Belgrade, Serbia

[†]*Department for Economic Policy and Development*
Faculty of Economics and Business
University of Belgrade, Kamenička 6, Belgrade, Serbia
[‡]*marko.langovic@gef.bg.ac.rs*

Received 22 April 2023
Revised 1 March 2024
Accepted 1 March 2024
Published 30 April 2024

Landscape transformation, degradation and destruction are caused by fluvial processes as the predominant erosive processes in Serbia. The loss of arable land due to riverbank erosion is permanent, and the economic consequences are, therefore, especially pronounced. The primary aim of this study was to quantify the intensity of riverbank erosion in the lower part of the South Morava River (Serbia) during period 1924–2020, evaluate its economic consequences, and conduct a cost benefit analysis of revetment investments. The economic effects of riverbank erosion were analyzed by means of land loss and reduction in the quantity of agricultural production. An interdisciplinary research approach was applied using specific methodological procedures to calculate the riverbank erosion and soil (land) loss intensity (geographic information system-GIS), the economic consequences of riverbank erosion (ECRE), and the results of an investment decision-making model. The results showed that 202.6 ha of arable land was lost during the observed period, the value of arable land loss was almost 622,000 USD, and the loss in agricultural production was 7.5 million USD (discount rate 3.7%). The model is seen as the main research

[‡]Corresponding author.

output and can be used for the assessment of long-term capital-intensive infrastructure projects in developing countries. The analysis identified the river segments that are economically viable for investments in riverbank revetments to preserve the largest area of fertile agricultural land. The results are especially valuable for river channel management, environmental planners and policy-makers, who deal with decisions regarding planning and the protection of bank erosion in areas of particular interest.

Keywords: Riverbank erosion; soil loss; economic consequences; revetment.

1. Introduction

Lateral bank erosion of meandering rivers is responsible for the extensive destruction of arable lands and landscape degradation and usually has very severe ecological and economic consequences. Riverbank erosion represents a constituent element or phase of lateral channel migration and, accordingly, is recognized as the most significant geomorphological process of the alluvial plains (Hai *et al.* 2019; Gyenizse *et al.* 2020; Rahman and Gain 2020; Bernier *et al.* 2021; Hooke 2023). In this way, the fluvial landscape is modified, and different fluvial forms, such as degraded riverbanks, cutoff meanders, point bars and oxbow lakes, are formed. Due to geographic and environmental specificities, an understanding of riverbank erosion and the interfaces and consequences linked to these phenomena are of crucial importance for applications such as water and soil management, water economics, and landscape planning.

Accordingly, several different aspects have been identified in the framework of fluvial landscape transformation caused by intensive riverbank erosion. Previous studies have predominantly examined geographical (Palmer *et al.* 2014), economic (Ahmed and Fawzi 2011; Tošić *et al.* 2014; Rusnák *et al.* 2016; Dragićević *et al.* 2017a; Hassan *et al.* 2018; Myagmar *et al.* 2022), environmental (Bertalan *et al.* 2019), sociodemographic (Das *et al.* 2017; Dekaraja and Mahanta 2021), psychological (Hossain *et al.* 2021), and political aspects of this process (Dragićević *et al.* 2013).

The economic outcomes primarily comprise the loss of agricultural land and reduction in the quantity of agricultural production, destruction of infrastructure facilities, migration of the population from areas of intensive bank erosion, and loss of economic activities caused by land use changes. To assess the complex effects of economic consequences comprehensively, it is necessary to apply an interdisciplinary research approach (Bertalan *et al.* 2019; Kiss *et al.* 2019). Soil loss due to riverbank erosion is permanent, so the effect of this process is especially pronounced and requires appropriate evaluation. Productive and agricultural land on the concave part of the riverbank is eroded, whereas the land formed on the point bars is mostly covered by bushy or woody vegetation (Yousefi *et al.* 2017), with no significance for agricultural development. In addition, Bertalan *et al.* (2018) emphasize the positive effects of riverbank erosion and accumulation processes in terms of the promotion of riparian vegetation succession, nature conservation, the creation of dynamic riparian habitats, and ecological sustainability. Consequently, newly formed areas may even be recultivated by human activities (which can partially annul the economic loss caused by arable land destruction) but will most likely have less value in terms of fertility, potential and agricultural soil classification.

The Republic of Serbia is characterized by numerous meandering rivers with intensive lateral bank erosion. Therefore, in the last 10 years, several papers have focused on investigating this process from different scientific perspectives (Roksandic *et al.* 2011; Dragićević *et al.* 2013, 2017a; Langović 2020; Langović *et al.* 2021) and applied a disaster management approach to explain the economic consequences of riverbank erosion (ECRE) in the Kolubara River Basin in Serbia (Dragićević *et al.* 2013). The analysis advocated a proactive prevention approach using economic models (Gomez *et al.* 2018) to evaluate riverbank protection and economic consequences that might be mitigated by measures taken in areas of particular interest. The determination of river channel evolution and quantification of riverbank erosion intensity over the long-term period of almost 100 years provides a new research perspective for this type of study. The works mentioned above focused on assessing the amount of land lost and the intensity of the process due to changes in riverbanks, while our work goes further. It quantifies the ECRE and provides the first insights into revetment investment in less developed countries, adding value to previous analyses. These countries, including Serbia, face numerous methodological problems. Among them, the most important are those related to the lack of necessary data and the complexity of the quantification of long-run project results, including economic, social and environmental aspects. This study aims to help the decision-making process in these countries despite the challenges mentioned above.

The main goal of this study is to quantify and assess the ECRE in the lower part of the South Morava River in Serbia. The intensity of riverbank erosion was observed during the period 1924–2020 to evaluate the direct economic consequences, which is a long period rarely present in the broader literature. Most scientific research on riverbank erosion intensity refers to an observation period of up to 50 years. Consequently, particular attention is paid to the long-run economic analysis of the consequences of riverbank erosion, overwhelmed by historical and methodological issues (such as structural changes and transformation, monetary policy and banking restructuring, exchange rate and interest rate policy, and data availability). An interdisciplinary research framework involves close collaboration between geographers and economists. The analysis sheds light on both geographic and economic variables that influence the calculation of the economic effects of riverbank erosion and potential costs and revenues of investments in riverbank protection, as well as on the identification of geographic and economic variables that influence this calculation (with firm roots in theory and market practice), which is found to be the main contribution of the paper. This analysis is particularly important for less-developed countries, considering the overall challenges of sustainable rural development.

The main outputs of this study include (1) the creation of a significant database on riverbank erosion intensity for a period of almost one century, (2) the quantification of direct economic effects based on the different geographic and economic variables with the strongest influence, (3) the results of an investment decision-making model with the identification of river segments where investments in revetments would preserve the largest area of fertile agricultural land, (4) a scenario analysis (using different interest rates), and (5) applying the investment decision-making approach in less-developed countries.

2. Materials and Methods

2.1. *Study area*

The South Morava River Basin is situated in the southeastern part of the Republic of Serbia, the northern part of North Macedonia and the western part of the Republic of Bulgaria. It covers an area of 15,469 km^2. The main course of the South Morava River originates at the confluence of the Binačka Morava and Preševska Moravica rivers at an altitude of 392 m (Bujanovac). Near Stalać (145 m above sea level), the South Morava River (right-side tributary) and West Morava River (left-side tributary) form the Great Morava River (Figure 1). The South Morava River Valley is characterized by composite features in the south to north direction, with the presence of several gorges and valleys. In terms of the intensive morphodynamic aspect, frequent changes in the riverbed position, the meandering process, bank erosion, and accumulation formation consisting of sand and gravel are characteristic of the South Morava River lower sector (Langović 2020).

Consequently, the sector of the South Morava River that extends through the southern part of the Aleksinac Valley was determined to be a representative area for this study. The defined study area is occupied by the river course with the following river chainage: 62 km + 471 m (northern point) — 71 km + 470 m (southern point). This sector is characterized by a wide alluvial plain of the South Morava River, consisting of Pleistocene and Quaternary sediments, which causes

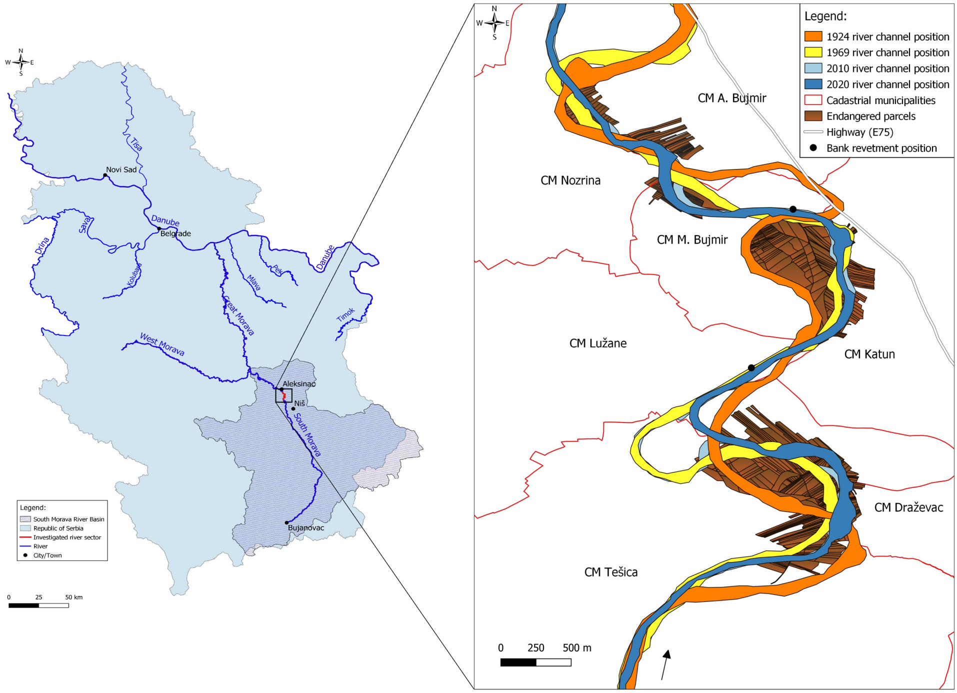

Figure 1. Defined Study Sector and Morphological Changes of the River Channel (1924–2020)

the river to change its course laterally. In general, the investigated section consists of five more pronounced meandering curves with different meander development stages (simple or complex) (Figure 1). The intensification of riverbank erosion in recent decades has been due to hydrological variability that is directly influenced by climate change (Schmidt and Taylor 2016). Although the South Morava River is characterized by a significantly decreasing trend in annual and seasonal river discharges, the occurrence of extreme hydrological conditions is pronounced. In addition, one extreme discharge value can be responsible for the intensity of riverbank erosion over several years. In the observed period of 96 years, it is necessary to highlight mid-February 1963 when intense precipitation caused a peak in the daily river discharge value at the Kurvingrad hydrological station (19.02.1963–1850 m^3/s or a value 97% higher than the average for the entire period).

Apart from specific natural characteristics, the South Morava River Basin is characterized by complex social features. The anthropogenic pressure on the South Morava River has remained constant over the last 96 years. During the 1960s, intensive regulation in the basin started and included two types of control activities: erosion control works in the basin, including the construction of reservoirs on important tributaries, and direct regulation of the South Morava River course (construction of bank revetment, stone dumps, meander straightening, etc.). The defined study sector (Figure 1) is characterized by the absence of significant regulatory works, especially in terms of decreasing the intensity of riverbank erosion, which classified it as appropriate. However, two bank revetments are located in this area (Figure 1): the first on the right side, built in the late 1960s ($L = 290$ m) for highway stability, and the second in 1996 on both sides ($L = 50$ m) because of a gas pipeline passage. Given their position and purpose, none of the revetments influenced the riverbank erosion process.

The entire sector is characterized by agricultural activities along the South Morava River, which particularly underscores the importance of investigating riverbank erosion in this area. The defined study area is located in the Aleksinac municipality and covers several cadastral municipalities: Aleksinački Bujmir, Nozrina, Moravski Bujmir, Katun, Lužane, Tešica, and Draževac (Figure 1). These settlements are characterized by agricultural production along the erodible banks of the South Morava River and by a significant share of the agricultural population in relation to the total. Furthermore, this was the base areal unit considered in the analysis of agricultural production data. The largest area of the riverbank zone is covered by corn fields, followed by different types of wheat and a small share of barley. Based on the statistical data for the earlier periods, fieldwork, orthophotos and aerial photogrammetry, corn and wheat were the dominant crop cultures along the study area, combined in a 60:40 ratio. The share of vegetable crops increases with increasing distance from the eroded banks. It is also important to emphasize that agricultural production in the study area is often seen as highly fragmented, characterized by the dominance of small family farms with subsistence orientation and implementation of traditional approaches in farm management in general (market orientation is neglected).

2.2. *Methodology*

The methodological workflow comprised three major processing steps (Figure 2): quantification of the riverbank erosion intensity, quantification of the ECRE, and identification of the outcomes of investment decision-making. The first step consisted of defining the spatial and temporal frameworks, acquiring data, quantifying riverbank erosion, and calculating the two main indicators. The second step relates to the quantification of the monetary value of the lost income in the observed period, and the third relates to the application of decision-making in the case of building riverbank revetments.

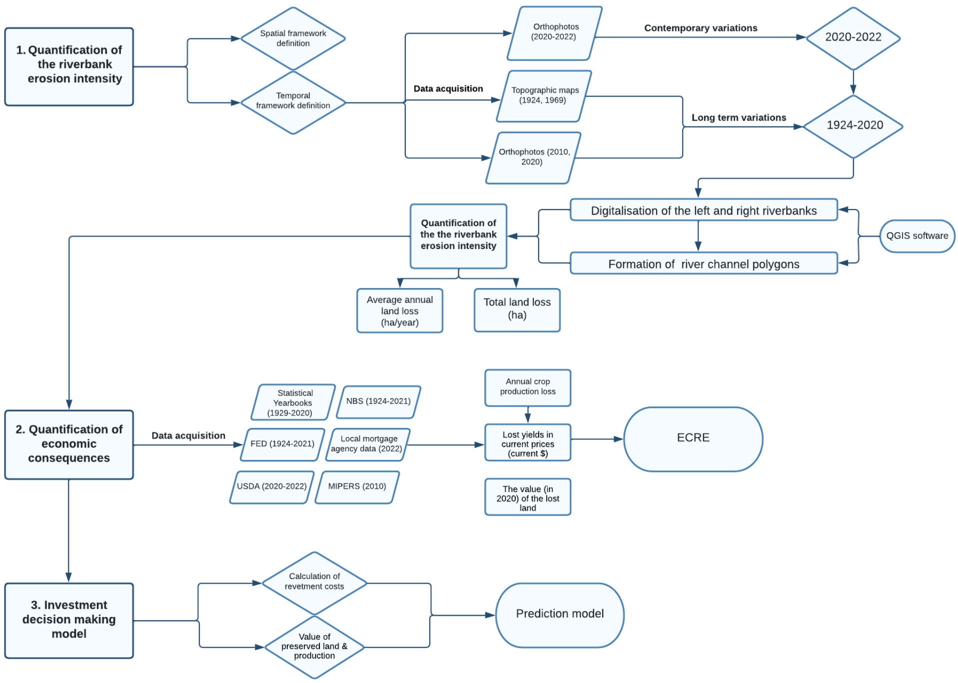

Figure 2. Methodological Flowchart

2.2.1. *Quantification of riverbank erosion intensity*

Riverbank erosion research is based on different methodological techniques related to the qualitative and quantitative determination of process intensity (Prosdocimi *et al.* 2015; Zhang and Rutherfurd 2020). Surveying fluvial landscape evolution in the spatial and temporal domains represents the first step toward determining the economic effects of riverbank erosion. The spatial and temporal dynamics of this process and the calculation of topographic changes are facilitated by the availability of cartographic and aerial documentation from different time periods (Rosli *et al.* 2021) as well as by the use of aerial and terrestrial photogrammetry (Dragićević *et al.* 2017b; Hemmelder *et al.* 2018; Binh *et al.* 2020).

The initial phase of this research included the selection of reliable sources and the determination of suitable time periods. Topographic maps at a scale of 1:25000 from 1924 and 1969 and orthophotos from 2010 and 2020 were used for data acquisition (Figure 2). The selected time period (1924–2020) made it possible to study the intensity of riverbank erosion and soil loss over a sufficiently long period to determine the economic consequences. Three-time intervals (1924–1969, 1970–2020, 2011–2020) were singled out to shed light on the process values in smaller time spans.

The second phase of the methodological procedure involved the use of different aspects of GIS software and geospatial analysis. In addition, the left and right riverbanks in the research sector were digitalized in all-time sections. The riverbank lines were digitalized according to the methodological concept proposed by Winterbottom and Gilvear (2000) and Grove *et al.* (2013) using the water boundary due to its clear definition on the topographical maps and in the orthophoto images and specific rules connected to the parts of the riverbanks covered with dense vegetation.

In the Quantum geographic information system (QGIS) software, polygons representing the river course at a certain time interval were formed. By overlapping and comparing data from various periods, the evolution of the river channel position over different time periods was defined. The occurrence of erosion along the outer channel line was estimated from the coordinates of each meander section during two distinct periods. After the implementation of the abovementioned procedure, the total soil loss (ha), which is one of the basic indicators of riverbank erosion, was quantified. Following this, the average annual soil loss (ha/year) was calculated for each period for a more precise comparison of the obtained results. On completion of this methodological segment, the values of total and average annual soil loss were calculated separately for every cadastral municipality (CM) that covers at least part of the research sector.

2.2.2. *Quantitative analysis of the ECRE*

The ECRE was assessed in the second part of the analysis. Different variables and circumstances were considered to investigate the ECRE. The methodology of Ervin and Mill (1985), Dixon *et al.* (1994) and Dragićević *et al.* (2017a) was employed to calculate the economic consequences of erosion. In the case of the South Morava River, the ECRE represents the agricultural production that could have been obtained in the area permanently lost due to the erosion of the South Morava riverbanks and the owner's income that could have been generated from the sales of that land in the observed period of 1924–2020:

$$\text{ECRE} = L_o + R_o + R_1(1+i)^1 + R_2(1+i)^2 \cdots + R_n(1+i)^{97}, \qquad (1)$$

where ECRE stands for the ECRE, L_0 is the revenue that could have been generated from land sale at the end of the observed period if conservation policies had been implemented, R_n is the value of the lost agricultural production (revenues or the conservation benefit during the period *0–n*, where n has the maximum value of 97 (1924–2020), i is the interest rate (chosen to compound the revenues lost in the past 96 years to obtain their value in 2020), R_0 is the lost revenue in 2020, R_1 is the lost revenue one year earlier, R_2 is the lost revenue two years earlier and R_n is the value of the lost agricultural production *n* years earlier (that is, the nominal yield — the value of crops lost in a given year and at dollar prices from that year).

Revenues are used for the analysis, not the profit, as what matters from the macroeconomic point of view is the total created value in the agricultural system. The costs of one agricultural producer represent the revenue for other stakeholders in the agricultural system. For the treatment of inflation, the methodology suggested by Prokofieva and Thorsen (2011), Zerbe and Scott (2015) and Australian Government, Department of Prime Minister and Cabinet, Office of Best Practice Regulation (2015) was used. Thus, since the value of crops is in nominal terms, interest rates used for compounding are also nominal (inflation premium is included).

The total and average annual soil losses were calculated under the assumption of constant intensity of bank erosion during the observation period. The dominant orientation of the agricultural production of the microlocations was analyzed. Crop production is dominant in most of the Aleksinac municipality according to multiple indicators method calculations.

Since the research covers a long-time horizon and the value of money changes over time, the nominal values of lost production were compounded to determine their values in 2020. The value of the lost production was calculated based on the average annual yields of crop production (corn and wheat) for the Aleksinac municipality and the prices of the selected crops in the observed period. To obtain the average annual production (corn and wheat in tons per hectare), different data were used, mostly selected from combined statistical publications of the Statistical Republic Office of Serbia (SROS) from 1924 to 2020. The missing crop production data for the period around the Second World War (1940–1947) were obtained using an interpolation method (Lepot *et al.* 2017). The prices of corn and wheat available from the United States Department of Agriculture database (USDA 2022) were used to overcome the lack of reliable prices in the local currency for the observed period (1924–2020). The use of world prices in dollars helped to understand how much producers would earn under the market economic conditions. Simultaneously, the exchange rate calculations were avoided.

The value of land loss (L_o) represents the total area lost by riverbank erosion until the end of the observed period (2020) multiplied by the current land price obtained from the mortgage agencies within the Aleksinac municipality. The lowest obtained land price of 2500 EUR/ha was taken as the reference, using the conservatism principle, because no significant land sales were recorded more recently (Birch and Sunderman 2003). Since all the values are in 2020 dollars (the lost yields and the land), the euro-dollar exchange rate for 31 December 2020, of 1.2271 dollars for one euro was used (European Central Bank 2020). As the research question was "what would be the value of the lost land if it existed today?" the current land price was used. The main reason for such an approach is derived from the fact that riverbank erosion is a cumulative process — there is no sense in calculating the market value of annual land loss. Based on a literature review, several interest rates were used in this research: 1% and 6% (following Dragićević *et al.* 2017a), 3.7% (average discount rate of the Federal Reserve Bank of New York for the United States (1950–2021)), 10% (social discount rate set by the Ministry of Finance of Serbia) (Ministry of Infrastructure and Public Enterprise Roads of Serbia 2010) and 13% (average discount rate of the National Bank of Serbia) (National Bank of Serbia 2022).

There were no protection works on the South Morava riverbanks upstream from the study area or within the studied area itself up to the time of the study. However, certain projects were carried out downstream to protect nearby highways and surrounding buildings, but these actions had no influence on the riverbank erosion process in the upstream area. In the third part of the research, investment decision-making was applied to the riverbank revetment investments that have long-term, complex and intangible benefits (Sapino *et al.* 2022).

Potential future revenues from building riverbank revetments were calculated using the following formula:

$$\mathrm{FR} = \frac{R_1}{(1+i)^1} + \frac{R_2}{(1+i)^2} + \cdots + \frac{R_n}{(1+i)^n} + \frac{L_n}{(1+i)^n}, \qquad (2)$$

where FR stands for the present value of future revenues (future revenues from the preserved land and yields), R_n is the value of agricultural production (potential revenues), L_n is the revenue that could have been generated from land sale at the end of the observed period if conservation policies had been implemented, i is the interest rate (chosen as discount rate for calculations), and n is the number of periods with a maximum value of 100.

Future revenues were used in calculations and not profit, as in the previous case, because the total value created in the agricultural sector is what matters for the analysis. Only the value created in agricultural production can be distributed among participants within the system and compared with the costs of building revetments.

To calculate potential yields in the future (future benefits of revetments), some restrictive assumptions were used. It is assumed that investment in revetments stops further riverbank erosion. The average yields for the period 2011–2020 were used as a proxy for annual yields in the coming years. This assumption is restrictive, as modern mechanization, better fertilizers and pesticides would make it possible to achieve even higher yields. This can be considered as the lower bound of the projection. The average prices for corn and wheat for the period 2011–2020 were used as the prices for each subsequent year. Keeping in mind the current food crisis, it is likely that these prices will be significantly higher in the future. Based on the same approach, the current land market price was used (2500 euro per hectare). This means that the calculated repayment period represents the upper limit in the studied case.

3. Results and Discussion

As the defined sector is characterized by an intensive rate of river meandering, lateral migration and riverbank erosion, the first part of the results includes an analysis of the lateral channel migration intensity during the selected time periods. The amount of lateral channel migration across the alluvial plain is a very important indicator of soil loss dynamics. According to the values of the obtained sinusoidal index, the selected sector was classified as meandering during the entire research period (1.75–1.84). The results show a gradational increase in river length in the period 1924–2020 of approximately 10% (Table 1). The maximum and average lateral channel migration rates were calculated separately for the two dominant meanders (M2 and M5) (Figure 3). The maximum lateral migration (M_{max}) had a value of 690.2 m, which indicates intensive riverbed extension. Notably, the highest values of average maximum lateral migration were recorded in the last period, 2011–2020, for both meanders, which suggests some intensification of riverbank erosion (Table 1).

Table 1. Main Morphometric Characteristics of the Studied Sector of the South Morava River

	1924	1969	2010	2020
L (km)	8.912	9.131	9.822	8.999
SI	1.75	1.79	1.84	1.76
	1969/1924	2010/1970	2020/2011	2020/1924
L (%)	2.3%	7.1%	−8.5%	0.02%
M5				
M_{max} (m)	488.1	57.4	202.3	690.2
AM_{max} (m/year)	10.8	1.43	20.23	7.2
M2				
M_{max} (m)	155.6	126.8	55.1	337.5
AM_{max} (m/year)	3.5	3.17	6.12	3.5

Notes: *L*, river length; SI, sinusoidal index; M_{max}, maximum lateral migration; AM_{max}, average maximum lateral migration; *L* (%), river length index change.

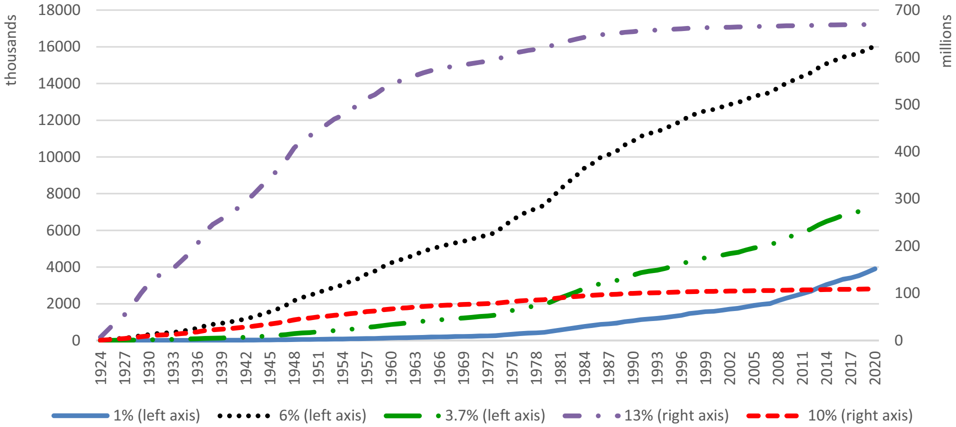

Figure 3. Value in Dollars of Lost Production with Different Interest Rates (used for Compounding) (*Source*: authors' calculation).

Long-term riverbank erosion analyses showed that in the period 1924–2020, 202.6 ha of soil along both riverbanks of the South Morava River, or 2.11 ha/year, was lost under the direct influence of this process. By comparing certain periods, it can be seen that the average soil loss was most intensive during the first part of the research period, 1924–1969 (3.35 ha/year). During the second time sequence, the process of soil loss showed a declining trend, as evidenced by data on the average loss in the period 1970–2010 (0.95 ha/year, see Table 2). In the last decade, process intensity has escalated, as determined by an average soil loss value of 1.56 ha/year. These results indicate that the defined sector is highly susceptible to intensive riverbank erosion.

Further analysis included observation of the total and average soil loss caused by riverbank erosion and lateral migration of the South Morava River according to the defined CM areas. The highest amount of soil loss was recorded in the CM of Tešica (109.4 ha or 54% of total soil loss), followed by Moravski Bujmir (28.02 ha or 13.9%) and Katun (24.8 ha or 13.7%). In contrast, the lowest amounts of soil loss for the entire research period were recorded in CM Nozrina (2.27 ha) and CM Draževac (7.46 ha), whose territories lie on the South Morava riverbed only in the peripheral parts. In the first period, soil loss intensity was significant in most of the studied municipalities and ranged from 1.96 ha/year in CM Tešica to 0.01 ha/year in CM Nozrina. The period 1924–1969 was characterized by an intensive morphodynamic phase distinguished by dynamic movements, free lateral migration and the development of meanders of the South Morava River (Figure 1). Simultaneously, a considerable expansion of agricultural land and production was also identified along the South Morava River during the same period.

Table 2. Total and Average Soil Loss Caused by Riverbank Erosion on the Defined River Sector

Period	1924–2020		1924–1969		1970–2010		2011–2020	
Cadastral Municipality	TSL (ha)	ASL (ha/year)	TSL (ha)	ASL (ha/year)	TSL (ha)	ASL (ha/year)	TSL (ha)	ASL (ha/year)
Aleksinački Bujmir	14.89	016	6.72	0.15	5.93	0.15	1.59	0.18
Nozrina	2.27	0.01	0.57	0.01	1.01	0.03	0.69	0.08
Katun	24.86	0.26	18.56	0.41	5.18	0.13	1.12	0.12
Moravski Bujmir	28.02	0.29	17.52	0.39	8.61	0.22	1.89	0.21
Lužane	15.54	0.16	15.22	0.34	0.00	0.00	0.32	0.04
Tešica	109.35	1.14	88.32	1.96	14.37	0.36	7.98	0.89
Draževac	7.46	0.08	3.68	0.08	2.95	0.07	0.83	0.89
Total	202.65	2.11	150.59	3.35	38.05	0.95	14.01	1.56

Note: TSL, total soil loss; ASL, average soil loss.

A decrease or stagnation in the intensity of riverbank erosion, influenced by the low variability of the South Morava River discharge values and a large amount of anti-erosion and regulatory work carried out in the Great Morava River Basin, was the main characteristic of the second period, 1970–2010. As mentioned before, a particular focus was placed on the period 2011–2020 to analyze more recent trends in agricultural soil loss caused by riverbank erosion. The average annual rate of soil loss in almost all areas increased compared to the middle research period, with maximum values in CM Draževac and CM Tešica (0.89 ha/year). Particularly significant are the examples of the settlements Draževac and Aleksinacki Bujmir, which recorded the maximum average soil loss value in relation to the entire research period in the last time sequence.

To identify recent trends in riverbank erosion dynamics, the first results of a short-term analysis conducted in the period 2020–2022 were used. The rate of bank erosion in the entire short-term period was more intensive than that in the long-term period. The maximum lateral channel migration of the South Morava River amounted to 104.7 m (M5), that is, 52 m/year on average. Compared with the previously examined period of 2010–2020, considerable intensification of the process was observed (63%). The results suggest the importance of extreme climate–hydrological events (days with extreme hydrological events) that intensified under the influence of climate change. Accordingly, estimation of the probability of maximum discharge occurrence (2010–2022) represents an important technique for determining the return periods of extreme discharge. The probability model results showed that extreme hydrological events that have the most significant impact on intensive riverbank erosion are expected every 1.7–2 years on average. These findings justify the collection of data on riverbank erosion intensity along the South Morava River, which can indeed be used as a predictive variable for future intensity dynamics. Similar conclusions were obtained by Rusnák *et al.* (2016), who extracted the economic and financial consequences of riverbank erosion of the Topla River in Slovakia using remote sensing, GIS, and economic models for the period 1987–2009. They emphasized the last part of the examined period, which is characterized by an increased intensity of riverbank erosion influenced by extreme river discharge occurrence. Therefore, the problems caused by the South Morava riverbank erosion are considerable and must be fully observed in the *economic context*.

According to the calculations in the second part of the analysis, the value of the lost land within the study area (202.65 ha) was close to 622,000 USD (in 2020). The values of the lost revenues from agricultural production ($\sum R_n$) and the value of lost land (L_0) based on earlier assumptions and different interest rates are summarized in Table 3. A similar methodology was used in Dragićević *et al.*

Table 3. ECRE, 2020 Dollar Value

		1924–2020	1924–1969	1970–2010	2011–2020
Interest rate = 1%	$\sum R_{n^*}$	3,902,851.1	343,875.9	332,142.1	59,134.5
	$\sum R_{n^*} + L_0$	4,524,530.64	965,555.44	953,821.62	680,814.00
Interest rate = 3,7% (average discount rate of the Federal Reserve System)	$\sum R_{n^*}$	7,410,803.2	1,919,197.6	612,030.2	64,019.9
	$\sum R_{n^*} + L_0$	8,032,482.69	2,540,877.13	1,233,709.75	685,699.42
Interest rate = 6%	$\sum R_{n^*}$	16,052,935.0	8,481,187.0	1,077,414.4	68,638.1
	$\sum R_{n^*} + L_0$	16,674,614.54	9,102,866.51	1,699,093.95	690,317.61
Interest rate = 10% (social discount rate set by the Ministry of Finance, Serbia)	$\sum R_{n^*}$	109,194,648.6	119,428,794.8	3,159,928.3	77,805.1
	$\sum R_{n^*} + L_0$	109,816,328.10	120,050,474.37	3,781,607.88	699,484.67
Interest rate = 13% (average discount rate of the National bank of Serbia)	$\sum R_{n^*}$	669,872,103.7	915,443,372.6	7,544,788.3	85,756.9
	$\sum R_{n^*} + L_0$	670,493,783.22	916,065,052.18	8,166,467.87	707,436.48

Note: *Compounded values since 1924.
Sources: Authors' calculation based on data from: General State Statistics (1929–1939); Statistical Office of the Republic of Serbia (SORS) (1948–2020); SORS (1965–2011); SORS (2012) and USDA (2022).

(2017a) to monetize the lost land due to riverbank erosion and the lost revenue of agricultural production in the Kolubara River Basin (Serbia), but for a significantly shorter period of time and without investment decision-making. Other studies on the socio-economic consequences of riverbank erosion (Rusnák *et al.* 2016; Hassan *et al.* 2018; Myagmar *et al.* 2022) were based on field observations and surveys without monetization of the final results.

The results for lost revenues differ depending on the interest rate used to calculate the ECRE. The choice of interest rate for discounting/compounding depends on the situation within the economy, the environment, inflation, related risks and their perception, policy decisions, costs of investments, maturity of projects, opportunity costs, availability of data, among other factors. A literature review suggests several choices: (1) the marginal cost of capital (Gittinger 1982; Latruffe *et al.* 2006), (2) opportunity costs (Clayton 1968; Harrison 2010; Florio *et al.* 2020), (3) the social discount rate (Livingstone and Tribe 1995; Pingali 2001; Florio *et al.* 2020), (4) the risk-free rate (Damodaran 2008), (5) the interest rate, which includes the average market risk premium (Gittinger 1982; Ivanović *et al.* 2015) or (6) interest rates that reflect specific characteristics of a given country (Dragićević *et al.* 2017a). Furthermore, in several of these studies, the authors conducted a sensitivity analysis to understand how different interest rates would influence the profitability of projects, ranging from 0% to very high levels (e.g., 18% in Ivanović *et al.* (2015)). The choice of the appropriate interest rate is important for both ECRE calculation and investment decision-making. For example, the use of conventional, relatively high discount rates in less developed countries for the net present value (NPV) calculation of long-term project investments would give less significance to benefits and costs in a more distinct future (e.g., environmental damage). In agriculture, the use of high interest rates would favor annual crops in comparison to perennial crops (Livingstone and Tribe 1995; Keča 2018).

As expected, the revenue lost in the previous century due to the movements of the river is higher if a higher interest rate is used for compounding. Since the analyzed period is almost 100 years, higher rates would probably provide an unrealistically high value of loss, but this could be understood as a simulation or sensitivity analysis, as in a number of the studies mentioned above (Figure 3). The influence of different choices of interest rates for compounding can also be observed in the data for the three subperiods. In the first period, from 1924–1969, the average annual loss of soil was the largest, at almost 3.3 ha annually. This period is historically the oldest; thus, when compounding the lost yield with low-interest rates, a smaller present value was obtained (with 1%, the lost value of production is only approximately 344,000 USD), whereas, with the highest rates, the value of the lost yield substantially increases (with 13%, it is 915.4 million USD).

In the third part of the analysis, the investment decision-making model was applied to understand whether it is economically viable to invest in the construction of riverbank revetments and in which period the investments might be paid off. The cost of constructing riverbank revetments was compared with the value of production and the land that would be lost without these investments for different interest rates and under the assumption that the investments in revetments were made in 2011. Discount rates of 1% and 3%, the social discount rate for Serbia (10%), the average discount rate of the National Bank of Serbia and the average discount rate of the Fed (averages taken for the period 2011–2020) were used.

According to Dragićević *et al.* (2017a), the price of building riverbank revetments was 495 euros per m (this price was for 2011, and the euro-dollar exchange rate for 31 December 2011 was 1.29; (European Central Bank, Statistics, 2011)). The estimated value of the construction works on the left riverbank is close to 218,000 EUR (approximately 281,000 USD), and it is estimated that it would prevent the erosion of an area of land of 0.299 ha per year on average. The construction of the right revetment (M5) (Figure 4) would cost 198,000 EUR

(255,000 USD) and would save 0.647 ha of arable land per year. Since future cash flows are discounted, higher discount rates tend to diminish the significance of revenues in the more distant future. Using a 1% interest rate, it takes less than 60 years for the investment to pay off (the present value of the lost yields and the land in this period would be 320,000 USD). At higher interest rates, investing in the construction of the left revetment would not be profitable even in 100 years. Costing approximately 255,000 USD, the construction of the right revetment is more profitable. Additionally, a larger area of land would be saved annually. At interest rates of 1%, the investment would pay off in slightly less than 35 years (the present value of the yield and the land that would be lost in 35 years is 276,500 USD) and at rates of 3% in less than 50 years (the lost value in that period would be approximately 294,000 USD). At high interest rates, the investment would not pay off even in 100 years. However, higher interest rates should not be used to discount future cash flows in long-run projects (Figure 5).

Future intensification of the riverbank erosion process will have an impact on earlier repayment of revetment costs. As rapid floods with high discharge become more frequent owing to climate change, the future dynamics of lateral migration and soil loss will be more intense, similar to previous short time periods. Short durations and significant destruction were the main features of bank erosion

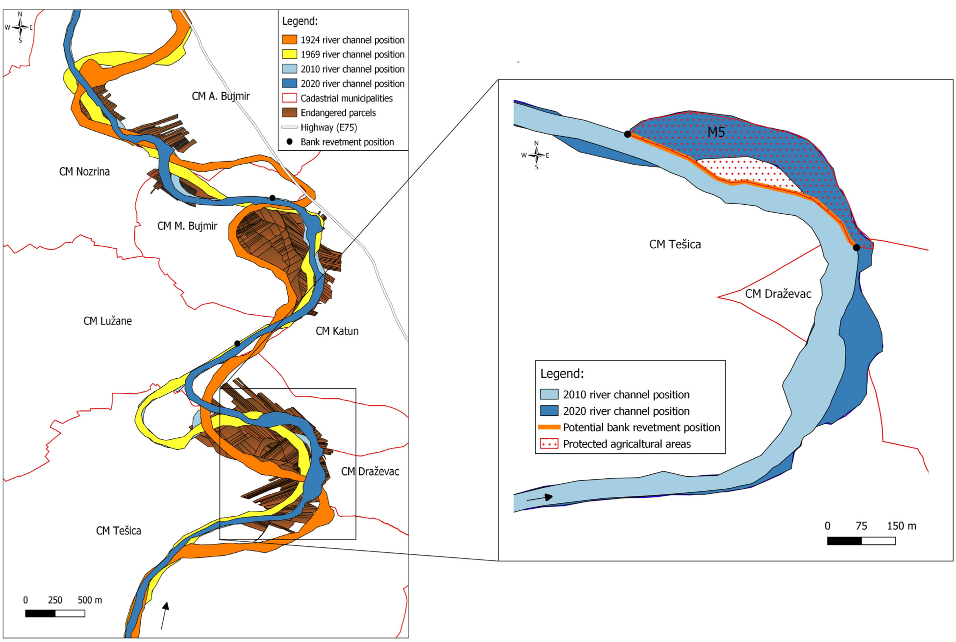

Figure 4. Position of the Potential Right Riverbank Revetment (M5)

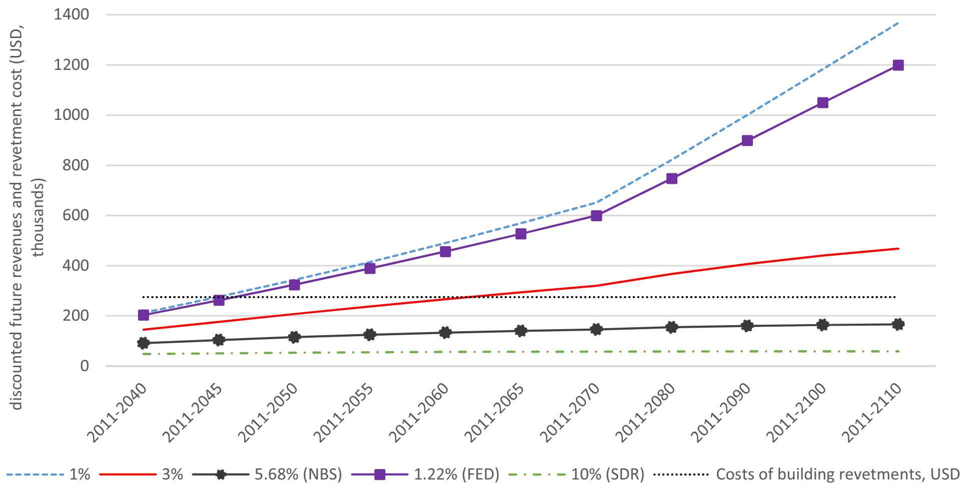

Figure 5. Potential Revenues Versus Costs of Building Revetments, Right Riverbank (*Source*: authors' calculations).

during these periods. According to the results obtained, the intensity of riverbank erosion would be 61.3% higher in the part of the right bank where revetment construction was proposed. In the same period, 2.71 ha of agricultural land for wheat and corn would be lost, or 1.33 ha/year. If the model on the repeatability of extreme hydrological events every 1.7–2 years is accepted, the full profitability of the right bank revetment construction will be fulfilled much earlier at all rates.

These results are unique and significant in several aspects. The observed intensity of riverbank erosion, which has shown an increasing trend in recent decades and is influenced by a greater frequency of extreme atmospheric and hydrological events, is consistent with the results of several studies from the region (Tošić *et al.* 2014; Rusnák *et al.* 2016; Kiss *et al.* 2019). It should be emphasized that a particularly long period of almost 100 years was covered in this study, which is a considerable difference compared to the aforementioned studies. In contrast to the majority of research that has focused on the socio-economic consequences of this process by analyzing land loss, land use change, human migration and the attitude of local population and communities toward riverbank erosion (Das *et al.* 2017; Rahman and Gain 2020; Dekaraja and Mahanta 2021) or the impact on quality of life and poverty (Hassan *et al.* 2018), this study quantified the direct economic consequences.

The methodology used in this study can be applied to other case studies characterized by intensive riverbank erosion and agricultural activities on endangered riverbanks. Considering the attractiveness of floodplains for the concentration of population and agricultural development, it is possible to single out potential case studies in Serbia (e.g., the Great Morava and West Morava rivers) to which a similar methodology can be applied. As the South Morava River is part of the Great Morava River Basin, the results obtained can be relevant for a comprehensive overview, which is of a great importance for broader and internationally sustainable water and land management to reduce negative impacts. This case can also be relevant for many rivers in the surrounding countries and especially for developing countries in other parts of the world (e.g., South and Southeast Asia) which are facing far-reaching economic, financial and demographic consequences of riverbank erosion.

4. Conclusions

The study shows the significance of quantifying the economic consequences of river channel management and environmental planning. Special importance is identified in water and soil planning, as well as in the protection of bank erosion in areas of particular interest. The analysis provides a methodological tool for decision-making in the long run for sustainable riverbank management. Additionally, the study considers a decision-making model on activities taken to protect arable land, agricultural production and rural livelihoods, which are justified both economically and over time. Investments in riverbank protection are of importance, although the government budget is often limited. Moreover, the interests of stakeholders are usually conflicting. Therefore, the benefits of such projects are only evident in the long run, realized over decades and important for future generations.

As extreme events with high discharge become increasingly common as a result of climate change, future lateral channel migration and soil loss will be even more pronounced. This is already evident from the latest changes in the observed area due to climate extremes. Riverbank erosion during these periods will be characterized mainly by short durations and severe destruction. Extreme hydrological events are characteristic of most rivers in Serbia, so timely measures to protect riverbanks can be applied on a wider scale. To reduce the risk of riverbank erosion and loss of land, this study strongly recommends the following:

- Any delay in the management of riverbank protection of the South Morava River can result in multiple negative economic consequences;
- Continuous quantification and assessment of the ECRE must be applied in areas of intensive agricultural production. This is particularly important for developing countries. Furthermore, social and environmental problems caused by erosion, as well as positive effects of riverbank erosion in terms of ecological sustainability, must also be considered, which can be done through further research.

- A riverbank erosion intensity database must be established for river basins of particular interest (including transborder areas) to monitor the potential vulnerability of different economic, social or environmental systems;
- The suggested methodology is important for improvements in decision-making at the macro level and requires a fully applied interdisciplinary approach, as it relies on different quantifications and different fields of expertise.

The suggested model can be particularly useful for the assessment of long-term capital-intensive infrastructure projects in developing countries in the areas of river channel management and environmental planning. The analysis indicated the importance of identifying river segments profitable for investments in riverbank revetments to preserve the largest area of fertile agricultural land.

Acknowledgment

This work is supported by the Ministry of Education, Science and Technological Development, Republic of Serbia, No. 451-03-47/2023-01/200091.

ORCID

Marko Langović https://orcid.org/0000-0002-4614-7265
Svetlana Popović https://orcid.org/0000-0001-5133-8704
Slavoljub Dragićević https://orcid.org/0000-0002-1417-5405
Žaklina Stojanović https://orcid.org/0000-0003-2878-9835
Emilija Manić https://orcid.org/0000-0002-6592-1068

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