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Sanja Manojlović^{1*}, Milica Dobrić*, Jovan Petronijević*

** University of Belgrade, Faculty of Geography, Belgrade, Serbia*

DYNAMICS OF SUSPENDED SEDIMENT IN THE JUŽNA MORAVA RIVER, SOUTH-EASTERN SERBIA

Abstract: This study estimate the temporal trends of recent suspended sediment in Južna Morava river. The variations of suspended sediment transport were analyzed at different time scales (inter-annual, monthly and seasonal, among different periods), based on 47-year hydrological data from the outlet hydrological station. The results indicate of a decline in suspended sediment concentration and sediment load in the long-time series, which can be divided into three periods: high SSC or Qs (1961-1976), medium SSC or Qs (1977-1988) and low SSC or Qs (1989-2007). The average annual SSC and Qs of these three periods are SSC=0.7284 g/l, SSC=0.3580 g/l, SSC=0.1865 g/l, and Qs=4260x10³ t, Qs=2277 x10³ t, Qs=789 x10³ t, respectively. The decrease in SSC and Qs is at the significance level of $\alpha=0.001$. The frequency distribution of the daily SSC show that cumulatively 92% of daily SSC during the low stage was u distributed in classes up to 0.5 g/l, versus 82% during the medium and 67% during the high period. The frequency of daily SSC in the class of 1-5 g/l decreases over time, from 14% in high period to 6% in low period. In the period 1989-2007 have not been reported SSC greater than 5 g/l. Different patterns of suspended sediment concentration SSC-Q hysteretic loops have been observed for each period. Two types of hysteretic loops were found at Južna Morava River: figure-eight typical of periods 1961-1976 and 1978-1988 and counter-clockwise in period 1989-2007. Human impact is the main factor in reducing suspended sediments. An important change in agriculture land in the basin recorded a significant impact on sediment transport.

Keywords: suspended sediment concentration, suspended sediment load, temporal scale, intraannual variability, hysteresis loop, Južna Morava

¹ sanja.manojlovic@gef.bg.ac.rs (corresponding author)
Sanja Manojlović (<https://orcid.org/0000-0003-2224-5183>)
Milica Dobrić (<https://orcid.org/0000-0002-6035-8835>)
Jovan Petronijević (<https://orcid.org/0009-0002-0571-2819>)

Introduction

Suspended sediment flux and changes in dynamics of suspended sediment over time is a central topic in river management because large sediment fluxes can reduce habitat quality through increasing turbidity, increase the cost of water treatment and contribute to channel clogging and increased flooding (Luo et al., 2013). Long-term variations in suspended sediment in rivers are closely associated to natural conditions in the basins (geology and geomorphology, meteorological and hydrological conditions), as well as to various human activities (Yang et al., 2004; Yang et al., 2007; Yang et al., 2018; Restrepo et al., 2006; Xu & Milliman, 2009; Rossi et al., 2009; Zhang et al., 2011). Multiyear sets of river suspended-sediment concentrations are valuable because they can reveal trends related to the effects of natural and human-caused changes to rivers basins (Warrick, 2014). River sediment regime has been strongly regulated by human impacts in recent decades, leading to a drastic decrease in the sediment flux as a result of significant alterations of the environment. In many large rivers in the world, sediment fluxes have declined by 60–90% over recent decades (Walling, 2006; Walling & Fang, 2003; Miao et al., 2011; Guo et al., 2019). Reduction in suspended sediment can be attributed to several anthropogenic activities, such as soil and water conservation and sediment erosion control programs, construction of dams, water diversion and mining (Wang et al., 2017; Bobrovitskaya et al., 2003; Panda et al., 2011; Zhang et al., 2020). Important changes in socio-economic factors also record significant impacts on suspended sediment transport in rivers systems (Zhong et al., 2020).

As one of the largest river systems in Serbia, the Južna Morava River basin is of major socio-economic and ecological significance. In the valley of the Južna Morava and its larger tributaries the Nisava, major traffic corridors are located, such as the pan-European corridor X (international line Belgrade-Skopje-Athens and Belgrade-Sofia-Istanbul). Also, the territory is vulnerable to various types of natural hazards such as devastating torrential floods, landslides, excessive erosion. Study of the dynamics and transport of suspended sediment in this river has mainly of practical interest in terms of analyzing the sustainable development of river basin geosystems. The overall aim of this research was to investigate the variations of suspended sediment transport at different temporal scales in the Južna Morava River, based on 47-year hydrological data from the outlet hydrological station. Specific objectives of this work were (1) to analyze the dynamics of suspended sediment at different temporal scales among inter-annual periods, (2) to analyze monthly and seasonal variations of suspended sediment and (3) to analyze frequency distribution of the daily suspended sediment concentration during different periods. So far, few studies have been investigated changes in suspended sediment load in Južna Morava river (Manojlović et al., 2018; Manojlović et al., 2021a). However, previous research has not incorporated the changes in intra-annual time scale. The intra-annual sediment dynamics in the Južna Morava river have been studied through the analysis of hysteretic loops. Identification of different species hysterical loops and the conditions of their generation is very important, because can indicate the dominance of different processes over time. Research of suspended sediment dynamics in different temporal scales become essential for implementing basin management strategies. Changes in riverine suspended sediments have environmental, ecological and social implications. Understanding the sediment load regime is a prerequisite of sediment management, fluvial ecosystem and water resources.

Study area

Južna Morava River is selected as the study area in this research. River passing through southeastern region of Serbia (Figure 1). It formed by Binačka Morava and Preševska Moravica at an altitude of 392 m above sea level (a.s.l.), near Bujanovac. The total length of the Južna Morava River is 234.3 km (Langović, 2020). Južna Morava river basin is one of the largest river basins in Serbia (15,469 km²), which represents 17.8% of the territory of Serbia. The elevation ranges from 130 m a.s.l. to 2,169 m a.s.l. at mountain Stara planina. The relief of the basin consists of mountains of the Serbian-Macedonian mass in west, southwest and south parts of the basin (Besna Kobila, Vardenik, Kukavica) and Carpathian-Balkan mountains in the east and southeast (Stara Planina, Suva planina, Svrljiške planine). According to climatological studies, it was found that the frequency of droughts in the southern part of Serbia was higher than in the other parts of the country (Tošić & Unkašević, 2014). The valley of the South Morava is one of the regions most exposed to droughts (Gocić & Trajković, 2013; Trajković et al., 2020) in which the longest heat waves were recorded (Unkašević & Tošić, 2009). Average annual precipitation in the basin ranges from 550 mm in the valley of the Južna Morava, to 1300 mm in the highest eastern and southeastern parts of the basin (Milovanović et al., 2017). The basin of Južna Morava has a continental precipitation regime (Blagojević et al., 2019). The maximum monthly precipitation is in May and June (11.1% and 10.8% of the annual precipitation) and the minimum monthly precipitation is in January and February (about 6.7% of the annual precipitation). The rivers in Južna Morava basin mostly belong to pluvio-nival type of water regime, with maximum water discharges in March and April, and minimum in August and September (Dobrić et al., 2023). Južna Morava is one of the average water abundant rivers of Serbia with its mean annual specific runoff is 5.6 l/s/km² (Urošev et al., 2020). The Južna Morava valley belongs to potentially flooded areas (Gavrilović et al., 2012), and on its tributaries some of the the most devastating torrential floods in Serbia in the last hundred years (Petrović et al., 2014). The largest tributaries of the Južna Morava are Nišava, Toplica, Jablanica and Vlasina.

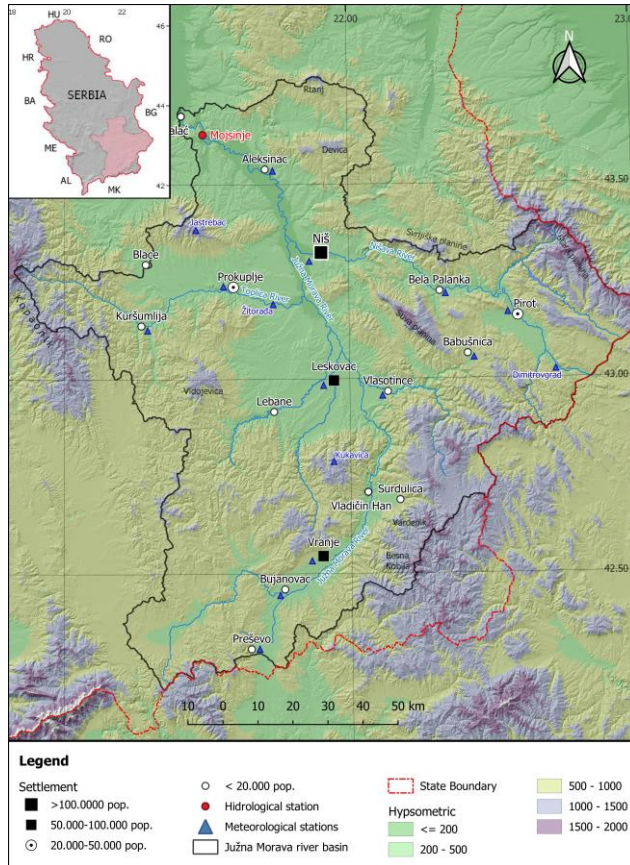


Fig. 1. Location on the Južna Morava river basin in Republic of Serbia

Methodology

Data

The Mojsinje station, is a key hydrological station that records the water discharge of the Južna Morava River basin. Measurements of water discharge and suspended sediment concentration from the 1961 to 2007 were collected by the Hydro-Meteorological Service of Serbia (HMSS) (Hydrometeorological Office of the Republic of Serbia 1961-2007).

Suspended Sediment Time Series Classification

For the determination of long-term time series in the study of the dynamics and transport of suspended sediment, two methods are generally used. Most often, the non-parametric Pettitt test is widely used to identify the change point at a certain level of statistical significance, which divides the time series into two periods (Pettitt, 1979). Also, the percentile method was used to determine the time series: annual values of suspended sediment concentration and suspended sediment transport were divided into three periods according to the 25th and 75th percentile index (Dai et al., 2016).

In this study, the differentiation of time series was performed according to the standard deviation method (Manojlović et al., 2021b). In the long-term analysis of suspended sediment concentration (SSC) and sediment load (Qs), the standard deviation (δ), was used to classify high, medium and low years. Specifically, the year with average annual SSC greater than the $SSC_{ma} + 0.5\delta$ is set as a high SSC event and the year with average annual SSC less than the $SSC_{ma} - 0.5\delta$ represents a low SSC event (SSC_{ma} presented mean annual total over the study period). In the same method, the classifications of years for suspended sediment load were performed. All years were divided into three categories as follows:

$$\begin{aligned} & \text{High SSC or } Q_s \text{ when } \delta < -0.5 \\ & \text{Medium SSC or } Q_s \text{ when } -0.5 \leq \delta \leq 0.5 \\ & \text{Low SSC or } Q_s \text{ when } 0.5 < \delta \end{aligned} \quad (1)$$

According to this method, thresholds for high events can be defined as the occurrence of value of suspended sediment concentration or sediment load above $SSC = 0.5575 \text{ g/l}$ and $Q_s = 3464 \times 10^3 \text{ t}$. The thresholds for low events can be defined as the occurrence of value of suspended sediment concentration or sediment load below $SSC = 0.2678 \text{ g/l}$ and $Q_s = 1323 \times 10^3 \text{ t}$. Applying these thresholds the long-term series of annual SSC and Q_s are divided into three periods: period I (1961-1976), period II (1977-1988) and period III (1989-2007).

Trend Analysis

For the analysis trends of precipitation (P), water discharge (Q), suspended sediment concentration (SSC) and sediment load (Q_s) non-parametric Mann–Kendall (MK) test were used. The MK test is often used to investigate if the trend exists in a given time series. Depending on the confidence level (α) value, Z statistic was obtained from MK test. The positive values of Z point out upward trend and negative values point out downward trend. Sen's slope approach was used for linear trend value calculation. The test was initially proposed by Mann and Kendall (Mann, 1945; Kendall, 1975) and is generally applied in hydrological and meteorological data analyses.

Categorization of SSC–Q Hysteresis Loops and Sediment Rating Curve

Research on variations in riverine SSC is mainly based on the suspended sediment concentration- water discharge relationship, which is used to gain a comprehensive understanding of river processes (Dai et al., 2016). The curve representing suspended sediment concentration vs. water discharge through time is a hysteretic loop. The categorization of SSC–Q hysteresis patterns at different time scales was determined mainly according to the patterns observed and described by Williams (Williams, 1989). Hysteresis loops for a different time scale were applied and described in the previous literature (Xu & Milliman, 2009; Grenfell & Ellery, 2009; Dai & Lu, 2014; Sun et al., 2016). In this study, at monthly and seasonal scales, the averaged SSC and Q values were used for analyzing SSC–Q hysteresis patterns for different periods.

The sediment rating curve (SRC) are used to understand the dynamics and conditions of suspended sediment transport in the rivers. Changes in sediment rating curve over time have been noted for many rivers systems (Yang et al., 2007; Walling D. E., 1977; Jansson, 1996; Asselman, 2000; Iadanza & Napolitano, 2006; Efthimiou, 2019). To characterize patterns and trends in river sediment concentrations, data are often fit with regression

method, such as the commonly used power regression model between water discharge (Q) and suspended sediment concentration (SSC) data:

$$SSC=aQ^b \quad (2)$$

where is SSC - suspended sediment concentration (g/l), Q - water discharge (m³/s), a and b are the rating coefficients of the sediment rating curve.

The sediment rating coefficients represents soil erodibility and erosivity of the river. The a coefficient represents an index of the erosion severity. High a values indicate availability of weathered sediment in the basin, which can be easily eroded and transported by runoff. The b coefficient describes erosivity of the river, where high value indicating strong increase in erosive power of the river (Morgan, 2009; Gao et al., 2017).

Results and discussion

Long-Term Changes in Suspended Sediment

According to the presented method, the long-term series of annual SSC and Qs are divided into three periods. Average annual SSC and Qs greater than the $SSC+0.5\delta$ or $Qs+0.5\delta$ mainly occurred before 1976, and average annual SSC and Qs smaller than the $SSC-0.5\delta$ or $Qs-0.5\delta$ occurred after 1988 (Fig. 2). Linear regression analysis was applied to determine the trends of SSC and Qs in the long-term period 1961-2007 and for the separate three periods 1961-1976, 1977-1988 and 1989-1990 presented in Fig. 2. Generally, the annual suspended sediment concentration and sediment load in the Južna Morava river decreased significantly from 1961 to 2007. The SSC and Qs decreased at significance level of $\alpha=0.001$, with average annual decrease rate being $SSC=0.0144$ g/l/yr and $Qs=84.7 \times 10^3$ t/yr, respectively. Z statistics values indicate more pronounced trend of decreasing SSC. The average values SSC and Qs of these three periods are $SSC=0.7284$ g/l, $SSC=0.3580$ g/l, $SSC=0.1865$ g/l, and $Qs=4260 \times 10^3$ t, $Qs=2277 \times 10^3$ t, $Qs=789 \times 10^3$ t respectively. In the first period 1961-1976 SSC and Qs trends are not in accordance with hydrological and climatic conditions. SSC and Qs present decreasing trends, with a greater regression slope in SSC. In the second period between 1977 and 1988, SSC and Qs also have a decreasing trends, but the slope of the regression lines is slight. In the third period 1989-2007, the annual SSC is stable. In the same period Qs shows a tendency to increase, which is in accordance with the hydrological and climatic conditions. The increased transport of Qs in this third period is related to the years in which the water discharge was above the average long-term values, which are classified as moderately wet and very water years, and according to the amount of precipitation belong to the wet years (Manojlović et al., 2021b).

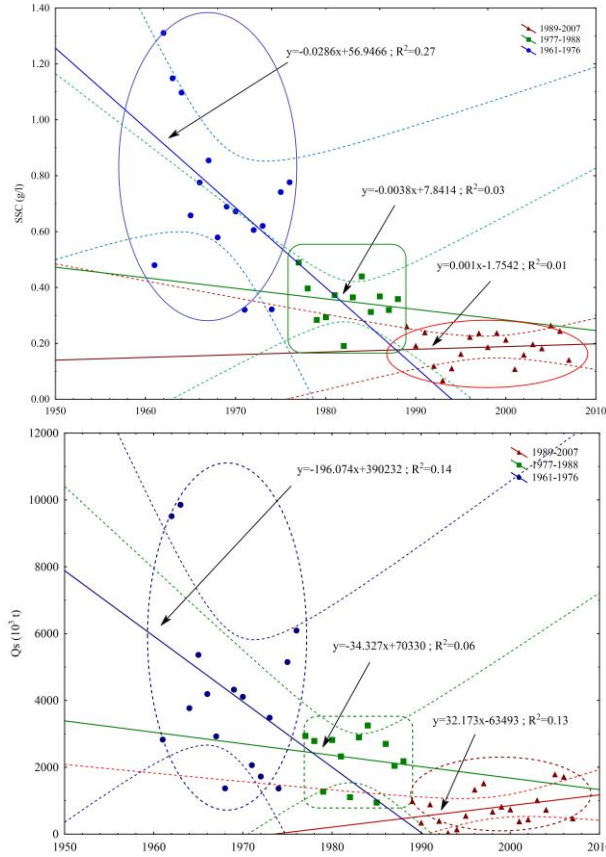


Fig. 2. Scatter-plot of long-term changes in A) suspended sediment concentration (SSC) and B) suspended sediment load (Q_s). The results presented regression bands at confidence level of 0.99 (Manojlović et al., 2021)

Frequency Distribution of Suspended Sediment Concentration

The study of the frequency distribution of the daily suspended sediment concentration during the high SSC period I (1961–1976), the medium SSC period II (1977–1988), and the low SSC period III (1989–2007) is presented in Fig. 3. The most common SSC values are in the range of 0.1–0.5 g/l, representing 43%, 46% and 53% of the total values in high, medium and low periods. These data indicate that in the period 1989–2007 there was an increase in days dominated by concentrations up from 0.1 g/l to 0.5 g/l. Cumulatively as much as 92% of daily SSC during the low stage was distributed in classes up to 0.5 g/l, versus 82% during the medium and 67% during the high period. On the other hand, it can be seen that the frequency of SSC in the class of 1–5 g/l decreases over time, from 14% in high period to 6% in low period. In the period 1989–2007 have not been reported suspended sediment concentration greater than 5 g/l.

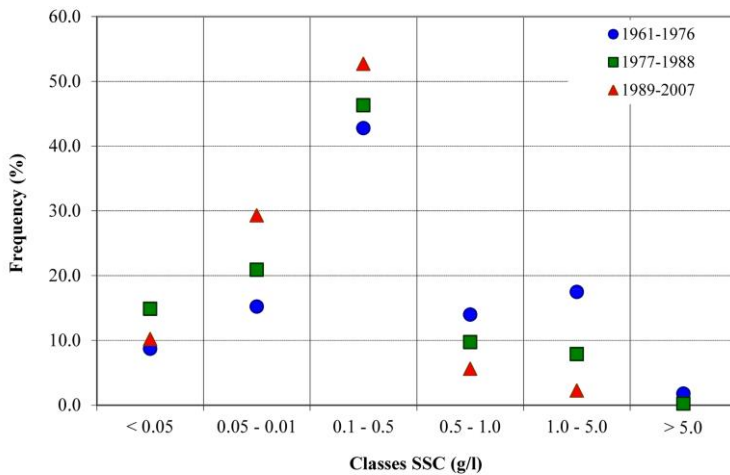


Fig. 3. Frequency of daily suspended sediment concentration (SSC) in the studied periods

The box-plots of daily SSC versus the classified daily water discharge indicates that the SSC at station Mojsinje in the studied period increases corresponding to the increasing water discharge (Fig. 4). Exponential type regression for three periods with a coefficient of determination between $R^2=0.73$ and $R^2=0.95$ indicates a high correlation between SSC and Q (Table 1). However, the plots of boxwhisker SSC for different classes Q indicates that the daily value of SSC reduced during the studied periods. For example, the results indicate that the mean daily values SSC reduced from 2.8661 g/l in the period I to 1.169 g/l in the period III when the water discharge was more than 500 m³/s. Also, the results show that the 95th percentile values of SSC in the period I for the different classes Q ranged from 0.5359 g/l to 6.5127 g/l compared to the period III when they ranged from 0.1933 g/l to 2.1238 g/l, which is an obvious decline. The results show that high SSC values for the same water discharge class reduced significantly over time.

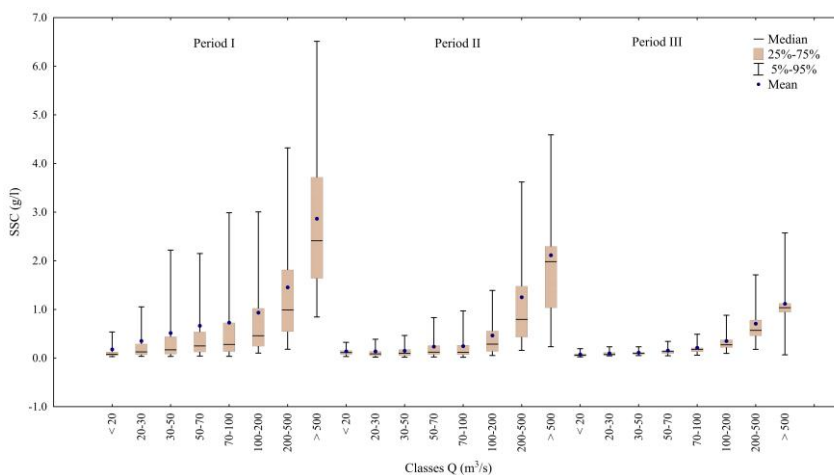


Fig. 4. Box-Whisker plot of daily SSC corresponding to different classes of daily water discharge for the period I (1961-1976), period II (1977-1988) and period III (1989-2007)

Table 1. Coefficients (a) and (b), coefficients of determination (R^2) for the exponential regression $SSC=aebQ$ relating to suspended sediment concentration and water discharge for data collected of SSC on 5th percentile, mean and 95th percentile values of SSC presented for different classes of daily water discharge.

Periods	5th percentiles		R^2	Mean		R^2	95th percentiles		R^2
	a	b		a	b		a	b	
Period I	0.0115	0.4117	0.73	0.1541	0.3380	0.95	0.5677	0.3070	0.91
Period II	0.0073	0.4061	0.79	0.0576	0.3897	0.87	0.1720	0.3921	0.95
Period III	0.0218	0.2404	0.85	0.0399	0.3877	0.95	0.0988	0.3704	0.94

Intra-annual Variability of Suspended Sediment

The relationship between water discharge (Q) and suspended sediment concentration (SSC) was represented by a hysteresis loop and analysed for all the individual periods (Fig. 5). At Mojsinje station the temporal analysis of SSC-Q hysteresis loops show large change. Monthly SSC-Q hysteresis loop showed figure-eight pattern in the period 1961–1976. In the period 1977–1988 the SSC reduced compared to the previous period, but the hysteresis loop remained the same. Counter-clockwise pattern was presented in monthly SSC-Q hysteresis loop during the 1989–2007.

Analysis of hysteretic patterns over time provides a simple concept for interpreting variability of location and activity of sediment sources at the basin scale (Mao & Carrillo, 2017). Intra-annual variations in SSC suggesting a significant spatial and temporal variability in sediment source areas (Williams, 1989). Observed two different kinds of relationships between SSC and Qs in the Južna Morava, indicate a change in the transport suspended sediment in the basin area. The figure-eight hysteresis loop indicates complex conditions in the dynamics and transport of suspended material. This type of loop can be understood as a sequence of dominant conditions during the year, that is, a combination of partial clockwise followed by counter-clockwise events (Seeger et al., 2004). Research has shown that eight-shaped loops are related to more complex events occurring after dry antecedent conditions (Soler et al., 2008). In particular, in this case, in the period I (1961–1976) the first stage is formed after the dry season during the autumn. In the first phase, hysteresis loop has clockwise pattern (Fig. 5A). Increase the SSC from October to February in accordance with an increase in Q, and the maximum values of SSC is reached before the peak of water discharge. SSC decreases from February to April. Since to April, the values of SSC increases, and the hysterical loop turns into counter-clockwise pattern. SSC values reach a maximum in June, i.e. after the occurrence of the maximum of water discharge. From June to October SSC decreases rapidly. In the period II (1977–1988) hysteresis loop retains the figure-eight pattern. However, there are two maximum in the concentration of suspended sediment: the first maximum in March when the maximum Q was recorded, and the second in June (Fig. 5B). In period III (1989–2007) the curve changes shape into a counter-clockwise hysteresis loop. The maximum SSC is in April and coincides with the peak of water discharge (Fig. 5B). According to previous studies (Seeger et al., 2004; Soler et al., 2008) clockwise SSC-Q hysteretic loops appear when sediment concentration transport in conditions when the catchment is very moist and runoff generation and sediment supply is limited to areas next to the channel: sediments are removed, transported and depleted rapidly. During counter-clockwise looped events, sediment sources are widespread throughout the catchment and not exhausted rapidly. The incorporation of sediment is from areas that are not constantly connected to the channel network.

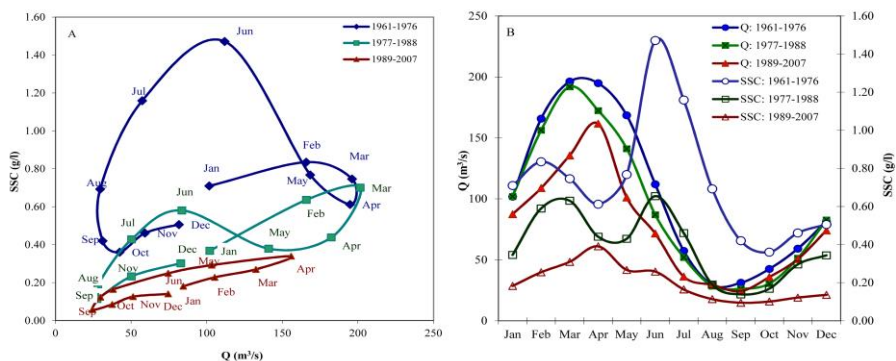


Fig. 5. A) Monthly SSC-Q hysteresis loops. The curves shifted from eight shaped loop in 1961–1976 and 1977–1988 to counter-clockwise in 1989–2007. B) Average monthly suspended sediment concentration and water discharge during the studied period

Changes in the intra-annual variability of SSC on the Južna Morava river are obvious. The hysteresis loop in 1989–2007 is the narrower than that in 1961–1976 because, for the same level of water discharge, monthly average SSC in period III is significantly less than that in period I. In general, water discharge shows insignificant decreasing or increasing trends (except June), while the decrease in SSC is evident in all months (Table 2). Applying the Mann-Kendall test, significant decrease trend of SSC was found in all months (except for October). Statistic values show that the decreases in the SC are most dramatic in June ($Z=-5.43$, $\alpha=0.001$) and July ($Z=-4.92$, $\alpha=0.001$), with an average declining trend $SSC=0.0265$ g/l/month and $SSC=0.0197$ g/l/month, respectively. Namely, in the period 1989–2007 the suspended sediment concentration in June and July decreased by 82% and 84% compared to the period 1961–1976. In other months, the reduction of SSC in last period compared to the base period is between 38% and 81%.

Table 2. Results of MK test for water discharge (Q), suspended sediment concentration (SSC) and sediment load (Qs) in period 1961–2007 (Z - Mann-Kendall trend, α - significance level, $+\alpha=0.1$, $*\alpha=0.05$, $**\alpha=0.01$, $***\alpha=0.001$, / α - no significance; b - Sen's slope).

Months	Q		SSC		Qs				
	Z	α	b (m ³ /s/month)	Z	α	b (g/l/month)	Z	α	b (10 ³ t/month)
January	-0.90	/	-0.48	-2.88	**	-0.0073	-2.27	*	-1.61
February	-1.36	/	-1.03	-3.21	**	-0.0125	-2.57	*	-5.48
March	-1.61	/	-1.81	-2.38	*	-0.0098	-2.29	*	-5.32
April	-0.55	/	-0.57	-1.78	+	-0.0046	-1.65	+	-3.62
May	-1.98	/	-1.20	-3.41	***	-0.0092	-2.75	**	-4.17
June	-1.25	*	-0.50	-5.43	***	-0.0265	-4.15	***	-7.61
July	-1.03	/	-0.27	-4.92	***	-0.0197	-4.31	***	-2.67
August	1.12	/	0.13	-4.27	***	-0.0093	-3.15	**	-0.62
September	-0.61	/	-0.05	-4.02	***	-0.0044	-2.70	**	-0.28
October	1.43	/	0.25	-1.61	/	-0.0018	-0.44	/	-0.04
November	1.17	/	0.31	-2.60	**	-0.0038	-1.41	/	-0.36
December	0.33	/	0.08	-3.32	***	-0.0070	-2.44	*	-1.42

As shown in Fig. 6A, intra-annual variations of sediment load in the studied periods is also evident. Decreasing trend of sediment load, which is evident in all months, and the most significant changes are in July ($Z=-4.31$) and June ($Z=-4.15$) with an average reduction rate of $Qs=2.67 \times 10^3$ t/month and $Qs=7.61 \times 10^3$ t/month, respectively (Table 2). The decrease in Qs for the same months is amounts 89% and 88%. In other months, the reduction of Qs in

last period compared to the base period range from 56% to 89%. In general, seasonal variations of Qs have a similar distribution in the observed periods (Fig. 6B): the largest transport of sediment load is during spring (March to May) and winter (December to February), then in summer (June to August) and autumn (September to November). However, some differences in the intra-annual distribution sediment load between the studied periods. The biggest seasonal changes observed in the summer and spring. During the summer, a decline in the transport of suspended sediment was observed. For example, 22 % of the sediment load was transported during the summer in period I and only 12% transported in period III. On the other hand, 41% of the total annual sediment load was transported during spring in period I, as opposed to 54% in period III. As shown in Fig. 6, monthly variations of Qs in period I and period III the highest contributions occurring in March (16% of annual sediment transport) and April (25% of annual sediment transport) respectively.

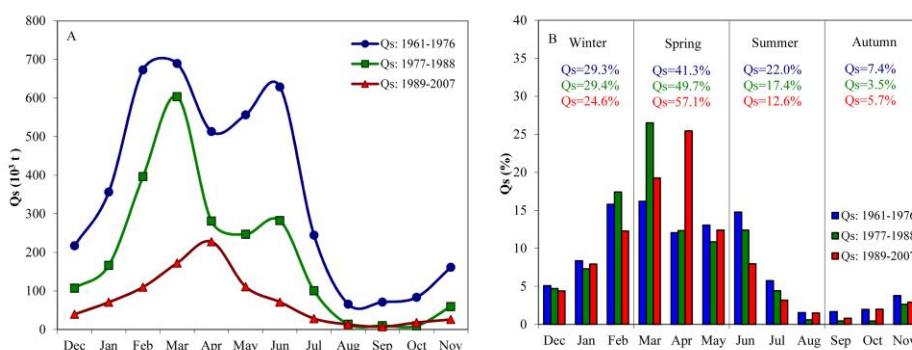


Fig. 6. A) Monthly average sediment load and B) Variations of monthly and seasonal sediment load expressed as a percentage to annual value during the studied period

Suspended Sediment Rating Curve Variation

Sediment rating curves were established between stream discharge and suspended sediment concentration for datasets covering the 47 years. The study has objective is to determine differences in the relationship between water discharge and suspended sediment concentration for studied periods. As noted, the combination of the a-values and b-values can be understood as a measure of soil erodibility and erosivity of the river. There is a general assumption that these changes reflect alteration of the erodibility and/or supply of sediment in the watershed, or the power of the river to erode and transport sediment (Asselman, 2000; Morgan, 2009). Sediment rating curves results provideuseful insights on the impact of anthropogenic factor on the sediment transport regime (Iadanza & Napolitano, 2006).

Sediment rating curves obtained for three periods according to the average monthly data presented in Fig. 7. The interannual variability time-series of the sediment rating coefficients for each year individually shows in Fig. 8A and Fig. 8B. The a-values ranges from 0.0003 to 0.6730 and that of b-values from 0.0124 to 1.5913. The analysis indicate a significant decrease in the a-values during the 47 years and an increase in the b-value for the same period of time. Generally, the coefficients of the regression between the water discharge and the suspended sediment concentration between the periods differ considerably. Since soil erodibility is represented by an a-coefficient (Efthimiou, 2019), high a-values indicate intensively weathered materials, which can be easily transported. The rating parameters characteristic of each periods are shown in Table 3. The results indicate an evident

decrease in the a-coefficient. The mean values regression a-coefficients are $a=0.1133$ in period I, $a=0.0170$ in period II and $a=0.0109$ in period III.

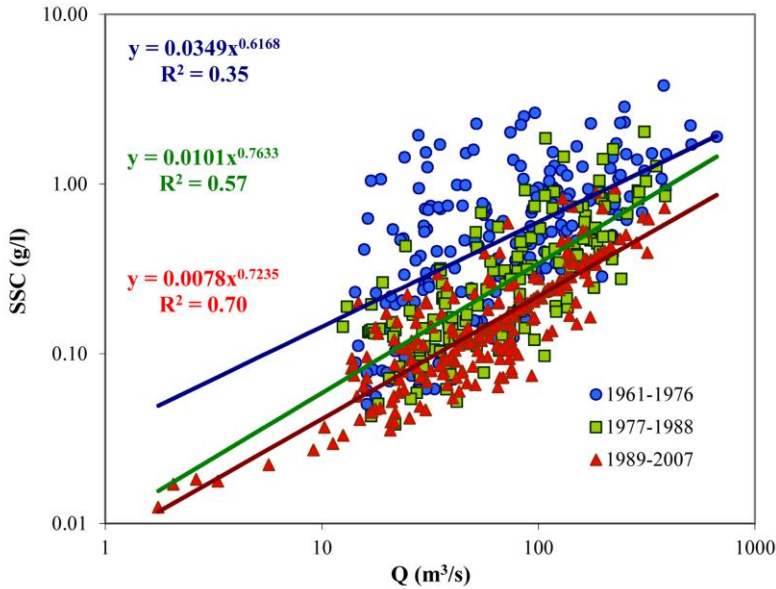


Fig. 7. Sediment rating curves presented on the relationship between water discharge and suspended sediment concentration using power regression $SSC=aQ^b$. Analysis based on average monthly data for three periods ($n=192$ for 1961-1976; $n=144$ for 1977-1988; $n=228$ for 1989-2007)

Namely, the analysis of the correlation between the regression coefficients a and b may indicate a change in sediment regime transport (Asselman, 2000). The rating coefficients a and b obtained for each year, from three periods, are plotted in a a - b graph (Fig. 8C). In the Južna Morava river, a and b -coefficients are connected by the regression relationship $b=-x\ln(a)-y$. The a and b -coefficients of sediment rating curves are inversely correlated (Rannie, 1978; Thomas, 1988; Achite & Ouillon, 2007). A negative correlation between the regression coefficients, is to be related to the sediment transport regime of the river. All coefficients pairs that plot on the same line in the graph are characterized by a similar sediment transport regime [50]. Pairs that plot on different lines are characterized by a different sediment transport regime. The period that has higher values of a -coefficients, carries a higher sediment load. It is noticeable that a - b pairs of period I are dispersed ($R^2=0.83$), in relation to the coefficients of period II and period III which are linear ($R^2=0.97$ and $R^2=0.95$). Also, the coefficient of variability of the a and b -coefficients have a greater scatter in the period 1961-1976 and decreases over time. Sediment rating curves, with low a -values and high b -values, it characteristic for period 1989-2007. These values of the a and b -coefficients indicate changes in conditions in the transport of the suspended sediment. An increase in discharge results in a large increment of suspended sediment concentrations, indicating that the power of the river to erode material during high discharge periods is high, and that important sediment sources become available when the water level rises. This conditions are characteristic of counter-clockwise hysteresis loops, as shown in previous research. On the other hand, the results show an evident decrease in the a -coefficient which can be caused by a reduction in the sediment supply.

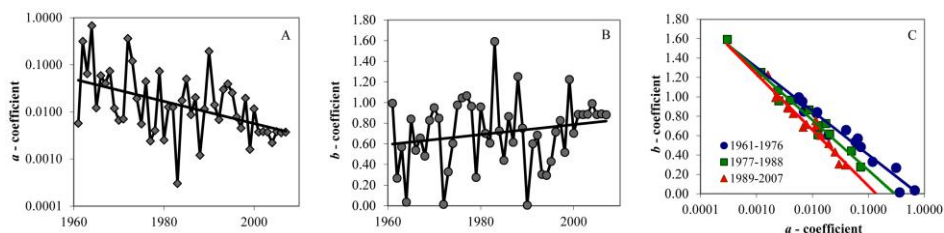


Fig. 8. The interannual variability time-series of the sediment rating coefficients a (A) and sediment rating coefficients b (B). Correlation between a and b -coefficients of sediment rating curves (C). Trend a -coefficient significance level of $\alpha=0.001$. Analysis based on average monthly data for each year.

Table 3. Parameters of the suspended sediment concentration versus water discharge regression relationship for the period I (1961-1976), period II (1977-1988) and period III (1989-2007).

Periods	Mean values regression coefficients		Coefficient of variability		Regression relationship	R^2
	a	b	Cv a	Cv b	b versus a	
Period I	0.1133	0.6230	162	54	$b = -0.1941 \ln(a) - 0.0125$	0.83
Period II	0.0170	0.8313	130	43	$b = -0.2247 \ln(a) - 0.2758$	0.97
Period III	0.0109	0.7406	102	34	$b = -0.2511 \ln(a) - 0.4992$	0.95

Previous studies suggest that in stable climatic-hydrologic conditions, the trend of decrease in sediment can be explained solely by anthropogenic impacts. Recent research has shown that changes in suspended sediment in Južna Morava river were predominantly impacted by human activities (89%), while precipitation explained 11% of the reduction in suspended sediment (Manojlović et al., 2021a). The process of deagrarization is the main factor in the reduction of suspended sediment. Namely, the most important agrarian characteristic of rural areas in the Južna Morava river basin is the intensive and unplanned reduction of agricultural land (Gajić et al., 2021). Namely, the abandonment of arable land (the transition from cultivated agricultural areas to natural vegetation) is a direct consequence of population reduction in mountainous rural areas.

Trends of decreasing suspended sediment concentrations are directly related to the decrease in rural population and agricultural land. Data from ten-year census indicators for agricultural land and rural population, and mean suspended sediment concentration for ten-year time series at the statistical significance level of 0.05, show a high degree of correlation between anthropogenic variables and suspended sediments (Manojlović et al., 2021a; Manojlović et al., 2021b). Actually, the results of this study indicate an association between sediment availability in the basin and the transport of suspended sediment in the river. The high values of a -coefficient the sediment rating curves obtained by the regression power function, which indicate intensively weathered sediment materials that is easily transported, coincide with the period that records the highest value of SSC and the largest share of agricultural land in the basin. In fact, the period 1960th notes the highest SSC ever, because anthropoppression and deforestation had reached their highest level, and impacts of industrialization were insignificant at this time. Over time, the values of the a -coefficient decrease, which indicates the decreasing production of sedimentary material. Thus, in the first decade of the 21st century a -coefficient has a low value, which is consistent with reduction of agricultural land in the basin.

Conclusion

This study estimates the temporal trends of suspended sediment concentration and sediment load in Južna Morava river. The variations of suspended sediment were analyzed at different time scales: inter-annual, monthly and seasonal. Also the analysis included the frequency distribution of the daily suspended sediment concentration during different periods. The volume of suspended sediment particles, eroded and transported by the rivers exhibits great temporal variability. The results of this study are as follows:

The research find that the suspended sediments in Južna Morava river has generally declined in recent decades. Statistics analysis indicate more pronounced trend of decreasing SSC. The long-time series are divided into three periods: high SSC or Qs (1961-1976), medium SSC or Qs (1977-1988) and low SSC or Qs (1989-2007). The average annual SSC and Qs of these three periods are $SSC=0.7284$ g/l, $SSC=0.3580$ g/l, $SSC=0.1865$ g/l, and $Qs=4260 \times 10^3$ t, $Qs=2277 \times 10^3$ t, $Qs=789 \times 10^3$ t, respectively.

The frequency distribution of the daily SSC show that the most common SSC values are in the range of 0.1-0.5 g/l, representing 43%, 46% and 53% of the total values in high, medium and low periods. Cumulatively 92% of daily SSC during the period 1989-2007 was u distributed in classes up to 0.5 g/l, versus 82% during the 1977-1978 and 67% during the period 1961-1976. The frequency of daily SSC in the class of 1-5 g/l decreases over time, from 14% in high period to 6% in low period. In the period 1989-2007 have not been reported SSC greater than 5 g/l.

In this study examined intra-annual variation of suspended sediment. Different patterns of SSC-Q hysteretic loops have been observed for each period. The hysteresis of sediment rating curves in the Mojsinje station had shifted from figure-eight loop (characteristic of the periods 1961-1976 and 1977-198) to counter-clockwise loop (characteristic of the period 1989-2007). The characteristic of the counter-clockwise loop is that the maximum SSC is in April and coincides with the peak of water discharge, unlike figure-eight where the maximum SSC occurs in June, i.e. after peak of water discharge. The change in the shape of the hysteresis loop indicates changes in the regime of the suspended sediment. The biggest seasonal changes observed in the summer and spring. During the summer, a decline in the transport of suspended sediment was observed: 22 % of the Qs was transported during the summer in period 1961-1976 and only 12% transported in period 1989-2007. On the other hand, monthly variations of Qs in 1961-1976 and period 1989-2007 the highest contributions occurring in March (16% of annual sediment transport) and April (25% of annual sediment transport) respectively.

The research has shown that changes in suspended sediment in Južna Morava river were predominantly impacted by human activities. The impact of the anthropogenic factors on the reduction of suspended sediment in the basin is a consequence of the agricultural land use change (intensive process of deagrarization) which is conditioned by the intensive process of depopulation in the rural areas of the basin.

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