Hydrological and suspended sediment regime in the Kolubara River during the extreme year of 2014

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ABSTRACT

The previous methodology of sampling and determining the suspended sediment concentration (*SSC*) in the rivers of Serbia is characterized by a number of disadvantages, so that any research of this kind has a large water management impact. In the largest number of hydrological stations in Serbia, daily *SSC* were obtained based on only one sampling, which raises the question of the representativeness of such sample. Previous *SSC* – water discharge relationship and detailed analyses of errors in calculating the suspended sediment transport on the profile of Draževac were done for the year of 2004, when the annual difference was very high, which required a very detailed analysis and methodological improvements. In order to define the sediment regime in the Kolubara River, precise monitoring of *SSC* has been implemented since 2013. The Kolubara River has an unfavourable water regime which is reflected in the excessiveness of water runoff, with floods that are sudden, expressive and short-term, and long-term low waters, so, that are why it is characterized by a large discharge and *SSC* variability. Incidentally, monitoring also covered the year of 2014, when the area of western Serbia (in particular the Kolubara River Basin) was under the influence of extreme climate events that strongly reflected on the hydrological condition with the absolute highest daily discharge. A total of 220 water samples were collected on Draževac gauging station in 2014, in order to determine *SSC* and sediment discharge. The total number of days covered was 206, which means that there were even more samplings per day, when the discharge was changing fast. The minimal daily measured *SSC* was only 0.0016 g/l and the maximal recorded value of *SSC* was 2.6122 g/l and was measured in May at the water discharge of 1 260 m^3/s. The total amount of suspended sediment discharge at the profile of Draževac in 2014 was 1 104 435 t (the specific suspended sediment yield – 308 t/sqkm/yr). The main objective of this study is to improve *SSC* – water discharge relationship in the Kolubara River based on the extreme hydrological conditions in 2014.

KEYWORDS
flood events, water discharge, *SSC*, sediment discharge, Kolubara River, Serbia

1. Introduction

River sediment fluxes are sensitive to many influences, including soil erosion intensity caused by human activities and land use changes, erosion and sediment control works, extreme weather events caused by climate change, etc (Walling, 1995; Chen *et al.*, 2001; Dragićević, 2002; Lu *et al.*, 2003; Zhang *et al.*, 2008; Petković *et al.*, 2009). Some of these influences cause sediment loads to increase, whilst others, namely, erosion control works and reservoir construction cause decreased sediment fluxes (Walling and Fang, 2003, Rãdoane and Rãdoane, 2001, 2005; Walling, 2006; Milevski, 2011; Tošić *et al.*, 2012, 2013; Kostadinov *et al.*, 2014; Živković *et al.*, 2015). Studies intended to highlight the pattern of sediment concentration and sediment discharge during single hydrologic events, such as a flood, have been reported (Wolman and Miller, 1960; Walling and Webb, 1981; Lenzi and Marchi, 2000; Romanescu and Nistor 2011; Obreja, 2012; Mustafić *et al.*, 2013; Dragićević *et al.*, 2013). These studies have shown that the bulk of sediment in most rivers is transported during single floods and that the relationship between suspended sediment concentration (*SSC*) and water discharge (*Q*) during floods is highly variable. Suspended sediment concentrations during flood events depend primarily on sediment supply, which is greatly affected by factors such as climate, topography, drainage basin area or land use (Salant *et al.*, 2008). Comparison of the results for the discharge and *SSC* records emphasized the complexity of the relationships between the two variables, but provided some insight into the causes of the changes in sediment load (Dragićević, 2002; Walling, 2005; Walling and Fang, 2003; Gautier *et al.*, 2007; Mustafić *et al.*, 2013a). Based on the previous analyses (Dragićević, 2001, 2002, 2007), it has been clearly recognized that under the influence of extreme hydrological conditions for two months, 70% of the annual suspended sediment discharge can be evacuated from the Kolubara River Basin. It happens that most of the sediment discharge is done over several days in a year, or floods that are present almost every year (Petrović *et al.*, 2015). So, during the previous studies were analyzed a lot of extremely water and extremely dry years, and sediment transport during the large number of flood waves. Therefore, the intent of this study was not a comparison of sediment transport during different flood waves because we published many similar results. The primary idea was to analyze the historical maximum in 2014, in which we could not applied previous relationship between *Q* and *SSC*.

The methodology of studying the concentration of suspended sediment in Serbian rivers is different, depending on the observed aspects. There were about 200 gauging stations for stationary monitoring of suspended sediment concentrations on watercourses in Serbia in the seventies of the twentieth century (actually in 1975). In addition to the network of stations that were under the jurisdiction of the Republic Hydrometeorological Service of Serbia (RHMSS), there was also a number of stations that were managed by individual universities and research institutes, as well as sites with periodically exercised stationary and itinerary observations in order to develop a number of projects related to resolving specific water management problems. Methodology of sampling at gauging stations in the Kolubara River Basin was completely different, so that the water sampling frequency ranged from a seven-day rhythm (Dragićević, 2002), over a two-day, to everyday (RHMSS, Dragićević, 2007). Unfortunately, the number of gauging stations for suspended sediment is continuously decreasing, so that none of the stations within the RHMSS no longer worked in 2004. Since 2013, the Laboratory of Physical Geography on the Faculty of Geography of the University of Belgrade has again established the suspended sediment monitoring in the Kolubara River, on Draževac gauging station. We even could not have an idea that already the year of 2014 would be the year that, in research terms, was waited once in many centuries.

The Kolubara River has an unfavourable water regime, and it is reflected in the excessiveness of water runoff, with floods that are sudden, expressive and short-term, and long-term low waters that approach to minimum discharges to ensure the maintenance of biological functions. As an index of unfavourable runoff characteristics, a ratio of the extreme discharge is usually taken which places the Kolubara River in the highest place among the rivers in Serbia (of similar river basin size). The ratio is 101, taking into account the average maximal discharge

in Draževac for the last 46 years, which amounts to 255 m^3/s and the average minimal discharge of 2.53 m^3/s. At absolute extremes, it is about 2 100 (1 260 m^3/s on May 15th, 2014 – towards 0.6 m^3/s). Previous measurements in the Kolubara River Basin (Dragićević, 2002, 2007) have shown that reliable conclusions regarding the suspended sediment concentration in the water should not be made if we only have available data of lower water discharge, but the authoritative conclusions can be made only if we have data of a higher range of discharge as well.

In 2014, water samples were collected in order to determine suspended sediment transport on Draževac gauging station in the Kolubara River. The total number of covered days was 206, which means that there were more samplings per day, when the water discharge was changing fast. Since the intention was to make a connection between the amount of water discharged in the river and the suspended sediment concentration, these multiple data were very useful in defining their relationship, because it is known that at the time of the flood, the sediment concentration in the river is rising sharply. Considering that during 2014 the area of western Serbia (in particular the Kolubara River Basin) was under the influence of extreme climate events that strongly reflected on the hydrological condition, the analysis presented in this paper offered the possibility of determining the relationship between suspended sediment concentration and discharge during extreme hydrological conditions. The highest

discharge in a hundred years would be 740 m^3/s, and the highest discharge in a thousand years would be 960 m^3/s. In 2014 year, the absolute highest daily discharge on Draževac gauging station was 1 260 m^3/s (15.05.2014.). The main objective of this study was to improve *SSC*–discharge relationship interpretation in the Kolubara River based on extreme hydrological conditions in 2014.

2. Study area and methods

The Kolubara River Basin is located in the western part of Serbia and covers 4.12 % of Serbia's surface area (Fig. 1). The watershed drainage area is open towards the north, the highest point is at 1346 m and the lowest has an altitude of 73 m. The Kolubara River is the last large tributary of the Sava River, and according to the flow length (86.4 km) and the watershed drainage area (3 641 km^2), is classified as a middle-sized river within the territory of Serbia. The Kolubara River flows through the different parts of terrain. This diversity is reflected in geologic structure and age of some parts of the basin, as well as in the geotectonic complexity of the terrain through which the river flows. The drainage basin is built of Mesozoic and Cenozoic age igneous and sedimentary rocks and of Paleozoic metamorphic rocks (Dragićević *et al.*, 2012).
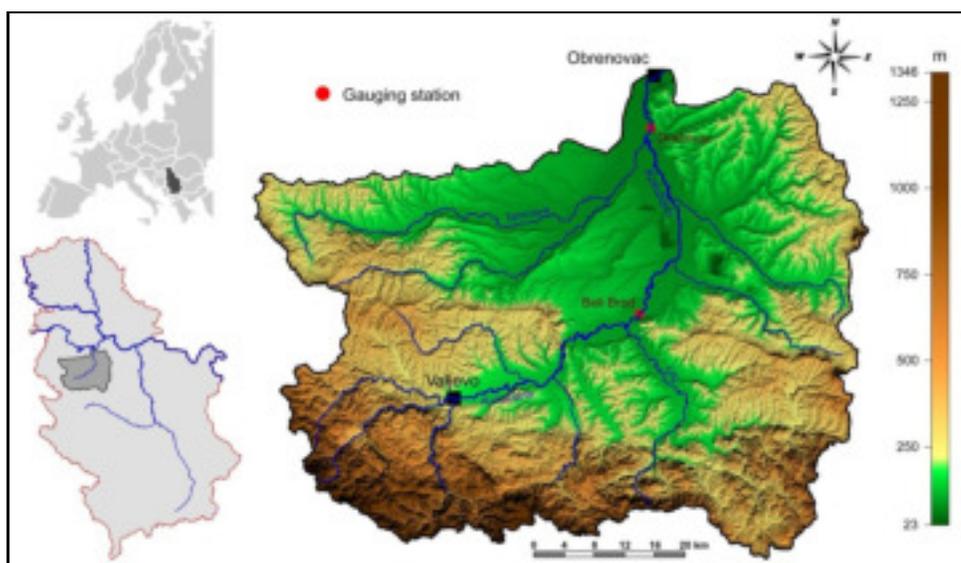
Figure 1 Hypsometric map of Kolubara River Basin in Serbia.

Analysing 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 characterised by a maximum rainfall at the beginning of summer and a minimum rainfall in the winter. Based on rainfall data from 27 rain-gauge stations in the Kolubara River Basin, the most quantity of precipitation falls in warmer part of the year – June (13.4% of annual sum), July (10%), May (9.9%), and the lowest quantity in February (5.5%) (Petrović *et al.*, 2015). Average annual rainfall in the Kolubara River Basin is 809 mm for the period 1959-2010. The Kolubara River has the highest coefficient of monthly flow variation in comparison to other larger river basins in Serbia, and very disbalanced ratio between high and low waters. The highest discharge of the Kolubara River in the period 1959-2013 was 646 m³/s and it was registered on Draževac gauging station. According to probability curve of high discharges, the discharge of 646 m³/s may occur once in 46 years. The lowest value of annual maximum discharge would be about 25 m³/s, the highest discharge in a hundred years would be 740 m³/s, and the highest discharge in a thousand years would be 960 m³/s (Dragićević *et al.*, 2007; 2013). And that happened 2014 year with the absolute highest daily discharge on Draževac gauging station of 1 260 m³/s (15.05.2014.).

Table 1 Main characteristics of the Kolubara river basin

Variables	Symbol and measuring unit	Values
Drainage basin area	A (km²)	3641
Perimeter	O (km)	317.5
Average elevation	H_{av} (m)	272.0
Highest point	Hp (m)	1346.0
Confluence point	Cp (m)	73.0
River length	L (km)	86.4
Drainage density	D (km/km²)	1.1
Mean annual water discharge 1959-2014	Q_{av} (m³/s)	21.1
Mean specific sediment discharge 1985-1992	Q_s (t/km²/yr)	16.5

Sediment monitoring methodology is standard and consists of daily sampling of water and sediment, with laboratory determination of the sediment concentration. All measurements on which performed RHMOS, as our measurements were performed at the same location, on Draževac gauging station! In order to avoid methodological errors and to provide a representative sample at the hydrological profile were carried out very precise measurements of suspended sediment during the 2013/14 year. Specifically, using the sampler with extended filling water sampling was carried out on the left and the right river bank, and then in the middle of the river flow (from the bridge) at a depth of 0.2 and 0.6 h. Such methodology is determined by the profile concentration of suspended load. To obtain a profile of the concentration for the days when there was only the measurement data along the bank, was introduced corrective coefficient *K*. The proposal for the introduction of corrective coefficients in order to determine the concentration profile is known from earlier (Michalec, 2003).

Figure 2 Sampling location

As is known, on the basis of many experiences showed that it is "*possible on the basis of previous results more complete measurements to choose a permanent place in the profile (period or vertical) in which the concentration of suspended sediment (Ka) is in unambigouous depending on the average concentration throughout Profile (Ksr)*" (Dragicevic, 2004).

Daily measurements of suspended sediment concentration and daily recording of water level permit determination of the suspended sediment discharge for a given time period (using the water discharge rating curve).

Suspended sediment concentrations (*SSC*) of each sample taken in 2014 were determined by filtering, drying and weighing the samples. Water sampling for the use of determining the suspended sediment concentration was carried out on the hydrological profile Draževac. All analytical procedures were done in the
Laboratory of Physical Geography on the Faculty of Geography, University of Belgrade.

The calculation of one-day sediment discharge on the monitored hydrological profile includes the values of mean daily flow (Q – m^3/s) and the relevant concentration of the suspended sediment (*SSC*–g/l). Consequently, sediment discharge (*Qs*) is obtained from the following equation (1):

$$Qs\ (t) = Q\ (m^3/s) \times SSC\ (g/l) \times 86.4 \qquad (1)$$

where, 86400 is the number of seconds in one day. Shortening is made, for the conversion of the t/day.

Very important steps were done in order to improve establishment of the mean daily concentration. Considering the fact that instruments for continual deposit monitoring are quite expensive, good results were obtained during the flood waves by sampling on several samples in 24 hours, which provided realistic value of the mean daily concentration, which was more significant than doing one sampling per day.

3. Results and discussions

Dataset of 121 recorded torrential flood events in the Kolubara River Basin for the period 1929-2013 is derived from the Inventory of torrential floods in Serbia. The first maximum of flood events occurs in May (33 or 27.3%) and June (22 or 18.2%) in warmer part of the year and the second maximum is related to March (18 or 14.9 %) in colder part of the year (Ristić R. *et al.*, 2009, 2012; Petrović *et al.*, 2014; *2015*). Catastrophic floods of the Kolubara River and

its tributaries spread over the area of lower part of the Kolubara River Basin during the spring of 1937, and they lasted two months approximately (from March to May). In this area big floods also happened in 1965, 1975, 1981, 1996, 1998, 1999, 2001, 2004, 2006, 2008 and 2010.

The flood in the Kolubara River Basin which occurred in May 2014 and caused catastrophic material damages and casualties was the latest and historical flood. The highest amount of rain was recorded in the period between May 14th and 16th, 2014. Western and central parts of Serbia were the most affected, with three-day rainfalls exceeding the average values for the month of May. Parts of the Kolubara River Basin were affected by rainfall which exceeded 1,000-year three-day rains. As the cyclone was stationary between May 14th and 18th it caused intensive rainfalls of over 200 l/m^2 and in some parts in the watershed of over 300 l/m^2 (RHMOS, 2014). Rainfalls over a 48-hour period exceeded the amount that in some places would normally occur over three months. At a measurement station Valjevo, 180 mm of rain was recorded in 48 hours, equal to the normal average rainfall for three months. In Serbia, Belgrade's rainfall was even higher, with 225 mm in the same period, equivalent to the maximum rainfall normally recorded over three months. The city of Obrenovac (where 90 percent of the city was flooded, with flood waters in some areas more than 4 meters deep) in the lowest part of the Kolubara watershed was significantly affected. This combination of circumstances caused disastrous floods, excessive erosion and sediment discharge, landslides, etc.

3.1 Temporal variability of water discharge and *SSC* during the year of 2014

As we know, sediment supply is usually greatest in the first freshet or early period of a flood event, as readily available sediment sources - typically from outside the channel - are mobilized and rapidly transported. Under these conditions, small increases in discharge contribute to rapid increases in *SSC*. As these sources are depleted, however, *SSC* will rapidly decline, often long before a decrease in discharge.

Taking into account that we had only mean daily discharge at our disposal, it was concluded that the error in the daily suspended sediment transport from the basin can be significant. If the sampling was done at a stable discharge in the morning, and after that the high wave of water came, it was calculated that the error in assessment of the daily sediment discharge can be from several hundred to several thousand tons. The same is true if there is a delay in sampling, and the shock wave passes. Thus, on May 5th, 2014, the sampling was done at 8, 12 and 18 o'clock, and the suspended sediment concentrations amounted to 1.38, 0.82 and 0.74 g/l. At the mean daily discharge of 49.3 m^3/s, the suspended sediment transport of the individual concentrations would amount to 5 860, 3 494 and 3 145 t/day. Since we have no intraday changes in water discharge, the only thing left is to reduce the measured sediment concentrations to the mean value. Thus, the daily transport of 4 166 t of suspended sediment is received for 0.978 g/l. In the event that we only possessed the value of the lower *SSC* (0.74 g/l), and assuming that it was constant throughout the day, as well as the water discharge, more than about 1 000 t of suspended sediment would be evacuated from the basin. Error at the estimate of sediment discharge for the concentration of 1.38 g/l would be about 1 700 t, but now below the real value. Such detailed analyses of errors in calculating the suspended sediment transport on the profile of Draževac were done for the year of 2004, when the annual difference was about 100 000 t, which was a serious error that required a very detailed analysis and methodological improvements (Dragicević *et al.*, 2007a).

As the water discharge and the suspended sediment concentrations are highly variable over time, it is obvious that the methods of sampling once a day, as well as reducing water dis-charge to mean daily values, has serious difficulties to explain the relationship water discharge-*SSC*, and also the sediment discharge from the Kolubara River Basin. However, since these were the only valid data in the historic water year of 2014 (there have been no measurements of the *SSC* concentration by RHMSS since 2002), we tried to achieve the best assessment of the *SSC* for those days when there was no sampling and hence derived conclusions about annual sediment discharge in extreme hydrological conditions.

By establishing the dependence *SSC* = f (*Q*), we get the following diagram of the relationship of water discharge values and suspended sediment concentrations (Fig. 3). The basic idea of this research is to try and linking *SSC* and *Q* due to the fact that the year 2014 was extremely wet and that these conditions have never appeared so far on the Kolubara River (recurrence period of max. *Q* is over 1000 years). In addition, at the time of the high water coming samples were taken and determined turbidity, which is rare in Serbia over the last 10 years. Since the analyzed year had the minimum and maximum flows of the historical period it was concluded that this is sufficient reason to try to form the models which would result in the link *SSC* and *Q*. Otherwise, the procedure itself is not new, but given the fact that the conditions were gained, the challenge was not allowed to drop. Another objective was to calculate the annual sediment transport and set up what is the share of him in May of maximum flow. Figure 3 should not have any practical use, except that we visualize the position of points and point to two different formations. Therefore the function was unnecessary, be it linear or non-linear. However, if we use logarithm for data or axes we will not get a good look of points at the scatterplot.

It can be seen that the required relationship does not have the best references, but also that there is a grouping of data that should be examined. Taking into account all paired values (n = 206), we have found that the best result is achieved through the polynomial connection of the second degree, where the coefficient of explanation of *SSC* through water discharge is 0.64. What has obviously spoiled the assessment is a group of samples which had the increased values of *SSC* at a relatively small water discharge. This group is concentrated by the y-axis on the graph and it has a difference in *SSC* of 1 g/l for small changes in water discharge. It is obvious that their occurrence is associated with the special conditions of runoff, and this can be examined through analysis of the hydrograph and correspondent values of *SSC*.

Suspended sediment discharge from the Kolubara River Basin calculated through the measured values for 206 days during 2014 amounted to 915 514 t, and the one achieved through the formula was 1 047 075 t (Fig. 3). Thus, the difference was 131 561 t, or 14.4%. This difference is important, so that any rational explanation of turbulences of *SSC* and improvement of the relationship with water discharge significantly contributed to the understanding of the erosion processes in the basin and estimation of the sediment discharge. It is obvious that this relationship should be researched in some other way as well, so as to understand its nature, and that is what statistics is missing. The dispersion diagram shows the points formed of pairs of data (*Q* and *SSC*), but they are completely independent and do not have a time dimension.
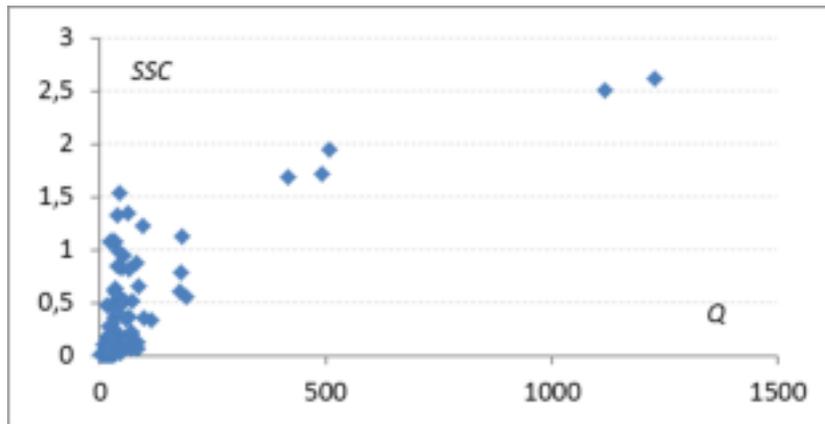
Figure 3 Relationship between water discharge Q (m^3/s) and *SSC* (g/l)
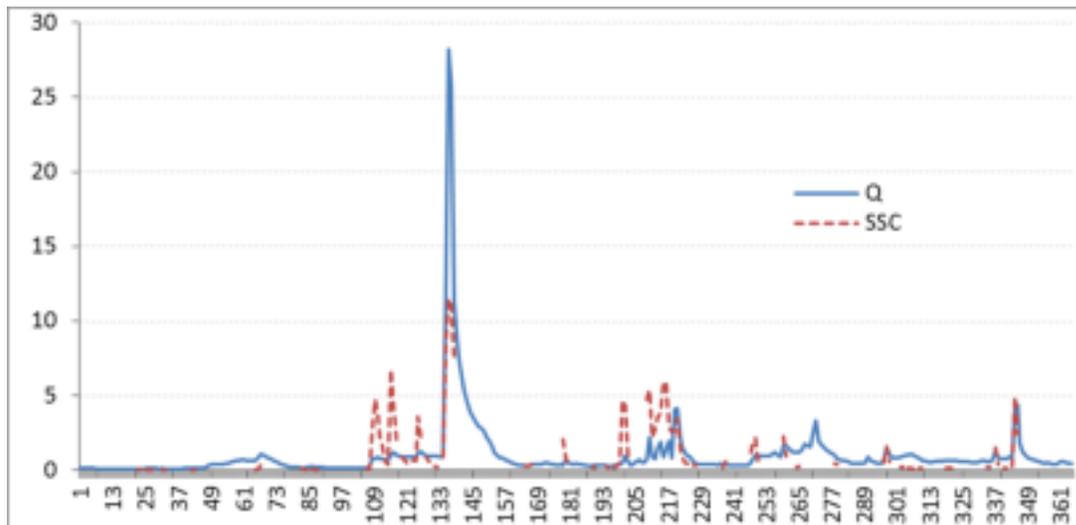
Figure 4 Relationship of modular values of Q and *SSC* during year 2014

Compatibility of the researched phenomenon is most noticeable on the graph where the water discharge (for a calendar year) and suspended sediment concentrations (for 206 days) are presented via modular values (each daily value is divided by the arithmetic mean of the entire series). At first glance it has been already noticed that there is a certain relationship between the water discharge and *SSC*, especially in periods when high waters occurred.

**Table 2** Daily values of water discharge and *SSC* at the end of April, 2014

Date	Time of sampling	Q (m^3/s)	C (g/l)	M_Q	M_C
16.04.	19⁰⁰	6.18	0.0149	0.1762	0.0311
17.04.	15⁰⁰	13.2	0.0156	0.3763	0.0325
18.04.	18⁰⁰	33.7	0.6124	0.9607	1.2774
19.04.	10⁰⁰	35.0	1.0774	0.9977	2.2474
20.04.	11⁰⁰	39.6	0.8437	1.1288	1.7599
21.04.	13⁰⁰	35.1	0.5196	1.0006	1.0839
22.04.	15⁰⁰	33.4	0.3606	0.9521	0.7522
23.04.	17⁰⁰	31.9	0.1314	0.9094	0.2741
24.04.	17⁰⁰	32.3	0.0887	0.9208	0.1850
25.04.	18⁰⁰	44.7	1.5363	1.2742	3.2046
26.04.	12⁰⁰	54.3	0.9456	1.5479	1.9725
27.04.	15⁰⁰	45.0	0.4756	1.2828	0.9921
28.04.*		41.6		1.1859	
29.04.	8⁰⁰	40.7	0.1993	1.1602	0.4157
30.04.	15⁰⁰	39.5	0.1424	1.1260	0.2970
Aug.		35.08	0.4974		

*Water sampling was not done on April 28th. M_Q and M_C – modules of water discharge and *SSC*.

Visual confirmation would be even more convincing if the May flood did not "pulled" the ordinate to unbelievable 28 (so many times the mean daily discharge was higher on May 16th than the average for 2014). It is obvious that the analysis of individual high water waves had to be done in order to obtain the more concrete conclusions, and there were 7 such waves in 2014. For this, it was necessary to have continuity in the sampling for those days when the wave appeared. The longest such series of holding data on *SSC* was in the second half of April of the analyzed year.

Graphic display of the last two columns gives a much clearer picture of the nature of these relationships. Namely, by April 17th, 2014, water discharge on the Kolubara River at Draževac was constantly low and almost thirty days ranged from 6 to 10 m^3/s. At the same time, the *SSC* was also low with a mean of 0.018 g/l. With the significant increase in water discharge to 33.7 m^3/s, the *SSC* increased 35 times and reached 0.6124 g/l on April 18th. The next day, the water discharge slightly increases, and the *SSC* rises to 1 g/l. It was only the third day since the beginning of the flood that the *SSC* is showing signs of decrease and this trend holds no matter the fact that the water discharge is maintained at a constant level. After that, since water discharge increases sharply to 45 m^3/s on April 25th, the *SSC* also reaches its maximum of 1.5 g/l. And as in the previous wave, the maximum discharge is followed by the slight decrease in *SSC*. What conclusion could be drawn? What this case demonstrates is that the erosion processes in the basin are the most intensive at the beginning of the flood wave. They cannot be in the increase long, at most one or two days, after that a decrease in *SSC* follows. Such a relationship is also greatly confirmed by the situation from the end of July and beginning of August, when there is continuity in the daily water sampling and the water discharge had significant fluctuations.
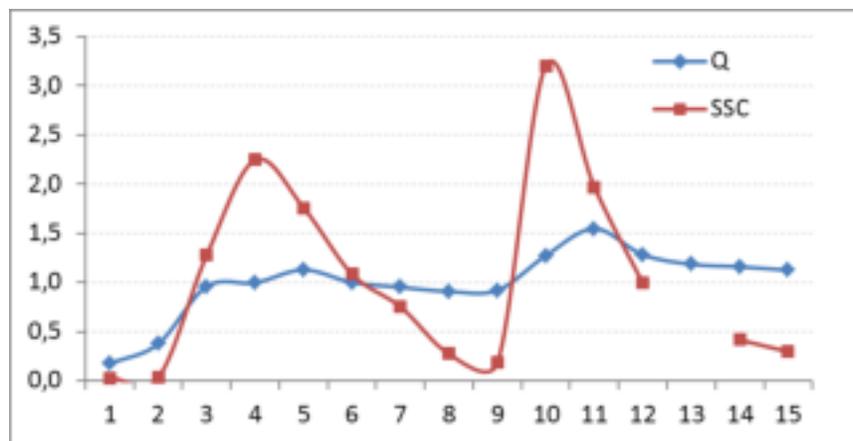
Figure 5 Relationship of modular values of *Q* and *SSC* during 15 days (16 – 30.4.)
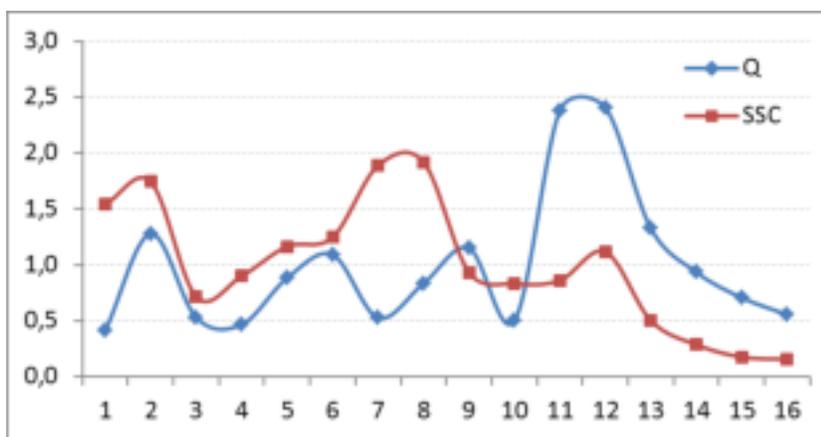
Figure 6 Relationship of modular values of *Q* and *SSC* during 16 days (28.7. – 12.8.)

During the period from July 28th to August 12th, 2014, the water discharge was in the range from 35 to 180 m^3/s, and the *SSC* from 0.11 to 1.34 g/l. This period is slightly more complicated than the one in April. First illogicality represents the seventh day in a row (August 3rd), when the water discharge decreased doubly compared to the previous day, the *SSC* increased 50 % for the same time. The second less clear situation is transition from the 10th to the 11th day (from 37.5 to 178 m^3/s) when the *SSC* remains unchanged. This only shows that the relationship water discharge-*SSC* should not be taken strictly formal, since the erosive processes in the basin are not only affected by the amount of water (rainfall) but also their intensity, the previous condition of the basin, soil moisture, vegetation, etc. Longer field research is required for such an analysis, and our intention was the attempt to separate the data from the chart that disrupt a good relationship water discharge-*SSC*, find the real explanation for that, as well as to define a new relationship for them in order to be actively involved in determination of the sediment discharge. What is likely, and for which we have no concrete proof, is that the anomalies in the relationship discharge-*SSC* arise in situations where bank erosion takes place, and all the material passes through the gauging point, and that it has not been initiated by discharge water. It belongs to the different nature of the problem that is well expressed in the Lower Kolubara Basin (Roksandić *et al.*, 2011, Dragićević *et*

al., 2013a, 2015). That is why in the records of the final results on the annual basis, we will not be able to turn them into specific erosion, at least not in the classical sense which implies the denudation process.

3.2 *SSC*–discharge relationship at the normal and flood time-scale

Dispersion diagram (Fig. 3) clearly shows that water discharge and *SSC* have double relationship. It is obvious that it is conditioned by the time of the characteristic water discharge appearances. Making rules meant the separation of these data and the analysis of individual values.

There have been separated 28 pairs of data (Fig. 3) in the first sample (Model 1) obtained by analyzing the dispersion diagram, which did not fit into the scheme of the vast majority of the daily values of water discharge and *SSC*. By their highlighting on the hydrograph, it was found that these were exactly those days when the water discharge suddenly increased, respectively, reaching the peak of the wave. These 8 days in 2014 have been already described in the period from April 18th to 27th (Table 2), then increase in the discharge on May 5th and 6th, June 27th, July 19th, 20th and 24th, the entire turbulent period from July 28th to August 6th (Fig. 6), September 4th to 6th and October 17th. Therefore, these are the days when the sampling was done, but the concentrations were higher than the expected. The period from May 15th to 19th should be added to

this, when the absolute water discharge maximums and highest *SSC* were recorded. Therefore, the establishment of the *SSC* depending on the water discharge for these 33 pairs of data led to the coefficient of determination of 0.733 obtained through the logarithmic relationship. However, given that we have already had a large number of original data with the lowest water discharged *SSC* (which belong to the "regular" group), there were no obstacles to include them in this relationship in order to make counterweight to the upper extremes.
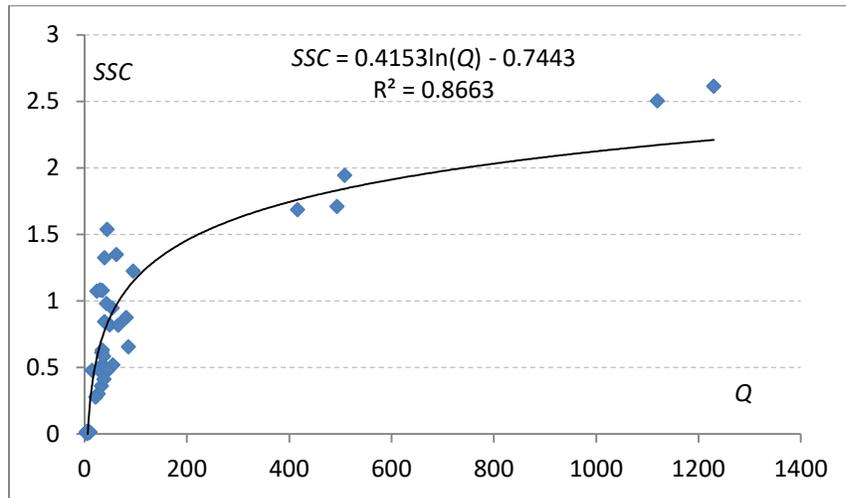

Figure 7 Model 1 (*SSC* dependence of *Q*)

With the Logarithmic function of data, or without, clearly noticeable that when the value of the discharge is about 10 m^3/s something is going on with turbidity. That is, when a sudden increase in flow over this value rapidly increases and sediment transport. The reason for this is the hydraulic nature and is subject to other research, but on this occasion it was essential to define a relationship that would be able to assess the sediment transport. That is why the linearization of the model (over power functions) unnecessary. First, this procedure did not want to make comparisons with the world's examples, and secondly, that the annual assessment *SSC* by Logarithmic function (model 1) and Polynomial function (model 2) is much better than Power function (it has been observed and by the residuals).

In this way a very good assessment of the *SSC* in the water was achieved that the Kolubara River water discharge explains by 86.7%. The maximum deviation from the line of the equation have the samples (3 samples) grouped around the value of the *SSC* of 1.5 g/l, as well as the two extremes at the highest water discharge. Subsequent analysis will show how far these deviations are really essential in assessment of the sediment discharge on a daily, and how much on an annual level. The second sample (Model 2) for the assessment of the *SSC* is formed of all daily pairs of data, except those 28, which are the basis of the first group. Thus, this group involves a total of 178 samples. Here the dependence is adjusted to the polynomial relationship of the second degree, which has made the coefficient of determination of 0.953.

An important question that arises is which functions would be implemented for which water discharge? The answer has been already given largely through way of forming the derived dependences. However, one should know that the proposed models have not yet solved the sediment transport for the whole year, because they have yet to be applied on those days when there was no water sampling, and their number was 159. This was followed by a detailed analysis of the hydrograph for 2014.

Selection of daily water discharge that will be used for Model 1 or Model 2 was dependent on the previously observed rules of conduct in the movement of the suspended sediment:

1. All of the water discharge belonging to a multi-day uniform water discharge was adapted to Model 2, regardless of the water discharge value in question. It is mainly small water discharge, typical for summer or winter.
2. All of the Kolubara River water discharge of over 100 m^3/s on the profile of Draževac belongs to Model 2. Namely, it has been shown that the upper extremes of water discharge are more adaptable to the function of this model (this can be seen on the graphs as well).
3. Model 1 includes the turbulent days with values of up to 100 m^3/s. Depending on the size of the flood it can only be one day of a sudden increase of water followed by a rapid decrease of the recession curve (as on October 17th). In the event that a high water wave lasts several days with daily oscillations as in the period from July 28th to August 6th (Fig. 6), then Model 1 is applied to water discharge of all these days.
4. If successive peaks, between which discharge was stable, more than one day, occur, these values from the "bottom" of the hydrograph belong to Model 2.
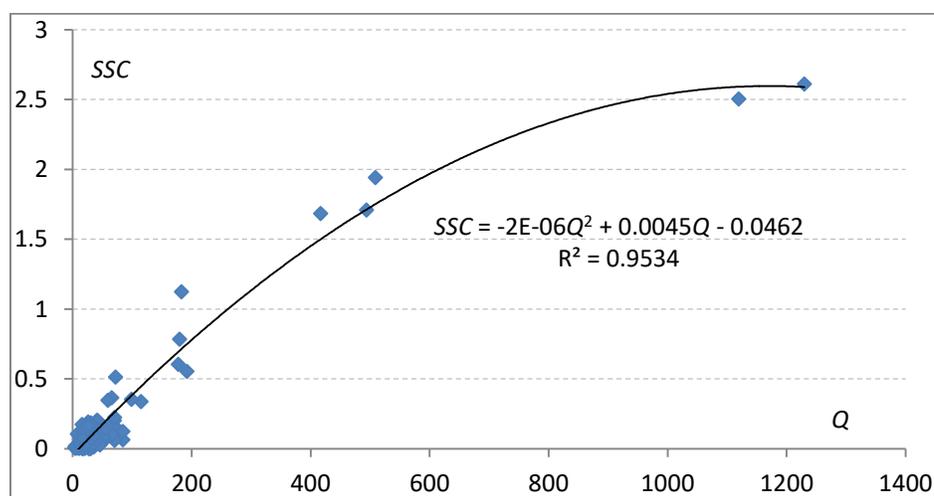

The equation shown on the figure:

$$SSC = -2E\text{-}06Q^2 + 0.0045Q - 0.0462$$
$$R^2 = 0.9534$$

Figure 8 Model 2 (*SSC* dependence of *Q*)

According to the measured data and Models which were applied, we obtained that the average suspended sediment concentration (*SSC*) was 0.187 g/l at the average annual discharge of 43.64 m^3/s on Draževac gauging station in 2014. The minimal daily measured *SSC* was only 0.0016 g/l and the maximal recorded value of the *SSC* was 2.6122 g/l and was measured after the extreme precipitation in May at the discharge of 1 260 m^3/s. The ratio between the daily extremes was 1:1 633.

3.3 Annual sediment discharge in the year of 2014

Taking into account that our attention is focused on the annual sediment discharge from the basin, we are aware of the fact that many of the daily values will be assessed. However, the proposed models for the assessment of the *SSC* are there in order to carry out leveling of the overestimated and underestimated values and in the given circumstances provide the most realistic results on the annual level.

3.3.1 Analysis of Model 1

The annual sediment discharge of 824 850 t was obtained by calculating the original values of the mean daily water discharge and *SSC* for those days that belong to Model 1. The sediment discharge of 761 709 t was achieved by applying Model 1 to them. The difference between these two numbers is 63 141 t, or 7.6%, which exactly represents the error in calculation. Analysis of certain values leads to the

conclusion that the biggest mistake occurred when there was also the greatest water discharge. Daily sediment discharge on May 15th was 277 604 t, and 234 704 t was estimated, so the difference amounted to 42 900 t. The next day, the difference was 32 326 t. However, due to the fact that this water discharge is not in the domain of Model 1, such errors cannot even happen. The model itself was designed precisely to solve the problem of water discharge within the range from 20 to 100 m^3/s. Their error is much smaller, and the highest recorded was 3 350 t (August 4th). Taking into account only those days with a water discharge of 20 to 100 m^3/s, there is a difference of 5 834 t, but now in surplus.

3.3.2 Analysis of Model 2

Suspended sediment discharge of each day when water sampling was done (without 28 days belonging to Model 1) amounted to 829 833 t. The assessment for these same days through Model 2 was 802 398 t, which meant that the error amounted to 27 435 t, or 3.3%. For the sample of 178 members this is an excellent result, which affirms the obtained model. If we accept this model also for the years to come, and we assume that the distribution of suspended sediment will follow water discharge by the line of the same model, we can expect much more accurate results. Namely, if from the obtained residuals of Model 2 we only exclude two highest values (water discharge over 1 000 m^3/s), then the sum of all the other errors of the estimated values is of 9 729 t or 1.2%.

To determine the total annual suspended sediment discharge on the profile of Draževac, it was necessary to assess their values for those days when there was no sampling. By following the rules set in this paper, of the remaining 159 daily water discharge, we should only choose the ones between 20 and 100 m^3/s, which are in the zone of described turbulent water discharge and add them to Model 1. All the other water discharge will be part of Model 2. The analysis of the hydrograph has reached the following results:
- Only 6 of the daily water discharge belong to the group of those that will realize the assess-

ment of *SSC* through Model 1, and those were on May 7th, July 23rd, 25th, September 13th, 23rd and October 18th. Total amount of the sediment discharge for these days was 17 419 t.
- On the basis of Model 2, 153 data were assessed and a total of 169 439 t obtained.

Finally, after establishing the dependence of water discharge and *SSC* and obtaining daily values of suspended sediment discharge, the calculation of the monthly and annual transport values was done. According to the original water discharge data and their corresponding *SSC* (206), and according to the estimated values (159), the total amount of suspended sediment load that was transported at the profile of Draževac in 2014 was 1 104 435 t. The absolute daily maximum was reached on May 16th, 2014, when the calculated transport was even 277 603.7 t, at the water discharge of 1 260 m^3/s. The absolute minimum was measured on January14th, 2014, when only 1.97 t of the suspended sediment load was transported.

When it comes to intra-annual distribution, the large differences and deviations of one month in respect to the other are observed. On the basis of the perennial values (1985-1992) of the sediment discharge obtained from the daily measures of *SSC* for the profile of Draževac, the highest sediment discharge was done in the spring part of the year, and the lowest in the autumn (Dragićević, 2001; 2002). In 2014, the sediment discharge was highest in May (80.3%), August (5.2%), September (3.7%), which constituted almost 90 % of the annual sediment discharge.

If we compare the year of 2014 with the years of 1999 and 2010, when there were high sediment levels, we observe similarities in the excessiveness of sediment discharge, but the values were significantly below those in 2014. In 1999, 70% of the annual sediment discharge was taken away from the Kolubara River Basin for two months (in July and December), and then the monthly sediment discharge in July amounted to 203 962 t and the yearly was 583 954 t. Only for two days (May 16th and 17th) in 2014, the sediment discharge amounted to 207 604 t and 242 278 t, which was about as much during the whole year of 1999 (583 954 t) and 2010 (452 877 t)!

4. Conclusion

The research results have showed that there is a strong correlation relationship between the suspended sediment concentration and water discharge in the Kolubara riverbed, but when considering the problem of *SSC* in a function of water discharge, the correct conclusions cannot be made if larger water discharge in the observed watercourse is not represented. Analyses have showed that the largest suspended sediment concentration appear at the very peak of the incoming flood wave, and together with its passing, it comes to an outstanding non-linear decrease in their values. During multi-peak floods such as this, *SSC* rises rapidly on the first rising limb, peaking a few hours before the discharge peak (positive lag), and drops on much lower levels during subsequent peaks. That is precisely why it was necessary to form two independent relationships that would be used in the assessment of *SSC*, and depending on time of the water discharge peaks appearance, their size and duration:

1) Turbulent days of the water discharge values up to 100 m^3/s belong to Model 1 (mostly of the average annual values up to 100 m^3/s).
2) Model 2 includes all the water discharge of multiday uniform water runoff, no matter which water discharge value is in question. Mostly, it is the case of lower water discharge, typical for summer or winter. Every water discharge above 100 m^3/s belongs to this model as well.

Further research should go in the direction of testing the quality of the obtained relationship between the year of 2014 and measured values of the *SSC* of the average water and low water years. There are indications that these models cannot be replicated in each year, and at all discharge conditions, but it will certainly be a good basis for further analysis leading to the universal solution.

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