Towards Practical Guidance for Sustainable Sediment Management using the Sava River Basin as a Showcase

Estimation of Sediment Balance for the Sava River

December 2013

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Abbreviations

a.s.l.	Above see level
ADCP	Acoustic Doppler Current Profiler
ARSO	Slovenian Environment Agency
BA	Bosnia and Herzegovina
BOBER	Better Observation for Better Environmental Response (project)
DHMZ	Meteorlogical and Hydrological Service of Republic of Croatia
DIKTAS	Dinaric Karst aquifer System (project)
EEA	European Environment Agency
EQSs	Environmental Quality Standards
FASRB	Framework Agreement on the Sava River Basin
GPS	Global Positioning System
HPP	Hydropower Plant
HR	Republic of Croatia
IJC	Institute Jaroslav Černi
ISI	International Sediment Initiative
ISO	International Organization for Standardization
ISRBC	International Sava River Basin Commission
Koc	Organic carbon adsorption coefficient
Kow	Organic water adsorption coefficient
LT	Load transport rate
NPP	Nuclear Power Plant
Q	Discharge
RHMSS	Republic Hydrometeorlogical Service of Serbia
RS	Republic of Serbia
SedNet	European Sediment Network
SI	Republic of Slovenia
SSC	Suspended sediment concentration
UNESCO	United Nations Educational, Scientific and Cultural Organization
WFD	Water Framework Directive

1. Introduction

The Sava River Basin is a major sub-basin of the Danube River, located in South Eastern Europe. The basin is shared by five countries: Slovenia, Croatia, Bosnia and Herzegovina, Montenegro and Serbia, while a negligible part of the basin area also extends to Albania.

Slovenia, Croatia, Bosnia and Herzegovina, and Serbia are Parties of the Framework Agreement on the Sava River Basin (FASRB). The implementation body of the FASRB is the International Sava River Basin Commission (ISRBC) which is responsible for development of joint plans and programs regarding the sustainable water management among others.

ISRBC has developed the Protocol on Sediment Management to the FASRB which affirms the need for efficient cooperation among the Parties and for promotion of sustainable sediment management (SSM) solutions. To respond to the above mentioned needs, a project Towards Practical Guidance for Sustainable Sediment Management using the Sava River Basin as a Showcase has been launched upon the initiative of UNESCO Venice Office, together with the UNESCO International Sediment Initiative (ISI), European Sediment Network (SedNet) and the International Sava River Basin Commission (ISRBC). The main objective of this project is to develop and validate a practical guidance on how to achieve a SSM Plan on the river-basin scale, using the Sava River Basin as a showcase.

The core expert group has been established to analyze the sediment balance for the main Sava River course, also considering the input from the main tributaries, and thus to form a basis for sustainable transboundary sediment and water management.

After collecting existing data the core expert group analyzed and evaluated the existing sediment data in the Sava River Basin, and made the best estimation of basin-wide sediment balance. Also, the core expert group analyzed temporal variability of the sediment data at the mean annual scale, estimated seasonal pattern and identified the role of floods in sediment transport.

In addition to the best expert knowledge and estimations, the identification of monitoring and sampling gaps and the recognition of data uncertainties led to the proposal of effective sediment monitoring system and recommendation of future joint activities towards its establishment.

2. Overview of the Sava River Basin and its main rivers

2.1. Main characteristics of the Sava River Basin

This overview gives only the main characteristics of the Sava River Basin that influence the sediment balance, such as/namely its relief, river network, land cover, climate, and runoff.

2.1.1. Relief and topography

Total area of the Sava River Basin is 97,713 km^2. Terrain in the Sava River Basin significantly changes from the source in the west towards its confluence with the Danube River in the east (Figure 1).

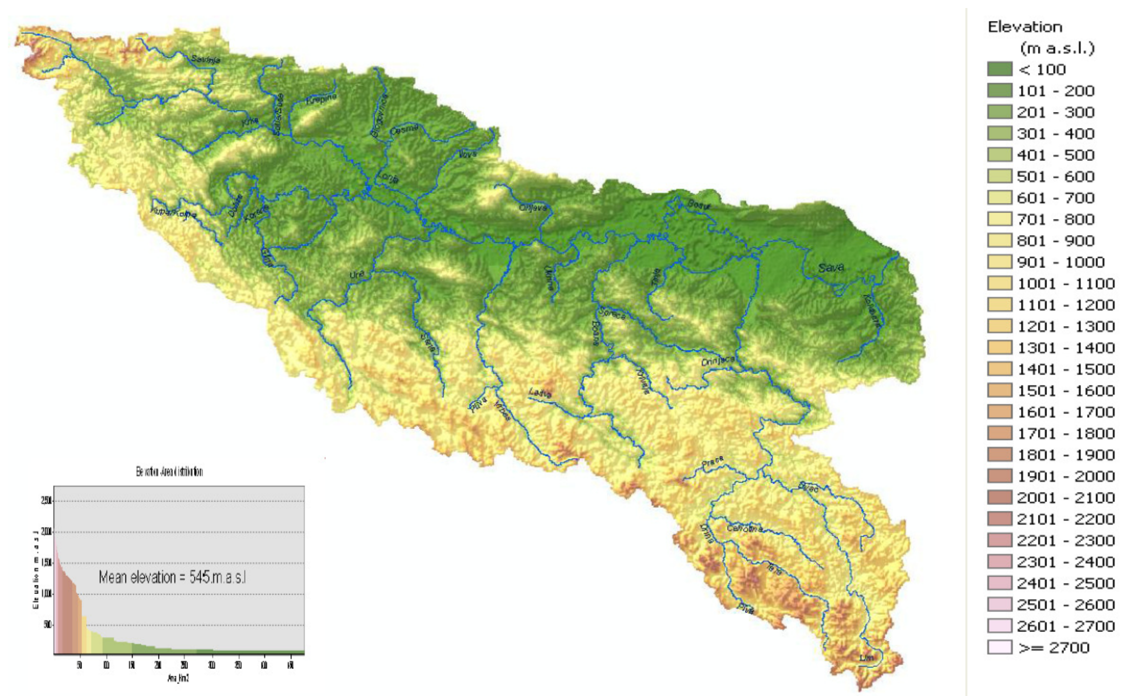


Figure 1: Relief of the Sava River Basin

A remarkable distinction between the landscapes of the northern part and southern part of the basin exists in its middle part. High mountains dominate in the upper part of the basin which belongs to Slovenia.The middle and lower part of the Sava River Basin are characterized by low mountains and flat plains representing the Pannonian Plain, a low-lying, agricultural region, while.the southern part is hilly and mountainous, with mountains up to 2,500 m a.s.l. high, particularly in Montenegro and Northern Albania.

Generally, elevation of the Sava River Basin varies between approx. 71 m a.s.l. at the mouth of the Sava River in Belgrade (Serbia) and 2,864 m a.s.l. (Triglav, Slovenian Alps). Mean elevation of the basin is 545 m a.s.l.

Figure 2 represents slope gradient of the terrain in the Sava River Basin (derived from the Shuttle Radar Topography Mission), which is one of the main factors influencing the sediment yield and transport.

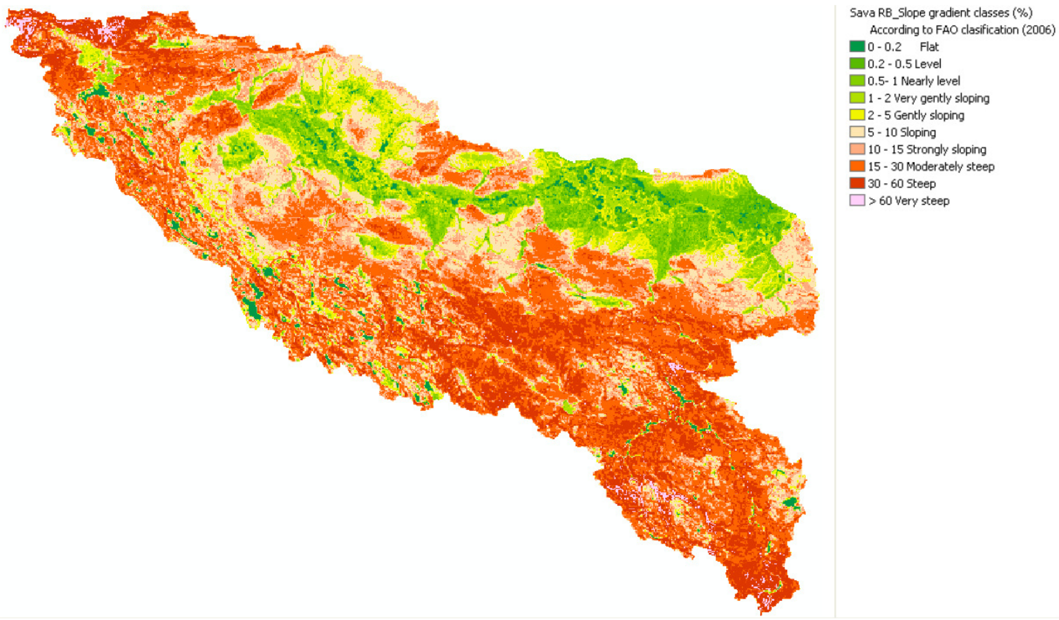


Figure 2: Slope gradient of the terrain in the Sava River Basin

2.1.2. Hydrography

River network in the Sava River Basin is well developed, with 15 first-order tributaries having a catchment area >1000 km^2 (Figure 3). The basin is very asymmetric; app. 70% of its area is covered by the basins of large right tributaries. (Figure 4).

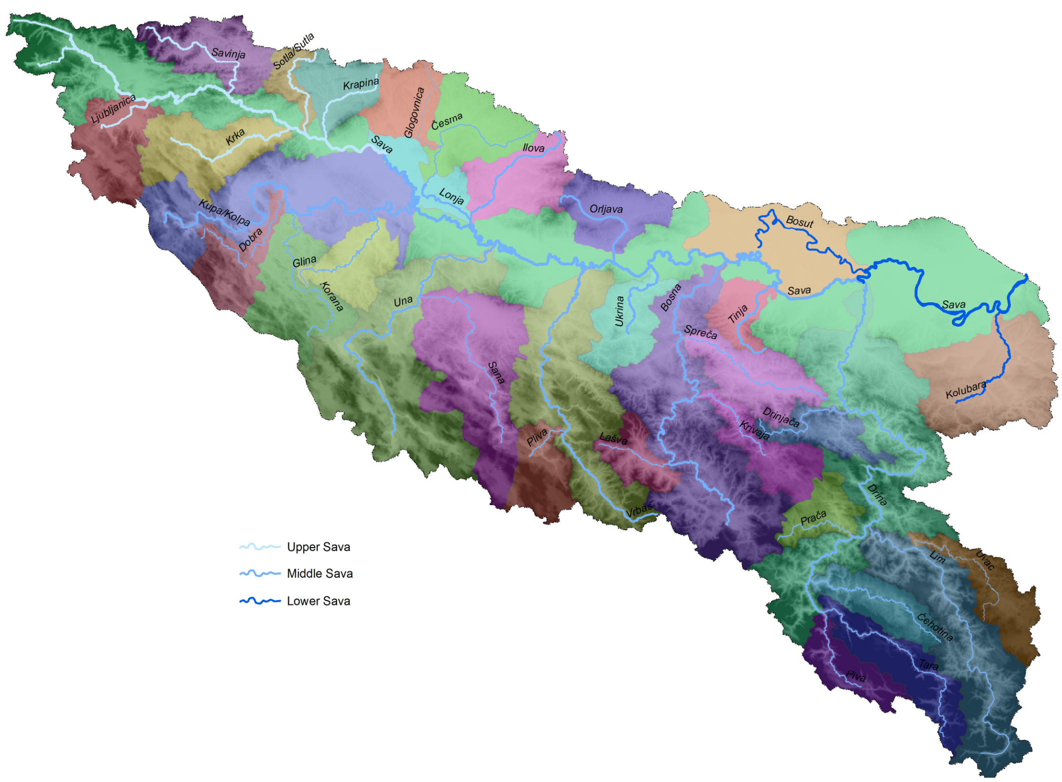


Figure 3: Sub-basins of the Sava River Basin

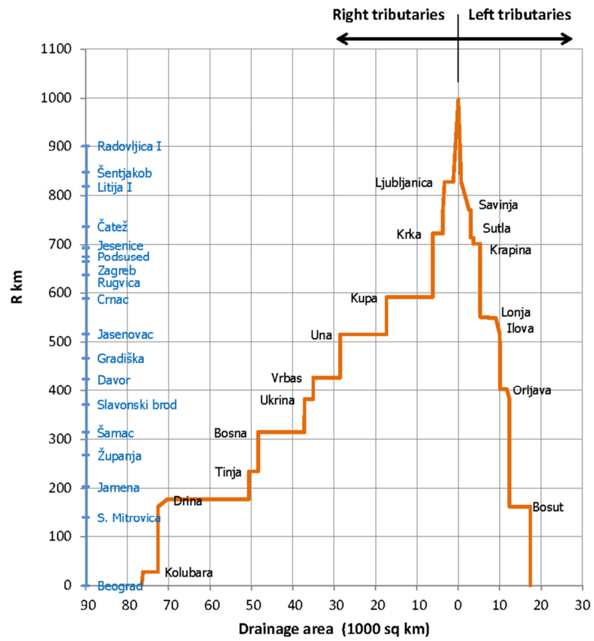


Figure 4: Schematic presentation of the Sava River Basin

2.1.3. Geology and hydrogeology

The most important geological characteristic of the Sava River Basin, influencing the regime of water and sediment is the presence of the karst phenomena. According to results of DIKTAS project (diktas.iwlearn.org), Dinaric karst region spreads from the Italian to the Albanian frontier, covering a part of the Sava River Basin (Figure 5). Karst regions are present only in the southern part of the river basin. This terrain mostly belongs to the zone of the External Dinarides, consisting in very thick layers of limestones from Jurassic and Cretaceous ages (shaded part of the Figure 5).

The rest of the river basin, between the External Dinarides and the border of the Sava catchment belongs to the Inner Dinarides zone and Pannonian basin. In this zone, limestones are much rarer in comparison with the zone of the External Dinarides, with prevailing of following lithological units: sandstone, marls, claystones, intrusive and extrusive igneous rocks (diabase, spilite, dacite, andesite etc), metamorphic rocks (serpentinite, phylite, argiloshist etc). The main aquifers are formed in alluvial deposits. The aquifers characterise large reserves of groundwater, especially alluvial deposits.

Figure 5: Dinaric karst regions in the Sava River Basin

2.1.4. Land cover

According to the EEA Corine database, forests and semi natural areas (marked green on Figure 6) prevail in the Sava River Basin, covering 53,450 km^2, or 54.71% of its total area. Broad-leaved, coniferous and mixed forests are present on 44,360 km^2, or 45.40%. The second largest category is agricultural land (marked yellow on Figure 6), covering 41,390 km^2, or 42.36% . Other land cover classes are present on less than 3% of the total area.

Figure 6: Land use in the Sava River Basin

2.1.5. Climate

The Sava River catchment has in general moderate climate, with clearly distinctive cold and hot seasons. The winter can be severe with abundant snowfalls, while summer is hot and long. There are 2 general types of climate conditions within the basin:

- *Alpine or mountainous climate*, prevailing in the upper Sava Basin within Slovenia and and also in Dinaric Alps at higher elevations;
- *Moderate continental or mid-European climate*, dominating in lower elevations of the catchment including Pannonian lowland;

Dividing lines between these climate types are not sharp.

2.1.6. Precipitation and runoff

Average annual rainfall over the Sava River Basin was estimated at about 1,100 mm. Precipitation amount is very variable within the basin (Figure 7). Mountainous parts of the basin have considerably more precipitation (2,200-2,300 mm) than northern regions (600-700 mm). Most rain occurs in late summer season or during autumn. Significant portion of precipitation falls in form of snow. This causes relatively high spring runoff.

The average discharge at the confluence of the Danube River is about 1,700 m^3/s which results in the long-term average unit-area-runoff for the complete catchment representing about 17.5 $l/s \cdot km^2$.

The runoff in the Sava River Basin is unevenly distributed – it is very high in the mountains, while the contribution of the northern part of the catchment to the Sava River flow is much less significant (Figure 8). The runoff varies from 2,020 mm (the Sava Bohinjka catchment) to 218 mm (the Bosut catchment), and these catchments also have extreme values of water yield 64.2 $l/s \cdot km^2$ versus 6.87 $l/s \cdot km^2$. All right tributaries (except Kolubara and Tinja Rivers) have high water yields (>15 $l/s \cdot km^2$), while left tributaries (except the Savinja River) have less water on average.

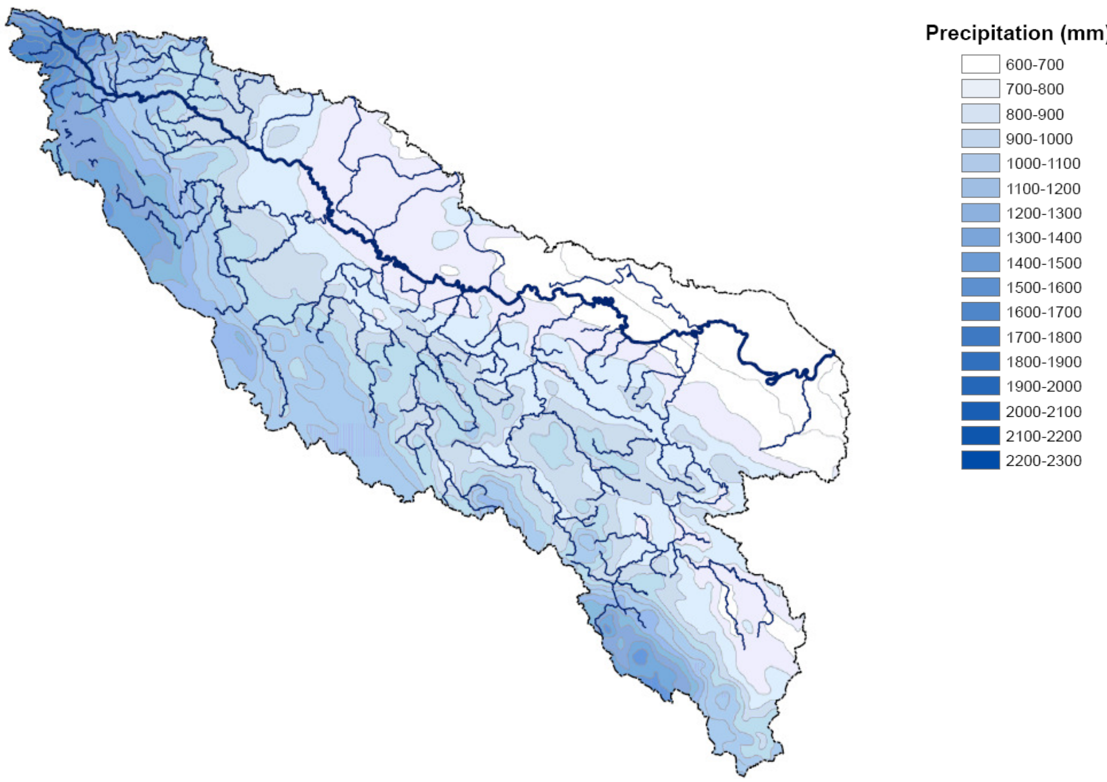


Figure 7: Mean annual precipitation in the Sava River Basin (The Danube and its Basin – Hydrological Monograph, 2006)

Figure 8: Mean annual runoff in the Sava River Basin (The Danube and its Basin – Hydrological Monograph, 2006)

Floods usually appear in the spring and in the autumn. Spring floods are the result of snow melting, autumn floods are caused by heavy rainfall. Depending on the cause, these types of flood exhibit different features. Spring floods are longer, while autumn floods have shorter duration and very high extreme flows. Duration of floods on the Sava River varies between 10-20 days near Zagreb and 40-70 days near Sremska Mitrovica.

2.2. Main characteristics of the Sava River main course

2.2.1. Specific sections

The Sava River is formed by two mountain streams: the Sava Dolinka (left) and Sava Bohinjka (right) in Slovenia. It then flows in a NW –SE direction through Croatia, forming the border with Bosnia and Hercegovina, and runs through Serbia on the lower stretch. The total length of the watercourse is 945 km. There is a common understanding that the course of the river can be divided into 3 sections:

- Upper Sava, between the confluence of Sava Dolinka and Sava Bohinjka and Rugvica (km 658). The catchment area of the Upper Sava comprises mountainous and hilly relief;
- Middle Sava, between Rugvica and the mouth of the Drina River (km 178) is a lowland, alluvial section, characterized by wide floodplains, and mouths of numerous tributaries;
- Lower Sava, downstream of the mouth of the Drina River, is also alluvial section. There are no significant tributaries on this section. The most downstream, 100 km long section is under the influence of the Danube.

It should be noted that changes of the Sava River alignment due to fluvial erosion are not pronounced. The unstable banks were present in sharp river bands, but numerous river structures were built to prevent further bank erosion.

Table 1: Basic characteristics of Sava River sections

Section	Upstream basin area A (km^2)	Specific flow q ($l/s{\cdot}km^2$)
Upper Sava (at Rugvica, km 658)	12,680	31
Middle Sava (at the Drina River mouth, km 178)	86,154	20.1
Lower Sava (at the mouth to the Danube, km 0)	97,713	17.5

2.2.2. Longitudinal profile

The longitudinal profile of the Sava River from its mouth into the Danube River in Belgrade to the hydrological station Radovljica (410 m a.s.l., river km 890) is shown in Figure 9. The most obvious detail on the longitudinal profile of the Sava River is the knickpoint around river km 660, close to the City of Zagreb. Upstream of the hydrological station Radovljica(river km ~890), the average longitudinal slope of the Sava River is close to ~10‰ (this Sava River part definitely has a pronounced torrential character) . Between Radovljica and Rugvica (river km 658) it drops to ~ 2‰, and lowers to ~0.05‰between Rugvica (km 658) and Belgrade (km 0).

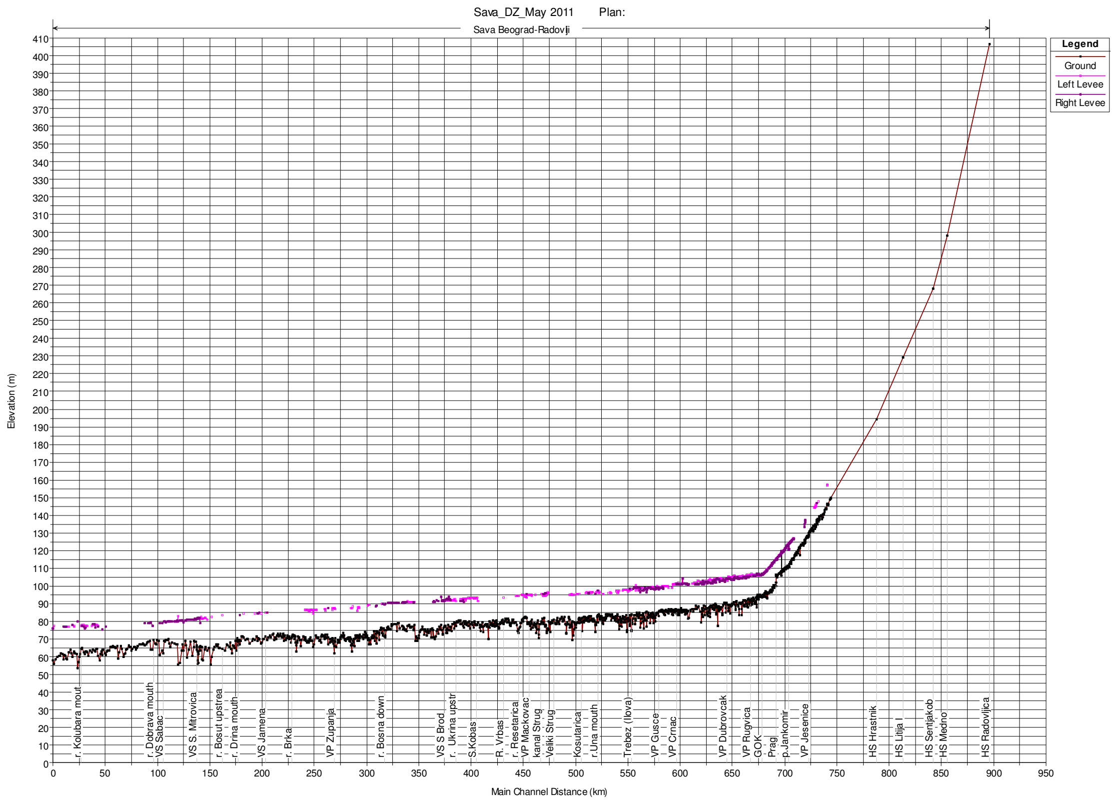


Figure 9: The longitudinal profile of the Sava River between the mouth to the Danube (RS) and Radovljica (SI)

2.2.3. *Bottom sediment*

Near km 680 is also a rather sharp transition from a gravel-bed river (at the Upper Sava) to a sand-bed river (at the Middle Sava). The mean sediment diameter from the Sava source to the knickpoint close to Rugvica is of the order of several tens of mm. Riverbed material on the Middle and Lower Sava is finer (sand and find gravel), having $D_{50\%}$ mainly bellow 12 mm (Figure 10). It should be noticed that the main right tributaries (Vrbas, Bosna and Drina Rivers) bring coarse gravel material into the Sava Riverbed, forming large and visible gravel bars at the mouths (Figure 11).

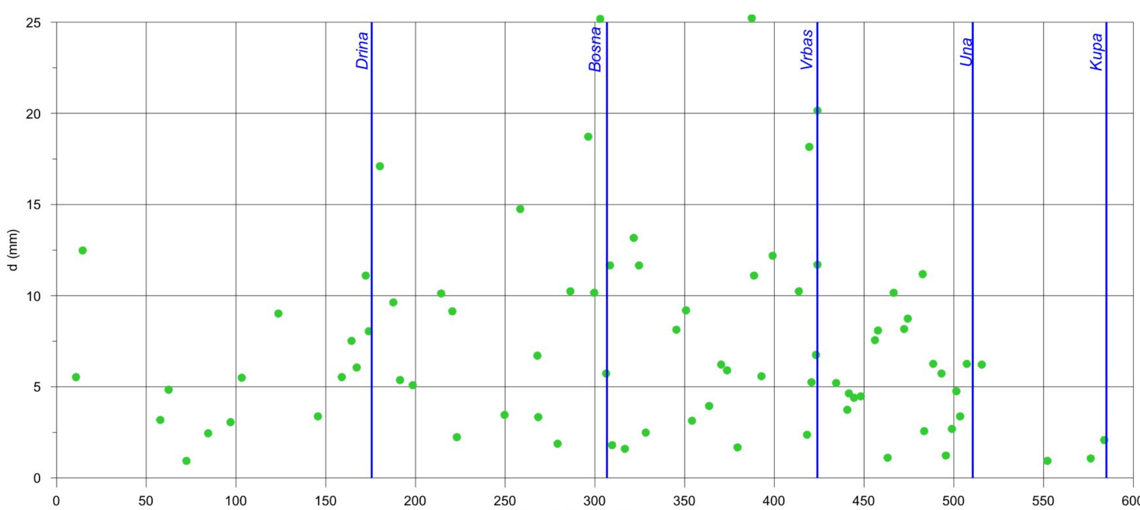


Figure 10: Longitudinal distribution of the Sava Riverbed sediment diameter D50%

Figure 11: Large gravel bar at the mouth of the Drina River

2.2.4. Dams and hydropower plants

Seven hydropower plants (HPP) are built on the Upper Sava in Slovenia: HPP Moste (1952), HPP Mavčiče (1986), HPP Medvode (1953), HPP Vrhovo (1993), HPP Boštanj (2005), HPP Arto-Blanca (2008), and HPP Krško (2013); two more (HPP Brežice and HPP Mokrice) are planned.

The most downstream section of the Sava River, between Šabac and the mouth to the Danube, is under the influence of the Iron Gate 1 HPP operation regime (HPP was built in 1970, 227 km downstream of the Sava River mouth, at km 943 of the Danube River). This section is a shallow part of the Iron Gate reservoir, where the water levels and flow velocity during low and average flows were changed, thus influencing the sediment regime of the Sava River.

2.3. Main characteristics of the Sava River tributaries

2.3.1. Overview of Sava River tributaries

The most important **right tributaries** are: Ljubljanica, Krka, Kolpa/Kupa, Una, Vrbas, Ukrina, Bosna, Drina and Kolubara Rivers. Common feature of almost all right tributaries of the Sava River is their torrential behaviour, particularly in their upper sections. River channels are often deeply cut into the hard rocks, with very violent flow through gorges.

The main **left tributaries** are Savinja, Sotla/Sutla, Krapina, Lonja, Orljava and Bosut Rivers. Except in Slovenia, left tributaries drain mostly flat areas and low hills of the Pannonian basin. Consequently, the slopes and flow velocities are smaller and the streams are meandering.

Longitudinal profiles of the main Sava River tributaries are presented on Figure 12. It can be stated that the slopes are very different, but the increase of slope in the upstream direction is a common feature of all tributaries.

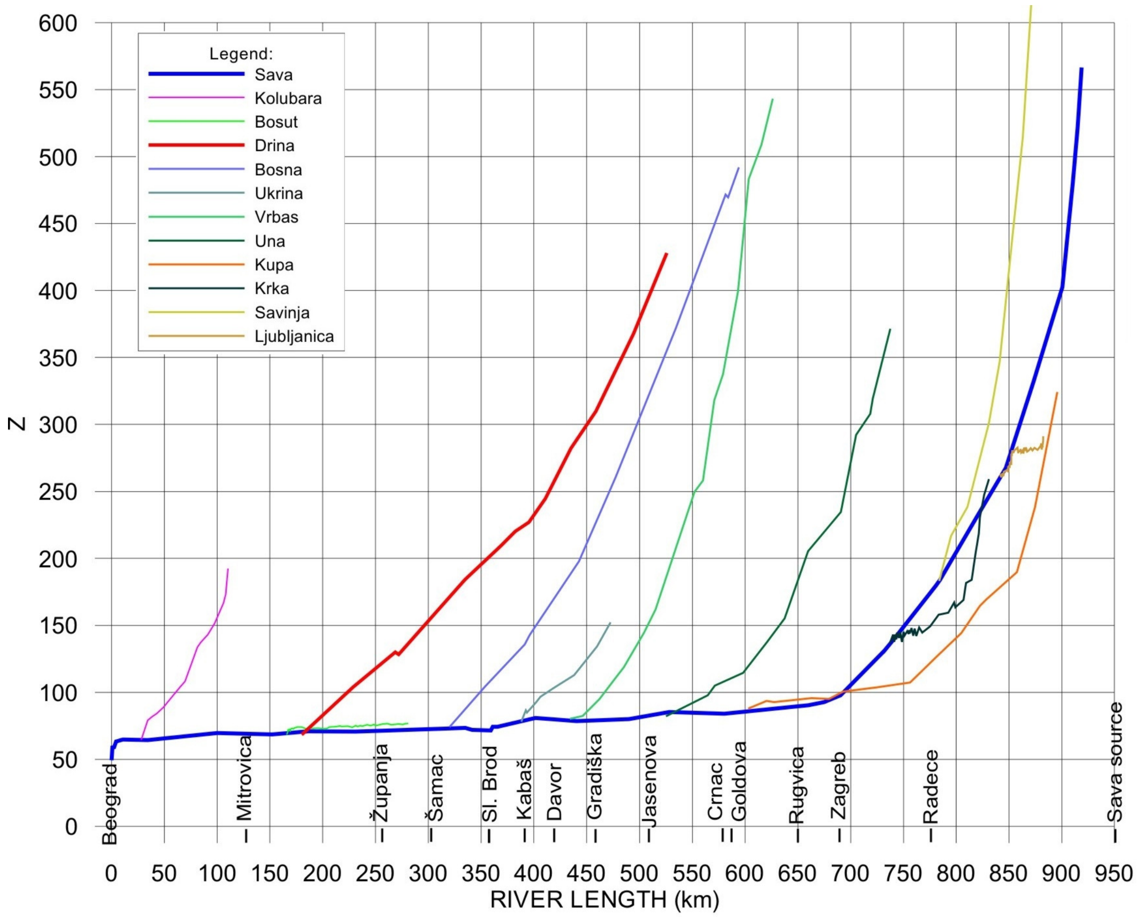


Figure 12: Schematic longitudinal profiles of the Sava River and some of its main tributaries

Table 2 presents the main characteristics of the Sava River tributaries, including morphology, karst (as percent of the basin area in karst) and specific inflow. These numbers can be used for a rough estimate of the role of a certain tributary in the sediment balance of the Sava River.

Table 2: Basic characteristics of the Sava River tributaries

River basin	Left /right bank	Countries sharing sub-basin	Basin area	Length of river	Mean altitude of drainage area	Average slope of drainage area	Average slope of the lower section	Percent of basin area in karst	Specific inflow
			(km^2)	(km)	(m a.s.l.)	(m /km)	(m /km)		($l/s{\cdot}km^2$)
Ljubljanica	R	SI	1860	41	617.1	158.8	0.8	55	35.2
Savinja	L	SI	1849	94	611.6	272	1.5	-	23.7
Krka	R	SI	2247	95	447.9	147.9	0.2	62	27.8
Krapina	L	HR	1237	67	251	143.7	0.9	-	13.9
Kupa/Kolpa	R	HR, SI, BA	10257	297	378.2	124	0.3	0.46	23.5
Lonja	L	HR	4259	49	146.5	54	0	-	9.5
Ilova	L	HR	1796	105	213.2	81.1	0	-	7.0
Una	R	BA, HR	9829	215	620.2	165.5	0.4	59	23.1
Vrbas	R	BA	6274	250	764.2	201.3	0.6	33	18.8
Orljava	L	HR	1618	88	280.8	117.5	0.9	-	9.1
Ukrina	R	BA	1504	81	250.7	113.8	0.6	2	11.0
Bosna	R	BA	10810	282	680.1	223.8	0.6	17	15.0
Drina	R	AL, ME, BA, RS	20320	346	963.7	262.7	0.7	40	19.8
Bosut	L	HR, RS	2943	186	88.2	12.2	0	-	6.9
Kolubara	R	RS	3638	87	275.8	111.1	0.9	9	7.5

2.3.2. Previous estimation of sediment yield and transport

The rough estimate done in 1970es (following Gavrilovic's methodology), showed that the average production of sediment in the Sava River Basin amounts to 21,074,851 m^3/year, while the sediment runoff/transportation across water streams is 7,685,178 m^3/year or 36.5% of the total production.

The highest sediment production occurs in Bosnia and Herzegovina (BA), followed by Croatia (HR) and Serbia (RS), and the lowest production can be found in Slovenia (SI). The average specific production of sediment is the highest in the territory of BA, and the lowest one in Croatia.

Sediment runoff is directly related to the density of the hydrographical network and topography, morphological and geological characteristics. Table 3 presents the results of the estimate of sediment yield and transport in the Sava River Basin, done in 1970es.

Table 3: Overview of assessment results of sediment yield and transport in the Sava River Basin and its tributaries

Tributaries	Tributaries ' catchment area F (km^2)	Annual sediment production Wg (m^3)	Specific annual sediment production per 1 km^2 Wg/F (m^3/km^2)	Annual sediment runoff Gg (m^2)	Specific annual sediment runoff per 1 km^2 Gg/F (m^3/km^2)
Slovenia					
Sava Dolinka	434,7	521.565	1000	173.860	400
Sava Bohinjka	380,0	143.600	437	19.100	58
Ljubljanica	1.941,4	278.000	143	70.000	36
Savinja	1.858,0	585.000	315	145.000	78
Krka	2.053,3	305.300	149	58.000	28
Interbasin	2.413,3	774.960	321	302.640	125
Σ	9.080,7	2.608.425	394	768.600	121
Croatia					
Sotla/Sutla*	140,3	35.300	252	20.000	142
Krapina	1.052,7	40.200	380	179.560	170
Kolpa/Kupa*	5.330,5	1.941.940	364	752.670	141
Lonja	4.200,9	1.237.180	300	397.950	95
Orljava	1.508,7	291.210	423	126.575	184
Interbasin	6.418,6	1.169.340	182	470.415	74
Σ	18.651,7	4.715.170	317	1.947.170	134
Bosnia and Herzegovina					
Una*	9.798	1.289.933	780	426.928	260
Vrbas	6.260	508.745	400	107.600	85
Ukrina	1.500	226.690	830	86.230	317
Bosna	10.551	3.235.090	508	711.590	112
Drina*	16.309	5.247.258	322	2.765.960	170
Interbasin	1.170	507.500	433	230.800	196
Σ	45.588	11.015.216	546	4.329.108	190
Serbia					
Kolubara	3.616,8	1.940.000	536	442.000	122
Interbasin	2.041,6	796.040	390	198.300	97
Σ	5.658,4	2.736.040	463	640.300	110
	Σ	21.074.851	220	7.685.178	80

*** Catchment is shared by two or more countries**

According to the data presented in the table above, on the territory of Slovenia, the largest amounts of sediment found in the Sava River originate from Sava Dolinka and Savinja Rivers. Yet according to the above mentioned data, the largest amounts of sediment in fact originate from the interbasin-an area located in between catchment areas of the mentioned tributaries, abundant in smaller streams.

In the territory of Croatia, the largest amount of sediment is transported by Kupa, Lonja and Krapina Rivers. It should be noted that the interbasin covers a significant area originating a large amount of sediment to the Sava River; nevertheless the amounts are lower than those in Slovenia.

In Bosnia and Herzegovina, the highest amount of sediment originates from the Drina River basin, Una River Basin and Bosna River Basin. However, if only specific production is taken into account, the highest contribution to the sediment production of the Sava River per km^2 originates from the Ukrina River Basin.

On the territory of Serbia, the largest amounts of sediment are transported by the Kolubara River, while the interbasins yield a significantly smaller amount of sediment. This is expected, considering that the territory of Serbia, which appertains to the Sava River Basin, is characterized by the smaller streams with no particularly pronounced erosion.

2.3.3. Dams and hydropower plants on the tributaries of the Sava River

A large number of dams and hydropower plants are built on the tributaries of the Sava River. Table 4 presents the most important ones.

Table 4: Reservoirs on the Sava River tributaries

Country	Subbasin	River	Name	Volume	Purpose	Year
SI, HR	Sotla/Sutla	Sotla/Sutla	Vonarje (Sutlansko jez.)	12.4	DW, IW, FP, IR	1980
HR	Ilova	Pakra	Pakra	13.3	DW, IW, FP	1996
BA	Vrbas	Vrbas	Bocac	52.7	EP	1981
BA	Drina	Rastosnica	Snjeznica	20.6	EP	1984
BA	Bosna	Spreca	Modrac	88	IW, DW, FP, EP	1964
ME	Drina	Cehotina	Otilovici	17	IW, DW, FP	1981
RS	Drina	Drina	Zvornik	89	EP	1955
BA	Drina	Drina	Visegrad	161	EP	1989
RS	Drina	Beli Rzav	Lazici	170	EP	1983
RS	Drina	Uvac	Uvac	213	EP	1979
RS	Drina	Uvac	Kokin Brod	273	EP	1962
RS	Drina	Drina	Bajina Basta	340	EP	1966
ME	Drina	Piva	Mratinje	880	EP, FP	1973
RS	Drina	Uvac	Radoinja	7	EP	1959
RS	Drina	Lim	Potpec	44	EP	1967
RS	Kolubara	Velika Bukulja	Garasi	6.27	DW	1976
RS	Kolubara	Kladnica	Paljuvi Vis	14	IW	1983
RS	Kolubara	Jablanica	Rovni	270	DW, IR	-

Legend on purpose: IR – irrigation; DR – drainage; DW - drinking water supply; IW – industrial water supply; R – recreation; EP – electricity production; FP – flood protection.

Most of the reservoirs are located in the Drina River Basin. Natural sediment regime on this most important tributary of the Sava River was altered in the previous 60 years, and new alterations are expected.

The role of these reservoirs in the sediment balance of the Drina River is highlighted in the following three case studies.

2.3.4. Case study 1: The impact of the construction of HPP Mratinje on the sediment system in Foča

The watercourse of Drina is formed by merging of Piva and Tara Rivers. Features of the river basin enable Piva and Tara Rivers to contribute to almost 40% of the total water of Drina River at mouth, although they include only 20% of the river basin. One of the features of the Drina River Basin includes high slopes (up to 50%), which produce a fast concentration of high water. In addition to the hydro-power production, mitigation to the problem of water discharge levelling resulted in the construction of HPP Mratinje.

HPP Mratinje has a large reservoir with total annual levelling. Therefore, it is possible to conclude that water in the reservoir is retained for a relatively long period. As a result, this creates favourable conditions for the sedimentation of suspended matter in the reservoir.

Gauging station Foča is located ~ 50 km downstream from the dam profile of HPP Mratinje. The measurements show a strong connection between water discharge and suspended sediment load on the profile in the pre-charging period, i.e. they show disrupted dependence after the reservoir Mratinje has been charged.

Mean monthly water discharge and mean monthly sediment transport ratio before filling of the HPP Mratinje reservoir (1966-71) is given on Figure 13, while the same ratio for the operation period is given on Figure 14.

In relation to the system established for the construction state of the reservoir, water discharge of the gauging station Foča amounts to over 45 m^3/s. It is typical that the suspended sediment load at same profile is more and more reduced as opposed to the suspended load during the pre-charge system.

Table 5: Values of mean annual water discharge and mean annual sediment discharge before and after charging the reservoir

Period	Mean value		
	Mean annual water discharge Q (m^3/s)	Mean annual sediment discharge G (t/d)	Total annual sediment discharge T(t)
1926-75	212.6	726.6	265209
1976-89	206.8	260.3	95086

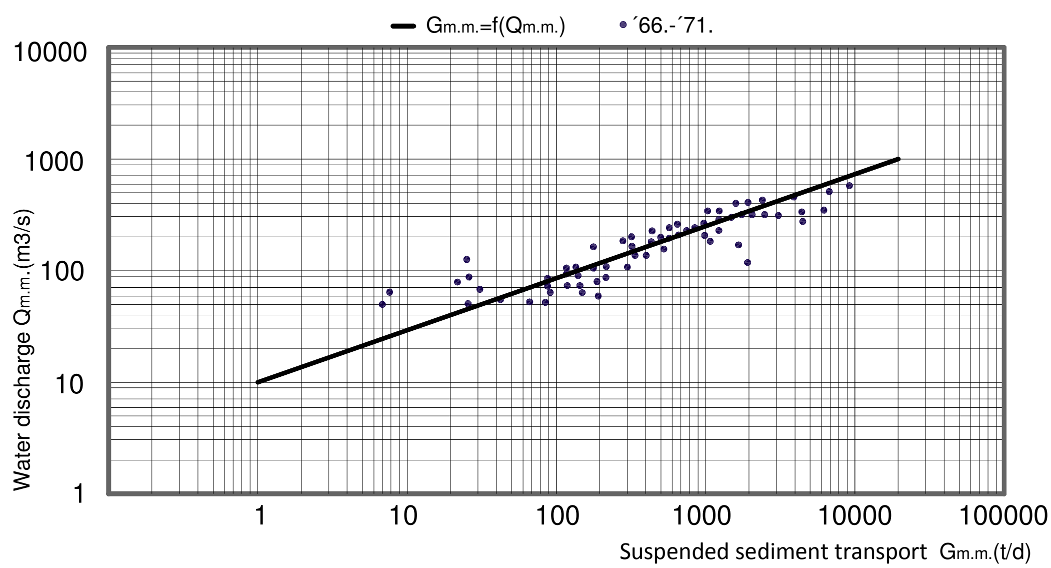


Figure 13: Relation between mean monthly water discharge and mean monthly sediment discharge (Drina River, gauging station Foča), 1966-1971

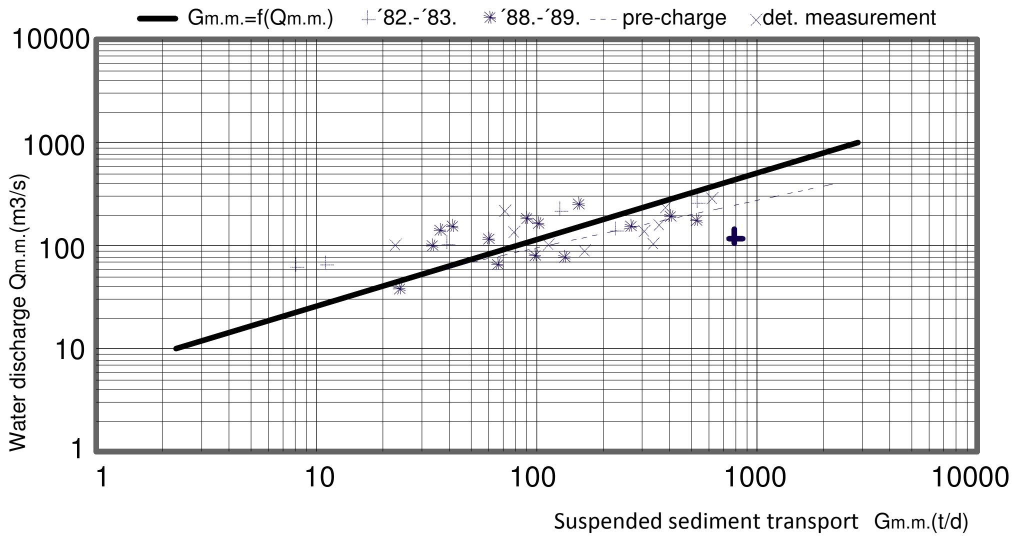


Figure 14: Relation between mean monthly water discharge and mean monthly sediment discharge (Drina River, gauging station Foča), 1982-1989

Values in Table 5 confirm that the reservoir Mratinje has an impact on the reduction of total suspended load, since the charging of this reservoir started in the end of 1975.

Mean monthly water discharge and mean monthly sediment discharge diagram with and without impact of the construction of HPP Mratinje on the sediment is given below.

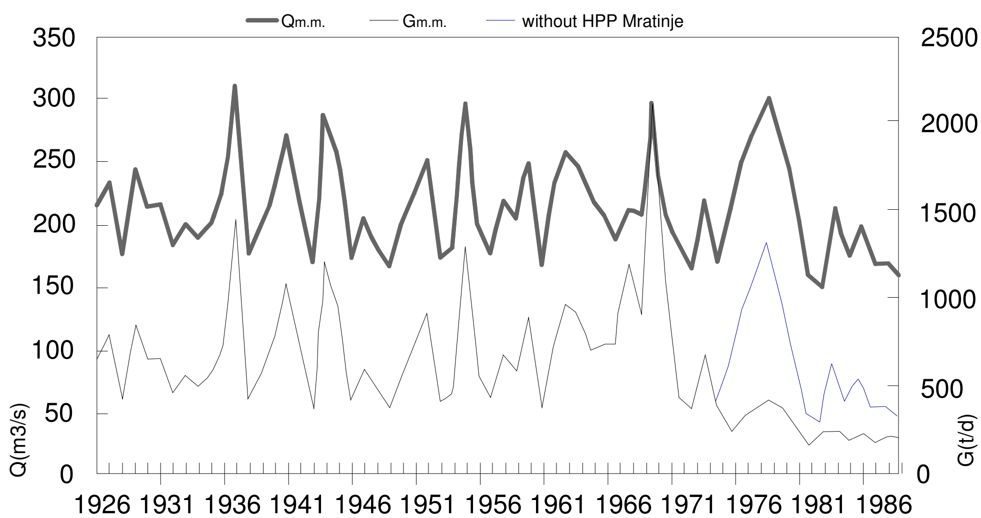


Figure 15: Mean monthly water discharge and mean monthly sediment load diagram (Drina River, gauging station Foča)

Although the analysis of suspended load on the Drina River was conducted during several surveys, single analysis of the measurement results on the profile of gauging station Foča enabled reaching certain conclusions about the modification in the suspended sediment regime during the construction of HPP Mratinje. The results of such survey indicate that relatively small quantity of suspended sediments have been retained in the reservoir of cca 2.4% of the total reservoir volume.

2.3.5. *Case study 2: Sedimentation of HPP Zvornik and its influence on fluvial processes on the downstream Drina River section (Lower Drina)*

After the construction of Zvornik dam (in 1955), the sediment transport from the upstream parts of the river basin was interrupted. The initial volume of the reservoir was 95 million m^3, but in between 1955 and 1967 about 30% of volume was lost due to sedimentation. The average sedimentation rate was $2.92 \cdot 10^6$ m^3/year.

Sedimentation rate diminished after the start of operation of the upstream reservoirs, and the average sedimentation rate between 1967 and 2005 was $0.42 \cdot 10^6$ m^3/year. Nevertheless, almost 50% of the reservoir volume is presently filled with sediment (Figure 16).

The alteration of natural sediment regime induced severe fluvial erosion on the 100 km long Lower Drina (a section running from the Zvornik dam to the mouth), where the upstream narrow valley abruptly changes to the wide alluvial plain, and watercourse becomes typically lowland. Fluvial processes on this part of the river include frequent changes in river course, wandering branches, bank sliding, and loss of riverine agricultural land.

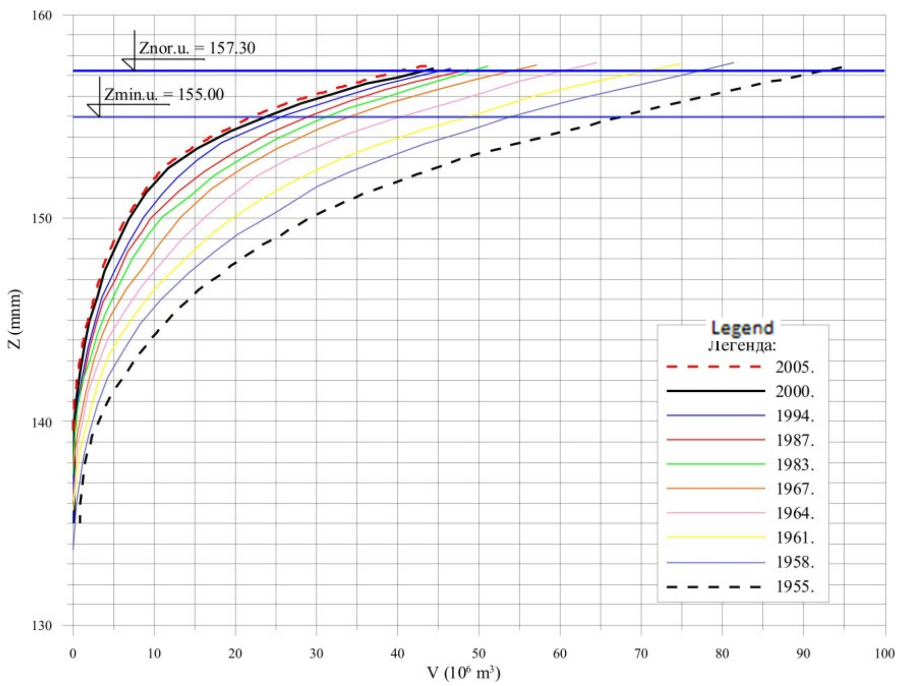


Figure 16: Decrease of the HPP Zvornik reservoir volume, 1955-2005

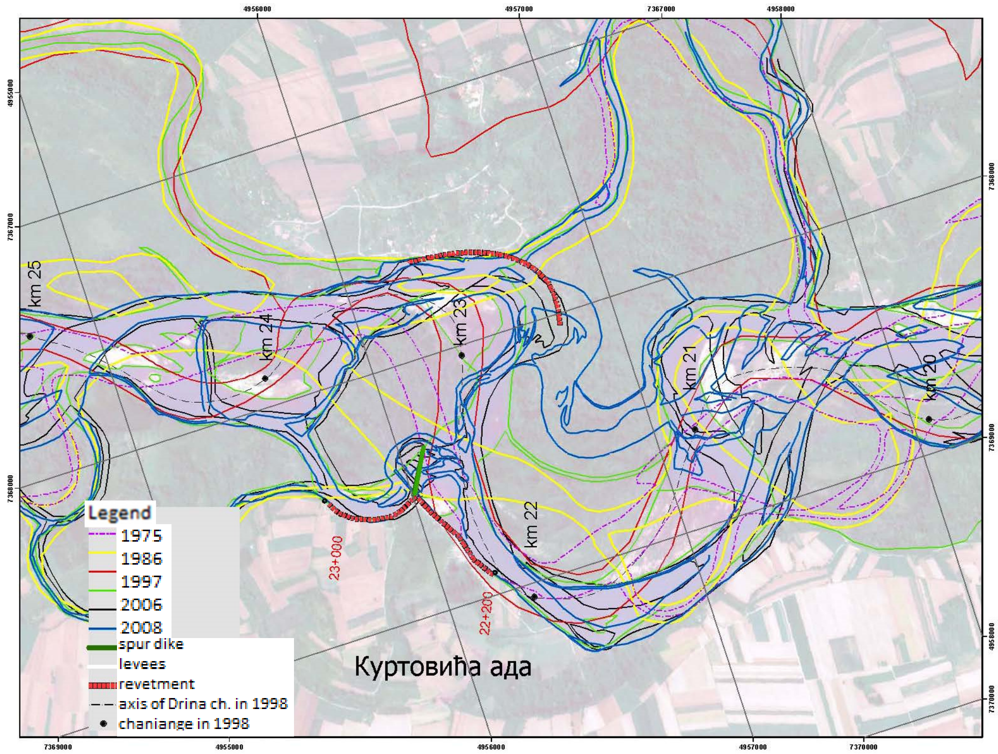


Figure 17: Changes of the Drina river alignment, 1975-2012

2.3.6. Case Study 3: Sediment Quantity in the reservoir Modrac

The measurements of 2012 showed that sediment volume at the regular backwater elevation of 200.00 m.a.s.l. amounted to 15,019,902.71 m³, i.e. 15,025,121.21 m³ at the elevation of 202.00 m.a.s.l. Sediment quantities per every elevation meter are shown in Figure 18.

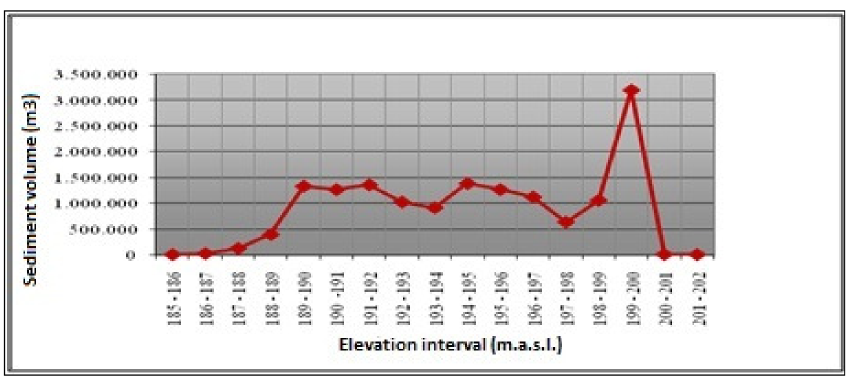


Figure 18: Curve of sediment deposited into the reservoir Modrac per every elevation difference meter

Sediment volume for available elevation from the minimal operating level elevation of 194.00 m.a.s.l. to the regular backwater elevation of 200.00 m.a.s.l. amounts to $V_{sediment}$ = 8,621,261.28 m³, which is 12.95% of available water volume amounting to $V_{available}$ = 66,522,627.33 m³.

It was identified that in the reservoir Modrac for the regular backwater elevation of 200 m.a.s.l. the average annual sediment deposits amounted to:

- 374,000 m^3 in the period of 1964 – 1979,
- 376,666.67 m^3 in the period of 1979 – 1985,
- 262,446.47 m^3 in the period of 1985 – 2000.

This measurement showed that the average of 268,831.27 m^3/year had been deposited in the period of 2002 – 2012.

3. Sediment monitoring and assessment

3.1. Methodologies

Sediment monitoring on the river basin level comprises regular field surveys, aerial mapping and aerial photography of soil erosion, stream bank erosion, landslides, mechanical movement and regular measurements of suspended and bedload, reservoir sedimentation and sediment quality.

Regular measurements of sediment transport quantity and temporal variation of that quantity is necessary for the sustainable sediment management at river basin level. The sediment discharge is usually measured by gauging stations that also measure water levels and water discharge, but auxiliary stations may be set up if necessary. Some recommend that the minimum network standard for sediment measurement is one station per 1000 to 2500 km^2 for flat regions and 300 to 1000 km^2 for mountainous regions.

On the stations that play an important role in controlling sediment yield from the drainage basin and are focal to the design and operation of major water managements projects including river regulation, usually on the main basin channel, following measurements should be taken:

1. Regularly: suspended sediment concentration and suspended load , size gradation of suspended sediment and bed material.
2. Occasionally: bedload measurements.

3.1.1. Suspended sediment measurements

Sediment load may be classified as suspended load or bedload according to the mode of movement in the river. Bedload is the part of sediment load that moves in almost continuous contact with the streambed. According to its origin, or source of supply, the total amount of sediment transported in rivers may be divided into two parts: wash load and bed material load. Wash load consists of fine particles, which refers generally to sediment size finer than 0.062 mm, and the amount depends mainly upon supply from the source area. The discharge of bed material is controlled by the transport capacity of the stream. Real transport depends upon bed composition and the relevant hydraulic parameters. Wash load moves entirely in suspension, while the river bed material may be transported either as temporarily suspended load or as bedload.

The desirable timing and frequency of suspended sediment sampling depends on the runoff characteristics of the basin. For many rivers, an average of 70 to 90 per cent of the annual sediment load is carried down the river during the flood season. Suspended sediments should be sampled more frequently during the flood period than during low flow periods. During floods, hourly or even more frequent sampling may be required to define sediment concentration accurately. During the rest of the year, sampling frequency can be reduced to daily or even weekly sampling. In general, the accuracy needed from the sediment data determines how often a stream should be sampled.

It is recommended that settling diameter, rather than sieve diameter, should be used in the particle size distribution of the suspended sediments. Also, it is preferable to use methods based on the settling principle, such as the VA-tube method or the size analyser method for the analysis of sizes ranging from 0.062 to 1.0 mm, which are commonly found in suspended sediments. According to the settling medium, methods based on the settling principle may be classified into two groups: settling in clear water (two-layer system), and settling in sediment-laden water (dispersed system).

3.1.2. Bedload measurements

The temporal distribution of the bedload is characterized by its intensive transport during the flood season, particularly during heavy floods. The spatial distribution of the bedload rate over a cross-section is also not uniform. Heavy transport may take place over only fractions of the bed width, while the transport rate outside these strips may be very small or seem to approach zero. The measurement of bedload over an entire cross-section is laborious and time-consuming. In the measurement of suspended sediments, simplified methods are usually adopted for routine work. However, fluctuations observed in bedload are far larger than those of suspended sediments. Simplified methods may induce appreciable error and should not generally be used. In general, the measurement of bedload should be planned to cover a large variation in water discharge. The frequency of measurements should be much higher during floods than in the low flow season. If the bedload cannot be carried out satisfactorily during the rising limb of a large flood, the bedload may be extrapolated from the discharge-to-bedload relationship established under low and medium flow conditions.

The direct method measures the bedload by taking samples directly from the stream with a properly designed sampler. Apparatuses or samplers used in the direct method may be classified into the basket-type, pressure-difference-type, pan or tray-type and slot or pit-type. The weight of the sample taken by these samplers in a specific time interval represents the bedload over the width of the sampler. Sampling efficiency should be obtained by calibration in laboratory flumes and also in the field when the bedload can be determined by other reliable methods. The efficiency of a sampler is defined as the ratio of the quantity of sediment trapped in a bedload sampler to that being actually transported as bedload in the space occupied by the sampler. The duration of sampling, namely the time the sampler is left on the river bed to take a sample, is limited by the transport rate and the volume or capacity of the sampler. In general, the quantity of a sample should not exceed two thirds of the effective volume of the sampler.

Sieve analysis is a traditional method used for the mechanical analysis of sand and gravel. When sieve analysis is adopted for the size analysis of fluvial sediment, two methods may be used. The wet-sieving method carries out the analysis by immersing the whole sample in water while the sieving operation is performed, or a small water jet is used to rinse all the particles to speed up the process. In the dry-sieving method, sieving is performed in the usual way. The sieves are shaken to speed up the process.

3.1.3. Monitoring of the river channel evolution

Evolution of the river channel may take place in the horizontal and/or vertical direction. Throughout river channel evolution horizontal displacements tend to be smaller than the vertical once. Methods for monitoring the landform evolution can include satellite images and photogrammetry for larger areas or the insertion of metal pins of light-sensitive cells into the bank face for the point information about bank retreat.

The hydrographic surveys are methods for monitoring vertical channel evolution, as well as horizontal. The repeated surveys are usually performed by using acoustic depth sounding for depth measurements and the RTK[1]-GPS for the determination of the boat position. Acoustic soundings include single beam transducer systems, multiple transducer channel sweep systems and multibeam sweep systems. Although multibeam systems are increasingly being used for surveys concerning large and deep areas, single beam systems are still mainly used for river surveys. Calibration of the sounding system is required to maintain quality control in single beam echo sounding equipment. Vertical channel evolution can also be assessed indirectly by analysis of trends of surface water levels. But this also requires analysis of corresponding trends of river discharges in order to assess the influence of discharge trends on water surface levels.

Single beam surveys run normal to the channel alignment (cross-sectional) and are repeated on a single location (hydrological monitoring profile, gauging station) or on series of predefined locations.

[1] **Real Time Kinematic** (RTK) satellite navigation is a technique used to enhance the precision of position data derived from satellite-based positioning systems, being usable in conjunction with GPS

Surveys for hydrological profiles are usually performed on a yearly basis and for series of locations on a project to project basis.

3.1.4. Sediment quality monitoring

The Water Framework Directive (WFD, 2000/60/EC) requires that all inland and coastal waters achieve ‘‘good status’’ by 2015. The Article 16 of WFD) sets out the strategy against chemical pollution of surface water bodies. The chemical status assessment is used alongside the ecological status assessment to determine the overall quality of a water body. Environmental Quality Standards (EQSs) are tools used for assessing the chemical status of water bodies. Thus a directive (2008/105/EC) was approved to establish "Environmental Quality Standard" (EQS) limits for 33 priority substances and 8 priority hazardous substances in surface waters, but also for some of these compounds in EQS, and to verify that the concentration of substances concerned does not increase significantly in sediments and/or the relevant biota. The directive also foresees the design of the most cost-effective set of measures aimed at achieving load reduction of those substances, taking into account both product and process sources.

List of priority substances in the field of water policy

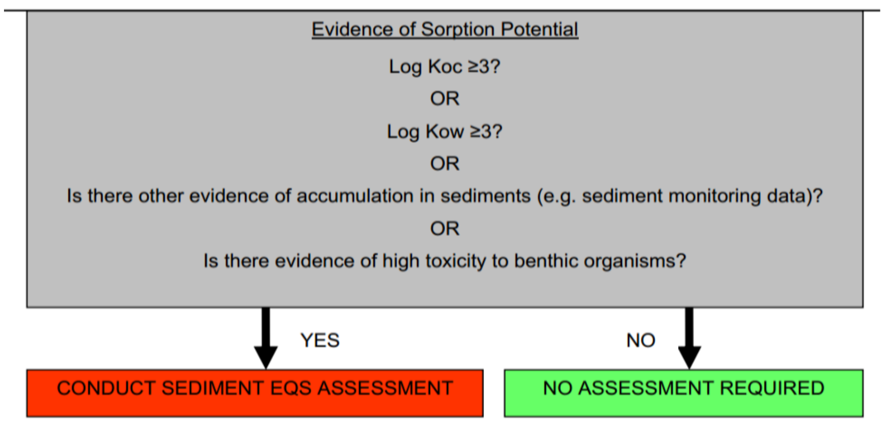
Number	CAS numberi	EU numberii	Name of priority substanceiii	Identified as priority hazardous substance
(1)	15972-60-8	240-110-8	Alachlor	
(2)	120-12-7	204-371-1	Anthracene	X
(3)	1912-24-9	217-617-8	Atrazine	
(4)	71-43-2	200-753-7	Benzene	
(5)	not applicable	not applicable	Brominated diphenyletheriv	X
	32534-81-9	not applicable	Pentabromodiphenylether (congener numbers 28, 47, 99, 100, 153 and 154)	
(6)	7440-43-9	231-152-8	Cadmium and its compounds	X
(7)	85535-84-8	287-476-5	Chloroalkanes, C10-13 iv	X
(8)	470-90-6	207-432-0	Chlorfenvinphos	
(9)	2921-88-2	220-864-4	Chlorpyrifos (Chlorpyrifos-ethyl)	
(10)	107-06-2	203-458-1	1,2-Dichloroethane	
(11)	75-09-2	200-838-9	Dichloromethane	
(12)	117-81-7	204-211-0	Di(2-ethylhexyl)phthalate (DEHP)	
(13)	330-54-1	206-354-4	Diuron	
(14)	115-29-7	204-079-4	Endosulfan	X
(15)	206-44-0	205-912-4	Fluoranthenevi	
(16)	118-74-1	204-273-9	Hexachlorobenzene	X
(17)	87-68-3	201-765-5	Hexachlorobutadiene	X
(18)	608-73-1	210-158-9	Hexachlorocyclohexane	X
(19)	34123-59-6	251-835-4	Isoproturon	
(20)	7439-92-1	231-100-4	Lead and its compounds	
(21)	7439-97-6	231-106-7	Mercury and its compounds	X
(22)	91-20-3	202-049-5	Naphthalene	
(23)	7440-02-0	231-111-4	Nickel and its compounds	
(24)	25154-52-3	246-672-0	Nonylphenols	X
	104-40-5	203-199-4	(4-nonylphenol)	X
(25)	1806-26-4	217-302-5	Octylphenols	
	140-66-9	not applicable	(4-(1,1',3,3'-tetramethylbutyl)-phenol)	
(26)	608-93-5	210-172-5	Pentachlorobenzene	X
(27)	87-86-5	201-778-6	Pentachlorophenol	
(28)	not applicable	not applicable	Polyaromatic hydrocarbons	X
	50-32-8	200-028-5	(Benzo(a)pyrene)	X
	205-99-2	205-911-9	(Benzo(b)fluoranthene)	X
	191-24-2	205-883-8	(Benzo(g,h,i)perylene)	X
	207-08-9	205-916-6	(Benzo(k)fluoranthene)	X
	193-39-5	205-893-2	(Indeno(1,2,3-cd)pyrene)	X
(29)	122-34-9	204-535-2	Simazine	
(30)	not applicable	not applicable	Tributyltin compounds	X
	36643-28-4	not applicable	(Tributyltin-cation)	X
(31)	12002-48-1	234-413-4	Trichlorobenzenes	
(32)	67-66-3	200-663-8	Trichloromethane (chloroform)	
(33)	1582-09-8	216-428-8	Trifluralin	

Sediments can act as a sink for chemicals through sorption of contaminants to particulate matter, and may act as a source of contaminants to particle feeders through resuspension (e.g. by dredging or natural events) or back to the water phase by desorption.

The derivation of sediment EQSs is particularly relevant for hydrophobic substances and some metals. EQSs for sediments are required to protect benthic (sediment-dwelling) species. Sediments are a major sink for historic pollutants and changes in bioavailability of such contaminants makes compliance assessment more complex than in other compartments.

The enclosed Technical Guidance Document for Deriving Environmental Quality Standards under WFD has been developed to support the derivation of EQSs for priority substances and for river-basin-specific pollutants that need to be regulated by Member States according to the provisions of the WFD. The Technical Guidance Document for Deriving Environmental Quality Standards along with guidance and documents on monitoring provides further suggestions to policy makers on how sediment quality can be assessed and how to identify where management measures may be warranted. Sediment quality monitoring incorporates measurements of sediment chemistry, sediment toxicity, and benthic macroinvertebrate community structure.

In general, substances with an organic carbon adsorption coefficient (Koc) of <500– 1000 l·kg–1 are not likely to be adsorbed to sediment. Consequently, a log Koc or log Kow of ≥3 is used as a trigger value for sediment effects assessment. Some substances can occur in sediments even though they do not meet these criteria so, in addition, evidence of high toxicity to aquatic organisms or sediment-dwelling organisms or evidence of accumulation in sediments from monitoring would also trigger derivation of a sediment EQS.



Data used for the derivation of EQS for sediment can include:

(i) ecotoxicity data from experiments with benthic organisms
(ii) water column ecotoxicity data used in conjunction with equilibrium partitioning
(iii) empirical field or mesocosm data (e.g. co-occurrence of benthos and chemical contamination in the field)

3.1.5. *Soil erosion surveys*

Erosion is an essential factor to be considered in any territorial planning. This assertion relies in the fact that the degree of erosion is a primary indicator of the sustainability of the land use scheme of a territory. Erosion mapping is the essential tool for the knowledge of the distribution and geographic extent of the phenomena as well as for its qualitative characterization. Through erosion mapping, it is possible to incorporate the erosion phenomena as a factor in the process of land-use planning and management.

Water erosion is the most important type of erosion because runoff is essential to transport the eroded sediment. In the entire process of erosion and transport, soil erosion, soil loss and sediment yield in a basin are three different but closely related concepts. Sediment yield is defined as the total sediment outflow from a watershed or drainage basin in a specified period of time. As far as the amount of deposition or erosion in a river reach is concerned, it is usually far less than the amount of sediments transported through the river system. Therefore, surveys of soil erosion, stream bank erosion, landslides and mechanical movement have to be conducted to provide more reliable and accurate data on the sediment production and transport rather than the estimations made from data only obtained through measurements on gauging stations.

3.1.6. Reservoir sedimentation measurements

Sedimentation surveys in reservoirs are used to determine the quantity of erosion and deposition, as well as the distribution of deposits (as indicated in chapter 2.3.5). Such measurements are useful for studying consequences of management measures on fluvial process upstream and downstream from a dam. The range of sedimentation surveys should meet the requirements for a revision of the reservoir capacity curve at normal high water levels and for an evaluation of upstream extension of reservoir deposits. Ideally, the survey should be conducted before and after the flood season and under relatively stable conditions. Sedimentation analyses are conducted either as surveys along predefined reservoir profiles or as area surveys. This method, if the profiles are arranged at reasonable intervals, has desired accuracy and is generally used for most reservoir sediment surveys. For this kind of measurements, the echo sounder with GPS is commonly used. The type of echo sounder is selected mainly according to its ability to distinguish the bed surface. The results of depth measurements may differ with transducers of different power and frequency response in the detection of the top of soft mud. During the reservoir surveys sediment samples should be taken at representative locations to obtain grain size and composition data of deposits.

3.2. Actual monitoring in the Sava River Basin countries

3.2.1. Overview of the sediment monitoring in Sava River Basin

In the overview of the sediment monitoring and assessment the traditional and new methodologies were presented. Based on that concept this chapter gives an actual monitoring of sediments in each country in the Sava River Basin for suspended and bedload measurements, for monitoring of the river channel evolution and sediment quality, as well as for soil erosion surveys and reservoir sedimentation measurements.

Table 6: Network of sediment monitoring stations in the Sava River Basin.

Country	STREAM	Code	Monitoring site	G - K Position	Monitoring variable	Op. period	Institution	Daily		Occas.	Granulometry	
								SSC	LT	Prof. SSC	SL	BL
SLOVENIA	SAVA - main channel	3420	Radovljica I	Y 5436120; X 5133220	H,Q,SSC,LT,	1953-	ARSO	x	x			
		3570	Šentjakob	Y 5468075; X 5104515	H,Q,SSC,LT,	1955-1994	ARSO	x				
		3725	Hrastnik	Y 5507381; X 5108630	H,Q,SSC,LT,	1993-	ARSO	x	x			
		3740	Radeče	Y 5514390; X 5103055	H,Q,SSC,LT,	1955-1993	ARSO	x				
	SORA	4200	Suha I	Y 5448320; X 5113319	H,Q,SSC,LT,	1953-	ARSO	x	x			
	SAVINJA	6200	Laško I	Y 5518410; X 5112230	H,Q,SSC,LT,	1953-	ARSO					
	SAVINJA	6210	Veliko Širje I	Y 5515244; X 5105337	H,Q,SSC,LT,	1955-	ARSO	x	x			
	SOTLA	4740	Rakovec I	Y 5555070; X 5086540	H,Q,SSC,LT,	1965-	ARSO			x		
CROATIA	SAVA - main channel	3087	Podsused	Y 5565652; X 5074098	H,Q,SSC,LT,	1979-	DHMZ	x	x	x	x	x
		3096	Rugvica	Y 5595979; X 5067325	H,Q,SSC,LT,	1978-	DHMZ	x	x	x	x	x
		3219	Jasenovac	Y 4614661; X 5014177	H,Q,SSC,LT	1978-	DHMZ	x	x	x	x	x
		3098	Slavonski Brod	Y 6500781; X 5000950	H,Q,SSC,LT	1960-	DHMZ	x	x			
	KRAPINA	3054	Kupljenovo	Y 5563758; X 5088155	H,Q,SSC,LT	1980-	DHMZ	x	x			
	KUPA	4016	Hrvatsko	Y 5477111; X 5043087	H,Q,SSC,LT	1963-	DHMZ	x	x			
	ILOVA	3185	Munije	Y 6445034; X 5058159	H,Q,SSC,LT	1979-	DHMZ	x	x			
	BIJELA	3171	Badljevina	Y 6437061; X 5040307	H,Q,SSC,LT	1984-	DHMZ	x	x			
	BJELOVARSKA R.	3188	Bjelovar	Y 6411531; X 5083507	H,Q,SSC,LT	1979-	DHMZ	x	x			
	Reserv. NOVSKA	3151	Novska g. step.	Y 6424413; X 5023989	H,Q,SSC,LT	1980-	DHMZ	x	x			
BA	SAVA - main channel	No actual monitoring site*										
	Tributaries	No actual monitoring site*										
SERBIA	SAVA - main channel		Sremska Mitrovica	Y 7388292; X 4981825	H,Q,SSC,LT,	1974-	IJC	x	x	x	x	x
			Beograd	Y 7453377; X 4961362	H,Q,SSC,LT,	1986-	IJC	x	x	x	x	x
			Sremska Mitrovica	Y 7390175; X 4981125	H,Q,SSC,LT,	1958-1980	RHMZ					
			Sabac	Y 7397450; X 4959150	H	1958-2002	RHMZ					
			Beograd	Y 7456875; X 4963650	H	1958-1998	RHMZ	x	x	x	x	x
	DRINA		Mihaljevici	Y 7369129; X 4896888	H,Q,SSC,LT,	1991-2002	RHMZ	x	x			
	DRINA		Radalj	Y 7352975; X 4921075	H,Q,SSC,LT,	1984-2002	RHMZ	x	x			
	DRINA		Badovinci	Y 7369845; X 4961554	H,Q,SSC,LT,	1990-2001	RHMZ	x	x			
	KOLUBARA		Slovac	Y 7427150; X 4910975	H,Q,SSC,LT,	1958-1992	RHMZ	x	x			
	KOLUBARA		Beli Brod	Y 7436750; X 4914330	H,Q,SSC,LT,	1986-2001	RHMZ	x	x			
	KOLUBARA		Drazevac	Y 7438150; X 4939050	H,Q,SSC,LT,	1958-2002	RHMZ	x	x			

* BA only occasionally measurements of SSC, BL (Drina, upstream of Višegrad, period 1989/1990) in order to define reference conditions before HEPP Višegrad has been buildt, and very rare measurements on the River Bosna and some tributaries of the Sava River in BA.

Monitoring parameters include:

- H - water level [cm]
- Q - discharge [m^3/s]
- SSC - suspended sediment concentration [g/m^3]
- LT - load transport rate [t/day; t/month; total t/year]
- SSC - Integrated SSC measurement in the river cross section
- SL - suspended load particle size distribution
- BL - bedload size distribution

3.2.2. Slovenia

Sediment monitoring in Slovenia is performed by the Slovenia Environment Agency (ARSO). Monitoring was modernized in the last decade and is today in accordance with the Water Framework Directive. In the next period more improvements are planned (so-called project BOBER). The project BOBER was postponed for a few years due to economic situation in the country. The results of the regular hydrologic monitoring are published by the Slovenian Environment Agency (ARSO) in annual reports and the results of additional measurement, performed during flood events, are published in special reports.

Suspended sediment measurements are part of hydrologic monitoring. Suspended load is measured on gauging station Hrastnik on the Sava River, gauging station Suha on the Sora River and gauging station Veliko Širje I on the Savinja River. There are no sediment measurements on the Ljubljanica, Krka, Sotla/Sutla and Kolpa/Kupa Rivers which are the 1st order tributaries of the Sava River. The number of monitoring sites for suspended load is far from being optimal. The suspended sediment measurements are usually performed using point or depth integrating samplers. Sample volume is usually 1 litre and sediment concentration is obtained through conventional filtration method in laboratory. During flood events sediment concentration is measured along river profile on several locations and depths (several times a day, due to concentration variation) to provide profile sediment concentration. The usual methods for discharge measurements are nowadays Acoustic Doppler Current Profilers (ADCPs) or ultrasonic wing, depending on water velocities. Knowing the profile sediment concentration and discharge (measured at the same time), sediment transport (kg/s) is calculated through profile.

Bedload measurements are currently non-existent in Slovenia.

Sediment quality monitoring comprises sampling of river sediments using standards SIST ISO 5667 - 12 & ISO 5667 – 15. For the chemical analysis of sediments the wet sieved fraction < 63 µm is used. Primary substances in sediments are sampled 4 to 12 times a year s in 6 water bodies – river reaches (2 reaches in the Sava Dolinka River, 2 sites in tributaries of the Lower Sava River (Krka, Sotla/Sutla Rivers), and 2 sites in the Lower Sava River (Vrhovo-Boštanj, border cross section at Jesenice na Dolenjskem).

Soil erosion surveys are currently non-existent in Slovenia.

Reservoir sedimentation measurements are performed on the HPP. Sediment balance is estimated using river reservoir sedimentation data (HPP Moste on the Sava Dolinka River, HPP Mavčiče and HPP Vrhovo on the Sava River) and to a lesser extent sediment dredging data (Hrušica in the Sava Dolinka River upstream of the HPP Moste, cross section Hotič upstream of Litija on the Sava River, reservoir upstream of the weir for cooling water intake for the Nuclear Power Plant Krško on the Sava River).

Figure 19: Locations of suspended sediment measurements on the Sava River in Slovenia

3.2.3. Croatia

Parameters of the sediment load regime in Croatia are monitored by the Hydrological and Meteorological Service, Hydrology Department (DHMZ).

Suspended sediment measurements are part of a regular hydrologic monitoring system and include:

- Point measurements of sediment concentration on daily basis at 10 gauging stations in total on Sava River Basin (4 stations on the Sava River and 6 stations on the tributaries)
- Calculation of sediment load on the Sava River gauging stations on daily basis from the point sampling
- Profile measurements of sediment concentration and sediment load, at 3 stations on the Sava River, periodically
- Grain-size distribution of suspended load on 3 stations on the Sava River, periodically

The suspended sediment data are usually obtained from grab samples (dipping a bucket/container in the river) or by using the point or depth integrating samplers. These types of measurement are conducted according to ISO 4365:2005 standards. ISO 4363:2002 standards are followed for profile mean suspended sediment concentration and mean particle size distribution measurements. The samples are processed in laboratory using the standard vaporization and filtration methods. The usual methods for discharge measurements are Acoustic Doppler Current Profiler (ADCP) or hydrometric wing. ADCP is also used in suspended sediment concentration measurement.

Suspended load data is gathered on daily, monthly and annual basis and its correlation with water levels, discharges, and grain size distribution of the material is derived. These and other hydrological parameters, obtained by analysis of long-term measurements, are saved up to date in hydrological database (Hydrological Information System 2000) developed by Hydrological and Meteorological Service, Hydrology Department.

Annual overview of daily suspended load concentration and transportation rates is published in the Hydrological yearbooks.

Periodic profile measurements of concentrations,transportation rates and grain size distribution of material are published in annual reports and studies. Distribution of sediment size in suspended load has been performed since 1985 at tree stations on the Sava River following the standard Andreassen method. Figure 20 shows the sediment weight distribution from 2011 sampling.

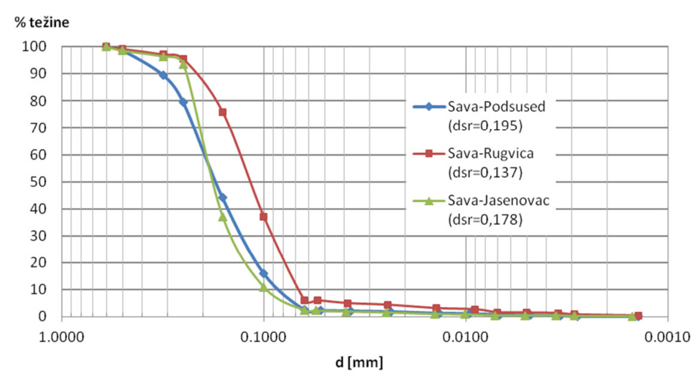


Figure 20: Sediment weight distribution of suspended load from 2011 sampling in Croatia

Bedload measurements are currently non-existent in Croatia. Previous measurements were periodic and included the grain size distribution of bedload on 3 locations on the Sava River and bedload measurements. Historical data of bedload measured are available for the hydrological station Podsused Žičara for the period 1975-1986.

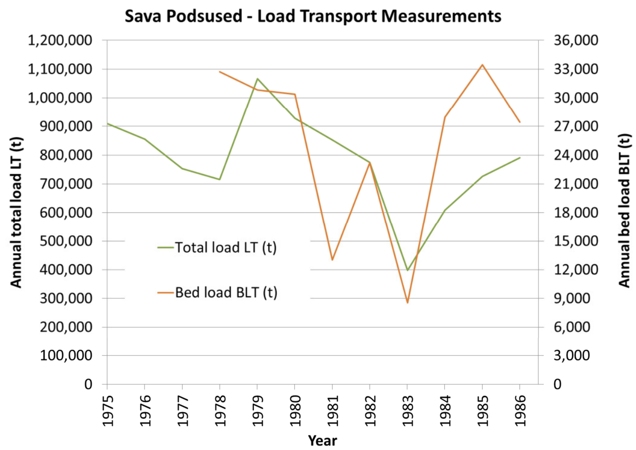
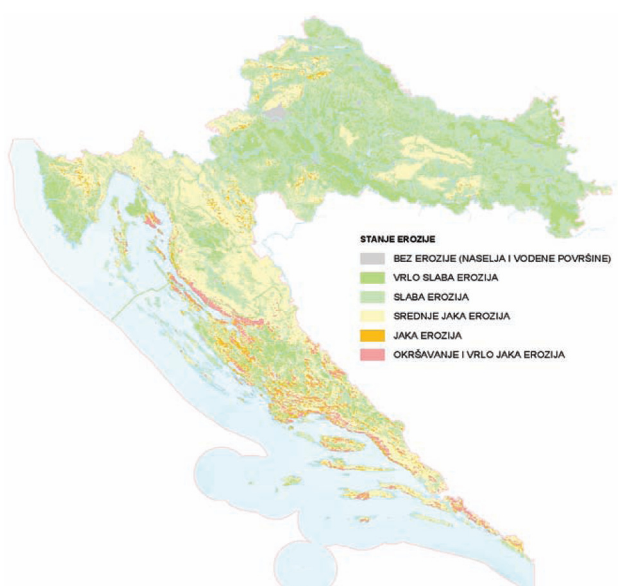


Figure 21: Annual total and bedload at h.s. Podsused Žičara on the Sava River

The analysis of bedload composition has been made at Rugvica and Jasenovac according to the standard screen sieve fractions.

Sediment quality monitoring in the Sava Basin is conducted by Croatian Waters on seven locations as part of the general plan for water quality monitoring (according to WFD requirements). The chemical analysis of sediments includes total nitrogen, total phosphorus, cadmium, nickel, lead, mercury, mineral oil, polychlorinated biphenyls, organochlorine pesticides, alachlor, triazine pesticides, pentachlorobenzene. As there is no standards for the assessment of the sediment quality, the content of substances are compared between different streams. Besides the regular monitoring, periodic chemical analysis are performed by different institutions on a project-to-project basis.

Soil erosion surveys are currently non-existent in Croatia. The soil erosion potential is presented in the Water Management Strategy by Croatian Waters (2009). Figure 22 shows that out of six categories of soil erosion potential, the Sava River Basin in Croatia has low erosion potential on 20% of the area and moderate potential on 40% of the area which comprise the lowland continental parts (green). The middle erosion potential is founded on 20% of the area for the hilly parts of the basin.



ID	Soil erosion potential	Area [%] of the Sava River Basin
1	No erosion	8%
2	Very low	20%
3	Low	40%
4	Middle	20%
5	High	2%
6	Very high	0%

Figure 22: Soil erosion potential in Croatia (Croatian Waters 2009)

Reservoir sedimentation measurements have been performed on a reservoir upstream of the Novska lake in order to control intake of sediment load into the lake.

Figure 23: Active locations of suspended sediment measurements on the Sava River in Croatia

3.2.4. Bosnia and Herzegovina

Systematic monitoring of sediment on the Sava River or its tributaries in Bosnia and Herzegovina does not exist. Occasional monitoring of sediment is conducted for individual projects, like:

- The Sava River waterway design - monitoring on the Sava River,
- HPP Vranduk project – monitoring on the River Bosna.

In the Republic of Srpska the soil erosion map is currently developed and it will be used as basic document for the "Study for Sediment Management in river basins in Republic of Srpska". The erosion map will provide data on erosion process in the basin and data for estimation of sediment yield.

Sediment quality measurements were only conducted within "Sava River Basin project: Sustainable usage, management and protection of resources". Samples were collected four times (08/2005, 11/2005, 05/2006, 10/2006) after drought and rain periods and the NATO project Science for Peace, Development of Decision Support System for Reducing Risk form Environmental Pollution in the Bosna River, 2012-2014..

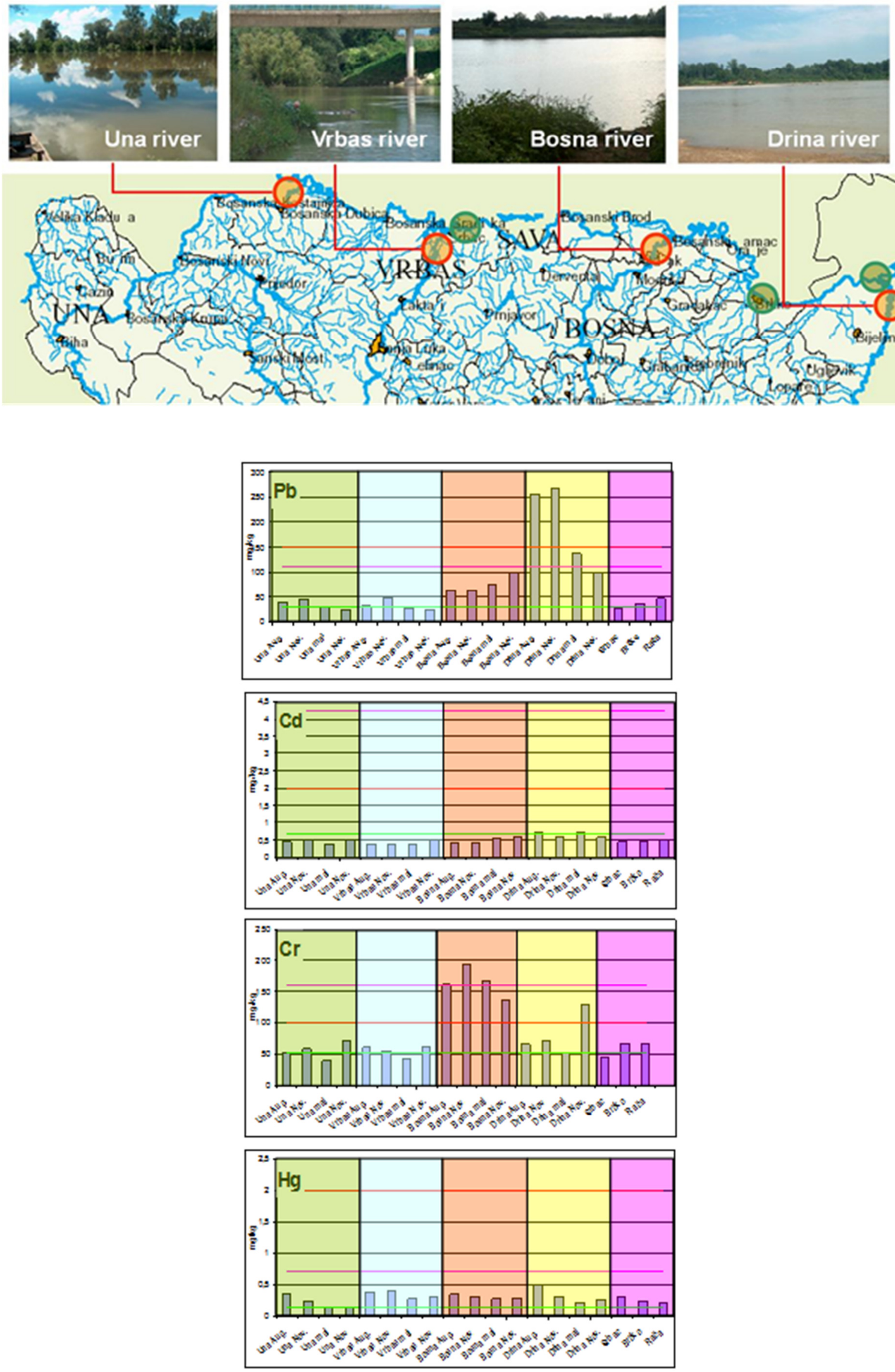


Figure 24: Locations of sediment sampling on the Sava River in Bosnia and Herzegovina

The results of the project are provided below:

- Nickel concentration higer than threshold effect level TEL, probable toxic level PEL on all measurement location, mostly in the Bosna River; Significantly elevated concentrations of nickel have also been established in the sediment of the Sava river, especially at the Brčko measuring point located downstream of the Bosna River inflow.
- Lead concentration found in most samples was above the given limit values according to the BA legislation. The same applies for concentration of zinc. The concentration of lead in the Bosna River is significantly above the values established in the Una, Vrbas and Sava Rivers, but below the TEL and PEL limit values.
- The chrome concentration above TEL and PEL limit values has only been found in the sediment of Bosna River.
- Cadmium concentration was always within all threshold levels.

Nickel and chrome in the Bosna River as well as lead and zinc in the Drina River are considered to be significant pollution indicators while other indicators are insignificant.

3.2.5. Serbia

Suspended sediment measurements are available for stations Sremska Mitrovica and Beograd on monthly and yearly basis. Quantity of monthly and annual suspended load is derived from the correlation with the average flow rate. Regular sediment sampling is non-existing. Although the sediment monitoring is still present in the Program of the Republic hydrometeorological service of Serbia (RHMSS), it is not re-established because the instruments and methodology should be updated.

On the Sava River RHMSS conducted suspended sediment monitoring at Sremska Mitrovica in period 1958-1980, Šabac in period 1958-2002 and Beograd in period 1958-1998. Currently, the Institute Jaroslav Černi (IJC) is monitoring the sedimentation of the Iron Gate 1 reservoir, including the sediment-related processes on its part on the Sava River, between its mouth to Danube and Šabac (100 km). Collection of water and sediment samples is done at Sremska Mitrovica and Beograd, on a daily basis, while complete field measurements of water and sediment parameters are performed periodically (1-3 times a year), to identify the water flow and sediment characteristics at various points, verticals and across the monitoring profile.

On the Drina River the RHMSS conducted suspended sediment monitoring at Mihaljevci (1991-2002), Radalj (1984-2002) and Badovinci (1990-2001) and on some tributaries (Lim River and Crni Rzav). The Jaroslav Černi Institute (IJC) conducted sediment measurements on the Lower Drina downstream of Zvornik dam (1985-1987).

On the Kolubara River the RHMSS conducted suspended sediment monitoring at Slovac (1958-1992), Beli Brod (1986-2001), Drazevac (1958-2002) and Stuborovini (1983-1993).

Bedload measurements were previously conducted only for individual studies and projects, together with the bed material sampling along the Sava River and in reservoirs on the Drina River.

Sediment quality monitoring was monitored by the RHMSS by sampling of river and reservoir sediment in the Sava River Basin until 2010, when this became the regular task of the Agency for Environmental Protection. Presently, the river sediments are analysed at 4 locations on the Sava River (Jamena, Sremska Mitrovica, Šabac, Ostružnica) and many locations on the Drina, Lim, Kolubara and Topčiderska Rivers.

Soil erosion surveys were performed for individual studies and projects and comprised estimation of sediment yield based on erosion maps and investigations of alluvial deposits along the Lower Drina.

Reservoir sedimentation measurements are conducted occasionally through the sampling of bed material in reservoirs and by analyses of sedimentation in Bajina Bašta and Zvornik reservoirs.

Figure 25: Locations of suspended sediment measurements on the Sava River in Serbia

3.3. Elements and persisting pollutants in sediments of the Sava River

A concern over the presence of pollutants in the Sava River Basin has resulted in support of the European Union to fund the 6th FW EC project: Sava River Basin: ***Sustainable Use, Management and Protection of Resources (SARIB)***. As a part of SARIB project ecological status of sediments was investigated. In order to assess the geographical distribution in sediment contamination of the Sava River, sediments were analysed at 20 selected sampling sites along the Sava River from its spring to its outfall into the Danube River. Sampling sites are presented in Figure 26. For comparability of data with other river basins, the sediment fraction below 63 µm was studied. The extent of pollution was estimated by determination of the total element concentrations and by the identification of the most hazardous highly mobile element fractions and anthropogenic inputs of elements to sediments. The extent of pollution cannot be estimated solely on the basis of the determination of the total metal concentrations in sediments because bioavailability and toxicity towards organisms depend on their chemical forms. So, to assess the mobile metal fraction, extraction in 0.11 mol L^{-1} acetic acid was performed, while anthropogenic inputs of elements were estimated on the basis of normalization to Al. According to the Water Framework Directive (WFD) the following elements were investigated in sediments: Cd, Pb, Ni and Hg as well as organotin compounds (OTC). Furthermore, Cu, Zn, Cr, As and P were determined. In addition, following the recommendations of the WFD, selected persistent organic pollutants, e.g. polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCB) and selected chlorinated pesticide,s were determined in sediments.

In industrially exposed sites (Moste, Srbac, Županja, Brčko, Bosanska Rača, Sremska Mitrovica, Šabac), slightly elevated concentrations of Hg (up to 0.6 mg kg^{-1}), Cr (up to 380 mg kg^{-1}) and Ni (up to

210 mg kg^{-1}) where determined. However, as can be seen from Figure 27, Cr and Ni exist in the sparingly soluble forms. Namely, the easily soluble Cr fraction in sediments represent less than 0.35 % and Ni less than 15 % of total elements concentrations. So, Cr and Ni do not represent an environmental burden. High percentage of easily soluble fraction was found in Cd (around 40 %). Since total concentrations of Cd is low (less than 0.6 kg^{-1}), CD also do not represent an environmental burden. Concentrations of P were found in elevated concentrations at agricultural areas and big cities (up to 1000 mg kg^{-1}). Among organic pollutants organotin compounds were not detected in sediments of the Sava River. PAH's were present in moderate concentrations (sum of 16 PAHs: up to 4000 ng g^{-1}) and their concentrations increased downstream the river. Concentrations of PCB in sediments of the Sava River were low (sum of 7 indicator PCBs: below 4 ng g^{-1}). Among selected pesticides, p,p-DDT were found in moderate concentrations in sediments at two sampling sites in Croatia (up to 3 ng g^{-1}) and HCB in high concentration in Belgrade (91 ng g^{-1}), although the use of these persistent pesticides has been banned for many years. The environmental status of sediments of the Sava River is in general comparable to other moderately polluted rivers in Europe.

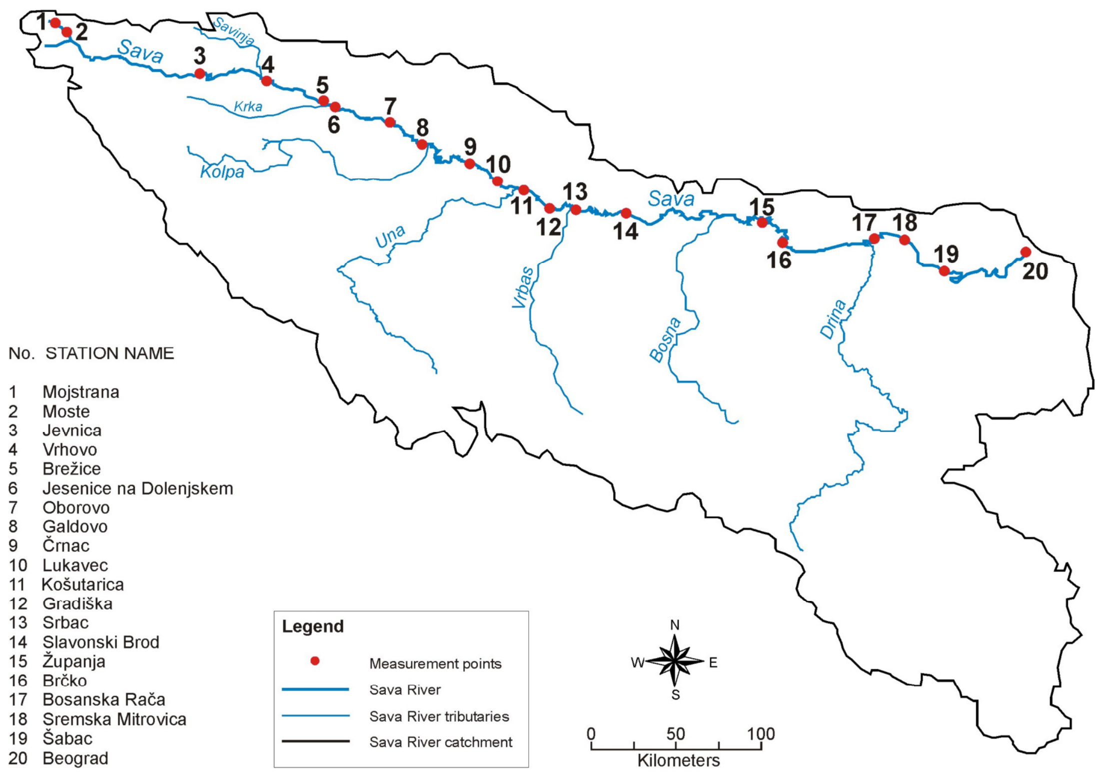


Figure 26: Sediment sampling sites along the Sava River

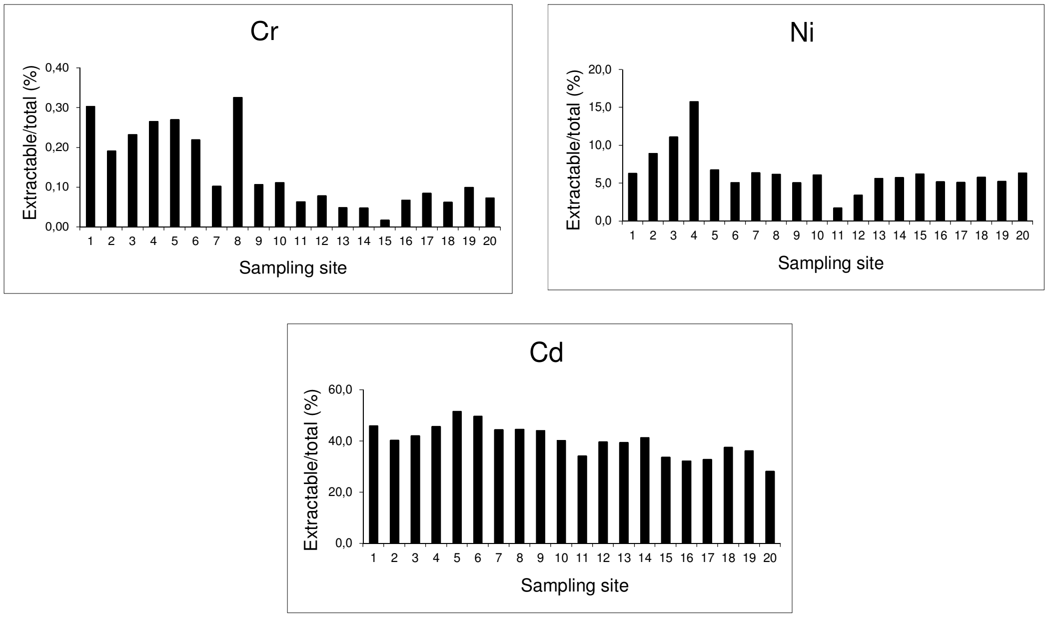


Figure 27: Percentage of Cr and Ni in the easily soluble fraction of the Sava River sediments

Within the project ***"Development of a Decision Support System for Reducing Risk from Environment Pollution in the Bosna River"*** financed by the NATO Science for Peace and Security Programme, samples of river sediment have been collected at 7 locations starting from the spring of Bosna River to just upstream Modriča city. The sampling campaign was carried out from 27 to 29 August 2012 as part of a wider study including sampling of the river water (for priority substances and biological parameters), wastewater from main polluters and the use of passive sampling techniques to obtain average values over a longer time frame. The overall goal is to assess the Bosna River status and to link water and sediment quality with potential source of pollution. With regards to sediments, heavy metal concentration (As,Cr,Cu,Ni,Pb,Zn,Hg and Cd)of PAHs, VOCs and PCBs pesticides were analyzed. Volatile Organic Compounds, Poly Chlorinated Biphenyls and Pesticides were under limit of quantification in all samples.

Heavy metals

Arsen low values along majority of the Bosna River (average 17 ppm) with only one sample clearly spiking from the average (34 ppm just before Zenica). Tentatively this increase of Arsenic concentration may be related to the activity of the Thermo Power Plant Kakanj or more generally due to coal extraction activities. The minimum concentration has been recorded before Modriča (10 ppm). Cupper does not show any specific trend with more or less constant values along the Bosna River profile with average value 35 ppm. The highest value is recorded after Zenica (47 ppm) while the minimum have been recorded before Modriča (19 ppm). Cadmium, Copper, Nickel, Lead and Zink present a similar pattern with average concentrations of1.2 ppm, 35 ppm, 75 ppm, 107 ppm and 348 ppm and a well-defined peak value just downstream Zenica (3.8 ppm, 47 ppm, 157 ppm, 491 ppm and 1270 ppm respectively) due to metal processing activities in the area. The minimum concentration has been recorded for all these metal before Modriča with the only exception of Nickel which before Modriča is recorded with highest concentration (157 ppm). Chromium concentration presents a first substantial increase in the sample downstream Visoko (from 37 ppm before Sarajevo to 152 ppm after Visoko). Tentatively this rise can be related primarily with the leather industry in Visoko although the sample downstream Visoko may also contain the potential contribution of the Sarajevo region. After a partial decrease to 75 ppm in the sample retrieved before Zenica, the concentration of Chromium rises again in the 2 samples collected after Zenica (108 ppm) and before Doboj (133 ppm) and stay more or less constant in the final sample collected upstream Modriča (116 ppm). Mercury distribution present minimum values at spring (0.22 ppm) and before Doboj (0.24 ppm) and Modriča (0.15 ppm) while the central section of Bosna River presents about 5 times higher concentrations (0.84-1.58 ppm) with the highest concentrations located just downstream dense populated areas such as Sarajevo,Visoko and Zenica.

Poly Aromatic Hydrocarbons

PAHs present a general increasing trend along the Bosna River profile proceeding from the Spring to the last sample collected upstream Modriča. The largest increase in PAHs is located between the samples collected upstream Doboj and upstream Modriča and tentatively it may be related to the contribution of the Spreča River joining Bosna at Doboj and collecting water from a dense industrial area around Tuzla region. The second largest increase in PAHs concentration is located around the city of Zenica. Fenantren, Antracen, Fluoranten and Pyren are widely present along the whole river while Benzo(a)antracen, Chrysen, Benzo(b)fluoranten, Benzo(k)fluoranten, Benzo(a)pyren were detected in significant concentrations only at Modriča upstream profile.

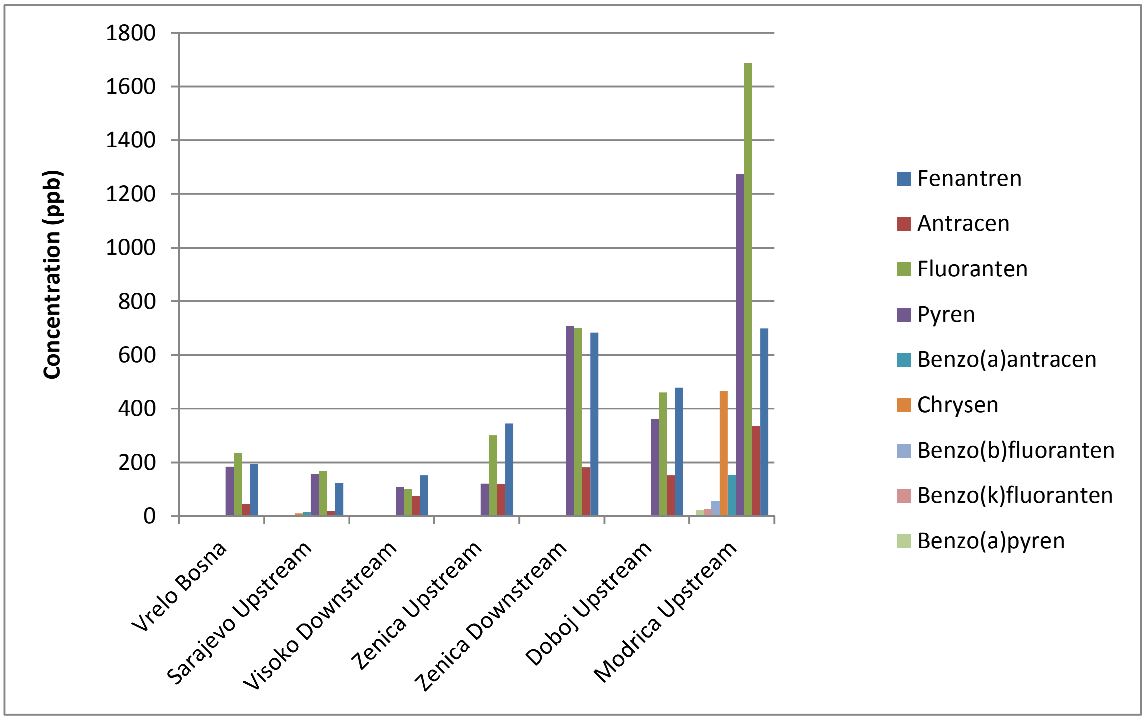


Figure 28: Concentration of pollutants in sediments in the Bosna River

3.4. Concluding remarks on the actual monitoring in the Sava River Basin countries

From the overview of the sediment monitoring and assessment on the Sava River Basin it is obvious that the existing number of monitoring stations and analysis have decreased from the past period. The only active monitoring of suspended sediment concentration and load on the Sava River main channel is currently existing in Croatia on 4 stations and on 2 stations in Serbia. Moreover, suspended measurements differ in sampling technique and suspended load evaluation between the two countries. There is no suspended sediment measurements in Bosnia and Herzegovina, and currently no measurements in Slovenia either. Bedload measurements are currently not existent in the Sava River Basin, whenthey were previously conducted only in Croatia and Serbia in the Sava River main channel. Soil erosion surveys are not conducted, there are just maps of the soil erosion potential and without unique methodology of potential assessment between countries. Sediment quality monitoring is established in Slovenia and Croatia only, and together with some periodic chemical analysis for individual project. There is no standard for assessing the quality of sediment. Reservoir sedimentation measurements exist but are random and the data were not available for this project.

The general issues on the sediment monitoring and assessment on the Sava River Basin are:

- Insufficient and decreasing number of sediment monitoring sites,
- Limited availability of suspended load data,
- Low sediment monitoring on the tributaries,
- Very limited data on bedload,
- No unique sampling and measurement of suspended load and bedload methodologies between countries,
- Lack of measurement equipment and the need for update, especially for continuous monitoring and during high flood events,
- Sediment quality measurements according the Water Framework Directive (2000/60/EC).

4. Sava River channel evolution in time

4.1. General remarks

The Sava River is a typical large alluvial river, flowing mostly in its own alluvial deposits. Only in its upper course in Slovenia it has cut its channel into the mountains or hills. Elsewhere, the river flows on plains where it has deposited large amounts of coarse and fine-grained sediments, and where we can observed different river terraces and wide alluvial floodplains, formed in the past (since the last glaciation). Without local regulation works and generally speaking mankind interventions, the Sava River would mainly be a large meandering river in almost its entire course. Part of its river dynamics is, e.g. a permanent river channel shifting caused by river erosion of cut banks and deposition on point bars, initiating river cuts and forming new meanders, abandoning old ones, showing a wide river corridor with abundance of oxbow lakes, semi-active meanders, and parallel channels. In the past, the Sava River corridor was changing, but it is not the main theme of this study to present a full description of all historical Sava River channel changes in the past along its entire course. An example of the Sava River channel two and a half centuries ago in its upper stream in today's Slovenia is shown in Figure 29, where a wide river channel with numerous islands, bars and floodplain forests can be observed.

Figure 29: The Sava River channel at Brežice (Rann on the map)[2], Slovenia – in 1756 (Source: Verbič, 2006).

The changes of an alluvial river can be put into three categories:

- Planform pattern (cascade, step-pool, rapids, riffle-pool, braided, wandering, single thread sinuous (meandering), anastomosing)
- Channel evolution (braid bars, scroll bars, point bars, islands, meanders, oxbow lakes, … bed forms)
- Longitudinal profile evolution (degradation, incision, forming of fluvial terraces, bedrock erosion, aggradation)

[2] **Brežice** (German: *Rann*)[2] is a town in eastern Slovenia in the Lower Sava Valley, near the Croatian border.

In this study we present selected local case studies in Slovenia, Croatia and Serbia to show the changes in the past and to stress the need to a systematic monitoring of the Sava River morphodynamics in order to close this gap in more detailed river channel data.

4.2. The case study of the Sava River channel bed changes in the Ljubljanska Sava River reach, Slovenia

4.2.1. The history of river engineering works in the Ljubljanska Sava River

The Ljubljanska Sava is in water management field in Slovenia a reserved term for the Sava River stretch downstream of Tacen all the way along the river to Radeče (downstream of the confluence with the Savinja River. Radeče used to be important inland river port in the past). Nevertheless, the majority of river engineering (regulation) works have been done on this reach between Tacen and Litija. The Ljubljanska Sava is probably the river that was regulated and maintained at most in Slovenia in the past several centuries or even millennia. In 1928, close to the modern two bridges in Črnuče, remnants of an old Roman bridge were discovered during protection works for the new bridge.

Prior to 1600, the main works that were done in this Sava reach were cleaning of the river channel and the preparation of the pathways along the river banks. This building of tracks (footpaths) was performed in connection with the Radeče river port to the smaller river ports in Dolsko, Kleče and Zalog close to Ljubljana. After 1600, they started gradually building trails on the Sava River banks (so-called towpaths, "Treppelwege" in German) and regulate the Sava channel in order to be able to tow ships with yoke cattle (and not only by ropes or poles). This enlarged freight on ships and imposed further needs for channel regulation. This was done mainly by using the water power is such a way that they manually dig out a small channel in the direction of a new river meander that was afterwards enlarged and deepened by the river flow.

Before 1780, the first regulations works as a combination of rip-rap made of quarry stone manually levelled and dry stone wall were done close to Dolsko to protect the river port and the settlement. These works can still be partially found in situ. More systematic works started after 1880, namely as protection works on the Sava River right banks between Tacen and Črnuče – the river regulations works stopped with the World War I. Typical of the Austrian system, submerged bundles made of willow and poplar stakes from local Sava River floodplains were used as the base that was loaded with quarry stone made of different rocks from limestone to sandstone. The regulation between Tacen and Črnuče forced the Sava River into a more or less straight channel, however today there are no traces left of this regulation. The regulation between Črnuče and Šentjakob was finished in 1890. Water stone of rather deteriorated quality were used; but the moste problematic issue was the choice of the riverbed width (only 37m, today it is 64m). Moreover, the works were executed rather fast. Due to these factors, in only a few years the Sava River took its natural course in this reach, except for the last 1000m upstream of Šentjakob Bridge. After that, several attempts at realigning the channel were made, but with no success. After the WWI the regulation was extended by 400m according to the old Austrian plans, 1400m upstream of the Šentjakob Bridge. This reach survived until nowadays, with several maintenance works needed to be performed during this period. This is the reason why this reach is still aligned (straight) and too narrow today. The Sava reach between Šentjakob and Dol, where Ljubljanica and Kamniška Bistrica Rivers flow into the Sava River, was regulated between 1900 and 1905. Although this reach was also too narrow, it has survived as it used to be until today; thanks to regulation works after each major flood. The reach between Dol and Senožeti was regulated between 1905 and 1910. The chosen riverbed width is unknown; the regulation was not made of fully connected works, and the Sava River changed its course many times and flew into dead arms. The reason for such a regulation was a shortage on rip rap stone (rock rubble).

Figure 30: The map in the scale 1:75,000 (showing situation in 1887), showing the upstream part of the Ljubljanska Sava from Tacen to Dolsko.

Figure 31: The map in the scale 1:75,000 (showing situation in 1914), showing the upstream part of the Ljubljanska Sava from Tacen to Dolsko at the beginning of the World War I; the red line is the state border during the World War II between Italy (in the south) and Third Reich (in the north) (Spezialkarte der Österreichisch-ungarischen Monarchie 1:75.000 Laibach; Militärgeographisches Institut, Wien, 2. Ausgabe, 1941).

Before the World War I, regulations works were executed from Ribče to Hotič, and from Litija to Ponoviče. During the World War I, only urgent maintenance works were performed (banks along roads, and spots close to bridges). Also,for a few years after the end of the World War I, the maintenance of the existing Austrian regulation was not fully carried out. This was fatal for the regulation of the Ljubljanska Sava. On November 28, 1923, there was a large flood and for nearly three weeks the flows were well above the average flows. After the flood the devastation was seen in its full extent: all hydraulic structures built for the regulation of the Ljubljanska Sava downstream of the Tacen Bridge to the 1 km upstream of the Šentjakob Bridge were fully destroyed or displaced (out of function). The 1923 Sava flood caused intensive bank erosion (new cut banks close to the settlements on the right banks of the river). Each new flood after the Sava 1923 flood worsened the situation, and the river went back to its natural course.. The lowest damage was observed in the reach Ribče-Dolsko, where the Sava riverbed width was chosen to be 70m.

The regulation of the Ljubljanska Sava after the Sava 1923 flood was organisationally and financially taken over by the Kingdom of Yugoslavia (state budget). But not much happened in this Sava reach; several times the maintenance or regulation works under construction were abandoned due to financial cut off or money being spent elsewhere (possibly redirected towards the regulation of the Ljubljanica River through the city of Ljubljana that started at the same period).

In the Ljubljanska Sava reach, different river engineering works have been tried out (different from the practices in the neighbouring countries): submerged bundles made of willow and poplar stakes overloaded by large blocks of casted concrete due to shortage of rock rubble, sometimes additionally fixed by pilots. Frequent floods, i.e. in 1926 and 1931, worsened the situation. At first, the pilots seemed to solve the problem, and the regulation works were afterwards financed without any problems until the WW II. But, many pilots could not be driven through the rocky underground (conglomerates, greyish clay stone called “sivica”), and frequently, concrete blocks and submerged wattles were used without driven pilots. In this reach, cuts through sandy banks were made to realign the river course. For that period between WW I and WW II, regulation works done without a proper plan were typical and executed to minimise the bank erosion problems and natural sifting (wandering) of the river course.

During the World War II, the new border between Germany and Italy stretched to the Ljubljanska Sava between Črnuče and Laze. In Italy, not much was done on the right river banks, only some local rip rap protection works against bank cuts. In Germany, much more activities were taken on with local works executed downstream of the Tacen Bridge, in Laze, Kresnice and downstream of Litija. The field railway was built from local quarries to the construction sites on the river banks the executed protections works therefore had enough rock rubbles and were of good quality.

After the World War II, the maintenance works immediately started in Črnuče and Dolsko, but were soon stopped in favour of drainage works in the Ljubljana Moors (south to the City of Ljubljana) and in the flat Sava River floodplains to the north of Ljubljanska Sava. The river was left untouched for some years, and the river renaturalised to a natural perialpine gravel-bed river with riffles,pools and white alluvial banks. The river was an attraction for occasional river swimming. But on the other hand, the river was a risk for all settlements on the right banks between Ježica and Sneberje. Many works from the Austrian (prior to World War I) period were broached and asked for immediate repair. After 1952, and with a new organisation for the water management sector in Slovenia, a new push for the regulation works (especially between Tacen and Sneberje) was initiated. The basis for the regulation works was not a single large project; solutions were taken on the site with the aim to inter-connect shorter reaches in a connected regulation with a chosen riverbed width of 64m and more or less uniform longitudinal slope of 1.5‰ to 1.6‰. In 1956, they started to form cuts through the alluvial banks by manually digging smaller channels so that the Sava flow should enlarge them during floods by its own shear forces. They also startedto dig ditches along the foreseen longitudinal structures for the protection of the future water side rip rap (rock rubble). The longitudinal and transverse structures (groins) built in water were done out of submerged fascines (several km ofwattles, mainly 5 to 6m long, were built each year), on the water side protected by rip rap and loaded by pitched stone.

After 1960, mechanisation started to be used to excavate the full new river profile, but success was again not achieved; the Sava River soon abandoned the new profile and started flowing again in its old channels. Therefore, the old channels were closed by bulldozers and large pitched quarry stones. Nevertheless, if there were two river channels, “Sava river decided” each time which channel would be the main channel after a flood. Introduction of deep rock blasting in large quarries made available large amounts of rock material for rip rap protection. This was very important to repair damages after large flood events, such as downstream of Šentjakob Bridge in 1976, or to use rock rubble to protect the crossing of the central gas pipeline with a diameter of 1300mm from the Ljubljanska Sava at Brod. Due to extensive usage of rock material, fascines were soon not applied any more, and the expertise and knowledge of this important green river engineering technique was forgotten. On the reach between Tacen and Sneberje, five large alluvial banks were cut.

Parallel to the mentioned correction works on the Ljubljanska Sava, the construction of the hydropower plants upstream of Tacen started to show impacts on this river reach. Especially HPP Medvode, which cut off the sediment inflow from upstream (annual sediment transport was estimated at ~60.000m^3). The reach incised for 2m, locally for 4m; worsened the situation downstream of Črnuče with impacts on bank protection works. After 1980, a temporary calmness set in with no large damages. During this period, the major problem was the drop of the ground water in the alluvial aquifer to the south of the Ljubljanska Sava, which is the main drinking water source for the City of Ljubljana. In order to stop the incision and to raise the ground water level, four river bottom ramps were built; their hydraulic impact and subsistence were checked in a hydraulic laboratory. The downstream-most ramp was built in 1990 to protect the Šentjakob Highway Bridge.

In 1980’s, natural river engineering was tried to some extent in the Ljubljanska Sava River but without much success due to poor technical expertise in the field of water management companies, and due to low financial support. Nevertheless, for the Ljubljanska Sava River a study on side arms and dead arms was performed and made an inventory of their ecological values, water management meaning and life species abundance. A study also listed river engineering measures needed to ensure their temporary or steady watering. The dead arms are presented downstream the confluence with the Ljubljanica River to Litija (dead arms were not filled in), not so upstream of the confluence with the Ljubljanica River to Tacen due to the rather “mechanical” way of executing regulation works of the past decades.

The Ljubljanska Sava River is meant to be used for hydro power generation in its entire length between Tacen and the confluence with the Savinja River: 10 run-of-river HPPs are planned (HPPs Tacen, Gameljne, Šentjakob, Zalog, Jevnica, Kresnice, Ponoviče, Renke, Trbovlje, Suhadol) of installed power of 338 MW and planned production of 1,029 GWh. The first three (downstream) HPPs got a green light in 2013 for the preparation of the National Spatial Plans. The rest of HPPs are problematic due to their expansion over Nature 2000 areas in Slovenia that encloses this part of the Sava River.

Figure 32: The riverbed ramp downstream of the Šentjakob highway Bridge prior to the Sava 2012 Flood (source: Atlas okolja, http://gis.arso.gov.si/atlasokolja).

Figure 33: The riverbed ramp downstream of the Šentjakob highway Bridge after the Sava 2012 Flood. The flood caused a local right bank cut downstream of the ramp; the repair works have been already done (source: Google Earth, July 17, 2013).

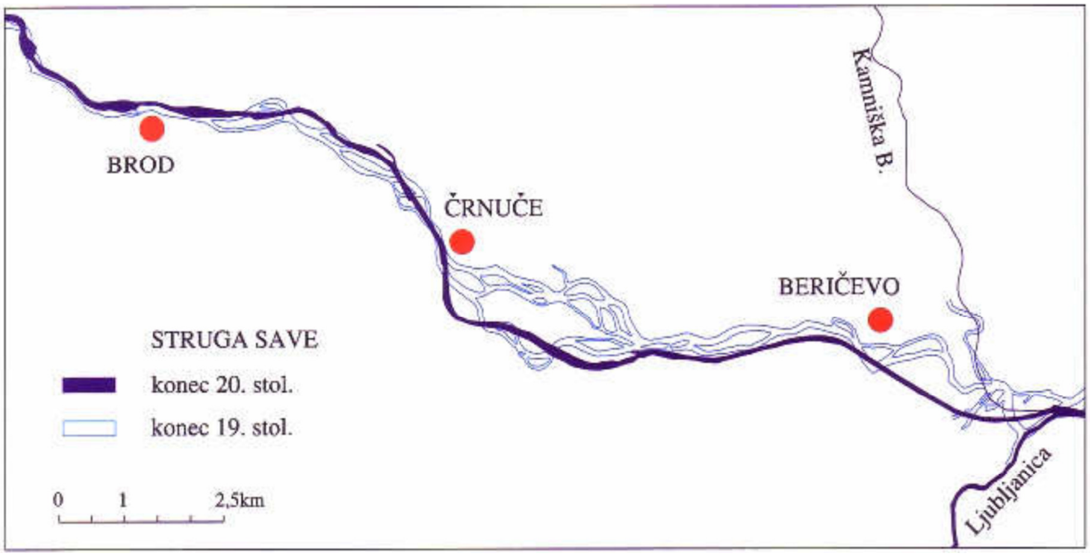


Figure 34: The Sava River changes from the end of the 19th century to the end of the 20th century – the reach shown is upstream of the confluence with the Ljubljanica River and Kamniška Bistrica River to the east of the City of Ljubljana (Source: Savič, 2009).

4.2.2. The longitudinal profile

According to historical analysis of available data, the channel of the Sava River was changed (regulated) several times in this river reach over the past 100+ years (see the above section 4.1.1). Before 1895, the channel bed was braided with several braids, after 1895, the channel was regulated to only 50 meters causing higher flow velocities and river erosion (channel incision). Between 1895 and 1922, the channel bed incised for 4.5 meters. The Sava 1923 Flood partially destroyed river engineering works and re-established the natural channel pattern. Until 1950, the channel bed rose back by 2 meters. In 1952, the river dam at Medvode for a new hydro power plant Medvode interrupted sediment inflow from upstream reaches, initiating a new channel-incision phase. Additionally, gravel mining at Tacen changed the sediment balance of this reach and caused latent erosion. Further incision of the riverbed was prevented by a series of riverbed ramps, built in 1980's. Nowadays, the riverbed is practically stabilised, the sediment transport is very limited (mainly only sediments flowing into the reach from the Sora and Kamniška Bistrica Rivers). The annually amounts of bedload in the Sava River reach downstream of the confluence with the Ljubljanica (karst river, no coarse river sediment inflow) and Kamniška Bistrica Rivers is estimated at of the order of 20,000 m^3. This amount is basically confirmed by the volumes dredged (mined) at Hotič close to Litija, where a concessionaire for gravel mining reported such amounts to have dredged annually in recent years.

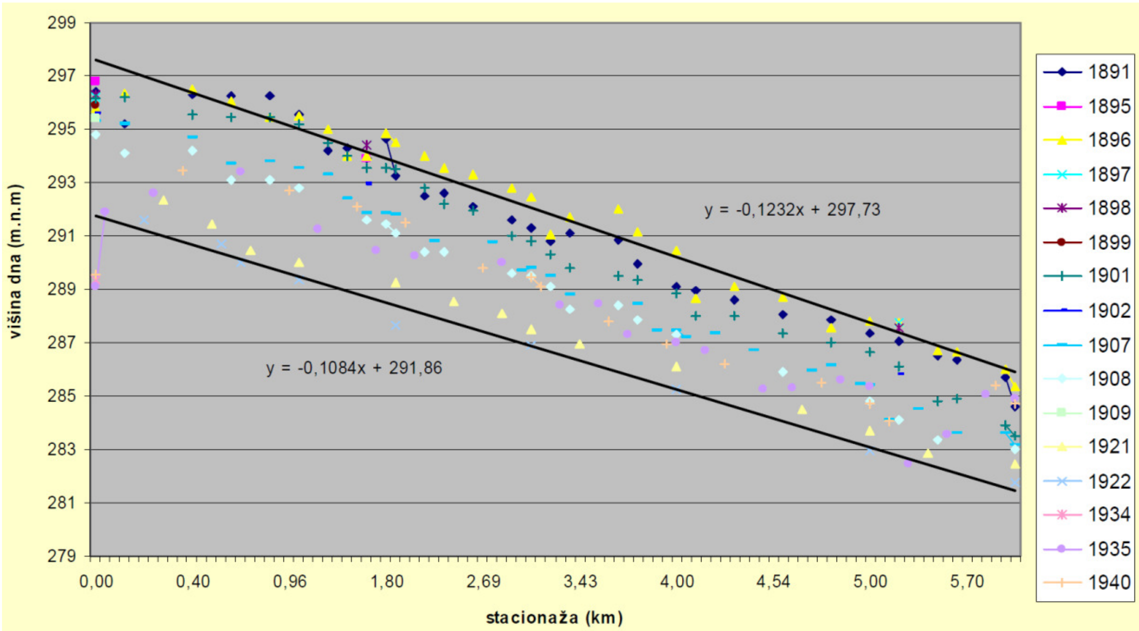


Figure 35: The Ljubljanska Sava River channel incision in the reach between Tacen and Črnuče in the period between 1891 and 1940 (source: ARSO; from Savič, 2009).

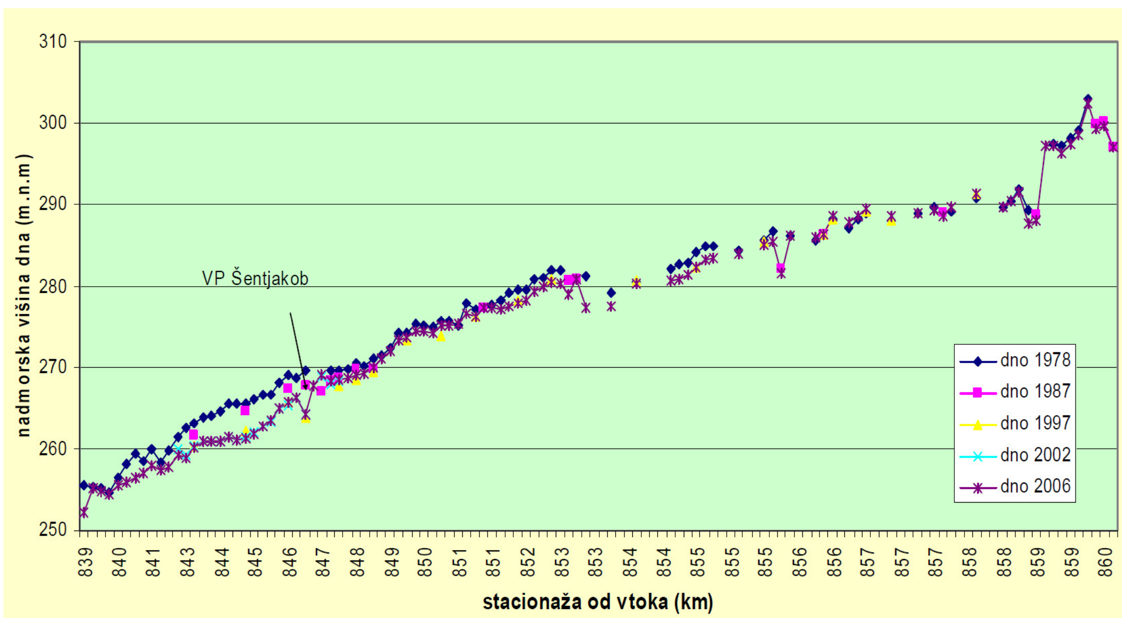


Figure 36: The Sava River channel incision in the reach between Tacen and Šentjakob in the period between 1978 and 2006 (source: ARSO; from Savič, 2009).

4.3. The case study of the Sava River channel bed changes in the reach along the Nuclear Power Plant Krško, Slovenia

The Nuclear Power Plant Krško (NPP Krško) has a major weir on the Sava River to get cooling water for the reactor.In the documents important for its operation (Updated Safety Analysis Report – USAR) in the section 9.2.5 Ultimate Heat Sink (UHS) and in NEK TS LCO 3.7.5, a minimal water level and a maximal water temperature for the Sava River in the reach between the weir of the NPP Krško and the Town of Krško is defined that must be available even if the weir of the NPP Krško is fully opened. The weir Krško has a concrete sill that assures the minimum water quantity for UHS. That is why the NPP Krško regularly measures the reservoir upstream of the weir Krško to the Town of Krško (each 5 years or after a large flood). If the reservoir is filled with sediments and the assured water volume for UHS tends to decrease below the minimum level, the NPP starts removing sediment deposits to achieve the prescribed water volume in the Sava River channel. The procedure and the results are internal documents of the NPP Krško.

Nevertheless, in the area of the NPP Krško, a local monitoring of Sava River aggradation due to sediment deposition was executed since 1970's. A comparison made in 2001, on the basis of the measured Sava River cross sections in this area between 1971 and 2001, revealed channel incision of between 1 and 2m between river km 743.087 and river km 745.814.

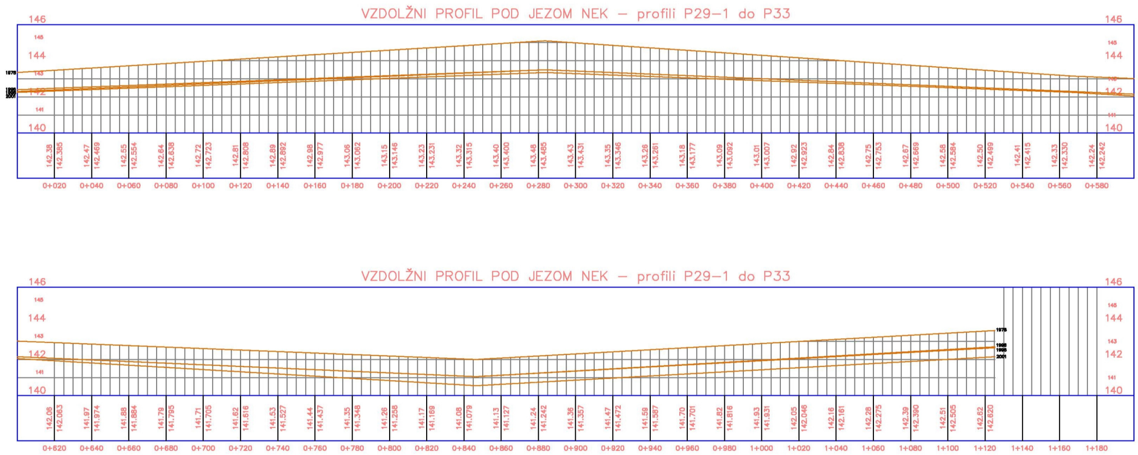


Figure 37: The longitudinal profile of the Sava River downstream of the weir of the NPP Krško in the period 1978 – 2001 (lines are given for 1978, 1996, 1998 and 2001) (Source: KSH-Chair of Hydrology and Hydraulic Engineering, 2001).

A comparison of the Sava River channel bed levels in the period 1989 – 2006 (also for 2009) are shown for the channel axis in Figure 38: they show a degradation immediately downstream of the weir for the cooling water for the NPP Krško (1.5m in the period between 1989 and 2001). Since 2001, there is an aggradation trend that can be recognized (until 2006 for ~0.4m, and in the period 2006 to 2009 for additional ~0.8m, nearly reaching the initial bed level from 1989). A comparable aggradation trend can be observed in a short 200m long reach downstream of the weir for the NPP Krško: in the downstream direction, the Sava River channel bed exhibits the state of latent erosion.

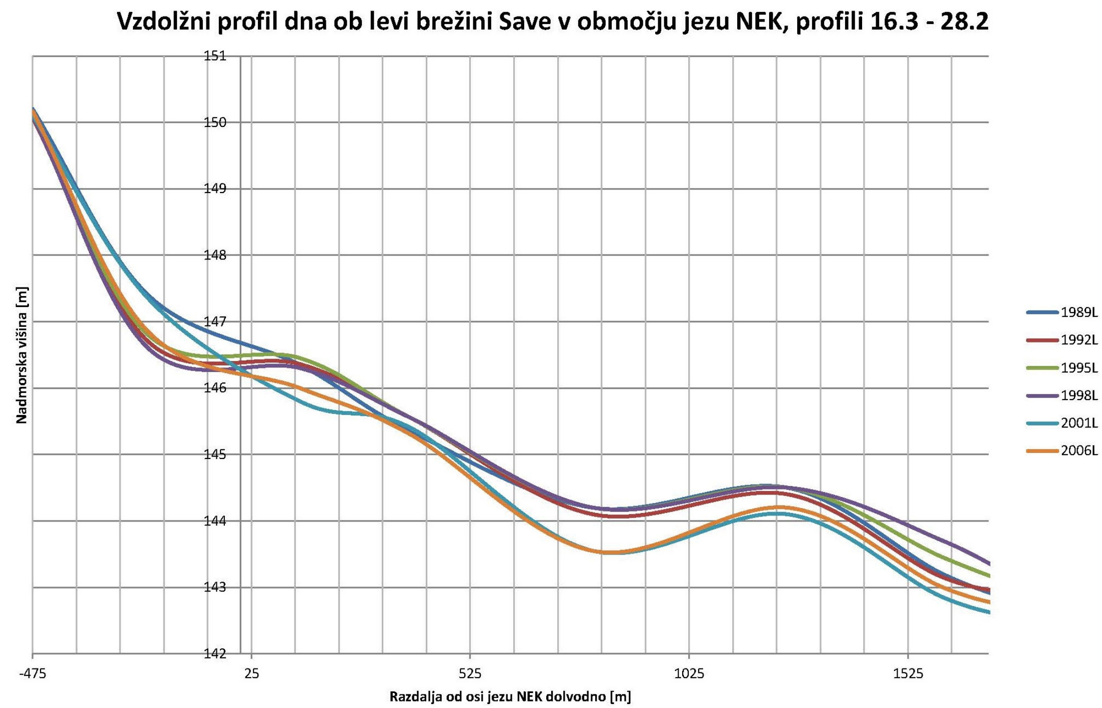


Figure 38: The longitudinal profile of the Sava River at the weir of the NPP Krško in the period 1989 – 2006

4.4. Riverbed measurements in the Lower Sava River in Slovenia

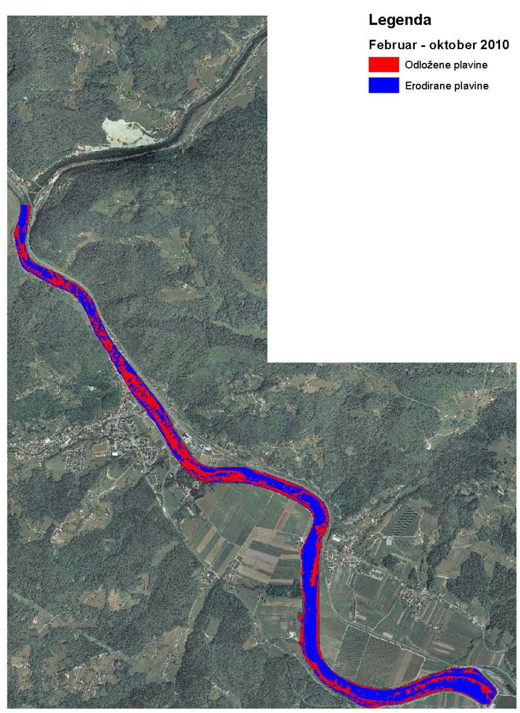


Figure 39: The measured changes in the volume of the sediment deposits in the reservoir of the HPP Vrhovo between February 2010 and October 2010 – erosion is given in blue and sedimentation in red (Source: Geateh, 2012).

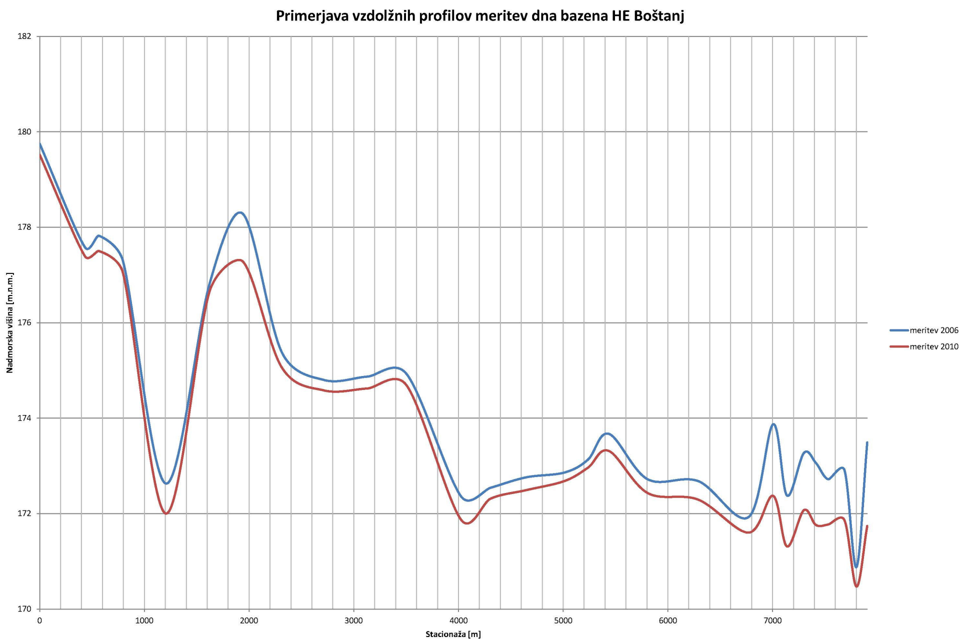


Figure 40: The changes of the Sava River bed levels in the reservoir of the HPP Boštanj between 2006 (blue) and 2010 (red) (Source: Geateh, 2010).

4.5. The case study of the Sava River channel bed changes in the reach through the City of Zagreb, Croatia

4.5.1. Introduction

Riverbed erosion and bottom deepening are part of natural fluvial processes in the upper stream of the Sava River. The increasing gradient of these changes is interconnected with the level of human influence in the Sava River Basin and its riverbed as well. In time, the consequences of riverbed erosion will become serious as well as dangerous, i.e. they may have an impact on the lowering of the underground water levels in the river basin or may threaten the stability of hydrotechnical structures. This process is usually not visible to the naked eye, it is lengthy and slow, but can be easily detected by analysis of specific types of measurements. In this case study we will show the section of the Sava River from the Croatian-Slovenian border down to the rkm 670+000, where the Drenje hydropower plant is planned (see Figure 42). Regular measurements of water levels, discharges, amount of sediment transport and cross section profiles along this reach of the Sava River prove that significant changes in the Sava riverbed have occurred in the last 20 years. Such a development was also confirmed by the measurements of annual stages at the hydrological station Zagreb in the period between 1926 and 2009 (Figure 41). In comparing maximum, mean, and minimum recorded stages, one can see that there is a decreasing trend after 1975.

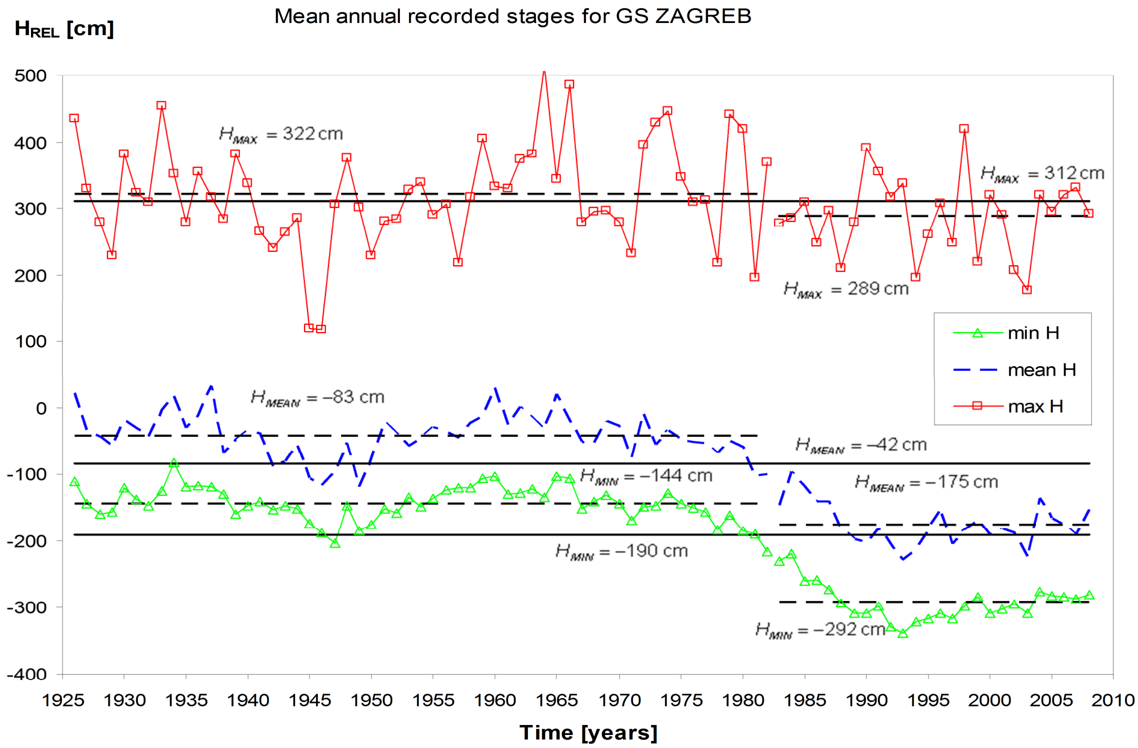


Figure 41: The annual recorded stages at the hydrological station Zagreb for the period 1925-2009 (Source: Oskoruš et al., 2010).

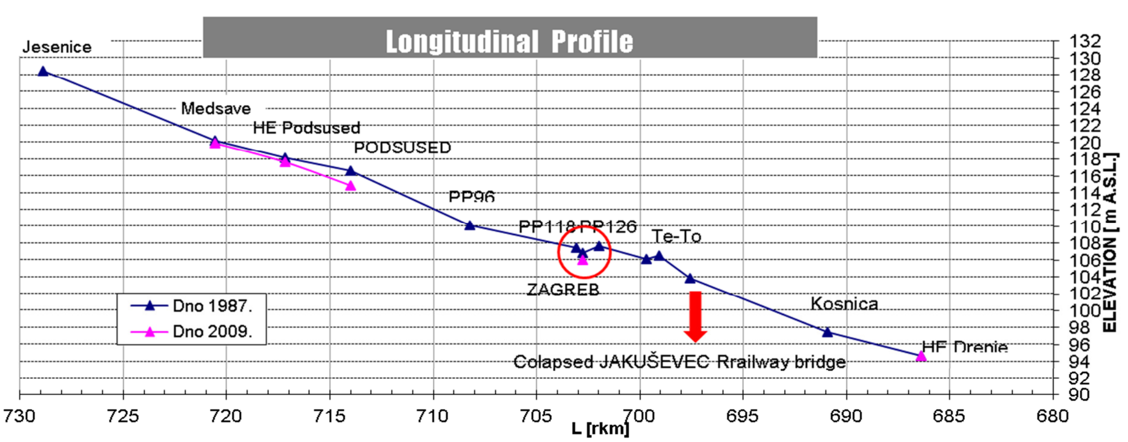


Figure 42: The Sava River longitudinal profile in the reach between river kilometre 685 and km 730 (from Oskoruš et al., 2012).

4.5.2. *Stability of bridges*

Figure 43: The railway bridge Jakuševac in Mičevac on the Sava River that collapsed on March 30, 2009, at 22:30 when a freight train was crossing the bridge, the bearing structure of the bridge lost its stability and resulted in a deformation of the bridge structure and tracks

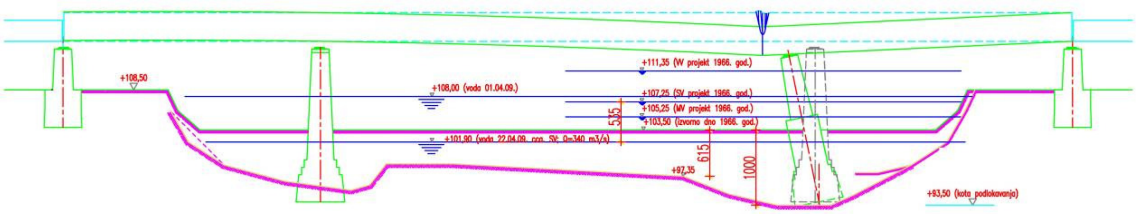


Figure 44: The cross section of the railway bridge Jakuševec that collapsed in 2009

Because of the lowering of the Sava riverbed, at some locations, by more than 3.5m, the stability of bridges in Zagreb and in the surrounding areas is especially threatened. As a result of regional and local erosion (river incision), the railway bridge Jakuševac in Mičevac (see Figure 42 for location) was damaged on March 30, 2009 (Figure 43), during a large Sava Flood. This case proved that a combination of a long-termed river incision and a large flood may damage bridge piers' foundations and bring bridges to collapse or being badly damaged (Figure 44). The railway bridge Jakuševac in Mičevac is an example of a loss of bridge stability caused by global and local erosion, aided by flood discharge conditions during extreme events. A similar problem arose with the Old Sava pedestrian bridge in Zagreb – for morphological changes see the cross section of the hydrological station Zagreb for the period from 1966 to 2009 (Figure 45).

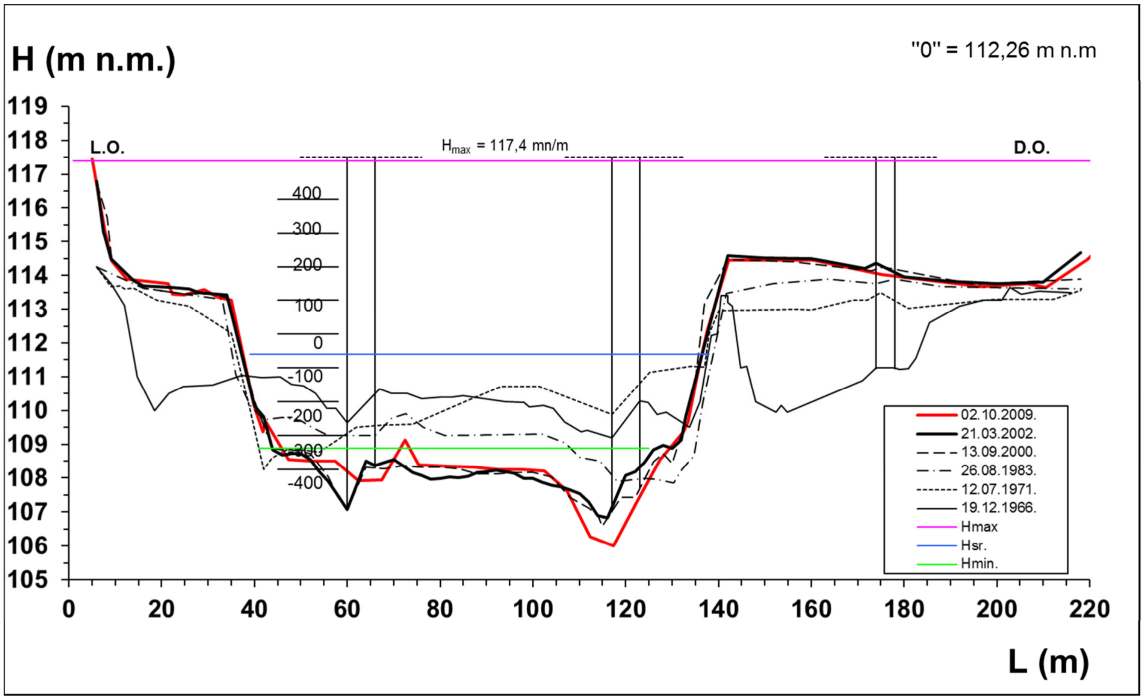


Figure 45: The morphological changes of the cross section of the hydrological station Zagreb on the Sava River in period 1966-2009 (Source: Oskoruš et al., 2010)

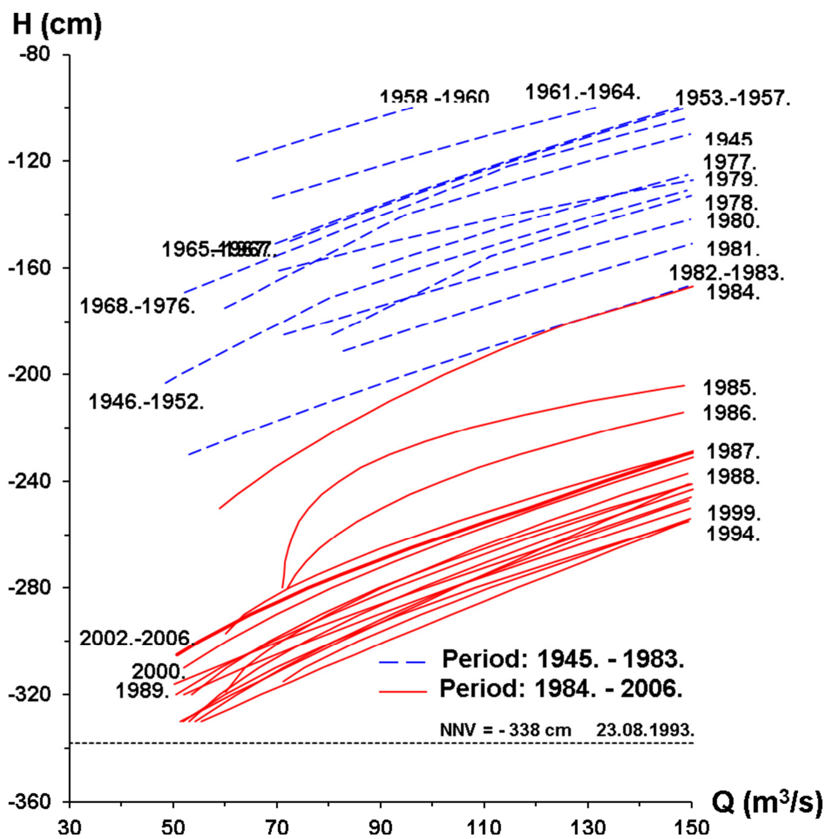


Figure 46: The discharge (Q) – water stage (H) curves at the hydrological station Zagreb, given for the period 1945 – 2006 (Source: Oskoruš et al., 2010).

4.5.3. Flood protection scheme for the City of Zagreb

The Sava River incision over its longer distances may have also other consequences; as clearly revealed by the analysis of water levels in the reach between the Slovenian-Croatian border and the Town of Sisak during the Sava September 2010 Flood. The Sava River channel stability is important for the existing flood protection scheme of the City of Zagreb and neighbouring areas. For this scheme to be checked, a hydrological analysis of the series of characteristic annual water levels and discharges (primarily maximum, but also minimum and mean values) of the Sava River at the water gauging profiles Zagreb and Podsused in the period from 1926 to 2010 was performed (see Figure 41 for HS Zagreb, and Figure 47 for HS Podsused). The focus of this case study was the role of the weir Jankomir as the key facility for flood protection scheme of the City of Zagreb. The influence of the Sava River incision in the period 1946-2006 is shown in Figure 46.

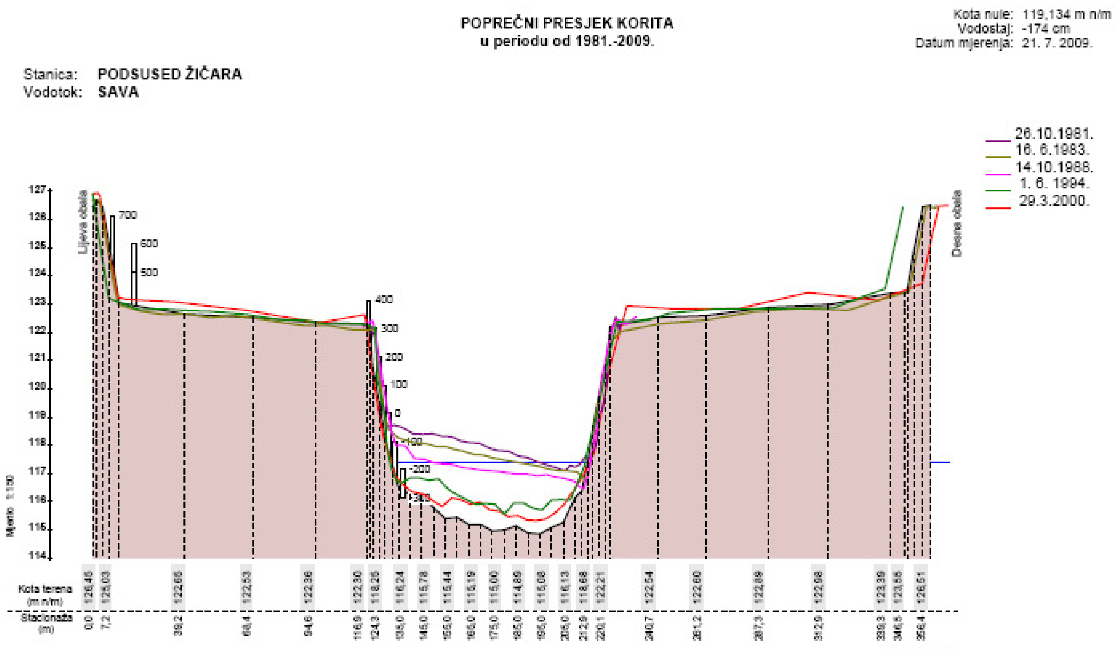


Figure 47: Morphological development of the Sava riverbed at the hydrological station Podsused in the period from 1981 to 2000 (Source: Oskoruš et al., 2010).

4.6. The case study of the Sava River channel bed changes in the reach upstream of the City of Belgrade, Serbia

Altogether, 202 permanent profiles were periodically surveyed between the Croatian border and its mouth to the Danube River, from 1967 to 2004. The only complete surveys, done in 1982 and 2004, indicate that the Sava River channel volume is increasing (Figure 48).

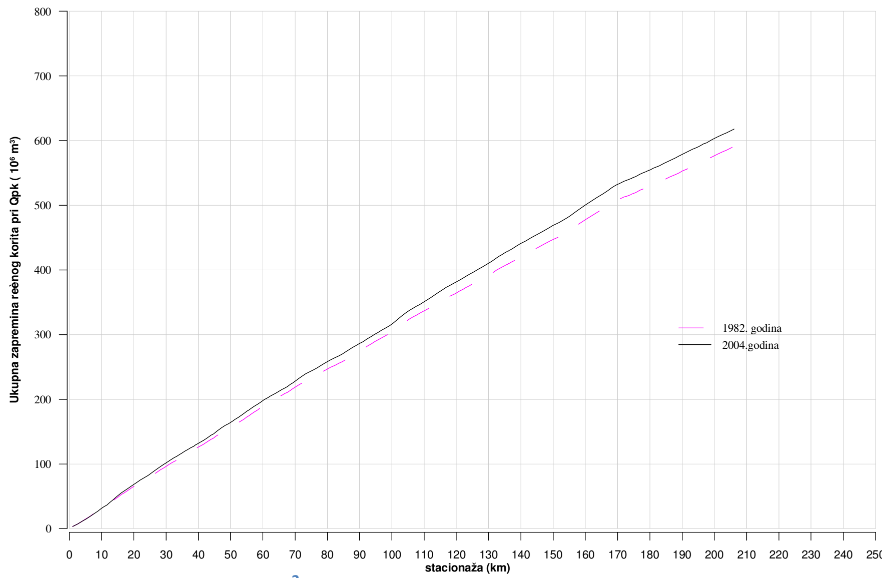


Figure 48: The total volume in million m^3 of the Sava River channel, period 1982-2004.

Table 7 presents the summary of riverbed deformation between 1982 and 2004, including dredging. Although quantities of the dredged sediments are not accurate, these are used as a justification of the morphological processes along the Lower Sava River. The only river reaches, where the sediment deposition is present, are in the vicinity of the Sava River mouth (till km 38.6) and near the Town of Šabac, at the upstream end of the Iron Gate 1 backwater effect.

Table 7: The summary of riverbed deformation between 1982 and 2004

No.	River reach km - km	Changes of the riverbed volume	Dredged volume	Summary deformation	Average
		10^6 m^3	10^6 m^3	10^6 m^3	m^3/m/year
1	*0 - 14.52*	*- 1.99*	*1.97*	*- 0.01*	*- 0.03*
2	14.52 - 38.62	- 3.59	3.90	0.31	0.58
3	38.62 - 41.6	- 0.45	0.12	- 0.32	- 4.71
4	41.6 - 60.42	- 2.64	0.97	- 1.67	- 4.05
5	60.42 - 78.32	- 2.10	0.05	- 2.05	- 5.20
6	78.32 - 99.25	- 0.54	0.63	0.09	0.19
7	99.25 - 124.16	- 5.88	2.95	- 2.93	- 5.34
8	124.16 - 132.72	- 1.52	0.18	- 1.34	- 7.11
9	132.72 - 141.58	- 1.41	0.16	- 1.25	- 6.41
10	141.58 - 149.76	- 1.13		- 1.13	- 6.31
11	149.76 - 154.25	- 0.09		- 0.09	- 0.93
12	154.25 - 157.22	- 0.60		- 0.60	- 9.16
13	157.22 - 169.84	- 1.65		- 1.65	- 5.95
14	169.84 - 176.6	- 0.78		- 0.69	- 4.63
15	176.6 - 179.6	- 0.34		- 0.34	- 5.12
16	179.6 - 184.4	- 0.16		- 0.16	- 1.54
17	184.4 - 206.11	- 1.57		- 1.57	- 3.29

5. Estimation of the Sava River sediment balance

5.1. Introductory remarks

The Guidance on Sustainable Sediment Management, developed within the project "**Towards the Sustainable Sediment Management with the Sava River Basin as a showcase"** proposed the following list of issues to be included in the estimate of sediment quantity in a river basin:

Highlights	Issues concerned
Elements of sediment budget	Definition of inflows, outflows, storage Use of Conservation of mass equation Consideration watershed from source to mouth Consideration of possible sources outside the area Assessment of residual products from chemical and mechanical weathering
Soil loss and erosion	Estimation of processes
Estimation of components of sediment budget	Soil erosion (rainfall detachment, freeze/thaw, overland flow) Sediment delivery ratio: delivered/eroded Landslides Mechanical movement Stream bank erosion Reservoirs associated with dams Tributary input
Estimation of river transport of sediment	BedloadBedload Suspended load Wash load
Assessment of the sediment budget	Sediment yield as a sum of all components Computer modelling

According to the previously presented monitoring in Sava River Basin countries, the proposed scheme cannot be applied because most of the data is not available.

Only data on suspended sediment quantities are accessible, but only for the Sava River main stream. The chapter 5.3 is therefore devoted only to suspended sediment balance on yearly, monthly and daily basis (during floods), while the indication of other components of sediment balance is given in chapter 5.4.

5.2. Modes of sediment transport

The Sava River and downstream reaches of its tributaries are typical alluvial courses whose channels are incised into their own sediment, with a permanent exchange of sediment particles between the riverbed and the suspension.

Alluvial rivers carry varying amounts of sediment, which depend on the intensity of erosion within the river basin and the characteristics of sediment transport in the river network.

In every alluvial river, including the Sava, sediment is transported in different modes. Coarse particles of sediment (gravel, coarse and medium sand) move along the riverbed, as bedloadbedload, while finer fractions (fine sand, silt and clay) are suspended in water, and move as suspended load. The mode of sediment transport (along the bottom or in suspension) depends on hydrologic and hydraulic conditions. It was roughly estimated that the ratio between suspended load and bedloadbedload goes up to 10:1.

A portion of suspended sediment is in permanent exchange with the riverbed material, and takes part in morphological processes (bed-material load); the finest particles pass by without any interaction with the bottom of the river (wash-load).

The natural channel of the Sava contains a percentage of suspended sediment whose particle sizes are the same as those of the riverbed sediment. This suggests that an intense exchange process is taking place between suspended and bedload particles in the channel of the Sava.

The presence, volume, and grain-size composition of bed-material fractions of suspended sediments depend on turbulence and general hydraulic characteristics of the flow (composition of the riverbed, and variation in these parameters along the course over time); the wash-load depends, for the most part, on the conditions that prevail in the catchment area.

A clear distinction between wash-load and bed-material load in suspended sediments cannot be made because the ratios vary, both for the same cross-section over time (due to flow variation) and along the flow due to varying levels of turbulence.

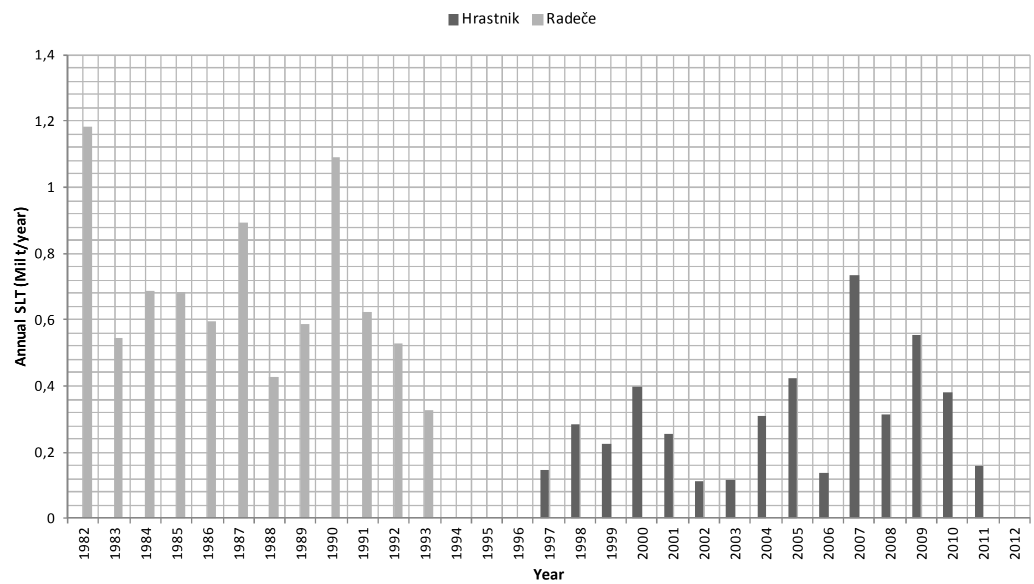
It is well known that wash-load is comprised of fine particles, smaller than those found in the riverbed. The vertical and transverse distributions of these fine sediment particles are quite uniform. Due to their size, fine particles are deposited very slowly, even in still water. Conversely, turbulence that overrides the force of gravity causes these particles to disperse across the entire flow profile. On the other hand, the force of gravity has a major influence on large particles of channel-forming sediment. Turbulence forces are able to lift large particles only to a limited height from the riverbed. This is why concentrations of large particles close to the surface are much lower than near the riverbed. Different sized particles, therefore, have different cross-sectional concentrations.

5.3. Suspended sediment balance along the Sava River

5.3.1. Annual quantities of suspended sediments

Data on suspended load on monitoring stations in Slovenia, Croatia and Serbia for the period 1982-2012 were collected and analysed.

The bar charts containing values of the annual sediment load transport (million tons per year) and the average flow (m^3/s) are presented on Figure 49 for Slovenia, Figures 50 and 51 for Croatia and Figure 52 for Serbia.



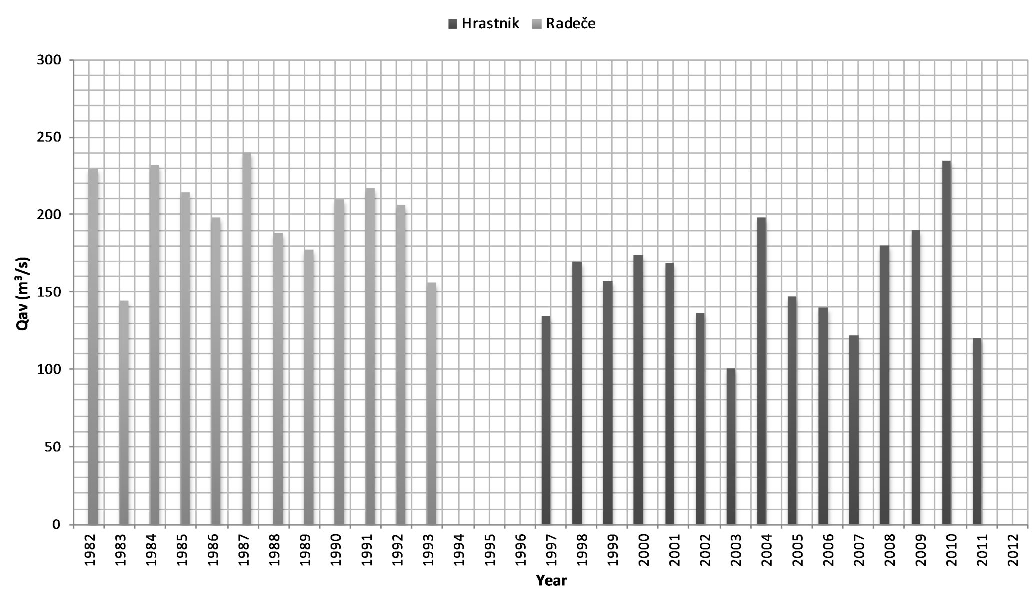
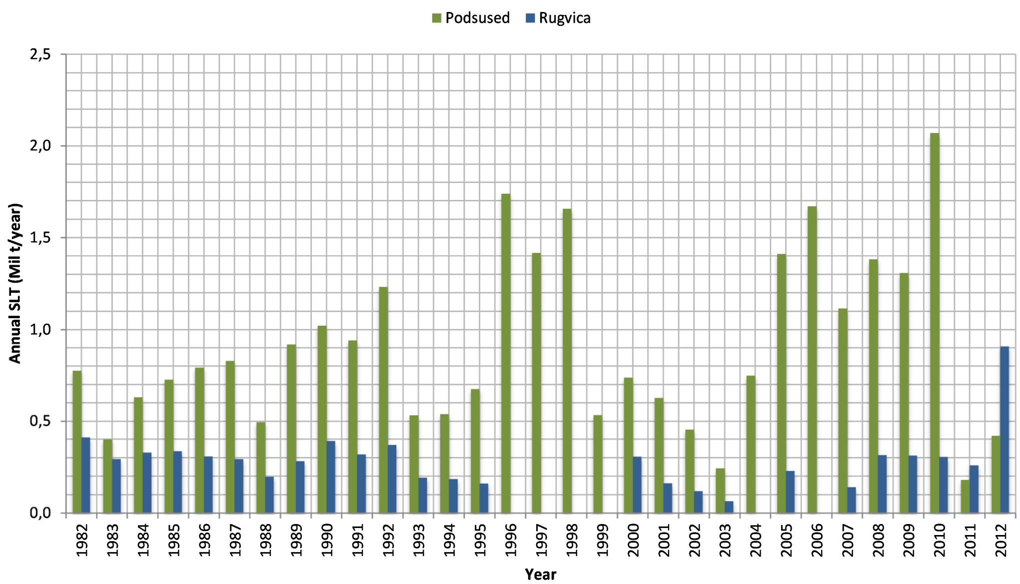


Figure 49: Annual suspended load transport and average river flow - Upper Sava, Slovenia



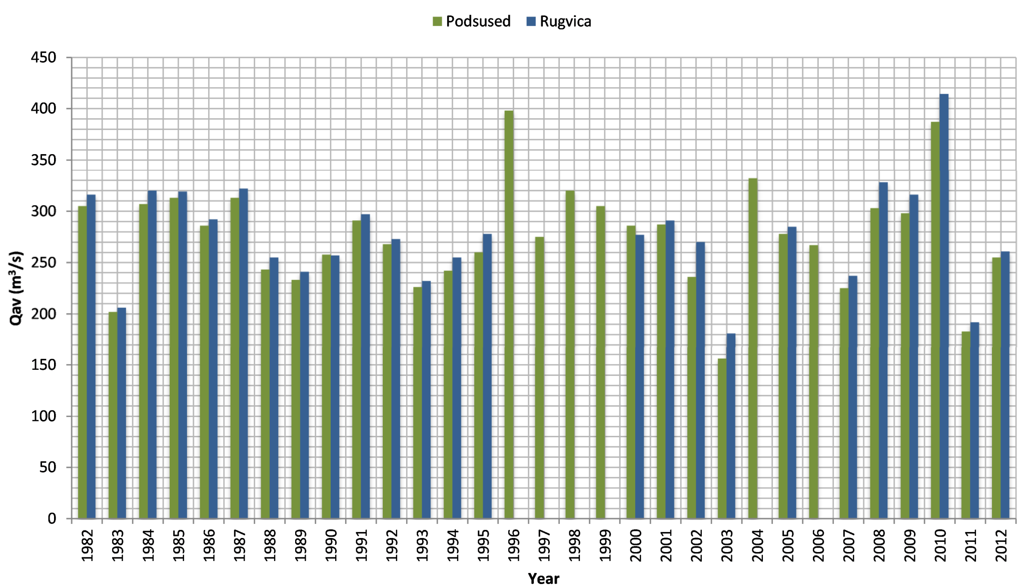
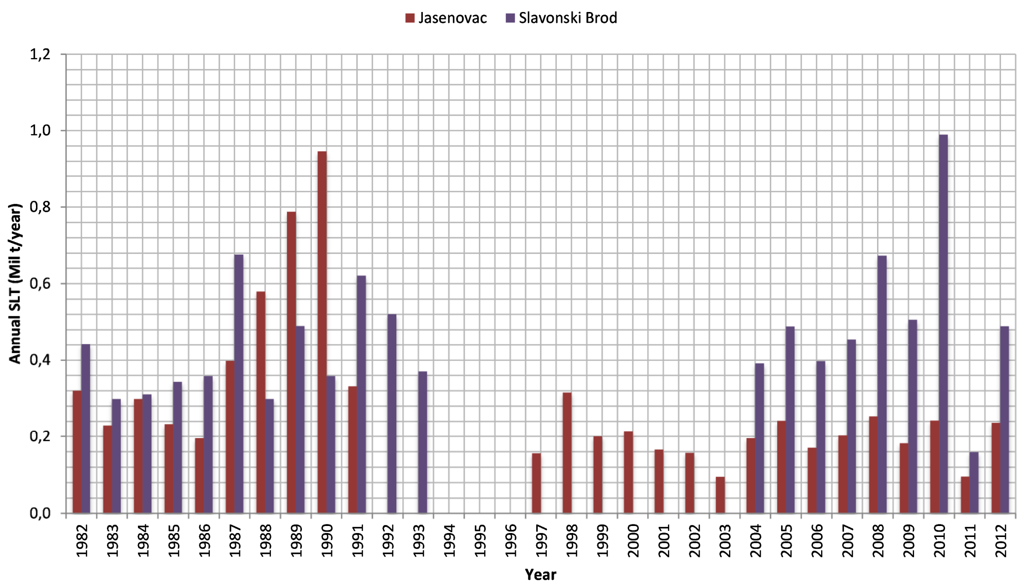


Figure 50: Annual suspended load transport and average river flow – Upper and Middle Sava, Croatia



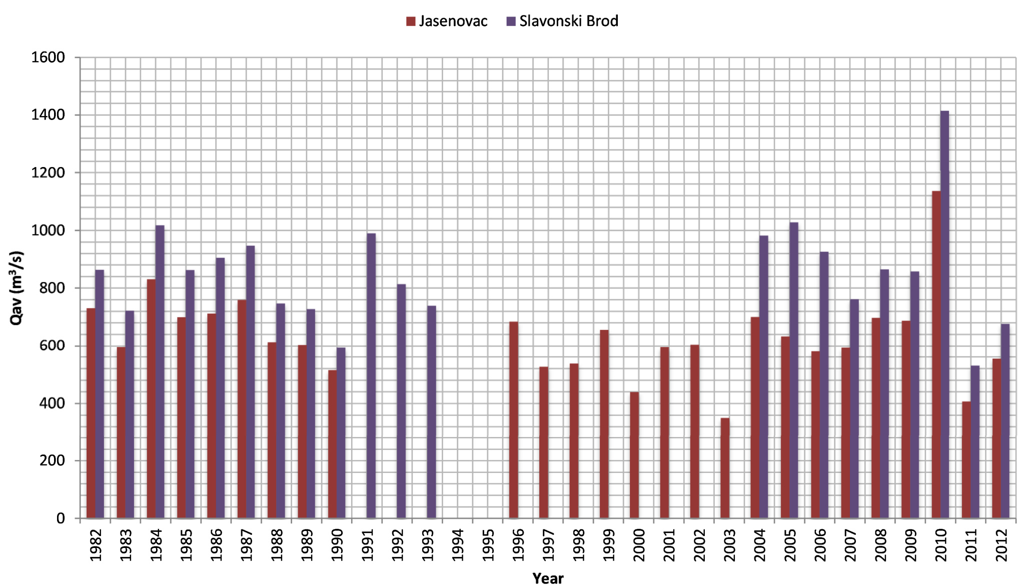


Figure 51: Annual suspended load transport and average river flow – Middle Sava, Croatia

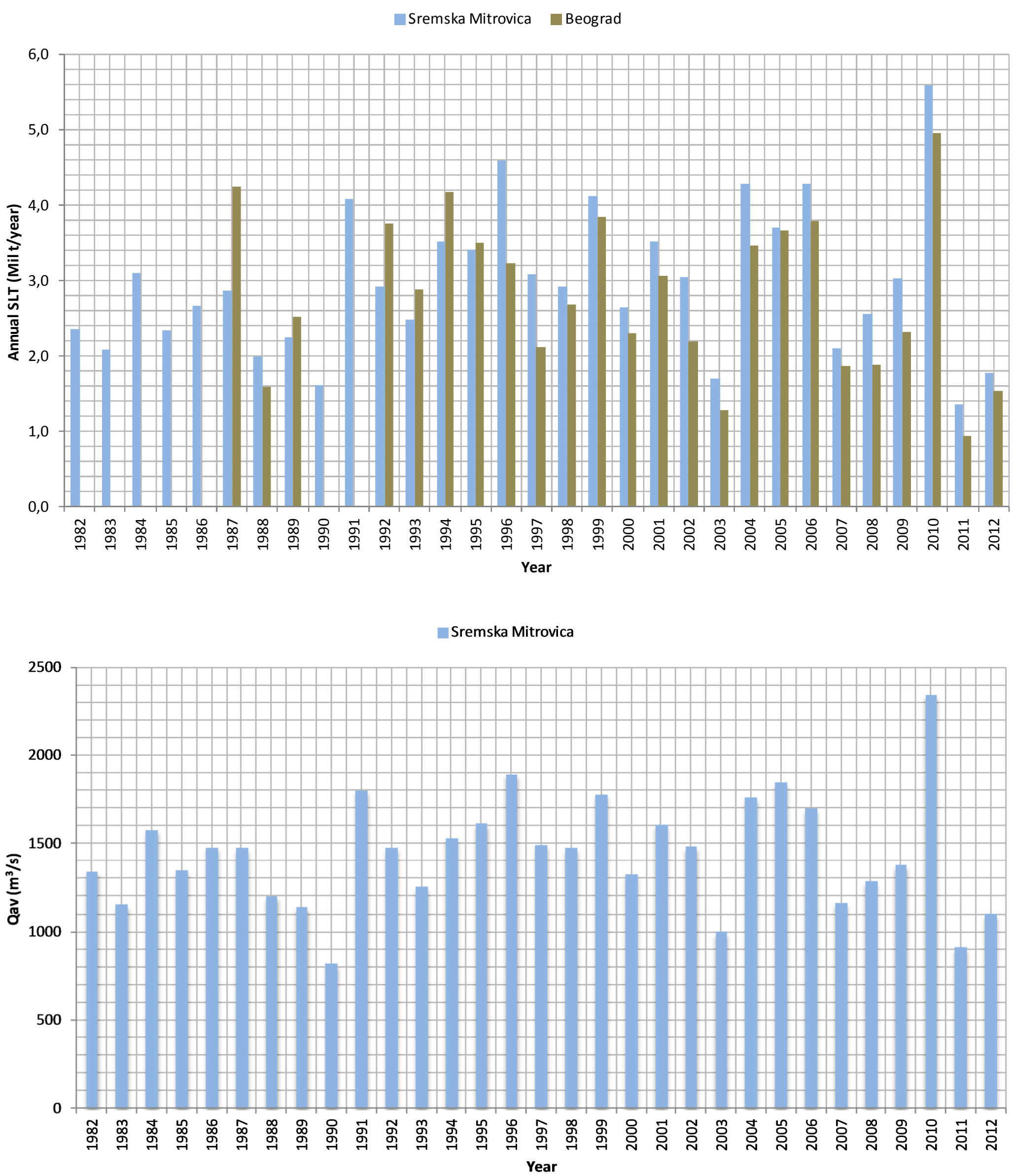


Figure 52: Annual suspended load transport and average river flow - Lower Sava, Serbia

The basic assumption is that suspended load transport along the Sava River should increase in the downstream direction, because of the increase of the catchment area and inflow from tributaries. Sediment transport can decrease as well, due to the fall of the transport capacity, caused by natural circumstances (variation of the river morphology) or anthropogenic factors (structures in river bed as dams and sluices).

To examine this assumption, a basic analysis was carried out including a correlation of annual suspended load transport and the average flow on all measuring stations along the Sava River (Figure 53).

It is obvious that the assumption of gradual increase of sediment load transport along the Sava River cannot be confirmed, due to significant difference between annual quantities.

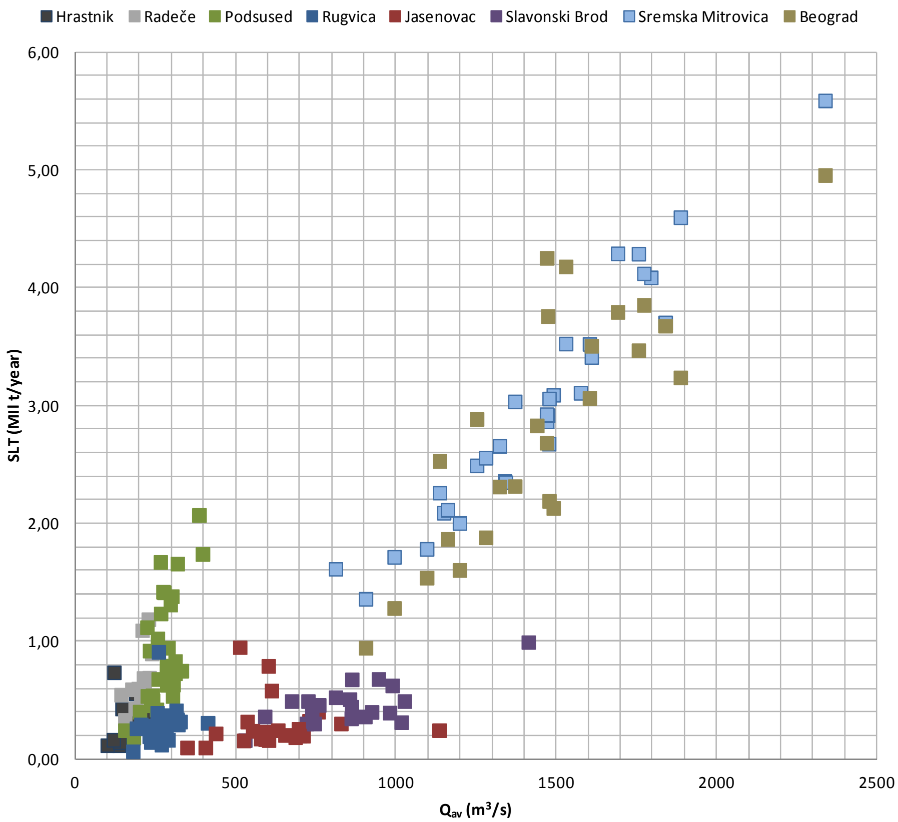


Figure 53: Correlation between the annual river flow and suspended load transport along the Sava River (all stations)

The results of in-depth analysis of annual suspended load transport on adjacent monitoring stations are presented on Figure 54, as correlations of data for the downstream (on x axis) and upstream station (on y axis). Grouping of points at the right of the “line of perfect agreement” indicates that larger sediment quantities are measured on the downstream monitoring station than on the upstream one. The opposite case – grouping of points at the left side – indicates that the sediment quantities are lesser at the downstream monitoring station (as on Figure 54b – correlation of Podsused and Rugvica).

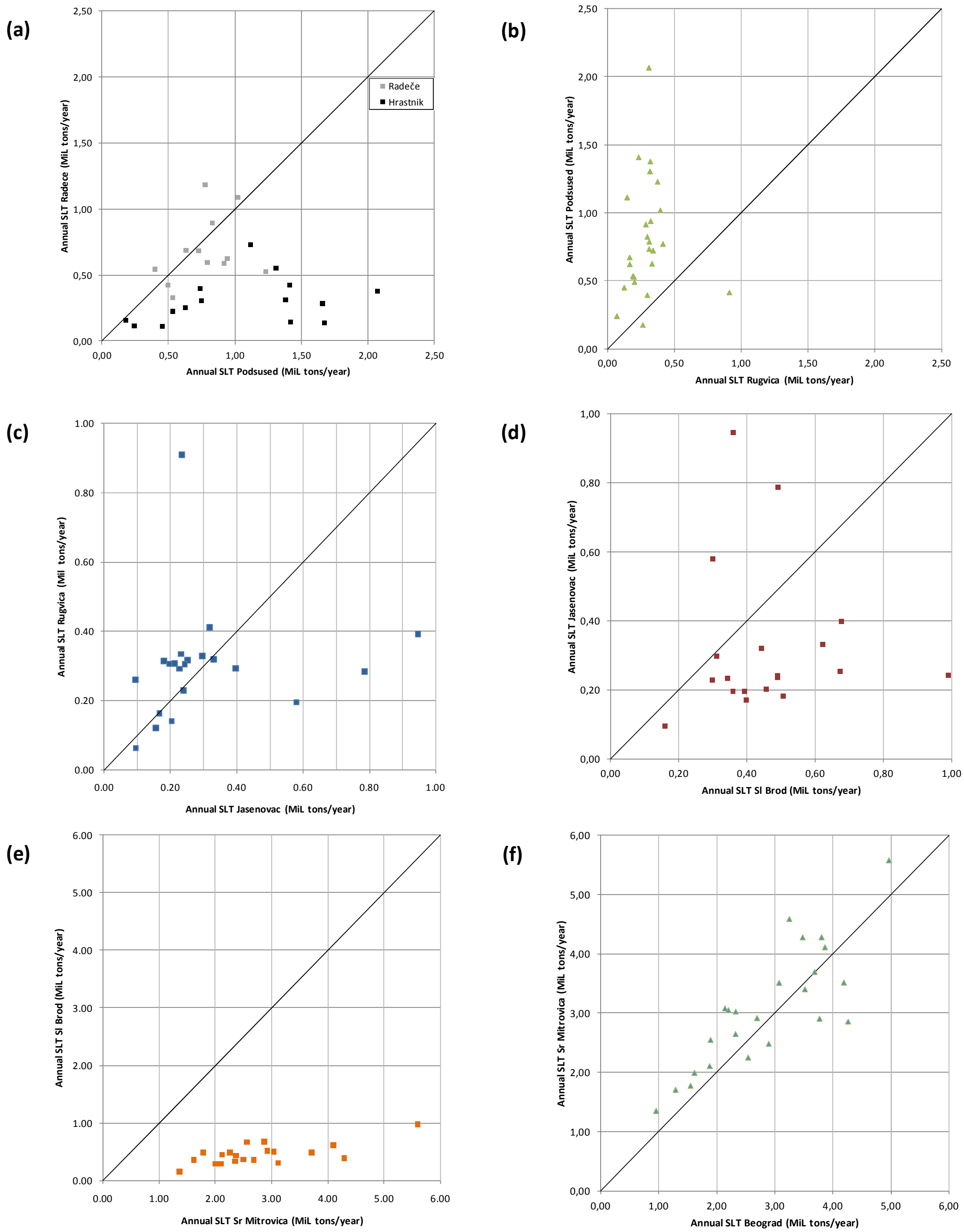


Figure 54: Correlations of annual suspended load on adjacent measuring stations

<u>Stretch Radeče/ Hrastnik – Podsused (Figure 54a)</u>

- Upstream monitoring stations (in Slovenia) operated in different periods. Radeče at km 783.5 of the Sava River operated between 1982 and 1993, while monitoring at Hrastnik (km 793.6) was organized between 1997 and 2011. Downstream monitoring station Podsused (at km 650) continuously operated in the analysed period (1982 – 2012).

- This stretch belongs to the Upper Sava section, which has a gravel bed and high longitudinal slope. The mouth of the Krka River is at km 722.2 of the Sava River.
- Correlation of annual suspended sediment transport on monitoring station Podsused and the upstream ones (Hrastnik/Radeče) is scattered, which might be explained by different methodologies of suspended sediment measurements in Slovenia and Croatia.

Stretch Podsused – Rugvica (Figure 54b)

- Monitoring stations Podsused (at km 698) and Rugvica (at km 658 are the closest of all, and monitoring is conducted by DHMZ of Croatia. Measurements at Rugvica had a few interruptions (1996-1999, 2004, 2006).
- There is a significant difference between annual suspended sediment load on the downstream station – Rugvica (less than 0.4 million tons per year) and the upstream one -Podsused (0.5–2 million tons per year), which cannot be explained by different measurement methodologies. Also, there is no indication of sediment deposition on this short river stretch.

Stretch Rugvica – Jasenovac (Figure 54c)

- On this stretch is the mouth of the Kupa River (at km 591).
- Monitoring station Jasenovac, previously located downstream of the Una River mouth (at km 515), did not operate between 1992 and 1996.After 1997 it is located upstream of the mouth, on km 516.1.
- Since the Sava River catchment area significantly enlarges between these monitoring stations, a significant increase of suspended sediment load might be expected. On the other hand, both the Kupa and the Una have karst on ~50% of the basin area, and thus a production of suspended sediment might be low.

Stretch Jasenovac – Slavonski Brod (Figure 54d)

- No monitoring was conducted at SlavonskiBrod (km 314.5) between 1994 and 2003.
- Mouths of two significant tributaries – the Vrbas River and the Ukrina River are at km 427 and km 381.5.
- Correlation of annual suspended transport on Jasenovac and Slavonski Brod indicates a significant increase of the sediment transport in the downstream direction – suspended sediment quantities at Slavonsk iBrod are 2 times larger than at Jasenovac.

Stretch Slavonski Brod – Sremska Mitrovica (Figure 54e)

- Monitoring at Sremska Mitrovica (at km 141.5) had long periods when the sediment samples were not taken (1984-1988, 1990-1991, and 1993-2008). Nevertheless, monthly and annual quantities of suspended load were derived from correlation with the average flow (Figure 55)
- The Sava River catchment enlarges 2 times between Slavonski Brod and Sremska Mitrovica because the river receives water and sediment from two large tributaries: the Bosna River (at km 314.5) and the Drina River (at km 178). The sediment inflow from the Bosut River can be neglected. Thus, a significant increase of the sediment transport in the downstream direction can be expected.
- Correlation of annual suspended load at Slavonski Brod and Sremska Mitrovica exhibits the increase of sediment transport in the downstream direction, but the ratio is too large. Namely, values at Sremska Mitrovica are 5 to 10 times larger than at Slavonski Brod, which cannot be related to conditions within the river basin. It means that divergence originates from different methodologies for the assessment of suspended sediment load which are applied on Slavonski Brod (DHMZ Croatia) and Sremska Mitrovica (Jaroslav Cerni Institute).

Stretch Sremska Mitrovica - Beograd (Figure 54f)

- Sediment data for Beograd monitoring station (km 5.6) are available since 1987, with the gaps 1990-1991 and 1999.

- Kolubara River is the only important tributary on this stretch.
- The sediment regime on this stretch is under the influence of the Danube River regime, or the backwater of the Iron Gate 1 HPP.
- Correlation indicates the good agreement of data, due to the fact that the same methodology of suspended sediment monitoring is applied on both stations. Annual suspended sediment load is larger at Sremska Mitrovica than at Beograd in many years, indicating the siltation of this part of the Iron Gate 1 reservoir.

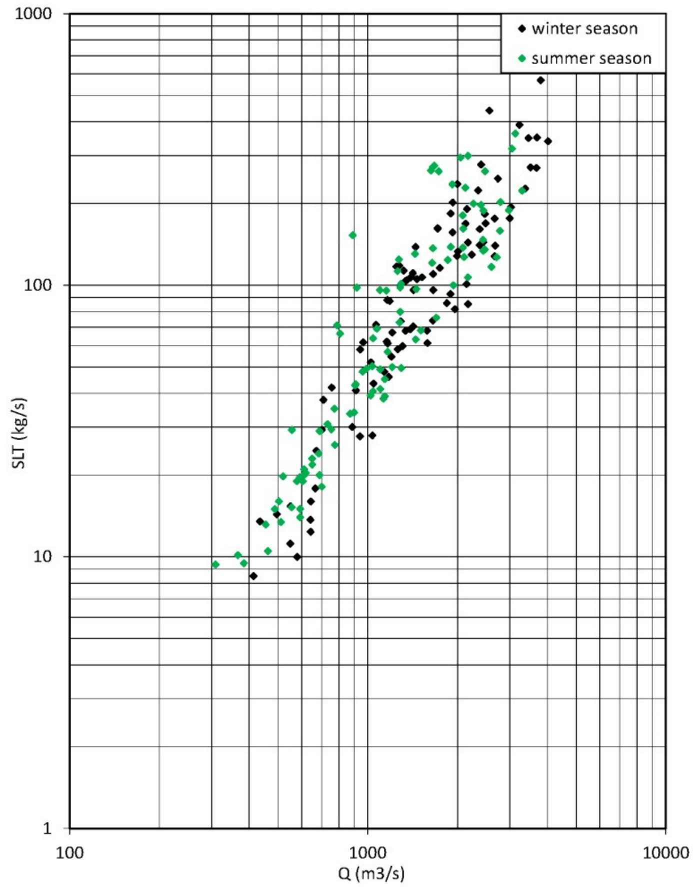


Figure 55: Correlation of the monthly suspended load transport and average monthly flow at Sremska Mitrovica monitoring station

At the end, it can be concluded that the reliable balance of the suspended sediment (even very roughly - on yearly basis) cannot be done. There are significant discrepancies between data for Upper and Middle Sava (decrease of the annual sediment load) and then between data for Middle and Lower Sava (as depicted on Figure 56).

The fact that yearly suspended sediment transport is very similar on the Upper and Middle Sava brings the question about the role of large tributaries along the middle course of the Sava River (Kupa, Una, Vrbas, Ukrina as the important right tributaries, but also a few left tributaries) in the sediment balance.

On the other hand, there is unusual increase of the annual suspended sediment load on the Lower Sava (5-10 times higher than on Middle Sava), which can be only the result of significant differences in sediment measurement technology.

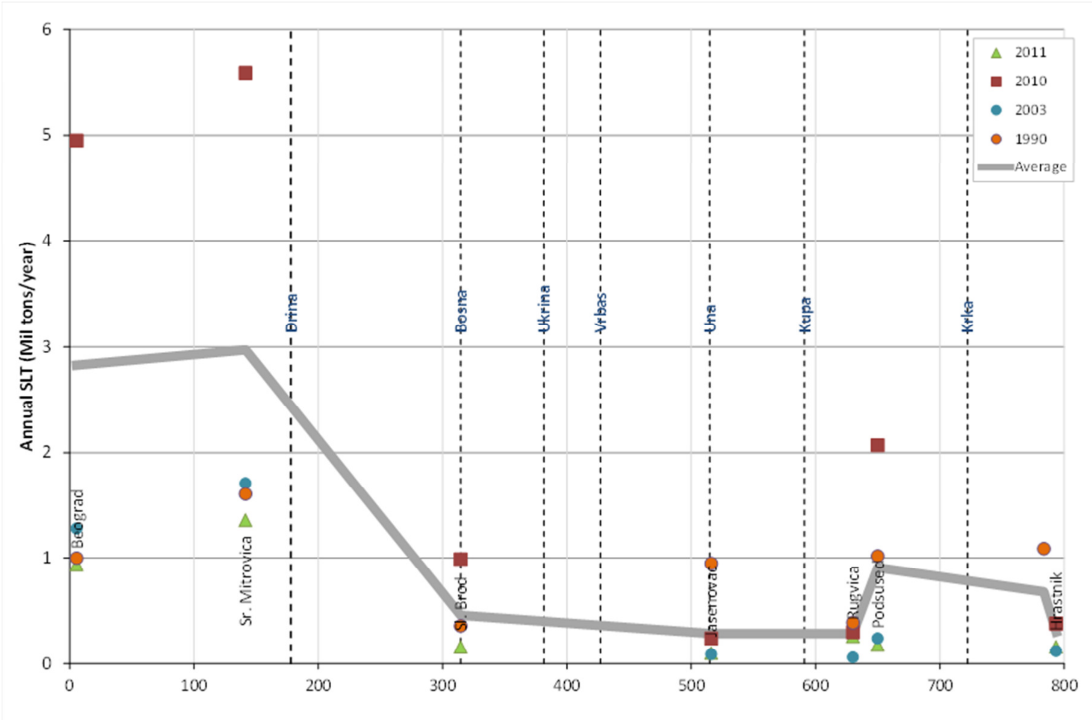


Figure 56: Longitudinal presentation of the annual suspended sediment transport along the Sava River

Having in mind previous statements, it would be very useful to start joint sediment transport investigations in the Sava River Basin. These activities should encompass:

- Joint measurements of suspended sediment parameters on selected profiles near border, to investigate differences which might be result of instruments used for sediment sampling, procedure and location of the suspended sediment sampling, methods of laboratory testing etc.
- Simultaneous measurements along the Sava and on main right tributaries, near the mouth.

5.3.2. Seasonal variability of suspended sediment transport

Seasonal variability of suspended transport is analysed on the base of average monthly data for the period 1982-2012. Figures 57 to 59 show that sediment transport varies within the year, mainly corresponding to the meteorological conditions in the river basin and hydrology of the river.

On the Upper Sava, sediment transport in spring is low, because the river flow is originating from snow melt. On the Middle and Lower Sava is the opposite distribution – the highest monthly sediment quantities appear in spring. Along the whole river, high sediment transport also appears at the end of fall, when high river flows originate from intensive rains.

In wet years, as 2010, monthly sediment transport can considerably exceed the average values.

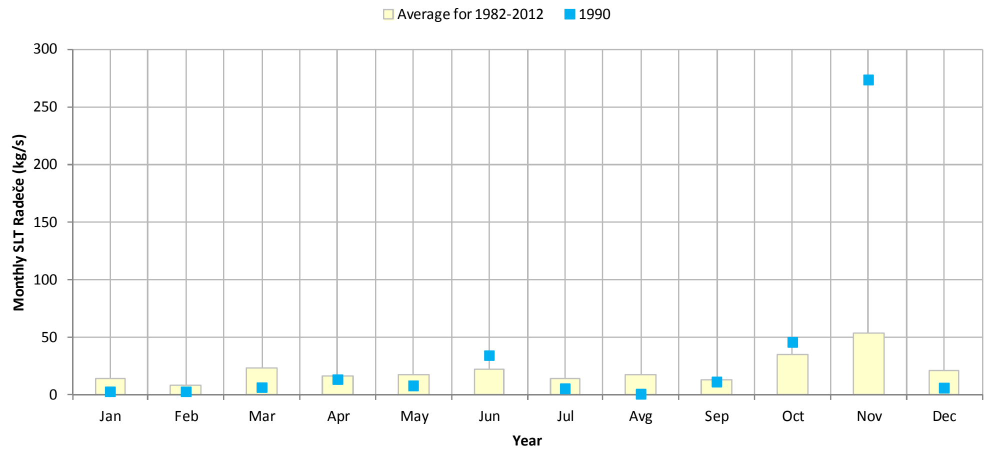


Figure 57: Comparison of the average monthly suspended sediment transport in the period 1982-2012 and wet year (1990), at the Upper Sava (Hrastnik, Slovenia)

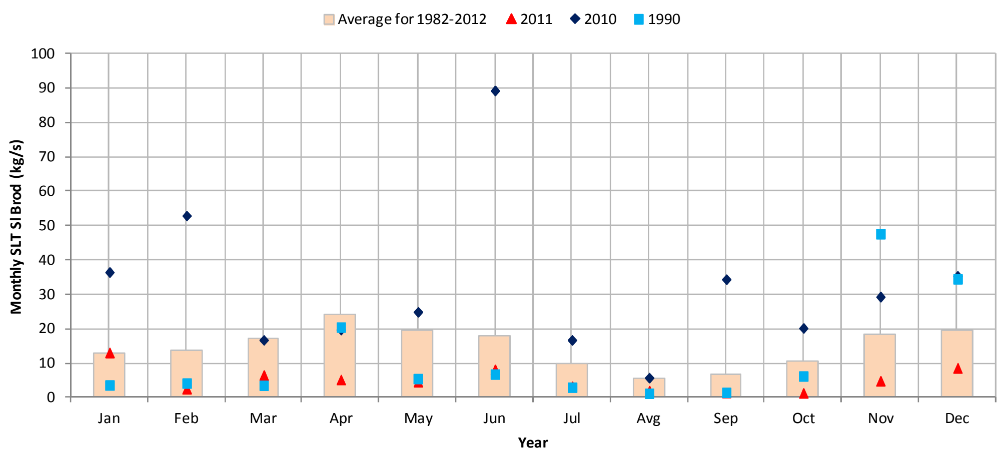


Figure 58: Comparison of the average monthly suspended sediment transport in the period 1982-2012, wet years (1990 and 2010) and dry year (2011), at the Middle Sava (Slavonski Brod, Croatia)

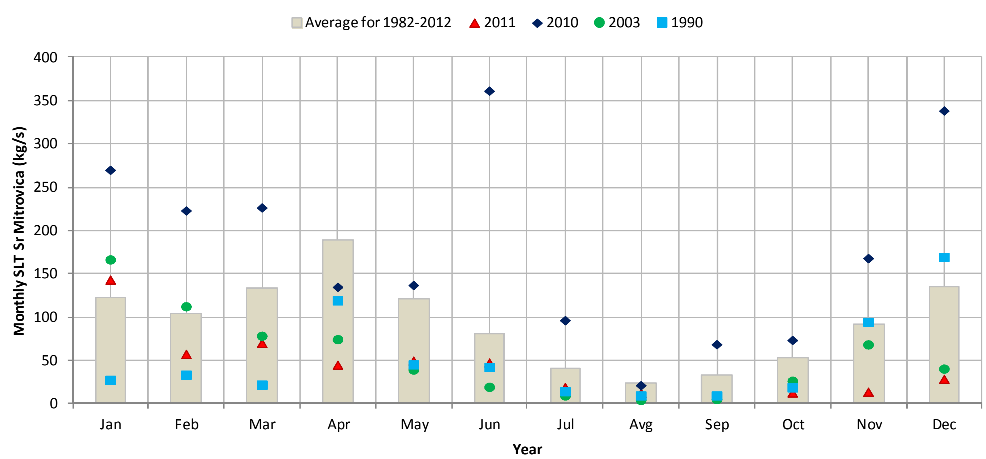


Figure 59: Comparison of the average monthly suspended sediment transport in the period 1982-2012, wet years (1990 and 2010) and dry years (2003 and 2011), at the Lower Sava (Sremska Mitrovica, Serbia)

5.3.3. Role of floods in suspended sediment transport

It is well known that floods have a very important role in the sediment transport on rivers, because high flows initiate sediment motion and carry large quantities of suspended and bedloadbedload. The share of sediment transport during floods in the total annual quantity depends on the size of the stream and its basin (in small streams it goes up to 70-90%, in major rivers is 30 - 50%).

In the particular case of the Sava River, the analysis of sediment transport during floods encounters several problems, as:

- Previously discussed differences in methodology of suspended sediment monitoring;
- Acquisition of representative sediment samples (usually hydrograph peak and the maximum sediment concentration appear in different moments of time);
- Complete lack of data on sediment inflow from tributaries;
- Complete lack of bedload measurements, since bedload material is transported almost exclusively during high flows and plays a major role in the morphological processes.

The role of floods in sediment transport along the Sava River is illustrated using data from year 2010. That year was wet, with the highest annual discharge all along the Sava, and a few flood waves (in January, March, June, September and December). The 2010 sediment graph and hydrograph are presented on Figure 60.

Extreme values of sediment transport and dates are given in table 8. It can be seen that none of the observed flood waves was equally important along the whole Sava River. Extreme sediment transport was measured in September on the Upper Sava and on Middle Sava till Jasenovac at the Una River mouth. In December it was observed only on the Lower Sava, since the high flows originated from the Drina River Basin.

In conclusion, the largest sediment transport along the river is very complex and depends on flood wave propagation and sediment inflow from tributaries. Its exact pattern is hard to be determined, as shown on Figure 60.

Table 8: Dates and values of maximum daily suspended sediment transport

Station	Max SLT (kg/s)		
	June	September	December
Hrastnik		19.9 :1140	
Podsused		18.9: 2353	
Rugvica		18.9: 762	
Jasenovac		20.9: 75.4	
Slavonski Brod	25.6: 414		
Sremska Mitrovica			6.12: 1262
Beograd			5.12: 1751

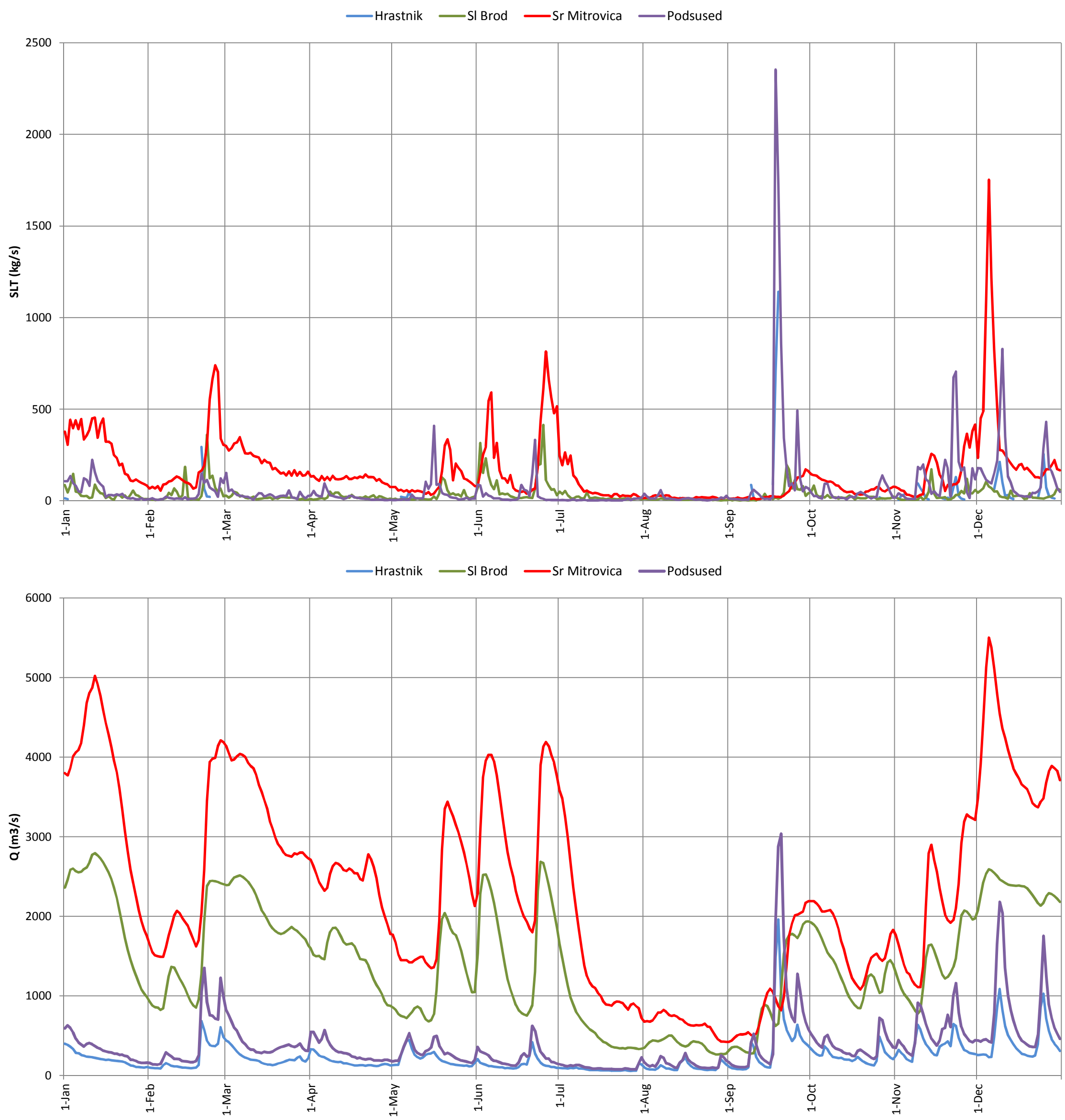


Figure 60: Suspended sediment transport and discharges along the Sava River in 2010

5.4. Other components of sediment balance along the Sava River

5.4.1. Bedload

On large rivers as Sava, bedload has a relatively small share in the total sediment transport, but it has an important role in morphological processes. For the overall balance of sediment, bedload is almost negligible. In the absence of bedload measurements, usual estimate of its contribution to the total sediment transport is about 5-10%. It is certain that transport of bedload is more important on the Upper Sava, characterized by high longitudinal gradient and gravel bed, than on Middle and Lower Sava.

Complete lack of bedload measurements represents a serious gap for the reliable analysis of sediment balance. Future activities should encompass also measurements of bedload on a few selected reaches along the Sava.

Grain size distribution of the riverbed material gives some indication on bedload. Parallel consideration of the riverbed composition and hydraulic regime can give a qualitative image of the bedload regime, while quantitative assessment must rely on mathematical modelling.

Data on the composition of the Sava riverbed are rare and related to some localities. The only systematic bottom sediment sampling along 600 km long section of the Sava was done more than 50 years ago. A downstream trend of sediment size decrease was noticed, but with a number of local variations related to the impact of tributaries and morphology along the river. However, these historical data are not sufficient, and new investigations should be organized.

Figure 61: Gravel bed at Rugvica

Figure 62: Fine sediment deposited at the river bank at Jasenovac

5.4.2. Fluvial erosion

Systematic assessment of fluvial erosion along the Sava River are not available. However, on the Sava stretch upstream of Zagreb significant deepening of the riverbed is encountered. This phenomenon indicates that the effect of fluvial erosion on the sediment balance is not negligible.

Consideration of river bank erosion along the Sava River is not available. However, the main indicator of the intensity of bank erosion is change of the river alignment. Since no significant changes were reported, a conclusion can be that there are no significant bank erosion processes, which should be encountered in the sediment balance.

5.4.3. Dredging of sediments

Intensive dredging is present along the Sava River channel, mainly in the vicinity of large tributaries. Namely, commercial interest is to obtain mainly coarser sediment - sand and gravel. These are the sediment fractions that belong to the range of bedload. Therefore, dredging may affect mainly the balance of bedload, while its impact on the overall balance of sediment is almost negligible (with respect to participation of bedload in total sediment load).

It should be noted that data on dredging along the Sava River are not gathered systematically. It would be useful to collect all available information on dredging for a realistic assessment of its importance in the sediment balance of the river.

5.4.4. Sediment deposition in reservoirs

Reservoirs have the important role in the balance of sediment within the river basin, because sediments are retained within the reservoir areas. In this case of the Sava River Basin, the large storage reservoirs are built only on tributaries, affecting both bedload and suspended load. The run-off- river hydropower plants on the Upper Sava affect mainly bedload.

There is a general lack of data on reservoir siltation processes within the Sava River Basin. Rough estimates made for the Drina River basin are based on monitoring of reservoir siltation and estimates of sediment yield in the basin. Figure 63 presents the effect of reservoirs on the inflow of sediment into the Sava River. In the past 50 years, the inflow is reduced approximately 4 times in comparison with the natural regime of the Drina River.

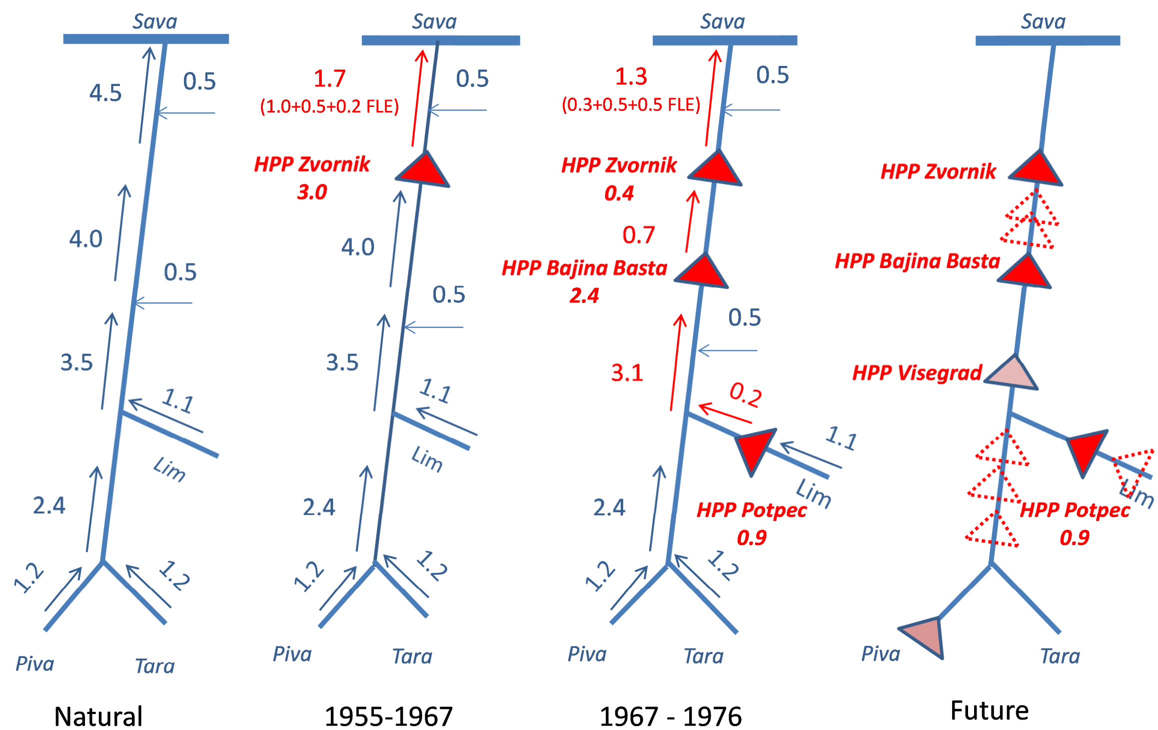


Figure 63: Changes of suspended sediment inflow from the Drina River

5.5. Concluding remarks on sediment balance

The size and highly heterogeneous natural characteristics of the Sava River Basin significantly affect the inflow of water and sediment. Although these processes occur in parallel, under the influence of the same basic factors (meteorological, geomorphological and hydrographic), their dynamics and intensity exhibit considerable differences. For example, a flood wave may be generated on the Sava River due to rainfall or snowmelt in different parts of the basin with very specific characteristics. If the flood wave originates in a part of the basin with high-intensity erosion and sediment production, sediment discharge by the wave may be higher, and vice-versa. For this reason, sediment discharge by the Sava channel, varies and does not depend only on hydrologic conditions.

Significant alluvial tributaries close to the mouth bring large sediment load and have a major influence on the hydrologic, hydraulic and sediment regimes of the recipient. Coincident water and sediment discharges of the Sava and its tributaries play a special role in the sediment transport and deposition processes.

The heterogeneity of geomorphological and morphological conditions along the course of the Sava River also effects sediment transport and deposition processes.

The controlled regime of the Iron Gate 1 reservoirs' backwater levels is the most important artificial influence on the sediment transport and deposition processes in the Lower Sava.

Excavation of material from the Sava riverbed is a relatively important component of these processes, even though the effects of dredging are generally local and depend on the location of the excavation field.

River training structures and HPP play a significant role in riverbed formation along some stretches of the Sava**.**

6. Gaps and data uncertainties

6.1. Gaps in suspended sediment measurements

Table 9 shows the monitoring period for each of the hydrological station on the Sava River Basin together with the gaps in the measurements of water levels H [cm], discharges Q [m^3/s], suspended sediment concentration SSC [g/m^3], [mg/l] and suspended load transport rate LT [t/day]. Suspended sediment monitoring for the Sava River main channel are clearly evident on chart (see Figure 64).

Table 9: Gaps in suspended sediment measurements for hydrological stations in the Sava River Basin

Country	River	Hydrological station	L [rkm]	Monitoring period of SS	H,Q gaps	SSC gaps	LT gaps	Institution	Active
SLOVENIA	SAVA	Radovljica	900.95	1953-2012		1953-2004 2007-2012	1953-2004 2007-2012	ARSO	Active
		Hrastnik	793.5	1993-2012		1993-1996 2007-2012	1993-1996 2007-2012	ARSO	
	SORA	Suha I		1953-2012	H,Q 1991	1953-2008 2011	1953-2008 2011	ARSO	
	SAVINJA	Laško I		1953-2012		1953-1989 1994-2012	1953-1989 1994-2012	ARSO	
	SAVINJA	Veliko Širje I		1967-2012	H,Q 1991-1993	1974, 1977 1990-1993	1974, 1977 1990-1993	ARSO	
	SOTLA	Rakovec I		1965-2012		1965-1977 2007-2012	1965-1977 2007-2012	ARSO	
	SAVA	Šentjakob	847.1	(1955-1994)		1974-1977 1995-2012	1974-1977 1995-2012	ARSO	Inactive
	SAVA	Radeče	783.62	(1955-1993)		1974 1994-2012	1974 1994-2012	ARSO	
CROATIA	SAVA	Podsused žičara	675.4	1979 -	no gaps	no gaps	no gaps	DHMZ	Active
	SAVA	Rugvica	636.3	1978 -	Q 1996-1999 2004-2006	only daily gaps*	1996-1999 2004-2006	DHMZ	
	SAVA	Jasenovac	500.5	1978 -	Q 1992-1996	1992-1996	1992-1996	DHMZ	
	SAVA	Slavonski Brod	360	1960 -	Q 1994-2003	only daily gaps*	1994-2003	DHMZ	
	SAVA	Stara Gradiška	453.4	(1963-1991)	H 1992-1997 Q 1992-2004	1965 1991-2013	1965 1991-2013	DHMZ	Inactive
	UNA	Kostajnica	42.1	(1967-1991)	H1992-1996, Q1992-2001	1991-2013	1991-2013	DHMZ	
	ORLJAVA	Mijači		(1975-1991)	no gaps	1991-2013	1991-2013	DHMZ	
	PAKRA	Manastir		(1984-1991)	H1992-1994, Q1992-1998	1987 1991-2013	1991-2013	DHMZ	
SERBIA	SAVA	Sremska Mitrovica	141.5	1974-	**	1984-1988 1990-1991 1993-2008	1984-1988 1990-1991 1993-2008	IJC	Active
	SAVA	Beograd	5.6	1986-	**	1990-1991 1999	1990-1991, 1999	IJC	
	SAVA	Sremska Mitrovica	139.24	1958-1980	no gaps	1981-2012	1981-2012	RHMZ Srbije	Inactive
	SAVA	Sabac	106.38	1958-2002	only H	2003-2012	2003-2012	RHMZ Srbije	
	SAVA	Beograd	2.0	1958-1998	only H	1999-2012	1999-2012	RHMZ Srbije	
	DRINA	Mihaljevici	132	1991-2002	not operational, 2004-2012	2003-2012	2003-2012	RHMZ Srbije	
	DRINA	Radalj	85.5	1984-2002	no gaps	2003-2012	2003-2012	RHMZ Srbije	
	DRINA	Badovinci	16.5	1990-2001	not operational, 2002-2012	2002-2012	2002-2012	RHMZ Srbije	
	KOLUBARA	Slovac	88	1958-1992	no gaps	1993-2012	1993-2012	RHMZ Srbije	
	KOLUBARA	Beli Brod	72	1986-2001	no gaps	2002-2012	2002-2012	RHMZ Srbije	
	KOLUBARA	Drazevac	12	1958-2002	no gaps	2003-2012	2003-2012	RHMZ Srbije	

* Daily gaps due to ice or flood events
* H-Q monitoring on nearby station of RHMZ Srbije

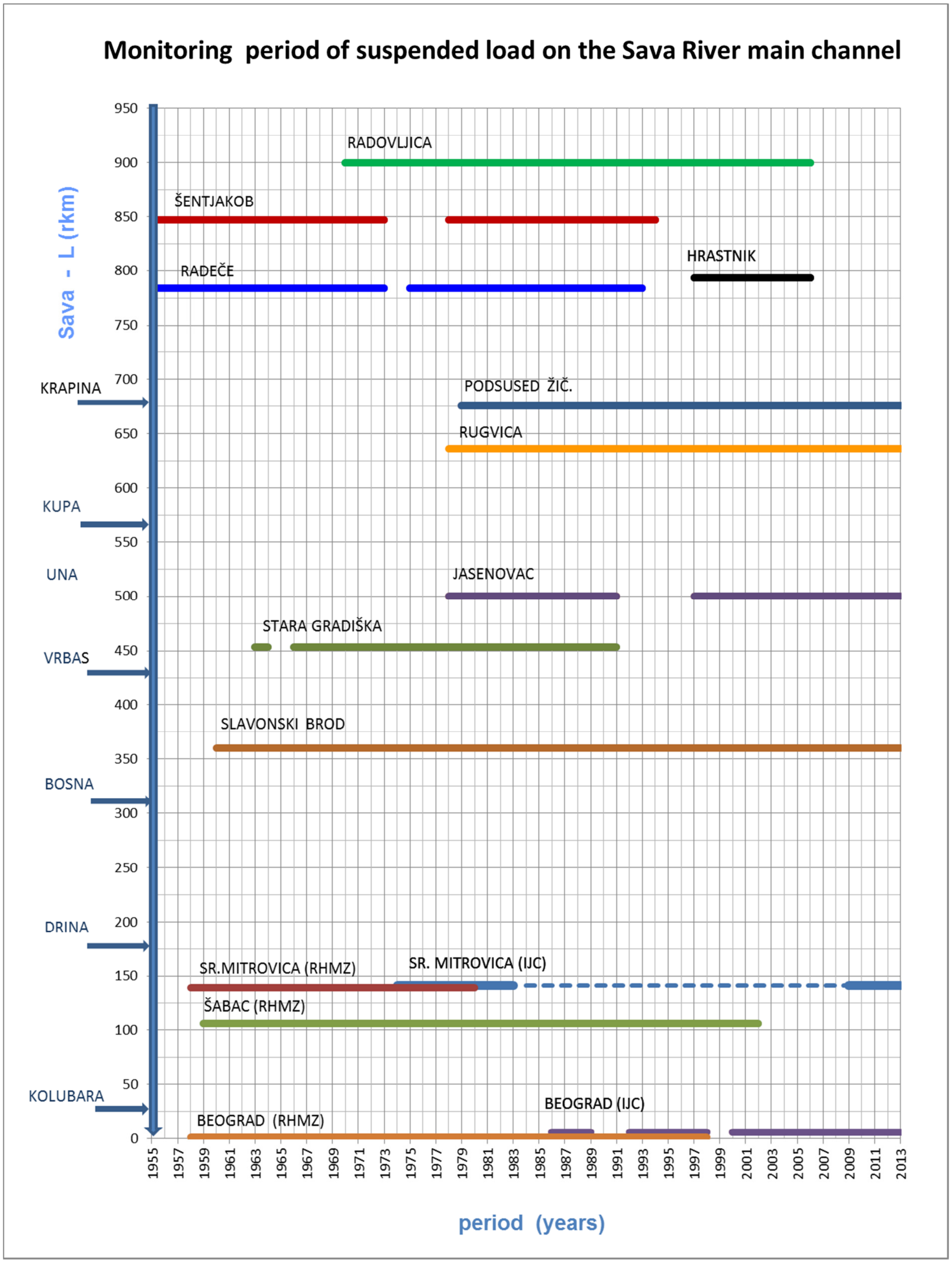


Figure 64: Suspended sediment measurements on the Sava River main channel.

6.2. Data uncertainties

6.2.1. General remarks

The assessment of erosion and sediment transport rates is a task subject to major difficulties and severe errors. It is worth emphasizing that such errors can be typically of one or two orders of magnitude. There are four main sources of errors in estimating sediment transport in streams:

a) **Quality of samples**. During the transport process, sediment particles experience their own dynamics that are not exactly the same as those of the water mass: particles continuously fall due to gravity, and are moved to the all directions by the turbulence of the flow. This means that sediment concentrations can be very different within the flow section, and that any instrument placed within the flow will modify its local dynamics. Furthermore, some dilution or concentration of the sediment can be produced through the sampling process or during the handling or fractionating of the sample.

b) **Representatives of samples**. The sediment concentrations at the same place are usually subject to strong variations in time. These variations are usually linked to the variations of water discharge but the relationship is usually nonlinear and subject to hysteresis phenomena. The temporal change in sediment concentration and the nonlinearity of its relationship with water discharge increases with the decreasing area of the basin.

c) **Interpolation and extrapolation of samples**. Because the sediment concentration is obtained for instantaneous samples, it is necessary to use some interpolation or extrapolation procedure to estimate a continuous sediment concentration that multiplied by the water discharge will give the sediment discharge.

d) **Temporal integration of solid discharges**. The temporal irregularity of sediment concentration and the nonlinearity of the relationship between sediment concentration and water discharge can be a major cause of error during temporal integration of solid discharges.

6.2.2. Uncertainties for the Sava River Basin

Specific data uncertainties for the Sava River Basin are derived from several reasons:

- Suspended sediment and bedload measurements
    - different sampling techniques
    - different frequency of measurements
    - different duration of time series in the long-term measurements
    - complete lack of measurements
    - changing of the gauging station location during time (upstream/downstream of tributary)
    - changing of the measurement technique during time
- Monitoring of sediment quality
    - monitoring of different parameters by countries
    - different frequency of monitoring
    - complete lack of monitoring
- The period of measurements and monitoring with regard to the construction of large structures and other impacts on watershed and in the river channel

6.2.3. Examples of typical data uncertainties

Changing of the gauging station location during time may be experienced as similar to the hydrological station Jasenovac in Croatia. Since March 1997 sediment sampling is located upstream of the confluence of the Sava and Una Rivers. Before 1997 the sampling was located downstream of the confluence. Between June 1991 and March 1997 suspended sediment samples were not taken.

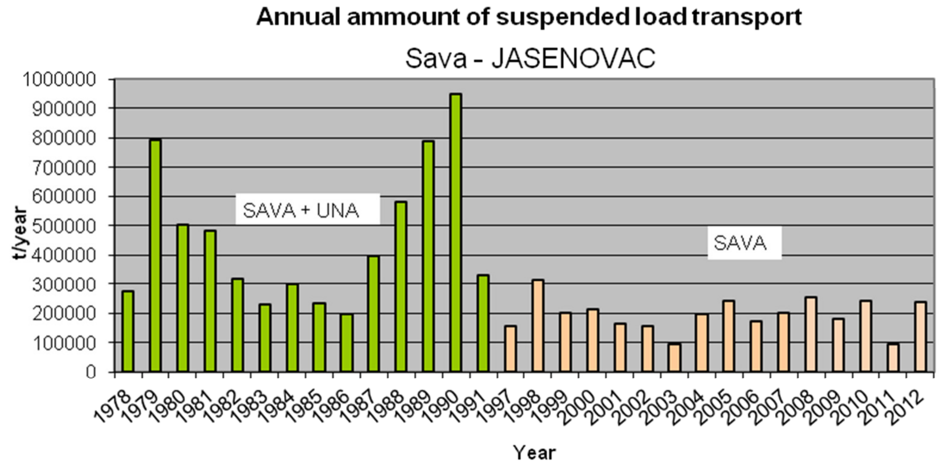


Figure 65: Uncertainty due to changes of the sampling location, g.s. Jasenovac in Croatia

Uncertainty due to the changes of the sediment sampling technique and definition of the correlation between sediment load and discharge is possible for the 50-years sampling in the g.s. Slavonski Brod in Croatia.

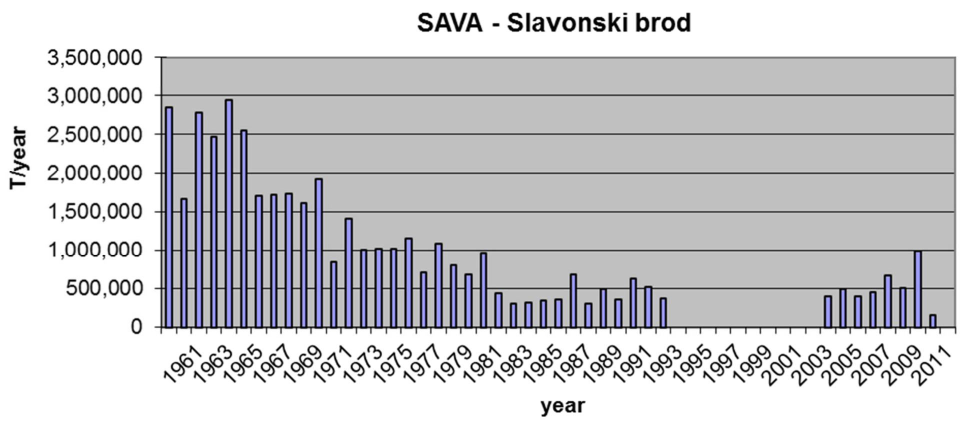


Figure 66: Example of g.s. Slavonski brod in Croatia

Construction of large river structures influences the suspended sediment load and bedload, and thus alters sediment balance on the downstream river sections. For the evaluation of the basin wide sediment balance an essential knowledge is the construction period of large river impoundments and other construction activities on the watershed that influence the sediment production and transport.

Table 10: Timing of construction of dams on the River Sava main channel and tributaries

Year	Country	Subbasin	River	Name
1955	RS	Drina	Drina	Zvornik
1959	RS	Drina	Uvac	Radoinja
1962	RS	Drina	Uvac	Kokin Brod
1964	BA	Bosna	Spreča	Modrac
1966	RS	Drina	Drina	Bajina Basta
1967	RS	Drina	Lim	Potpec
1973	ME	Drina	Piva	Mratinje
1976	RS	Kolubara	Velika Bukulja	Garasi
1979	RS	Drina	Uvac	Uvac
1980	SI, HR	Sotla/Sutla	Sutla	Vonarje (Sutlansko jez.)

Year	Country	Subbasin	River	Name
1981	BA	Vrbas	Vrbas	Bocac
1981	ME	Drina	Cehotina	Otilovici
1983	RS	Drina	Beli Rzav	Lazici
1983	RS	Kolubara	Kladnica	Paljuvi Vis
1984	BA	Drina	Rastosnica	Snjeznica
1989	BA	Drina	Drina	Visegrad
1996	HR	Ilova	Pakra	Pakra
-	RS	Kolubara	Jablanica	Rovni

7. Proposal of further joint activities

In order to improve the basin-wide assessment of the Sava River sediment balance and to improve the present situation with regard to this issue that exhibits too many gaps and uncertainties, the joint activities of the states along the Sava River Basin are proposed, such as joint sediment monitoring programme and joint sediment database.

7.1. Joint Sava River Basin Sediment Monitoring Programme

The overview given in this expertise on the existing sediment monitoring programme in the Sava River Basin (let it be in the Sava River main channel or in its major tributaries) shows an unsatisfactory situation. In the past, more hydrologic stations were active where also sediment-balance related parameters (suspended solids concentrations, turbidity) were monitored. Nowadays, many such stations are non-operative or monitor only water-related parameters (stage, discharge).

In order to improve the current situation we propose the following activities:

- The currently monitored sediment-balance related parameters in all hydrologic stations along the Sava River main channel and in its major tributaries should be connected to a joint Sediment Database, available on-line for free (see the sub-section 7.2).
- A further step should be the effort towards the harmonisation of monitored sediment data by applying the same technical international standards (ISO standards; see [10] for details) for different monitoring tasks (water levels, discharges, surface temperature, SSC, turbidity), such as field sampling, laboratory tests in order to harmonise sampling frequency, sampled parameters and the way how these parameters are determined. These steps are to be done by the state hydrometeorological offices in the Sava River Basin, also in the field of data processing.
- The monitoring network should be made denser with additional new hydrologic stations to be taken into operation in the years to come. As an example of a possible improvement is the project BOBER in Slovenia with possible introduction of new techniques to monitor suspended sediment related parameters (horizontal ADCPs, continuous on-line turbidity measurements). It is important to install such a new technology in an existing hydrologic station and to run the classic technique (e.g. bottle sampling, pump sampling) parallel with the new technique for at least several years to be able to establish a possible conversion between the results of the both techniques.
- The sediment monitoring should integrate regular cross-section measurements in selected cross sections along the Sava River main channel. In Slovenia, it is possible to replace such measurements with the regular surveying of the river accumulations of the existing Hydro power plants on the Sava River (HPP Moste, HPP Mavčiče, HPP Vrhovo, HPP Boštanj, HPP Arto-Blanca, HPP Krško), and HPP Brežice in HPP Mokrice when constructed). This will help to assess the evolution of the longitudinal profile of the Sava River main channel and to assess real bedload rates.
- The data on gravel mining from the Sava River main channel are an important part of the sediment balance assessment, but they are hardly to be made available; due to different reasons. Without such data it is not easy to assess real bedload rates and coarse sediment transport. A step further would be to perform a numerical modelling of sediment transport in the Sava River main channel that would be hardly to perform without reliable sediment data to validate the model.

7.2. Joint Sediment Database preparation

In order to improve basin-wide sediment management and land-use decision making the composition of a joint Sediment Database is proposed. The Sediment Database would also give opportunity to provide valuable data for research, studies and engineering projects. It is proposed to establish a Sediment Database that would be linked to the existing system of the Sava Commission through the Sava GIS. The Sediment Database would present some static data as well as dynamic data on sediment monitoring.

It is suggested that the database would comprise:

- Maps of hydrographic network, sediment monitoring stations, reservoirs, soil erosion areas
- Descriptive information for each monitoring station: station number, station name, drainage basin area, latitude, longitude, monitoring parameters, methods and equipment being used, start date of record, end date of record, number of days of missing record.
- Daily records for each monitoring station: discharge, water level, water temperature, suspended sediment concentration, suspended sediment load.

On the basis of the information in the database the annual sediment monitoring reports can be published in a form of:

- Annual hydrological yearbook which would include daily measurements (discharge, water level, water temperature, suspended sediment concentration, suspended sediment load).
- Annual reports on periodic measurements and monitoring (bedload, sediment grain size distribution at reference gauging stations, reservoirs sedimentation, sediment yield, sediment quality analysis, statistical analyses)

In Slovenia a hydrologic monitoring database is available online (http://vode.arso.gov.si/hidarhiv/pov_arhiv_tab.php; Figure 67), providing date, water level (cm), discharge (m^3/s), water temperature (°C), sediment transport (kg/s) and sediment concentration (g/m^3) or even turbidity (NTU) in some cases data for all gauging stations currently in operation, as well as for un-active ones. The values can be extracted as daily values or extreme values from the archive for the selected hydrologic station and selected year(s) of operation as an Excel file (*.xls) or as a CSV (Comma Separated Values, *.txt file) for further analysis.

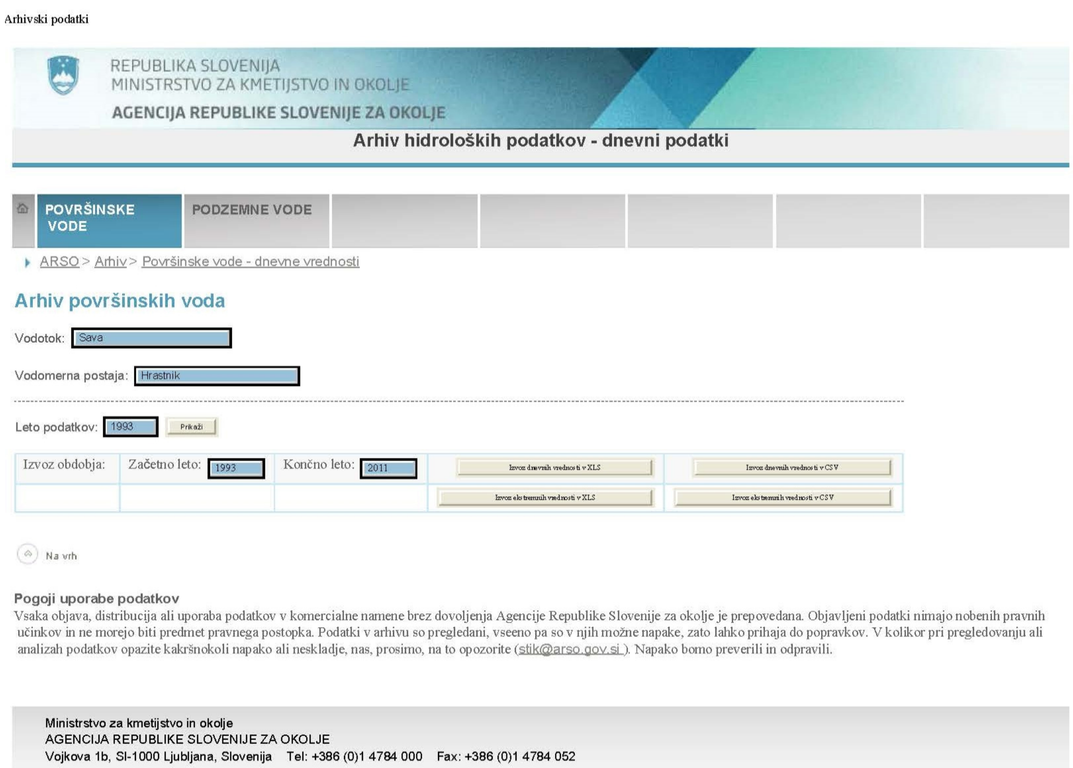


Figure 67: A monitor snapshot of the Slovenian ARSO hydrologic monitoring database

Meteorological and Hydrological Service in Croatia created the hydrologic monitoring database "HIS2000", which is on line available for some client ("Croatian Waters, HEP Company) but not for the public purpose.

There are up to date water level (cm), discharge (m^3/s), water temperature (°C), cross sections, sediment transport (kg/s) and sediment concentration (kg/m^3) data for all active and historical gauging stations (Figure 68).

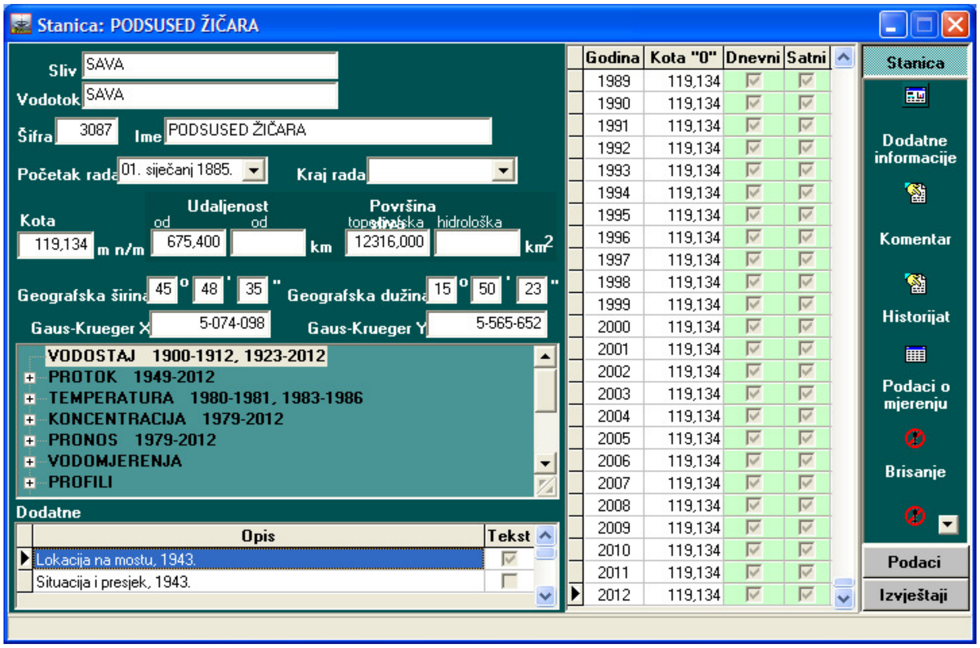


Figure 68: Example of hydrologic monitoring database "HIS2000" in Croatia

8. Conclusions

The Sava River Basin is a major sub-basin of the Danube River, located in South Eastern Europe. The basin is shared by five countries, Slovenia, Croatia, Bosnia and Herzegovina, Montenegro and Serbia and four of them, except Montenegro, are Parties of the Framework Agreement on the Sava River Basin (FASRB). By ratification of FASRB the Parties have committed themselves to act in compliance with the EU directives related to water management. The EU directives do, as well as the Sava River Basin Management Plan, address the sediment management as one of the key issues concerning both, the ecological, as well as hydromorphological targets.

Following the provisions of the FASRB, the International Commission on the Sava River Basin (ISRBC) has developed the Protocol on Sediment Management to the FASRB which affirms the need for efficient cooperation among the Parties and for promotion of sustainable sediment management (SSM) solutions. To respond to the above mentioned needs, a project *Towards Practical Guidance for Sustainable Sediment Management using the Sava River Basin as a Showcase* has been launched upon the initiative of UNESCO Venice Office, together with the UNESCO International Sediment Initiative (ISI), European Sediment Network (SedNet) and the ISRBC. The main objective of this project is to develop and validate a practical guidance on how to achieve a SSM Plan on the river-basin scale. In October 2012 the practical training course was held where the top experts from Europe and the United States taught the theoretic fundamentals on sediment balance throughout the river system, sediment monitoring and evaluation of sediment quality and quantity. Based on the training course, a draft Guidance on Sustainable Sediment Management - Part I, has been developed and the project ***Estimation of Sediment Balance for the Sava River- BALSES*** launched. In this context, the purpose of the BALSES project is the application of the Guidance Part I in the Sava practice. The project has been implemented by the core expert group which has analysed the sediment balance for the Sava River considering the input from the main tributaries, and thus to form a basis for sustainable transboundary sediment and water management.

Table 11: Main conclusions of the BALSES project with the proposal of future activities

Issue	Conclusions
Sediment monitoring and assessment	• Insufficient and decreasing number of sediment monitoring sites, • Limited availability of suspended load data, • Low sediment monitoring on the tributaries, • Very limited data on bedload, • No unique sampling and measurement of suspended load and bedload methodologies between countries, • Lack of measurement equipment and the need for update, especially for continuous monitoring and during high flood events, • Sediment quality measurements according the Water Framework Directive (2000/60/EC).
Estimation of Sava River Sediment balance	• The size and highly heterogeneous natural characteristics of the Sava River Basin significantly affect the inflow of water and sediment. • Significant alluvial tributaries close to the mouth bring large sediment load and have a major influence on the hydrologic, hydraulic and sediment regimes of the recipient. • The heterogeneity of geomorphological and morphological conditions along the course of the Sava River also effects sediment

Issue	Conclusions
	transport and deposition processes. • The controlled regime of the Iron Gate 1 reservoirs' backwater levels is the most important artificial influence on the sediment transport and deposition processes in the Lower Sava. • Excavation of material from the Sava riverbed is a relatively important component of these processes, even though the effects of dredging are generally local and depend on the location of the excavation field. • River training structures and HPP play a significant role in riverbed formation along some stretches of the Sava.
Proposal for further joint activities	• The currently monitored sediment-balance related parameters in all hydrologic stations along the Sava River main channel and in its major tributaries should be connected to a joint Sediment Database, available on-line for free. • The effort towards the harmonisation of monitored sediment data by applying the same technical international standards should be made. • The monitoring network should be made denser with additional new hydrologic stations to be taken into operation in the years to come. • The sediment monitoring should integrate regular cross-section measurements in selected cross sections along the Sava River main channel and the main tributaries. • A numerical modelling of sediment transport in the Sava River main channel based on reliable sediment data to validate the model should be performed.

Annex 1. Methods for the sediment measurement

1.1. Methods for suspended sediment measurement

1.1.1. Grab samples

The simplest way of taking a sample of suspended sediment is to dip a bucket or other container into the stream preferably at a point where it will be well mixed. The sediment contained in a measured volume of water is filtered, dried and weighed. This gives a measure of the concentration of sediment and when combined with the rate of flow gives the rate of sediment discharge. A study of alternative sampling techniques showed that dip sampling in bottles generally gives concentrations about 25% lower than results obtained from more sophisticated techniques. For single samples taken by scooping a sample, a depth of 0.3 m below the surface is recommended as better than sampling at the surface. If the single sample can be taken at any chosen depth, 0.35-0.4 the depth of flow is recommended as giving the best estimate of average sediment concentration.

1.1.2. Depth integrated samplers

Using the depth integrating samplers, water and sediment mixture can be sampled continuously while the sampler is moving at a constant transit rate along the vertical. If the ratio of intake velocity to ambient velocity is equal to 1, the volume of samples at each point will be proportional to the local velocity. The sediment concentration of the sample taken by the depth integration method is the discharge - weighted average concentration in the vertical. A typical sampler consists of a glass bottle inserted in a fish - shaped frame mounted on a rod when gauging small streams or suspended on a cable for larger streams. For the bottle to fill smoothly and evenly when below the surface it is necessary to have one nozzle or orifice for entry of water, and a second pipe through which the displaced air is ejected. The entry nozzle is usually designed with a slightly expanding cross - section behind the point of entry in order to reduce the risk of back pressure which could interfere with the flow into the bottle. In operation, the sampler is moved from the surface down to the bed and back up to the surface while sampling continuously. It is undesirable for any type of bottle sampler to continue to accept more inflow after the bottle is full as this can lead to an accumulation of sediment in the bottle. In some depth - integrating samplers the bottle is lifted out of the flow when or just before it is filled; other types of sampler may have some device to stop further sampling once the bottle is full.

1.1.3. Point - integrating samplers

The point - integrating sampler remains at a fixed point in the stream and samples continuously during the time it takes for the bottle to fill. Opening and closing the valves of the sampler are controlled from the surface electrically or by cables. Samples should be taken at a number of depths at each of several vertical sections.

1.1.4. Pumping samplers

One of the characteristics of this type of sampler is its ability to collect samples at regular time intervals or in response to a rise or fall in stream flow at a definite point in the river. The entire variation in sediment concentration during a flash flood may be followed. Sufficient samples can be obtained automatically to define the variations in sediment concentration during a flood. However, all automatic pumping systems are vulnerable to pipe blockages and may also require efficient flushing systems. Portable pumping samplers may be used for taking point - integrated or depth - integrated samples at any point or vertical in a cross - section. Regulating the intake water velocity in order to be equal of that of the stream, the operator can obtain a sample that is representative of the sediment concentration at the point of measurement.

1.1.5. Photoelectric turbidity meter

The development of the photoelectric turbidity meter is based on the principle of attenuation of light transmitted through sediment - laden water. From light scattering theory, the photodensity (the ratio of intensity of the transmitted light and incoming light, I/Io) depends not only on the concentration but also on the particle size existing in the medium. It would be possible to establish a relationship between the sediment concentration and a photo density reading only if the grain size were relatively constant. In operation, the instrument must be calibrated carefully to establish such a relationship. Determination of sediment concentration on the basis of the photoelectric effect can only be adopted in rivers where variation in grain size is very small and the concentration is fairly low.

1.1.6. Acoustic Doppler Current Profiler (ADCP)

Acoustic current profilers were originally designed to measure 3 - D flow structure but they also record the intensity of the return echo. The latter is proportional to the number of backscatters present in the water column and can be used as a proxy for suspended sediment concentration. However, the software for such computation is limited, and considerable post - processing is needed to correct and normalize ADCP data for this use.

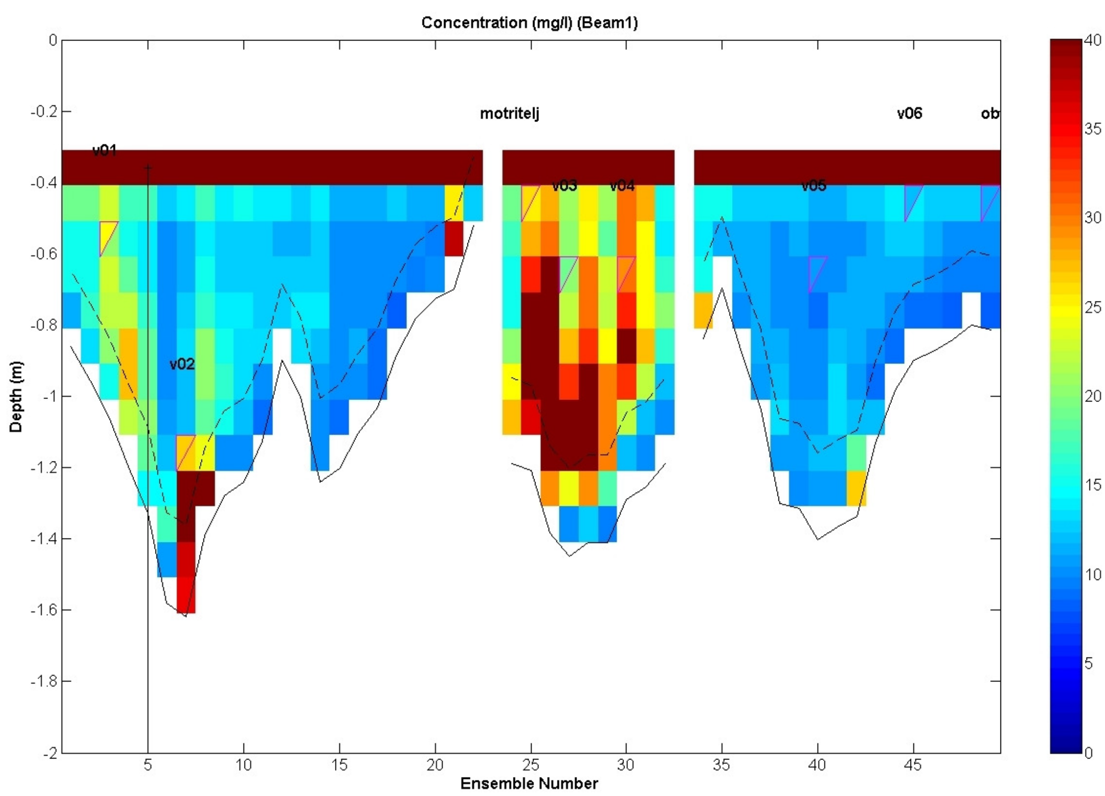


Figure 69: SSC spatial distribution (mg/l) on the hydrometric profile SAVA – PODSUSED (6/4/2012)

Other methods not commonly used for suspended sediment concentration measurements are optical backscatter, optical transmission, focused beam reflectance, laser diffraction, nuclear, spectral reflectance, digital optical, vibrating tube, differential pressure and impact sampler.

Table 12: Comparison of suspended sediment measuring methods.

Technology	Operation principles	Advantages	Disadvantages
Acoustic	Sound backscattered from sediment is used to determine size distribution and concentration.	Good spatial and temporal resolution, measures over wide vertical range, nonintrusive.	Backscattered acoustic signal is difficult to translate, signal attenuation at high particle concentration.
Bottle sampling	Water - sediment sample is taken isokinetically by submerging container in stream and is later analyzed.	Accepted, time - tested technique, allows determination of concentration and size distribution, most other techniques are calibrated against bottle samplers.	Poor temporal resolution, flow intrusive, requires laboratory analysis to extract data, requires on - site personnel.
Pump sampling	Water - sediment sample is pumped from stream and later analyzed.	Accepted, time - tested technique, allows determination of concentration and size distribution.	Poor temporal resolution, flow intrusive, requires laboratory analysis, does not usually sample isokinetically.
Focused beam reflectance	Time of reflection of laser incident on sediment particles is measured.	No particle size dependency, wide particle size and concentration measuring range.	Expensive, flow intrusive, point measurement only.
Laser diffraction	Refraction angle of laser incident on sediment particles is measured.	No particle - size dependency.	Unreliable, expensive, flow intrusive, point measurement only, limited particle - size range.
Nuclear	Backscatter or transmission of gamma or X - rays through water - sediment samples is measured.	Low power consumption, wide particle size and concentration measuring range.	Low sensitivity, radioactive source decay, regulations, flow intrusive, point measurement only.
Optical	Backscatter or transmission of visible or infrared light through water - sediment sample is measured.	Simple, good temporal resolution, allows remote deployment and data logging, relative inexpensive.	Exhibits strong particle - size dependency, flow intrusive, point measurement only, instrument fouling.
Remote spectral reflectance	Light reflected and scattered from body of water is remotely measured.	Able to measure over broad areas.	Poor resolution, poor applicability in fluvial environment, particle - size dependency.

1.2. Methods for bedload measurement

1.2.1. Basket - type sampler

A basket - type sampler is generally adopted for sampling coarse bedload material such as gravel and pebbles. Metal or nylon mesh is put on the side and top of a metal frame. The mesh should pass the suspended material, but retain the sediment moving along the bed. Loosely woven iron rings or other elastic materials may be put at the bottom to deal with variations in bed surface.

The average sampling efficiency of a basket - type sampler calibrated in the laboratory is reportedly about 45 per cent, although this may vary from 20 to 70 per cent.

The problems with bedload samplers are:

- The sampler disturbs the flow and changes the hydraulic conditions at the entry into the sampler.
- The sampler has to be resting on the streambed and tends to dig in as scour occurs round it.
- To remain stable on the bed it has to be heavy, and this restricts the use to lowering from bridges or purpose - built gantries.
- A sampler needs to rest on a reasonably smooth bed and not perch on large stones or boulders.

1.2.2. Pressure - difference - type sampler

Pressure - difference - type samplers are designed to produce a pressure drop at the exit of the sampler, sufficient to overcome energy losses, to ensure an entrance velocity equal to that of the undisturbed stream. A perforated diaphragm with a sampler body forces the flow to drop its sediment into the retaining chamber and to leave through the upper exit.

1.2.3. Pan or tray - type sampler

There are various types of this sampler, here are some:

- Flat pan divided into compartments by transverse vertical strips of sheet metal which were intended to trap the moving material.
- Flat wedge - shaped pan container pointing upstream, thus forming an upward slope on the top of the container. The bedload material moves up the slope and falls into the container through a slot entrance in the top.

This type of sampling method is used primarily to obtain the total amount of bedload in a flood period, since it is not easy to remove or replace the traps during floods. The top of the inner container may be adjusted to make it even with the riverbed. The height of deposition in the trap can be recorded and the sampled material can be extracted from the trap using a submerged slurry pump.

1.2.4. Slot or pit - type sampler

Concrete troughs or trenches are constructed across the. The slot is divided into sections fitted with gates. Sediment falling into the open slot is carried laterally to a sump in the riverbank. After continuous sieving and weighing, the sediment is returned to the river downstream of the trap by a conveyor belt. The measurement of bedload using this type of installation is reliable and accurate. However, it is adaptable mainly for relatively small rivers and particularly for experimental studies or the calibration of samplers.

1.2.5. Dune tracking method

The dune tracking method of bedload involves measuring the rate of bed material movement in dune shaped forms in the direction of flow. It is generally difficult to measure the bedload in an alluvial river that consists mainly of fine sands by means of existing measuring methods.

The dune tracking method has the advantage that only hydrographic surveying techniques are employed. With this method, a sounding system should be established which permits the recording of bottom profiles along pre - fixed courses in a river reach. Bedload rate can be estimated from the propagation of dunes, calculated by successive surveys. The accuracy of the dune tracking methods relies on the accurate determination of the bed elevation and positioning of the measuring points.

1.2.6. Tracer method

The tracer method is based on the detection of the sediment movement by tracers. This method is feasible for measuring bed material discharge and sediment dispersion. The procedures and techniques involved are the selection and labelling of the sediment tracer particles, the method of introducing the tracer into the flow system, and the method of detection. Field data collection includes tracing labelled particles, sampling the bed material and measuring hydraulic elements in the river reach under investigation. Four labelling methods are available for use with the tracer method. The fluorescent tracer, radioactive tracer and stable isotope tracer can all be used in rivers where the bed material is composed of relatively coarse particles such as gravel and sand. However, only the radioactive tracer seems to be suitable for use in places where the bed material is composed mainly of fine sand, silt and clay. In all cases, the labelled particles should have the same hydraulic behaviour after labelling as before and should resist leaching, abrasion and decay of their traceability.

Annex 2. Methods for the soil erosion surveys

2.1. Aerial photography and satellite images

Photographs (air/land) and satellite images of landslides, mechanical movement areas, active stream bank erosion areas and other interesting areas.

2.2. Erosion pins

The method consists of driving a pin into the soil so that the top of the pin gives a datum from which changes in the soil surface level can be measured. Alternatively called pegs, spikes, stakes or rods, the pins can be of wood, iron or any material which will not rot or decay and is readily and cheaply available. The pin should be a length which can be pushed or driven into the soil to give a firm stable datum: 300 mm is typical, less for a shallow soil, more for a loose soil. A small diameter of about 5 mm is preferable, as thicker stakes could interfere with the surface flow and cause scour. A rectangular or square grid layout will give a random distribution of points with spacing appropriate to the area being studied. Individual measurements of change in level at a single point will vary widely, but if it is an inexpensive and simple method, and a large number of points can be sampled resulting in a usable result.

2.3. Catchpits

Surveys of sediment in reservoirs can be used to make quantitative estimates of erosion. It is not possible to get a reliable estimate of the total soil movement unless the receiving reservoir is large enough to contain the whole flow and sediment load, but smaller pits which only catch an unknown proportion of the sediment can still be used to obtain comparative information.

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