ANALYSIS OF CONCENTRATION AND SEDIMENTATION OF SUSPENDED LOAD IN THE RESERVOIRS

BOJANA DOLINAR, HELENA VRECL-KOJC and LUDVIK TRAUNER

about the authors

Bojana Dolinar
University of Maribor,
Faculty of Civil Engineering
Smetanova 17, 2000 Maribor, Slovenia
E-mail: bojana.dolinar@uni-mb.si

Helena Vrecl-Kojc
University of Maribor,
Faculty of Civil Engineering
Smetanova 17, 2000 Maribor, Slovenia
E-mail: helena.vrecl@uni-mb.si

corresponding author

Ludvik Trauner
University of Maribor,
Faculty of Civil Engineering
Smetanova 17, 2000 Maribor, Slovenia
E-mail: trauner@uni-mb.si

Abstract

This paper deals with the sedimentation of suspended load in the reservoirs. As an example the reservoir of the hydroelectric power plant Boštanj on the Sava River is shown. The objective of the described studies was to determine the quantity and type of deposited material in the reservoir during the selected time period. For this purpose, the mineral and chemical composition, and the concentration and the particle size of the suspended load at the intake of the water into the reservoir and at its outflow were examined.
In order to determine the concentration of the suspended load, 24 water samples from the area of the intake and outflow from the reservoir were taken. At the same time the discharge of the Sava River was measured. Solid particles were removed from the water with the help of sedimentation and in the final stage of water evaporation. The results of the studies showed that the concentration of the suspended material was changing in relation to the location and the flow rate of the water. This ratio can be described with an exponential function.
In suspended load composition carbonates, muscovite/illite and quartz dominate; however, chlorite was also found, as well as small quantities of plagioclase and organic detritus. With regard to the size of the particles the examined samples are classified as silt.
It was determined that the concentration of the suspended load, at the same flow rate of water, at the intake into the reservoir is larger than at the outflow. The difference is represented by the material that was sedimented in the reservoir due to the decreased speed of the water as a result of the river's impoundment. A comparison of the composition of the samples from both collection sites showed that at the outflow site of the water from the reservoir there is a somewhat smaller share of carbonate grains and heavy minerals than at the intake site, and a higher content of organic detritus and clay particles can also be observed.
Considering the actual discharge of water in the period between July 2006 and July 2007 and the examined ratio between the flow rate of the water and the quantity of suspended and deposited material, the total quantity of sedimented material in this period was estimated.

Keywords

suspended load, sedimentation, sediment transport, water storage reservoir

1 INTRODUCTION

Because of the washing away of weathering material, the erosion of banks or, as a result of artificial interventions, various inorganic and organic materials can be found in watercourses. Due to the water turbulence, the load is transported in a suspended form or by rolling along the river bottom. In a water environment the load is floating under the condition that its sedimentation speed is lower than the vertical speed component of the turbulence regime; otherwise, it quickly starts to sink. The speed of the sinking load also depends on other characteristics, such as the water temperature and the concentration of suspended matter, which consequently affect the density and the viscosity of the fluid.

The paper discusses survey of the suspended load in the water-storage reservoir of the hydroelectric power plant

Boštanj on the Sava River. The concentration and the particle size of the suspended load and its mineral and chemical composition were examined. On the basis of these data, the total quantity and the type of sedimented material in the reservoir in the selected time period were assessed.

2 SAMPLING AND TESTING METHODS

The water samples, from which the suspended material was removed, were taken at the intake of the water into the reservoir of the HPP Boštanj and at its outflow (Fig.1). For reasons of data comparability, the water was always taken at the same site and depth (1 m). A total of 24 samples were collected, and each contained at least 40 l of water. At the site of the sample collection the discharge of the Sava River and its temperature were examined during the sampling (Table 1).

The concentration of suspended load in the water was examined at the Soil Mechanics Laboratory at the Faculty of Civil Engineering in Maribor. The solid was removed from the water with the help of the sedimentation of particles and water evaporation (Table 1).

The particle size analyses of the solids were determined by the Geological Survey of Slovenia using a laser particle sizer "analysette 22"/ Nano Tec made by FRITSCH GmbH - Manufacturers of Laboratory Instruments, Germany. Analytical instruments based on laser diffraction for the determination of a particle size distribution use the physical principle of the scattering of electromagnetic waves. The design consists of a laser beam directed through a measuring cell to a detector. A dispersion module transports the particles to the measuring cell and through the laser beam. The light scattered in proportion to the particle size is projected by a lens onto a detector. The particle size distribution can be calculated from the distribution of scattered light with the help of complex mathematics. A total of 16 samples were examined.

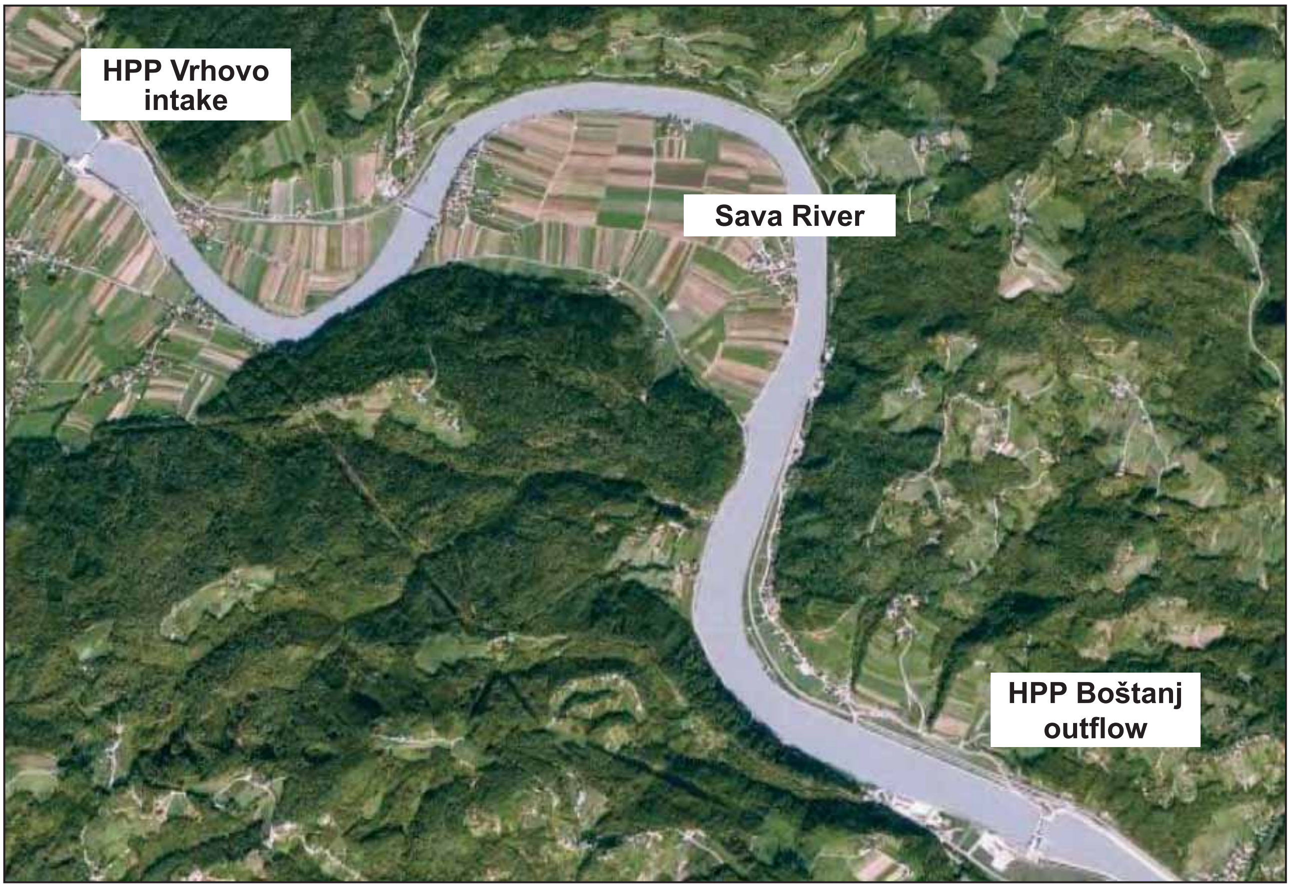

Figure 1. Reservoir of the HPP Boštanj.

Table 1. Time of sampling, temperature of water (T), discharge (Q), concentration of suspended load (c).

Sample	Date	hour / min.	T (°C)	Q (m^3/s)	c (g/m^3)
1 Intake	01.09. 2006	12 / 20	13,3	175	6,8
1 Outflow		13 / 00	16,6	152	1,1
2 Intake	20.09. 2006	8 / 40	13,0	252	12,7
2 Outflow		8 / 40	13,0	252	8,6
3 Intake	26.10. 2006	8 / 40	12,0	248	19,6
3 Outflow		8 / 20	12,5	264	10,0
4 Intake	15.11. 2006	11 / 50	9,5	65	1,7
4 Outflow		12 / 30	9,5	61	0,8
5 Intake	23. 11. 2006	12 / 00	10,0	210	18,3
5 Outflow		12 / 30	10,0	180	18,3
6 Intake	24.11. 2006	12 / 30	10,0	134	5,8
6 Outflow		12 / 50	10,0	130	8,3
7 Intake	11.12. 2006	11 / 20	9,5	407	47,5
7 Outflow		11 / 45	9,5	383	25,0
8 Intake	24.01. 2007	11 / 05	7,0	478	75,4
8 Outflow		10 / 40	9,0	525	40,8
9 Intake	09.03. 2007	11 / 55	10,0	340	15,8
9 Outflow		12 / 20	10,0	316	11,3
10 Intake	24.04. 2007	10 / 05	15,0	100	6,6
10 Outflow		10 / 30	15,0	114	0,8
11 Intake	21.05. 2007	7 / 50	17,0	74	1,7
11 Outflow		8 / 15	17,0	63	5,8
12 Intake	05.06. 2007	9 / 40	19,5	79	5,2
12 Outflow		9 / 08	19,5	62	3,7

The bulk mineralogy of the composed samples from each site was determined by the Geological Survey of Slovenia using X-ray diffraction techniques. Samples were scanned using a Philips PW 3710 X-ray diffractometer with an 1820 goniometer, an automatic divergence slit, and a curved-crystal graphite monochromator. The instrument was operated at 40 kV and 30 mA using Cu-Kα radiation.

The microscopic analysis of the solids was determined by the Geological Survey of Slovenia. Because of a relatively high content of clay fraction and other submicroscopic particles, this fraction was removed by leaching before the examination of the samples.

The results of the chemical analyses of the composed samples from both sites were used to check and confirm the quantities of the individual minerals in the solid. The chemical composition was determined by Acma Analytical Laboratories Ltd., Vancouver, Canada. The inductively-coupled plasma emission spectrometry method was used to determine the main elements quantitatively and qualitatively, whilst inductively-coupled plasma mass spectrometry was used to determine the trace elements. Carbon and sulphur were determined using a Leco CS444 element analyser.

3 RESULTS

3.1 PARTICLE SIZE ANALYSIS OF THE SUSPENDED LOAD

Grain size analyses were performed on 16 samples from the intake and outflow area of the water from the reservoir. The samples from both sites were collected simultaneously, and therefore the discharge of the water was similar. In this way it is possible to compare the particle sizes in suspension with regard to the collection site. The results of the analyses show that the suspended load mostly has the size of silt, and only 5-20 % of the grains belong to the clay fraction. Larger grains were found at the water-intake site, when an increased share of the clay fraction was observed at the outflow. The results of the grain size analyses for individual samples are presented in Figures 2 and 3 with the discharges at the times of the sample collection marked in the legend. The difference in the size of the suspended load between the first and the final part of the reservoir is presented even more clearly in Figure 4, where the grain size distribution is provided for the composed samples from individual sites. The ratio between the concentration of the suspended material (g/m^3) and the grain size at the water intake and outflow sites from the reservoir is presented in Figure 5. It is evident that the quantity of larger grains (10-100 μm) of solids in the water is smaller at the outflow from the reservoir than at the intake.

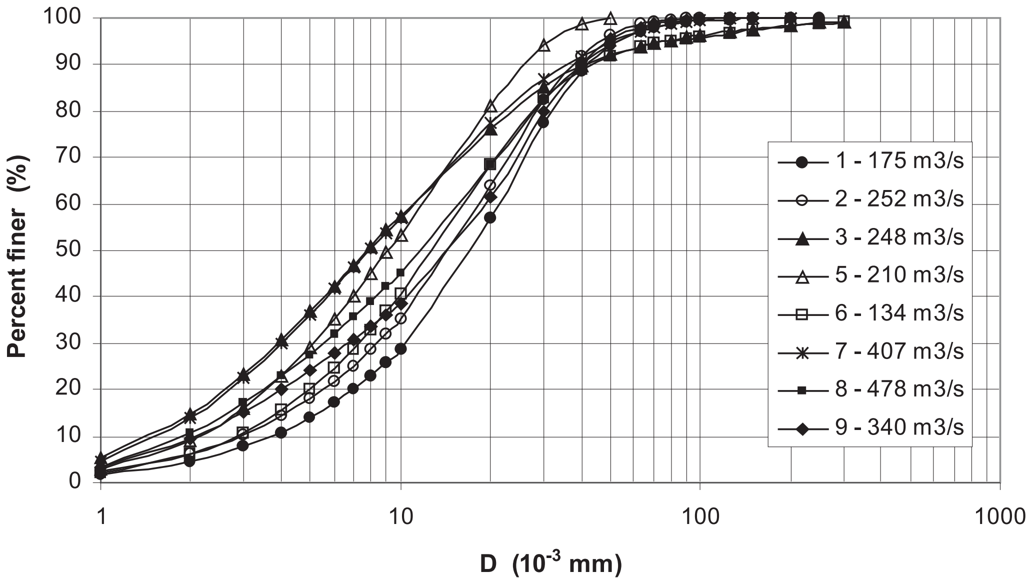

Figure 2. Grain size distribution of suspended load at the water intake into the reservoir of the HPP Boštanj. The legend contains discharges for the time periods of sample collection.

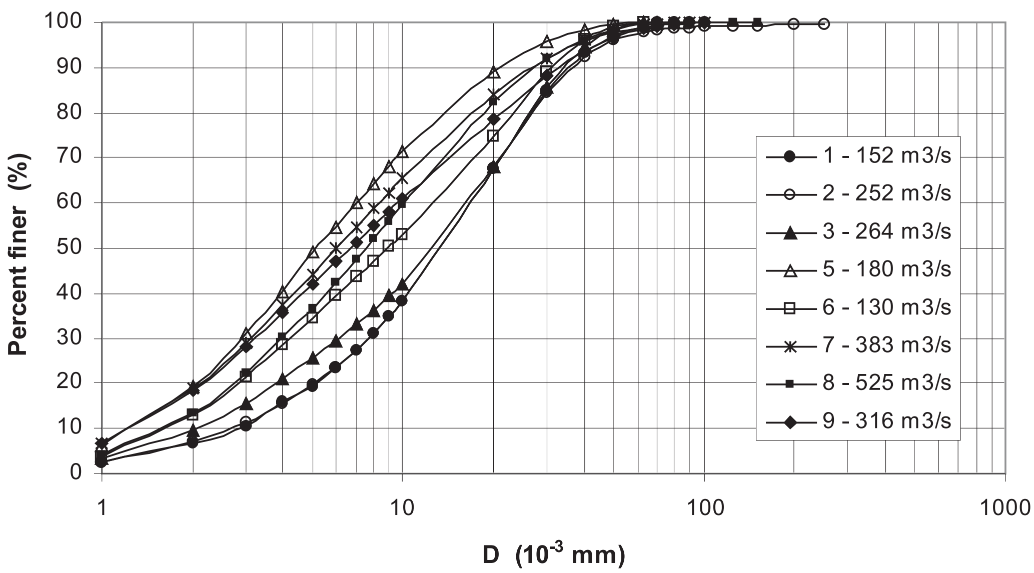

Figure 3. Grain size distribution of suspended load at the outflow of the water from the reservoir of the HPP Boštanj. The legend contains discharges for the time periods of sample collection.

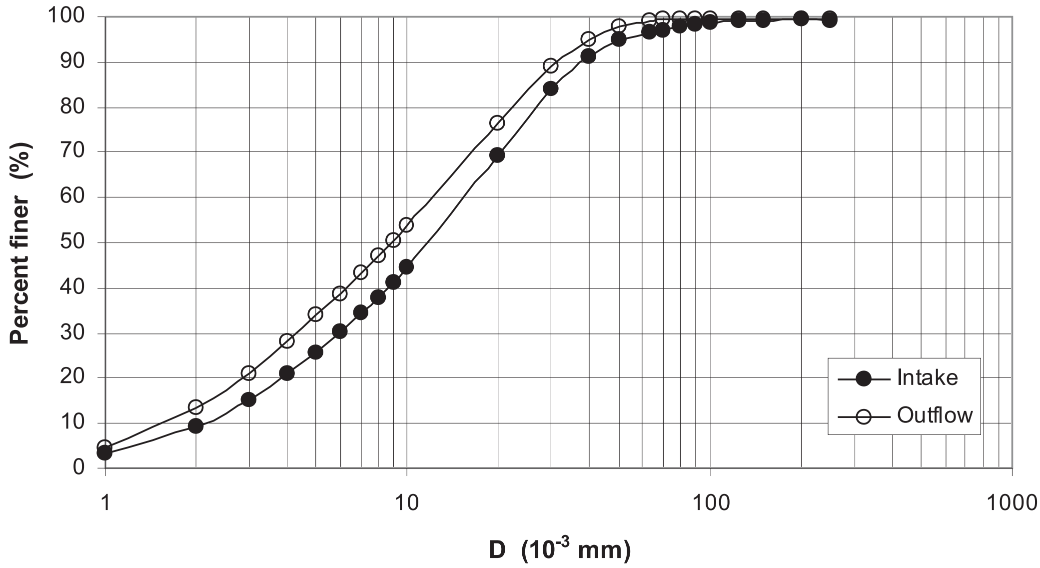

Figure 4. Comparison of the grain sizes of the composed samples of solids from the intake and the outflow area of the water from the reservoir.

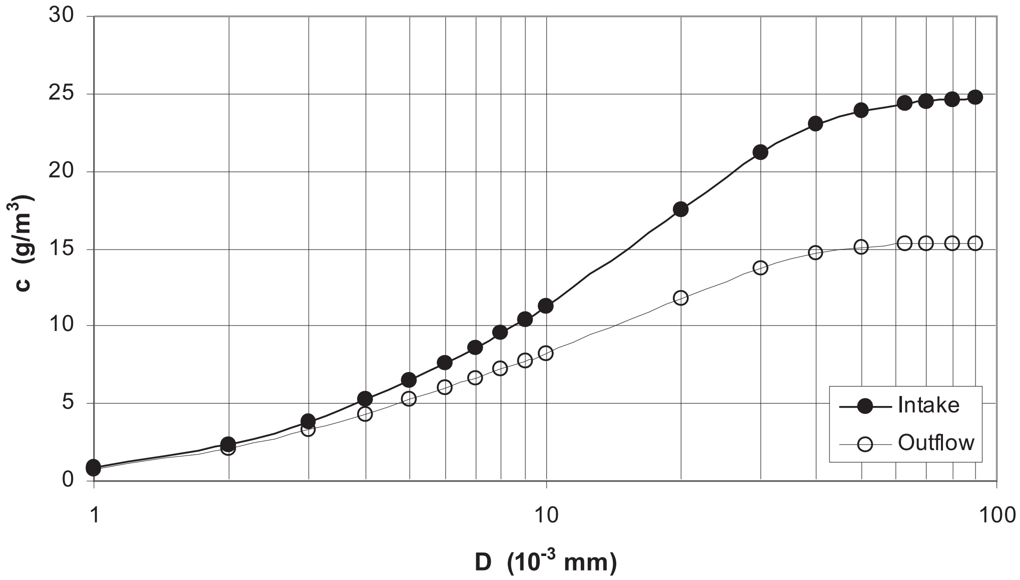

Figure 5. Relationship between concentrations of the suspended load and the grain sizes of the composed samples from both collection sites.

3.2 MINERAL AND CHEMICAL COMPOSITION OF THE SUSPENDED LOAD

The chemical composition of the composed sample of the suspended material from the reservoir and the mineral composition of the composed samples from the water intake and outflow area are presented in Table 2. The comparison of the mineral composition of the samples from both sites shows a smaller share of carbonate particles and larger share of quartz at the outflow of water from the lake than at the intake.

Microscopic examination of the solid from the intake and the outflow of water from the reservoir (Figs. 6 and 7) did not show any special difference in the mineral composition. Only a larger quantity of organic detritus and clay particles and the absence of rare heavy minerals are evident among the suspended material at the outflow of water.

Table 2. Mineral and chemical compositions of the suspended load.

Mineral composition (%)			Chemical composition (%)	
	Intake	Outflow	SiO_2 = 37,76	TiO_2 = 0,54
Muscovite/illite	33	33	Al_2O_3 = 13,43	P_2O_5 = 0,32
Chlorite	15	15	Fe_2O_3 = 5,12	MnO = 0,12
Quartz	17	21	MgO = 2,85	Cr_2O_3 = 0,016
Plagioclase	5	5	CaO = 11,15	TOT/C = 7,62
Calcite	20	18	Na_2O = 0,57	TOT/S = 0,06
Dolomite	10	8	K_2O = 2,20	LOI = 25,6

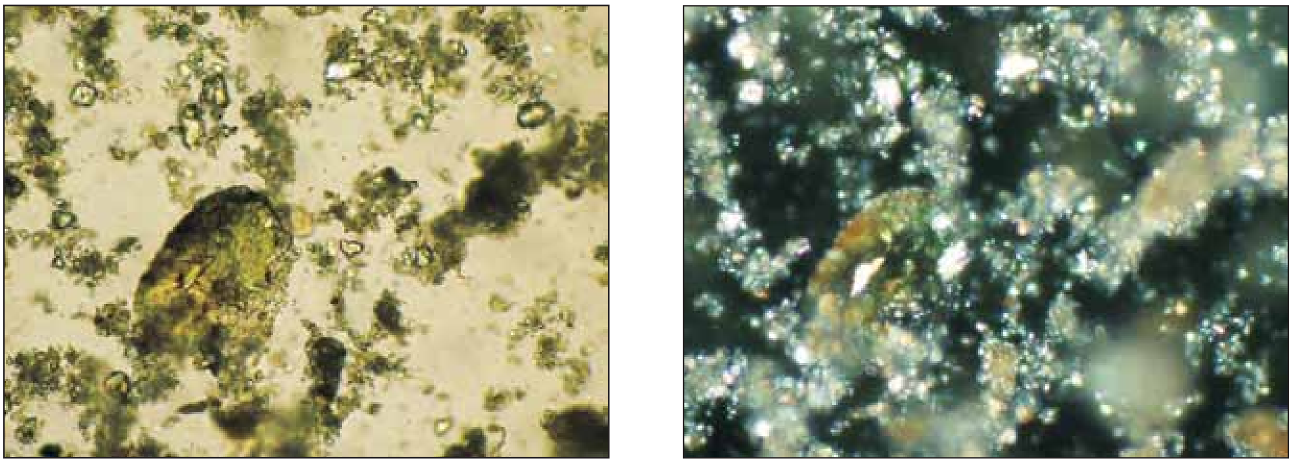

Figure 6. Suspended load at the intake of water into the reservoir of the HPP Boštanj. Green chlorite, transparent carbonate grains, black non-transparent matter and submicroscopic particles of clay and carbonate minerals; II N (Fig. left) and + N (Fig. right), zoom: 190 X.

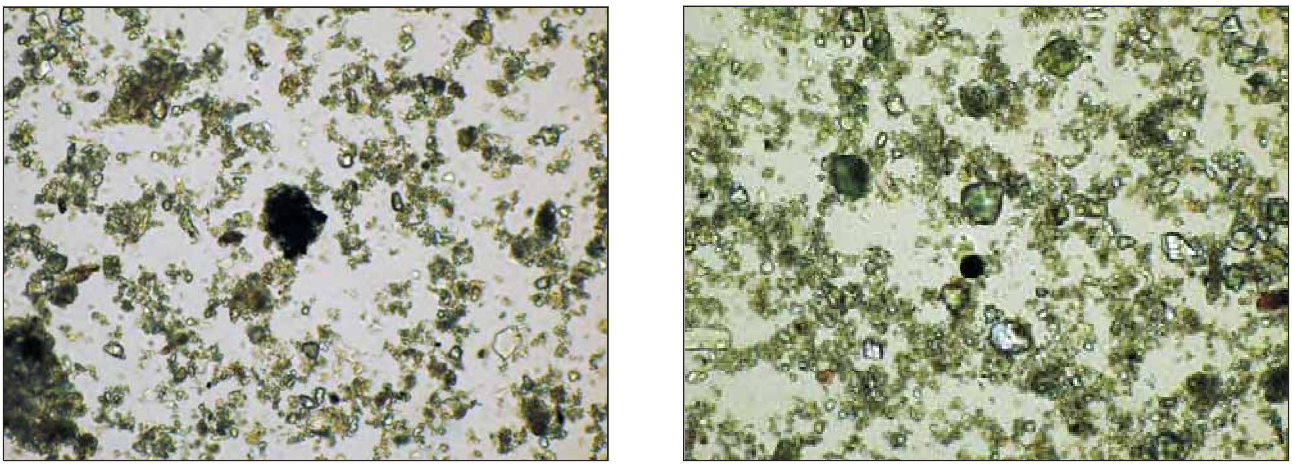

Figure 7. Suspended load at the outflow of water from the reservoir of the HPP Boštanj. Larger grains belong to the black non-transparent matter, transparent carbonate grains, rare sericite leaves, quartz, fine green chlorite and submicroscopic particles of clay minerals; II N (Fig. left) and + N (Fig. right), zoom: 170 X.

3.3 CONCENTRATION OF THE SUSPENDED LOAD

The concentration of the suspended load in the water-courses depends on many factors from the environment, which is why a study of the dynamics of their transport and sedimentation is quite demanding (Rusjan and Mikoš, 2007). However, at an individual measuring station we can see a correlation between the concentrations of the suspended material and the flow rates of the water (Ulaga, 2005; Morris and Fan, 1997).

The results of the measurements at selected sites of reservoir of the HPP Boštanj showed that the share of suspended load is increasing with the increase of the discharge (Table 1). This ratio is shown in Figure 8, in which both variables are presented separately for the samples from the intake and the outflow site of the water from the reservoir. Due to an almost simultaneous collection of the samples from both sites, the discharge was very similar; however, there is a difference in the quantity of the suspended material, which is much smaller at the water outflow.

A comparison of the concentrations of suspended load from both collection sites showed that this ratio is approximately linear (Fig. 9). We can describe it with Eq. (1).

$$c_{outflow} = 0{,}55\ c_{intake} \qquad (1)$$

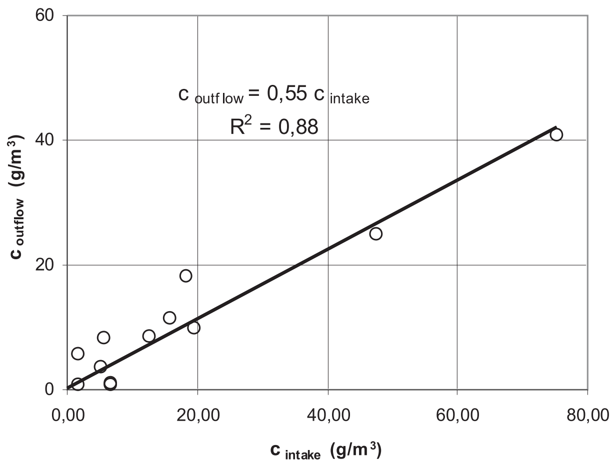

Figure 9. Ratio between the concentrations of suspended load at the intake and at the outflow of water from the reservoir.

From the presentation of the concentrations of suspended load at the water intake and outflow, and discharges (Fig. 10, next page) it is evident that it is possible to describe this ratios with Eqs. (2) and (3).

$$c_{intake} = 1{,}85\ e^{0{,}007Q} \quad (g/m^3) \qquad (2)$$

$$c_{outflow} = 1{,}45\ e^{0{,}007Q} \quad (g/m^3) \qquad (3)$$

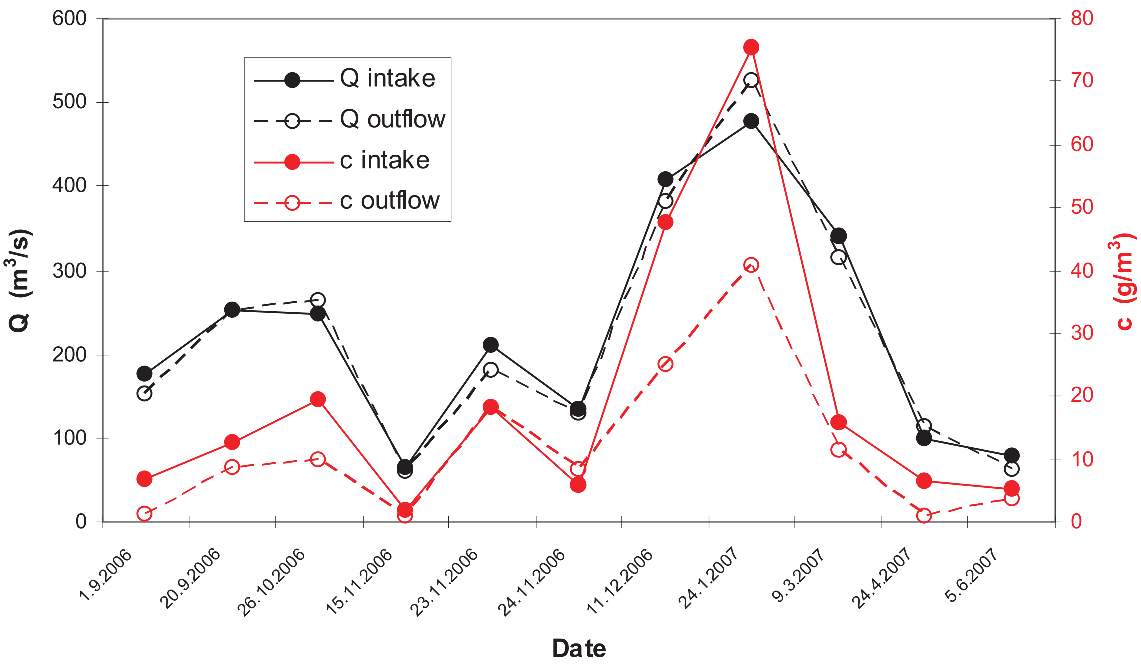

Figure 8. The concentration of suspended load in relation to the discharge and the time periods of sample collection.

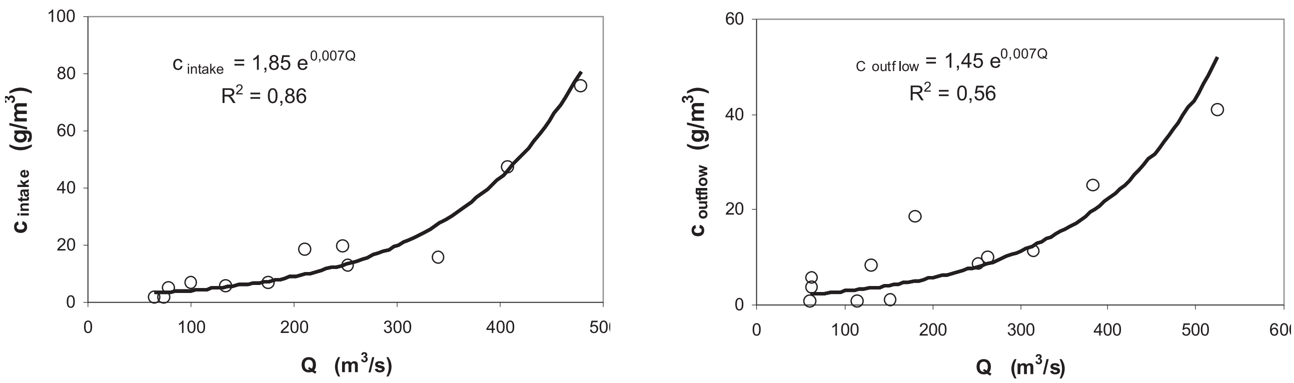

Figure 10. The concentration of suspended load in relation to the discharge at the intake (Fig. left) and outflow (Fig. right) of water from the reservoir of the HPP Boštanj.

3.4 ESTIMATION OF THE QUANTITY OF DEPOSITED MATERIAL

The studies of the concentrations of suspended load at both collection sites showed that there is less suspended load at the outflow of the water from the reservoir than at the intake. The difference is represented by the share of grains that sedimented on the bottom of the reservoir. The quantity of these sediments (c_{sed}) when considering Eqs. (2) and (3) can be expressed in relation to the discharge of water with Eq. 4.

$$c_{sed} = c_{intake} - c_{outflow} = 1{,}85\, e^{0{,}007Q} - 1{,}45\, e^{0{,}007Q} = 0{,}4\, e^{0{,}007Q}\ (g/m^3) \quad (4)$$

An estimation of the quantity of deposited material in the reservoir was prepared on the basis of the actual hourly discharges for the period between 12 July 2006 and 12 July 2007 (Fig. 11). Considering the volume of water flowing through and the portion of deposited material in dependence on the actual discharges (Eq. 4), the estimated quantity of deposited material in reservoir is 1,08 x 10^4 t for selected period of time.

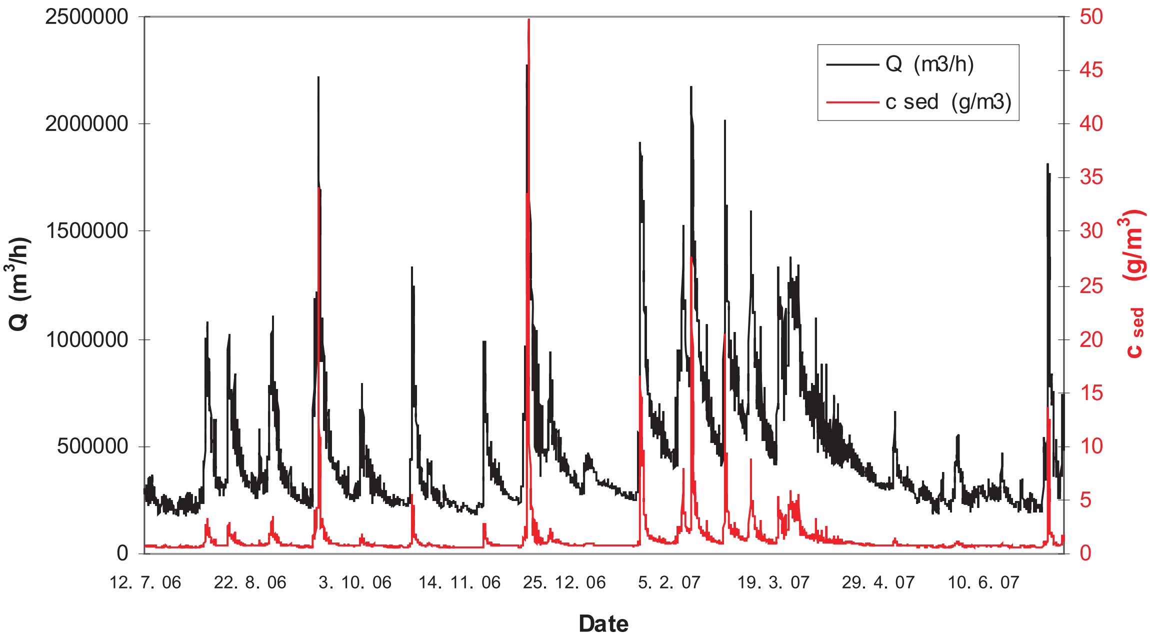

Figure 11. The discharge and the quantity of deposited material for the period between 12 July 2006 and 12 July 2007.

4 CONCLUSIONS

This paper deals with the sedimentation of suspended material in the reservoir of the hydroelectric power plant Boštanj on the Sava River. The objective of the described research was to determine the quantity and type of sedimented material in the reservoir during the selected time period. For this purpose, the mineral and chemical composition, and the concentration and the particle size of the suspended load at the intake of the water into the reservoir and at its outflow were examined. On the basis of the gathered data, the following conclusions can be established:

Because of the changed geometry of the riverbed and, consequently, the lower speed of the water, part of the suspended load is sedimented on the bottom of the reservoir. Based on a comparison of the average quantities of solids in the water at the intake and the outflow, it is evident that at the same flow rate of water this ratio is approximately linear (Eq.1).

The concentration of suspended load increases with an increase in the water discharge; however, this increase is not linear. This dependence can be expressed for the samples of both collection sites with exponential functions (2) and (3).

The quantity of sedimented particles depends mostly on the discharge of water. This ratio in the examined case can be described with equation (4).

The estimated quantity of sedimented material in the period between 12 July 2006 and 12 July 2007 amounts to $1{,}08 \times 10^4$ t. The actual quantity of this material in the resevoir was lower due to its transport at very high discharges of water.

Based on the ratio between the concentration of the suspended load and the size of the grains at the intake and the outflow of the water, it can be concluded that especially the particles with the size between 10 μm and 100 μm are sinking.

The mineral composition of the suspended load is a reflection of the environment in which the Sava River and its tributaries flow. As expected, carbonates, muscovite/illite and quartz predominate, chlorite can also be found, as can plagioclase and organic detritus, in smaller quantities. The structure of the solids at both collection sites is similar. A somewhat smaller share of carbonate grains and heavy minerals and an increase in the content of organic detritus and clay particles were observed at the water outflow from the reservoir compared to the intake.

ACKNOWLEDGMENT

Funding for this research project was provided by the Government of the Republic of Slovenia - Ministry of the Economy and Utilities Management Company KOSTAK, Krško. This financial support is gratefully acknowledged.

LITERATURE

Morris, G.L. and Fan, J. (1997). Reservoir Sedimentation Handbook. 1. ed., McGraw-Hill Professional.

Rusjan, S. and Mikoš, M. (2006). Suspended load transport dynamics in river basins. *Acta hydrotechnica* 24, 40, 1-20.

Trauner, L., Škrabl, S., Žlender, B., Dolinar, B., Macuh, B., Vrecl-Kojc, H., Šketelj, E., Petrešin, E., Jecl, R., Nekrep, M., Lobnik, A., Poberžnik, M., Turel, M., Zlatolas, D., Greifoner, R., Bauman, M., Senica, H. (2007). Razvoj tehnologije za odstranjevanje plavja in usedlin pred akumulacijsimi jezovi: razvojno-investicijski projekt: končno poročilo. Fakulteta za gradbeništvo, Maribor. (*Development of the technology to remove sediments and debris before the accumulation dams: development and investment project: the final report. Faculty of Civil Engineering, Maribor.*)

Ulaga, F. (2005). Vsebnost in premeščanje suspendiranega materiala v slovenskih rekah. *Agencija Republike Slovenije za okolje*, www.arso.gov.si. (*The content and transport of suspended material in the Slovenian rivers. Environmental Agency of the Republic of Slovenia.*)