Erosion of the Sava riverbed in Croatia and its foreseeable consequences

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Abstract

Riverbed erosion and bottom deepening are part of natural fluvial processes in the upper stream. The increasing gradient of these changes is interconnected with the level of human influence in the river basin and 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 threaten the stability of hydro technical structures. This process in not usually visible to the naked eye, it is lengthy and slow, but can be easily detected by analysis of specific types of measurements. The article 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. Regular measurements of water levels, discharge, amount of load transport and cross section profiles along this section of the Sava River prove that significant changes in the riverbed have occurred in the last 20 years. Because of the deepening of the riverbed, at some locations by more than 3.5 m, the stability of bridges in Zagreb and the surrounding area are especially at risk. As a result of unpredictable bottom erosion, the railway bridge Sava Jakuševac was damaged on March 30, 2009. This incident showed that erosion may lead to the wearing away of bridge foundations which in turn is very likely to lead to serious damage to other bridges.

Keywords: Bottom erosion, load transport, level of underground water, stability of hydro technical structures

Introduction

According to their stability, alluvial riverbeds can be divided into statically and dynamically stable riverbeds. Statically stable riverbeds are those which do not display any bed-load movement, whereas in dynamically stable riverbeds the amount of incoming transported bed-load in the observed cross-section is equal to the amount of outgoing bed-load. They are, therefore, stable in their mean height position, provided every single riverbed section receives and releases the same amount of sediment. In case natural balance of bed-load transport is disrupted, deepening of the riverbed (global erosion), river bank erosion and even discharge profile obstructions occur. Under critical flow velocity conditions in riverbeds with movable bottoms, rivers and channels adapt their riverbed shape to the boundary conditions and mould a natural flow and bed-load transport («Grundlagen der Sedimentbewegung», U.Zanke, Berlin, Heidelberg, New York, 1982). The shape of a river valley is a result of fluvial erosion and is influenced by hydrodynamic forces which act on non-coherent material in riverbeds. The magnitude of hydrodynamic forces is linked to the amount of water and lowering of energy line, and transports eroded material in the form of suspended and bed-load. For this reason Water and bed-load sediment flow in a mixture through natural watercourse. In a dynamic process, bed-load particles periodically move and then settle. During calm periods, bed-load forms the riverbed.

When watercourses are regulated, riverbed morphology changes in comparison with the natural state of the watercourse; it is shortened and, therefore, causes greater longitudinal slope and concentration of the river flow energy. Due to greater longitudinal slope, river velocity as well as riverbed shear force are locally higher causing changes in the riverbed morphology. When hydrodynamic force reaches its critical value and disrupts the balance of forces keeping the particles on the river bottom in place, the particles are lifted from the bottom and transported downstream. After a while they settle again thus influencing the morphological development of the riverbed. In hydrotechnical engineering, the need to evaluate river behavior in altered conditions, caused primarily by anthropogenic influence, is extensive. Considering bedload transport is never exactly determined and depends on hydrological and hydraulic flow parameters, the amount of transported bed-load as well as transport distance cannot be precisely defined. The most accurate methods in determining the creation and movement of riverbed bed-load in a watercourse are in-situ bed-load and hydrological-hydraulic flow parameter measurements.

Influence of flow forces is more emphasised when the riverbed is not oversaturated with bed-load. In case of the Sava River, recharge with bed-load sediment yield is non-existent due to gravel exploitation at 12 locations in the Zagreb area. The gradient of morphological changes in that section is thus higher. This paper will present the effects of anthropogenic influences on the morphological development of the Sava River, based on the observed characteristic stages collected from the Zagreb and Bundek gauging stations over a number of years. Beside measurements of morphological changes and hydraulic flow parameters in a control profile, lowest annual stage trend is the best indicator of morphological changes and, therefore, this paper will concentrate on it. In practice, there are numerous examples of problems caused by riverbed deepening, tilting of the Sava-Jakuševac bridge pier to mention only one. It is worth noting that the Sava River reach from the Slovenian-Croatian border to Zagreb and Drenje is very interesting for two reasons: flood protection and planned water accumulations for future hydroelectric power plants. According to the research paper *Uređenje i korištenje rijeke Save od granice sa Republikom Slovenijom do Rugvice* (*Management and Use of the Sava River from the Slovenian-Croatian Border to Rugvica,* Elektroprojekt, Zagreb, 2004.), some of the primary tasks in that area are:

- flood protection of 3,100 ha of land from the Slovenian-Croatian border to Podsused, especially in situations when hydropower plants are built in Slovenia
- disabling the process of further lowering of low waters of Sava River and ground waters
- ensuring long term existence of the water supply system capacity of the City of Zagreb and the region
- development of sports recreation and tourism on app. 960 ha of water area on the Sava River
- increasing of land and real estate value on approximately 1,700 ha along the Sava River

Deepening of the Sava riverbed

At the end of 1981, on the reach of the Sava River between the stations of HEPP Podsused and Zagreb, significant problems appeared connected to a continuous and reliable supply of the necessary amount of cooling water to the thermal power plant 'Termoelektrane – Toplane Zagreb' (TE-TO Zagreb) (rkm 696+400). That was the first time the TE-TO Zagreb plant needed to be shut down due to the low Sava River water level and inability to supply the necessary amounts of cooling water. This incident announced the existence of significant changes in the hydrological regime of the Sava River. Extremely low water levels of the Sava River at the pumping station, causing shut downs of the TE-TO Zagreb plant during 1982, became increasingly frequent and urgent improvements had to be made in order to ensure the necessary amounts of cooling water during low water periods. Research results showed a submerged weir in the riverbed, functioning as a temporary barrier, to be the best solution to the problem of ensuring necessary water level for unhindered functioning of water pumps and stabilization of the riverbed upstream from the barrier weir cross-section. First submerged weir in the Sava riverbed was built in 1983 resulting in a slow down of the Sava River flow in the area where cooling water is taken, and ensuring the necessary water level for normal functioning of the TE-TO Zagreb plant during low water periods. Since then, due to continuous and significant weir damage caused by riverbed erosion and lowering of the riverbed as well as low waters, the TE-TO Zagreb plant has been regularly maintaining and improving the existing slowing down structures.

Part of the Srednje Posavlje flood protection system, designed and partially constructed after the 1964 Zagreb flood, is the Sava-Odra flood relief canal. The Jankomir overflow, acting as the flood relief canal's starting point was designed to activate when the river discharge reaches 1900 m^3/s. However, in the period from its construction in 1979 until 2000, lowering of the Sava riverbed on the overflow location amounted to 2m (Kratofil, 2000.), and additional 70cm in the last 10 years. Under these new circumstances, the overflow activates only when the river discharge reaches 2350 m^3/s and not 1900 m^3/s, which was originally the maximum allowed discharge. The downstream reach of the river is therefore exposed to influences which dramatically exacerbate the already negative riverbed erosion process. According to the discharge measurements conducted by the DHMZ (Croatian Meteorological and Hydrological Service), the overflow should have been activated 9 times in the period between 1979 and 2006. In fact, it was activated only 5 times: twice in 1979 and once in years 1980, 1990 and 1998 (Trninić & Bošnjak 2009). The Srednje Posavlje flood relief system was designed only to alleviate problems concerning the safety of people and material goods in the immediate river surrounding area, whereas the influence of building structures on the downstream part of the river was not taken into consideration.

Beside regular stage measurements, The DHMZ conducts periodical discharge measurements on the Sava River and uses them to define discharge curves. At the same time, the geometry of control cross-section profiles is recorded. In this paper the following control profiles of the Sava River were taken into account: the Jesenice GS (rkm 728+900), Medsave GS (rkm 720+550), HEPP Podsused GS (rkm 717+200), Podsused cableway GS (714+000), Jankomir overflow GS (rkm 708+800), Zagreb GS (rkm 702+800), Bundek GS (rkm 699+700), Kosnica GS (rkm 690+920) and the Drenje GS (rkm 686+400).

Deepening of the riverbed, in some locations by more than 3m, is visible in the surveyed cross-section profiles taken over last 25 years on the section of the Sava River from the HEPP Podsused to Rugvica. Such riverbed degradation has been directly influenced by gravel exploitation at 12 locations in the Zagreb area, from Rugvica to Podsused, with Drenje being the most profuse with 3302000 m^3 (Beraković 1992).To asses the level of riverbed deepening, the Zagreb GS was taken as a control profile for the period between 1964 and 2009 (Fig. 1.). The graph shows constant lowering of the riverbed, from 110.5m a.s.l. in 1964 to 108.15m a.s.l. at present. The fact that causes greatest concern is deepening of the erosion trench around the central bridge pier, which has reached 106m a.s.l.

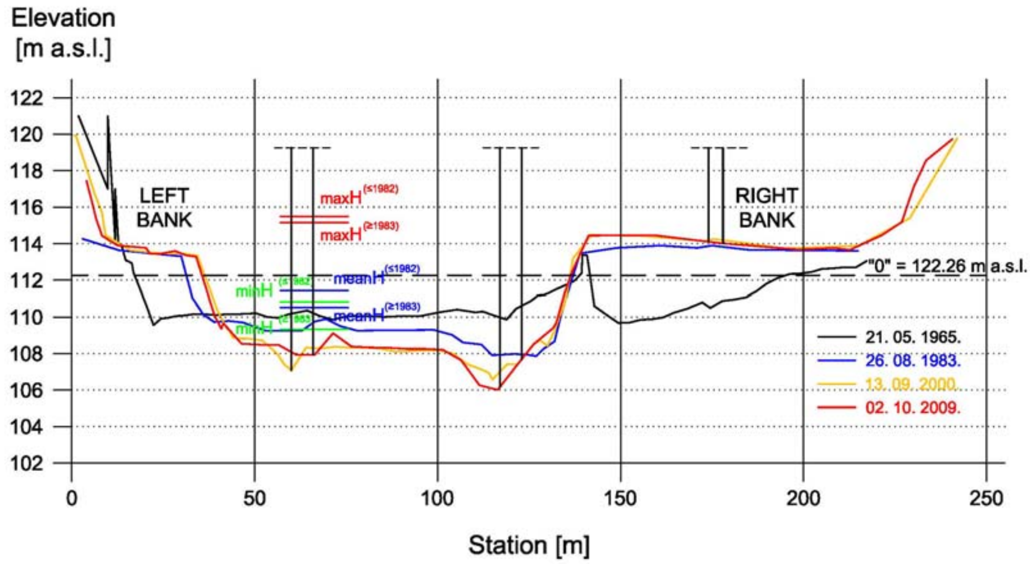

Figure 1. Morphological development of the Sava riverbed at the Zagreb GS

Hydrological indicators of morphological changes

Water-gauges

The Sava River stage and discharge readings at the Zagreb gauging station, situated at rkm 702+800, and the Bundek gauging station, situated at rkm 699+700 were used in this paper. Available data was collected and originally processed by the DHMZ. Annual mean stage and discharge values were calculated for low, mean and high waters, depending on the duration curve. This type of measurements has been available since 1926 for the Zagreb GS and for the Bundek GS since 1967, i.e. immediately after the flooding of City of Zagreb. Cross-section riverbed profiles have also been measured in discrete time periods, providing an insight into the morphological riverbed development.

Based on these measurements, trends in hydrological parameters over a longer time period can be observed for the Sava River reach flowing through Zagreb, and so determining ecological, economical and social sustainability of the capital. The time line is divided into two periods: one spanning over the 1925-82 period and the other covering the period between 1983 until today. These two periods were chosen for two reasons, both having a great impact on the hydrological regime of the Sava River. One reason was the afore mentioned construction of the weir at the TE-TO Zagreb location (rkm 696+400) in 1983, and the other was the occurrence of a long dry period on the territory of the Republic of Croatia after 1980 (Žugaj, Plantić 2003). In 1983 a unique limit was accepted since dry years added to the first time period could not significantly affect the homogeneity of the data (Trninić, Bošnjak 2009).

Declining trends in water level

Observing stage and discharge values at control river profiles over a number of years provides an insight into the trends of hydrological parameters as well as the ground for drawing conclusions on the morphological development of the riverbed on the observed river reach. Changes in riverbed level can be deducted from annual minimum and mean stages. The following figures show trends in annual maximum, minimum and mean stages at the Zagreb GS and Bundek GS.

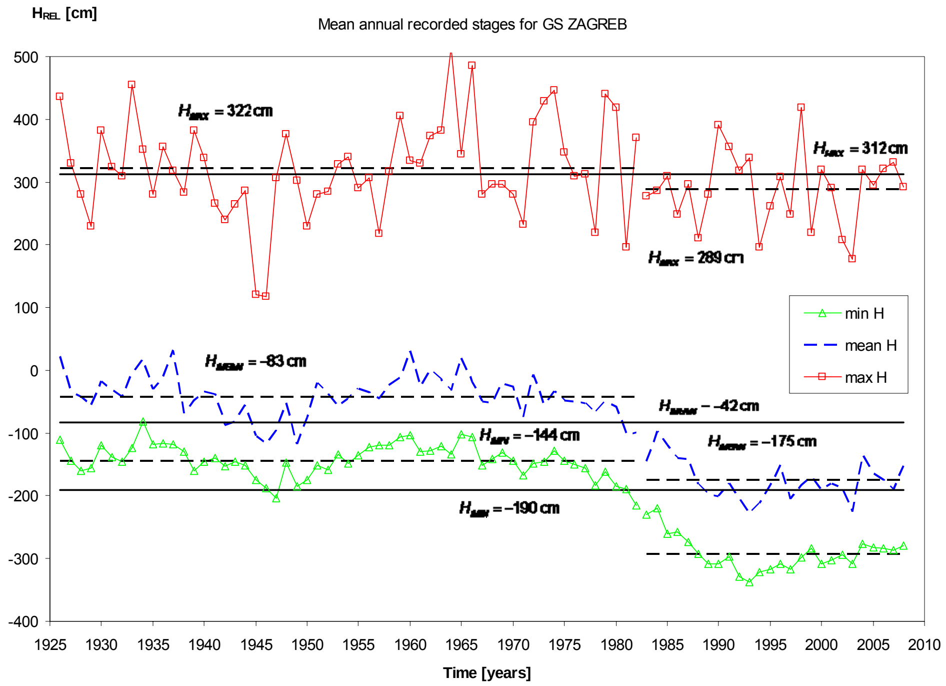

Figure 2. Characteristic measured stages for the Zagreb GS.

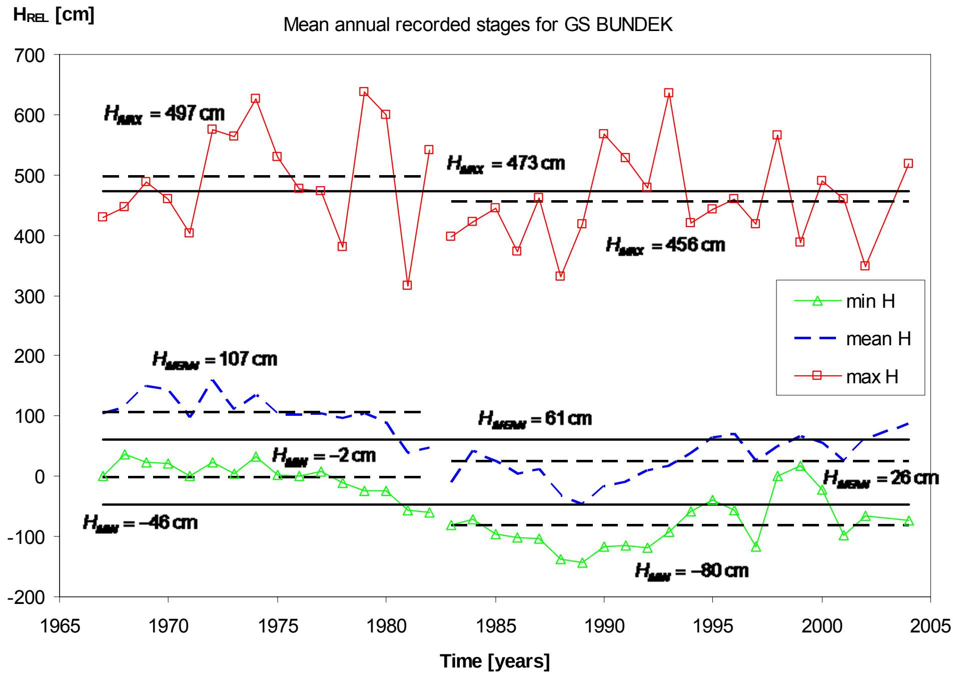

Figure 3. Characteristic measured stages for the Bundek GS

Fig. 2 and Fig. 3 show two main stage trends: one that lasted until 1983 and is characterized by equable values of mean annual stage for minimum, medium and maximum stages, and the other, which started in 1983 and is still present today. There was an abrupt decline in characteristic annual stages in the period between 1982 and 1986, followed by a period of stage stabilization. Stabilization of the hydrological regime was accomplished by construction and continuous maintenance of the weir at the TE-TO Zagreb location on the Sava River. There was a significant decline predominantly in minimum and mean annual stages caused by riverbed degradation (Fig.1). The decline in minimum and mean stages amounted to approximately 140cm at the Zagreb GS, whereas at the Bundek GS the stages lowered for approximately 80cm. Riverbed degradation did not significantly affect the regime of annual maximum stages which lowered for 40cm at both stations (Table 1). The effect of riverbed degradation would probably have been more visible had the weir not been built. The average value of the annual mean stages in the period following the weir construction is 31cm lower than the mean value of the annual minimum stages before building the weir (Table 1) and, therefore, shows significant changes in the hydrological regime.

Table 1. Difference in annual mean stages at the Zagreb GS and Bundek GS

	Hmin ≤1982 [cm]	Hmin ≥1983 [cm]	ΔHmin [cm]	Hmean ≤1982 [cm]	Hmean ≥1983 [cm]	ΔHmean [cm]	Hmax ≤1982 [cm]	Hmax ≥1983 [cm]	ΔHmax [cm]
GS Bundek	-2	-80	-79	107	26	-81	497	456	-41
GS Zagreb	-144	-292	-148	-42	-175	-133	322	289	-33

Although characteristic mean stage values are a good indicator of morphological riverbed changes, they are not sufficient to complete the picture of the Sava River hydrological regime. This would require constant observations of changes in discharge regime (Fig. 4). Right before the weir construction a dry period started (Žugaj & Plantić 2003), which manifested itself in lower discharge of the Sava River (Table 2). Annual mean discharge for the period after 1983 fell by 15%, from 325 m^3/s to 275 m^3/s, whereas the mean value of the annual minimum discharge fell by 21%, from 87 m^3/s to 69 m^3/s.

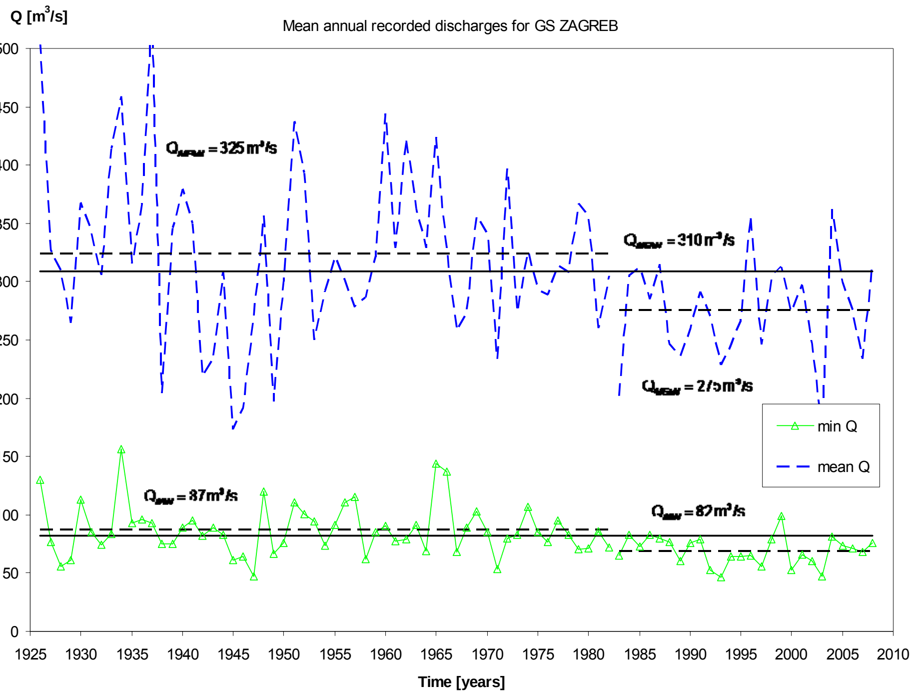

Figure 4. Characteristic discharges at the Zagreb GS

The analyses show riverbed degradation not to be the only cause of a declining trend in characteristic stages. Although deepening of the riverbed, in places by almost 3m (Fig. 1), is cause for concern, declines in characteristic discharges of the Sava River in Zagreb are equally important. Measures for erosion protection exist and can be implemented as required, but on the other hand, there can be no influence on natural forces which supply the discharge and that should be also taken into consideration.

Table 2. Difference in annual mean discharges at the Zagreb GS

	Qmin ≤1982 [m^3/s]	Qmin ≥1983 [m^3/s]	ΔQmin [%]	Qmean ≤1982 [m^3/s]	Qmean ≥1983 [m^3/s]	ΔQmean [%]	Qmax ≤1982 [m^3/s]	Qmax ≥1983 [m^3/s]	ΔQmax [%]
Discharge	87	69	21	325	275	15	1816	1698	7

Because of the afore mentioned changes, namely gravel exploitation, riverbed erosion, weir construction and climate changes, regular measurements of stages as well as discharge changes are needed. Abrupt changes in the geometry of control profiles influence the changes in the discharge curve (Fig. 5). Fig. 5, showing the relation of characteristic annual stages to the discharges, implies that this relation has been preserved up to a point, but also that, due to the deepening of the riverbed, it has been translated along the stage axis towards lower values. This situation calls for more frequent discharge measurements during all hydrological events as well as comparison of the results with the existing stage - discharge relations and possible corrections of the discharge curve in accordance with the trend of the hydrological regime stated on the control profile.

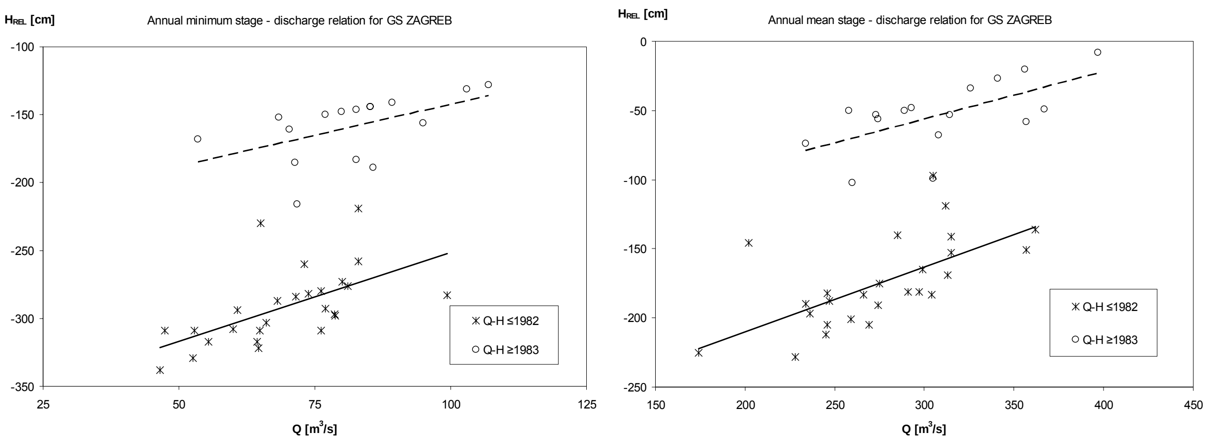

Figure 5. Traslation of Q-H relation due to the deepening of the riverbed

Consequences of riverbed degradation

Intensive riverbed degradation over many years causes damage to structures built in riverbeds. Every structure is designed to withstand conditions relevant at the time of construction, with appropriate safety factor. When the conditions change, the balance of forces affecting the structure is disrupted. The balance can be affected by changes in the hydrological regime of the river, global erosion and local erosion around the structure or a combination of these changes. Flood events cause greatest damage and disruption of the stability of the bridges spanning over rivers. Harmful effects to the structures are various, the most significant being the local washing away of the riverbed material in the area around bridge foundations (abutment and pier foundation erosion). Loss of bridge stability due to erosion is considered to be the result of inadequate criteria used during bridge design and insufficient field analysis of erosion on the built structures.

Local erosion in alluvial riverbeds appears in places where river currents are disrupted by a submerged body, namely an artificial building structure, such as the piers and abutments. A significant hydraulic structure in the river usually reduces the local discharge profile, causing backwater effects and disruption of the flow pattern. The flow lines are elongated and concentrated along the solid contour, resulting in increased velocity and unit discharge, as well as increase in local shear stress. This can result in intensive scouring of material from the channel bed, aided by high turbulence. Although structures may be inherently strong enough to withstand water forces their stability may be endangered by transportation of the bed material from the channel. The process of channel deepening in the zone influenced by the structure is finalized when equilibrium conditions are established, i.e. when the quantity of sediment entering the scour hole and sediment removed from the scour hole become equal $(Q_S)_{in} = (Q_S)_{out}$, being inversely proportional to the sediment particle diameter. Most investigations of the local erosion phenomenon were conducted to determine the effect on bridge piers.

The railway bridge ‘Jakuševac’ in Mičevac is an example of a loss of bridge stability caused by global and local erosion, aided by discharge conditions during extreme water levels. 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. Tilting of the pier was caused by the superposition of two influences: disruption of the global riverbed stability leading to considerable lowering of the riverbed compared with the time the bridge was designed and constructed, and the appearance local scour in area around the bridge pier. Because of advanced riverbed global erosion, the bottom of the river became considerably lower compared with the time the bridge was designed and constructed, and presence of the bridge piers in the river stream caused local erosion on the upstream side of a bridge pier, resulting in additional lowering of the riverbed (Fig. 7). The stability of the bridge was compromised by scour, in other words, by the removal of the bearing ground under the bridge piers. At the time of the accident, the Sava River water level, as well as the discharge and velocity were high. Combined with the static and dynamic loads, brought about by a moving freight train, they led to a loss of bridge stability and tilting of the bridge into the cavern. Proportions of the riverbed changes compared with the time of the bridge design were the following:

1. in the period between 1985 and 2009, the riverbed lowered by about 5-6m
2. local scour in the area around the pier was 4-5m
3. total scour in the area around the pier compared with the time the bridge was designed was approximately 10m.

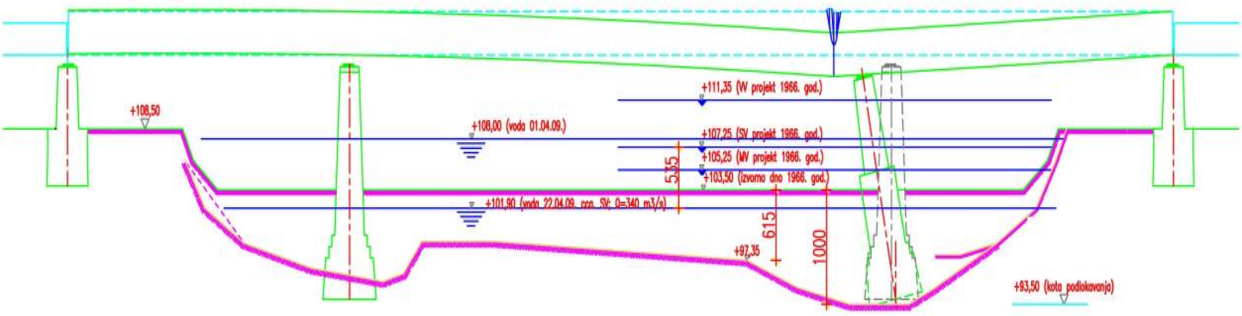

Figure 6. Influence of global and local scour in the Sava riverbed on the Jakuševac bridge profile over a 20-year period

Degradation of river bed in the upper reaches, including the Sava River in the area of Jakuševac is a natural phenomenon. However, the gradient of changes is heavily influenced by a human factor. More specifically, the following parameters have caused the acceleration of the process: reduction of sediment inflow due to construction of dams and weirs in upstream reaches; increased tractive force due to increased longitudinal slopes as a result of shortening of the river course by regulation works; increase of water depth during flood waves due to flow concentration in the channel, without natural floodplains and gravel excavation from the riverbed.

During 2009, in the period between April and October, The Faculty of Civil Engineering in Zagreb (Institute for Hydrotechnics) in collaboration with the Faculty of Geodesy (Department of Hydrography), conducted hydrographic surveys of the Sava River bathymetry. Geodetic and hydrographic surveys included monitoring of the morphologic changes measurements with multibeam echo sounder. The area covered by hydrographic measurements stretches over 2 ha and encompasses the area to the north and south of the Mičevec bridge, totaling 200m in length, including the river bank and the Sava River inundation area. Field surveys were conducted four times during the monitoring of hydraulic parameters on the selected section of the river: on April 22, May 7, September 28 and October 26, 2009. On all field surveys, measurements were taken at six control cross-sections, three upstream and three downstream from the bridge. The flow velocity field in the observed section of the river and around the bridge piers was obtained by monitoring velocity profiles. The following parameters were measured at each profile: flow velocity profile, flow area, free flow width, stages and discharge.

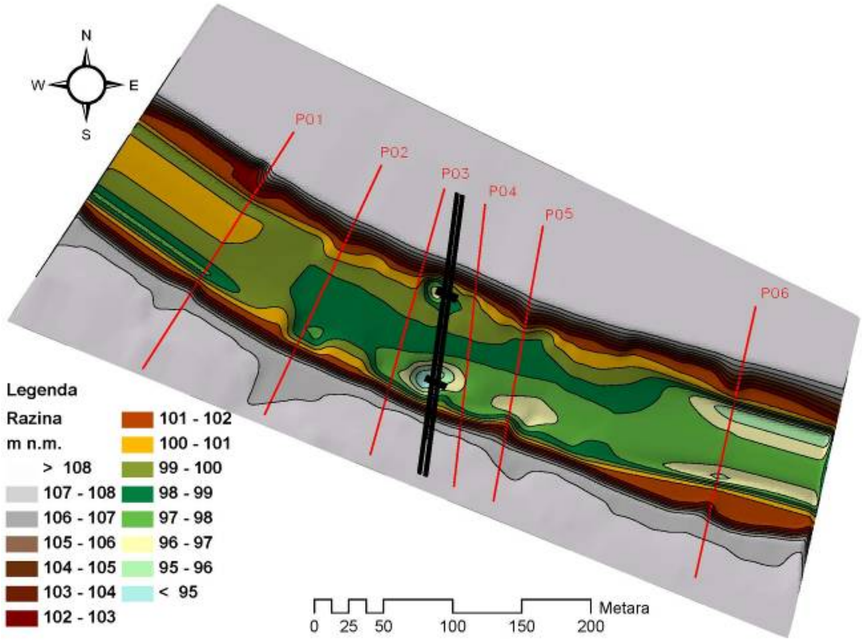

Figure 7. Bathymetric image of the bridge area

Since the bridge is situated at a river bend, higher flow velocity is found on the concave side, namely, the south pier side. Because of this, unit bed-load transport rate and riverbed erosion are more pronounced on that side of the river (Fig. 6, Fig. 7). The process of local scour around piers is finite until balance is achieved, in other words until the amount of bed-load entering the cavern and the amount of bed-load being washed away from the cavern become equal $(Q_S)_{in}=(Q_S)_{out}$. The depth of the cavern as result of local scour at both piers exceeds 4m compared with the mean riverbed height and the caverns around both piers are approximately the same depth. This means that erosion at this phase has reached its peak and is in the state of temporary equilibrium until the entire riverbed is additionally deepened by global erosion.

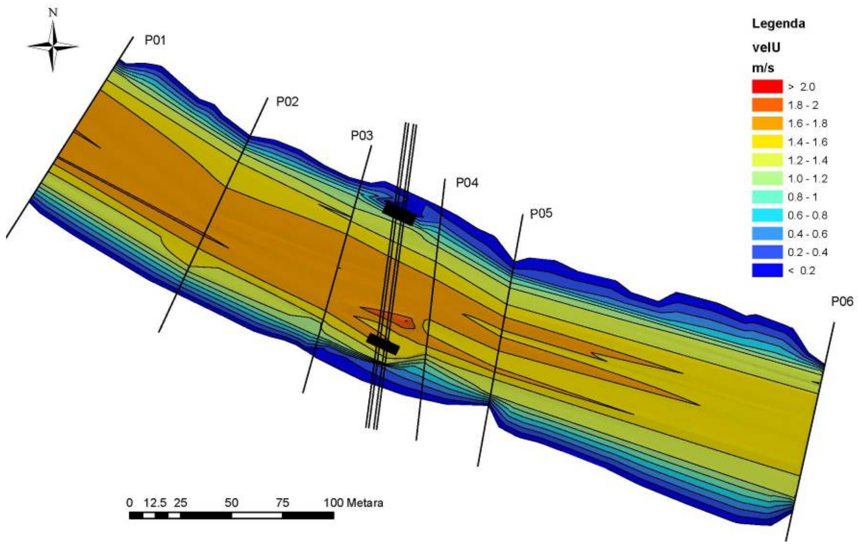

Figure 8. Measured flow velocity field

In the observed velocity field in the 'Jakuševac' bridge area, at the discharge of 340 m^3/s, a concentration of the highest velocities can be seen around the south pier. Settling down of velocities is visible in the downstream area.

Conclusions

To become aware of natural events, one often needs to suffer their consequences, and they are usually of catastrophic proportions, causing human losses and material damage. In order to react on time and undertake improvements or reconstructions of the endangered structure, continuous surveys of physical phenomena trends in nature are needed. A network of gauging stations has been established on the watercourses in Croatia where stage measurements are taken regularly, including daily surface samplings of suspended sediment load at some stations. In this paper, as in the ones done by other authors in the past, annual minimum and mean stage trends at gauging stations in the Zagreb area of the Sava River have been analyzed. Although stages are a good indicator of the changes in the riverbed morphology, they are not an independent physical value since they directly depend on the amount of discharge coming from the upstream catchment area. Conclusions based solely on stage measurements are not accurate and it is necessary to concurrently conduct discharge measurements as well. It is often possible to create a consumption curve on the control profilewhich enables credible calculations of river discharge based on the stage readings. This paper has shown that a discharge curve changes with the riverbed degradation, which means it needs to be regularly audited and updated with new measurements. Unfortunately, discharge measurements are not conducted as often and on as many watercourses as they should be, they are not continuous but discrete in time. Lack of monitoring causes lower awareness about the problems relating to structures in riverbeds, which in turn may lead to grave consequences, such as the accident at the 'Jakuševac' railway bridge in Zagreb. Advances in information technology, particularly in the field of acoustic equipment which operates on the basis of Doppler effect, simplify and speed up the methodology of measuring stream flow and riverbed bathymetry. Such equipment is available in Croatia. In accordance with this, monitoring of hydrological parameters at more important river sections, where there are bridges and other building structures, should be completed with discharge measurements and cross-section profile geometry.

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