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The Sava River Channel Changes in Slovenia
Spremembe struge reke Save v Sloveniji

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Abstract

Large alluvial rivers are often subject to changes in their planform, channel form (cross sections), and longitudinal profile of their channels; also due to human interventions such as river navigation and flood protection works. We have shown such temporal changes in two severely modified reaches of the gravel-bed river Sava, the largest river in Slovenia (11,735 km^2). The Ljubljanska Sava has significantly changed since the 19th century until today and this is largely due to long-term regulation of its channel, and later due to construction of hydroelectric power stations upstream of this section. The Lower Sava River, downstream of the confluence with the Savinja River, is severely modified due to regulation works and in the last years due to hydro power plants, in the reach at the Nuclear Power Plant Krško also due to the Krško weir. This study contributes to the understanding of fluvial processes when assessing the Sava River sediment budget, especially at the cross section with the Republic of Croatia.

Keywords: alluvial rivers, erosion, degradation, river dynamics, Sava River.

Izvleček

Večje aluvialne reke so pogosto podvržene spremembam v tlorisnem poteku, obliki svoje struge (pretočnega prereza) in vzdolžnega profila svoje struge; tudi zaradi človekovih posegov kot so ukrepi za zagotavljanje plovnosti reke in za varstvo pred poplavami. Zaznavne spremembe v daljšem časovnem obdobju smo prikazali na dveh močno preoblikovanih odsekih prodonosne reke Save, ki je največja reka v Sloveniji (11.735 km^2). Ljubljanska Sava se je bistveno spremenila od 19. stoletja do danes in sicer predvsem zaradi dolgoletnega reguliranja njene struge in kasneje zaradi izgradnje vodnih elektrarn na Savi gorvodno od tega odseka. Spodnja Sava, dolvodno od sotočja s Savinjo, je močno preoblikovana zaradi regulacijskih posegov in v zadnjem času zaradi vodnih elektrarn, na odseku pri Jedrski elektrarni Krško tudi zaradi jezu Krško. Ta študija prispeva k razumevanju rečnih procesov, ko poskušamo oceniti prodno bilanco reke Save, predvsem na mejnem prečnem prerezu z Republiko Hrvaško.
Ključne besede: erozija, naplavinske reke, poglabljanje, rečna dinamika, reka Sava.

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1. Introduction

The Danube River basin (length of the Danube River is 2857 km, catchment area 801,463 km^2, population ~81 million in 2005) is the second largest in Europe and shared by 19 countries and as such treated as the most international river basin in the world. Its major sub-basin is the Sava River basin (catchment area 97,713 km^2, population ~8.5 million in 2011), contributing ~25% to the Danube River discharge and covering 12% of the Danube River basin (Strategy, 2011). The Sava River basin is the major drainage basin in South-Eastern Europe, and is shared by »only« six countries: Slovenia, Croatia, Bosnia and Herzegovina, Montenegro and Serbia, while a negligible part of the basin area also extends to Albania. The Sava River basin catchment area in Slovenia is 11,735 km^2 and thus it covers more than a half (i.e. 58%) of the territory of the Republic of Slovenia (20,273 km^2), and is definitely the most important river in Slovenia.

International cooperation in the Danube River basin started in 1965 under the framework of the *International Hydrological Decade* and the *International Hydrological Programme* (Hofius, 1991). The cooperation in the Sava River basin was effectively an internal Yugoslav affair that changed after the establishment of new states in the basin. The cooperation got momentum in the second half of 1990s and culminated in 2002 by the signing of the *Framework Agreement of the Sava River Basin* between Sava River basin countries in Kranjska gora, Slovenia (FASRB, 2002). The document established the *International Sava River Basin Commission* (ISRBC), based in Zagreb, Croatia; it prepared the first *Strategy on Implementation of the FASRB* in 2008 that was later updated (Strategy, 2011).

One important achievement of the activities within the SRB guided by ICSRB was the preparation of the *Sava River Basin Management Plan* (SRBMP, 2013a) that has been developed according to the requirements of the *EU Water Framework Directive* (WFD). This directive establishes a legal framework to protect and enhance the status of all waters and protected areas including water dependent ecosystems, prevent their deterioration and ensure long-term, sustainable use of water resources.

During the preparation of the SRBMP, many issues were analysed in detail. However, the intention was to provide readable but condensed information in the SRBMP itself. Among those issues was also the question of hydromorphological alterations (SRMBP, 2013b).

Modification of the river morphology was recognised as an integrated pressure, which includes assessment of many man-caused changes. Based on the expert judgments and availability of the data in the Sava River Basin, and on the basis of the hydromorphological features mentioned in the British Standard EN 15843:2010 (BSI, 2010), the following parameters were selected (SRBMP, 2013b):

1. <u>River geometry (river in sinuosity meandering for one-channel river or cut-off side /secondary arms for braided river).</u>
   Man-caused changes in natural meandering of the water body have a clear negative effect on the ecological status of water body because they increase the flow in the main channel and change local habitats.
2. <u>Substrate/sediment composition (e.g. assessment of gravel extraction).</u>
   Sediments define the habitat type for biological quality elements (BQEs). Changes in them lead to changes in composition of BQEs, which are the key parameters for ecological status assessment.
3. <u>Large woody debris in the water body.</u>
   Large woody debris in water also provides habitat for biological quality elements (BQEs). Therefore their removal negatively affects the ecological status of water body.
4. <u>Bank structure (assessment of bank enforcement).</u>
   Non-natural bank enforcement also negatively affects environmental status of the water bodies because it causes significant erosion at the banks.
5. <u>Lateral connectivity of river and floodplain.</u>

A connected floodplain ensures the development of self-sustaining aquatic populations, flood protection and reduction of pollution in the entire river basin.

6. Riparian zone vegetation structure/type (land use in the riparian zone).
   According to the national legislations, land use in the riparian zone is limited.
7. Floodplain cover (land use in the river corridor beyond the riparian zone).
   Non-natural land use in the floodplain such as recreational and high intensity agricultural grassland, cultivated land, urban areas etc. have a negative impact on the ecological status of the water body.

The assessment of the selected hydro-morphological features was done according to the before-mentioned standard EN 15843:2010 (BSI, 2010). The results are shown in tables and graphically in maps added as annexes to the SRBMP (2013a).

One should notice that the EN 15843:2010 standard (BSI, 2010) aims to assess "departure from naturalness" as a result of human pressures on river hydromorphology. The EN 15843:2010 standard provides guidance on characterising the modifications of river hydromorphological features described in EN 14614:2004 standard (BSI, 2004). Both standards focus more on structural features (morphology) and continuity than on hydrology and geology; with regard to continuity they focus more on lateral and longitudinal continuity rather than on vertical continuity, which is difficult to measure. The importance of river longitudinal continuity was recently noticed also for Slovenian rivers; for the Mura River (Globevnik and Mikoš, 2009), and for the Sava River (Globevnik et al., 2010).

The assessment of modification of river morphology performed for SRBMP (2013a) was performed using five classes: "near-natural", "slightly modified", "moderately modified", "extensively modified", and "severely modified" (see Fig.1 for results). The names used to describe each class have been deliberately chosen to be different from corresponding terms used in the WFD (2000) (such as "high" or "good") to emphasize that hydromorphological classifications using the EN 15843:2010 standard (BSI, 2010) are basically unrelated to classifications of ecological status for the WFD (2000). Nevertheless, the five colours listed for reporting hydromorphological modification are the same as those in the WFD (2000); they are also used in Fig. 1.

The main drivers of morphological alterations in the Sava River basin are flood protection, navigation, hydropower, and urbanization. Based on the methodology of assessment of morphological alterations of rivers described in Background paper No. 4 (SRBMP, 2013b), 130 water bodies have been assessed. Morphological alterations have only been assessed for non-HMWBs (non-heavily-modified water bodies).

The main causes of river morphological alterations (3rd, 4th and 5th class of morphological quality) are changes to river geometry, channel longitudinal section and cross sections, substrate/sediment, bank structure, and lateral connectivity of river and floodplain.

The SRBMP (2013a) shows that in Slovenia (Fig. 1), severely modified reaches of the Sava River are those altered by hydro power plants (HPP Moste, HPP Mavčiče, and the HPP chain on the Lower Sava River – under construction: HPP Vrhovo, HPP Boštanj, HPP Arte-Blanca, HPP Krško, HPP Brežice, and the planned HPP Mokrice (HSE, 2016) and a short urbanized reach of the Ljubljanica River through the city of Ljubljana. In this review paper we present two examples of these hydromorphological alterations in the Sava River in Slovenia at a more detailed (regional) scale as shown in the SRBMP (2013a) (Fig. 1): the morphologically slightly modified reach of the Sava River close to the city of Ljubljana (called also Ljubljanska Sava River), and the morphologically moderately modified reach of the Lower Sava near the Nuclear Power Plant Krško.

These two examples of the Sava River changes in Slovenia collected from different studies performed in the past two decades presented in this paper, were also used when preparing the practical guidance for sustainable sediment management using the Sava River basin as a showcase: estimation of sediment balance for the Sava River (BALSES, 2013; Babić Mladenović et al., 2014).

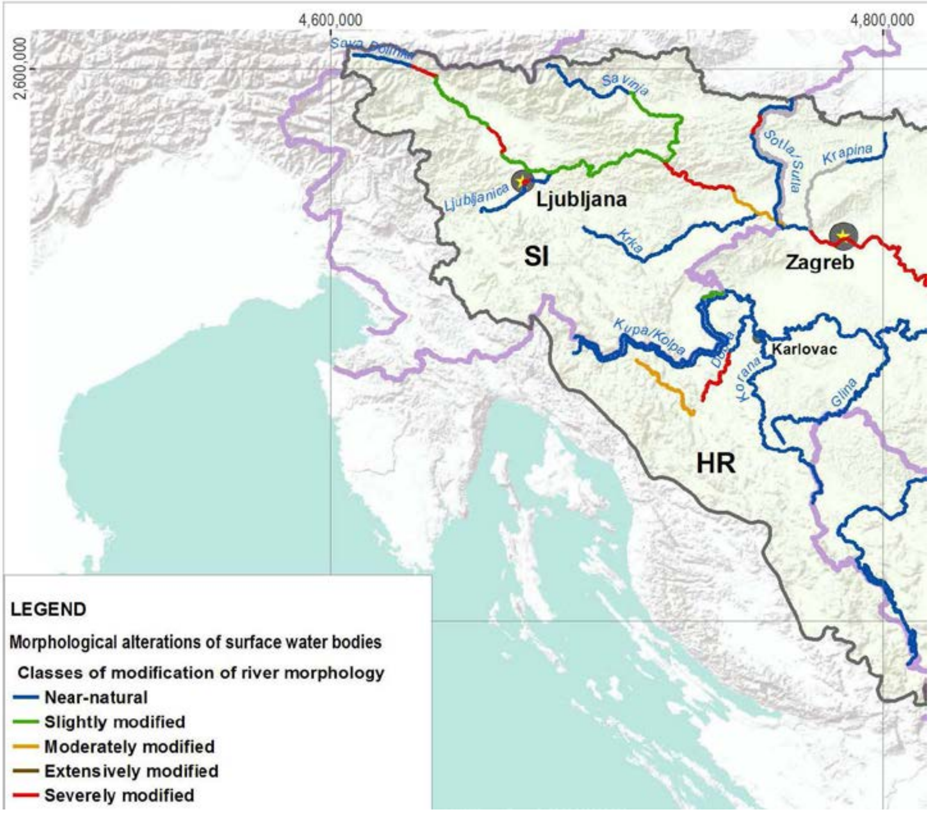

Figure 1*: Morphological alterations of surface water bodies in the Sava River Basin in a detail from Map 9 of (SRBMP, 2013a).*

Slika 1: *Morfološke spremembe vodnih teles površinskih voda v porečju reke Save v Republiki Sloveniji (detajl kartografske priloge 9 iz SRBMP, 2013a) – prikazanih je 5 razredov sprememb rečne morfologije.*

2. The Ljubljanska Sava River reach

2.1 The history of river engineering works (according to Muck, 2013)

In the area of water management in Slovenia, the name Ljubljanska Sava is reserved 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 an 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 (see Fig. 2). The Ljubljanska Sava is probably the river that was regulated and maintained the 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 river navigation works - preparation of the pathways along the river banks. This building of tracks (footpaths) was performed to connect the Radeče river port to the smaller river ports in Dolsko, Kleče and Zalog close to Ljubljana.

After 1600, trails on the Sava River banks (so-called towpaths, "Treppelwege" in German) were gradually being built and the Sava channel was regulated in order to tow ships with yoke cattle (and not only by using ropes or poles).

This enlarged freight on ships and imposed further needs for channel regulation. This was done mainly by using the water power in such a way that a small channel was manually dug out in the direction of a new river meander that was afterwards enlarged and deepened by the river flow.

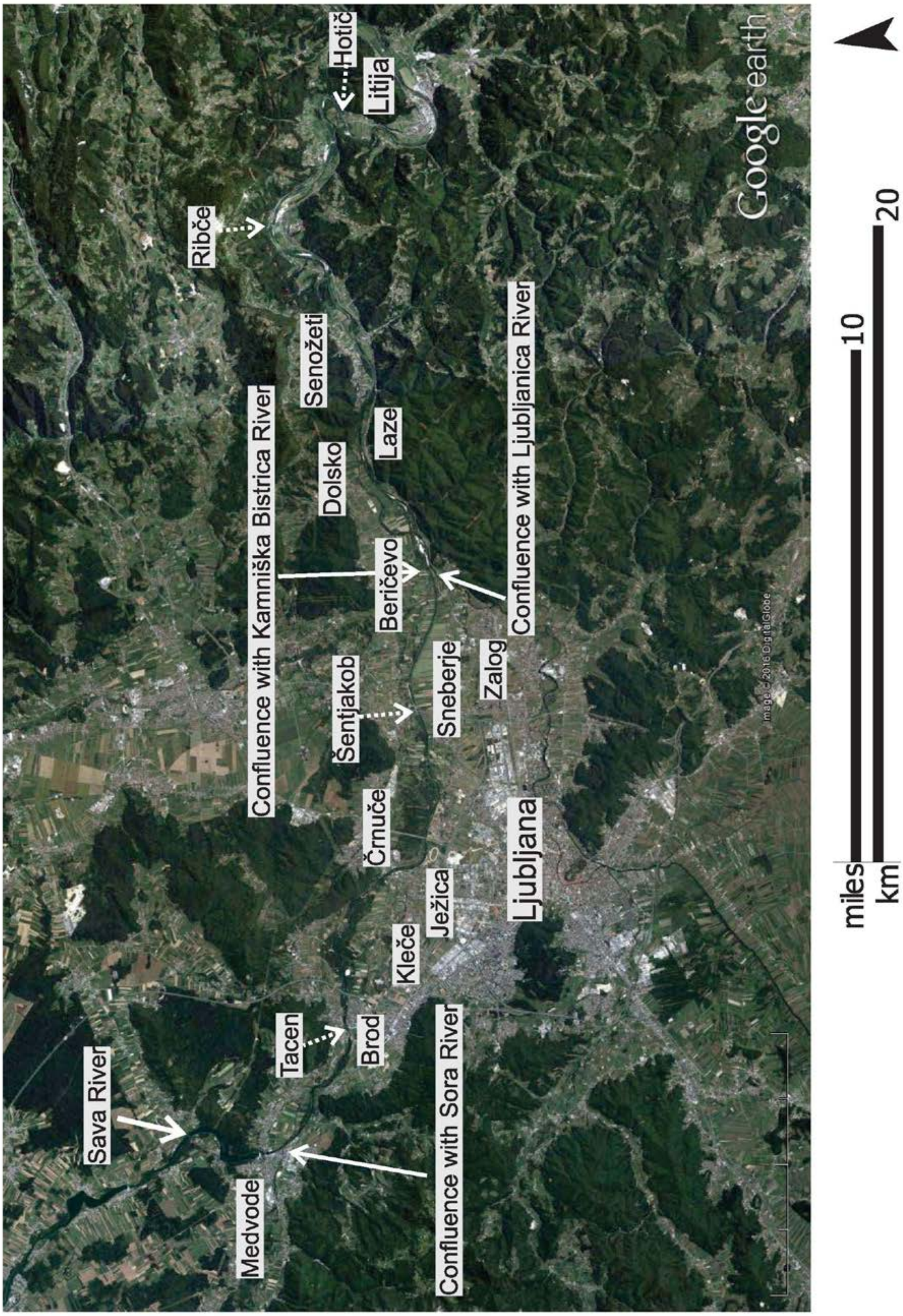

***Figure 2**: A reach of the Ljubljanska Sava River between Tacen and Litija – a section of an ortho photo map (Google Earth, 2016) – white arrows indicate confluences and cross sections of the Ljubljanska Sava River.*

***Slika 2:** Odsek Ljubljanske Save med Tacnom in Litijo – izsek iz orto foto zemljevida (Google Earth, 2016) – bele puščice označujejo sotočja s Savo in prečne prereze Ljubljanske Save.*

Before 1780, the first regulation works as a combination of riprap made of manually levelled quarry stone and dry stone wall were done close to Dolsko to protect the river port and the settlement. This 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 regulation works stopped with the First World War (WWI) (for situation in 1887 see Fig. 3, and in 1914 see Fig. 4).

Typical of the Austrian river engineering system, submerged bundles made of willow and poplar stakes from the local Sava River floodplains were used as the base and loaded with quarry stone made of different sized rocks from limestone to sandstone. The regulation between Tacen and Črnuče forced the Sava River into a more or less straight channel; today there are no traces left of this regulation. The river regulation works between Črnuče and Šentjakob were finished in 1890. The works used water stone of rather deteriorating quality; more problematic was the choice of the Sava riverbed width (only 37m, today it is 64m), and also the works were executed rather fast. Due to these facts, in only a few years the Ljubljanska Sava River took back its natural course in this reach except for the last kilometre upstream of the Šentjakob Bridge. After these works had been done, the realignment of the Sava River into a channel was tried several times, but with no success.

After WWI they prolonged the Ljubljanska Sava River regulation by 400m according to the old Austrian plans to 1400m upstream of the Šentjakob Bridge. This reach was rather stable and survived in more or less original form until today, but several maintenance works needed to be performed during this period. This is the reason why this reach is still aligned (straight) today and too narrow.

The Ljubljanska Sava River between Šentjakob and Dol, where the Ljubljanica and Kamniška Bistrica rivers flow into the Ljubljanska Sava, was regulated between 1900 and 1905. Also this reach was too narrow but has survived as planned and executed until today; mainly thanks to steady implementation of regulation works after each major flood.

The Ljubljanska Sava River between Dol and Senožeti was regulated between 1905 and 1910. The chosen riverbed width is unknown today; the regulation was not made of fully connected works, and the Ljubljanska Sava River changed its course many times and flew back into the dead arms between executed works. The reason for such a regulation was shortage on riprap stone (rock rubble) at the time.

Before WWI, the regulations works were also executed from Ribče to Hotič and from Litija to Ponoviče. During WWI, understandably only urgent maintenance works were performed (banks along roads, and sites close to bridges). Also for a few years after the end of WWI, the maintenance of the existing Austrian river regulation was not fully carried out.

This fact was unfortunately fatal for the regulation of the Ljubljanska Sava River. On November 28, 1923, a large flood set in and for nearly three weeks the discharges were well above the average ones. After the flood retreated, the devastation was immense: all existing hydraulic structures built for the regulation of the Ljubljanska Sava River downstream of the Tacen Bridge to 1 km upstream of the Šentjakob Bridge were completely destroyed or displaced (i.e. out of function).

The 1923 Sava Flood caused intensive bank erosion (new cut banks close to the settlements on the right bank of the river). Each new flood after 1923 worsened the situation, the river recovered its natural course (nowadays, such a state is highly desirable…). The lowest damage was observed on the reach Ribče – Dolsko, where Ljubljanska Sava riverbed width was chosen to be 70m.

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

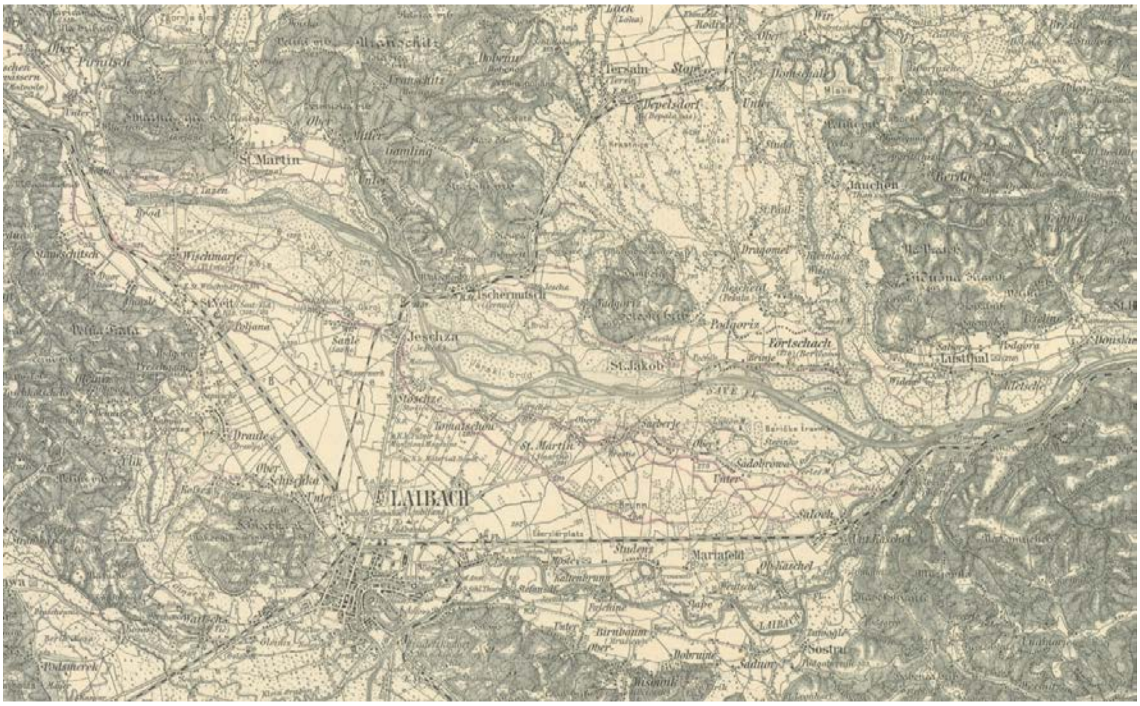

Figure 3*: The map in the scale 1:75,000 (situation in 1887), showing the upstream part of the Ljubljanska Sava from Tacen to Dolsko (downstream of the confluence with Ljubljanica and Kamniška Bistrica rivers).*

Slika 3: *Zemljevid v merilu 1:75.000 (razmere iz leta 1887), prikazuje gorvodni del Ljubljanske Save med Tacnom in Dolskim (pod sotočjem Save z Ljubljanico in Kamniško Bistrico).*

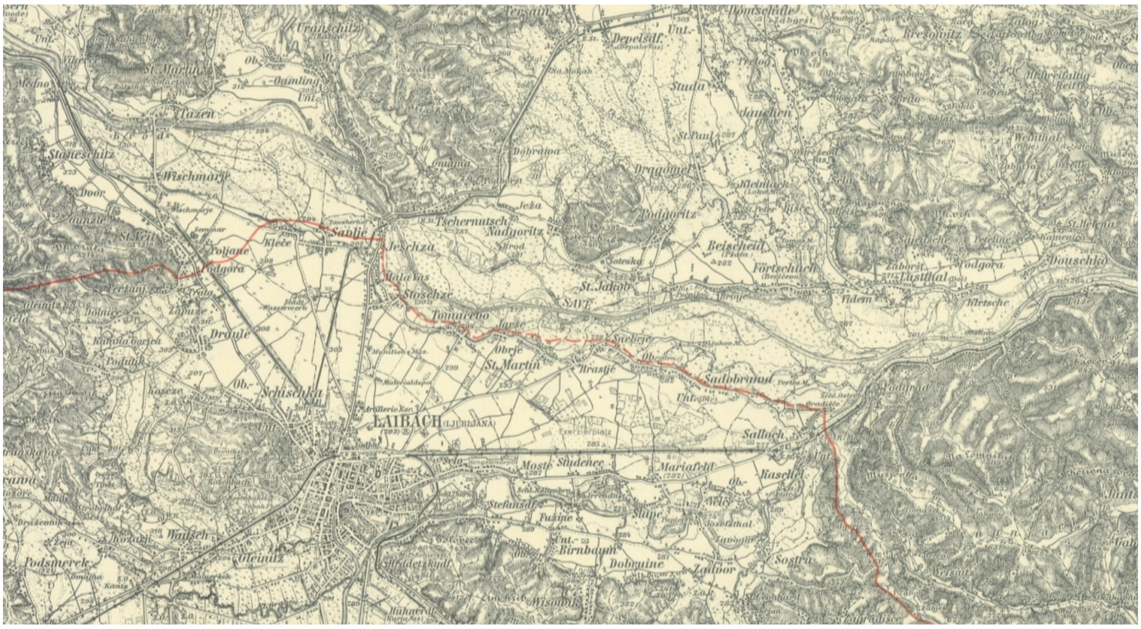

Figure 4*: The map in the scale 1:75,000 (situation in 1914), showing the same reach as shown in Fig.1 at the beginning of WW I; the red line is the state border during WW II between Italy (in the south) and Third Reich (in the north) (Militärgeographisches Institut, 1941).*

Slika 4: *Zemljevid v merilu 1:75.000 (razmere iz leta 1914), prikazuje odsek kot na sliki 1 na začetku 1. svetovne vojne; rdeča črta prikazuje državno mejo med 2. svetovno vojno med Italijo (na jugu) in Tretjim rajhom (na severu) (Militärgeographisches Institut, 1941).*

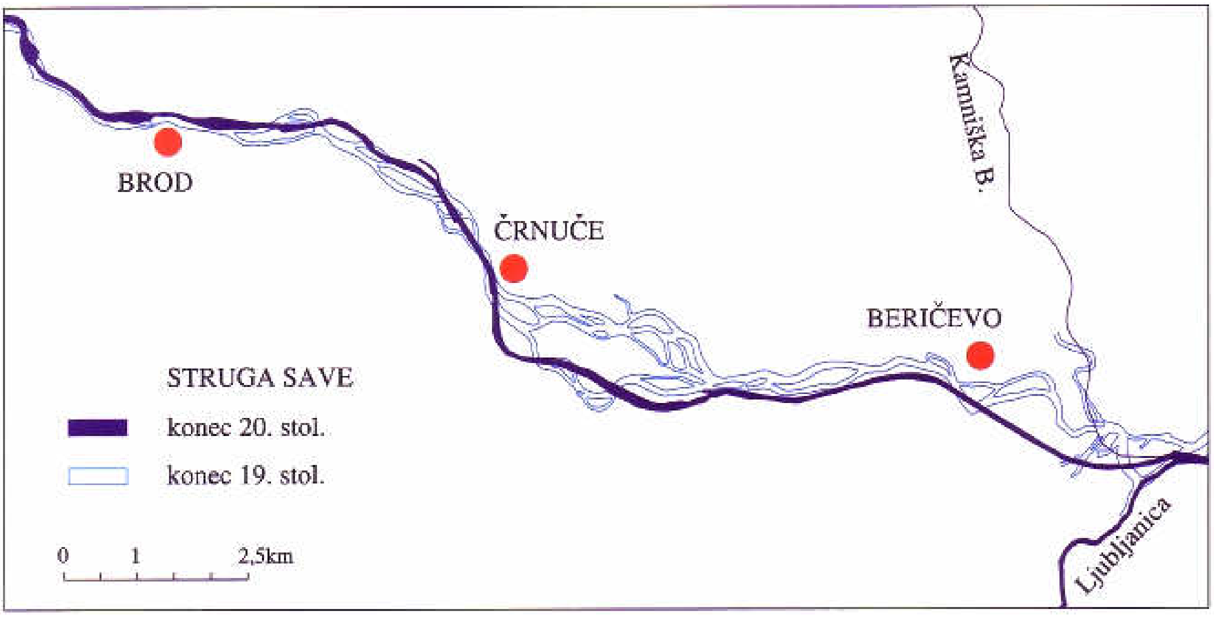

Figure 5: *The Sava River planform changes from the end of the 19th century to the end of the 20th century – the reach shown is upstream of the confluence with the Ljubljanica River and Kamniška Bistrica River (source: Mikulič, 1997 – after Savić, 2009).*

Slika 5: *Spremembe tlorisnega poteka struge reke Save od konca 19. stoletja do konca 20. stoletja – prikazan je gorvodni odsek od sotočja Save z Ljubljanico in Kamniško Bistrico (vir: Mikulič, 1997 – povzeto po Savić, 2009).*

In the Ljubljanska Sava River, different river engineering works have been tried out (differing from the practice in 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 piles. Frequent floods, i.e. in 1926 and 1931, worsened the situation. At first, the piles seemed to solve the problem, and the regulation works were afterwards financed without problems until the Second World War (WWII). However, many piles could not be driven through the rocky underground (conglomerates, greyish clay stone called in Slovenian "sivica"), and frequently, concrete blocks and submerged wattles were used without driven piles. On this reach, also some cuts through sandy banks were executed to realign the river course.

During the period between WWI and WWII, it was typical that the regulation works were done without a proper plan and were executed rather to minimise the bank erosion problems and natural sifting (wandering) of the river course.

During WWII, the new border between Germany and Italy was on the Ljubljanska Sava between Črnuče and Laze (3 km downstream of the confluence with the Ljubljanica River). In Italy, not much was done on the right river banks, only some local riprap protection works against bank cuts. In Germany, more activities were performed with local works executed downstream of the Tacen Bridge (close to Brod, Fig. 5), in Laze, Kresnice and downstream of Litija. The field railway was built from local quarries to the construction sites on the river banks, and therefore the executed protections works had enough rock rubbles and were of good quality.

After WWII, the maintenance works immediately started in Črnuče and Dolsko (~3 km downstream of the confluence with the Ljubljanica River), but were soon stopped in favour of drainage works in the Ljubljana Moors (south of Ljubljana) and in the flat Sava River floodplains to the north of Ljubljanska Sava River. The river was left untouched for some years, and it re-naturalised into a peri-alpine gravel-bed river with riffles and pools and white alluvial banks. The river was occasionally used for swimming. On the other hand, the river presented a risk for all settlements on the right bank between Ježica and Sneberje. Many works from the Austrian (prior to WWI) period were broached and required immediate repair.

After 1952, and with the new organisation of the water management sector in Slovenia, a new push for regulation works (especially between Tacen and Sneberje) was initiated. The basis for the regulation works was not a single large project; solutions were sought on 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, cuts through the alluvial banks were made by manually digging smaller channels so that Sava flow should enlarge them during floods by its own shear forces, ditches were dug along the foreseen longitudinal structures and the future water side was protected with riprap (rock rubble). The longitudinal and transverse structures (groins) built in water were made out of submerged fascines (wattles, mainly 5 to 6m long, several km a year were built), on the water side protected by riprap and loaded by pitched stone.

After 1960, mechanisation started to be used to excavate the full new river profile, but was still not successful; the Sava River frequently abandoned the new profile and started to flow again in the old channel. Therefore, the old channels were closed by bulldozers and filled with large pitched quarry stones. Nevertheless, after each flood, Sava chose which channel would be the main one. Introduction of deep rock blasting in large quarries made available large amounts of rock material for riprap protection. This was very important to repair damages after large flood events, such as downstream of the Šentjakob Bridge in 1976, or to use rock rubble to protect the crossing of the central gas pipeline of the diameter 1300mm with the Ljubljanska Sava River at Brod. With the extensive use of rock material, fascines were soon no longer applied, 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.

Figure 6: *The riverbed ramp downstream of the Šentjakob highway Bridge prior to the Sava 2012 Flood (source: Atlas okolja, 2016).*

Slika 6: *Drča dolvodno od avtocestnega mostu v Šentjakobu – pred poplavo 2012 (vir: Atlas okolja, 2016).*

Figure 7: *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 already been done (source: Google Earth, July 17, 2013).*

Slika 7: *Drča dolvodno od avtocestnega mostu v Šentjakobu – po poplavi 2012. Poplava je dolvodno od drče spodjedla desno brežino reke Save; sanacijski ukrepi so že bili izvedeni (vir: Google Earth, 17. 7. 2013).*

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 cut off the sediment inflow from upstream - annual sediment transport was estimated at ~28,500m^3 (Mikoš, 2000a). The reach incised by 2m, locally by 4m; the situation is worse downstream of Črnuče with impacts on bank protection works. After 1980, a temporary hiatus set in and no large damages occurred.

During this period, the major problem was the drop of the ground water level in the alluvial aquifer to the south of Ljubljanska Sava, which is the main drinking water source for the city of Ljubljana. In order to stop the incision and raise the ground water level, four riverbed ramps were built; their hydraulic impact and subsistence were checked in a hydraulic laboratory (Pemič, 1981). The downstream-most ramp was built in 1990 to protect the Šentjakob Highway Bridge.

In the 1980s, natural river engineering was tried to some extent in the Ljubljanska Sava River but without much success due to poor technical expertise of water management companies in this field, and due to low financial support. Nevertheless, for the Ljubljanska Sava River a study on side arms and dead arms was performed that made an inventory of their ecological value, water management impacts and species abundance. A study also listed river engineering measures needed to ensure their temporary or steady overtopping. The dead arms are presented downstream of the confluence with the Ljubljanica River to Litija (dead arms were not filled in), and not upstream of the confluence with the Ljubljanica River to Tacen due to a rather “mechanical” way of executing regulation works in 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), installed power of 338 MW, 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 are problematic due to the enlargement of the Natura 2000 areas in Slovenia that include this part of the Sava River in Slovenia.

2.2 The changes in the longitudinal profile

According to historical analysis of available data, the channel of the Sava River was changed (regulated) in the last 100+ years several times in this reach (see section 2.1).

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 (see Fig. 8). The 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 dam at Medvode for a new hydropower 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 the 1980s.

Nowadays, the riverbed is practically stabilised (see Fig. 9), the sediment transport is very limited (mainly only sediments flowing into the reach from the Sora and Kamniška Bistrica rivers). The annual amounts of bedload transport 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 the order of 20,000 m^3; see Mikoš (2000a) for the assessment of the Sava River sediment budget between Jesenice and Mokrice, and Mikoš (2000b) for the assessment of sedimentation in river storages of the Sava River run-off-the-river hydropower plants in Slovenia. This amount is confirmed by the volumes dredged (mined) at Hotič close to Litija, where a concessionaire for gravel mining reported such amounts to have been dredged annually in recent years (GEATEH, 2010) – these numbers should be taken into account with some precautions.

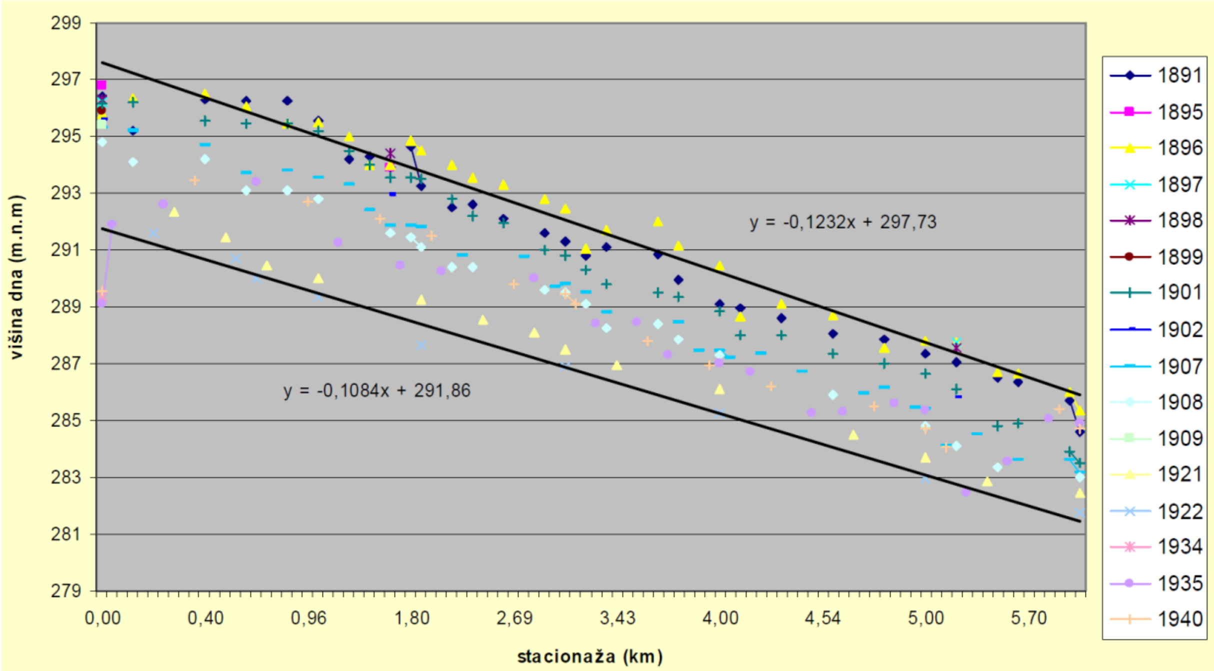

***Figure 8**: The Ljubljanska Sava River channel incision in the reach between Tacen and Črnuče in the period between 1891 and 1940 (source: ARSO; from Savić, 2009).*

***Slika 8:** Poglabljanje dna Ljubljanske Save na odseku med Tacnom in Črnučami v obdobju od 1891 do 1940 (vir: ARSO; iz Savić, 2009).*

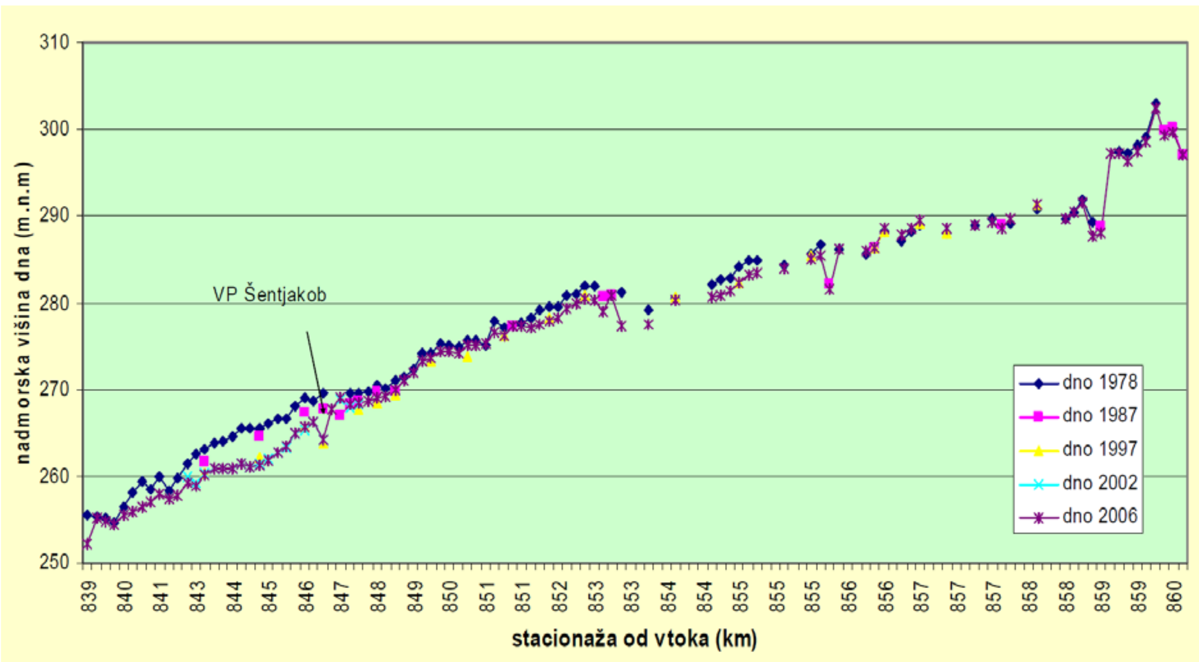

***Figure 9**: The Sava River channel incision in the reach between Tacen and Šentjakob in the period between 1978 and 2006 (source: ARSO; from Savić, 2009).*

***Slika 9:** Poglabljanje dna Ljubljanske Save na odseku med Tacnom in Črnučami v obdobju od 1978 do 2006 (vir: ARSO; iz Savić, 2009).*

3. Changes in the Sava River channel bed on the reach by the Nuclear Power Plant Krško, Slovenia

In the upstream reach of Krško, the Sava River flows downstream of Ljubljana through the Zasavje Hills in a narrow canyon-type valley. In the past few centuries (and before), the Sava River in its downstream-most reach in Slovenia flows on the Krško-Brežiško polje, i.e. large alluvial plains on top of the recent Sava fluvial deposits. It was a typical meandering gravel-bed river; see Fig. 10 for the changes in its planform for the period between 1784 and 2007, and Javornik and Stojič (2008) for more historical details.

The Nuclear Power Plant Krško (NPP Krško) has a major weir on the Sava River to obtain cooling water for the reactor. The documents important for its operation (Updated Safety Analysis Report – USAR) in the section 9.2.5 Ultimate Heat Sink (UHS) and NEK TS LCO 3.7.5, define a minimal water level to ensure the minimal required water intake for cooling the NPP Krško safety systems and condensate cooling system and the maximal water temperature of the Sava River in the reach between the weir of the NPP Krško and the Town of Krško that must be available even if the weir of the NPP Krško is fully opened (MOP, 2010). The Krško weir has a concrete sill that assures the minimum water quantity for UHS. That is why NPP Krško regularly (each 5 years or after a large flood) measures the reservoir upstream of the weir to the Town of Krško. 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 is being executed since the 1970s. 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 1m and 2m between river km 743.087 and river km 745.814 (GEATEH, 2011).

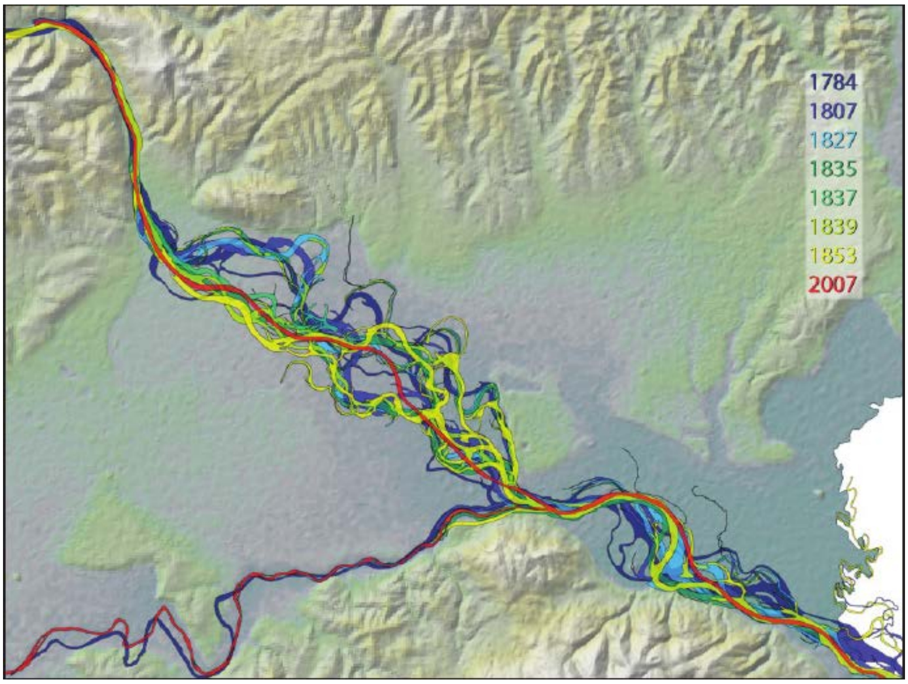

Figure 10*: The Sava River channel between Krško and the present boundary with the Republic of Croatia in years 1784, 1807, 1827, 1835, 1837, 1839, 1853, and 2007 (source: ZVKDS, 2008; Fig. 16, p. 9).*

Slika 10: *Struga reke Save dolvodno od Krškega do sedanje državne meje s Hrvaško v letih 1784, 1807, 1827, 1835, 1837, 1839, 1853 in 2007 (vir: ZVKDS, 2008; slika 16, str. 9).*

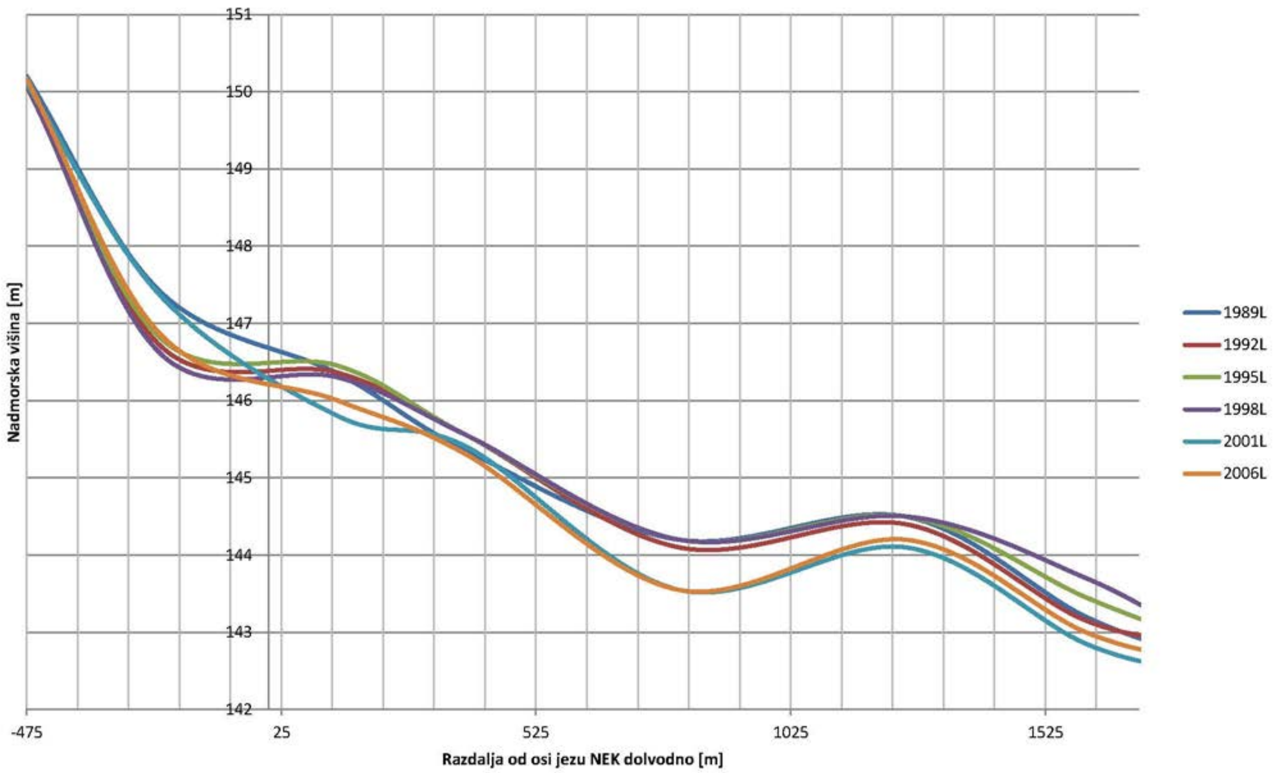

Figure 11: *The longitudinal profile of the Sava River at the weir of the NPP Krško in 6 years in the period 1989 – 2006; x-axis shows the downstream distance from the Krško weir axis in m, and y-axis shows the height above the sea level in m (Source: GEATEH, 2011).*

Slika 11: *Vzdolžni profil reke Save ob jezovni zgradbi Jedrske elektrarne Krško v 6 letih med 1989 – 2006: x os prikazuje razdaljo od osi jezu NEK dolvodno v metrih in y os prikazuje nadmorsko višino v metrih (vir: GEATEH 2011).*

A comparison of the Sava River channel bed levels in the period 1989 – 2006 (also for 2009) is shown for the channel axis in Fig. 11: it shows 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 by ~0.4m, and in the period 2006 to 2009 by 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. This effect might be explained by the fact that coarse sediments have already filled the HPP Vrhovo reservoir and during recent floods a part of deposited sediments in the HPP Vrhovo reservoir were resuspended and transported to the downstream Sava River reaches, contributing to a partial saturation of the river flow with sediments. The latent erosion in the Lower Sava River is now partially counterbalanced by the sediments passing through the HPP Vrhovo reservoir.

4. Discussion and conclusions

From a historical overview of river works done in the Ljubljanska Sava, we can conclude that for quite a long time the executed works were rather ineffective and that the first Sava flood took them right away – a yet another regulation of this reach took place. After WWII, and the construction of hydropower plants on the Sava River itself as well as many torrential works done in the watersheds of main Sava River tributaries upstream of the Ljubljanska Sava, the effective sediment transport rates decreased, the river started to incise into its own alluvium, and as a countermeasure, ground sills (riverbed ramps) were built in order to stop incision. The groundwater levels of the Ljubljansko Polje to the north and to the south of the Ljubljanska Sava River were soon observed to be closely related to the position of the Sava riverbed (Radinja, 1951), and groundwater is the main source of the Ljubljana drinking water supply. The river engineering works changed in decades from river navigation and flood protection to stabilising the riverbed in order to secure drinking water supply. As a consequence, latent erosion started to prevail in the Ljubljanska Sava River, and the effective sediment transport rates decreased, as noticed by sediment dredging in Hotič (downstream of Litija).

The proposed chain of up to nine hydro power plants on the Sava River between HPP Medvode and the confluence with the Savinja River may improve flood protection of the neighbouring land - but potential siltation of the proposed reservoirs, and hence decreased infiltration of the Sava River water through the river banks and bottom to recharge the groundwater aquifer in the Ljubljansko Polje should be carefully examined and technical countermeasures may be foreseen, such as artificial recharge in excavated infiltration ponds close to the Ljubljanska Sava river banks.

For the Lower Sava River reach close to NPP Krško, the historical evolution is not very different from the one of the Ljubljanska Sava River. The Sava river regulation works for river navigation turned into flood protection works, and their importance was even more stressed after the construction of the NPP Krško in 1981 (net electrical power 696 MW, average annual production 5.1 TWh). The inflow of sediments from the upper reaches of the Sava River decreased (see the evolution in the Ljubljanska Sava River), and the sediment inflow from the Savinja River was stopped to a large extent after the construction of HPP Vrhovo in 1987 – the situation started to change in the last decade after the last few large floods on the Lower Sava River when partially deposited sediments in the HPP Vrhovo reservoir were resuspended and transported to the downstream reaches, partially saturating the river flow with sediments. However, any sediments coming to the cross section of the NPP Krško are blocked by the Krško weir, and dredged out in order to secure sufficient water levels for safe operation of the NPP Krško – its cooling water is extracted from the Sava River.

Since a chain of hydropower plants is under construction on the Lower Sava River that will eventually (with the construction of the HPP Mokrice) reach the border with the Republic of Croatia, it is essential to maintain such a sediment transport regime through the finally built run-off-the-river hydropower plants downstream of HPP Vrhovo that the inflowing sediments to this reservoir will be removed at high flows in the Sava River, and transported through the chain of reservoirs towards the border cross section at Jesenice na Dolenjskem.

The problem of the obligatory sediment dredging upstream of the Krško weir can be effectively solved by either:

- finding a new technical solution for the cooling water for NPP Krško that will not be based on the minimal water levels upstream of the Krško weir, such as building a large enough water pond close to the facility to be used instead of directly using the Sava River water, or by
- adding the dredged sediments from the upstream of the Krško weir back to the Sava River (redumping, artificial bedload supply) at some distance downstream of the weir (for a similar solution to stop incision of the Rhine River downstream of the Lake of Constance to ensure safe navigation, see Goelz (2008) and Goelz et al. (1995).

Other countermeasures, such as local river widening (removal of embankments) to increase sediment supply from river bank erosion cannot be performed in a river reach with a chain of run-of-the-river hydropower plants.

What can be done in other morphologically altered gravel-bed rivers in Slovenia, where constraints are not so strict?

For a successful river restoration to a “natural” river (i.e. to change back hydromorphological alterations caused by human interventions), scenarios should be planned at catchment scale; i.e. restoration measures for a river section are "nested" into large restoration scenarios. One possibility for doing so is to apply the River Scaling Concept (RSC), which suggests a two-step procedure (Habersack, 2000). In the first phase, called the downscaling phase, one should analyse major boundary conditions and processes as well as patterns in a selected river to be restored. We have done that for the Mura River in Slovenia (Globevnik and Mikoš, 2009), following experiences gained by a basic water management concept for the border reach of the Mura River between Austria and Slovenia in late the 1990s (Petkovšek and Mikoš, 2000; Novak et al., 2004) with the main aim of preventing further Mura River incision in this reach.

In the second RSC phase, called the upscaling phase, models are used to aggregate information in a way that allows for planning of detailed restoration measures to be suggested for each scale. In the Mura River in Slovenia this step has not been done yet, and for the Lower Sava River, this step will not be possible, since this river is hydro-morphologically severely modified due to a chain of HPPs. The same is true for the Ljubljanska Sava River, where a chain of hydropower plants is also planned to be built.

When planning the removal of existing river morphological alterations caused by human interventions in the past, e.g. as a part of river corridor management (IzVRS, 2014a), it is extremely important to balance interests of as many stakeholders as possible (fishery, energy production, flood defence, navigation, gravel mining, water abstraction, irrigation, nature conservation… to mention but a few) within the framework of an integrated river basin management, as shown for the Drava River in Slovenia by IzVRS (2014b) and NEKI (2014).

As an international example of good practice, we can mention the Sava River basin and the International Sava River Basin Commission (ISRBC) that takes the leading role in stimulating and governing international cooperation between the countries in the Sava River Basin. A step forward from management to governance was done in 2015, when the ISRBC established the Sava Water Council. This body had at the time of its establishment exactly 50 members (stakeholders) from five Sava River Basin countries (12 from Slovenia, including UL FGG, whose representative is the first author of this paper). It is a standing advisory group to the International Sava River Basin Commission, the first such advisory group of stakeholders to an international river commission in any river basin in Europe (!).

This was achieved by following examples of good practice outside Europe, such as the example of the Missouri River Recovery Implementation Committee, established in 2008 (MRRIC, 2016). The Missouri River drains one-sixth of the United States, and the Missouri River Recovery Implementation Committee (MRRIC) serves as a basin-wide collaborative forum to come together and develop a shared vision and comprehensive plan for Missouri River recovery.

It is a big challenge of the 21st century to come to a generally accepted agreement to overcome the classical state-driven top-down water management approach and replace it with a promising stakeholder-driven bottom-up water governance approach. Part of these efforts is also a better general knowledge of river processes and the impacts of past human interventions on river regime. We must find a way to satisfy our increasing needs (or perhaps reduce them!?) with the cry for environmentally friendly development without bringing the Earth out of balance.

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