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CHARACTERISTICS OF POINT-BAR DEVELOPMENT UNDER THE INFLUENCE OF A DAM: CASE STUDY ON THE DRÁVA RIVER AT SIGETEC, CROATIA

Tímea Kiss*, Márton Balogh

Department of Physical Geography and Geoinformatics, University of Szeged, Egyetem u. 2-6, H-6722 Szeged, Hungary
*Corresponding author, e-mail: kisstimi@gmail.com

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Abstract

Before the extensive engineering works the Dráva River had braided pattern. However in the 19-20th centuries river regulation works became widespread, thus meanders were cut off, side-channels were blocked and hydroelectric power plants were completed. These human impacts significantly changed the hydro-morphology of the river. The aim of the present research is to analyse meander development and the formation of a point-bar from the point of view of indirect human impact. Series of maps and ortho-photos representing the period of 1870-2011 were used to quantify the long-term meander development, rate of bank erosion and point-bar aggradation. Besides, at-a-site erosion measurements and grain-size analysis were also carried out. As the result of reservoir constructions during the last 145 years floods almost totally disappeared, as their return period increased to 5-15 years and their duration decreased to 1-2 days. The channel pattern had changed from braided to sinuous and to meandering, thus the rate of bank erosion increased from 3.7 m/y to 32 m/y. On the upstream part of the point-bar the maximum grain size is 49.7–83.4 mm and the mean particle size is 7.6 mm, whilst on the downstream part the maximum grain size was only 39.7–39.9 mm and mean sediment size decreased to 6.1 mm. Due to the coarse sediment supply and the decreasing stream energy the point-bars develop quickly upstream and laterally too.

Keywords: point-bar, meander development, gravel-bar, grain-size distribution, effects of dams

INTRODUCTION

The number of hydroelectric power plants and their reservoirs built on rivers is increasing worldwide due to their sustainable power production, however no one should ignore their environmental effects (Bonacci and Oskorus, 2008). The major effect of hydroelectric power plants and reservoirs is the interruption of the continuity of sediment transport processes, thus the river system will be disconnected (Ristić et al., 2013). The disconnection is manifests in the form of flow regime alteration, changing in slope and velocity, which result in altered stream power conditions (Kiss and Andrási, 2011). Behind the dam, in the reservoir the power of the flowing water significantly decreases, thus most of the sediment (33-99%) retained, thus the reservoir is slowly filled up (Peter, 1997; Petts and Gurnell, 2005; Woodward et al., 2007). Usually on the downstream section the hydrology becomes more even, as the height and frequency of floods decreases, whilst the height and duration of low stages increases (Williams and Wolman, 1984; Petts and Gurnell, 2005; Lajolie et al., 2007). Downstream of the reservoirs the process of “clean water erosion” is significant (Knighton, 1998), therefore accelerated lateral or vertical channel erosion takes place (Williams and Wolman, 1984; Petts and Gurnell, 2005). As the result of the accelerated erosion and the controlled (usually decreased peak) discharge the river mobilizes the smaller particles from the riverbed, thus the bed-material gets coarser, therefore bed armour develops (Dietrich et al., 1989). These processes alter the morphology of the rivers, therefore very often downstream of the reservoirs the channel pattern changes (Gregory and Park, 1974; Williams and Wolman, 1984; Xu, 1996; Brandt, 2000; Magilligan et al., 2008), or the rate of the processes (e.g. meander development) alters (Shields et al., 2010; Blanka, 2009). Some of the hydroelectric power plants are peak-operated, thus during the main hours of energy consumption mini-floods are generated resulting in the mobilisation of the bed-load and modification of the bedforms (Merritt and Cooper, 2000; Kiss and Andrási, 2011). The spatiality and temporality of the bed processes could be evaluated by analysing the grain size of the bed-load (Belal, 2015). The gravel-bars in rivers are sensitive indicators of the altering fluvial morphology caused by dams, as they could be destroyed by floods or stabilised by vegetation (Fergus, 1997; Xu, 1997).

The main reason of the formation of fluvial bars is the local decrease in flow energy (Sipos, 2004). During the bar development the first step is the deposition of coarse bed-load sediment in the space between the high-energy transportation routes, later in the low-energy zones finer sediments also trapped behind the large gravels (Leopold and Wolman, 1957). Around the evolved form the flow splits, which results in increased bank erosion. Due to the lateral erosion the river widens locally, thus it loses energy (Ferguson and Werrity, 1983). Ashmore (1991) made laboratory experiments and measurements to understand the dynamics of the bar formation.

There are two main types of river bars (Balogh, 1991). The first group is located in the middle of the river, and the mid-channel bar, the crescent-shaped bar, the longitudinal bar and the transverse bar belong to this group. The second group is located along the banks and this group consists of the point-bar and the side-bar. The diagonal bar is a transitional form between these two groups (Knighton, 1998), though by time all these bar types can transform into each other, which makes their identification difficult. According to Dykaar and Wigington (2000) the spatial and temporal variations of the river bars causing braiding are determined by the speed of accumulational and erosional processes, and variations of discharge.

Human activities have been altering the hydrology and the morphology of the Dráva River since the 19th century. First the large meanders were cut-off resulting in metamorphosis, as the meandering pattern became braided (Kiss and Andrási, 2014). In the 20th century the regulation was completed by revetment and groynes constructions, side-channels blockages, and construction of reservoirs and hydroelectric power plants. These engineering works altered the water and sediment regime of the river, leading to morphological alterations. The aim of our research is to study the formation of a meander in detail, and to evaluate the role of indirect human impact in meander development.

STUDY AREA

The Dráva River springs in the Tyrolean Alps and runs to east, so after 749 km it flows into the Danube. Its catchment area (40,489 km^2) extends to five countries. The area studied in detail is downstream of the confluence of the Dráva and Mura Rivers (Fig. 1), near to the Croatian village Sigetec (at 220–222 fluvial km). The selected meander is just 26 km downstream of the Donja Dubrava Hydroelectric Power Plant, thus its indirect effects could be studied in detail, whilst no other direct or indirect human impact affected the evolution of the bend.

The slope of the studied section of the Dráva River upstream of Őrtilos gauging station is 80–130 cm/km, whilst along the studied section it decreases to 45–55 cm/km (Kiss et al., 2011). The mean discharge of the river is 510 m^3/s and the rate of sediment transport (280,862 t/y) is recently only the 28% of the amount it used to be before the construction of nearby hydroelectric power plants (Bonacci and Oskorus, 2008). The grain size of the bedload decreases downstream: cobbles with a diameter of 6-8 cm are frequent, though only coarse sand appears near Barcs, and at the confluence of the Danube and Dráva Rivers the dominant fraction is sand (Kiss and Andrási, 2012).

The hydro-morphologic properties of the Dráva have been greatly altered during the last one and half centuries (Kiss and Andrási, 2012). Between 1784 and 1904 altogether 65 meanders were cut off shortening the original length of the river by 185 km, the last cut-off was made in the 1990's (Remenyik, 2005). Several bank-sections were stabilized, and groynes were built to block side channels and to support shipping, especially downstream of Barcs. Since 1910's numerous (22) hydroelectric power plants have been constructed on the Austrian, Slovenian and Croatian section of the Dráva River. The Croatian hydroelectric power plants were built between 1975 and 1989, significantly changing the flow and sediment regime of the river (Bonacci and Oskorus, 2008). As a result of these regulation works the frequency of the floods decreased (Kiss and Andrási 2011). In the study area the lowest, Donja Dubrava Hydroelectric Power Plant generates 1.5–1.7 m high “mini flood-waves” twice a day due to its peak-hours operation.

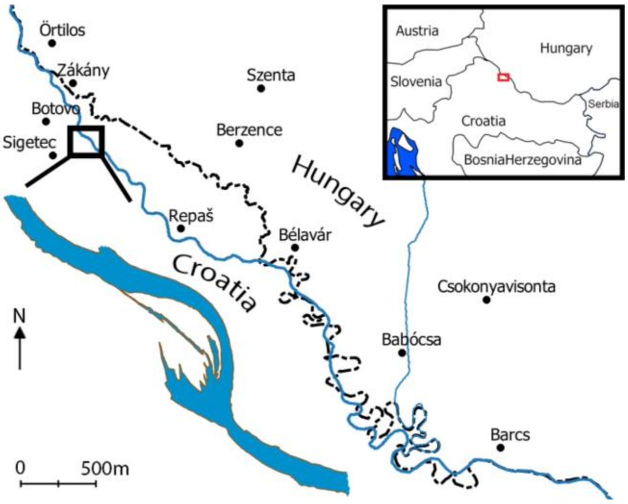

Fig. 1 The studied meander is located east of Sigetec, on the Croatian section of the Dráva River

METHODS

The hydrological changes of the Dráva were evaluated based on daily stage data measured at the Barcs gauging station since 1900. The frequency curves of the stages were made for each decade to evaluate the hydrological changes. As floods are very important forces in the fluvial system, the number of flood-days (over 420 cm) and their return period were also calculated.

The long-term development of the selected meander (section) was studied based on a map series containing the Third Military Survey (1870), the maps of the Hydrological Atlas of the Dráva (1966), topographical maps (made in 1944 and 2001) and an ortho-photo (2011). These maps were geo-corrected using ERDAS Imagine 9.1 and Quantum GIS 2.8., as they were made using different scale and projection systems. The average channel width of the Dráva was defined as the ratio between the area of the polygon between the bank-lines and the centreline. The lateral erosion was calculated based on the area of the polygon between bank-lines surveyed at two different times. The arch-length was measured between two inflection points along the centreline, whilst the chord length was measured directly between the two inflection points. The amplitude refers to the size of the meander, as it is the greatest perpendicular distance between the chord and the centreline. The radius of curvature is the radius of the greatest circle fitted into the meander's centreline. The development stage (β) of the meander was determined after Laczay, as the ratio between the centreline and the chord length.

The short-term bank erosion was measured annually between October of 2013 and January of 2015. Field measurements were made using the Real Time Kinematic network and the TOPCON total station theodolite with a centimetre accuracy.

Recently several researches attempt to derive the grain size distribution using digital images (Butler et al., 2001; Carbonneau, 2004; Graham et al., 2005; Chang and Chung, 2012) and we also applied this technique. In a low-stage-day we took 68 digital photos placing a reference frame (40*40 cm) on the dry gravel surface. The photos were imported into the Digital Gravelometer software, then the properties of the camera were given, finally we defined the corners of the reference frame. The programme calculates the grain-size distribution of the bar surface. During the study the Wentworth scale was applied.

RESULTS AND DISCUSSION

Hydrological changes of the Dráva River

Based on the characteristics of the hydrology the dataset of 1901-2012 could be divided into three periods. The first period (1901-1917) could be considered as almost natural, as nor the floods, neither the lower stages reflected decreasing tendency. This is reflected by the overlapping frequency curves (Fig. 2). At the beginning of the 20th century floods returned in every year and they covered the floodplain for 2-3 weeks (in 1904: 54 days). Within a year floods normally were rapid and their return period was 4-6 months.

In the second period (1918-1967) the average and minimum stages show decreasing trend, as they decreased by 90-100 cm, and the frequency curves also shifted down. The stage of the floods did not change considerably, though they became shorter and in some years they did not even occur, thus their return period increased to 1.4-2 years.

In the last period (1968-2012) the above described processes became more pronounced, which became especially characteristic after the beginning of the operation of the Varasd (1976) and Donja Dubrava Hydroelectric Power Plants (1989). The average and minimum stages decreased further by 130 cm, the height of highest stages did not reach the edges of the banks (thus floods disappeared). The frequency curves shifted down characteristically, so for example in the 2000-2010 decade stages were higher than 100 cm occurred just only in 20% of the period, though they were in 100% in the 1900-1910 decade. Floods almost totally disappeared, as their return period increased to 5-15 years, and their duration decreased to 1-2 days (Fig. 3).

Long-term meander development

At the time of the Third Military Survey (1870) the studied Dráva section had braiding pattern (Fig. 4) and the flow was split between 5 islands. The width of the channel varied between 536–1813 m.

Between 1870 and 1942 the morphology of the river reach changed, as the braided pattern was replaced by meandering, and the islands melted to the banks. The channel width decreased by 85–87%, as in 1942 it was only 81–225 m. The arch-length of the meander was 1573 m, the chord length was 1489 m, the amplitude was 239 m and the radius of curvature was 931 m. According to the meander classification method of Laczay the studied meander belonged to the group of "juvenile meanders" (β=1.06). The pattern change was probably caused by the regulation works, which terminated the braiding and created a meandering single-bed river.

Until the next survey (1968) the channel became wider, as the maximum channel width (266 m) increased by 18% and the minimum width (90 m) increased by 11%. The rate of lateral bank erosion varied between 3-40 m (0.1-7.3 m/y), and its average was 3.7 m/y. All horizontal parameters meander decreased between the two surveys (1942–1968). The arch-length of the meander (1025 m) decreased by 35%, the chord length (988 m)decreased by 34%, the amplitude (95 m) became smaller by 60%, and the radius of curvature (857 m) also decreased by 8%. The meander based on its β value (1.04) still remained juvenile.

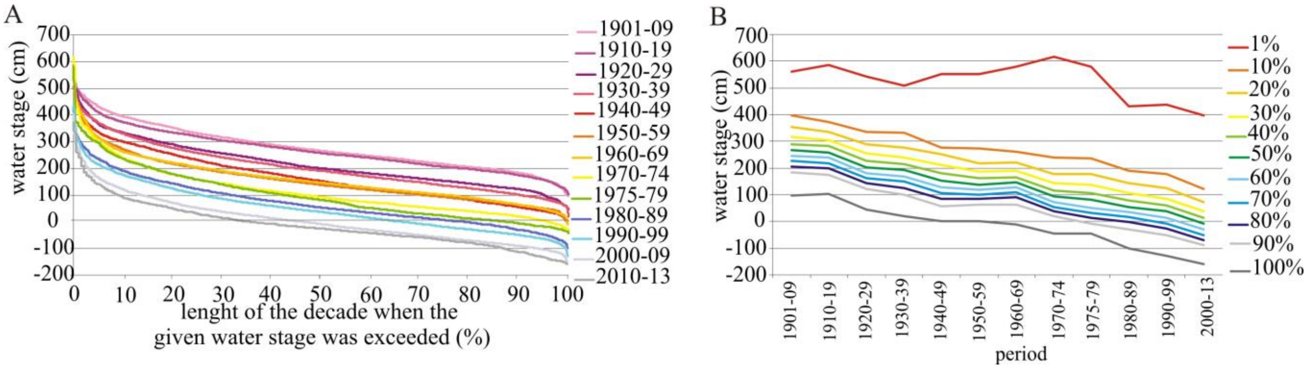

Fig. 2 Frequency distribution curves of decadal stages (A) and height (cm) of different stage frequencies (B) based on the dataset of Barcs gauging station

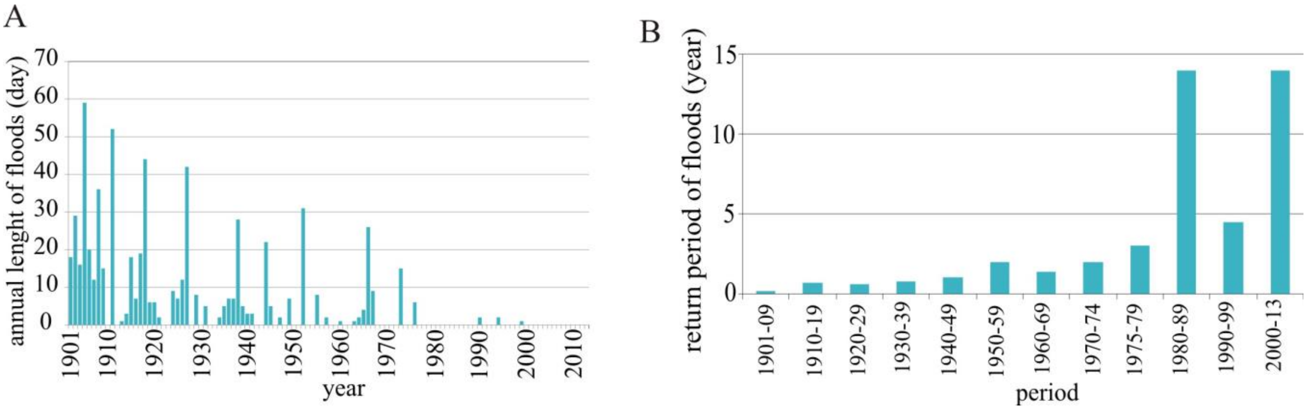

Fig. 3 Yearly number of flood (>420 cm) days (A) and the return period of floods (B) at Barcs gauging station (1901-2013)

By 1977 the studied section did not change considerably, however the meander upstream of the studied bend became sharper (decreased chord length and radius of curvature), thus it rapidly migrated downstream, thus the reach became more sinuous. The maximum width (247 m) of the studied meander decreased by 7 %, though the minimum width (108 m) increased by 20 %, thus the channel became more uniform. As the thalweg became more pronounced due to the shift of the upstream meander, the average rate of bank retreat increased to 5.6 m/y (151%). During the meander migration the erosion (11 ha) exceeded the accumulation (7 ha). All values of the horizontal parameters increased: arch-length became 1441 m (41%), chord length 1407 m (425), amplitude 140 m (47%), radius of curvature 1101 m (28%). As the parameters increased by the same rate, the shape of the meander did not change significantly (β=1.03), it remained a juvenile meander.

Between 1977 and 2001 the studied meander changed considerably, as it migrated downstream and a well-developed point-bar system evolved. The width of the channel decreased, as its maximum (216 m) and minimum (103 m) width reduced by 13% and 5% respectively. The annual rate of the lateral shift exceeded the former period by 4% (5.8 m/y). The greatest rate of the lateral migration increased by 72% (11.4 m/y) and the minimum decreased by 50% (0.1 m/y). The rate of the accummulational and erosional processes has been greatly increased, as the eroded area was 29 ha (+164%) and accumulated area was 38 ha (+443%). Most of the

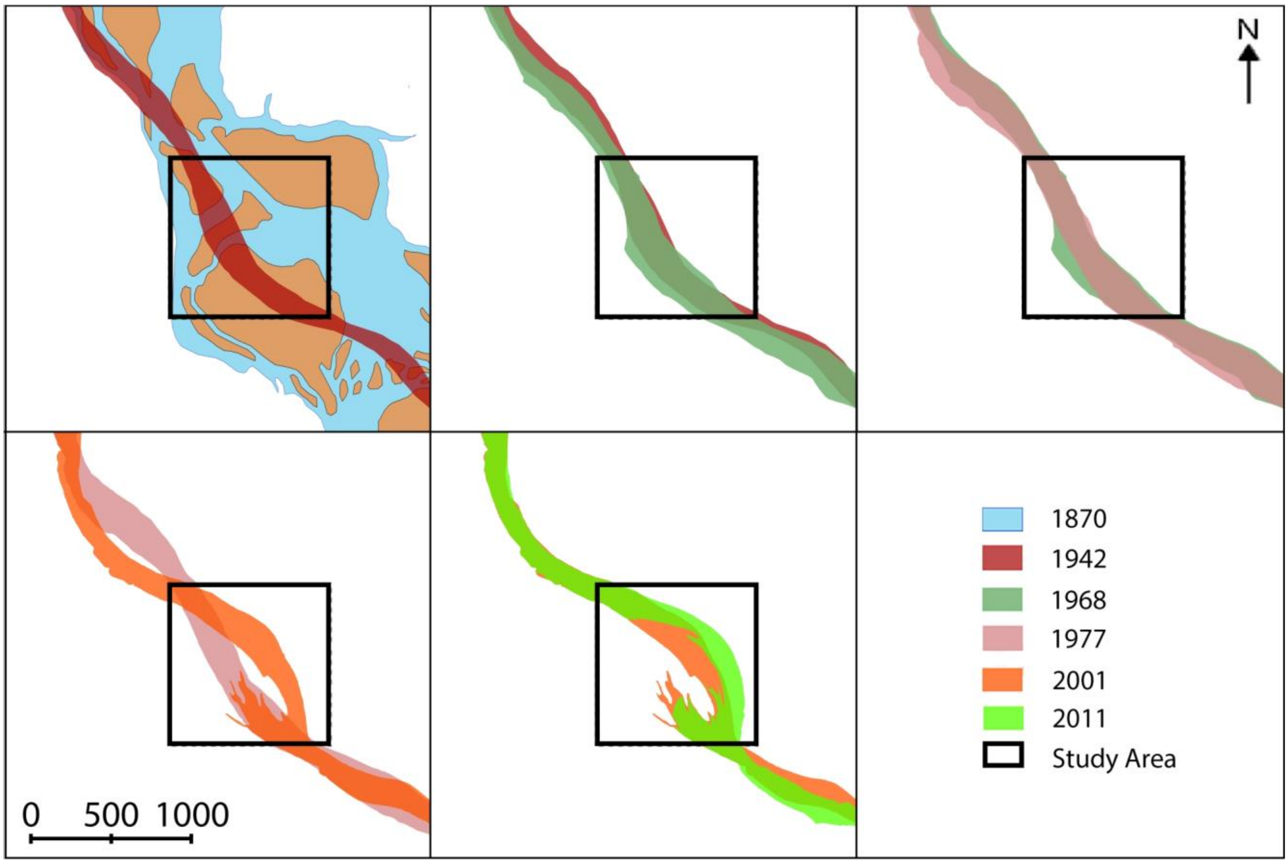

Fig. 4 Long-term meander development of the studied section

horizontal parameters decreased, for example the arch-length of the meander decreased by 13% (1254 m), the chord length by 16% (1177 m), and the radius of the curvature by 9% (999 m), meanwhile the amplitude increased by 33% (186 m). The β value increased to 1.07, indicating slow meander development.

Between the 2001 and the 2011 surveys the meander developed further on. The maximum channel width decreased by 11% (192 m) and the minimum decreased by 22% (80 m). The average rate of lateral shift was 9.5 m/y, which exceeded the former period by 64%. The maximum rate of the bank erosion was 189 m (18.9 m) and the minimum was 1 m (0.1 m/y). During the lateral migration the total amount of erosion was 14 ha, whilst the area of the point-bar increased by 18 ha, which means that the rate of these processes decreased by 52-53% and there was a net accumulation on the studied area. The former processes continued, as the arch-length of the meander decreased by 10% (1129 m), the chord length by 18% (965 m), the radius of curvature decreased by 34% (661), though the length of the amplitude increased by 24% (230 m). The meander became well-developed (β=1.17).

Short-term meander development

Between the snapshot of the ortho-photo (2011) and our first field survey (2013) the rate of the bank erosion was 2–40 m (1–20 m/y). In the following 15 months the rate of bank erosion has increased to 32 m/y (Fig. 5). Between the two field measurements (2013 and 2015) the area of eroded floodplain was 20.6 ha, which exceeds every previous data. The rate of bank erosion was spatially diverse, as it greatly increased downstream.

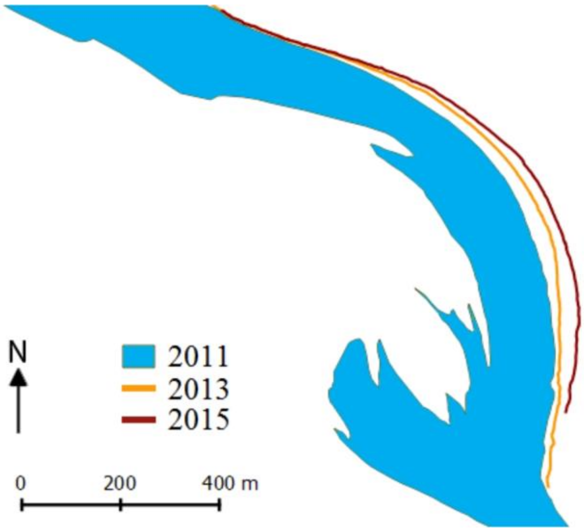

Fig. 5 Short-term bank erosion on the study area between 2011 and 2015

Grain size analysis of the point-bar

During the last almost 30 years a large point-bar system developed in the meander. The older surfaces were colonised by riparian forest, however the youngest point-bar surfaces are still bare, which enabled us to make superficial grain-size measurements. Most of the surface (73%) of the point-bar is built of pebble (4–64 mm), some areas (16%) are covered by granule (2–4 mm), 11% by sand, and only 0.1% of the area consists of cobbles (>64 mm).

The mean grain size of the whole point-bar is 6.6 mm, and the biggest cobble has a diameter of 123.9 mm. The material of the bar-system is moderately sorted (Fig. 6). Large grains appear in well defined areas, as on the upstream and central part of the point-bar, and in the secondary channel between the bank and the bar. The maximum grain-size decreases downstream: in the upstream part of the bar-system 100–120 mm large cobbles were deposited, whilst downstream the maximum sediment size decreased to 40–65 mm. This decrease does not show a linear trend, because the bigger sediment was deposited in patches and in between these patches fine-grained gravel aggraded. It suggests that the point-bar is built up of three smaller bar-heads, which were formed together.

The grain-size of the sediment is altering not only downstream, but laterally too. On the edges of the point-bar close to the thalweg the sediments are finer grained (50–90 mm) than those (60–120 mm) located closer to the bank-line. This could develop during high energy conditions, when during high stages the river could transport coarser sediments near the convex bank and in the side channel, but as the stage fall, these sediments remained in their location. However, closer to the thalweg the daily mini flood-waves generated by the power plants could transport further the coarse sediment, thus at the fall of the mini flood-waves finer grained bed armour develops.

Based on the grain-size distribution of the bare surfaces the point-bar could be divided into three parts (Fig. 6). On the upstream third of the active bar samples are coarser (mean grain-size: 7.6 mm) than the mean grain-size (6.6 mm) of the whole point-bar. The maximum grain size of this area varies between 49.7 mm and 83.4 mm, thus most of the sediment (78.5%) consists of pebbles. The material of this area is moderately sorted (S=1.7). On this area of the point-bar there is a clear tendency of decreasing grain-size toward downstream.

On the middle part of the point-bar where the mean grain size reduces to 6.7 mm, the maximum grain-size of the samples varies between 38.9 mm and 123.9 mm. Almost 74% of the sediments consists of pebbles. The material of this surface is also moderately sorted (S=1.8), but slightly better than in the upstream part. There is a decrease in grain-size towards downstream, however it is not continuous as it is in the upper part, because this central part is dissected by coarser and finer sediment patches referring to smaller bar-heads.

The mean grain size of the downstream part of the point-bar is finer (5.5–6.6 mm). The maximum grain-size is smaller (39.9–69.7 mm) than in the two upper parts, thus the proportion of pebbles decreases (70%). The material of this area is better sorted (1.9).

From the point-of view of grain-size distribution the side channel between the stabilised point-bar surfaces is diverse, as here the mean grain-size varies

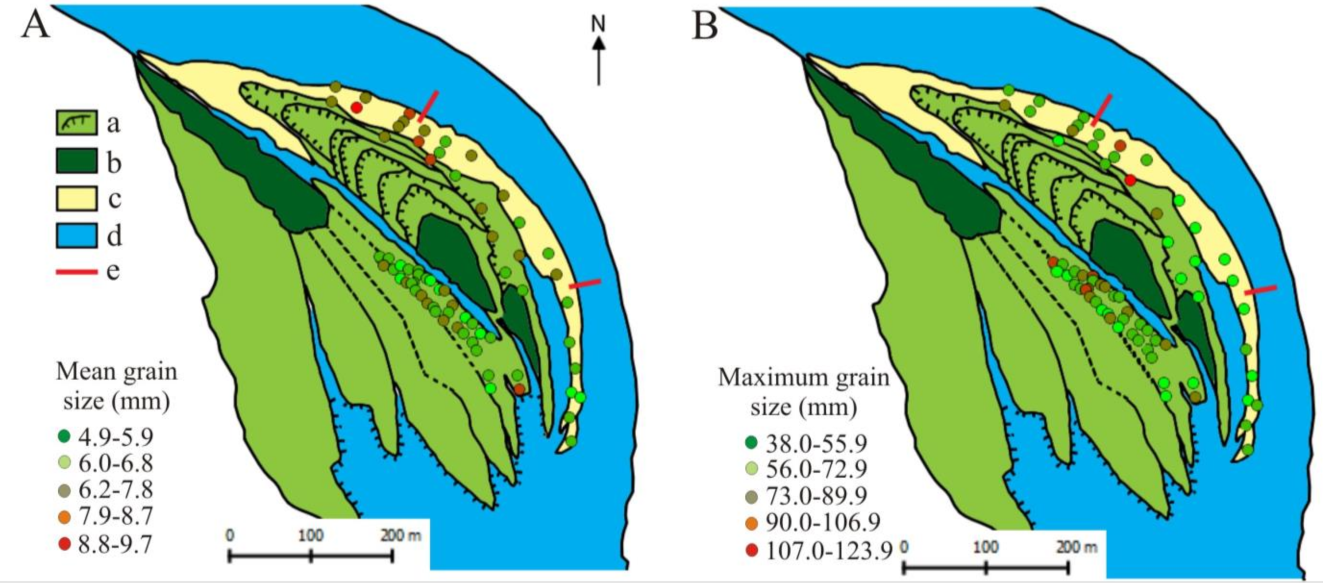

Fig. 6 Mean (A) and maximum (B) grain-size of the studied point-bar. a: slip-face of a bar; b: island-core; c: bare point-bar surface; d: water surface; e: zones of the active bar

between 4.9 mm and 7.8 mm. Here the largest particles are 44.3–103.8 mm. The maximum grain-size of the side channel decreases downstream: its upper is characterised by 70–100 mm large grains, whilst towards downstream it decreases to 50–70 mm. The material of the side-channel is 7moderately sorted (S=1.8). The varieties in grain-size distribution of the side-channel refer to high energy conditions during water cover (during the mini flood-waves), which transport large grains into the side-channel in the form of mid-channel bars. These bars slowly will aggrade the side-channel, thus the island will amalgate into the stabilised surface of the point-bar.

CONCLUSION

The hydrological analysis proved, that the floods gradually disappear from the Dráva River, thus the fluvial development of the floodplain will terminate. At the same time the stage of the mean and low stages decreases (by stabile discharge; Kiss and Andrási, 2011), which refer to rapid incision. These hydrological changes started when the first hydropower plants were constructed, but they were accelerated when the Varasd (1976) and Donja Dubrava Hydroelectric Power Plants (1989) started to operate. These hydrological changes triggered morphological changes too.

The analysis proved that the meander development and point-bar formation downstream of the Donja Dubrava Hydroelectric Power Plant is specific. In the 19th century (1870) prior the regulations the Dráva River had natural hydrological and sedimentological regime, thus braided pattern developed. However by the end of the 19th c. and in the 20th c. river regulation works became widespread, thus meanders were cut off, and side-channels were blocked. Their effects were emphasized by 20th c. dam constructions. As a result, the morphology of the river changed, as the braided river developed into a single-thread sinuous channel. The channel continuously narrowed, referring to more pronounced thalweg. Due to the sediment retention of the reservoirs clean water erosion became dominant, causing incision and simultaneous channel narrowing. As the sinuosity of the bend increased, the rate of erosional and depositional processes increased too. Because of the permanent drop in water stages, vegetation could stabilise the developed point-bars. These processes became accelerated since the end of 1970's, when the last members of the dam-reservoir system were built.

Probably due to the 1.5–1.7 m high "mini flood-waves" twice a day generated by the nearby Donja Dubrava Hydroelectric Power Plant bank erosion accelerated, despite of the fact, that real floods almost disappeared. The accelerated bank erosion is also influenced by the incision and the previous fluvial history of the area: The meander develops in the loose material of the former braided channel, thus it is easy for the Dráva to erode the young and unconsolidated material.

The incision, the development of the thalweg and the intensive bank erosion create favourable conditions for point-bar development since the end of 1970's (Fig. 7). The Dráva sorts its bed-load material downstream and laterally too. The maximum and mean grain-size decreases downstream and also laterally towards the bank. On the upstream part of the point-bar the maximum grain size was 49.7–83.4 mm and the mean sediment size was 7.6 mm, whilst on the downstream part the maximum grain size was only 39.7–39.9 mm and mean sediment size decreased to 6.1 mm. Along the bank and in the side-channel coarser sediment was deposited, as here the maximum grain size is 38.9–123.9 mm and 44.3–103.8 mm respectively.

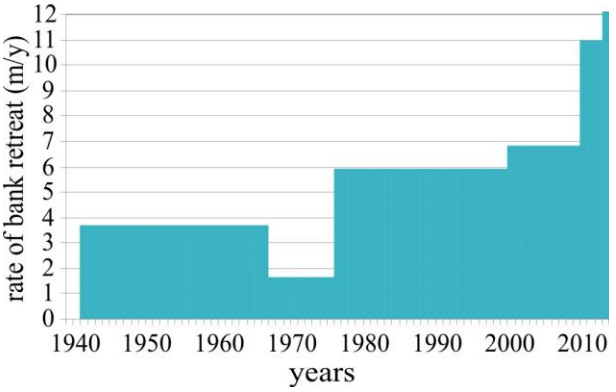

Fig. 7 Annual rate of bank erosion on the study area

Greater grains deposited in the upstream end of the point-bar, where the flow is diverted towards the main thalweg and into the side-channel, thus its energy drops. In this way the bar-system expands laterally and also towards upstream. The upstream expansion of the point-bar system is contradictory with the meander development of the sandy bed-load rivers, where the main location of the accumulation is at the downstream part of the bar (Sipos, 2006; Kiss and Blanka, 2011).

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