HYDRO-MORPHOLOGICAL RESPONSES OF THE DRÁVA RIVER ON VARIOUS ENGINEERING WORKS

HIDROMORFOLOŠKI ODGOVORI RIJEKE DRAVE NA RAZLIČITE INŽENJERSKE RADOVE NA RIJECI

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Sažetak

Hidrologija i morfologija rijeke Drave uglavnom su pod utjecajem brana i rezervoara izgrađenih na uzvodnom dijelu, ali i prepreka i odvodnih kanala, što također utječe na razvoj vodotoka rijeke. Naš cilj je pobrojati sve hidrološke i morfološke reakcije rijeke Drave, do kojih dolazi na različite inženjerske rade na rijeci, kao i tijek evolucije i razvoja rijeke. Na temelju morfološke analize možemo razlikovati četiri evolucijske faze rijeke Drave. Ove faze odražavaju vrijeme poremećaja i sam odgovor rijeke. U svom prirodnom stanju, sve do kasnog devetnaestog stoljeća, gornji tok je imao anastomozno pleteni uzorak, dok je donji dio bio vijugav. Kao posljedica usječenih kanala duljina je Drave, njezina sinuositeta i širina kanala smanjeni su privremeno, a tip vodotoka promijenio se od meandrirajuće-anastomoziranog do pletenog uzorka. Kasnije su konstrukcije zapreka protiv erozije rezultirale jednostavnijom morfologijom, jer su nestali otoci, ali i kompleksni sustav bočnih kanala također. Konačno, kao odgovor rijeke na brane i rezervoare, došlo je do usječenog i smanjenog kanala vodotoka. Krhki fluvialni sustav Drave predstavlja stupnjevitu evoluciju, a danas je Drava vjerojatno u stanju »daleko od uravnoteženoga«.

Ključne riječi: Drava, ljudski utjecaj, fluvialni odgovor, hidrologija, promjena kanala vodotoka
Keywords: Dráva, human impact, fluvial response, hydrology, channel change

1. INTRODUCTION

All over the world rivers are increasingly influenced by diverse human impacts, which can be considered as disturbing factors from the point of view of the fluvial systems. The rivers of the Pannonian Basin have been altered by various antropogenic activities, especially during the last ca 150 years, as since the mid-19th century the engineering works are almost continuously affect the rivers (Ihrig 1973). The rivers respond on the modification of their hydrology and sediment transport by changing their morphology (Thorne 1997), however this response is greatly influenced by the (in)stability and sensitivity of the given river (Hooke 1997).

The anthropogenic disturbing factors could be grouped into two main groups. The **indirect human impacts** (e.g. climate change, land-use and land-cover changes) usually affect the catchment, and by modifying the run-off, they alter the water- and sediment-regime (Stover and Montgomery 2001, Kondolf et al. 2002). Usually the extremities increase, thus low stages will be longer, floods disappear (Wyzga 2007), or in contrary flood frequency increases (Schumm and Lichty 1963, Baker 1977, Gilvear et al. 2000, Ma et al. 2014). The modified hydrology finally changes the channel processes and the evolution of the channel-floodplain complex (Wyzga 2007, Zawiejska and Wyzga 2010, Radoane et al. 2013). The other group involves the **direct human impacts.** In this case the aim of the human activity is to alter the channel and/or the floodplain of rivers, by building dams and reservoirs, creating new, usually straight sections, cutting off meanders, stabilizing the banks by revetments, and influencing the flow direction by groins (Newson 1997, Uribelarrea et al. 2003, Antonelli et al. 2004). These engineering works alter the slope and the friction of the channel, the material of the banks, therefore the stream power of the river usually increases. In contrary to the (areal) indirect human impacts, the direct human impacts are point-like, and these disturbing factors initiate aggression waves, which propagate upstream or downstream. The effects of these direct engineering works on channel development could be much greater than of the indirect impacts, as they initiate rapid and high magnitude changes on rivers. Regardless of the type of human impact, usually the depth or/and the width of the channel changes (very frequently they will be deeper and narrower), and the channel pattern simplifies (Doyle and Harbor 2003, Surian and Rinaldi 2003, Downs et al. 2013).

The response of the rivers on the above mentioned direct and indirect human impacts varies, even along the different reaches of the same river, depending on the equilibrium state and sensitivity of the reach (Lane and Richard 1997, Gilvear 1999). In general, the response can be reflected by the spatially and temporally altering parameters (e.g. discharge, flood height, channel depth), as their frequency, magnitude, duration or trend will change (Brunsden 2001). When evaluating the responses the greatest uncertainties derives from the determination of the reference state, from the non-linear behavior of the processes, and that the various responses can accelerate or diminish each other effects (Hooke 1997, Usher 2001, van de Wiel et al. 2012). From this point of view it is very important, that how close is the fluvial system to its threshold values, and what is its recovery potential (Phillips 1992, Thomas 2001).

The hydrology and morphology of the Dráva River is mainly influenced by dams and reservoirs built on the upstream section, though other engineering works (as groins, cut-offs) also affect the channel development. Our fluvial research team studies the hydrological and morphological processes since 2011. In this paper the summarized results of our research will be presented, the detailed descriptions of the applied methods and results can be found in previous papers (Andrási and Kiss 2013, Kiss and Andrási 2011, 2014, 2015, Kiss et al. 2011, Kiss and Balogh 2015).

In the present paper our aims are (1) to review the hydrological and morphological responses of the Dráva River given on different engineering works (cut-offs, groin and dam constructions), (2) to analyze the effect of these disturbances on the hydro-morphology of the river, and (3) to determine the evolutionary way of the Dráva channel.

2. MAIN HYDROLOGICAL CHARACTERISTICS OF THE LOWLAND DRÁVA

The hydro-morphological changes of the Dráva River were studied on its lowland reach (236 km), between Őrtilos (confluence with the Mura River) and the Danubian confluence (Fig. 1.). On this section the slope of the river considerably drops (from 50 cm/km to 5 cm/km; Mantuánó 1974), whilst its mean discharge doubles (Maribor: 300 m^3/s, Osijek: 653 m3/s). In the middle if the section, at Barcs gauging station the peak discharge (3160 m^3/s in 1966) is 31.6 times higher, than the lowest discharge (100 m^3/s in 1976).

In its natural state o the river floods appeared in May-June and in November due to Mediterranean climate effect, whilst low stages were characteristic in the end of winter (Mantuáno 1974). In the first half of the 20th century 5-9 overbank flood waves/year developed, though they lasted only for few days. The highest flood on record (in 1972) lasted only for 10 days, which can be explained by the great slope of the river. Nowadays the hydrology is totally different, as the natural hydrological regime was altered by dams and reservoirs. Floods disappeared, and low stages became characteristic. A good example on the altered hydrology is the fact, that by the spring of 2013 extremely great amount of snow accumulated on the catchment, and despite of the rapid snow-melt no flood-wave developed downstream of the reservoirs.

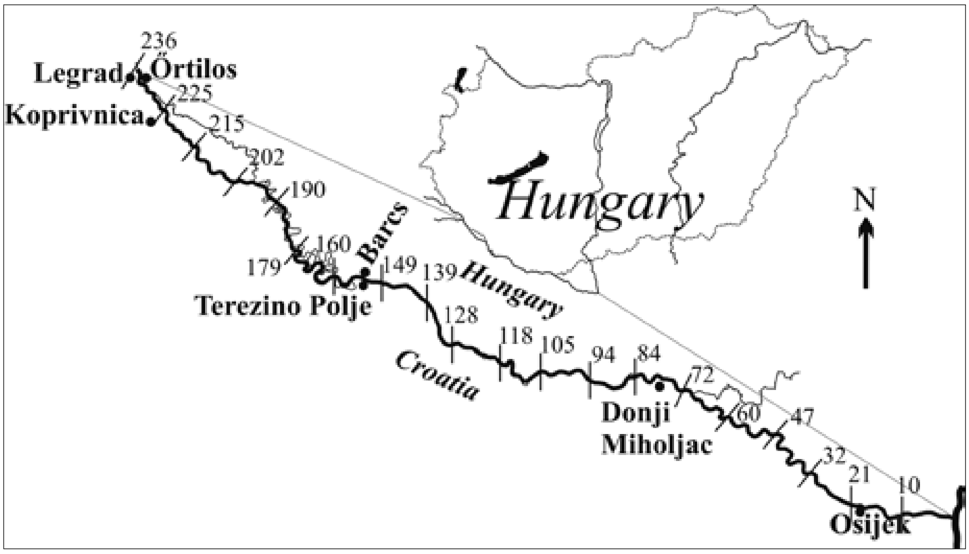

Fig. 1. *The lowland section of the Dráva was studied in detail. The section was divided into 20 units, where the morphological parameters were studied in detail. The numbers refer to the distance (fkm) from the Danube.*

The natural sediment load (suspended: 0.48-0.66 million t/year; bedload: 0.12 million t/year[1]) of the river was also altered in the 20th century, as nowadays 95 % of the bedload is trapped in the reservoirs (Bonacci and Oskorus 2008). The tributaries (e.g. Mura River) and the intensive bank erosion only partially replace the sediment load (Szekeres 2003, Andrási 2015). The last Croatian power station at Donja Dubrava produces daily »mini flood-waves« due to its peak-operation system, and these flood-waves cause intensive bed-scour which results in bed-amour development (Szekeres 2003). In the surrounding of the conjunction of the Mura large gravels are transported, whilst downstream of Barcs sand is the largest grain-size of the transported sediment (Horváth 2002, Varga 2002).

Engineering works on the Dráva River

The first step (1740s-1838) of the engineering works was the construction of flood-protection embankments (Remenyik 2005). Later to support navigation on the lowland reach (between the Mura and Danube) altogether 62 cut-offs were made, shortening the river by 182 km (ca. 40%). Most of them were created between 1784 and 1904, but even in the 20th century some cut-offs were made to solve local problems, like to protect a settlement (e.g. Vízvár, Őrtilos) or a road from intensive erosion during floods (Remenyik 2005). In the 20th century the shipping route was further improved: downstream of Barcs by groins and revetments, while upstream of Barcs the side-channels of the Dráva were blocked. The in-channel gravel mining also influenced the channel development, especially between Őrtilos and Vízvár, where too much gravel was extracted, therefore here the channel became deeper by 0.8-1.0 m (Horváth 2002).

The greatest disturbance on the hydrology and morphology of the Dráva was caused by dams and reservoirs (for hydropower production) built since the 1910s on the Austrian, Slovenian and Croatian sections of the river. The last hydropower plants were built in Croatia (1975: Varasdin, 1982: Cakovec, 1989: Donja Dubrava). The last one is the Donja Dubrava Hydropower Plant, which operates in peak hours, therefore the water level changes ca. 1.5 m during a day (measured at Őrtilos). These »mini flood-waves« are getting lower towards downstream, thus at Barcs their height is only 0.5-0.7 m (Horváth 2002, Kiss and Andrási 2011).

[1] *http://www.nimfea.hu/drava/ha/5.htm*

3. RESPONSES OF THE DRÁVA RIVER ON VARIOUS DIRECT HUMAN IMPACTS

3.1. Artificial cut-offs

The general aim of artificial cut-offs on the Dráva was to increase its slope, which would result in channel incision (deepening), so the river would be more easily navigable. However, the Dráva could not give clear response on this disturbance, partly because the recovery of the fluvial system was impeded by the construction of groins and dams, and partly because the construction of cut-offs did not terminate as one cut-off was made even in the close past.

The fluvial response on cut-offs was *channel width change*, however the artificial sections and the directly non-affected sections evolved differently (Andrási and Kiss 2013, 2014). According to the general engineering practice, during the creation of an artificial cut-off a pilot channel is dug, which is later enlarged by the river itself. On the Dráva these artificial sections widened quite rapidly due to the great slope and the loose bed-material. The eroded material was transported away by the river, and some kilometers downstream of the cut-offs the material deposited in the form of mid-channel bars and islands. For example, the meander by Vízvár was cut-off in 1979-82. Here, downstream the cut-off several new bars and islands appeared along a 1.6 km-long section. However, those sections which were not affected directly by cut-offs experienced channel narrowing, as it became half of the previous values. In the late 19th century (1882) the mean channel width was 513 m, however until the 1960s it became only 361 m (Fig. 2.). Later the narrowing was accelerated by further hydrological changes, groin and reservoir constructions, and in-channel gravel mining.

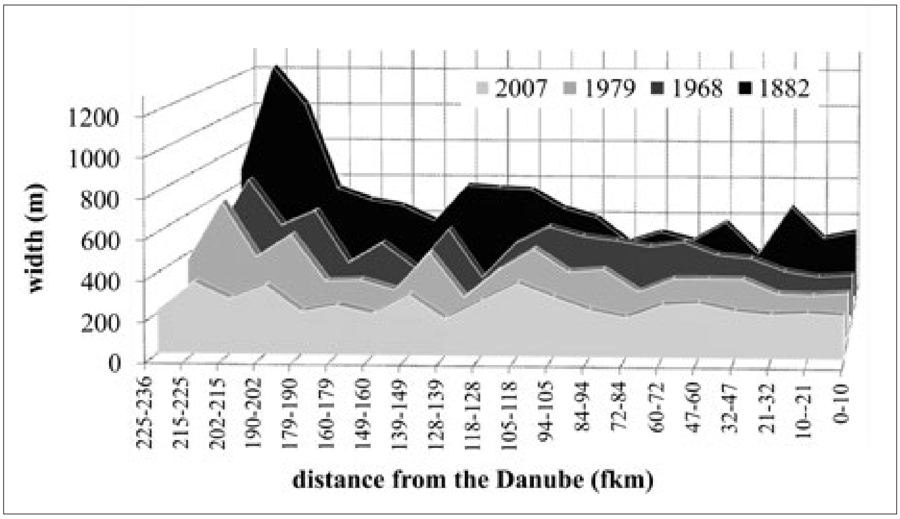

Fig 2. *Channe width changes of the Dráva between 1882 and 2007. The location of units is indicated on Fig. 1.*

Another striking effect of cut-offs was the *change in type and number of islands* (Andrási and Kiss 2013, 2014). The large floodplain islands merged to the banks, though simultaneously smaller mid-channel islands became dominant. The large number of floodplain islands in the 19th century could be explained by (1) the anastomosing natural pattern of the channel, as between the network of side channels large islands appeared, and by (2) the already completed artificial cut-offs, where the floodplain islands were surrounded by the artificial pilot channel on one side and the cut off ox-bow lake on the other. On the studied lowland reach of the Dráva in 1882 altogether 32 floodplain islands existed with a total area of 3797 ha. However, until the next survey in 1968 half of them already merged into the floodplain, thus their number (15) and their territory (1517 ha) decreased. Later on their number and area further declined, and nowadays only 8 such an islands (territory 976 ha) exist.

3.2. Construction of groins

Downstream of Barcs (0-175 fkm) groins have been widely constructed since 1885 to improve the navigation route, whilst upstream of Barcs only low number of groins were created (György and Burián 2005), most of them are blocking side-channels. The previously mentioned channel narrowing can be connected to the existence of groins too, as (1) the blocked side-channels aggrade and (2) behind the groins the flow velocity decreases and accumulation starts.

The process of declining side-channel was studied in detail by Vízvár (Fig.3.; Kiss et al. 2011). Here before the construction of a groin, in 1972 the side channel was even wider (140 m) than the main channel (120 m), which was created artificially, though the mean depth of the side channel was only 2.3 m, and of the main channel 5.8 m. At the confluence of the main and the side-channel a groin was built in 1982. As a result, the side-channel aggraded by bars and islands, and its thalweg became meandering. Until 2008 the width of the side-channel declined to 47 m, its depth decreased to 1.2 m. Thus the aggradation rate became ca. 5 cm/y and the water-conductivity of the side channel declined by 2% per year. Simultaneously, the main channel became deeper too: the depth of the main channel increased by 0.8 m (9.2%), and the previously changing thalweg became more defined.

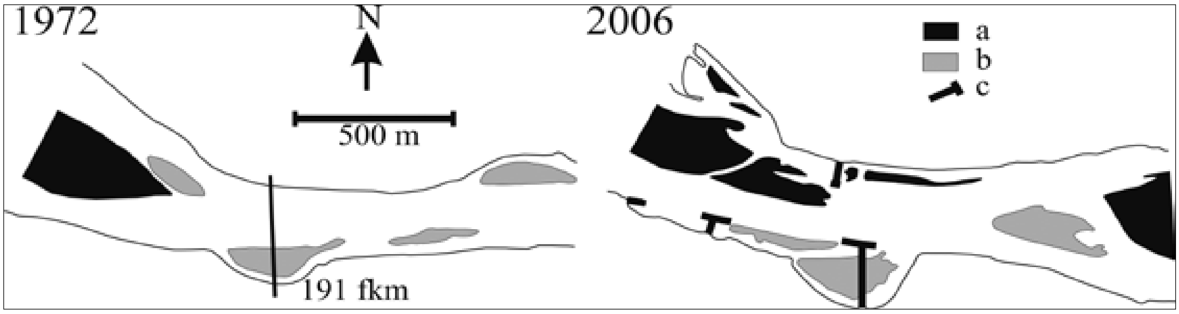

Fig. 3. *The channel development at Vízvár was greatly influenced by groins. a: island, b: gravel-bar, c: groin*

Behind the groins, in the area where the flow velocity decreased, altogether 69 islands developed on the lowland section of the Dráva (Andrási and Kiss 2013, 2014). Their total area is 88.6 ha. The development of such an island was studied in detail at Novo Virje (Fig. 4.) and Vízvár. Usually the core of the island develop relatively far from the groin, but in the pool behind the groin the islands grow both upstream and downstream. Simultaneously, the side channel between them and the banks slowly aggrades, thus soon or later these islands merge into the banks. In this way the development of these islands also contributes to the narrowing of the channel of the Dráva.

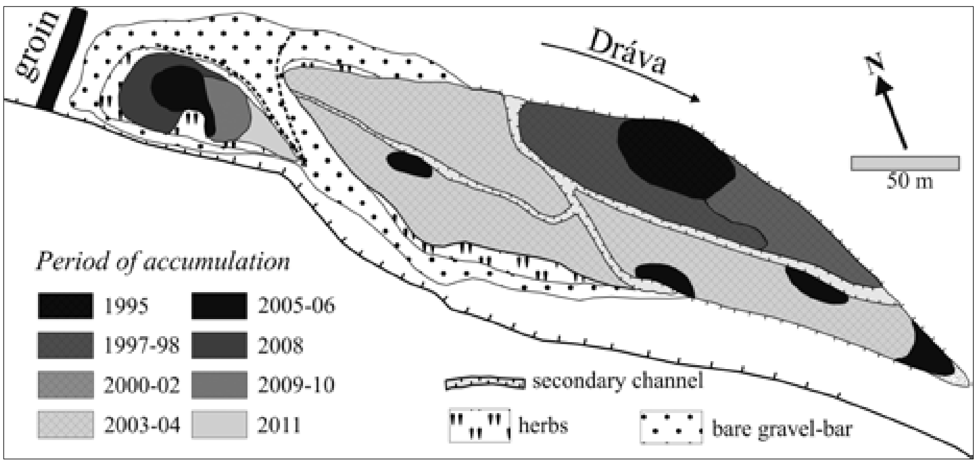

Fig. 4. *Development of islands behind a groin at Novo Virje. The age of the surface was determined by dendrology.*

3.3. Construction of dams and reservoirs

On the Dráva the first dam and reservoir was built in 1918 (Schmidt 2007), but their hydrological effect became pronounced at the Őrtilos gauge station just after the construction of the Varasdin dam (1975). This Croatian hydropower plant was followed by two others, and the last one was finished in 1989.

As the result of the construction of reservoirs the hydrology of the lower section was modified considerably (Kiss and Andrási 2011). The characteristic water levels (e.g. annual minimum, annual mean and maximum) dropped by 200-260 cm respectively (Figs. 5-6.). The duration of low stages (≤ 50 cm) increased (from 1% to 73%), whilst overbank floods almost disappeared (they return interval changed from 0.2 y to 15 y). Besides, the most downstream hydropower plant at Donja Dubrava operates in the peak hours, therefore twice a day 1-1.6 m large mini flood-waves are generated artificially. These hydrological effects have decreasing magnitude toward downstream. For example, the height of the mini flood-waves are 1-1.5 m high at Őrtilos (18 km far from Donja Dubrava), but they are only 0.6-0.8 m large at Barcs (100 km far). These flood-waves influence the slope of the water and thus the stream power of the Dráva. As these parameters are getting less variable with the distance from Donja Dubrava hydroelectric plant, the resulted morphological alteration of the channel also decreases.

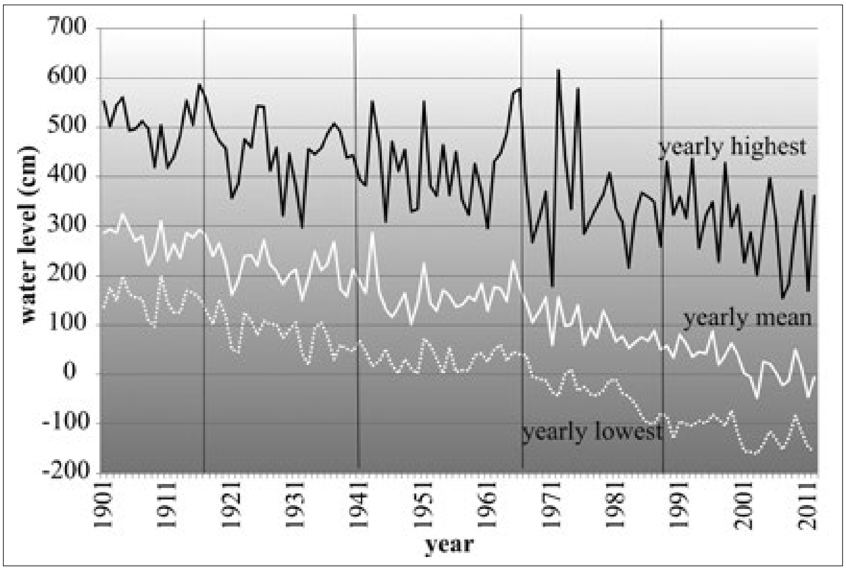

Fig. 5. *The yearly highest, mean and lowest water stages of the Dráva measured at Barcs (data source: DDVIZIG)*

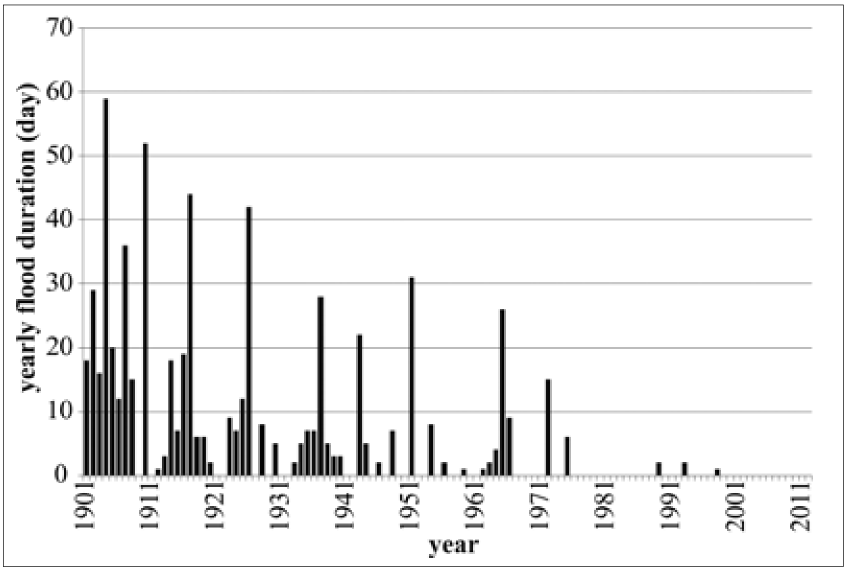

Fig. 6. *The number of overbank flood days at Barcs*

The changing hydrology and the sediment trapping effect of the reservoirs resulted in the incision of the channel (Horváth 2002). Unfortunately, only few cross-sectional channel profiles are available between Bélavár and Barcs to determine the depth changes. These profiles reflect 10-15% depth increase between 1972 and 2006, thus the mean channel depth increased from 4.5 m to 5.2 m, thus the channel incised by 2 cm/y.

The incision of the channel accelerated the already ongoing channel narrowing, which was initiated by the previous cut-offs and groins constructions (Fig. 2). Therefore, the most intensive narrowing was characteristic between 1968 and 1979, when the mean width reduction was 50% in average (max: 71%). The rate of narrowing before 1968 was 1.7 m/y, but as the construction of the Croatian reservoirs started, it increased to 3.6 m/y (1967-1978), and since it is 2 m/y. The channel narrowing is especially intensive, 65-75% on the upper section (179-235 fkm), which is only 19-75 km far from the lowermost reservoir, while in the middle of the section (at Barcs) it is 48-50%, and the narrowing s only 30-40% at Osijek. As the channel of the Dráva is dissected by island, we had also measured the area of the water (i.e. wetted channel). During the last 130 years it decreased by 47%, and its most intensive period (63 ha/y) was also between 1967 and 1978.

The islands in Dráva also changed dynamically, in connection with reservoir constructions: several of them merged into the banks, as the side channel between the island and the floodplain declined due to the loss of water supply in connection with incision. However, to balance this process, the Dráva started to build new mid-channel islands. Though on the studied section the number of islands increased only by 21%, their total area decreased considerably (by 65%), and this areal decline accelerated since 1979 (Fig. 7.). These parametric changes refer to the morphological alterations of islands. In the 1880s large (mean area: 118 ha) islands were characteristic, which were bordered by the dense network of side-channels and ox-bow lakes. However, as the thalweg incised, the side-channels became dry, and finally the islands merged into the floodplain. This process was the most rapid after the Croatian reservoirs and dams started tom operate. At the meantime, small (mean area: 5.8 ha) islands evolved in the main channel from the mid-channel gravel-bars. In the development of these islands the dropping water stages have important role, as in this way the surface of the gravel-bars is less frequently inundated, thus the riparian vegetation could stabilize their surface.

The effect of the reservoirs is declining toward downstream, therefore the alteration of the channel is also less intensive. The greatest morphological modification took place nearby to the reservoirs, in the upstream section (179-235 fkm) of the studied reach. Here the channel narrowing was very rapid, and the metamorphosis of the islands was very intensive. In its natural state the width of this section was over 1.2 km, however nowadays it is only ca. 350 m. The number of islands declined to the third, and their territory to the fourth. In contrary, far from the reservoirs (225-179 fkm) the island development accelerated, as on the downstream half of the studied section their number doubled, though their area dropped to half, and they appear much farther from each other. It suggests that the incision of the channel and the intensive bank erosion partly replace the »missing« sediment trapped in the reservoirs, and this sediment is available on the lower section for active channel development.

All these changes reflect the morphological modification of the channel of the Dráva. In its natural state the upstream section had an anastomosing-braided, while the downstream section had meandering pattern. However the morphological differences are getting smaller since the 1970s, as the channel width became more uniform, and the variety of islands also declined.

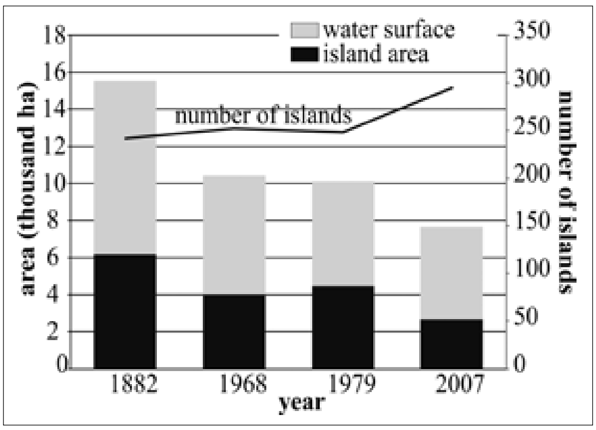

Fig. 7. *Island and water surface changes of the entire lowland reach of the Dráva*

4. EVOLUTIONARY PHASES

Based on the morphological analysis four evolutionary phases are distinguishable of the Dráva River. These phases reflect the timing of the disturbance and the response of the river. Unfortunately, not all the effects of the various disturbances are separable, as very often the disturbances co-existed, thus the Dráva gave a complex response. However, the upper section (between Őrtilos and Barcs) is mainly influenced by the dam and reservoir constructions, while the lower section (between Barcs and the Danube) is influenced by artificial cut-offs and groin constructions.

In its **natural state**, until the late 19th century, the upper section had and anastomosing-braided pattern. The channel width varied within a wide range, several side-channels existed and the bedload was dominated by gravel. In the main channel and also in the side-channels islands with various territory appeared, and when they merged into each other large floodplain islands developed. The spatiality of the side-channels, gravel-bars and the islands probably slowly changed, as the forms had rounded shape (the more elongated a form, the more powerful is its environment, and fastest its changes). This channel pattern gradually became simpler towards downstream, thus downstream of Barcs the channel became meandering, though islands appeared in it. It must be noted, that on the downstream section some of the meanders were already artificially cut-off.

During the period of intensive channel regulations the length of the Dráva, its sinuosity and temporally its channel width decreased. This period was quite long on the Dráva, as most of the works have been done in the 19th century, but even in 2007 a cut-off was made. However, most of them were created by the beginning of the 20th century. The fluvial *response on cut-offs* was a channel pattern change (i.e. channel metamorphosis). Along the new, artificial »pilot« channel-sections the lateral erosion accelerated, thus these sections became wider, whilst downstream of them the eroded material deposited, thus new mid-channel bars and islands evolved. In this way the mean depth of the channel decreased, and its pattern changed from meandering-anastomosing to braided. The widening usually terminated after ca. 20 years based on the detailed study on a cut-off made in 1979-82 at Vízvár (Kiss et al. 2011).

In the next period, groins were constructed (mainly in the 1960-1980s). They were needed, because after that the channel was trained by large number of cut-offs, the slope and sediment load conditions of the Dráva changed. The increased slope accelerated the erosion of the banks, therefore to stop the over-widening of the channel, to support navigation and to protect the artificial embankments the side channels were blocked and the main channel was trained by groins. As a *response on groin constructions*, the side channels gradually lost their flowing water supply and they rapidly aggraded, thus the islands merged to the banks and the channel became considerably narrower. However, it must be noted, that these responses were amplified by the declining water stages in connection with reservoir constructions. Several islands also evolved behind the groins, in the low-flow zones, but within short period they merge to the banks due to the dropping stages. Thus, the morphology got simpler as more islands disappeared than appeared, and the complex system of the side channels also vanished.

In the last period the most intensive disturbance was made by **the construction of dams and reservoirs**, especially after that the Croatian hydropower plants were built (1975-89). These are continuous disturbing forces, as they store water (causing dropping stages), they trap the sediment and produce mini flood-waves (intensifying erosion). As a response, the morphology of the channel changed again, as the channel started to incise. Due to the drop of stages and the lack of floods the gravel-bar surfaces are stabilized by riparian vegetation, thus new islands born, however they rapidly merge to the banks due to the decline of the side-channels.

These processes are the most spectacular on the *upstream section* (179-235 fkm), which is located closest to the dams. The channel pattern of this section shifted to sinuous-braiding. The braided pattern is supported by its great slope (40-50 cm/km; Horváth 2002), still wide channel (210-360 m), shallow riverbed (3.6 m), large width-depth ratio (58-100), and the appearance of wide channel sections with mid-channel bars and islands. Here, **in the future** the intensive ongoing channel narrowing and deepening, the lack of bedload and the disappearing floods will result in the metamorphosis of the channel: its braided pattern will change into meandering, with much simpler morphology.

On the *lower section* (0-179 fkm) channel metamorphosis is also characteristic, though here the effect of dams only accelerates the effects of the other direct engineering works. Those channel sections change, which were artificially cut off: these sections widen, mid-channel bars and islands appear, and the channel pattern shifts towards braided. However, in the future these sections will return to the meandering pattern too, as the islands merge to the banks, the thalweg gets more sinuous, and after ca 100 years (like at Drávatamási) the braided channel will be replaced by meandering.

5. CONCLUSIONS

From the point of disturbance, we believe, that the construction of groins and dams has much greater disturbing effect than of the cut-offs, because an artificial cut-off is just a temporal disturbance, and the river could naturally accommodate to the new slope conditions. In contrary, the groins and dams exist in a long-term: groins continuously impede the lateral erosion and confine the river, whilst the dams continuously influence the hydrology and sediment-load of the river. From this point of view the recovery of the river after groin and especially dam constructions is less probable, and the channel can shift towards a non-equilibrium state.

The fluvial responses on the various disturbances reflect that the Dráva belongs to the fragile systems, as these systems undergo a morphological metamorphosis (see Thomas 2001).

The hydrological and channel parameters of the Dráva change continuously, thus its development could be considered as »graded« (see Schumm 1979). In this gradually changing environment which is combined with continuous disturbances an equilibrium state could not be reached, thus the Dráva is probably in a »far-from-equilibrium state« (Thorn and Welford 1994). Considering these facts above, the success of planned floodplain restoration works is quite doubtful, as they aim to restore such a state, which is instable within the present hydro-morphological conditions.

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SUMMARY

The hydrology and morphology of the Dráva River is mainly influenced by dams and reservoirs built on the upstream section, but groins and cut-offs also affect the channel development. Our aims are to summarize the hydrological and morphological responses of the Dráva River given on different engineering works and to determine its evolutionary way.

Based on the morphological analysis four evolutionary phases are distinguishable of the Dráva River. These phases reflect the timing of the disturbance and the response of the river. In its natural state, until the late 19^{th} century, the upper section had and anastomosing-braided pattern, while the lower section was meandering. As the consequence of cut-offs the length of the Dráva, its sinuosity and temporally its channel width decreased, and the channel pattern changed from meandering-anastomosing to braided. Later, the groin constructions resulted in simpler morphology, as islands disappeared and the complex system of the side channels also vanished. Finally, as a response of dam and reservoir constructions the channel started to incise.

The fragile fluvial system of the Dráva represents a graded evolution, and nowaydas the Dráva is probably in a »far-from-equilibrium« state.

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