BME DEPARTMENT OF HYDRAULIC AND WATER RESOURCES ENGINEERING

Assessing causes and controls of bed erosion for the Drava River (between 0-236 rkm sections)

In the frame of project entitled Wise water management for the conservation of alluvial forest habitats along River Drava (LIFE17NAT/HU/000577)

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Assessing causes and controls of bed erosion for the Drava River (between 0-236 rkm sections)

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1 Introduction

This report has been prepared in the frame of the project entitled "Wise water management for the conservation of alluvial forest habitats along River Drava" by the Department of Hydraulic and Water Resources Engineering at the Budapest University of Technology and Economics (BME). The main goal of the study is to reveal and assess causes and controls of bed erosion for the Drava River (between 0-236 rkm sections). According to the contract, the following tasks have been performed:

- Literature review about potential causes for river bed erosion
    - anthropogenic impacts (changes in floodplain usage, river regulation, dredging, hydropower plants, …)
    - natural impacts (climate change, tectonic changes, river bed evolution, …)
    - characteristic bed erosion processes in Hungarian rivers, possible causes

- Bed topography maps
    - Digitalization of paper based maps from 1971 and projecting into EOV system
    - Processing bathymetry data from 1998-2003
    - Processing bathymetry data from 2018-2019

- Assessment of dredging data
    - Collecting dredging volume data
    - Assessment of temporal changes
    - Assessment of longitudinal changes
    - Estimation of impacts on bed changes

- Impact analysis of river regulation measures
    - Overview of relevant regulation measures in the past
    - Introduction of hydromorphological changes in the river
    - Estimation of impacts on bed changes

- Impact assessment of Croatian hydropower plants
    - Characteristic features of hydropower plants
    - Impacts of HPPs on flow regime
    - Impacts of HPPs on sediment regime
    - Impacts of HPPs on river morphology and bed elevations

- Assessment of morphological changes
    - Bed elevation difference maps
    - Island and river bend evolution processes
    - Longitudinal and temporal changes of low water levels

- Discussion
    - Assessment of causes, locations and magnitudes of river bed erosion along the Drava River
    - Analysis of bed erosion processes

2 Results

Part I - General introduction

General (anthropogenic and natural) causes of riverbed incision are overviewed, furthermore, we briefly present the intensity of the typical riverbed changes along Hungarian rivers which have been significantly incising. We discuss separately the previous studies about the significant incision of the Lower Drava.

The morphological reaction of rivers for changes in the water and/or the sediment regime can vary. Riverbed incision occurs when i) sediment supply decreases, but flow discharge remains constant, ii) flow discharge increases, but sediment supply remains constant, iii) flow discharge increases and sediment supply decreases – that is, there is a deficit in the sediment balance.

Two main groups of the causes of bed incision can be distinguished: anthropogenic and natural causes. Both causes can be direct or indirect – while the former has an immediate, local effect, the latter is slower as it affects the runoff and sedimentation processes on the catchment area. Anthropogenic causes are the land use (i.e. vegetation and urbanisation), the traditional river regulation measures (i.e. groynes, bank protection works, cut-offs, channel straightening and flood protection works), dredging (commercial and regulatory) and hydropower plants (HPP). Natural causes are the climatic changes, tectonic movements, the lateral movement of the river and the lowering of the base level. It is important to note, that the above-mentioned causes typically occur together and the effects cannot be easily distinguished.

Due to the river regulation measures (since the 18th century) tectonic subsidence of the Carpathian Basin, most of the Hungarian rivers are deepening. A more detailed overview is presented in Table 1.

Table 1: Rates and causes of incision along the rivers Hungary (summary)

River	Section	Time period	Incision (cm/y)	Main cause/s
Duna	Hungary	1901-2005	0.67 - 2.07	HPPs, dredging, river regulations (groynes), tectonical movements
	Hungary	n.a.	1.00	
	1850-1790 rkm	1959-2016	5.26	
	1850-1790 rkm	1971-2016	3.33	
	1850.20-1809.76 rkm	1938-2002	2.31-6.25	
	1809.76-1786.00 rkm	1970-2014	3.40-4.20	
	1786.00-1729.35 rkm	1949-2014	1.39-2.20	
	1729.35-1699.50 rkm	1970-2013	4.00-6.00	
	1628.45-1586.00 rkm	1965-2013	2.20-2.40	
	1605-1525 rkm	1996-2016	1.60	
	Hungary	1960-1990	2.00	only from dredging
Hernád	Hungary	1957-2009	1.25	tectonical movements, impoudment
	Hungary	1974-1985	0.23	only from tectonical movements
Ipoly	94.38-78.56 rkm	2010-2014	0.50-0.75	river regulations (cut-off)
Maros	lower section	1876-1912	1.94-6.94	river regulations (cut-off, bank protection), tectonical movements, climatic change,
	24.50-21.92 rkm	1960-1990	2.70	
Mosoni-Duna	lower section	1972-2004	3.13	river regulations (groynes, dredging), riverbed deepening of the Danube (base level lowering)
	Danube confluence	1972-2004	6.25-7.81	
Rába	51.24-41.17 rkm	1958-2002	2.27	dredging, river regulations (bank protection)
	41.17-29.04 rkm	1958-2002	1.82	
	29.04-14.02 rkm	1958-2002	4.55	
	14.02-0.00 rkm	1958-2002	2.73	
Sebes-Körös	upper section	1969-1993	1.20-2.00	HPPs
Tisza	Hungary	1842-1961	0.30-3.10	river regulations (cut-off, bank protection, flood protection), HPPs, tectonical movements
	246.20-173.60 rkm	1901-1976	2.00	
	225-205 rkm	1960-2006	2.17	

There are previous studies which had studied the morphological changes along the investigated section of the Drava River. Based on these preliminary studies, the average rate of the incision of the Hungarian section of the Lower Drava was ca. 3.00 cm/y in the period between 1970-2016. See Table 2 for the three section:

Table 2: Preliminary rates of incision along the Lower Drava (overview)

Section	Section (rkm)	Time period	Incision	Mean incision
	fkm		cm/y	cm/y
Hungary	235.90-70.20	1970-2016	2.00-4.00	3.00
Bélavár-Barcs	198.00-154.10	1972-2006	2.00-3.15	2.24
Barcs-Drávaszabolcs	154.10-77.70	1993-2002	0.50-1.08	1.08
Eszék-confluence	22.00-0.00	1886-2003	0.86-2.19	1.25

The studies used both direct and indirect methods in order to determine the value of incision in a given period. Direct methods are based on the known volume of the excavated material or riverbed surveys (Figure 1). Indirect methods are based on the time series analysis of water levels. In this study, we performed a similar, but extensive analysis.

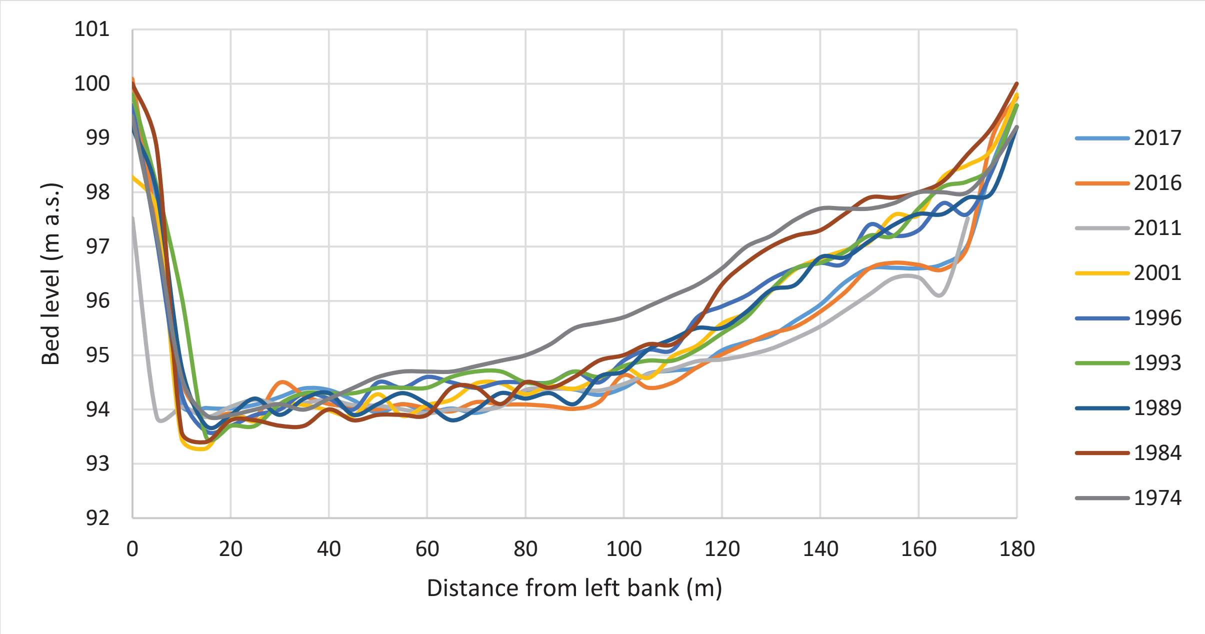

Figure 1: Geometric changes in the cross section of the "Barcs" station (154.10 rkm) between 1974 and 2017

Part II – Discussion of the various anthropogenic effects along the Lower Drava

In the first part of the study we examine in detail the anthropogenic causes of the morphologic changes along the Lower Drava as of the following:

- We overview the available bed topography data. There had been difficulties during the processing as there were discrepancies between the different formats of riverbed geometry.
- We present the available dredging data. There had been a significant dredging from the riverbed along the Lower Drava, especially between Botovo (227.10 rkm) and Drávaszabolcs (77.00 rkm). Between 1982 and 2011, the total amount of the excavated material was 6.29 M m^3. Upstream of Barcs, the excavated gravel amounted 2.77 M m^3, downstream of Barcs, the excavated bed material (from sandy gravel to fine gravel) was around 0.74 M m^3. (Note, that there are no data available about the illegal dredging activities.)

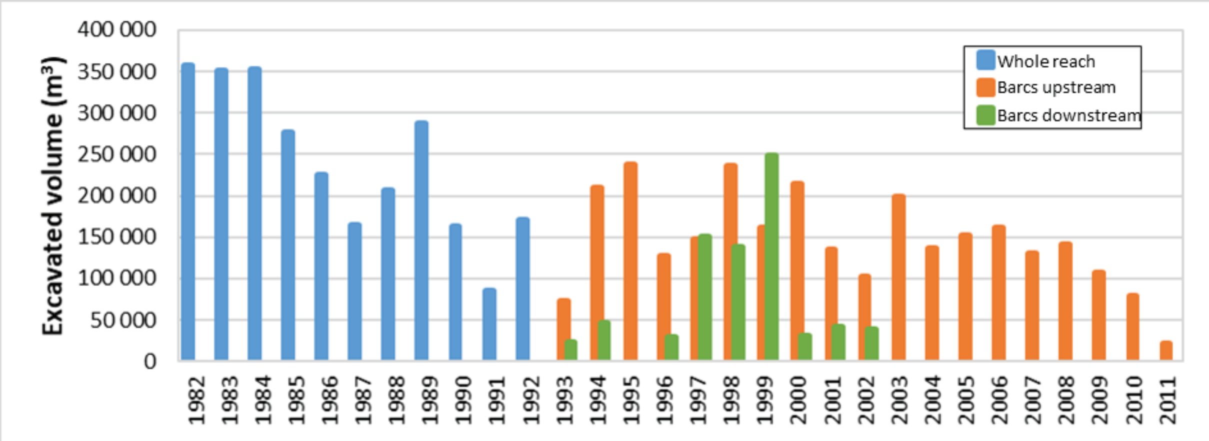

Figure 2: The excavated volume throughout the years (1982-2011) (Colours: blue: the whole Lower Drava section, orange: above Barcs, green: below Barcs)

We projected the excavated volumes on the estimated length of the known dredging sections and determined an approximate rate of incision (originating from dredging). This value was modified with the morphological changes calculated from the difference of the bedload between the sections, as the dredging pits trap sediments transported on the bed surface. The total incision was ca. 46 cm (1.53 cm/y) above Barcs, and ca. 20 cm (0.94 cm/y) downstream of Barcs.

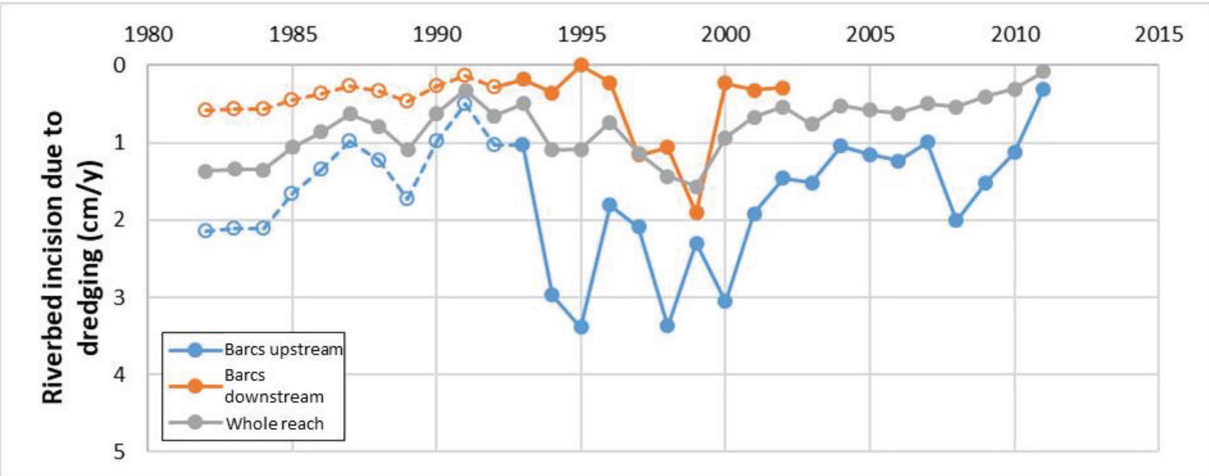

Figure 3: Riverbed incision due to dredging along the Lower Danube. (Colors: gray: the whole Lower Drava section, blue: upstream of Barcs, orange: downstream of Barcs)

Furthermore, we present the river regulation interventions carried out along the investigated section of the Drava. We briefly presented the changes in the Drava channel (based on previous studies) such as shortening, the development of meanders and islands along the Drava. Regulations started in the end of the 18th century. The length of the Drava was reduced by 40% due to meander cut-offs, the confluence moved to the north, the channel pattern simplified. In order to improve shipping conditions, the channel was straightened, groynes and bank protection works were built. Thus, the section below Barcs is almost completely regulated. However, during World War I and II, the maintenance of the regulation works stopped and the less regulated sections may have come into a state close to natural. Analyzing long-term time series of the low water before the first Croatian HPP was built (i.e. before 1975), we determined the rate of the deepening due to the traditional river regulations. We found, that before 1975, the riverbed deepened by approx. 1.00-2.50 cm/y.

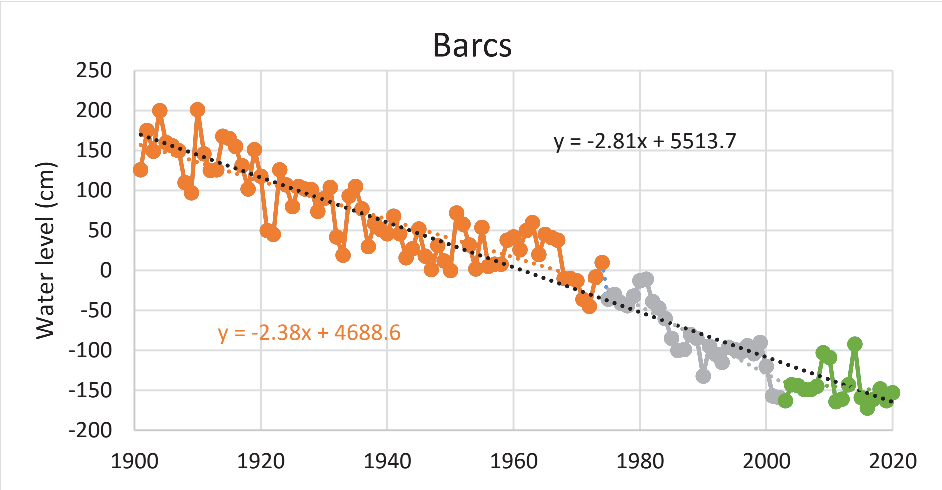

Figure 4: The annual low water levels at Barcs (154,10 rkm) between 1901 and 2020. (Colors: orange: 1901-1974 (only traditional river regulation), gray: 1975-2002 (HPPs and dredging as well), green: 2003-2020 (since dredging activities are discontinued), black: 1901-2020.

Last, but not least, we introduce the three Croatian HPPs (Varaždin, Čakovec and Donja Dubrava HPPs). Based on previous studies, we present in detail the hydrological and hydromorphological effects of the HPPs. The effects of newly installed HPPs are immediate. The longitudinal sediment continuity disrupts, deficit arises in the downstream. This „clear water" has a high erosion potential and initiates an intensive, downstream propagating incision process right below the dam. However, the vertical changes reach an equilibrium state sooner or later (for example by bed-armoring) and the horizontal changes (e.g. bank erosion) come to fore. Furthermore, when there are bank protection works that inhibit the bank erosion, the incision continues.

The HPPs also modify the hydrological regime. These effects cause other significant changes in the river morphology, such as narrowing and the simplification of the channel pattern. All the effects of the HPPs are spatially and temporally extensive, but not everlasting. The most significant changes occurred in Őrtilos (235.90 rkm), which is the closest section (of the investigated Drava section) to the three Croatian HPPs. The nearest, Donja Dubrava HPP is located only 10 kms upstream. It can be seen, that after putting the first two HPPs into operation, the new equilibrium state could be formed in 5-6 years, but after starting the operation of Donja Dubrava HPP, this process lasted a decade (1989-2000), during which, the riverbed deepened by ca. 140 cm. Note, that there are no other effects known at this station.

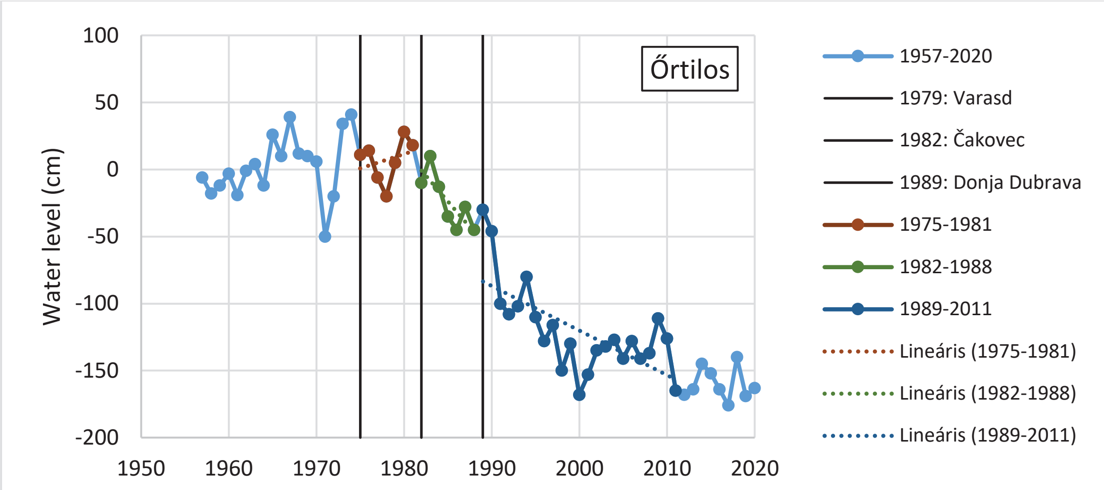

Figure 5: The effect of the Croatian HPPs according to the changes in low water levels in Őrtilos (235.90 rkm)

Downstream of Őrtilos, the effects of the anthropogenic causes cannot be entirely distinguished. By determining the total changes in the bed level (via time series analysis of the low water levels) and extracting the estimated value of the incision caused by dredging, we estimated the rate of morphological changes caused by HPPs and other anthropogenic effects. Upstream of Barcs, this rate was approx. 0.53 cm/y, while downstream of Barcs, it was 0.94 cm/y. As in case of the dredging and the river regulations, the vertical effects of the HPPs have also been ceased during the last decade.

Part III – Estimation of river bed incision (Time series analysis of low water levels)

The intensity of the morphological changes was estimated via the analysis of the changes in low water levels. We carried out the analysis of the low water levels measured at 10 hydrological monitoring stations along the Lower Drava. Time series for the Hungarian sites (water levels are measured every hour) had been provided by the South-Transdanubian Water Management Directorate. The Croatian values had been produced from the online available archive (containing daily values) of the Croatian Meteorological and Hydrological Service. As this part strongly relates to the evaluative analysis, we do not discuss the details here.

We also present and interpret the changes based on the cross-sectional shape of the river between 1971, 2006 and 2018. The changes in the cross-sectional shape of the river support these results, however, there are cross sections (e.g. the area of Barcs) where there are still some ongoing effects of the intensive dredging.

Part IV – Evaluative analysis and summary

Finally, we identify the possible causes of the intensive riverbed incision of the Lower Drava and estimate their share in the long-term morphological changes. We found that the most significant causes are mainly anthropogenic: the river regulations, the dredging of the riverbed and the HPPs are responsible for the 96% of the incision. Most of the natural processes (e.g. the lateral movement of the river) alone do not cause significant changes. However, together with anthropogenic effects, they can further intensify the processes. For example, if the lateral movement of the river is inhibited by bank protection works, the joint effect is incision. Nevertheless, the tectonic movements of the Lower Drava Valley cause a constant subsidence (1-2 mm/y) which had been negligible (ca. 4%) next to the incision related to the anthropogenic effects.

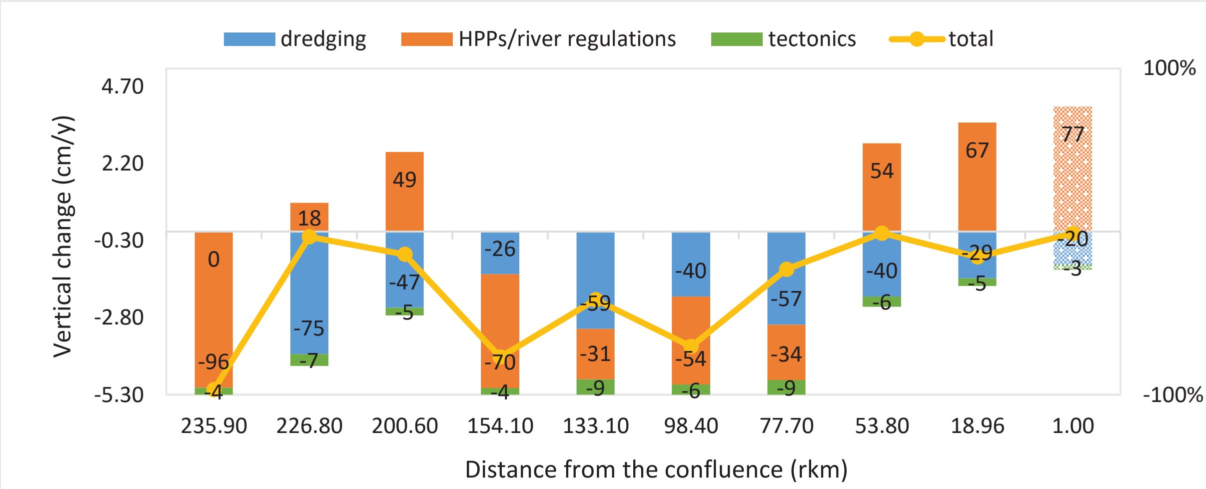

Figure 6: The vertical changes along the Lower Drava in the Second period (see below) (yellow) and the distribution (%) of the different factors. (Note: the different marking in case of the station by the confluence indicates that the time series is incomplete.)

Based on the available data (dredged volumes, time series of low water) analyzed the spatial and temporal changes of the riverbed incision. It is important to note, that the data (and therefore the results as well) should be treated with reservations, as:

- there is no detailed information about the locations of the dredging,
- the length of the time series of low water not always long enough, so in some cases, the representativeness is questionable,
- the response time is hard to determine,
- the effect of different factors is hard to distinguish,
- etc.

During the evaluative analysis, we determined three different periods depending on the major anthropogenic effect:

- **First period**: from the end of the 18th century until the first Croatian HPP (1975). During this period, only traditional river regulation measures were carried out. The natural equilibrium state of the Lower Drava had broken.

- **Second period**: from 1975 until 2002/2011 (downstream/upstream of Barcs), when the dredging activities discontinued. The effects of the different anthropogenic factors may cannot be distinguished.

- **Third period**: from 2003/2012 until nowadays. Analyzing the low water levels and the available riverbed geometry, we can conclude, that the vertical effects of the anthropogenic factors ceased and a new equilibrium state seems to be developing. However, it is important to note, that the analysis of this 10-20-years long period may not be representative.

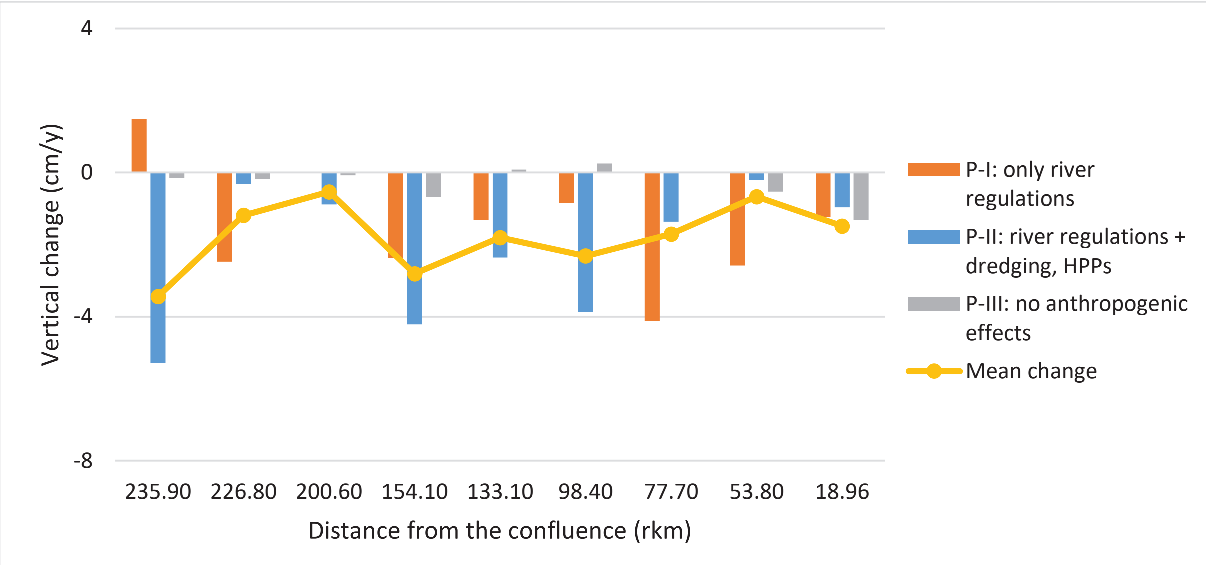

Figure 7: The intensity of vertical changes along the Lower Drava in periods determined by the anthropogenic effects. (Note: the length of the first period (P-I) varies at the different stations)

For the time period 1968-2018, the longitudinal profile of the vertical morphological changes could be produced as there was continuous data from each station. During this 50 years, the Drava deepened by ca. 86 cm. The most intensive incision (220 cm; 4.32 cm/y) occurred at the Őrtilos station which is the closest to the Croatian HPPs. The rate of the incision is decreasing towards the confluence: it was 170 cm (3.33 cm/y) at Barcs and 64 cm (1.25 cm/y) at Drávaszabolcs.

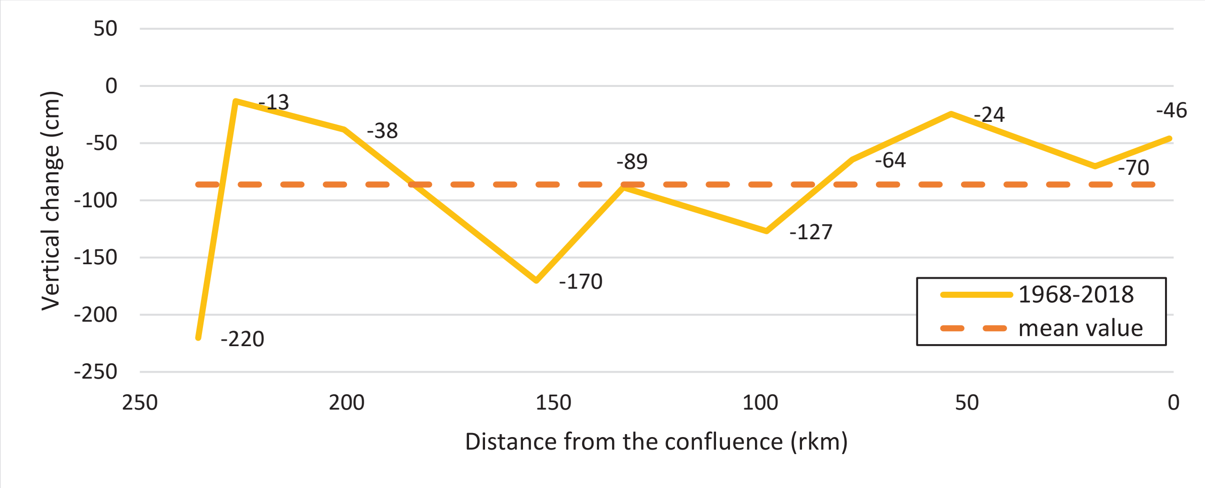

Figure 8: Bed level changes along the Drava River between 1968-2018

Summarizing the conclusions of the study:

- The length of the Lower Drava was reduced by about 40% due to meander cut-offs in the 19th century. This and the groynes, bank protection works and the dredging (with regulatory purposes) caused local narrowing and deepening. During the last ca. 120 years (1900-2020), the mean riverbed incision was 1.30 m along the Lower Drava. Examined separately the sections upstream and downstream of Barcs, the incision values are 1.20 m (upstream) and 1.40 m (downstream), respectively.

- Based on the long-term analysis of low water levels, the conventional river regulations (started in the end of the 18th century) caused the intensive deepening of the riverbed. Analyzing the period before the construction and operation of the three Croatian HPPs (i.e. before 1975), we estimate that the rate of the incision was approx. 0.50 cm/y upstream of Barcs and 2.00 cm/y downstream of Barcs.

- Between 1882 and 2007, the area of the water surface continuously decreased (almost by 50%). At the same time, the average cross-sectional width of the river also decreased by more than 50% (at a rate of 1.80-3.60 m/y). As a result of the change in these two parameters of the bed morphology, the channel pattern had been simplified, and the morphological features of the riverbed had become more uniform.

- The impact of regular river regulation measures was long-lasting yet steadily declining, apparently leading to a new equilibrium state until the commission of the Croatian HPPs and the intensive dredging began in the early 1980s. The equilibrium state applies to those sections of the river where there are bank protection works and transverse riverbed development cannot further develop. On sections without bank protection, the termination of vertical bed changes does not necessarily mean the development of a new equilibrium, as transverse bed changes, e.g. meandering may still occur.

- Based on the excavated material's volume, we could estimate the rate of incision (caused by dredging) in the period between 1982 and 2011, when the most intensive gravel and sand extraction took place on the Drava. The dredging caused approx. 1.20 cm/y incision upstream of Barcs and approx. 0.60 cm/y downstream of Barcs.

- Putting a Croatian HPP into operation, the bed incision began immediately in the downstream reach. The incision process is apparently long- but not everlasting. The most significant impact was caused by the lowermost HPP, the Donja Dubrava HPP (commissioned in 1989). In Őrtilos (235.90 rkm), the stabilization of water levels took up to a decade, during which time (1989-2000) the riverbed deepened approx. 140 cm (approx. 11.50 cm/y).

- In the natural state of the Drava, due to the large number of islands, the upper section was split into branches (thereby increasing the width of the river). This braided pattern was significantly simplified by the effects of the operating HPPs. Although the braiding index decreased, the sinuosity had not changed. The hydrological regime had been also modified by the HPPs. The decreasing water levels caused a decrease in the number and area of the islands, and the river narrowed at an intense pace.

- The most significant effect of the Croatian HPPs was experienced in the area of Őrtilos (235.90 rkm). Downstream of Őrtilos, the dredging was the main cause of the riverbed deepening from the 1980s until approx. 2010. Based on our estimations, in this period, the dredging caused ca. 50% of the incision. The other 50% was divided between the effects of HPPs and other local river regulation activities.

- From the beginning of the 2010s, after the discontinued dredging activities, the deepening of the riverbed largely decreased. The ca. 0.10 cm/y intensity meets the estimated value of the tectonic subsidence. There are shorter sections (e.g. near Barcs), where the morphological effects of the recent intensive dredging, though declining, but still occur. (Note, that the analysis of water level changes in the last 10 years is not necessarily representative.)

- In order to explore the Lower Drava River's flow, morphological, sediment transport processes and the interaction of these physical characteristics with biotic characteristics, more detailed investigations are needed in the future. The combination of modern, innovative field measurements and modelling (numerical and physical) with biological analyses may point to previously unexplored and unknown processes, based on which, future interventions can be performed with significantly greater reliability.

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