Chapter 10
Channel Incision Along the Lower Drava

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Abstract The Drava channel has not yet reached a hydromorphological equilibrium since the major human interventions two centuries ago. According to present knowledge, the fundamental reasons for prolonged channel entrenchment can be summarized in the following:

1. Among river regulation activities, the cutoff of bends should be emphasized. River length was reduced by about 40% and, as a consequence, current velocity increased. In addition, regulation structures narrowed down the channel and further accelerated flow.
2. Hydroelectric plants were built along the Upper and Middle Drava. In the reservoirs, the arriving masses of bedload and suspended load settle and this causes a sediment deficit on the lower section.
3. Channel dredging along the Hungarian Drava section (between Őrtilos and Drávaszabolcs) have also contributed to deepening of the channel. The rate of incision is not uniform all along the length of the river: upstream Barcs it is 4–6 cm y^{-1}, while downstream, at the Drávaszabolcs gauge it is only 1–2 cm y^{-1}. The average rate for the entire Hungarian section is 3 cm y^{-1}.

There are several approaches to establish the vertical displacement of the riverbed. It is estimated from water level changes and also from the shift of discharge curves in time. It is somewhat more difficult to reconstruct entrenchment from measuring the morphological alterations of channel cross-section. Channel changes have major environmental impact. The subsidence of the position of the river and the reduced frequency of high-water levels seriously influences the depth of the groundwater table in the riverine environment, including vegetation and wildlife. The water-bound plant communities and animal species are replaced by those

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favoring drier conditions. It is rather difficult to find a solution for the problem. There are possible but expensive engineering options to reduce the gradient of the riverbed and to recharge deficient bedload, but on the long term, the consequences of human interventions should be eliminated.

Keywords River regulation · Hydroelectric plants · Gradient · Bedload Suspended load · Cross-section · Sediment extraction · River discharge Water level · Groundwater table

10.1 Introduction

The Drava catchment comprises a wide range of geological formations from the oldest rocks in the central Alpine ranges to the alluvia of the Lower Drava plains (see Chap. 2 in this volume). An event-based regional investigation (Merz and Blöschl 2009), however, revealed that land use, soil types and geology are not so major control on runoff as climatic elements such as mean annual precipitation and the long-term ratio of actual evaporation to precipitation. The latter influences soil saturation and flood generation (see Chap. 4).

Compared to other European rivers, the Drava shows a relatively equable water regime. The river regime is primarily controlled by precipitation fallen on the high-mountain section of the drainage basin. The low water/mean water ratio is 1–2.6, while the mean water/high water ratio is between 1 to 3.7 and 1 to 5 (Lovász 1972). Average specific runoff is 20 L s^{-1} km^{-2}. From the long-term average of monthly mean water stages, it is clear that the largest discharges are usually observed in June, when snow cover in the high mountains of the upper catchment melts.

Due to Atlantic and Mediterranean influences, annual precipitation in the Drava catchment amounts to 660–1,530 mm with an average of 990 mm. Precipitation shows two basic patterns (Auer et al. 2001):

a. Atlantic air masses create a maximum in summer, from June to August, primarily in the Lavant and Gurk basins.
b. In addition, to the effect of Mediterranean cyclones an autumn maximum (in October and November) is typical, first of all, in the Gail Valley.

Moving downstream the Drava, the secondary autumn maximum in river discharge is becoming increasingly common. The reason is a strong Mediterranean influence. As good examples, the flood waves of November 2012 and September 2014. The latter only fell a mere 10 cm below the maximum observed to date at the Drávaszabolcs river gauge.

Climatic conditions in the future (see Chap. 4) may fundamentally change the river regime of the Drava, which involves hydromorphological and far-reaching environmental consequences (Majer 1994).

10.2 Riverbed Entrenchment

The entrenchment of the riverbed or channel incision along the Hungarian Drava section, between Őrtilos (236.000 river km) and Drávaszabolcs (70.200 river km) was first described by the experts of the Scientific Institute for Water Management during the preparation of the second Hydrographic Atlas of the Drava in the first years of the 21st century. At that time, the rate of riverbed entrenchment was estimated at 3 cm y^{-1}. Experts of the South-Transdanubian Water Management Directorate and the trustee responsible for the Drava River have been investigating the entrenchment process and made suspended and bedload measurements.

Few studies have been concerned directly with the explanation of riverbed entrenchment. Therefore, only alternative theories without appropriate scientific justification can be outlined. The relative contribution of the individual processes (counted in centimeters) responsible for the entrenchment are difficult to estimate. It is an important task of the future to underpin theories and actions of prevention by detailed measurements and analyses.

10.2.1 Tectonic Processes

One of the long-term processes, which could explain the subsidence of the Drava riverbed, is regional tectonics, the deformation of the Pannonian lithosphere (Dombrádi et al. 2010). Along with other sub-basins of the Pannonian (Carpathian) Basin, the Drava trough (depression) has been continuously subsiding ever since the Early Miocene, when the formation of the Pannonian Basin began. The total thickness of Neogene and Quaternary alluvial sequences may reach 7,000 m in the centre of the depression (Velić 2007). The southward shifting of the axis of the Drava graben subsidence zone (accommodating the meander belt of the river) has been known to scientists for a long time (Lovász 1972; Bognár and Schweitzer 2003), supported by geodetic measurements (Joó 1979) and explained by the compaction of the thick sedimentary fill (see Chap. 2). The rate of ground subsidence, however, was estimated at merely 1–2 mm y^{-1} (Joó 1992), i.e. one order of magnitude lower than the rate of the Drava incision. Therefore, tectonic processes obviously do not provide a satisfactory explanation for the rate of incision of the riverbed.

10.2.2 Flow Regulation

Although it is not easy to reconstruct the paleogeographic conditions of the Drava valley centuries ago, documents from the 107 villages of the Drava Plain in the Middle Ages supply us with some (descriptive) information on the environment.

Much later, the map sheets of the Military Survey (1784) depict the Drava Plain as a swamp area with interwoven with small watercourses and spotted with forests. The river channel itself used to be highly different from that what we see today. Multithread meandering was the typical river mechanism at that time. This pattern was highly dynamic with the continuous emergence and cutoff of meanders.

Flow regulation with the purpose of flood control began in the end of the 18th century (see Chap. 8). Between 1784 and 1848 62 artificial cutoffs were completed downstream the Mura confluence. These interventions reduced river length by 75 km, which meant ca 40% reduction and resulted in increased stream power and channel incision. The section first affected was between Drávagárdony and Felsőszentmárton and in the 19th century huge meanders were cut off between Drávasztára and Szaporca, too. This approach to regulation was practiced until 1885.

Regulation using stone and brushwood faggots–meant to be final solution to flood and navigation problems–started in the lowermost section between the confluence and Eszék (now: Osijek, Croatia) in 1887. Until World War I the regulation of the sections around Barcs, between Tótújfalu and Budakovac as well as between Zaláta and Kisszentmárton had been completed. In the interwar period, only maintenance operations were carried out. Following a treaty with Yugoslavia regulation works could continue, using stone and also involving some cutoffs.

Regulation has largely modified channel gradient, which is now 0.002 on the mountain section, 0.0005–0.00045 from the Mura confluence to Vízvár, 0.00025–0.0002 to Barcs, while only 0.00012–0.00007 at Drávaszabolcs. In parallel, the grain size of the bed material changes from gravels (16–52 mm diameter) at Őrtilos, to sandy gravel (20–0.5 mm) at Barcs and fine to medium sands in 20–30 m thickness at Drávaszabolcs.

A marked knickpoint in the longitudinal profile is observed at Vízvár (190 rkm). This could indicate the upper limit of regressive bed deepening due to the increased current velocity of the regulated river.

10.2.3   Flow Impoundment on Upper Sections

Although water levels show a clear decreasing trend over the recent decades, hardly any trend is observed in river discharges. Consequently, large-scale changes of the hydrological system in the Drava drainage basin cannot be evidenced. Since much of the bedload and a large part of the suspended load are retained by the 22 hydroelectric plants on the Austrian, Slovenian and Croatian river sections (see Chaps. 7 and 9), the majority of sediment load in the lower Drava channel derives from the Mura River. Out of the hydroelectric plants, the lowermost plant in Croatia, at Dubrava (254.000 rkm) has major impact on the hydromorphology of the Lower Drava. This is a peaking plant with considerable water (and energy) storage in its reservoir (Lake Dubrava, area: 17.1 km^2, the largest in Croatia; storage capacity: ca 100 million m^3). Peak-time operation results in diurnal cycles

of water level fluctuation, amounting to maxima of 120 cm and average ranges of 60–80 cm at Őrtilos and 30–40 cm at Paks.

The reservoirs store large amounts of suspended and bedload and, thus, create significant sediment deficit on the downstream reaches and induce 'clearwater erosion' there (Rollet et al. 2013).

10.2.4   Gravel Mining from Riverbed

The gravel and sand accumulations in the riverbed are common sources of building materials. Part of the local sediment surplus in the Drava channel is mined and this also contributes to sediment deficit downstream. At the end of the 20th century dredging affected an estimated amount of 500,000–700,000 t y^{-1} in Croatia and 160,000–180,000 t y^{-1} in Hungary (Horváth 2002). Calculated for the period 1982–2011, Croatian actors were responsible for the removal of 6,292,000 m^3 extracted material and Croatians for 2,658,000 m^3 on the joint Croatian-Hungarian section. This means the sediment deficit was concentrated on Croatian state territory.

10.3   Sediment Budget of the Hungarian Section

Regular suspended sediment measurements on the Drava began in 1961 and bed-load measurements in 1969 at Barcs and Drávaszabolcs on 4–6 occasions per year. In 1998 measurements started at Botovo and Bélavár, too (Fig. 10.1). At present, the frequency of sediment is conducted parallel with water discharge gauging on 8–10 occasions annually (see Chap. 9).

The recharge of coarse bedload is a crucial factor of channel incision (Simon and Rinaldi 2006). In addition to the water regime, the bedload transport of the Drava River is largely influenced by the operation of upstream hydroelectric plants, first of all, the plant built at Dubrava in 1989. The transported bedload declines between Botovo and Barcs and remarkably grows from Barcs to Drávaszabolcs (Table 10.1).

Suspended load transport represents a larger volume and less dependent on the operation of hydroelectric plants. It derives from the erosion of the riverbed and banks. Some suspended material is not trapped in the reservoirs but can pass through the turbines. The trends of suspended load are similar to those of bedload (Table 10.2).
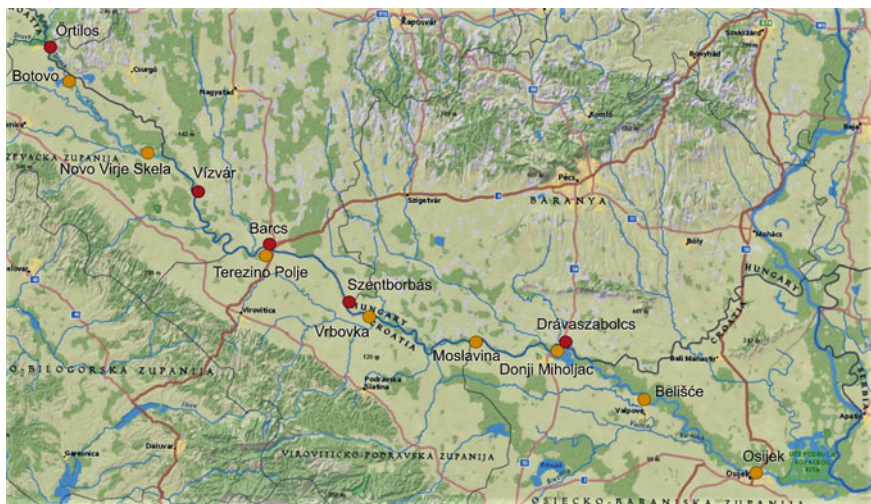
Fig. 10.1 River gauging stations on the Lower Drava River. Red dots: Hungarian (DDVÍZIG) stations; yellow dots: Croatian (Hrvatske vode) stations

Table 10.1 Bedload transport along the Lower Drava River (after Bonacci and Oskoruš 2010)

Measured section		Annual average bedload transport (t y^{-1})		Water discharge/bedload transport relationship (g s^{-1})
Site	River, km	1986–2003	2004–2011	
Botovo	227.200	109,038	24,452	$G_g = 4.5279 \times 10^{-10} \times Q^{4,552}$
Bélavár	198.700	37,261	n.a.	$G_g = 3.8113 \times 10^{-11} \times Q^{4,755}$
Barcs	152.700	77,909	22,692	$G_g = 8.7286 \times 10^{-10} \times Q^{4,407}$
Drávaszabolcs	77.700	194,024	71,845	$G_g = 3.1623 \times 10^{-8} \times Q^4$

G_g bedload yield; Q water discharge

Table 10.2 Suspended sediment transport along the Lower Drava River (after Bonacci and Oskoruš 2010)

Measured section		Annual average suspended sediment transport (t y^{-1})		Water discharge/ suspended sediment transport relationship (kg s^{-1})	Water discharge/ suspended sediment concentration relationship (g s^{-1})
Site	River, km	1986–2003	2004–2011		
Botovo	227.200	578,173	313,270	n.a.	$C_k = 136.01 \times Q^{0.3679}$
Bélavár	198.700	533,128	n.a.	n.a.	$C_k = 226.43 \times Q^{0.2818}$
Barcs	152.700	457,161	649,840	$G_L = 256,42 \times G_L^{0.2906}$	$C_k = 196.39 \times Q^{0.3191}$
Drávaszabolcs	77.700	583,573	599,755	$G_L = 220,78 \times G_L^{0.3321}$	$C_k = 169.81 \times Q^{0.3316}$

G_L suspended sediment yield; C_k suspended sediment concentration; Q water discharge

Table 10.3 Gauging stations for the determination of the rate of riverbed entrenchment

Gauging station					
Name	River, km	Base level (m above Baltic level)	Operating organization	Year of installment	Observations
Őrtilos	235.900	125.94	DDVÍZIG	1957	H, Q, T
Heresznye-Vízvár	187.590	101.195	DDVÍZIG	2012	H, Q, T
Barcs	153.800	98.14	DDVÍZIG	1976	H, Q, T, Ck
Szentborbás	133.100	94.74	DDVÍZIG	1934	H, Q, T
Drávaszabolcs	77.700	86.75	DDVÍZIG	1935	H, Q, T, Ck

H water level, *Q* water discharge, *T* temperature, *Ck* suspended load concentration

10.4 Trends in the Markers of Riverbed Entrenchment

For determining the vertical displacement of the Drava bed, data pointing to riverbed entrenchment from the gauging stations in Hungary were analyzed (Table 10.3).

10.4.1 Changes in Water Level

The analyzed time series (47 year, 1970–2016) reflects the impact of the three hydroelectric plants on the Croatian section (Varaždin at 302 river km, built in 1975; Čakovec at 278 river km, built in 1982 and Dubrava at 254 river km, built in 1989) (Figs. 10.2, 10.3, 10.4, and 10.5).

The changes in low and medium water stages are most marked at Őrtilos, where a 1.5–2 m drop (3–4 cm y^{-1}) was observed over the studied period (Fig. 10.2), while in high water levels 0.4 m decrease was found. The difference is explained by the water spread out over the floodplain. The linear trend of low and medium water levels at Barcs shows 1.3–1.5 m (2–3 cm y^{-1}), while that of high water levels 1 m lowering (Fig. 10.3). At the Szentborbás station the corresponding values are 0.65–0.75 m (low and medium water levels, 1.5 cm y^{-1}) and 0.6 m (high water levels) (Fig. 10.4) and at Drávaszabolcs 0.4 m and 0.2 m, respectively (Fig. 10.5) with only 1 cm y^{-1} annual lowering.

In summary, it is claimed that the reduction of low and medium water levels is more marked at all stations than that of the more fluctuating high water levels.
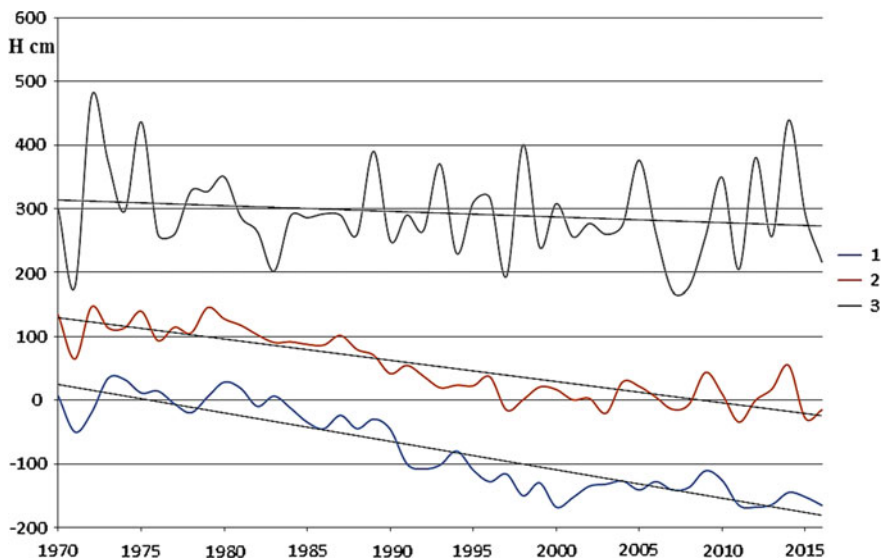
Fig. 10.2 Annual maximum, mean and minimum water levels at the Őrtilos gauging station, 1970–2016. 1, low water stages (cm); 2, medium water stages (cm); 3, high water stages (cm)
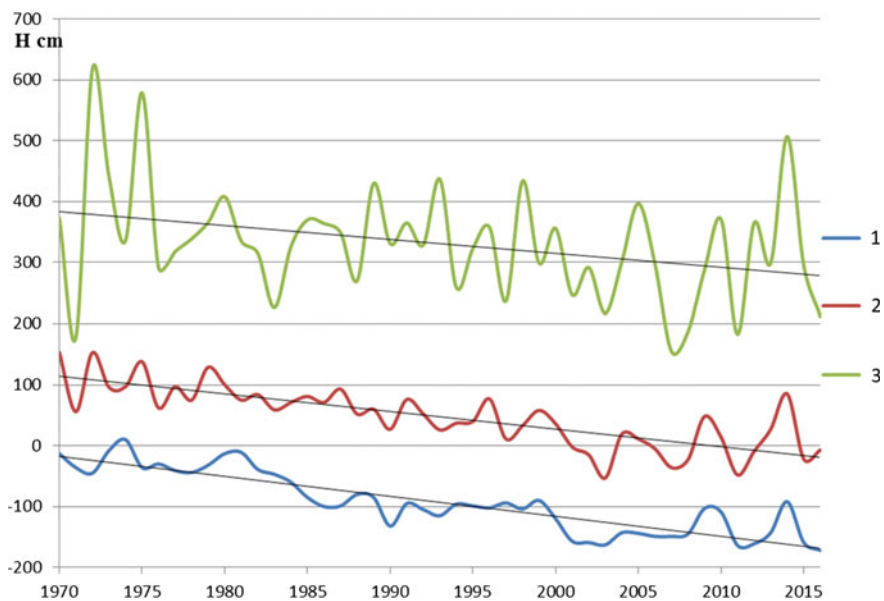

Fig. 10.3 Annual maximum, mean and minimum water levels at the Barcs gauging station, 1970–2016. For legend see Fig. 10.2
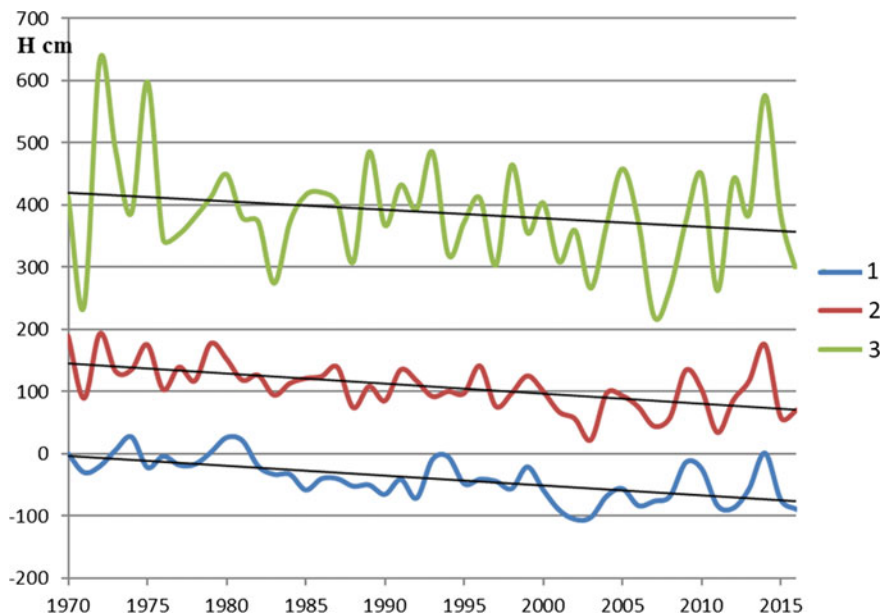
Fig. 10.4 Annual maximum, mean and minimum water levels at the Szentborbás gauging station, 1970–2016. For legend see Fig. 10.2
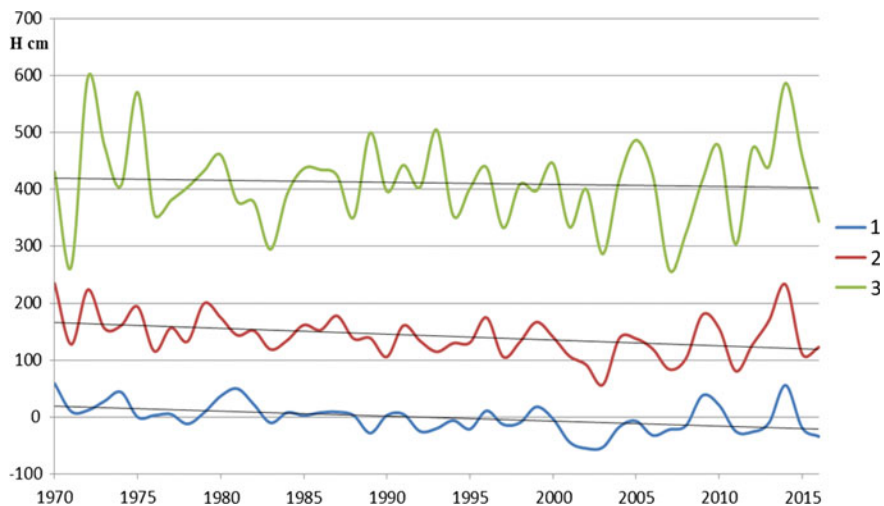

Fig. 10.5 Annual maximum, mean and minimum water levels at the Drávaszabolcs gauging station, 1970–2016. For legend see Fig. 10.2

10.4.2 Changes in Water Discharge

The length of the time series only allows the analysis of discharge trends in the case of two gauging stations, Barcs (observations since 1970) and Drávaszabolcs (since 1970) At Őrtilos and Szentborbás measurements only started in 2004. Thus, we cannot rely on their data.

The Barcs data are not unequivocal: minimum and medium water discharges show minimal growth and maximum water discharges a major decrease by ca 400 m^3 s^{-1}. It is to be noted that the large floods of the 1970s (in 1972 and 1975) have a decisive influence on the trend, which is compensated by the recent flood in 2014 (Fig. 10.6). At Drávaszabolcs the minor rise in low and medium discharges is negligible, but high water discharges were reduced by 100 m^3 s^{-1}, also influenced by the above mentioned flood events (Fig. 10.7).

In summary, water discharges on the Őrtilos-Drávaszabolcs section have not been modified over the 47 years of study, but high water discharges have dropped by 400 to 100 m^3 s^{-1}, more remarkably on the upper reaches.

10.4.3 Changes in Stage/Discharge Rating Curves

In recent decades, the stage/discharge curves tended to shift to the right at both Barcs and Drávaszabolcs (Figs. 10.8 and 10.9). It means that ever lower water levels corresponded to the same water discharge. In the cross-section at Barcs, the extent of the right shift was 250 m^3 s^{-1} (100 cm drop in water level) for low stages, 500 m^3 s^{-1} (120 cm drop) for medium water stages and 2,000 m^3 s^{-1} (50 cm drop)

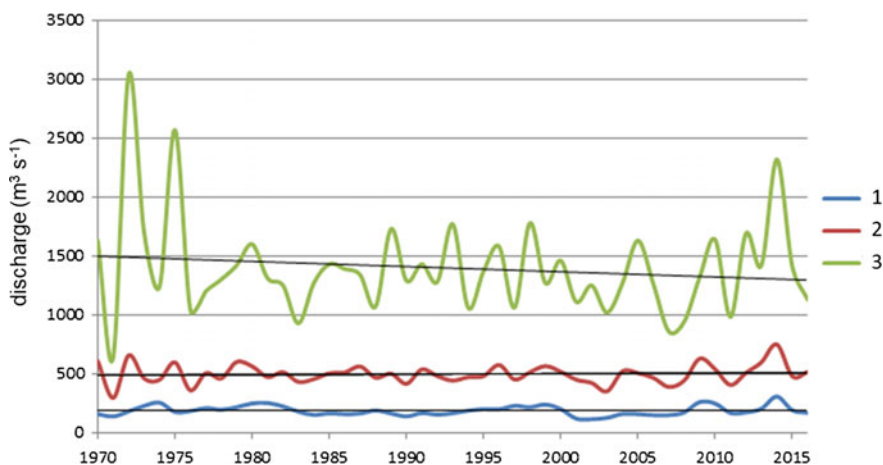**Fig. 10.6** Annual maximum, mean and minimum discharges at Barcs, 1970–2016. 1, low water discharges (m^3 s^{-1}); 2, medium water discharges (m^3 s^{-1}); 3, high water discharges (m^3 s^{-1})
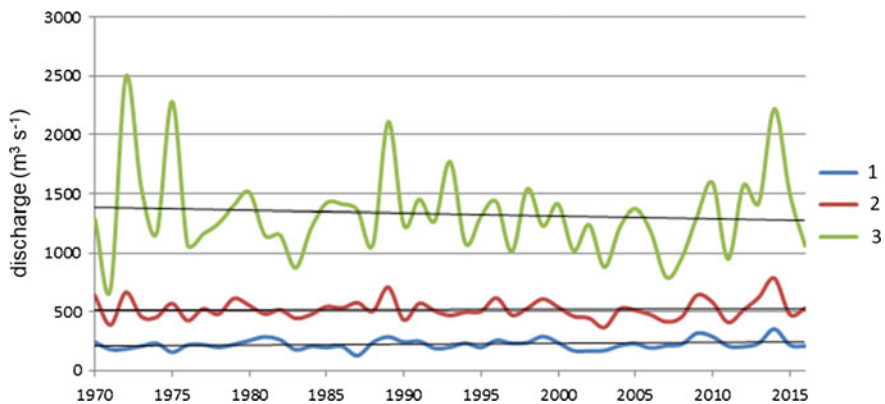
Fig. 10.7 Annual maximum, mean and minimum discharges at Drávaszabolcs, 1970–2016. For legend see Fig. 10.6
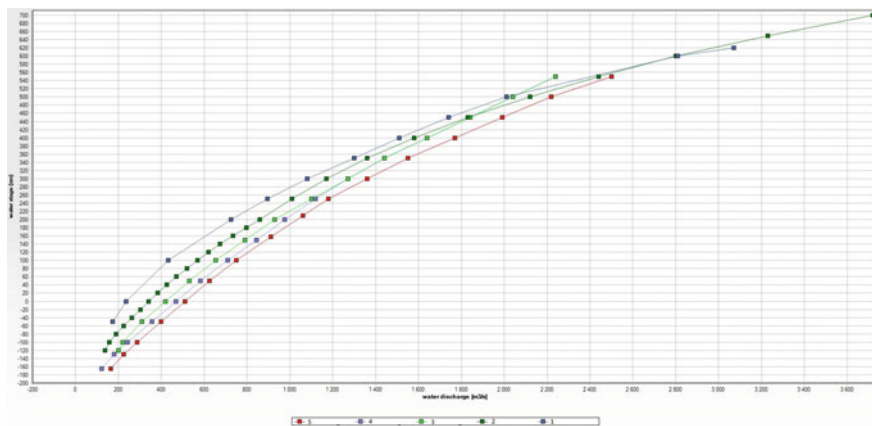

Fig. 10.8 Water discharge/water level relationships at Barcs. 1, curve #3: 1972–1974; 2, curve #13: 1988–1992; 3, curve #18: 1998–2000; 4, curve #21: 2003–2007; 5, curve#24: 2011–2017

for high water stages (Fig. 10.8). The respective ranges of values for the Drávaszabolcs station were 50, 50–60 and 0–10 cm (Fig. 10.9).

10.4.4 Changes in Cross-Section

The morphological changes of a river channel over time are best demonstrated by the repeated surveying of marker points along a fixed profile. Here the Barcs
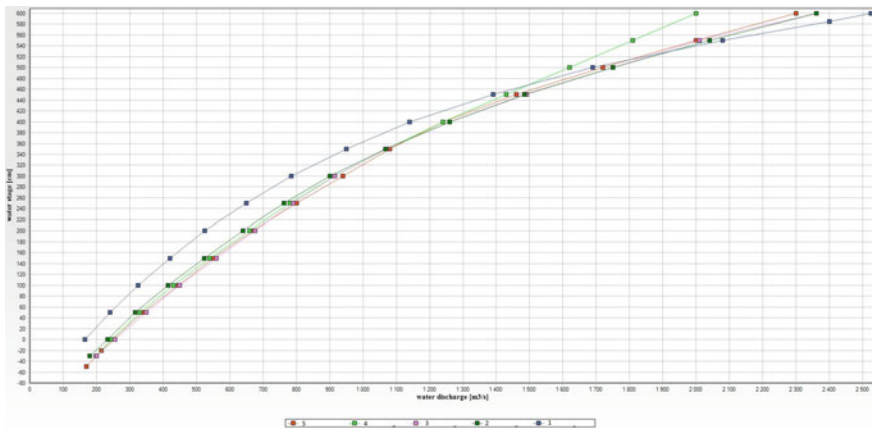
Fig. 10.9 Water discharge/water level relationships at Drávaszabolcs. 1, curve #2: 1971–1974; 2, curve #11: 1988–1993; 3, curve #15: 1997; 4, curve #18: 2000; 5, curve #23: 2009

cross-section is selected for analysis. Clear riverbed subsidence of varying rate is found for about two-thirds of the profile since 1970. The maximum value is 1.5 m. In correspondence with the observations of changes in water level (Sect. 10.4.1), this results in 3.5 cm incision in the most rapidly subsiding part of the cross-section (Fig. 10.10).

10.5 Discussion

The above presented analyses of data provided clear evidence for riverbed entrenchment on the Őrtilos–Drávaszabolcs section of the Drava River. The findings from various parameters and for the gauging stations are summarized in Table 10.4.

10.6 Impact of Damming on River Ice

Through modifying current velocity, the winter freezing conditions of rivers may also influence the rate of channel incision (Shen and Yapa 1986). Ice conditions on the Drava are presented on the basis of observations conducted–with shorter interruptions–at Barcs and Drávaszabolcs since the 1930s. The ice conditions at Drávaszabolcs altered significantly in 1975, when the first Croatian hydroelectric plant on the Drava was installed. Between 1936 and 1975 frozen river was observed on 18 occasions, drifting ice on three occasions and ice on banks on four occasions.
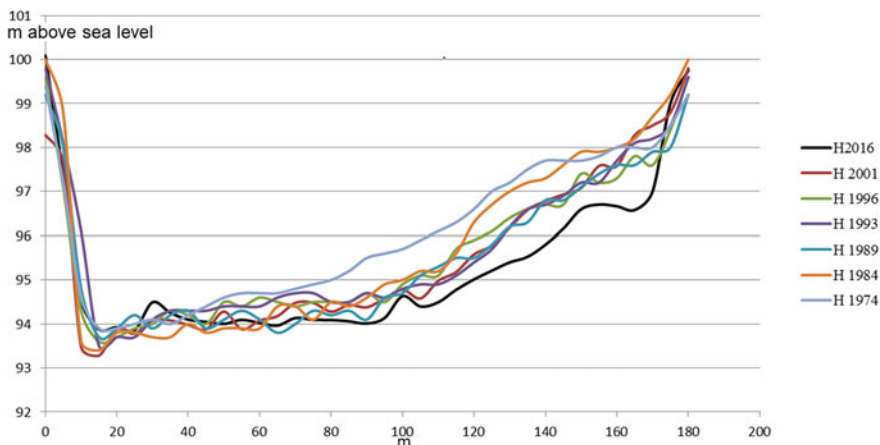
Fig. 10.10 Changes in the riverbed cross-section at Barcs, 1974–2016. 1, 2016; 2, 2001; 3, 1996; 4, 1993; 5, 1989; 6, 1984; 7, 1974

Table 10.4 Rates of channel incision reconstructed from various parameters for the period 1970–2016

Gauging station		Channel incision (cm y^{-1}) based on				
		Changes in water level		Changes in water discharge		Changes in cross-section
Name	River, km	Low and medium waters	High waters	Low and medium discharges	High discharges	
Őrtilos	235.900	3–4	1			
Barcs	153.800	2–3	2	2–2.5	1	3.5 cm
Szentborbás	133.100	1.5	1.5			
Drávaszabolcs	77.700	1	<1	1	<0.5	

After 1975 ice occurrence was drastically reduced (Lovász 2016). In the Barcs cross-section, the river was frozen over on 26 occasions between 1936 and 1975, in 15 years drifting ice was observed and the number of ice-free years was only four. After 1975, the river froze over in only 2 years and ice drifted in 9 years. Probably to the impact of global warming and increased current flow during medium water stages (caused by river regulation), ice formation was often inhibited and for 30 years no ice cover was detected on this river section (Fig. 10.11).
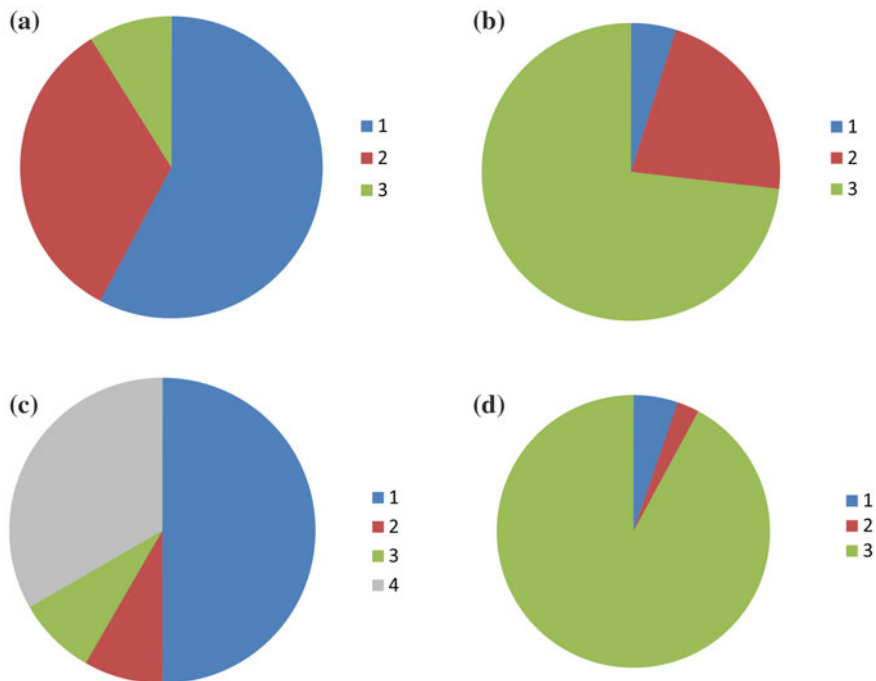
Fig. 10.11 Ice conditions (percentage of years in the given period) on the Drava at Barcs (A and B) and at Drávaszabolcs (C and D). A. 1936–1975; B. 1976–2016; C. 1936–1975; D. 1976–2016. 1, frozen river; 2, drifting ice; 3, ice on banks; 4, no ice

10.7 Environmental Impact of Channel Incision

Human impact is detectable in all directions of change in channel morphology: vertical (channel incision), horizontal (bank erosion, meander formation) and longitudinal (shifting knickpoints, channel regression) alterations. The environmental impact covers both channel and floodplain modification (Timár and Telbisz 2005). In this chapter, the direct influences on geometrical parameters and groundwater conditions are presented, but, naturally, there are far-reaching effects on the physical environment, also involving changes in vegetation and animal life.

Riverbed entrenchment reduces the duration of water stages related to the absolute level on the river gauge. The process is demonstrated through the chart of water level exceedance curves at the Barcs and Drávaszabolcs gauging stations for the period 1950–2016 (Figs. 10.12 and 10.13).

The charts show time series split up into two: one for 1950–1983 and the other for 1984–2016. The chart of 50% duration shows about 60 cm decrease of water stage, i.e. of riverbed level, for Drávaszabolcs and about 100 cm for Barcs over the

Fig. 10.12 Water level
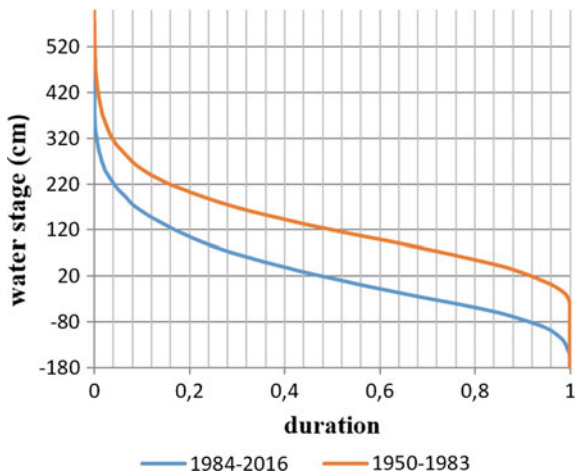exceedance curves at Barcs,
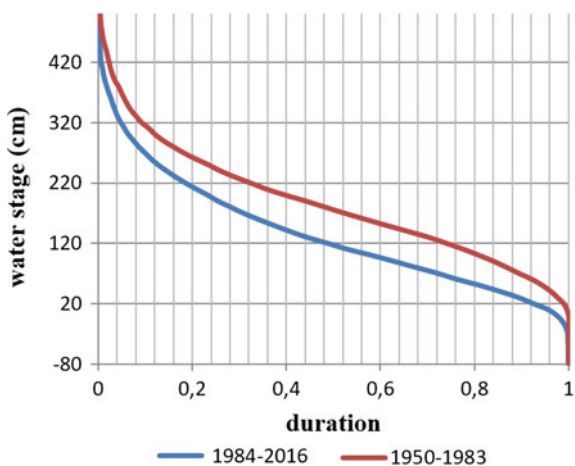1950–1984 and 1984–2016

Fig. 10.13 Water level
exceedance curves at
Drávaszabolcs, 1950–1984
and 1984–2016

67-year period. This is, however, only a rough indication of river incision since
other processes not treated here may also be influential.

An observation well which shows typical groundwater conditions is located at
Lakócsa village, at some kilometers distance from the Drava River (Fig. 10.14).
The analysis presents a slightly declining trend for the 1980–2016 period. With
regard to the close communication between the Drava channel and groundwater,
this trend allows the conclusion that the riverbed is entrenching. Since observations
took place twice a week before 2010 and hourly reading after 2010, the sections of
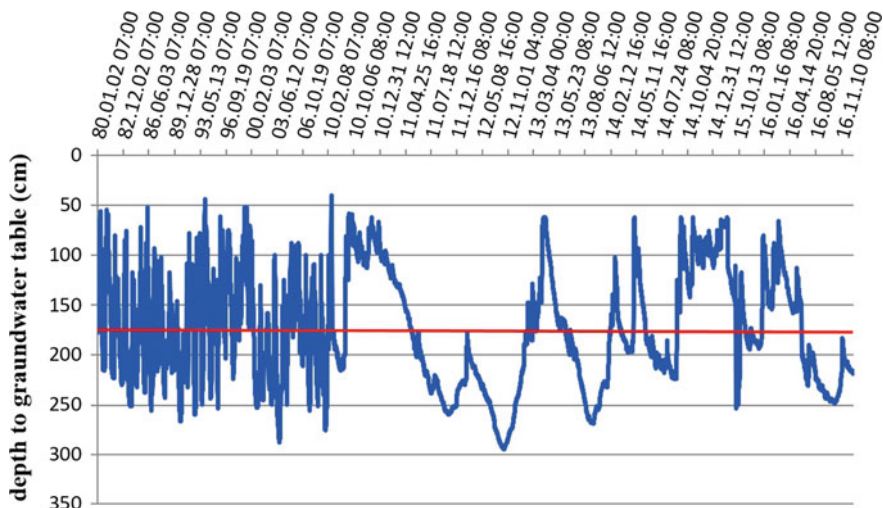the chart in Fig. 10.14 before and after 2010 are different in detail.

Fig. 10.14 Groundwater levels at the observation well of Lakócsa, 1980–2016

10.8 Conclusion: Possible Solutions

At first, river regulation increased the channel gradient of the Drava River, increased current velocity and induced channel deepening. Later, the construction of hydroelectric plants on the upper and middle sections and sediment mining from the channel generated a sediment deficit, which further intensified riverbed entrenchment. The interplay of the three human interventions results in channel incision of about 3 cm y^{-1} rate on the Őrtilos–Drávaszabolcs river section. This is a detrimental process to the physical environment.

To plan preventive engineering action against riverbed entrenchment, detailed numerical data on the process should be available. Natural and anthropogenic components of incision should be separated and characterized quantitatively. It is also questionable whether the consequences of human interventions could be eliminated by another anthropogenic effect, which may also start yet unknown detrimental processes. This may sound a philosophical question, but before venturing on solving the problem, it has to be answered. Although the engineering response is not too complicated (reducing the curve through establishing an equilibrium in sediment budget), the involvement of all stakeholders is necessary if we want to arrive at a solution to the satisfaction of (almost) everybody affected.

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