Chapter 12
Oxbow Lakes: Hydromorphology

Dénes Lóczy, József Dezső, Péter Gyenizse, Szabolcs Czigány and Gabriella Tóth

Abstract Cut-off oxbows are the most remarkable fluvial landforms and the most valuable wetland habitats in the protected floodplain of the Lower Drava River in Hungary. Their geomorphic evolution, however, has not been studied yet. Recently, a complex hydromorphological survey of oxbows covered their geographical position, connection with the main Drava channel, water balance, hydrogeological properties, water retention capacity and groundwater flow in their environs. The purpose of the investigations was to assess the potential for oxbow lake and floodplain rehabilitation. Two zones of oxbows, possibly differing in age and geomorphological evolution (the date of cutoff), have been identified and preliminarily described. The focus of research was on the Cún-Szaporca lake system, part of the Danube-Drava National Park and a Ramsar area, where the clogging of the oxbow bed, a critical factor of transmissivity, was analyzed in detail. For planning landscape-scale rehabilitation (the Old Drava Programme) more information on the old courses of the Drava and its preserved but gradually disappearing traces (the present-day oxbow lakes) would be necessary.

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D. Lóczy (ed.), *The Drava River*, Springer Geography,
https://doi.org/10.1007/978-3-319-92816-6_12

Keywords Cutoff · Water balance · Evapotranspiration · Groundwater flow Floodplain connectivity · Oxbow lakes · Water replenishment · Floodplain rehabilitation

12.1 Introduction

Water availability is of primary importance for all kinds of landscape. As a consequence of human interventions and probably of global climate change, even river floodplains–rich in wetlands under natural conditions–can regularly experience water shortage (Brookes 1996; Amoros and Bornette 2002). In other parts of the world, riverine environments with alternating extreme floods and droughts are also typical (e.g. in Australia—Erskine and Warner 1988).

In this situation, an important landscape function of floodplain lakes is floodwater retention in wet years and groundwater recharge in dry years. This ecosystem service is indirectly influenced by the trophic state of floodplain water bodies (external and internal nutrient loadings and littoral macrophytic vegetation—Reckendorfer et al. 2013). Evidence have been found for the opinion that the life span of backwaters has a significant effect on ecosystem services (in the Danube basin by Hein et al. 2015; along the Rhône by Dépret et al. 2017). Since there have been dramatic losses of floodplain wetland habitat due to river regulation and land drainage, a functional degradation of these ecosystems resulted worldwide (Heiler et al. 1995; Tockner et al. 2010a, b). The reduction in area and impairment of the environment have diminished the capacity of floodplains (particularly of floodplain lakes) for water retention and flood risk was enhanced (e.g., Lóczy et al. 2009; Habersack et al. 2015), while other key services, such as groundwater replenishment, nutrient storage (Hein et al. 2004) and water purification have also suffered serious limitations. The ecosystem services of floodplain wetlands are significantly influenced by the position they occupy in the landscape (Schwarz et al. 1996), which also influences their rehabilitation potential (Dragun et al. 2014; Lóczy et al. 2017).

In the floodplain of the Hungarian section of the Drava River, traditionally *floods* represented the most serious natural hazard (see Chap. 8 in this volume). The most perilous event of the 19th century was certainly the 1827 flood. This probably involved the largest inundated area ever (28 villages on ca 25,000 ha). In the 20th century, the 1972 flood of the Drava River was a disaster of special significance (Buchberger 1975). Although his time no dyke breach happened, the event brought attention to the insufficient protection provided by defence lines. In 1975 the next flood took place, but it stayed below the 1972 water level. Nevertheless, a supervision of flood-control strategy was required. The structures previously only protected by temporary ('summer') dykes (e.g. at the Majláth-puszta manor) became encircled by main dykes by 1979. In spite of channel incision and theoretically higher floodway capacity, high waters almost reached the maximum again in 2013, and particularly in September 2014, when a Mediterranean cyclone brought heavy and prolonged rainfall (Bizjak et al. 2014). The recently built dykes, however, successfully prevented overbank flow.

Although *droughts* must have been common in earlier times, too, even less archive data are available on severe water shortage conditions (Kiss and Nikolić 2015). Following profound human interventions (river regulation, barrage constructions and enhanced water retention in the reservoirs of hydroelectric plants upstream, sand and gravel extraction from riverbed etc.), recently low water stages show an increasing duration over the year (see Chaps. 6 and 9 in this volume). Floodplain drainage related to river regulation and the drawdown effect of channel incision reduced groundwater levels by several metres (Viczián and Zatykó 2011).

Water shortage is also due to the aridification trend related to global climate change. At the same time, channel incision and increased gradient result in the more rapid conveyance of flood waves (WWF 2002), reducing opportunities for floodwater retention (Kiedrzyńska et al. 2015). The flood retention role of floodplain wetlands has been studied from several approaches in international literature (Valentová et al. 2010; Schober et al. 2015).

Although it is agricultural areas which are most severely affected by drought, the water availability of oxbow lakes under protection is also endangered. As a result of water shortage and increasing sedimentation, only traces of *vegetation* with higher naturalness value (Borhidi 1997) can be detected in wetlands. The open water surfaces of oxbow lakes are shrinking; riverweed biodiversity is declining, while riparian (reed, bulrush, tall forb) vegetation and plants characteristic of dry habitats are spreading (see Chap. 13). Invasive weeds, including the Giant Goldenrod (*Solidago gigantea*), Common Milkweed (*Asclepias syriaca*), False Indigo-bush (*Amorpha fruticosa*), Boxelder (*Acer negundo*) and Tree of Heaven (*Ailanthus altissima*), are also proliferating (WWF 2002). The water bodies are surrounded by agricultural fields and improper land use (insufficient management of grasslands, large-scale intensive arable farming in the closest proximity, separated by a very narrow buffer zone) aggravates environmental problems.

12.2 Study Area

The *Drava Plain* is a lowland at 96–110 m elevation above sea level and with 2 m km^{-2} average relative relief (Fig. 12.1). It is more undulating with sand dunes in the west and flattens out towards the east. The Hungarian Drava section is 75 km long, and the corresponding catchment extends to 1.143 km^2. On this section, there are 20 major side channels, 13 tributary streams and 19 major cut-off meanders with oxbow lakes (of ca 150 ha total area) on the floodplain (Fig. 12.1). Although the oxbow lakes along the Drava have been inventoried for general hydrological (Pálfai 2001) and ecological conditions (Ortmann-Ajkai et al. 2003), no systematization and typology have been made to date.

In Croatia, 222 objects of various size, including side-arms, cut-off meanders and largely infilled abandoned channels, were identified in an inventory and studied for biodiversity (Grlica 2008). The largest oxbow lake has an area of 101.7 ha at mean water level (the Old Drava of Križnica, an overdeveloped composite meander system on the left bank, but on Croatian territory, between 173 and 166 rkm).

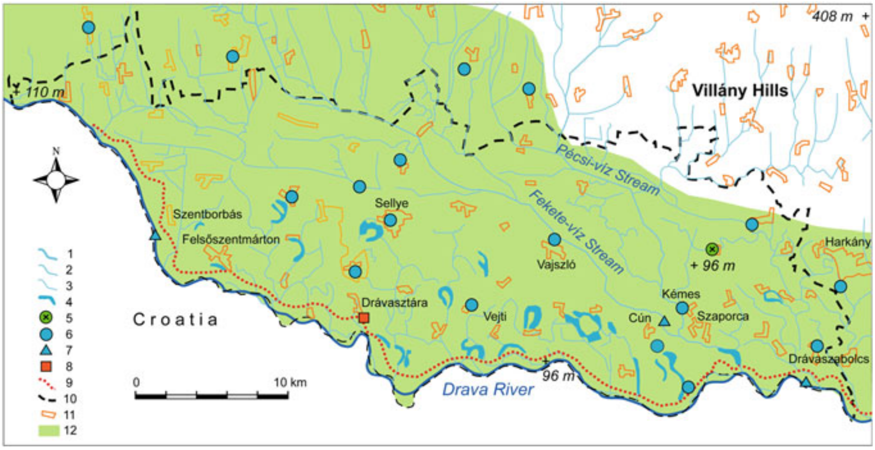

Fig. 12.1 Location of the lower Hungarian Drava section and its floodplain. 1, Drava main channel; 2, major stream; 3, small watercourse, drainage canal; 4, oxbow lake; 5, deep groundwater observation well; 6, shallow groundwater observation well; 7, river gauge; 8, hydrometeorological station; 9, main flood-defence line; 10, boundary of planning area in the Old Drava Programme; 11, built-up area; 12, morphological floodplain

The *climate* of the floodplain is moderately warm and wet in the west (under Atlantic influence) and moderately warm and moderately wet in the east (under Mediterranean influence) (WWF 2002). Mean annual temperatures are 10.2 °C in the west, 10.8 °C in the east (above 11 °C in recent decades) and in the growing season they are between 16.5 °C and 17.5 °C. Absolute minimum temperature is −17 °C and maximum temperature is 35 °C. The number of severely cold days (below −10 °C mean daily temperature) is 9–11 and that of hot days (above 30 °C) is 20–22 on the average. Annual precipitation drops from ca 800 mm in the west to below 700 mm in the east. May is the rainiest month and January and February are the driest. Absolute daily maxima rise to 104 mm. Summer water deficit has shown an increasing trend in recent decades (Blanka et al. 2013; Mezősi et al. 2016).

The genetic soil types occurring on the floodplain (in parentheses: WRB soil classes) are

- alluvial soils next to the Drava channel (Fluvisols);
- meadow soils in a zone further away from the channel and at higher elevation, locally with chernozem dynamics (Histosols);
- sandy soils near Barcs (Arenosols);
- marsh soils on the shores of oxbows (Gleysols).

Soils are more acidic in the west and calcareous in the east. Soil erosion is only observed on sandy soils (deflation) and in the vicinity of high loess bluffs (gully erosion).

The representative area selected for a more detailed study, the *Cún-Szaporca oxbow* (Fig. 12.2), is a cut-off composite meander of the Drava River of 275 ha total area (Fleit et al. 2012; DDKÖVÍZIG 2012). After artificial cutoff in the mid-19th century, it was eventually disconnected from the main channel in 1975,

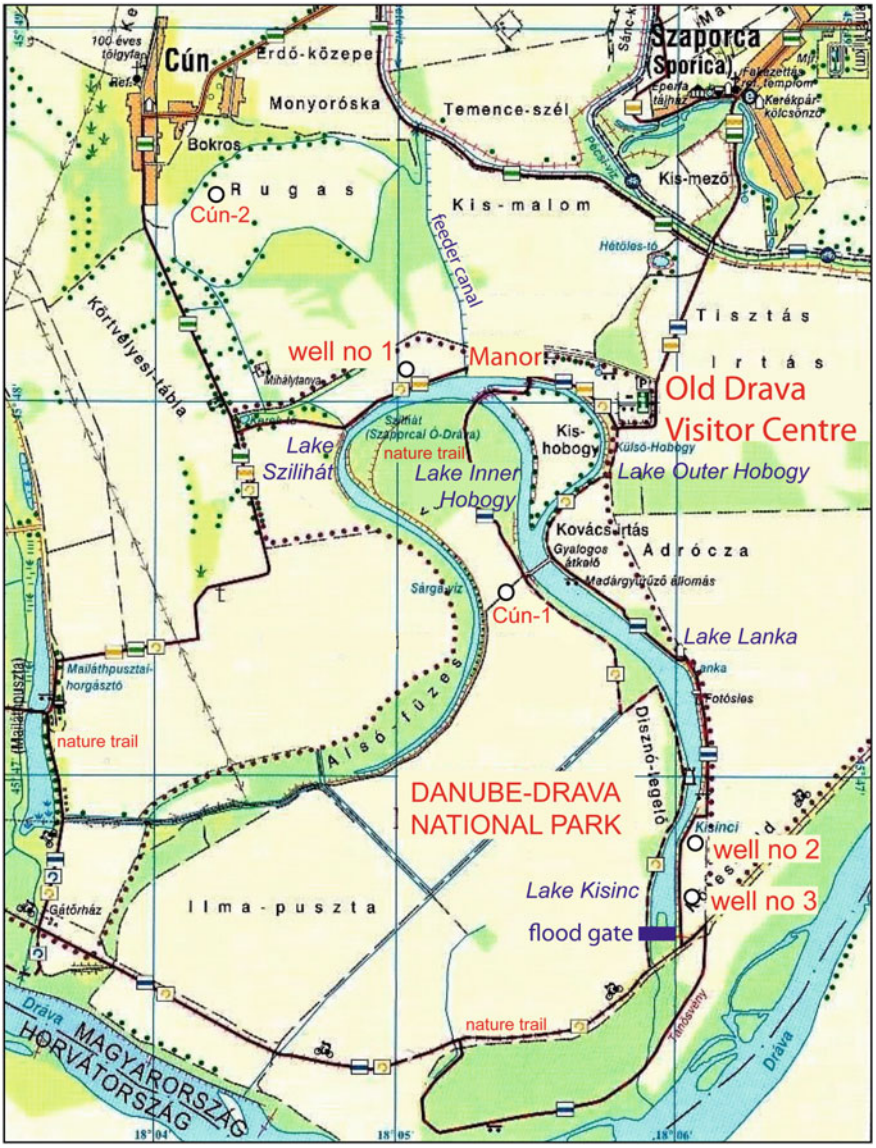

Fig. 12.2 The Cún-Szaporca oxbow with water management structures: feeder canal, groundwater observation wells, Cún-1 and Cún-2 monitoring sites and flood gate (base map: Szaporca–Kémes map, scale: 1:35,000. Cartographia, Budapest, 2016)

when the principal flood-defence line was built. Open water surface prevails on the oxbow, which certainly used to be the main channel of the Drava in 1784, over most of the year. The water surface is composed of four distinct lakes: Lake Kisinc (20 ha), being the largest, the lakes Lanka, Szilihát and Inner Hobogy (Majer 1998).

An intermittent pond (Outer Hobogy) occupies the bed of an earlier active river branch in the east. Since 1996 the oxbow area is an important waterfowl sanctuary under the Ramsar Agreement. Therefore, good water supply is not only vital for agriculture, but also for nature conservation. The maintenance of water level in the oxbow lakes, however, is difficult under increasingly arid climatic conditions, exacerbated by the long-term impacts of river regulation.

Oxbow lakes have played a significant part in the history of *human settlement* of the Drava Plain (Vajda 2001; Gyenizse and Lóczy 2010). In accordance with the wandering meandering pattern, there is much evidence that the positions of river channels shifted significantly over the floodplain in historical times. For instance, in the 16th century the village Szaporca lay on the left bank of the main Drava River branch of that time (Káldy-Nagy 1960), but permanent flood hazard forced its inhabitants to resettle on higher ground (a natural levee), where the other village of the neighbourhood, Cún, was built. (The abandoned site is called Lanka, which gave its name to one of the present-day oxbow lakes.)

12.3 Objectives

Within the frame of the four-year project "Rehabilitation potential of the Hungarian Drava floodplain" (2012–2017), the main objectives of research on the Drava oxbows were

(1) to survey the distribution of oxbow lakes in the floodplain and analyze their connectivity with the main channel;
(2) to outline geomorphic evolution;
(3) to reveal water balance with special regard to water retention capacity (cf. Dawidek and Ferencz 2014);
(4) to assess rehabilitation potential (on the example of the Cún-Szaporca oxbow).

12.4 Methods and Discussion

12.4.1 General Hydromorphological Properties

The hydromorphological character of the river and its floodplain in the Cún-Szaporca reach is presented with the help of the *indicators* elaborated for the EU project REFORM (**RE**storing Rivers **FOR** Effective Catchment **M**anagement) (González del Tánago et al. 2015) (Table 12.1). Mean river discharge (at the Barcs gauge for the period 1896–2016) is 595 $m^3\ s^{-1}$, its maximum (assumed to be of 0.1% probability, estimated for the 1827 flood) is around 3,100 $m^3\ s^{-1}$, while baseflow is around 170 $m^3\ s^{-1}$ and bankfull discharge is around 900 $m^3\ s^{-1}$ (VKKI 2010).

Table 12.1 Hydromorphological indicators of the Drava River reach in the study area (selection of indicators based on González del Tánago et al. 2015)

Key process/ features	Indicator	Literature source	Unit	Value/class at Cún-Szaporca	
				Pre-regulation	Post-regulation
Channel/ floodplain types and dimensions	Basic river type (BRT)	Rinaldi et al. (2015)		Single-thread: meandering (4)	Heavily artificial (0)
	Extended river type (ERT)	Rinaldi et al. (2015)		Unconfined, sand (+ fine gravel) bed, meandering (18)	Heavily artificial (0)
	Floodplain type	Rinaldi et al. (2015)		(Sinuous/ meandering) lateral migration (G)	
	Floodplain type	Nanson and Croke (1992)		Meandering with lateral migration (2b)	
	Planform	Richards (1982)	Dimensionless sinuosity index	3.8	1.1
	Channel bankfull width	Graf (2006)	Metres	Active channel: 350	Oxbow lakes: 200
	Channel bankfull depth	Graf (2006)	Metres	Active channel: ca 5.5	Oxbow lakes: 3.3
	Channel slope		mm^{-1}	0.00023	0.000114
Flooding extent	Morphological floodplain accessible by flood	Ward et al. (2002)	%	80	7
	Floodplain inundation frequency		Times per decade	>10	1
River energy	Specific stream power at bankfull discharge		$W\ m^{-2}$	ca 10	35 (FLUVIUS 2007)
Channel adjustment	Eroding/ aggrading channel banks		% of active channel length	ca 50/50	90/10
	Lateral bank movement	Brierley and Fryirs (2005)	$m\ year^{-1}$	>1	<0.1
	Bed incision		$cm\ year^{-1}$	n.a.	2.4 (Lovász 2013)

(continued)

Table 12.1 (continued)

Key process/ features	Indicator	Literature source	Unit	Value/class at Cún-Szaporca	
				Pre-regulation	Post-regulation
Riparian vegetation	Riparian corridor		Average width (m)	>80	20
	Age structure	Corenblit et al. (2007)	% of old, mature and young forests	n.a.	Old forest: 20%; mature forest: 70%; young forest: 10%
	Dominant plant associations	Corenblit et al. (2007)	Association type	Softwood and hardwood forests	Alluvial and mixed riparian forests
Aquatic vegetation	Aquatic plant coverage	Gurnell et al. (2010, 2015)	% of channel bed	n.a.	In oxbow lake: <10
Constraints on channel adjustment	Bank revetments, embankments, artificial levees		% of channel length	<10	100
	Average width of erodible corridor for 50 years	Piégay et al. (2005)	Channel widths	n.a.	1.5 (Kiss et al. 2011)

12.4.2 Oxbow Position Related to the Main Channel

A first step towards the reconstruction of the geomorphic evolution of the floodplain is an inventory of hydromorphological characteristics of oxbow lakes as traces of shifting meanders. Their topographical location was determined from GoogleEarth satellite images and a Digital Elevation Model (see later). For a rough estimate of relative position (connectivity) compared to the main Drava channel, straight-line distance from and relative height difference above the channel were measured. For calculating height difference, the altitude of maximum water levels in the lakes were invariably considered.

The studied oxbows are referred into *two groups*: one is constituted by lakes whose proximal tip is within 1 km from the main Drava channel and less than 2 m above that, while the others are located at 2.8–5.7 km distances and at 2–4 m relative height (Table 12.2). The altitudinal position also indicates their association with former Drava channels which used to exist in different periods.

Table 12.2 Topographical data of oxbows in the Hungarian Drava Plain

No	Oxbow	Length (m)	Width (m)	Mean depth (m)	Mean lake level above sea level (m)	Water surface area in August 2014 (ha)	Height above the Drava channel (m)	Distance from the Drava channel (m)		Geomorphological character
								Straight line	Along drainage lines	
1	Lakócsa-Drávafok oxbow	6,310; 1,373; 2,007	150–200	n.a.	98.0	4	3	3,760	4,677	Series of composite meanders
2	Fenék swamp	2,570; 1,165; 1,642	140–185	0	98.0	0	1.5	3,934	5,953	Infilled composite meander
3	Kanszki-berek	1,210	170	0	98.0	0	2.5	2,800	3,760	Infilled simple meander
4	Mrtvica of Felsőszent-márton	1,947	110–150	0.5	96.0	16	0.2	374	408	Simple meander loop
5	Lake Sellye	3,276	245–405	0.3	96.0	2.5	3	5,677	6,424	Simple meander
6	Lake Dráva-keresztúr	2,721	130–215	0.8	97.0	0.1	1	336	336	Simple meander
7	Lake Bresztik	1,841	150–250	0.8	93.6	10	0.5	153	192	Simple meander
8	Adravica of Drávasztára	3,680	150–340	1	93.6	9	2	355	370	Simple meander
9	Lake Fekete	860	120–175	1	93.0	19	1	865	1,893	Short meander section
10	Lake Nagysziget	2,387; 1,971; 3,370	170–250	0	93.0	0	2	425	1,211	Simple meander

(continued)

Table 12.2 (continued)

No	Oxbow	Length (m)	Width (m)	Mean depth (m)	Mean lake level above sea level (m)	Water surface area in August 2014 (ha)	Height above the Drava channel (m)	Distance from the Drava channel (m)		Geomorphological character
								Straight line	Along drainage lines	
11	Lake Kápolna-puszta	5,619; 2,290	130–190	n.a.	93.0	7	3	5,421	8,015	Double meander
12	Lake Piskó (Hosszú + Kerek)	3,306; 1,817	110–240	n.a.	93.0	0.5	2	3,270	3,829	Double meander
13	Lake Verság	5,854	130––340	1.2	92.9	12.8	4	1,438	3,160	Simple meander loop
14	Lake Kelemen-liget	1,912; 938	50–100	0.5	92.0	8.5	1	2,848	4,712	Composite meander
15	Lake Kis-szent-márton	5,890	130–190	dry	92.0	0	2	1,450	2,270	Simple meander
16	Lake Majláth-puszta	6,954	220–475	2	91.5	4	0	290	290	Simple meander
17	Cún-Szaporca oxbow	7,840; 1,400	151–290	1; 0.5; 0.5	90.15	20; 6; 6	0	280	285	Composite meander
18	Lake Matty	4,022; 963	50–200	1.2	86	10	2	2,972	3,630	Composite meander
19	Hótedra	1,846	100–170	1.5	86	4	2	1,356	2,982	Simple meander

12.4.3 Geomorphic Evolution

The geomorphic evolution of landforms in the Hungarian morphological floodplain of the Drava River has never been studied. From the above described hydromorphological properties, however, it can be at least presumed that *evolution history* has been largely different for older and younger oxbow rows (Fig. 12.3). Accepting the concept of gradual shift of the meander belt in southwestern direction over the Quaternary (Lovász 1964, 2013), this allows the conclusion that oxbows in the distal zone were cut off through natural processes during the lateral migration of the Old Drava in the Late Holocene at latest. In lack of absolute dating of oxbow deposits, no estimates can be made for the date of cutoff in the case of old oxbows. Their morphology (e.g. water depth, 'freshness' of banks and sediment plugs), thickness of organic fill and sporadic archaeological (human settlement) data (Bándi 1973) point to a loss of communication with the Drava mostly by neck cutoff some millenia ago. Most of the oxbows in the close neighbourhood of the present-day Drava channel, however, were detached from the main channel during river regulation works in the 19th century. The approximate time intervals when cutoff happened can only be estimated for the younger oxbows using map sheets of the 1st and 2nd Military Surveys as well as other archive maps (Table 12.3).

Table 12.3 shows that several meanders of the younger zone had been cut off from the present-day Drava channel shortly before river regulation started. Unfortunately, map representations before the 18th century are rare and difficult to interpret.

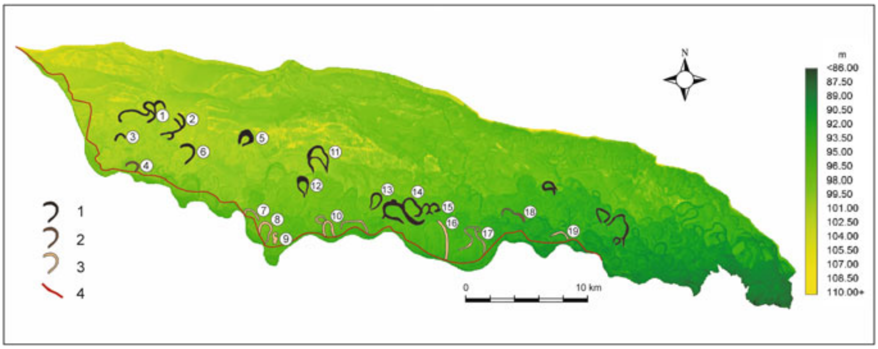

Fig. 12.3 Classification of oxbows according to the date of cutoff (by Dénes Lóczy). 1, 'old oxbows' with natural cutoff from a previous Drava channel in prehistorical times; 2, 'young oxbows' cut off by natural processes in historical times; 3, 'young oxbows' artificially cut-off in connection with river regulation; 4, main flood-control line. Numbered oxbows: 1, Lakócsa-Drávafok oxbow; 2, Fenék swamp; 3, Kanszki-berek; 4, Mrtvica of Felsőszentmárton; 5, Lake Sellye; 6, Lake Drávakeresztúr; 7, Lake Bresztik; 8, Adravica of Drávasztára; 9, Lake Fekete; 10, Lake Nagysziget; 11, Lake Kápolna-puszta; 12, Lakes of Piskó (Hosszú and Kerek); 13, Lake Verság; 14, Lake Kelemen-liget; 15, Lake Kisszentmárton; 16, Lake Majláth-puszta; 17, Cún-Szaporca oxbow; 18, Lake Matty; 19, Hótedra

Table 12.3 Estimated dates of cutoff for the younger series of oxbows

No	Oxbow	Date (register mark) of archive map	
		With meander still active	With meander already cut off
4	Mrtvica	None	1784 (1st Military Survey)
6	Lake Drávakeresztúr	1784 (1st Military Survey)	1850 (2nd Military Survey)
7	Lake Bresztik	None	1784 (1st Military Survey)
8	Adravica of Drávasztára	None	1784 (1st Military Survey)
9	Lake Fekete	None	1784 (1st Military Survey)
10	Lake Nagysziget	None	1784 (1st Military Survey)
16	Lake Majláth-puszta	1833 (06 BmT 260)	1850 (2nd Military Survey)
17	Cún-Szaporca oxbow	1833 (06 BmT 260)	1850 (2nd Military Survey)

12.4.4 Water Balance

Detailed water balance studies were performed for the representative oxbow of Cún-Szaporca (Fig. 12.2), where a monitoring system of soil and hydrometeorological conditions was established. The parameters monitored for the period between July 2013 and December 2015 covered virtually all possible factors influencing water inflow into and outflow from the lake:

(1) infiltration (measured by Drain Gauge G2 Passive Capillary Lysimeter);
(2) water potential (MPS-2);
(3) soil temperature and
(4) soil moisture content (5TM) at various depths (25 cm and 70 cm from ground surface) (sensors manufactured by Decagon Devices, Pullmann, WA, USA);
(5) depth to groundwater table (monitored by Dataqua LB 601 instruments—Dataqua Co., Balatonalmádi, Hungary).

Data collection (EM50) intervals were set for 30 min for all subsurface measurements and 10 min for the rainfall measurements. Precipitation has been recorded by an ECRN-100 tipping-bucket rain gauge (Decagon Devices Inc, Pullman, WA, USA) next to the northeastern section of the oxbow.

The obtained time series of soil moisture contents and infiltration rates, however, were too short to reveal trends. Therefore, 16 characteristic rainfall events were analyzed. In the wake of these events, considerable changes in both groundwater table elevation and shallow subsurface soil moisture content were registered at monitoring sites (Lóczy et al. 2017). The findings were spatially extended on the basis of the map of physical soil types (AGROTOPO 2013–2017). Water retention capacity in floodplain soils is estimated from the porosity of various physical soil types, generalized from the analysis of 48 soil profiles (Fig. 12.4).

To reveal the hydrogeology of alluvial deposits and the dynamics of groundwater flow, both field measurements and laboratory investigations were performed. An *aquifer test* served to establish the rate of seepage from the oxbow after refilling

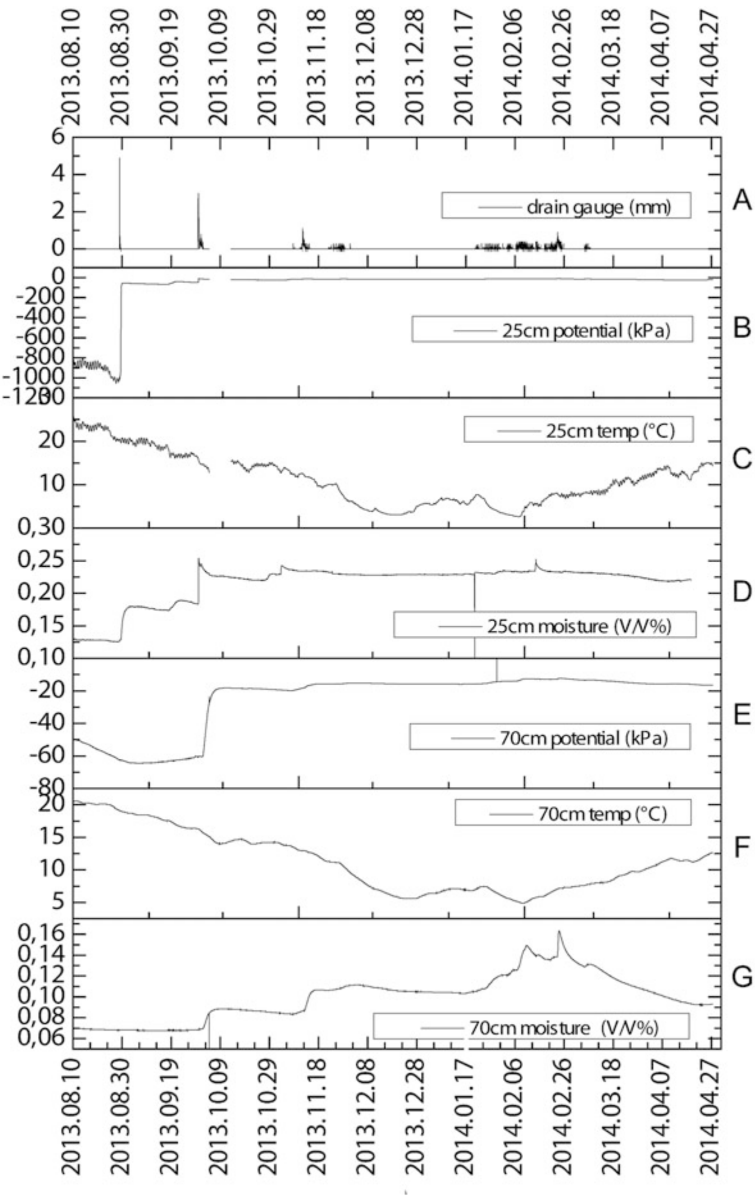

Fig. 12.4 Infiltration after various types of rainfall events (by József Dezső). A, daily rainfall (mm); B, water potential at 25 cm depth (kPa); C, soil temperature at 25 cm depth (°C); D, soil moisture content at 25 cm depth (v/v%); E, water potential at 70 cm depth (kPa); F, soil temperature at 70 cm depth (°C); G, soil moisture content at 70 cm depth (v/v%)

(cf. Halford and Kuniansky 2002; Mclin 2007). The hydraulic conductivity (k) of the deposits in the immediate environs of the oxbow was calculated. In a laboratory experiment hydraulic conductivity was established for three intact samples from the oxbow lake using the principle of water column with reducing pressure (for details see Neuman 1972 and Chap. 14).

Laboratory experiments were performed to establish water loss from the oxbow lakes by seepage. Soil moisture conditions in the alluvial deposits of complex stratification was modelled using Hydrus-1D applied for 69 profiles of various textural composition at three different groundwater table depths (modelling based on Sanford 2002—for details see Chap. 14). Oxbow beds are either clayey-silty or calcareous sandy. The clogging of the oxbow bed was found critical for groundwater flow. Water flow in impervious deposits is of the order of 10^{-8} m s^{-1}.

Both summer and winter periods are characterized by low infiltration rates. Recorded *groundwater levels* were found to drop with increasing distance from the oxbow (Fig. 12.5). This also proves that seepage from the oxbow takes place and it is the main source of groundwater recharge (cf. Winter 1999). Groundwater table dynamics in the area are rather controlled by lateral flow (hyporheic flow in the south and groundwater flow from the north) than infiltration. Through groundwater flow, the water regime of the Drava exerts a control on oxbow lake levels (Fig. 12.6).

Evaporation from open water surfaces was calculated using empirical formulas (see Lóczy et al. 2017) and was found to range between 500 and 600 mm y^{-1} adding up to 70,000–84,000 m^3 of water vapour from the average open lake surface of ca 140 ha. *Transpiration* of riparian softwood (willow and poplar) forests was estimated on the principle of analogy relying on Central European forestry literature (Čermák and Prax 2001, 2009). Cumulative evapotranspiration was calculated on the basis of the proportions of tree species in the softwood forests of the environs of the oxbow (Table 12.4).

12.4.5 Water Retention Capacity

Potentially, a major ecosystem function of oxbows is the storage of surplus water during extremely wet periods or high water stages of rivers (e.g., Thoms 2003). The volumetric estimation of maximum possible water retention capacity for all the floodplain lakes was performed (Lóczy et al. 2017). The Digital Elevation Model (DEM) used for the analysis was the Hidro-DEM, prepared for the South-Transdanubian Water Management Directorate (DDVÍZIG). It is based on LiDAR topographic survey and has 0.5-m vertical and 10-m horizontal resolution. Average volumes of water storage for 17 major Drava oxbows are calculated relying on the DEM, field checking and literature data (Pálfai 2001). Oxbow cross-sections were assumed to be trapezoid. Sedimentation in oxbow lakes since cutoff was estimated at an average of 20 cm. (For lakes used as fish and angling ponds dredging was considered.)

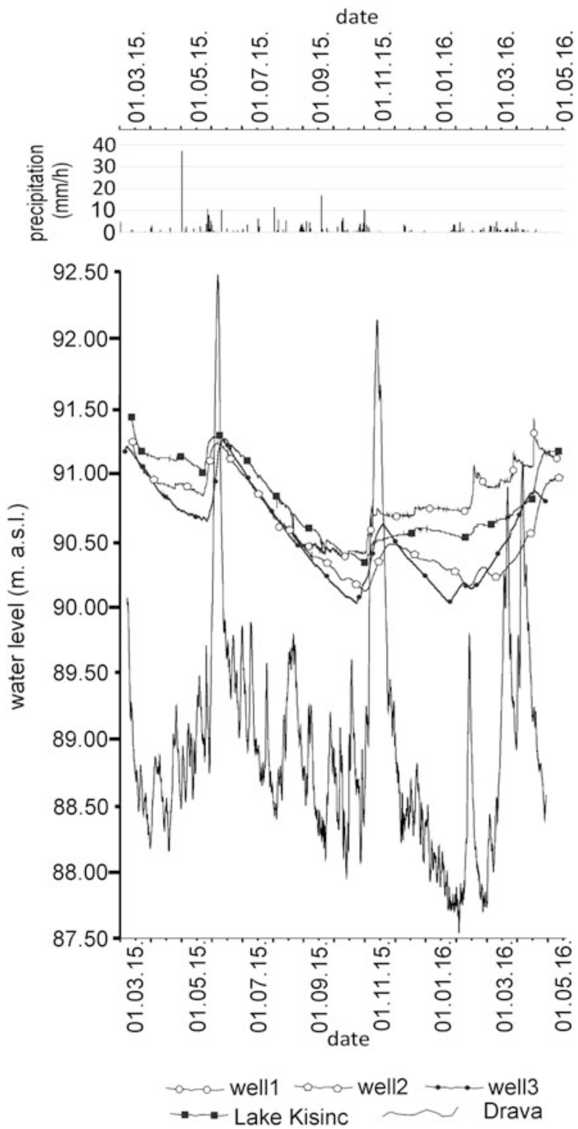

Fig. 12.5 Relationship between groundwater levels in three observation wells, water level of Lake Kisinc and the water regime of the Drava at the Drávaszabolcs gauging station (by József Dezső)

The results of volumetric estimates indicate a potential retention of almost 10 million m^3 of floodwater in the oxbows (Table 12.5). Naturally, the exploitation of this opportunity for water retention strongly depends on channel/floodplain connectivity on the surface, i.e. how easy it is to conduct floodwater and drain excess water into the oxbows.

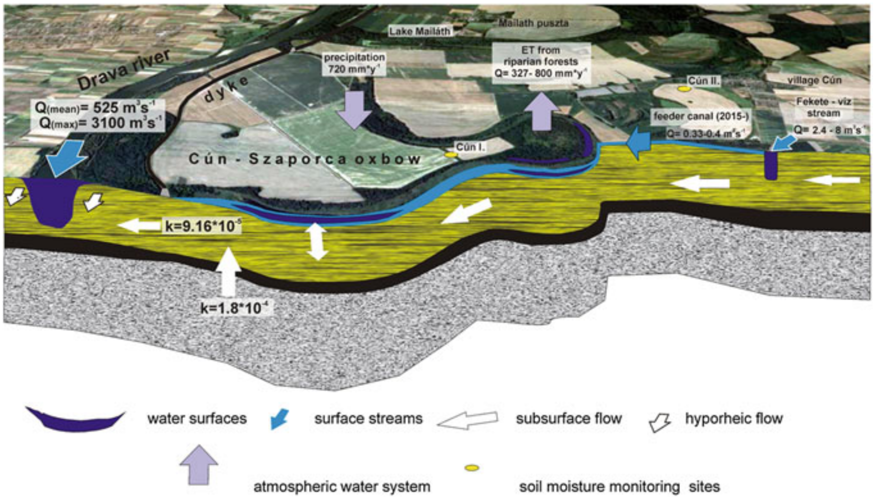

Fig. 12.6 Estimated water balance of the Cún-Szaporca oxbow (by József Dezső)

Table 12.4 Estimated water loss by transpiration from oxbow softwood forests (by Hedvig Prokos)

Tree species	Area (ha)	Share in total forest area (%)	Mean annual ETP (mm)	Total loss by ETP ($m^3\ y^{-1}$)
poplar (*Populus* sp.)	42.4	35	710	298,200
willow (*Salix* sp.)	30.4	25	750	225,000
black locust (*Robinia pseudoacacia*)	27.6	23	279	77,004
maple (*Acer* sp.)	15.6	13	ca 400	ca 60,000
sessile oak (*Quercus petraea*)	2.4	2	441	10,584
elm (Ulmus sp.)	2.4	2	ca 400	ca 10,000
Total	120.8	100		610,788 + ca 70,000
Total evapotraspiration				ca 3,660,000

12.5 Rehabilitation Potential

The assessment of restoration/rehabilitation potential covers the study of floodplain landforms (size, shape, configuration, connectivity), landscape pattern, vegetation, land use from the aspects of the maintenance of protected areas and provisioning various ecosystem services (National Research Council 1992; WWF International 2010; Waidbacher and Schultz 2005).

Table 12.5 Water retention capacities of oxbow lakes in the Hungarian Drava Plain (calculated by Péter Gyenizse)

	Oxbow, backswamp	Mean lake level above sea level (m)	Water level elevation when filled up (m)	Water surface area when filled up (total oxbow area, ha)	Planned dredging (thousand m^3)	Maximum water retention capacity (million m^3)
1	Lakócsa-Drávafok oxbow	98.0	99.0	119.7	200	0.86
2	Fenék swamp	98.0	98.5	23.3	0	0.08
3	Kanszki-berek	98.0	99.5	21.1	0	0.06
4	Mrtvica of Felsőszentmárton	96.0	97.2	22.4	30	0.26
5	Lake Sellye	96.0	98.0	70.5	100	1.10
6	Lake Drávakeresztúr	97.0	98.0	13.3	80	0.11
7	Lake Bresztik	93.6	95.0	18.2	0	0.07
8	Adravica of Drávasztára	93.6	94.0	12.6	70	0.29
9	Lake Fekete	93.0	98.0	134.7	50	1.60
10	Lake Nagysziget	93.0	96.0	45.3	100	0.26
11	Lake Kápolna-puszta	93.0	95.0	12.6	0	0.08
12	Lake Piskó (Hosszú + Kerek)	93.0	95.0	19.2	50	0.14
13	Lake Verság	92.9	93.5	27.7	100	0.25
14	Lake Kelemenliget	92.0	92.5	21.6	70	0.12
15	Lake Kisszentmárton	92.0	92.5	17.7	0	0.18
16	Lake Majláth-puszta	91.5	93.5	213.1	0	2.6
17	Cún-Szaporca oxbow	90.15	92.3	60.0	150	0.55

At present, during high water stages of the Drava River water recharge to oxbow lakes is possible through the opening of a flood gate from the direction of the Drava channel. This solution, although alleviates flood hazard downstream, is not found reliable for water replenishment. A probability analysis of replenishment options to the Cún-Szaporca oxbow shows the probability of a situation when the Drava water level reaches 360 cm (i.e., 91.50 m above sea level) is P = 2% (calculating with the summer half-year only: P = 14%). Naturally, raising water levels to 92.00 m would require even higher water levels of the Drava River: 410 cm on the Drávaszabolcs gauge – P = 1% (for the summer half-year: P = 3%) (DD-KTVF 2013).

As a consequence, water replenishment from northern direction, from the Fekete-víz Stream (mean discharge: 4.5 $m^3\ s^{-1}$), was decided on (DDKÖVÍZIG 2012). The natural discharge of the stream is increased by damming the Fekete-víz Stream. This reservoir is designed to be filled up gravitationally or, in periods when it becomes necessary, by pumping with Drava water (see Chap. 21). The main water transfer canal follows an old course of the river and for the distribution of water abandoned channels and infilled oxbows and backswamps are planned to be revitalized (Lóczy et al. 2014).

The rehabilitation potential is fundamentally determined by the processes of connectivity of the hydrological system: underground water flow from the oxbow and the communication with hyporheic flow (see Chap. 14). The ongoing rehabilitation scheme strives to improve both lateral and vertical connectivity (in the sense of Roni et al. 2013) along the Drava River (Lóczy et al. 2017). A principal factor of uncertainty for the envisioned water recharge is the insufficiently known hydraulic connection between the oxbow bed and the geology of its immediate neighbourhood. It is assumed that good ecological status can only be achieved if periodical flushing of oxbow lakes is ensured.

There is also much uncertainty about the quality of the replenished water. The water will be impounded for about two weeks in order the ensure sufficient flow (Q = 0.33–0.5 $m^3\ s^{-1}$) for the required rate of replenishment. Storage might cause water quality deterioration with respect to critical parameters.

12.6 Conclusions

The hydromorphological survey of the Drava floodplain was directed to practical purposes, i.e. underpinning the assessment of rehabilitation potential with new data. Therefore, the hydrogeological properties of alluvial deposits, the water balance and retention potential of oxbows were placed in the focus of research. The grouping of oxbows according to the date of their cutoff from a Paleo-Drava or from the present-day channel is purely hypothetical. With no means for dating oxbow lake deposits, it was not possible to reconstruct the chronology of geomorphic evolution. Tracing the gradual shift of the Drava channel in space and time would require more efforts in the interpretation archive maps, Ground Penetrating Radar profiles, Digital Elevation Models as well as field checking. Such activities are partly underway and partly planned in a follow-up project to be implemented in cooperation with Croatian experts. The practical implication of such a basic research would be an improved alignment of the planned water recharge routes.

Acknowledgements Authors are grateful for financial support from the Hungarian National Scientific Fund (OTKA, contracts K 104552 and K 108755) and for help from the South-Transdanubian Water Management Directorate.

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