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ESTIMATING SEEPAGE LOSS DURING WATER REPLENISHMENT TO A FLOODPLAIN OXBOW: A CASE STUDY FROM THE DRAVA PLAIN

Abstract: Dezső J., Halász A., Czigány S., Tóth G. & Lóczy D., *Estimating seepage loss during water replenishment to a floodplain oxbow: a case study from the Drava Plain.* (*IT ISSN 0391-9839, 2017).*

The water regulation and channelization works of the past centuries did not only alter the drainage pattern and individual stream channels, but also the water budget of the adjacent floodplains and wetland areas, particularly oxbow lakes. For the maintenance of the wetland habitat of the Cún-Szaporca oxbow in the Hungarian section of the Drava River floodplain lakewater/groundwater interchanges are of utmost importance. The implementation of a large-scale landscape rehabilitation scheme is under way. To estimate water budget for the oxbow at present and after water replenishment, field studies (pumping tests) and laboratory analyses (conductivity, effective porosity) were carried out. Our research shows that the critical factor in water retention is the transmissivity of lakebed deposits – not only the present ones, but also those which become lakebed after future upfilling. Based on the laboratory hydraulic analyses of the undisturbed sediment samples highly different conductivity values were found for the middle and offshore parts of the oxbow lakes – a pattern just the opposite expected for active river channels. Relatively coarse fraction (~80 µm) dominates the shoreline zone and allows higher seepage rate from the oxbow lake. With considerable losses to groundwater (and indirectly to the Drava River) expected, the success of the replenishment scheme is questionable.

Key Words: oxbow, water replenishment, seepage, groundwater, clogging zone

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Az elmúlt évszázadok folyószabályozási- és csatornázási munkálatai nemcsak a vízhálózat képét változtatták meg, hanem az ártér, különösen a holtágak vízgazdálkodását is. A vizes élőhelyek védelme szempontjából a Dráva magyarországi szakaszán a Cún-Szaporca holtág kulcsfontosságú helyszín, ahol a regionális léptékű tájrehabilitációs munkálatok első lépése van folyamatban. A feltöltés előtti és utáni vízháztartás becsléséhez terepi (kúttesztek) és laboratóriumi méréseket (vízvezető képesség, effektív porozitás meghatározása) végeztünk. Megállapítottuk, hogy a tavi üledékek szerepe meghatározó a vízmegtartásban – nem csak a jelenlegi állapotban, hanem a tervezett feltöltés után is. A laboratóriumi bolygatatlan üledékminta-vizsgálatok alapján jelentős eltérés mutatkozott a hidraulikus vezetőképesség tekintetében a partmenti és tóközepi minták esetén – ellentétben az élő folyómedrek szakirodalomban fellelhető szivárgáshidraulikai tulajdonságaival. A partmenti sáv viszonylag durva szemcseösszetétele (~80 µm) kedvez a holtágból történő intenzívebb elszivárgásnak és kérdésessé teszi a feltöltési tervek sikerességét.

Kulcsszavak: holtág, vízfeltöltés, szivárgás, talajvíz, vízzáró zóna

INTRODUCTION

Across Europe 50% of wetlands and more than 95% of riverine floodplains have been converted to urban and agricultural lands (Gumiero & *alii,* 2013). This intervention has fundamentally changed water availability in floodplain landscapes (de Vries 2013). As a consequence of human interventions and probably of global climate change, even river floodplains – rich in wetlands under (semi)natural conditions – can regularly experience water shortages (Brookes 1996).

The European Water Framework Directive provides a new framework for integrated river and drainage basin management, protection and restoration (EC 2000), including wetlands (EC 2007). Although it does not concern floodplain environments explicitly, the interchange between surface and subsurface waters is a central component of any habitat restoration scheme (National Research Council 1992, Mirtl & *alii,* 2015). The proportions between partially restored natural habitats and agricultural land have been debated in the Drava floodplain too (see

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Aquaprofit, 2007, 2010). Wetlands and forests are planned to expand at the expense of agricultural land. If pre-regulation conditions, permanently high groundwater levels favorable for nature conservation were restored, it would decrease productivity and yields on agricultural land or make farming completely impossible (WWF, 2002). As indicated in the Old Drava Master Plan, rehabilitation would raise lake water levels by as much as 1.5 to 2 m. How water replenishment would be influenced by the hydraulic properties of the floodplain sediments is a central issue (Aquaprofit, 2007).

The studied oxbow belongs to groundwater dependent ecosystems (GDEs), i.e. ecosystems for which current composition, structure and function are reliant on a supply of groundwater (Kløve & *alii,* 2012). Major streams like the Drava River and their hyporheic zones maintain a hydraulic balance with the adjacent groundwater (EA, 2009). Surface water and groundwater have to be conceived as components of a single system and impacts on either of these components will inevitably affect the quantity or quality of the other (Winter, 1999). Lakewater/groundwater interchange is influenced by the stratification, texture and isotropy of the sediments of the shoreline zone (Sanford, 2002, Slowik, 2014). Transmissivity is assumed to depend on the extent of clogging of the oxbow bed. During seepage calculations the clogging zone is defined as near-shore, semipermeable layer in the bottom of the water body (Kinzelbach, 1986), which realistically represents flow conditions.

In the planning phase of rehabilitation the identification of the target hydrological conditions as well as the duration, rate and frequency of replenishment for the sustainability of the replenishment project are crucial tasks. We analyzed the feasibility of the planned project in terms of physical properties (porosity, infiltration rate and hydraulic conductivity) of the vadose and phreatic zones. Our objectives were to reveal the extent of water loss from the oxbow lake and to determine the amount of water required for replenishment.

STUDY AREA

The studied area is located in SW Hungary, along the lower reaches of the Drava River (fig. 1). This section of the Drava roughly coincides with the Hungarian-Croatian border. There are 20 cut-offs and oxbows with very similar conditions on the Hungarian side of the river (of ca 150 hectares total area, varying seasonally – Pálfai, 2001).

Prior to the river regulation works, beginning in the 1740s and intensifying in the 19th century (Borzavári, 1981, Buchberger, 1975, Remenyik, 2005), traditionally floods represented the most serious natural hazard in the floodplain of the Hungarian section of the Drava River. 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 conditions show an increasing duration over the year (Fluvius, 2007). Drought hazard endangering both natural habitats and agricultural production has become equally serious and

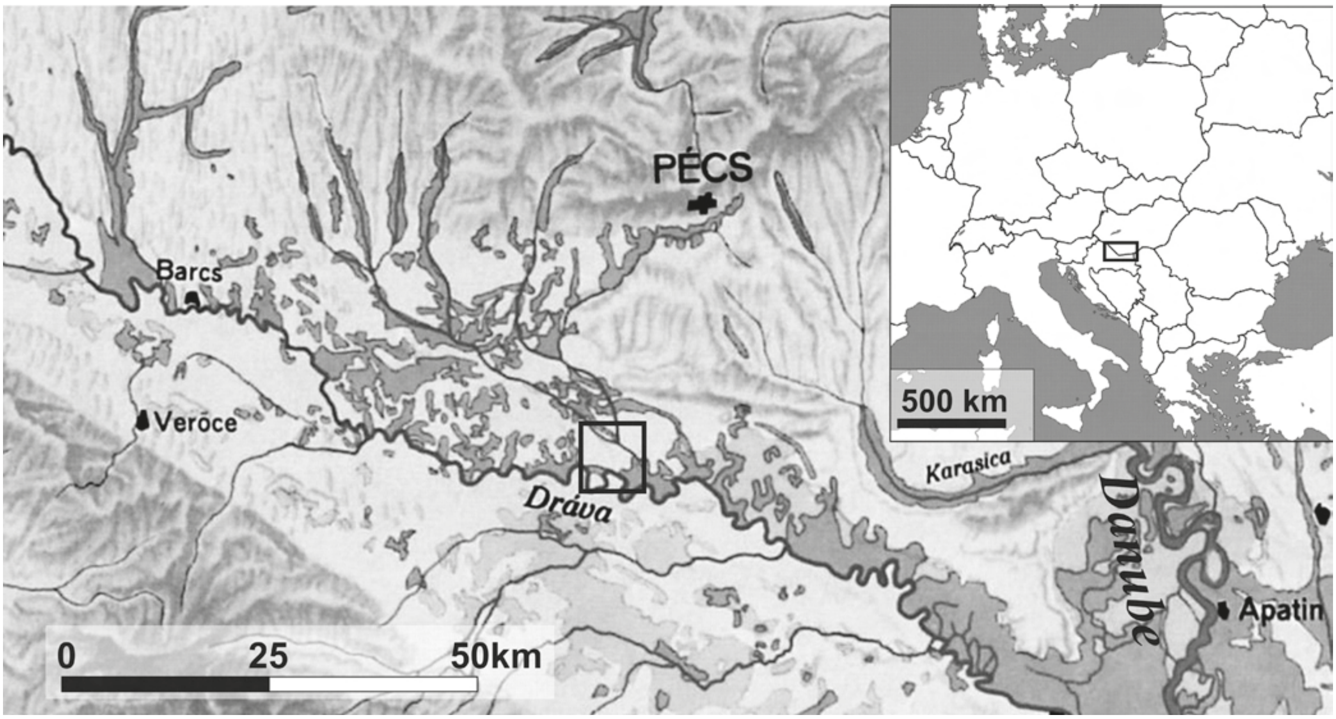

FIG. 1 - Detail of the map 'Flooded and waterlogged areas of the Carpathian Basin before the water regulation and drainage operations' with study area (dark grey: waterlogged areas for most of the year in 1850; light grey: inundated areas during floods (after the Hydrographic Institute, Royal Hungarian Ministry of Agriculture 1938)-

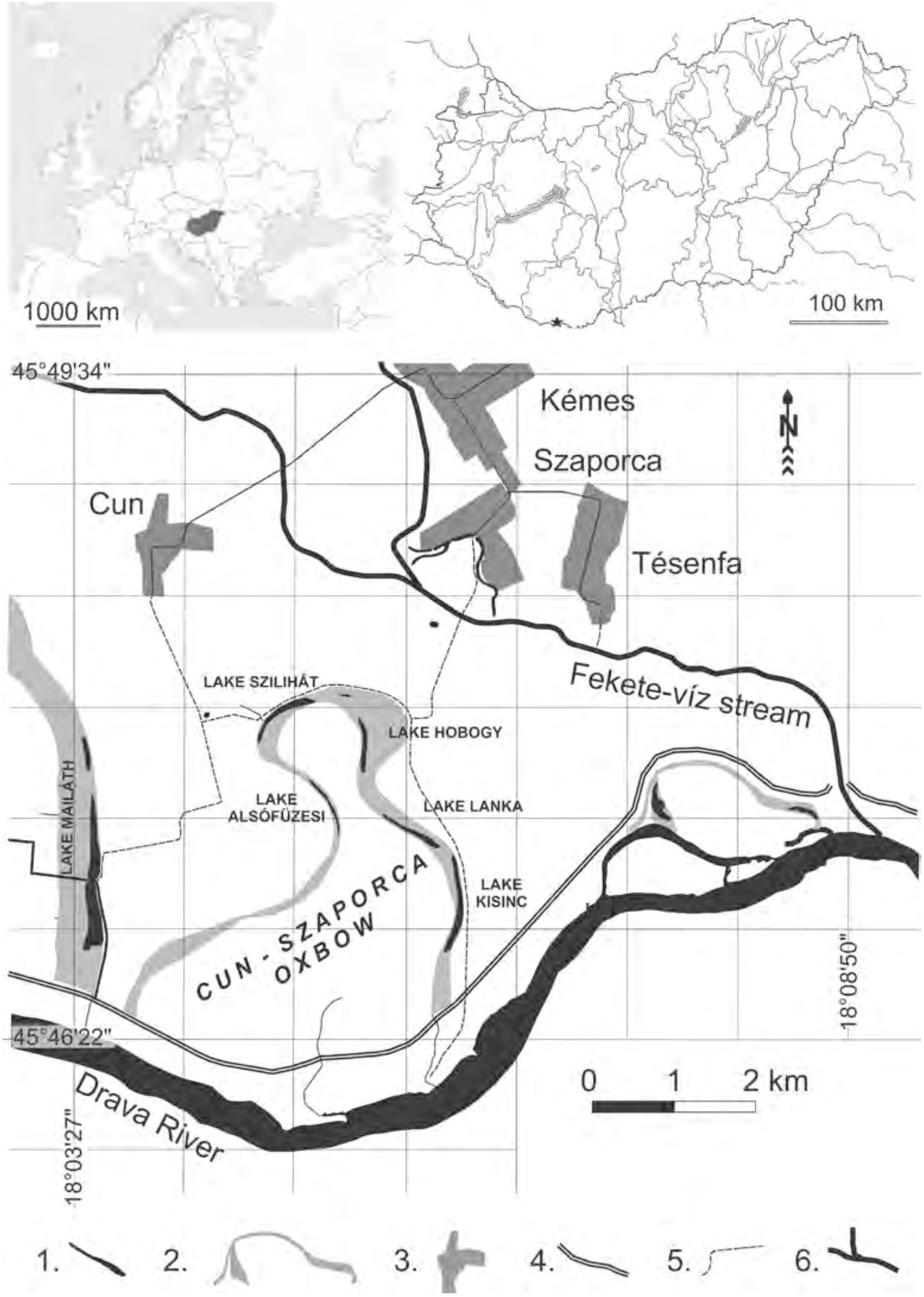

FIG. 2 - Location of the Cún-Szaporca oxbow. 1, lake, 2, wetland, 3, settlement, 4. dam, 5. road, 6. river, stream-

calls for landscape rehabilitation measures focusing on water replenishment to the floodplain (Lóczy & *alii,* 2014).

The area selected for a more detailed study, the Cún-Szaporca oxbow (figs 2 and 3) of an area of 257 hectares, is a cut-off composite meander of the Drava River (its centre is located at 45°50'N, 18°06'E). It was eventually disconnected from the main channel in 1975, when the principal flood defense line was built. It is composed of five lakes with open water surface: Lake Kisinc (20 ha, maximum water depth: 2.4 m), being the largest, the lakes Alsófüzesi, Szilihát, Lanka and Inner Hobogy (together ca 30 ha) (Majer, 1998). Lake Outer Hobogy is virtually filled up entirely.

Since 1979 the oxbow area is an important bird sanctuary under the Ramsar Agreement (Ramsar code: 3HU001 – Ramsar Information Sheets 2006). Based on the RAMSAR criteria the area is a natural wetland habitat that maintains vulnerable and endangered ecological communities in their critical life period. Additionally, it is protected area of national importance (1966), including a strictly protected area of 70 hectares and also a Natura 2000 area.

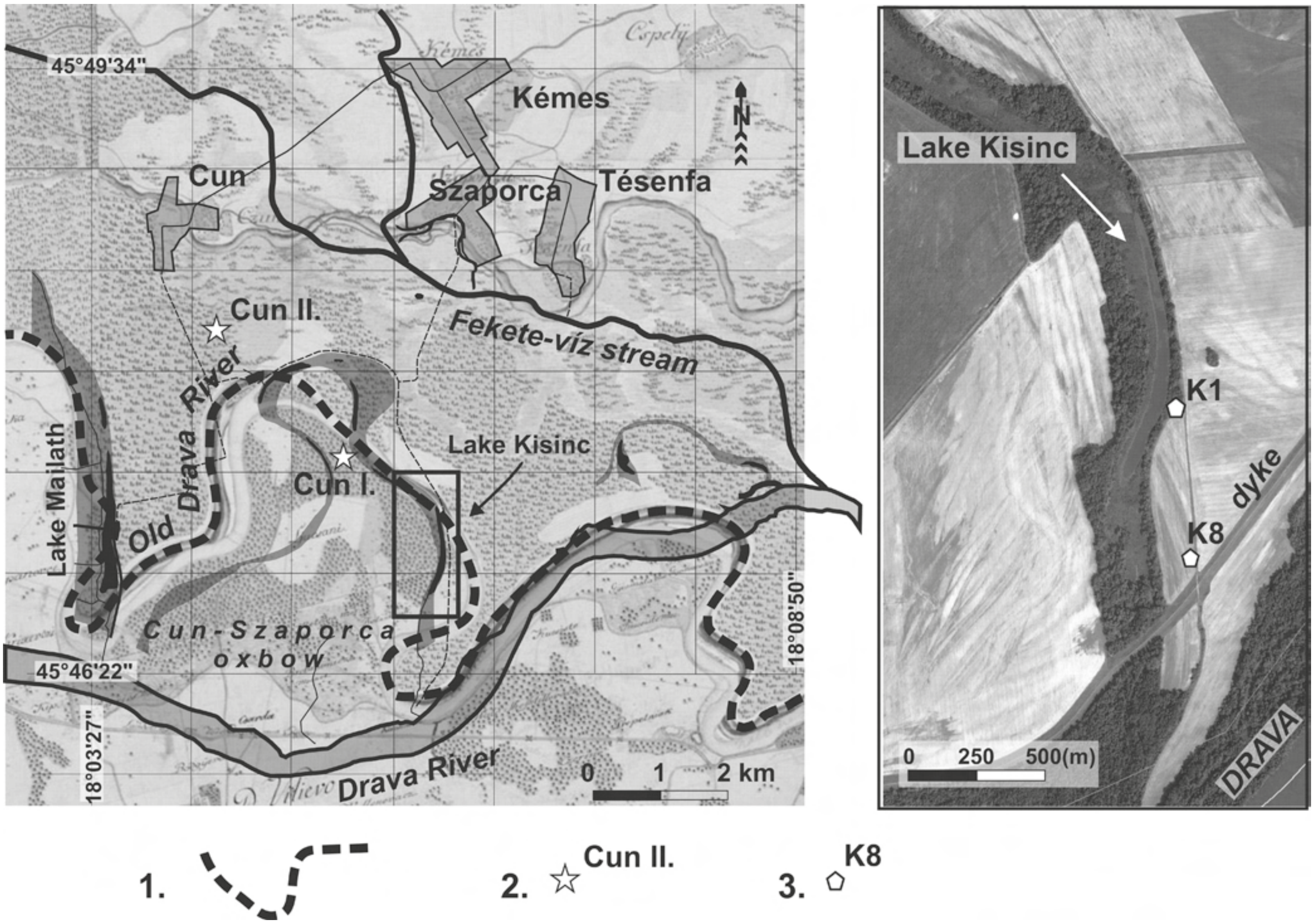

FIG. 3 - The study area shown on an archive map, location of Lake Kisinc, scroll bars around Lake Kisinc, location of soil profiles and pumping test sites (source: First Military Survey 1785 http://mapire.eu/hu/map/collection/firstsurvey/?zoom=6&lat=47.89034&lon=14.76556 and Google Earth). 1, old Drava channel, 2, soil profiles, 3, pumping test sites (for other symbols see Fig. 2)-

FIG. 4 - Horizontal stratification of bank deposits of the Drava (near the Cún-Szaporca oxbow).

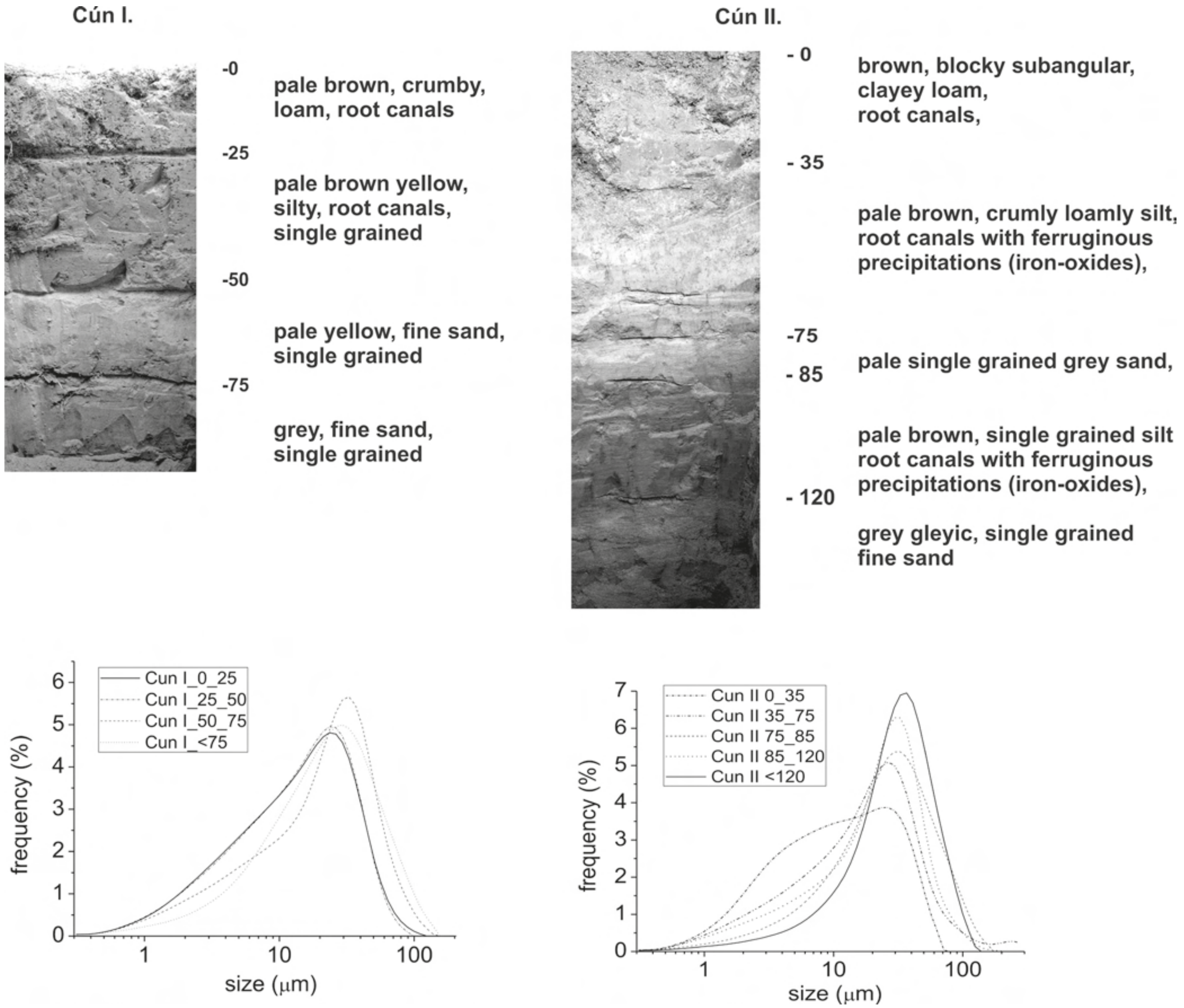

FIG. 5 - Soil textural properties and particle size distribution (PSD) data for the profiles Cún I and II.

Based on recent geomorphological studies the area is characterized by (sub)horizontal strata of a few centimeter thickness reaching a total depth of 15 to 20 m (fig. 4). The sediment texture ranges between clayey loam to sand.

Two selected representative soil profiles illustrate different environments of alluvial deposition reflected in variations of layer thickness and texture (fig. 5). The profile Cún I predominantly contains fine sand and silty sediments with a very low clay fraction, while the upper horizons of Cún II are fine-grained silts with a higher clay content (Eutric Fluvisol). Due to pedogenic processes (including root canal formation and bioturbation) the original layering is often hardly recognizable. It is assumed that the observed stratification and textural composition is representative of levee accumulation along the meander (Cún I), while the Cún II profile is located within an infilled abandoned channel.

OBJECTIVES

During rehabilitation planning, natural and manmade changes that altered floodplain hydrological systems have to be equally considered (National Research Council, 1992, Roni & *alii,* 2013). On the downstream reaches of the Drava River, one of the most significant reasons for increased drought hazard is river incision that lowered groundwater table in the adjacent floodplain (Lóczy & *alii,* 2014). The rehabilitation of wetland habitats requires the raising of oxbow lake and groundwater levels, comparable to the conditions that existed before the river regulation works. Although the incision rate of the Drava channel is estimated at 2.4 m in 100 years for a water gauge just upstream from the study area, at Barcs, the engineers who prepared the water replenishment plan (Ddkövízig, 2012) assume that fluvial deposits are clogged by fine (partly organic) sediments accumulated in oxbow lakes over almost a century without dredging and, thus, replenished water amounts can be retained over the long run.

At present, during high water stages of the Drava River water recharge is possible through opening the Kisinc Sluice (flood gate no I; base level: 90.15 m above Baltic Sea level) from the direction of the Drava channel (Fleit & *alii,* 2012). This solution, although alleviates flood hazard downstream, is not found reliable for improving water availability of the oxbow and its environs. A probability analysis of replenishment options shows that the probability of a situation when the Drava water level reaches 360 cm (i.e. 91.50 m above sea level) at the Barcs gauge is P = 2% (calculating with the summer half-year only: P = 14%) (Ddkövízig, 2012). Naturally, raising water levels to 92.00 m would require even higher water levels of the Drava River: 410 cm on the gauge – P = 1% (for the summer half-year: P = 3%). In the master plan an even higher replenishment elevation is shown where water level reaches 92.50 m (fig. 6A).

In accordance with the above considerations, an alternative option for additional water replenishment from northern direction, from a reservoir established on the Fekete-víz Stream (mean discharge: 4.5 m^3 s^{-1}), was decided on (Ddkövízig, 2012 - fig. 6B).

The planners set the following criteria for the regulation of water level in the Cún-Szaporca oxbow:

- Annual water level fluctuation should not exceed 0.5 m;
- Water recharge should take place step by step, in divisions;
- Water recharge should be implemented by not more than two fillings per year: the first from 1 to 15 March at 0.4 m^3 s^{-1} (43,200 m^3 d^{-1}) rate, totaling 515,000 m^3 and the second from 1 to 18 June at 0.33 m^3 s^{-1} (24,512 m^3 d^{-1}) rate, totaling 535,000 m^3;
- The length of the filling period should not be more than two weeks. (This criterion was not observed strictly in the modified version of the water replenishment plan – Ddkövízig, 2013).

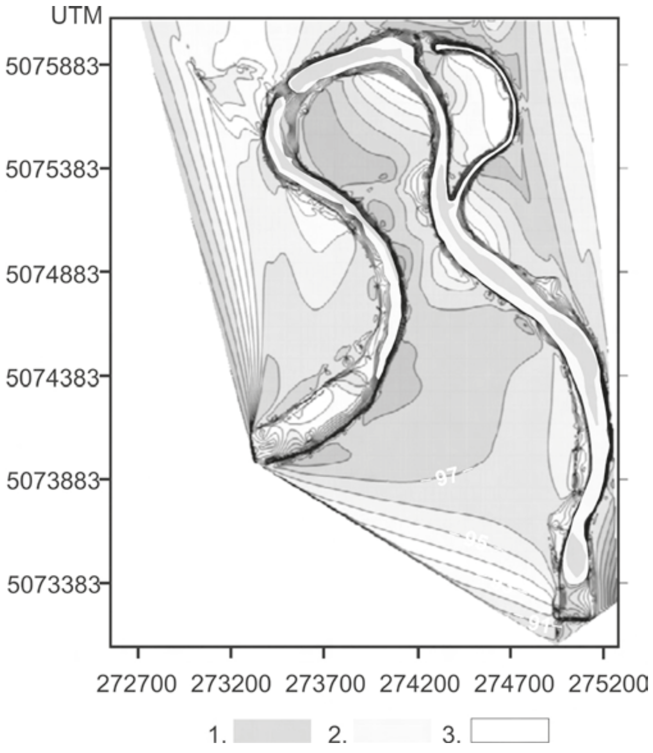

FIG. 6 - The planned recharges and general scheme of the water management. A. Flooding of the oxbow floor at raising water level to 1. 90.70, 2. 91.50 and 3. 92.50 m elevations. B. Cross-section of the feeder canal.

Unfortunately, no detailed information is available on where the above criteria derive from. The planned interventions may seem environment-friendly, however, in lack of an analysis of subsurface hydrological properties, the feasibility of the replenishment project is doubtful. These properties delineate the boundary conditions for rehabilitation, beyond these conditions an excessively large and non-ecological input is needed to maintain the desired water levels in the lake. To this end, we intend to assess the feasibility of the replenishment project in the light of hydrogeological properties.

The specific objectives of our research were the following:

1. To determine the hydraulic properties, namely (a) field saturated hydraulic conductivity, (b) effective porosity and (c) storage coefficient of the near-surface alluvial sequences which may influence seepage from the oxbow;
2. To explore and quantify the interconnectedness between the Kisinc Oxbow and the adjacent floodplain;
3. To determine optimal timing and volumes for the replenishment of Lake Kisinc with regard to the expected water loss.
4. To reveal general relationships among sediment texture, hydraulic properties and geomorphic evolution in the floodplain.

Since 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 (Fleit & *alii,* 2012), in our research we intended to determine the effectiveness and feasibility of the water replenishment scheme. To this purpose, we have studied the fundamental processes of connectivity of the hydrological system with both field (pumping tests) and laboratory analyses (determination of saturated hydraulic conductivity with the falling head method).

METHODS

Field methods

To study hydraulic conditions in the vicinity of the oxbow, pumping (aquifer) tests (Endres 2007, Brauchler, 2010) were performed at two locations from the upper part of the unconfined aquifer (wells K1 and K8). Due to the low flow values (1-2 L min^{-1}) a peristaltic pump was used at the K1 well while in the case of the K8 site a well pump (Q = 10-15-20 L min^{-1}) was employed (fig. 7). Several standard methods of interpretation were employed (Theis,

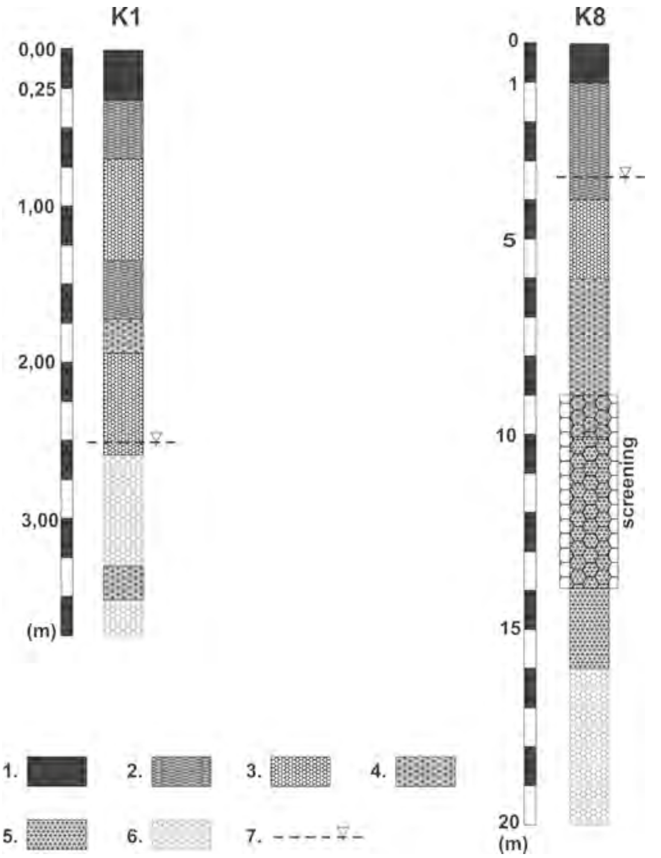

FIG. 7 - Major soil horizons of the two studied well profiles. 1, brown clayey topsoil, 2, clayey fine sand, 3, pale brown fine sand, 4, pale brown, fine to medium size sand with muscovite mica, 5, brownish grey fine sand with muscovite mica, common organic material, 6, grey fine to medium size sand less muscovite mica, less organic material, 7, water table.

1935; Cooper & Jacob, 1946; Neuman, 1972). The evaluation approach Bouwer & Rice (1976) has been applied to calculate unsaturated hydraulic conductivity values for the near-shoreline sediments.

To study the clogging zone, three undisturbed sediment samples were taken from Lake Kisinc in PVC pipes of 45 mm diameter for laboratory analyses (fig. 8).

Laboratory experiments

There exist a wide range of methods to determine the hydraulic conductivity of alluvial deposits (see the overview by Pliakas & Petalas, 2011). In our laboratory experiment hydraulic conductivity was calculated for three intact samples from the oxbow lake using the falling head method (Landon & *alii,* 2001). Intact columns of 40 cm in length and diameter of 45 mm, taken from Lake Kisinc, were covered with initially 1.5-m deep columns of water (fig. 9). Experiments lasted for 20 days.

Following the hydraulic measurements, grain size distribution analyses were carried out on undisturbed samples with a Malvern Mastersizer 3000 Hydro LW (Malvern Inc., Malvern, United Kingdom) particle size analyzer. Effective porosity, which is influential during pumping tests, was measured gravimetrically on a sand bed for 24 hours after saturating the undisturbed soil samples following the standard Hungarian method (Hegedűs & *alii,* 1980).

Additional calculations were done to estimate the length of the period of high water levels (91.5 m). The following boundary conditions were used during the calculations:

- No surface inflow,
- Groundwater level is fixed at an elevation of 89.5 m,
- Negligible evaporation from the water surface.

RESULTS AND DISCUSSION

Pumping test

Three-step pumping tests were carried out at two locations on alluvial topsoils (Eutric Fluvisol) to estimate the water budget of Lake Kisinc and its influence on the adjacent aquifers. With heterogeneous and complex sediment structure, it was challenging to assess the general hydraulic properties and the water retention capacity of the lake. Therefore, our studies focused on the sediments of the immediate lakeshore zone. Here pumping tests were carried out to determine hydraulic conductivity (*K*) for soil horizons and sediment layers. To calculate the water retention capacity and water balance of the lake, the highest hydraulic conductivity values were used.

The geometry of the fine-laminated anisotropic formations is not in accordance with the values derived from the particle size analyses, conductivity typically ranging from

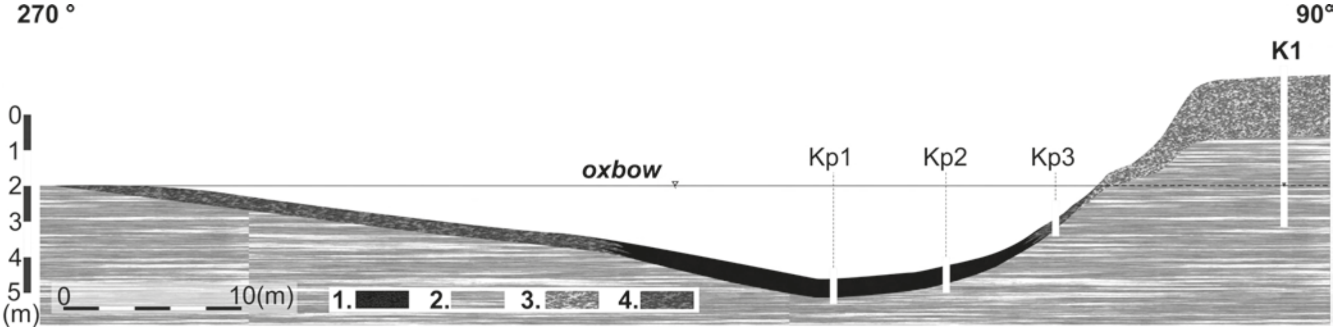

FIG. 8 - Cross section of Lake Kisinc with sites of the sampling (Kp1, Kp2, Kp3) and K1 well tests. 1, fine oxbow bed material, 2, alluvium (clayey, silty, sandy deposits), 3, brown topsoil with root canals, 4, mixed lacustrine sediments.

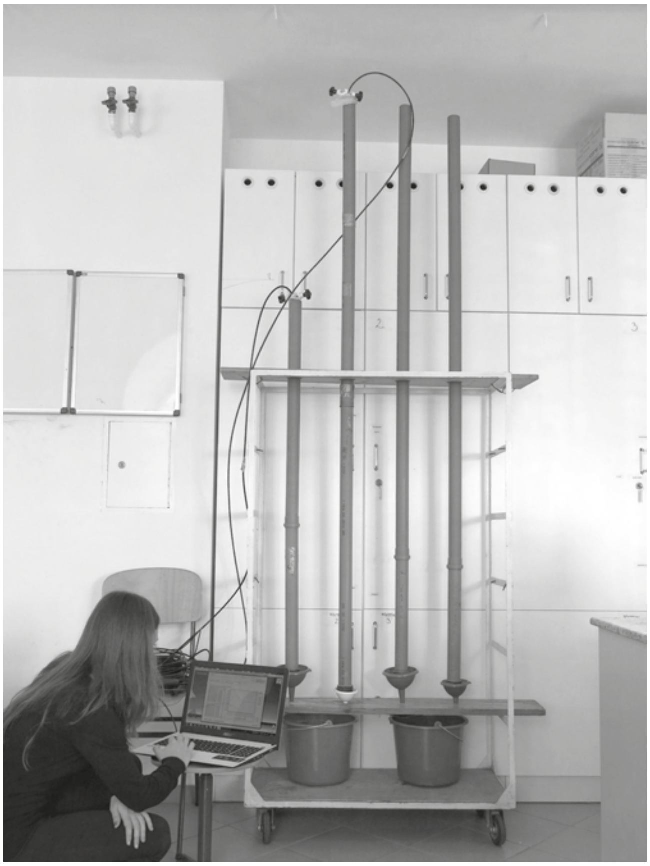

FIG. 9 - Laboratory investigation of clogging zone samples.

1.34×10^{-5} to 3.42×10^{-6} m s^{-1} and from 1.82×10^{-4} to 7.11×10^{-4} m s^{-1} in wells K1 and K8, respectively (tab. 1).

Transmissivity is low at the boundary between the oxbow and its environment (T = 2.18; 1.55 and 4.27 m^2 day^{-1} or 2.52×10^{-5}; 1.79×10^{-5}; 4.94×10^{-5} m^2 s^{-1}). From field measurements the hydraulic conductivity of well K1 inhomogeneous zone is $k = 1.78 \times 10^{-5} - 6.12 \times 10^{-6}$ m s^{-1}. Hydraulic conductivity values in well K8 ($5.87 \times 10^{-3} - 7.11 \times 10^{-4}$ m s^{-1}) significantly differed from those in K1, while their textural compositions were similar.

Recovery phases or wellbore pressure dynamic response (PDR) and the derivate time-drawdown analyses provide data on the hydraulic properties of wells and their vicinity and on the adjacent aquitards and aquicludes (Spane & Wurstner, 1993). In contrast to the derivate curve, the conventional log-log representation of pumping data, lacks a diagnostic shape. Despite the subjectivity of the PDR evaluation, the derivates still provide valuable information on the hydraulic properties of the fragmented aquifer (Samani & *alii,* 2006). The time derivates of the PDR curves include a hump peak at the beginning of the pumping (the first phase), which is representative of the immediate vicinity of the pumping well. This phase, however, is usually irrelevant for data interpretation and analysis due to the high pressure head difference (*s*). The step-like recovery phases on the derived curve indicate the replenishment of individual subunits of the sediment sequence. Decreasing values in the subsequent phase indicate the final stage of replenishment. Horizontal segments of the curve indicate hydrologic boundaries and permanent flow.

The individual PDR stages, obtained during our field measurements, are rather heterogeneous. At the K1 well the response of the subunits is divided into three major stages that usually last for a period of 15 to 20 minutes or, in some cases, just for a few minutes (fig. 10). The pressure increase during the replenishment phase is not gradual, but instead characterized by step-like phases: as pressure difference compared to the reference level does not increase monotonously, since the shape of the PDR is influenced by effective porosity and tortuosity. Consequently, the recovery times for the individual subunits vary significantly.

In the middle period of the PDR in well K8 no anomalies, which were typical for well K1, were observed, however, at lower *k* values they are distinct. Prior to reaching the steady-state flow conditions, 15-minute replenishment intervals were observed at well K8, and, therefore, the boundaries of the hydrologic subunits were identifiable (fig. 11).

The dissimilar stratification of the sediments in the two wells is likely responsible for the contrasting hydraulic behavior of the two wells. Adjacent sediment layers around well K1 are characterized by subunits of smaller volume and/or layers of lower effective porosity than that of the K8.

TABLE 1 - The hydraulic conductivity *(K)* values obtained from the pumping tests.

		Theis (1935)	Cooper-Jacob (1946)	Neuman (1972)	Bouwer and Rice (1976)
well No.	number of the steps		$m*s^{-1}$		
	1	$1,34*10^{-5}$	$7,81*10^{-5}$	$6,12*10^{-5}$	$3,42*10^{-6}$
Well K1	2	$2,32*10^{-5}$	$2,11*10^{-6}$	$2,31*10^{-5}$	$4,13*10^{-5}$
	3	$1,78*10^{-5}$	$3,22*10^{-5}$	$3,44*10^{-6}$	$5,23*10^{-6}$
	1	$4,52*10^{-4}$	$5,22*10^{-4}$	$7,19*10^{-3}$	$1,82*10^{-4}$
Well K8	2	$3,83*10^{-4}$	$7,11*10^{-4}$	$6,32*10^{-4}$	$3,1*10^{-4}$
	3	$9,12*10^{-3}$	$4,76*10^{-4}$	$5,87*10^{-3}$	$1,76*10^{-4}$

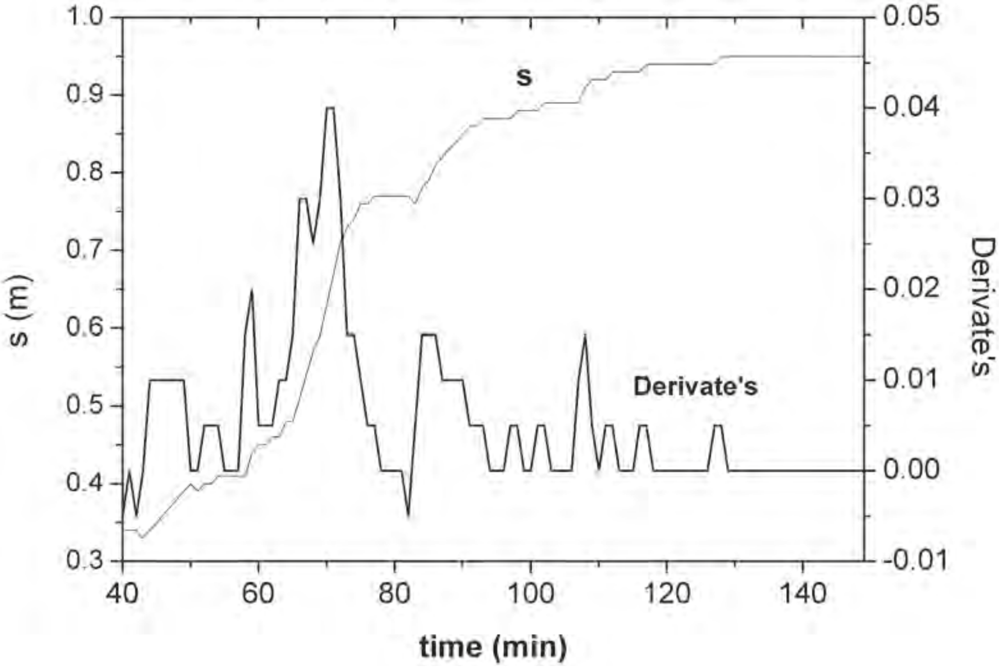

FIG. 10 - PDR of well K1 (cumulative curve, s) and its time derivate.

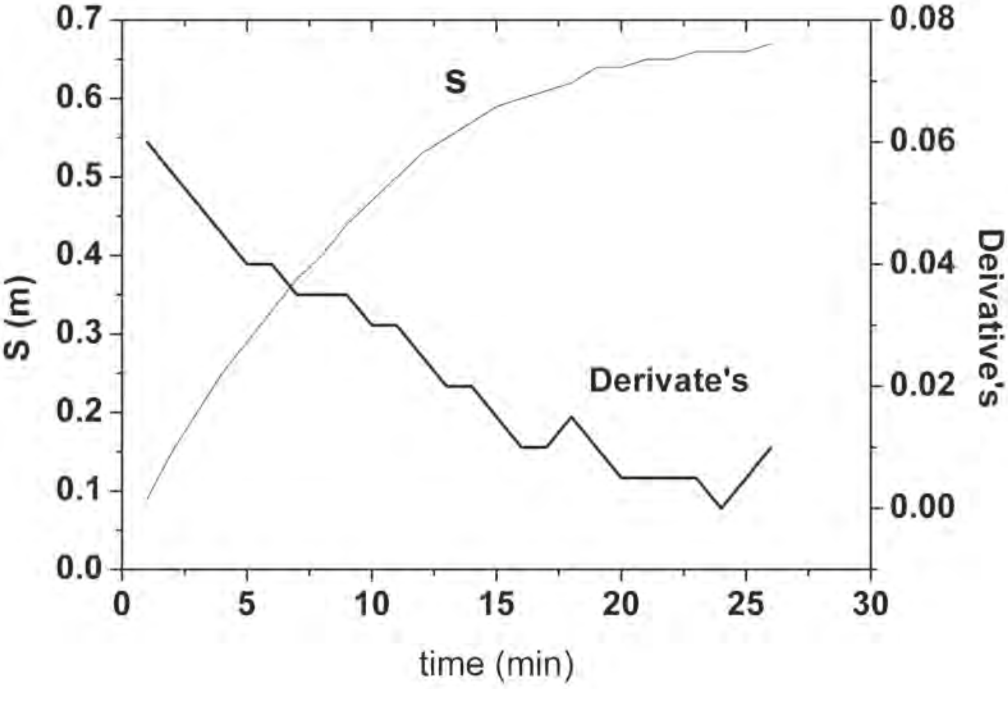

FIG. 11 - PDR of well K8 (cumulative curve, s) and its time derivate.

Hydraulic conductivity measurements

Geologically, the sediments of the oxbow floor can fundamentally be divided into two types: a clayey-silty and a calcareous sandy unit. Hydraulic experiments were carried out on undisturbed sediment samples that were taken from the deepest part (former thalweg) of the oxbow (KP1) and parallel with the shoreline (KP3) (figs 8 and 11). The modi of the PSD curves were markedly different, 80 µm along the shoreline and 10 µm in the deepest part of the lake (fig. 12).

Based on the laboratory hydraulic analyses of the undisturbed sediment samples, different seepage values were found in the middle and shoreline part of the oxbow (from 8.34×10^{-8} m s^{-1} to 2.82×10^{-7} m s^{-1}) – which is just the

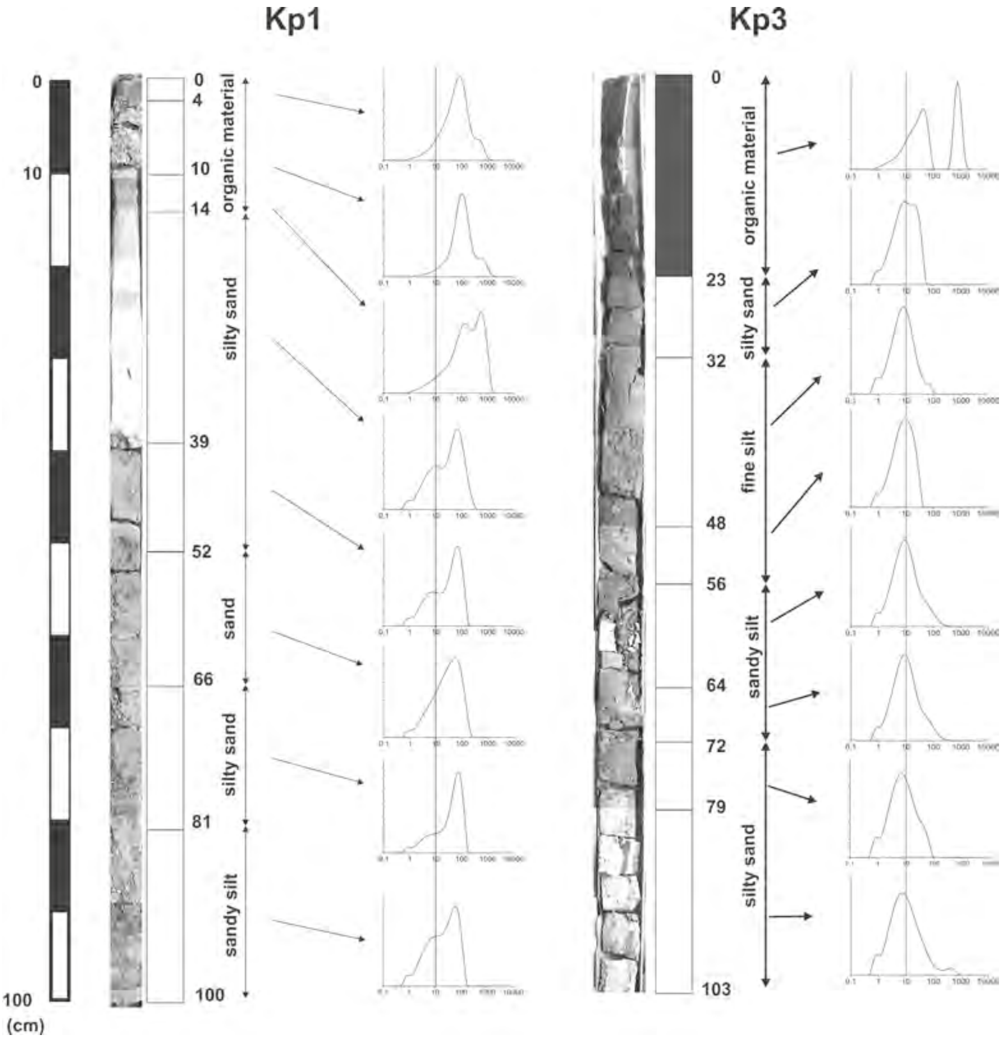

FIG. 12 - Stratification and grain size distribution of deposits in the deepest (KP1) and offshore part (KP3) of Lake Kisinc.

opposite to the corresponding pattern in river channels. It is explained by the presence of fine lacustrine silts in the deepest part and the dominance of fine fluvial sands (D_{med} = 80 µm) with high organic matter content in the offshore region.

At the beginning of the hydraulic conductivity experiments a hydraulic head of 1.5 m was set on the top of the samples (fig. 13). Subsequently, saturated hydraulic conductivity was calculated using the falling head method. The pressure head is representative of the water column height in Lake Kisinc after the accomplishment of the water replenishment scheme. (Water levels will be raised from the current 90.5 m to an operational level of 91.5 to 92 m). Saturated hydraulic conductivity was calculated from the following formula (Juhász 1987, Reynolds & Elrick, 2002):

$$k=\frac{L}{(t_2-t_1)}*ln\left(\frac{h_1}{h_2}\right)$$

where k is saturated hydraulic conductivity, L is the height of the soil core, t_1 and t_2 are initial and final times of the experiment, respectively, h_1 and h_2 are the corresponding pressure head heights.

Hydraulic conductivity was 8.3×10^{-8} m s^{-1} for KP1 sediment samples and 2.82×10^{-7} m s^{-1} for the cores KP2 and KP3 (fig. 13). When an initial head of 1.5 m was used during the laboratory experiments, water level drop ranged between 0.38 and 0.60 m for the sediment samples taken from the clogging zones. However, since its cutoff, the oxbow has been functioning as a depositional basin with ever finer sedimentation. The sediments taken from the shoreline borehole originate and have been transported into the lake from the levee of the oxbow. In addition to the dissimilarity in PSD, variations in hydraulic conductivity may be caused by the development of biofilms. (However, this latter effect cannot be proved from our measurements unambiguously).

Effective porosity

Although microstratification varied with samples, effective porosity was equally low in the samples and therefore relatively low infiltration rates were found. Although Singhal & Gupta (2010) publish equations for fractured rocks, the measured soil physical properties which originate

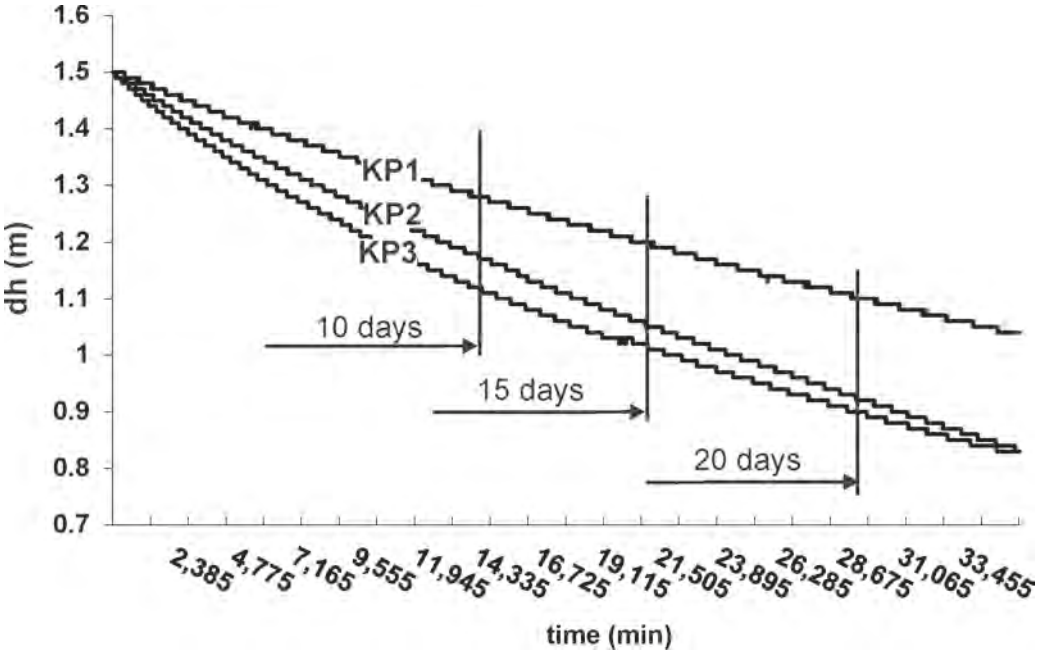

FIG. 13 - Cumulative infiltration as a function of time for the undisturbed samples KP1, KP2 and KP3.

TABLE 2 - Typical effective porosity data of the soil and sediment samples.

max porosity (V/V%)	*effective porosity (V/V%)*	*sediment*
46.52	22.14	pale brown loam, root canals
44.78	13.4	brown, subangular clayey loam
43.19	17.15	pale brown loamly silt with ferruginous precipitations
48.28	22.9	grey, single grained fine sand
49.51	30.15	pale grey single grained sand

during fluviosol formation result in similar hydrogeological conditions. Anisotropy and hydraulic conductivity caused by soil heterogeneity has been studied by Akis (2014). De Bartolo & *alii* (2013) built a fractal model for heterogeneous sediments of sandy loam-conglomerates mixture aquifer.

Effective porosity can be reduced by various precipitations (calcareous, ferruginous and organic matter) and increased by root canals and outwash of sediments from the matrix (tab. 2). Effective porosity was measured by gravimetric method on undisturbed samples. The samples were oven-dried for 24h at 105C° and filled with water to saturation. After saturation samples were placed on a sand bed for 24h during which soils lost their gravitational water. During this period the undisturbed samples lost the amount of capillarity the difference refers to the specific yield (S_y).

Seepage measurements

The rate of seepage from the oxbow lake can be calculated from the water balance equation. The used input parameters included geomorphological data for the oxbow and the measured hydrological parameters (tab. 3). Since the planned replenishment rates for the month of March and June were 43,200 and 24,512 m^3 d^{-1}, resp. (data obtained from Ddkövizig, 2012), a mean 30,000 m^3 d^{-1} replenishment rate was used in our calculations. The thickness of the saturated zone was set to 4 m in the calculations for the unconfined aquifer.

The amount of exchanged water between the oxbow lakes and the surrounding groundwater is proportional to the change of hydraulic head of *dh*, the surface area and the hydraulic conductivity (*k*) of the sediments and inversely proportional to the thickness of the clogging zone (*d*) and is described by the modified form of Darcy's equation (Brunner & *alii,* 2010):

$$Q_s = \frac{k}{d}\,(h_{ox} - h_{grw}) * \Delta x \Delta y$$

where Q_s is the total flow out from the oxbow, *k* is the hydraulic conductivity (m s^{-1}), *d* is soil depth (m), h_{ox} is relative water level of the oxbow lakes, h_{grw} is the adjacent relative groundwater level and $\Delta x \Delta y$ is the change of seepage surface area that corresponds to A_s.

TABLE 3 - Input and output parameters for seepage calculations.

input data					
from geomorphological investigation			from field and laboratory investigations		
volume of oxbow	V_{oxbow}	(m^3)	hydraulic conductivity (depending on sedimentological properties of the oxbow and newly flooded areas)	k	(m*sec^{-1})
area of oxbow lake surface	A_{oxbow}	(m^2)			
(relative) water level of oxbow	h_{oxbow}	(m)	effective porosity	n_o	(-)
output (calculation)					
amount of seepage from the oxbow				Q_s	(m^3*day^{-1})
total seepage area				A_s	(m^2)
change to oxbow lake surface				A_{om}	(m^2)
calulated water level of oxbow				h_{cw}	(m; m-a.s.l)
calculated water storage capacity of oxbow				V_{cws}	(m^3)

The lakebed was divided into two zones, one shallow (less than 1.5 m) and an area of larger depth (1.5 to 2.4 m). The hydraulic conductivities of the recently flooded shoreline areas are similar to the relevant values obtained from the pumping tests. The hydraulic analyses of the undisturbed samples indicate very different hydraulic conductivity values. The deeper zone, where the median particle size 10 µm, has an order of magnitude lower hydraulic conductivity (k ~ 10^{-8} m s^{-1}), while the shallow zone, where D_{med} = 80 µm has a k ~ 10^{-7} m s^{-1}. The additionally inundated areas have an even higher conductivity (k ~ 10^{-5} m s^{-1}). Due to the increasing total seepage area, an increasing volume of added water is lost due to the increased seepage surface area according to the following equation:

$$V_{cws}=V_0+Q_r[(1-Q_{s1})+(1-Q_{s2})+...(1-Q_{s20})]$$

where V_{cws} is the calculated water storage in the oxbow, Q_r is the daily replenishment volume (30,000 m^3 d^{-1}), V_0 is the initial water volume in the oxbow at the beginning of the replenishment (m^3) and Q_{s1},Q_{s2},...Q_{s20} are the daily seepage losses from the oxbow (fig. 14).

The rising water level in the oxbow triggers an increasing hydraulic pressure difference compared to the adjacent areas. With the increasing volume in the oxbow, the potential contact surface and seepage area also increases. Based on our calculations, on day 25 of the replenishment water level reaches an elevation of ca 91.3 m and this water level remains relatively constant for a long time (fig. 15).

However, occasionally, during exceptionally rainy periods, replenishment is capable to raise water level to the planned elevation of 91.5 m a.s.l. (DD-KVTF 2013) (fig. 16).

CONCLUSIONS

The main objectives of the rehabilitation operations are to increase the water capacity of oxbows and landscape diversity. However, due to the incision of the Drava River ($Q_{50\%}$ = 600 m^3 s^{-1}), increased drought hazard and the decreased groundwater levels of the adjacent floodplains, alternative solutions for water replenishment are needed. The alternative source is a stream of much lower flow but at higher elevation. The rehabilitation plan envisions water recharge from the Fekete-víz stream ($Q_{50\%}$ = 4.5 m^3 s^{-1}) (Ddkövízig, 2012).

We found that the replenishment period of 20 days, specified in the rehabilitation plan (Ddkövizig, 2012), is insufficient for the achievement of the optimal water level in Lake Kisinc (91.5 m a.s.l.). Since groundwater levels have rarely risen above 89.50 m recently, groundwater elevation was fixed at this value. If the rehabilitation goal is to set water level to 91.50 or 92.00 m in the oxbow lake, the hydrostatic head would be ca 1.50-2.00 m, which would markedly increase seepage loss.

Regarding hydrogeological properties, the PDRs of the pumping tests revealed hydraulic conductivity an order of magnitude lower than expected based the particle size distribution of the deposits. Based on the variable hydraulic conductivity of the individual sediment subunits, seepage from the oxbow is primarily influenced by oxbow deposits which are divided into three major categories: the deepest zone (the former thalweg), shoreline zone (point bars) and recently inundated oxbow margin.

The laboratory analyses proved that the hydraulic conductivity values of the lake deposits in the assumed clogging zone are less influenced by the organic matter

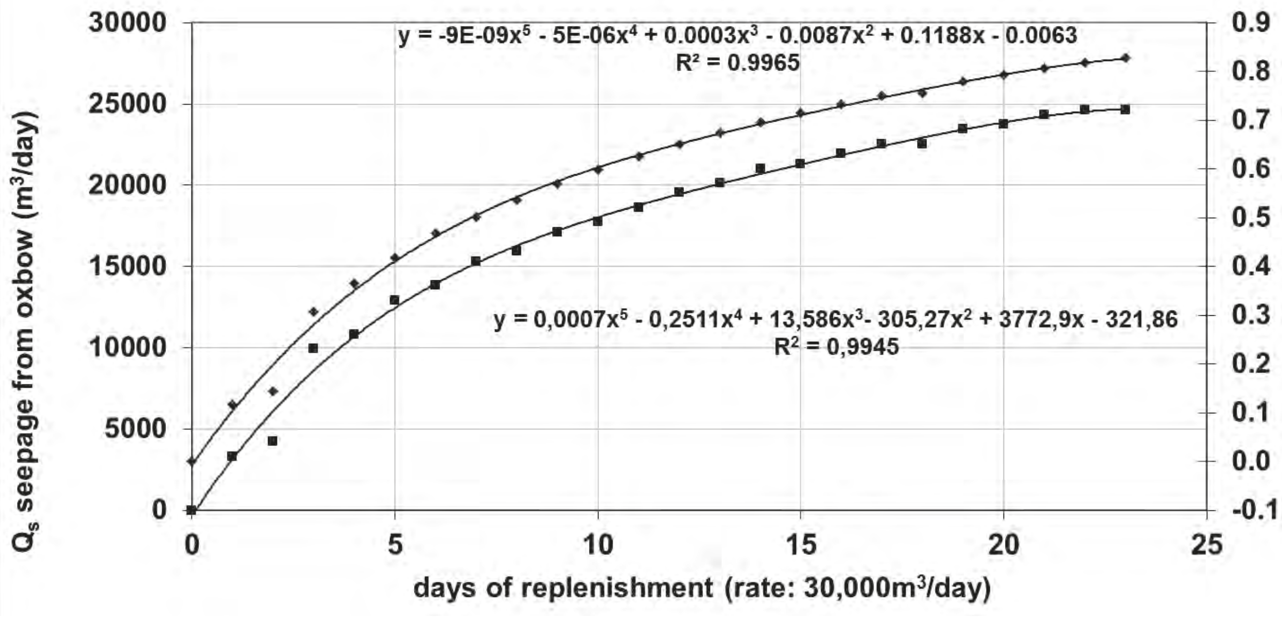

FIG. 14 - Functional relationship between the hydraulic pressure head difference and seepage.

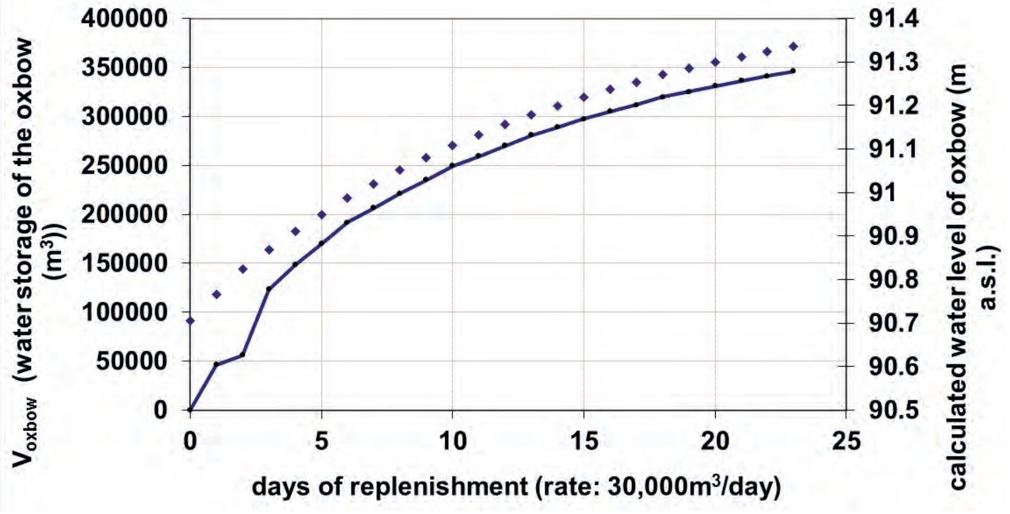

FIG. 15 - Relationship between water storage (V_{cws}) and relative water level (h_{oxbow}) during water replenishment in the oxbow.

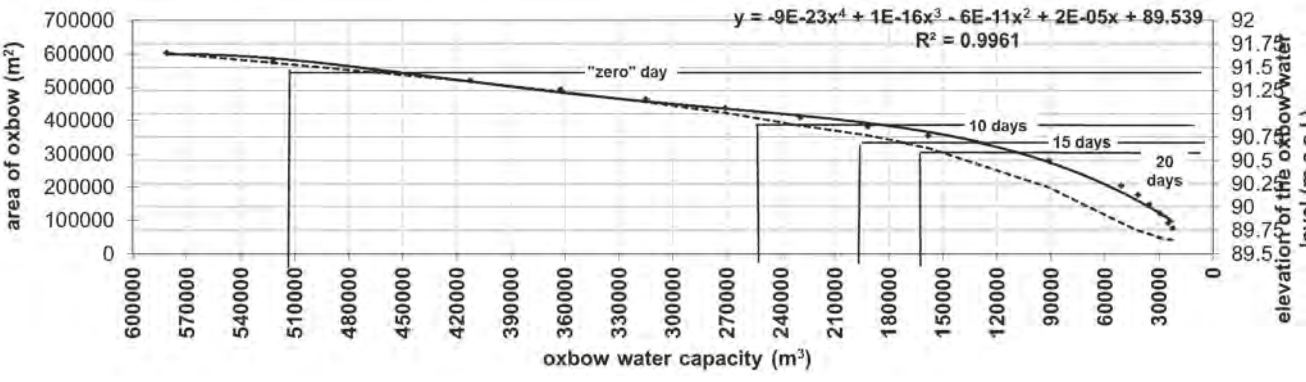

FIG. 16 - Change of water surface area as a function of volume of water in the oxbow at an initial water elevation of 91.5 m.

accumulation (presence of biofilm) than the sediment texture. Local fluvial landforms (point bars or steep undercut banks) exert site-specific control on the growth of seepage surface area.

Two hydrological scenarios were analyzed, one for replenishment and one for water retention. The first scenario set the replenishment rate at a 30,000 m^3 d^{-1}, with a water level rise from 90.5 m to 91.5 m a.s.l. The replenishment would last for more than 25 days due to the high seepage rate from the oxbow, consequently, the planned replenishment would take an undesirably long time.

The second scenario was intended to estimate seepage rate from and water retention in the oxbow. On day 20 after the onset of the replenishment water level was drained by 70 cm compared to the initial water elevation, while the volume of water decreases to one third of the initial volume, while water surface area experienced a decrease of 60%.

The fundamental statements concerning the water budget of the studied oxbow are the following:

- The elevation of the adjacent groundwater table is controlled by the water regime of the Drava River.
- The clogging of lake deposits is not sufficient to prevent large-scale seepage from the oxbow to groundwater and to retain raised lakewater levels.
- Under the present hydroclimatic conditions there is no sufficient water available to counter-balance and compensate for water losses.

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