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Modeling Surface Water-Groundwater Interaction in an Oxbow of the Drava Floodplain

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Abstract

Recently in Hungary, drought affects the Drava floodplain more severely than floods. The channelization of the Drava River changed the water budget of the Cún-Szaporca oxbow lakes in the floodplain. The paper presents a 3-D groundwater model for this oxbow of the Drava floodplain to gain a better understanding of the water budget of the whole system under the normal situation and for different lake replenishment scenarios. The model is developed using the finite difference code MODFLOW-2005 and calibrated with a mean error of -0.03 m, and mean absolute error of 0.08 m. Two scenarios for the replenishment of lake were analyzed. Water level is planned to be raised by 0.5 m and 1 m, for the first and second scenario, respectively. As a consequence, an increase of seepage from the lake was found. Around 65 % of the seepage recharges the groundwater system. Such a rise in groundwater table improves the sustainability of the aquifer and serves agricultural and environmental purposes. Additionally, they show the importance of the model for decision makers to select the right future management decisions.

1 Introduction

In the last centuries, 50 % of European wetlands and more than 95 % of riverine floodplains were converted to urban and agricultural lands [1]. The Water Framework Directive (WFD) provides a framework for an integrated management of rivers and wetlands [2]. River incision is a common reason for increasing drought hazard and the lowering of groundwater level in the adjacent floodplains [3]. In the historical periods several human activities lead to lower groundwater table and deteriorate the balance of natural systems [4]. Alluvial sediments indicate an extreme degree of heterogeneity in the hydraulic properties of sediment [5]. Exchange between alluvial aquifer system and surface water will be affected by the degree of the subsurface heterogeneity [6]. However, many studies address the interaction between the groundwater and surface water [7-9], the degree of subsurface heterogeneity for aquifer was rarely addressed.

Interactions between groundwater and surface water profoundly influence the provision of water-related ecosystem services. Floodplain areas provide places for aquatic ecosystems and shelters for bird population. Preserve and extend the mosaic pattern landscape, which is irrecoverable for biodiversity. This interaction influences water retention and the flood periods. The excess water caused reduced growth of crops, or total damage. The multi-layered sediments are crucial importance as geological background related to subsurface water dynamics. The knowledge of the role (in a hydrogeological means) of these layers is limited. Obviously, the randomly layered geological units cause anisotropy. Their position and extension modifies the velocity of subsurface flow. The optimal design of groundwater table is a complex task because of the conflicting demands of agriculture, forestry, flood control and nature conservation (for the Drava River floodplain see [3, 10].

The natural and/or artificial water budget is unbalanced; water supply is not efficient and sufficient for both agricultural activities and natural conservation. To solve the water scarcity problems, a large-scale landscape rehabilitation project, the Old Drava Programme (ODP), was launched in 2013. The main objective of the ODP [11], implemented by Hungarian Government, is to provide holistic approach to water policy along the Drava river floodplain depending on the nature conservation and sustainable management of lake ecosystems and land.

In this project, one of the most important plans envisages water replenishment to oxbow lakes by raising their level from different sources. During the program, hydrological constructions (feeder canals, reservoirs, dams and sluices) were constructed to achieve the determined ideas. The length of the feeder canal is 3.1 km and canal has capacity of 0.4 m3 s-1. The Fekete-víz reservoir has to be filled to a minimum level of 93.1 m to ensure gravitational flow from the canal to the level of the oxbow lake by at least 0.5% slope. Unfortunately, the best plans often go wrong because they neglected the hydrogeological reality [12] and did not take into account the clogging of the feeding canal bottom. The first replenishment took place on March 2016 and not more than a 20 cm increase in lake level has been achieved.

The objective of this paper is to assess the interactions between groundwater and surface water at critical part of this system: between a protected oxbow (which is feeded by water according the ODP) and the main river (Drava). Further, to investigate the seepage from the lake, change in aquifer recharge, and the changes in groundwater levels under each scenario of oxbow lake(s) replenishment.

2 Study Area

The Drava River coincides with the border between Hungary and Croatia. The Drava oxbow is located in south-western of Hungary and covers an area about 2.57 km2 as depicted in (Figure. 1a, b). To assess the replenishment scenarios of oxbow lakes, a meander of the Drava River was selected as a case study. The meander was partially cut off from the new Drava channel during the first stage of channelization between 1842 and 1846 [13]. In a period of drought summer, the oxbow separate to five lakes. The study area is Lake Kisinc which is the largest oxbow lake of 20 ha area, with a maximum water depth of 2.4 m and an average water depth of 1.12 m [14]. This area is part of the Danube-Drava National Park and considered as a Ramsar Convention area. Satellite images (Google Earth) were used to identify the morphological features. The Ground Penetrating Radar (GPR) surveys were implemented to study the sediment layers in detail. Pumping test results [12] and borehole information were compared with GPR records (as depicted in Figure. 1c, d).

Surface water (lake and river) groundwater interactions were characterized by subdued ridge-and-swale topography in the paleomeander systems. Albeit the area is topographically relatively uniform. Borehole sampling and GPR records showed extreme heterogeneity in the hydraulic properties of sediments. It was found that the fluvial landforms of area have four zones with different hydraulic conductivities. In situ saturated hydraulic conductivity for each borehole was measured using the fall head method [15] by using the following formula:

$$k=\frac{L}{(t_2-t_1)}*ln\left(\frac{h_1}{h_2}\right) \tag{1}$$

where, k is saturated hydraulic conductivity, L is the height of the soil core, t1 and t2 are initial and final times of the experiment, respectively, h1 and h2 are the corresponding pressure head.The Geographic Information System ArcGIS 10.3 was used for preparing the input data to MODFLOW which used as a pre-processing step after MODFLOW to analyse and present results.

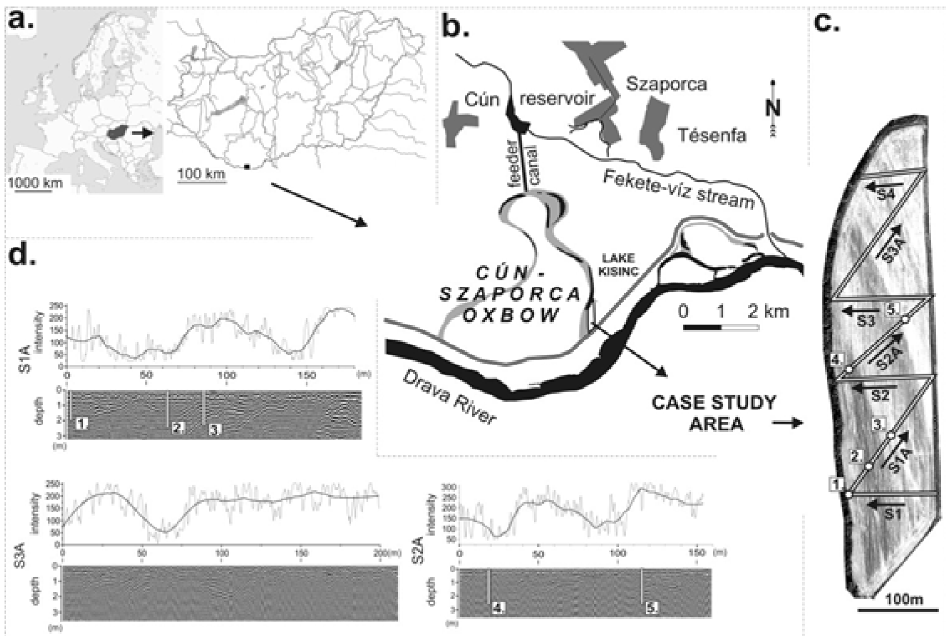

Figure 1: a) location of the research area; b) the Cún-Szaporca oxbow and surrounding area; c) direction and codes of GPR records, boreholes sites on in the case study area; d) Results of three important GPR records, with image gray scale intensities for Groundwater flow model setup

3 Groundwater flow model setup

The finite difference code MODFLOW-2005 [16], with ModelMuse [17] as a pre-processor graphical user interface, is applied to simulate groundwater flow. The model is discretized with a finite-difference grid that consists of 60 rows, 14 columns and 10 layers with cell size of 10 m by 10 m and with a total of 8400 cells, out of which 6540 are active cells. The top boundary of the model is represented by a 10-meter resolution Digital Elevation Model (DEM). The eastern and western boundaries are assigned with constant head values (interpolation between 89.68 and 90.69 m) and (interpolation between 89.8 and 90.91 m), respectively, based on initial groundwater level (see Figure 2). The modified version of [18] that based on water level fluctuation and rainfall depth [19, 20] was used of groundwater recharge of the study area R (mm/year). By the following equation:

$$R = (P- 14)^{0.5} \tag{2}$$

Where, R is the net recharge due to precipitation in inches, and P is the precipitation in inches

The groundwater recharge is found to be 2.5E-05 m d-1. Estimation of evapotranspiration based on the water table fluctuations. The equation is given as [21]:

$$ET = S_y\,(24r \pm s) \qquad (3)$$

where, ET actual daily evapotranspiration (L/day), Sy is the specific yield of soil, r is hourly rate of groundwater inflow (L/h) that represent the mean hourly rate of groundwater level increase from midnight to 4.00 a.m, s is the net rise of fall of water table during 24 h (L). The average daily evapotranspiration is estimated to 13 mm.

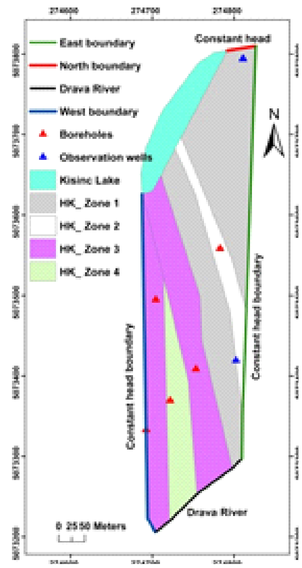

Figure 2: Hydraulic conductivity zonation, observation wells and the boundary conditions of the study area

3.1 Model calibration

3.1 The model is calibrated for steady-state using data from 3 boreholes and 2 observation wells (see Figure 2. The calibrated recharge is 1.35E-05 m d-1, the conductance of riverbed is 150 m2 d-1 and the hydraulic conductivity of zone 1, zone 2, zone 3 and zone 4 are 6.75, 60, 6.75, 500 m d-1, respectively. The results match with observed values with a correlation coefficient of R2 = 0.94 as depicted in (Figure 3) and the mean error is 0.03 m, while absolute mean error is 0.08 m. Moreover, simulated and observed heads are scattered around the mean values of observation heads which represent reliable model.

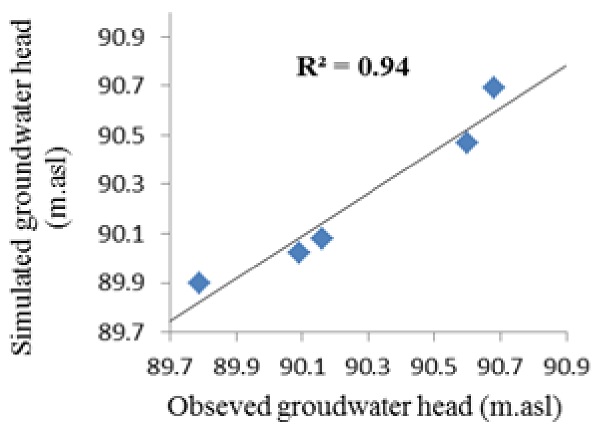

Figure 3: Scatter plot for simulated versus observed groundwater heads of steady states using five observation wells

3.2 Water Balance

3.2 Table 1 showed the water balance of the calibrated model. The total amount of inflow from lake to aquifer is 891 m3 d-1which represents 37% of the total inflow to aquifer and groundwater recharge from precipitation is 0.85 m^3 d^{-1}. The water budget of the system showed the importance of replenishment of oxbow lakes as a source to recharge aquifer and preserve the sustainability of ground water. The total discharge from aquifer to the river is 321.63 m^3 d^{-1} while evapotranspiration accounted for 223.95 m^3 d^{-1}. An amount of 1167.50 m^3 d^{-1} (or 48.87%) recharges the aquifer from western boundary and 329.38 (only 13.79%) from northern boundary. An amount of 1843.40 m^3 d^{-1} (77.16%) flows out the aquifer through the eastern boundary. This coincides with real situation that flows come from northern western direction to eastern direction.

Table 1: Water balance for the simulated steady state model

	In		Out		In-Out
	(m^3 d^{-1})	%	(m^3 d^{-1})	%	(m^3 d^{-1})
Eastern Boundary	0.00	0.00	1843.4	77.16	-1843.4
Northern Boundary	329.38	13.79	0.00	0.00	329.38
Western Boundary	1167.50	48.87	0.00	0.00	1167.5
Lake	891.00	37.30	0.00	0.00	891.00
River	0.00	0.00	321.63	13.46	-321.63
Recharge	0.85	0.04	0.00	0.00	0.85
Evapotranspiration	0.00	0.00	223.95	9.38	-223.95
Total	**2388.98**	**100**	**2388.98**	**100**	**0.00**

3.3 Effect of model discretization

To study the effect of the model discretization, various models were built. Summary of the simulated model discretization scenarios, water balance components and average groundwater level for every scenario are presented in Table 2.

Table 2: Water balance components compared to the base case situation

Case	Inflow through constant head boundary	outflow through constant head boundary	Aquifer recharge (from lake)	Discharge from aquifer to river	Evapo – trans-piration	Aquifer recharge from precipitation	Average ground-water level
			(m3d-1)				m.asl
(1) Model defined by 6 zones and 10 layers in vertical discretization	1497.12	1843.39	891	321	223.95	0.85	90.26
(2) Model defined 6 zones and one layer for vertical discretization	496.41	4195.83	4382.04	412.49	271.23	0.84	90.3
(3) Model characterized by grid cell 5m by 5m	1910.10	2161.9	989.11	506.17	231.97	0.84	90.274

Contour lines of the simulated groundwater levels of the model discretization scenarios with the base case are shown in Figure 4. The results clearly indicated that a major effect on the groundwater levels and water balance between the all scenarios. In case 2, the vertical discretization of the aquifer characterized by one layer with average vertical hydraulic conductivity, disregarding the sediment structure that reflected by the GPR investigation. Water leakage from the lake increases by 3491 m^3 d^{-1} with respect to the first case, resulting in the average groundwater level raise by 4 cm and increases in the amount of outflow through constant boundaries and ET increase. In case 3, with changing the cell size of the model to 5m by 5m. The water balance component is quite similar to the base case, which recharge rate from the lakes to the aquifer increases by 98.11 m^3 $d^{-1}$and discharge of aquifer to the river increases by 185.17 m^3 d^{-1}. The average groundwater level rises by 1.5 cm with respect to base case (Table 2). In case 4, the surface of the model defined by one zone with average horizontal hydraulic conductivity and one layer in vertical discretization, the simplification of sediments structure leads to increases in the seepage of the lake to groundwater system by 2846.23 m^3 d^{-1} and discharge from aquifer to river increases by 2135.71 m^3 d^{-1}. The average water table rises by 8cm regarding to first case.

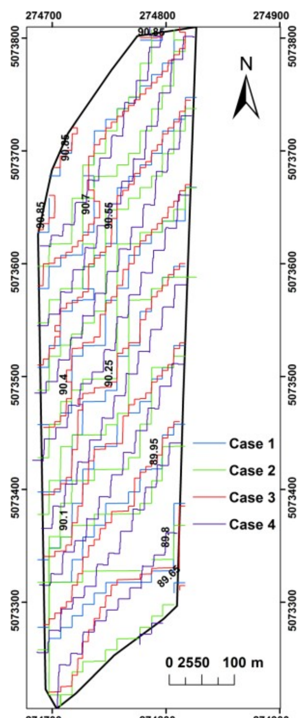

Figure 4: Contour lines of water table levels (m. asl) for model discretization scenarios compared with the base **case.**

4 Replenishment Scenarios

The baseline scenario represents the existing situation of the lake without replenishment, with water level at 90.5 m above sea level. This case is applied to calibrate the steady state model and to compare the results with replenishment scenarios. Two hydrological scenarios of lake - replenishment by setting two different lake water levels (91 and 91.5 m. asl) are applied to analyze the responses of the groundwater system.

4.1 Results and discussions

In the basic scenario (i.e., in the absence of the lake replenishment) in which lake stage is at 90.5 m. asl., the results show that leakage (outflow from the lake) is 895 m^3 d^{-1} and the outflow from evapotranspiration is 18 m^3 d^{-1}. Discharge from aquifer to river is 721. m^3 d^{-1}, from which the recharge from lake to aquifer is 174.95 m^3 d^{-1} and the average groundwater level is 89.68 m. asl. Figure 5a shows the distribution groundwater head for the basic case. The results of the simulated scenarios are summarized in Table 3. In the first replenishment scenario, with increasing the lake water by 0.5 m (91 m. asl). The seepage from the lake is 1,298.8 m^3 d^{-1} and outflows through evapotranspiration rise by 161.20 m^3 d^{-1} in respect to the baseline situation. Average groundwater level rises by 0.28 m. In the second scenario, at the maximum lake stage of 91.5 m. asl, recharge rate from the lake to the aquifer increases by 745.59 m^3 d^{-1}compared to the baseline case. Consequently, average water table rises by 0.77 m and the amount of evapotranspiration outflow increases.

Table 3: Water budget components and changes in groundwater level compared to the baseline situation

Scenario	Average lake level	Aquifer recharge from lake	Discharge from aquifer to river	Evapo-transpiration	Average change of groundwater level
	(m. asl)		(m^3d^{-1})		(m)
Baseline case	90.5	895.96	721.02	18	0
1st replenishment	91	1298.3	446.71	180.8	0.28
2nd replenishment	91.5	1409.7	488.46	685.66	0.77

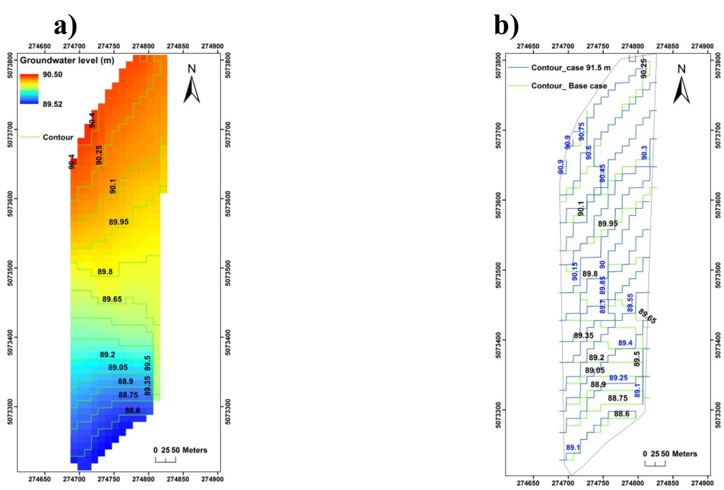

Figure 5: a) Simulated groundwater head contour map for basic scenario; b) Head contours for maximum replenishment lake stage 91.5 m.asl with head contours of basic scenario

Simulated groundwater head contours for the second scenario with the head contours of the basic scenario are presented in (Figure 5b). All results point out the planned replenishment scenarios of the lake will raise the groundwater level and augment, on the average, the groundwater system by over 65 % of the leakage from the lake.

5 Conclusion

The effects of different water management scenarios were studied for the lake replenishment to the Cún-Szaporca oxbow. A 3-D groundwater model was developed to gain a better understanding of groundwater-surface water interactions in the oxbow by using MODFLOW 2005. The model was applied to assess the water budget through calculating the changes in streams and groundwater system under a set of different lake water levels. The increase in water level to 91 and 91.5 m. asl would result in raising the average groundwater level by 0.28 and 0.77 m, respectively, compared to the baseline case (90.5 m). The simulated scenarios showed that the rate of recharge from the lake to aquifer increased by 677.17 and 745.59 m^3 d^{-1}, respectively. Water budget for the simulated scenarios will maintain the ecosystem and agriculture water in equilibrium. These outcomes will help the planners and the stakeholders in planning and management of water resources in the oxbow area.

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