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Numerical Modelling of Surface and Groundwater Interaction Affected with Bottom Sediments in the Canals of the Rye Island (Slovakia)

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Abstract. Natural water resources are in continuous dynamic interaction with each other. Hydrodynamic processes between surface water and groundwater are very complex, and they are influenced by many factors and conditions (topography, climatic conditions, hydrogeology, stream hydrology and morphology, etc.). Groundwater – surface water interactions are also influenced by riverbed sedimentation and clogging processes. The thickness and hydraulic conductivity of bed sediments can significantly affect the temporal and spatial patterns of hyporheic exchange. The aim of this study was to investigate the influence of riverbed clogging on groundwater – surface water interaction in a lowland area with intensive agricultural production (Rye Island, Slovakia). In this locality, a canal network was constructed for draining the excessive GW from the adjacent farmlands. Due to the topography, land use and climatic conditions the canals are exposed to intensive aggradation, what may negatively affect their draining function. Therefore, regular field monitoring of the canal bottom sediments should be performed. In this study, the sediment deposits in the Gabcikovo – Topolniky canal were investigated. The thickness of sediments was measured along the canal by 1 km step, and undisturbed sediment samples were taken in selected cross sections. From the samples the saturated hydraulic conductivity of bottom sediments was assessed by laboratory methods. The collected data were used for numerical modelling. The impact of canal sediments on the groundwater – surface water interaction was simulated by the TRIWACO model. Several model scenarios were considered for different sediment thicknesses. The results of the numerical simulations confirmed the influence of canal bottom sediments on groundwater – surface water interaction along the Gabcikovo – Topolniky canal. It was shown, that thicker sediment deposits (>0.5 m) would obstruct the canals drainage function in a great extent, possibly even cut off the communication between the canal and the aquifer. The results suggest that bottom sediments should be regularly removed to ensure the hydraulic connection between the canals and the surrounding aquifer, and hence guarantee the canals proper draining ability and the protection of adjacent agricultural areas from flood hazard.

Keywords: Groundwater (GW) – surface water (SW) interaction, riverbed sediments, model TRIWACO

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INTRODUCTION

In recent years, the issue of the interaction of surface waters (SW) and groundwater (GW) has increasingly come to the fore. Many publications point to the importance of focusing research on better understanding SW - GW dynamics and exchange processes between the stream and the aquifer [1], [2]. Interaction occurs mainly through the bottom of surface streams, therefore the morphology of the stream and bottom sediments can greatly influence the interaction processes and thus both the quantity and quality of GW [3]. The thickness of bottom sediments and their permeability significantly affect the drainage and infiltration resistance of streams and the interaction between the river and the aquifer [4], [5], [6].

In this study, we focused on the silting of the canal network on the Rye Island (Slovakia) and investigated the influence of bottom sediments on the groundwater regime in the surrounding area. The territory of the Rye Island has a very small slope; therefore, sedimentation processes take place here very intensively. Thick deposits of sediments can greatly limit the ability of the canal network to drain groundwater from the surrounding area. The thickness and saturated hydraulic conductivity of the sediments were determined by field and laboratory methods and the infiltration and drainage resistance parameters of bottom sediments were calculated. The obtained characteristics of the bottom sediments were used in numerical simulations of their influence on the interaction of groundwater and surface waters by the TRIWACO model. This model allows to use infiltration and resistance parameters of riverbed sediments as input data to the model directly. The results of this work can be used in planning the maintenance of the canal network.

STUDY AREA

The Rye Island is located on the Danube Lowland, between the Danube River and the Small Danube River (Figure 1). The geological structure of the Rye Island consists of Quaternary sediments, created by the sediments of the Danube River, the "Danubian gravels". These river sediments consist mainly of gravels with a sandy admixture, and in the area of interest their thickness is around 160 m, therefore the geological structure in this area can be considered homogenous. Thanks to their high permeability, the Danubian gravels are an important collector of groundwater, creating the largest resources of drinking water not only in Slovakia, but also in Central Europe.

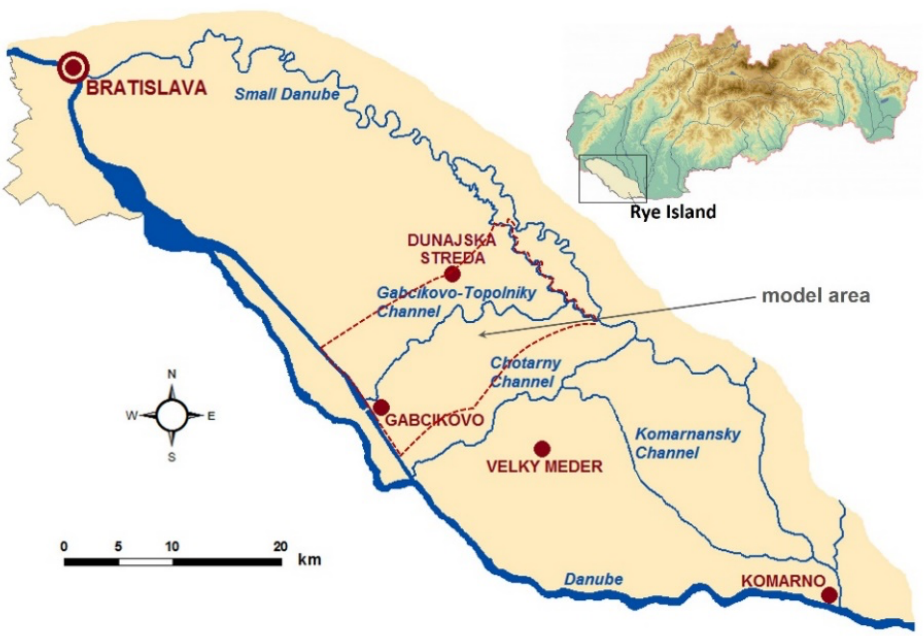


FIGURE 1. Map of the study area.

The area of Rye Island is characterized by an average annual air temperature above 10°C, an average annual potential evapotranspiration of 750 mm and an average annual actual evapotranspiration of 450 mm. The average

total annual precipitation in this area is around 500 mm; the average total annual effective precipitation is less than 50 mm.

From a geographical point of view, it is a lowland area with a very low slope of 2.5 10^{-4}. Thanks to the favorable climatic and geographical conditions, the territory of Rye Island belongs to the most productive agricultural areas of Slovakia.

On the Rye Island, a canal network was built to drain the agricultural land, later it was also used for irrigation. Due to the low slope of the terrain and small flow rates, the canal network is affected by strong sedimentation, which can significantly affect the interaction of groundwater and surface waters in this area.

In our study, we focused on determining the characteristics of bottom sediments and their influence on the regime of surrounding groundwater in the Gabcikovo – Topolniky canal (Figure 1). The Gabcikovo – Topolniky canal flows through the entire width of the Rye Island, connecting the Danube river with the Small Danube. Its length is 28.7 km, the average width is 14 m.

METHODS AND MATERIAL

Determination of the Characteristics of Bottom Sediments

Bottom sediments are an important factor in the interaction of groundwater and surface water. Their thickness and permeability affect the amount and time of exchange between the aquifer and the stream [7]. Their various characteristics are also important input data for mathematical modeling of interaction processes.

The silting of the Gabcikovo - Topolniky canal has been monitored by the Institute of Hydrology SAS since 1993. For this study, the results of field measurements from 2018 were used, when the thickness of bottom sediments was measured every rkm along the Gabcikovo – Topolniky canal, and undisturbed samples of bottom sediments were taken in selected profiles using the Beeker Sampler sampling device. The detailed procedure for measuring the thickness of bottom sediments and taking their samples is described in [8].

From the undisturbed sediment samples, the saturated hydraulic conductivity of bottom sediments was determined by the falling head method for the top, middle and bottom layers of sediments.

From the known values of the saturated hydraulic conductivity and the thickness of the bottom sediments it is possible to determine the drainage and infiltration resistance of the bottom sediments. These variables express the duration of water seepage from the stream to the aquifer and back. The drainage resistance (*CD*) [days] and infiltration resistance (*CI*) [days] of the bottom sediments were calculated as:

$$CI = \frac{d}{K_{CI}} \tag{1}$$

and

$$CD = \frac{d}{K_{CD}} \tag{2}$$

where d [m] is the sediments thickness, K_{CI} [m.day^{-1}] is the saturated hydraulic conductivity of the sediments at the top layer of sediments and K_{CD} [m.day^{-1}] is the saturated hydraulic conductivity of the sediments at the bottom layer of sediments.

Modelling the Influence of Bottom Sediments on the Surface Water – Groundwater Interaction

To solve the task of modelling the influence of bottom sediments on the interaction of groundwater and surface water in the study area the mathematical model TRIWACO 4.0 ([9], [10]) was chosen. The TRIWACO model is a quasi-three-dimensional groundwater flow model based on the finite elements method. The model can be used for both steady and unsteady groundwater flow [9]. Under natural conditions, the duration of drainage and infiltration through the bottom sediments is usually different. The TIWACO model allows the user to enter a different value of drainage and infiltration resistance as model parameters.

The boundary conditions of the model were defined by GW heads in monitoring wells on the model boundary and by the surface water level in the adjacent streams. The location of the canals, model boundary and the GW monitoring wells in the model area are shown in Figure 2. The model input data and model parameters were obtained from the database of the Slovak Hydrometeorological Institute (climatic data, hydrological characteristics), from field measurements of the Institute of Hydrology SAS (stream morphology, sediments characteristics) and from the State Geological Institute of Dionyz Stur (hydrogeology, geology).

In the TRIWACO model, the model calibration is performed automatically, by comparing measured and simulated groundwater heads. The aim of the calibration is to minimize the differences between the values calculated by the numerical model and the real measured data. Measured GW heads were available from 32 monitoring wells of the Slovak Hydrometeorological Institute (Figure 2). In order to achieve the best match between the measured and simulated data, selected model parameters were adjusted manually, by a trial-error method. More detailed information on calibration and model parameters is given in [9] and [10].

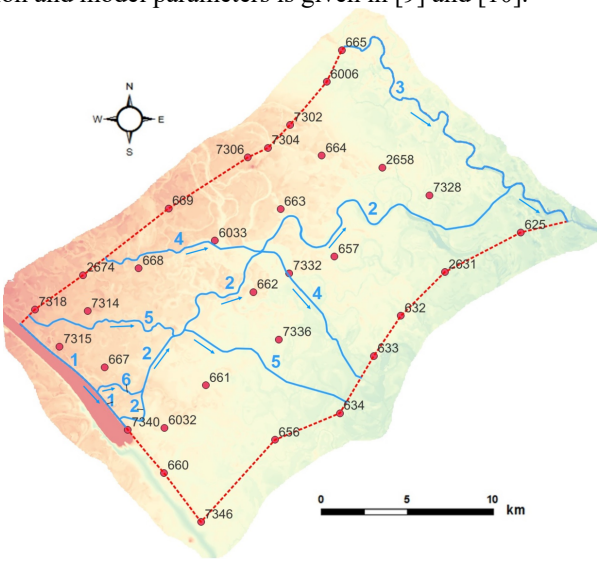


FIGURE 2. The location of the canals and GW monitoring wells in the model area. 1 – seepage canal of the Gabcikovo power plant system (Danube river); 2 – Gabcikovo – Topolniky canal; 3 – Klatovske branch of the Small Danube, 4 - Vojka – Kracany canal; 5 - Sulany – Jurova canal; 6 - Baka – Gabcikovo canal.

The model was validated by simulating the impact of the canals on the GW regime. To assess the model's applicability, simulations were conducted considering no hydraulic connectivity between the canals and the aquifer, and subsequently considering the canals influence in the model area. The following scenarios were created:

Scenario A: no irrigation/drainage canals in the model area;

Scenario B: considering only the Gabcikovo – Topolniky canal;

Scenario C: including all canals in the area.

Afterwards, the impact of canal network silting and the thickness of bottom sediments layer on the surrounding groundwater was modelled. We considered two scenarios for the following bottom sediment thicknesses:

Scenario D: thickness of bottom sediments $d = 0.2$ m;

Scenario E: thickness of bottom sediments $d = 1$ m.

RESULTS AND DISCUSSION

Characteristics of Bottom Sediments

The measured thickness of bottom sediments along the Gabcikovo – Topolniky canal exhibited considerable variability, with values ranging from 0.1 to 0.7 metres. The average value was 0.43 metres. The distribution was variable, the thickest sediment layers were generally observed in the middle part of the canal.

The composition of the canal sediment deposits was predominantly fine-grained material, including loamy sands, clay and organic material. The granulometric analysis proved that the sediments are more finely grained in the top layer than those in the bottom layer. The sediments particle size ranges from 0.001 to 0.05 mm in the top layer, while it ranges from 0.001 to 1.0 mm in the bottom layer.

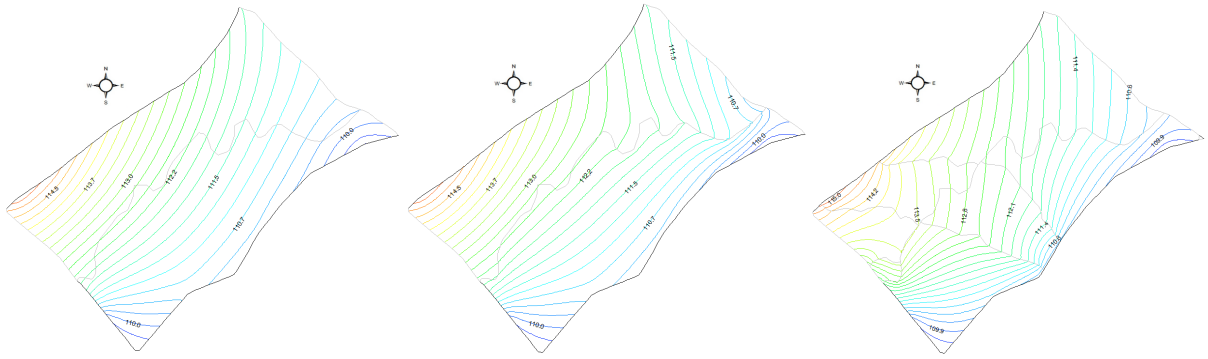
From the sediments samples the saturated hydraulic conductivity K [m.day^{-1}] of the bottom sediments was determined. The average value of K in the top layer was 0.09 m.day^{-1} and in the bottom layer 0.14 m.day^{-1}. In the top layer the values of K vary from 0.005 to 0.4 m.day^{-1} and in the bottom layer from 0.01 to 0.3 m.day^{-1}.

Afterwards the drainage resistance (CD) and infiltration resistance (CI) of bottom sediments were calculated. The average value of CD in the Gabcikovo – Topolniky canal is 3 days and of CI is 5 days. It was found out, that in general $CI = 1.5\ CD$ in the analyzed samples.

Influence of Bottom Sediments on the Surface Water – Groundwater Interaction

The results of numerical simulations showed, that in general the groundwater flow is from west to east, with groundwater levels gradually decreasing in accordance with the topography, from the Danube River to the Small Danube River. The highest groundwater levels are around 115 m a.s.l. on the west and the lowest around 109 m a.s.l. in the eastern part of the model area.

The results of the simulations testing the influence of canals on the groundwater regime in the area (Scenario A, B and C) are presented in Figures 3. It was demonstrated that the groundwater flow direction and levels are comparable across all three simulated scenarios, yet the distribution differs. The results of scenarios A, B and C corroborate the impact of the canals on the groundwater regime in the region. It was demonstrated that the canal network exerts a significant influence on the groundwater regime, particularly near the canals.

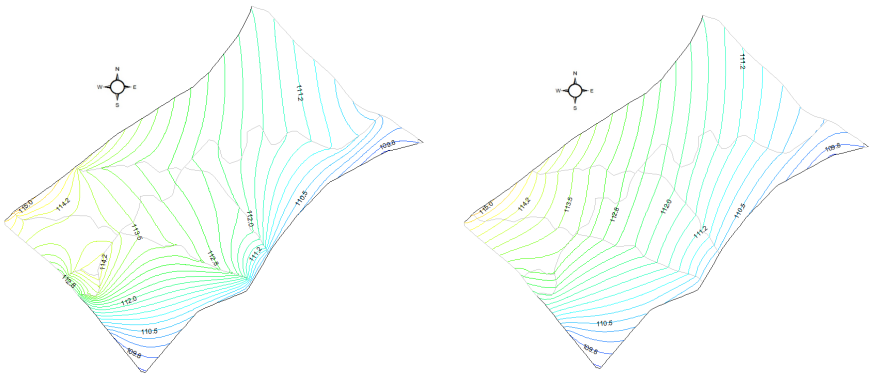


(a) **(b)** **(c)**

FIGURE 3. Contour map of GW heads [m a.s.l.] for Scenario A, B and C – the influence of the canals. Scenario A – no canals, Scenario B – only Gabcikovo – Topolniky canal, Scenario C – all canals.

The maps of isolines of groundwater levels, simulated for different thicknesses of bottom sediments according to scenarios D and E, are presented in Figures 6 and 7. From the results, it is clear that the canal network has a greater influence on the groundwater regime when the bottom sediment layer is thinner, or possibly none (Figure 4.a). The greater the thickness of the sediment layer, the less influence the canal exerts on the direction of groundwater flow (Figure 4.b, Scenario E). Thick sediment deposits can effectively isolate the canal from the aquifer, resulting in a

similar outcome to the simulations where no hydraulic connection between the canal and the aquifer was considered (Figure 3, Scenario A).



(a) **(b)**

FIGURE 4. Contour map of GW heads [m a.s.l.] for Scenario D and E – the influence of sediment thickness *d*. Scenario D: *d* = 0.2 m; Scenario E: *d* = 1 m.

CONCLUSION

Due to the low slope of the terrain and the small flow rates of water in the stream, lowland streams are often subject to intense bottom sedimentation. Among other parameters, the exchange of water and solutes between the stream and the aquifer is controlled by the thickness and permeability of the bottom sediments. Therefore, thick layers of bottom sediments can significantly affect the interaction between groundwater and surface waters. In this study, we employed a numerical modelling approach to investigate the impact of bottom sediments on the groundwater regime in the Gabcikovo Topolniky canal (Rye Island, Slovakia). The characteristics of the bottom sediments (thickness, saturated hydraulic conductivity, drainage and infiltration resistance) were identified and utilised as input data for numerical modellling. The influence of different sediment thicknesses on the groundwater regime in the study area was evaluated using the TRIWACO model.

During the field measurements it was observed that the distribution of sediments in the Gabcikovo – Topolniky canal is rather variable. Their thickness vary between 0.1 m and 0.7 m. Numerical simulations have confirmed that bottom sediments exert an influence on the interaction of groundwater and surface waters, particularly in the vicinity of the canals, where they can locally alter the direction of groundwater flow. The presence of thicker layers of bottom sediments can significantly impair the capacity of the canal network to drain groundwater, which may result in the flooding of nearby agricultural soils. To maintain optimal hydraulic connectivity between the canals and the aquifer, regular removal of bottom sediments is essential. The findings of this study can provide valuable insights for the maintenance and management of the canal network.

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