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Impacts of riverbed aggradation on groundwater regime in a lowland area

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Abstract: In this study, the influence of riverbed silting on the groundwater regime in a lowland area was investigated. The study area is situated at the Rye Island (Žitný Ostrov) in Slovakia, along the Gabčíkovo – Topoľníky canal, which is part of the drainage-irrigation canal system constructed in this locality. The Rye Island is an area with very low slope ($0.25\ 10^{-4}$) and good climatic conditions for aquatic vegetation, therefore the canals are influenced by intensive silting processes. The spatial and temporal patterns of surface water – groundwater exchange are significantly influenced by the thickness of riverbed sediments and their permeability. The aim of this study was to evaluate the thickness and hydraulic conductivity of bed sediments in the Gabčíkovo – Topoľníky canal and to examine their influence on the groundwater – surface water interaction in the area. The hydraulic conductivity of the sediments was assessed from undisturbed samples by the falling head method. The obtained data were used for numerical simulations of groundwater heads by the TRIWACO model for different drainage and infiltration resistance conditions in the area of interest. The results of this study can support the planning of canal maintenance.

Keywords: Groundwater – surface water interaction; Groundwater heads; Numerical modelling; TRIWACO; Sediment deposits; Rye Island.

INTRODUCTION

In the last decade, there was a paradigm shift in understanding the importance of interactions between groundwater and surface water bodies (Lewandowski et al., 2020). The growing awareness of the relevance of groundwater–surface water interactions lead to increased research into the quantification of water balances in systems with interacting river flow and aquifer dynamics (Lewandowski et al., 2020; Steiness et al., 2019).

The European Union Water Framework Directive addressed the need of a sustainable management of coupled groundwater (GW) – surface water (SW) resources and their ecosystems and recommends estimating the exchange flow rates and flow directions between SW and GW. The flow dynamics and spatial/temporal patterns of SW-GW exchange are influenced by many factors and conditions. Besides the fluctuation of SW and GW levels and their gradient, this exchange is also influenced by climatic conditions (precipitation, evaporation), the parameters of the aquifer (hydrogeological conditions, physical parameters) and by the properties of the riverbed itself (morphology, sediments) (Woessner, 2000). Conant et al. (2019) in their conceptual model, developed for evaluating the effects of SW - GW interaction on water quantity and quality, identified the type of SW body and geomorphological, hydrological, topographical, geological, chemical, biological, ecological, and climatological factors as the main influencing factors. The duration of SW-GW exchange is controlled by the drainage and infiltration resistance of riverbed sediments. Generally, these two parameters primarily depend on the hydraulic conductivity, and on the thickness, lithology and structure of riverbed sediments (Cui et al., 2021). Silting or erosion processes significantly affect the stream-aquifer interactions by altering the thickness of riverbed sediments and the bed permeability. Riverbed silting is caused by the infiltration or deposition of sediment particles, organic and inorganic solids, and a series of biological processes that lead to the formation of a silt layer at the bottom of the riverbed (Blaschke et al., 2010; Grischek and Bartak, 2016). The permeability of riverbed sediments is a key parameter determining the amount of river-water infiltration (Crosbie et al., 2014; Harvey and Gooseff, 2015), and it is an important parameter in many catchment-scale hydrogeochemical models (e.g. SWAT+, Bieger et al., 2017). The relationship between riverbed morphology and water infiltration was investigated in Cardenas et al. (2004) and Frei et al. (2009).

As the interaction and hydrodynamic processes between SW and GW are very complex, the application of field and laboratory experiments may be limited. Therefore, numerical hydrological models were developed as a tool for improving the understanding of flow dynamics in the aquifer and the exchange between GW and SW. A general overview on numerical solutions of GW-SW interaction and a theoretical and practical application of integrated surface-subsurface models are given by Fleckenstein et al. (2010), Kumar (2015) and Brunner et al. (2017). The hydraulic connection and dynamics of water exchange between the river and the aquifer were studied by Peyrard et al. (2008), Derx et al. (2010) and Baratelli et al. (2016). Brunner et al. (2009) is dealing with spatial and temporal aspects of the flow transition from connection to disconnection between SW and GW. Riverbed silting processes and the effect of sediments on water flow were studied in Gutknecht et al. (1996), Dulovičová et al. (2022), Okhravi et al. (2022a) and Okhravi et al. (2023).

Our study aims to assess the impact of bed sediments on the surrounding groundwater regime on the Rye Island (Slovakia), a lowland area with intensive agriculture. Despite of the fact, that the Rye Island is a very interesting and important area regarding the interaction of SW-GW due to its agricultural use and settlements, the monitoring network and measured water level data do not sufficiently reflect this fact. In addition, the results of

simulation models of GW levels regime in this area are absent in the scientific literature.

On the territory of Rye Island, a system of canals was built for draining and irrigation of the fields. Because of the very low slope and good climatic conditions for aquatic vegetation (mainly *Ceratophyllum demersum*, *Urticularia vulgaris*, *Elodea canadensis*) (Schügerl, 2019), the canals are undergoing intensive silting processes. Thick sediment deposits can totally disconnect the communication between SW and GW, which can negatively affect the draining ability of the canals. Limited draining function of the canals can impose flood hazard for the adjacent agricultural areas.

The estimation of streambed hydraulic conductivity is of interest due to its complexity in connection with stream-aquifer interaction (Naganna et al., 2017). An important novelty of this study is that we used the actual value of the hydraulic conductivity coefficient obtained from undisturbed bed sediment samples taken during our own field measurements at the investigated site.

The results of our study should confirm the importance of regular removal of bed sediments from the canal network on the Rye Island and support their maintenance by determining the effects of riverbed sediments thickness on the drainage ability of the canals and their influence on the surrounding groundwater regime.

The impact of canal sediments – their thickness, permeability and resistance – on the GW regime was assessed by numerical simulations. Rather than get the exact values of GW head fluctuations, our main goal was to determine whether the changes of the sediments thickness and thus the drainage and infiltration resistance of bed sediments have any influence on the GW regime, and whether this influence is only local or it applies in a wider scale spatially. For this task, the GW modelling software TRIWACO was chosen. The TRIWACO model allows to use infiltration and resistance parameters as input data (model parameters) directly. As stated by Jansen et al. (2003), a numerical model should be able to incorporate the canal resistance parameters. However, most of the models (for example the most widely used MODFLOW) do not provide a boundary condition with different resistances for drainage and infiltration (Zaadnoordijk, 2009). In most models, the infiltration and drainage resistance is expressed through other converted parameters (for example, in MODFLOW by hydraulic conductance of canal bed). These parameters have no clear, explicit physical meaning and cannot be measured or determined by field measurements (Jansen et al., 2003).

Some studies verified the applicability of the TRIWACO model to calculate SW - GW exchange for different geographical regions (Kovar et al., 2005; Shenga et al., 2018). Shenga et al. (2018) applied the TRIWACO model to study the interaction between the water level in the Nitra River in Slovakia and the groundwater level around the river and used these results for designing a groundwater extraction system to control excessive rise in the groundwater table.

MATERIAL AND METHODS

Study area – general overview

The study area is situated on the Rye Island, Slovakia, which is part of the Danube Lowland, between the Danube River and the Small Danube River (Figure 1). It is the biggest river island in Europe, with an area of almost 1900 km^2. Its geological structure is built by Quaternary sediments, in the area of interest mostly formed by a complex of river sediments consisting of gravels with an admixture of sands, denoted as "Danubian gravels". The "Danubian gravels" achieve the thickness of about 160 m in the study area (Maglay et al., 2009). The Quaternary formation of sandy gravels created ideal conditions for groundwater accumulation and storage, resulting in the formation of the richest groundwater reservoir of Slovakia but also of Eastern Europe. According to the Water Management Balance (WRI, 2005) there are 10 milliard m^3 of drinking water under the surface of the Rye Island, which equals to 18 m^3 s^{-1} of available groundwater resources.

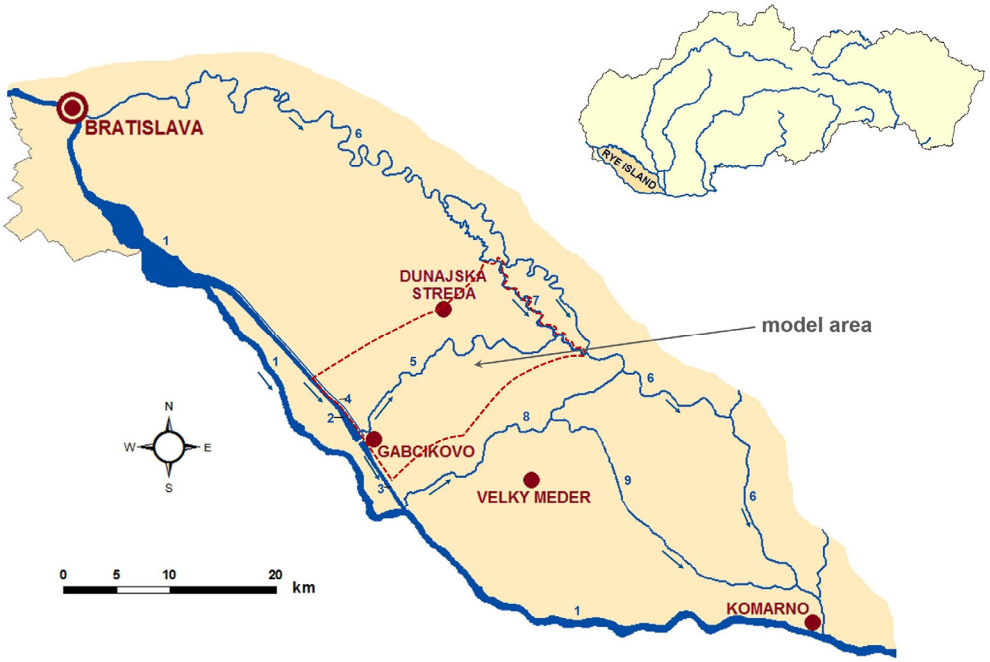

Fig. 1. Map of the Rye Island with the main canals: 1– Danube; 2, 3, 4 – parts of the Gabčíkovo power plant system: 2 – head race canal, 3 – tail race canal, 4 – seepage canal; 5 – Gabčíkovo – Topoľníky canal; 6 – Small Danube, 7 – Klátovské branch of the Small Danube, 8 – Chotárny canal, 9 – Komárňanský canal.

From a global point of view, the climate of Slovakia is transitional between maritime and continental. However, climatic conditions have a great spatial variability and they might be considered as local. Therefore, climatic classifications were created to distinguish variety of climate regions and sub-regions based on chosen criteria. A very common and accepted conventional climatic classification in Slovakia was defined by Konček and Petrovič (1957), based on the evaluation of temperature, as well as humidity conditions (more detailed description is given in the Climate Atlas of Slovakia, 2015). According to this classification, the Rye Island belongs to the warm, very dry climatic sub-region, with mild winter. The mean annual air temperature in this area is above 10 °C; the mean annual potential evapotranspiration is 750 mm, and the mean annual actual evapotranspiration is more than 450 mm. The mean annual precipitation total is about 500 mm (Miklós et al., 2002) and the mean annual effective rainfall in this area is less than 50 mm (Švasta and Malík, 2006).

Rye Island is located in a lowland area with very plain surface, with an overall inclination from North-West to South-East. Its average slope is only about 2.5 10^{-4}. Due to the flat terrain, favourable climatic conditions and high-quality soils, Rye Island is one of the most productive agricultural areas of Slovakia.

To protect this important agricultural area from floods, a network of canals with a total length of almost 1000 km interconnecting the whole territory of the Rye Island was constructed in the 18th century, originally for draining the groundwater table from the fields. Later, the canal network was utilized for irrigation and increasing the groundwater table within dry periods. The flow rates in the canals are primarily regulated, depending on the season, weather conditions and the needs of agriculture.

The canals are undergoing intensive aggradation and sedimentation processes (Dulovičová et al., 2022). The aggradation of canals and thick sediment deposits can totally disconnect the communication between SW and GW. This can obstruct the function of the canals and their ability to drain the excessive GW from the aquifer, what may lead to flooding and damaging the surrounding agricultural areas.

The canal system built in this locality, with the given geographical and climatic conditions is particularly suitable for studying the silting and its influence on SW-GW interactions. A relatively dense monitoring network including precipitation, GW and SW level was established in the area regularly surveyed by the Slovak Hydrometeorological Institute. Several studies were dealing with various aspects of SW and GW in this area, such as the quality and quantity of water resources (Červeňanská et al., 2021; Kováčová, 2022; Schügerl, 2019; Schügerl et al., 2021); riverbed silting processes (Dulovičová, 2019); interaction of the canals with the aquifer (Baroková et al., 2017, 2020; Dušek and Velísková, 2017; Okhravi et al., 2022b) and more.

The study area was selected along the Gabčíkovo – Topoľníky canal (GT canal), which is situated in the middle part of the Rye Island and is one of the largest canals of the network (Figure 1). It flows across the Rye Island, connecting the seepage canal (SC) of the head race canal of the Danube River as part of the Gabčíkovo power plant system and the Klátovské branch of the Small Danube (Figure 1). Its length is 28.7 km, the average canal width is 14 m, ranging from 11 m to 17 m. There are two water gauge stations on the canal: station Gabčíkovo at 25.7 km and station Topoľníky at 0.3 km. The topography along the GT canal vary from 108.4 to 121.5 m a.s.l., the terrain is declining towards the Small Danube River.

Three main subsidiary canals are connected to the GT canal: Vojka – Kračany (VK), Šulany – Jurová (SJ) and Baka – Gabčíkovo (BG) canal (Figure 2). These side canals can be closed from GT canal by water gates. There are several other smaller canals in the area, however most of them are inactive and dry, thus were not considered in this study.

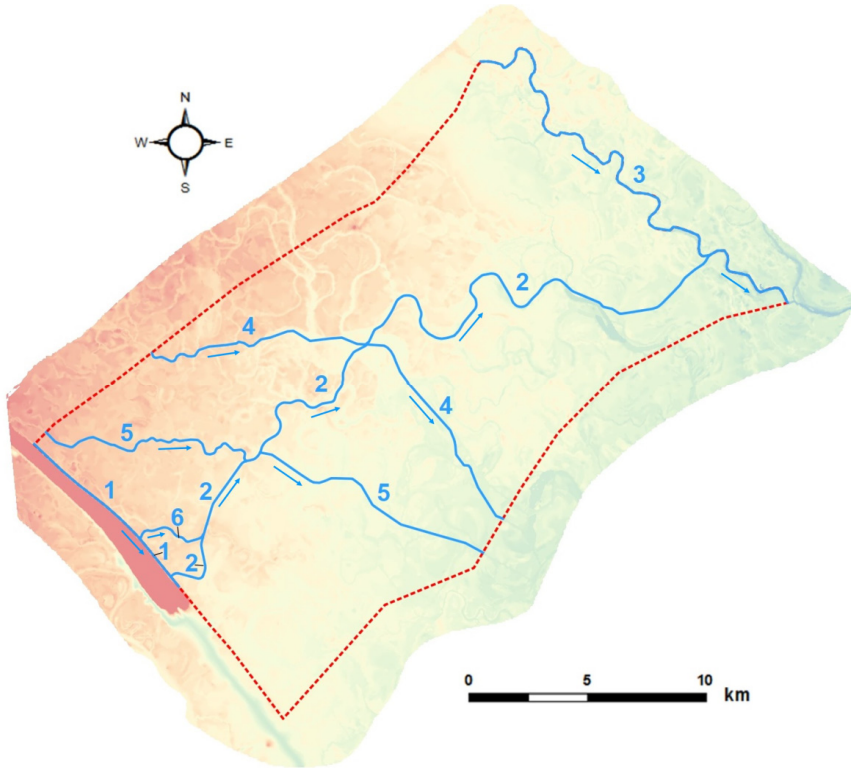

Fig. 2. Location of the canals in the study area: 1 – seepage canal of the Gabčíkovo power plant system; 2 – Gabčíkovo – Topoľníky canal (main canal); 3 – Klátovské branch of the Small Danube; side canals of GT canal: 4 – Vojka – Kračany canal; 5 – Šulany – Jurová canal; 6 – Baka – Gabčíkovo canal.

In general, the GW recharge comes mainly from precipitation. Although the effective rainfall is relatively low in the area, the GW level is rather high: around 112 m a.s.l., i.e. approx. 2 m under terrain. The GW level and flow direction are influenced mainly by the Danube River, the Small Danube River and the canals. Besides, the hydraulics of water bodies at Rye Island is affected by the Gabčíkovo power plant system, built on the Danube River.

Determining the characteristics of the aquifer

Measuring the thickness of sediment deposits and sediment sampling

The riverbed sediments play an important role in SW infiltration and GW recharge and they significantly affect the amount and time of GW-SW exchange (Frei et al., 2009). Along the GT canal, the monitoring of riverbed aggradation and sediments thickness started in 1993. From 2008 up to the present, detailed field measurements were performed. Besides measuring the sediments thickness, sediments samples are periodically taken in selected cross-sections. From 2014, the sediment sampling is performed by the Beeker sampler (Royal Eijkelkamp), which allows to extract undisturbed samples. In this study, the results of field measurements from 2018 were used. At these series of measurements, the thickness of riverbed sediments was measured along the GT canal (28.7 km) at the distances one km apart. At each cross-section, the sediments thickness was measured by 1.0–2.0 m step along the canal width. The sampling was done from the water surface, from a boat. The differences between sediments top and channel bottom levels were measured by a set of parallel rods with a scale. One of the rods has a disk, which settles on the sediments top, the other one is peak-edged and goes through the sediments layer until it reaches the canal bottom. The sediments thickness can be read from the scale, i.e. it is the difference between the two rods (one settles on the sediments top, the other goes through the sediments layer and stops at the bottom). The sampling person should know where the sediments end and where the bottom starts by experience. Undisturbed riverbed sediment samples were taken at 8 selected cross-sections according to the sediments thickness. The sediment sampling was conducted using the Beeker Sampler, which collects undisturbed samples of sediments in a 1 m long acrylic tube (Beeker Sampler Manual, 2005). From each whole sample there was extracted a part from the top, middle and bottom layer of the sediment and thus 24 samples of sediments were obtained.

Hydraulic conductivity of the canal sediments

The sediment samples were processed and the saturated hydraulic conductivity of the bed sediments was determined by the laboratory falling head permeability test. The description of the methodology is given by Šurda et al. (2013).

The saturated hydraulic conductivity K was calculated by:

$$K = \frac{l}{\Delta t} \ln \frac{h_2}{h_1} \qquad [\text{cm s}^{-1}], \tag{1}$$

where K is the saturated hydraulic conductivity of undisturbed samples [cm s^{-1}]; l is the height of sediment sample [cm]; h_1 [cm] is the initial static head at t_1 [s]; h_2 [cm] is the final static head at t_2 [s]; Δh is the head difference [cm] by the time $\Delta t = t_2 – t_1$ [s].

From the known values of hydraulic conductivity and layer thickness it is possible to calculate the river resistance parameters and to estimate the infiltration time of water through the layer of sediments.

Calculating the infiltration and drainage resistance of the canals

In this study, the infiltration resistance CI of canal bed sediments was calculated as:

$$CI = \frac{d_S}{K_{CI}} \qquad [\text{day}], \tag{2}$$

and the drainage resistance CD of canal bed sediments was calculated as:

$$CD = \frac{d_S}{K_{CD}} \qquad [\text{day}], \tag{3}$$

where d_S [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.

The effect of different infiltration and drainage resistance of canal bed sediments on the groundwater regime in the area of interest was simulated by the TRIWACO 4.0 model.

Modelling of SW-GW interaction with the TRIWACO model

Brief description of the TRIWACO model

For modelling the influence of canal sediment deposits on the groundwater regime in the study area, the TRIWACO 4.0 model (Royal Haskoning, 2004; Velstra et al., 2014) was chosen.

The model was built for solving GW flow and solute transport in horizontal plane, and it allows simulating water flow in several hydrogeological layers – aquifers. One of the distinct advantages of TRIWACO is its modular structure and flexibility. It offers an integrated modelling environment for unsaturated, saturated, drainage/infiltration and surface water flow.

The GW flow simulation in TRIWACO is solved by partial differential equations, which follow from Darcy's law and the equation of continuity, and the Finite Element formulation of these equations. Based on the Dupuit-Forchheimer assumption, the equation for steady-state groundwater flow can be written as (Royal Haskoning, 2004):

$$\frac{\partial}{\partial x}\left[T_{xx}\frac{\partial h}{\partial x} + T_{xy}\frac{\partial h}{\partial y}\right] + \frac{\partial}{\partial y}\left[T_{yx}\frac{\partial h}{\partial x} + T_{yy}\frac{\partial h}{\partial y}\right] + q = 0, \tag{4}$$

where T_{xx}, T_{xy}, T_{yx}, T_{yy} are transmissivity tensors [m^2 s^{-1}]; q is specific discharge/recharge [m^3 m^{-2} s^{-1}] and h is GW head [m]. In TRIWACO q is divided into four distinctive components, depending on the origin of the water (Royal Haskoning, 2004): q_a – recharge from the top aquifer due to precipitation, infiltration etc.; q_l – leakage between the aquifers; q_r – recharge/discharge from rivers, canals and drains; q_s – recharge/discharge from sources or point sinks.

In this study, we focused on interaction processes through the canal bed, i.e. the recharge/discharge from the canals to the aquifer. The inflow or drainage rate at each canal node is calculated as follows (Royal Haskoning, 2004):

$$q_r = A_r \frac{(h_r - h)}{C_r}, \tag{5}$$

where q_r [m^3 s^{-1}] is infiltration or drainage rate from/to the canal; A_r [m^2] is the area belonging to the canal node; h [m a.s.l.] is GW head in the aquifer (calculated by the model); h_r [m a.s.l.] is the water level in the canal and C_r [day] is the infiltration resistance

($C_r = CI$) or drainage resistance ($C_r = CD$) of the canal. The river (canal) resistance in natural conditions usually has different values for infiltration ($h_r > h$) and for drainage ($h_r < h$). Model TRIWACO offers the possibility to define a different resistance for drainage and for infiltration (Royal Haskoning, 2004).

Brunner et al. (2009) described spatial and temporal aspects of the flow transition from connection to disconnection between SW and GW. They show that the state of connection between SW and GW is a critical variable in the dynamics of infiltration in a non-steady system. However, model TRIWACO is not able to simulate transitional stages between the two flow regimes, what may lead to errors in simulations (Brunner et al., 2010). We realize that model TRIWACO has some limitations, nevertheless, it was considered to be suitable for solving our task, i.e. modelling the influence of canal sediments on the GW regime in the study area. In addition, the model TRIWACO has already been successfully used for GW modelling in Slovakia by Shenga et al. (2018) and Baroková et al. (2020).

Setup of the conceptual model – definition of model boundaries and input data

The first step is to correctly define the boundaries of the model and the inner and outer boundary conditions.

The model boundary was set to follow the line of existing GW monitoring wells and surface watercourses in the area. By this way, the boundary conditions are defined by GW heads in monitoring wells on the boundary and by water surface elevation in the adjacent rivers. From North-East, the model boundary is created by the Klátovské branch of the Small Danube. On North-West and South-East, the boundary conditions are defined by GW heads in monitoring wells. The South-Western boundary is partially created by the seepage canal of the Gabčíkovo power plant system and partially given by GW heads (Figure 3). The model boundaries and the monitoring network of GW heads on the model boundary are shown in Figure 3. GW heads on model boundary and water surface elevation were primarily taken from the database of the Slovak Hydrometeorological Institute. The data were supplemented by own field measurements and from the operating plans of the canal system.

Beside boundary conditions, the conceptual model is defined by the input or initial data set. For the purposes of this study, the following data were required: parameters describing the climatic conditions, surface parameters, parameters describing hydrogeological conditions and surface water parameters with respect to the geometry and resistances of the drainage system. In the TRIWACO model, the initial parameter set can be extended by more parameters, either internal or user defined.

Climatic data were obtained from the database of the Slovak Hydrometeorological Institute and maps (Climate Atlas of Slovakia, 2015). The geometry of the canals was obtained by the Institute of Hydrology SAS field measurements, from maps and photographs. The infiltration and drainage resistance of the canal bed sediments was calculated by Eqs. (2) and (3), using data from field measurements, where the hydraulic conductivity was evaluated/derived from canal sediments samples.

In the model, one homogenous aquifer with steady-state GW flow was considered. Generally, the geological structure is mostly heterogeneous, however at smaller scale, where one geological material (without much variability in physical characteristics) dominates, some regions can be considered homogenous. From hydrogeological point of view, the aquifer of the Rye Island is mostly built by thick sediment deposits of the Danube River – the "Danubian gravels" (more than 100m in the study area); thus, the geological structure can be considered homogenous (Malík et al., 2007). The water-bearing layer is created dominantly by gravels and sands of pleistocen-holocen with intergranular permeability. The coefficient of transmissivity in the study area is high, about 3 10^{-3} m^2 s^{-1} (Hydrogeological map of the Rye Island, 2005).

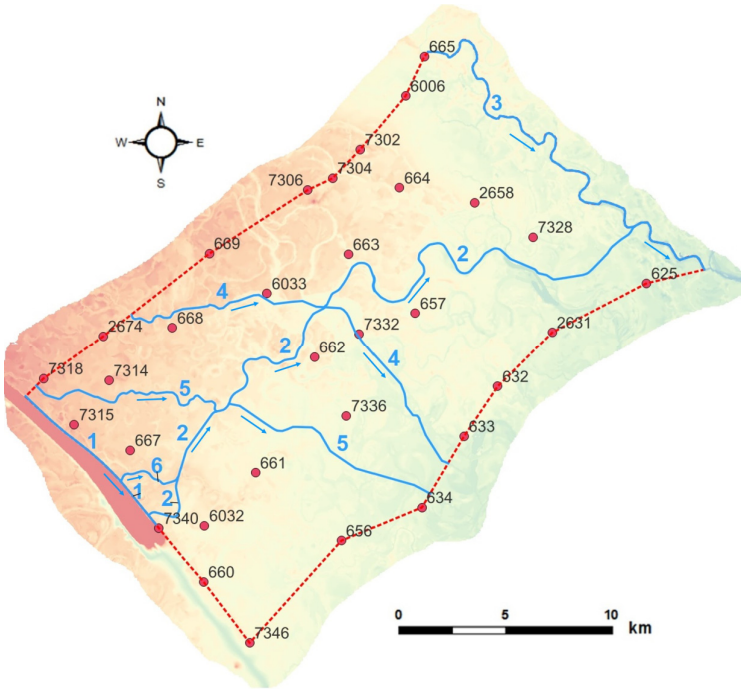

Fig. 3. Model boundary and the location of GW monitoring wells in the study area: 1 – seepage canal of the Gabčíkovo power plant system; 2 – Gabčíkovo – Topoľníky canal; 3 – Klátovské branch of the Small Danube, 4 – Vojka – Kračany canal; 5 – Šulany – Jurová canal; 6 – Baka – Gabčíkovo canal.

Calibration of the model

In the TRIWACO model, after a simulation has run, the calculated and measured GW heads are compared automatically. Measured data were available from 32 monitoring wells (Figure 3); the observed values were provided by the Slovak Hydrometeorological Institute. To achieve the best fit between the computed and observed GW heads the model parameters were adjusted manually after many trials. In the calibration process, the following model parameters were adjusted based on a-priori knowledge: boundary head in aquifer, infiltration and drainage resistance of canal sediments, canal widths, boundary conditions, precipitation excess, canal activity, transmissivity in aquifer, water levels in the canals.

Evaluation of the model performance

Groundwater head predictions in space (for all the wells at the same time) were evaluated using the determination coefficient (R^2). Additionally, a low-flow (August 2018) and a high-flow (December 2018) situation was visualized and analysed.

We used the determination coefficient (R^2), the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), the Percent bias (PBIAS) and the index of agreement (d) to evaluate the performance of the TRIWACO model in simulating GW head dynamics in different wells. These goodness-of-fit statistics were used to quantify the discrepancy between the observed and simulated discharge and sediment loads during calibration and validation periods as suggested by Moriasi et al. (2015) for dynamical hydrological simulations. Values of R^2, NSE, PBIAS and d were calculated from the observed and corresponding modelled data using an online calculator (AgriMetSoft, 2019).

The NSE is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information") (Nash and Sutcliffe, 1970). It ranges in the interval $(-\infty, 1.0\rangle$, with NSE = 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values < 0.0 show that the mean observed value is a better predictor than the simulated value, which indicates unacceptable model performance.

PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta et al., 1999). The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Gupta et al., 1999).

The index of agreement, d, proposed by Willmott (1981) is a standardized measure of the degree of model prediction error which varies between 0 and 1. It represents the ratio of the mean square error and the potential error. The agreement value of 1 indicates a perfect match, and 0 indicates no agreement at all. The index of agreement can detect additive and proportional differences in the observed and simulated means and variances; however, d is overly sensitive to extreme values due to the squared differences.

Model scenarios

First, the model was tested by modelling the influence of the canals on the GW regime. Simulations considering only the main canal GT and afterwards including the side canals were performed to verify the model applicability. The GW heads were calculated for three different options:

- Scenario A: considering no hydraulic connection between the canal and the aquifer, i.e. if there were no irrigation/ drainage canals in the model area;
- Scenario B: considering only the main canal GT;
- Scenario C: including the side (secondary) canals in the simulations, which are subsidiary to canal GT (Fig. 2).

Afterwards the influence of canal network silting and the sediments layer thickness on the surrounding GW in the study area was modelled. Different scenarios of canal silting were considered, and the resistance parameters *CD* and *CI* of the sediments layer were calculated for four different sediment thicknesses. The following sediment layer thicknesses d_S were used in the model scenarios:

- Scenario D: no sediment deposits, d_S = 0 m; *CI*, *CD* = 0 day;
- Scenario E: sediment layer thickness d_S = 0.1 m; *CI* = 1.16 day; *CD* = 0.73 day;
- Scenario F: sediment layer thickness d_S = 1 m; *CI* = 11.6 days; *CD* = 7.3 days;
- Scenario G: sediment layer thickness d_S = 2 m; *CI* = 23.2 days; *CD* = 14.6 days.

RESULTS AND DISCUSSION

To discuss and compare our study with other works is possible only in certain partial aspects. Results of simulation models of GW levels regime in the area are absent. In addition, relevant recommendations on the use of drainage and infiltration parameters of bed sediments as input for numerical simulations in the study area were not found in the available literature.

Canal aggradation and the characteristics of bed sediments

The sediments thickness along canal GT varies from 0.09 to 0.74 m, with an average of 0.43 m. The distribution of the sediments along the canal is rather variable, but generally the sediment deposits are thicker in the middle part of the canal. At the beginning and the end of the canal there are almost no silt deposits. For illustration, the deposition of canal bed sediments in 19 km is shown on Figure 4.

The canal sediment deposits composition was mainly fine-grained material: loamy sands, clay and organic material. The samples were processed and the saturated hydraulic conductivity of the bed sediments was determined. The calculated min, max and average values of saturated hydraulic conductivity *K* [m day^{-1}] of bed sediments in the GT canal are listed in Table 1.

Table 1. Minimum, maximum and average values of saturated hydraulic conductivity *K* [m day^{-1}] of bed sediments in the Gabčíkovo – Topoľníky canal.

K [m day^{-1}]	Top layer	Bottom layer
min	0.005	0.010
max	0.397	0.300
average	0.086	0.137

According to the classification of Antal and Igaz (2012), the saturated hydraulic conductivity *K* of the samples is low (values of *K* between 10^0 and 10^{-1} m day^{-1}) and very low (values of *K* between 10^{-2} and 10^{-3} m day^{-1}). The range of *K* values in the top layer is wider than in the bottom level. The average saturated hydraulic conductivity of bed sediments in the top layer is lower than in the bottom layer. This corresponds with the finding that according to the granulometric analysis the sediments in the top layer are more fine-grained (particles size vary from 0.001 to 0.05 mm) than in the bottom layer (particles size vary from 0.001 to 1.0 mm).

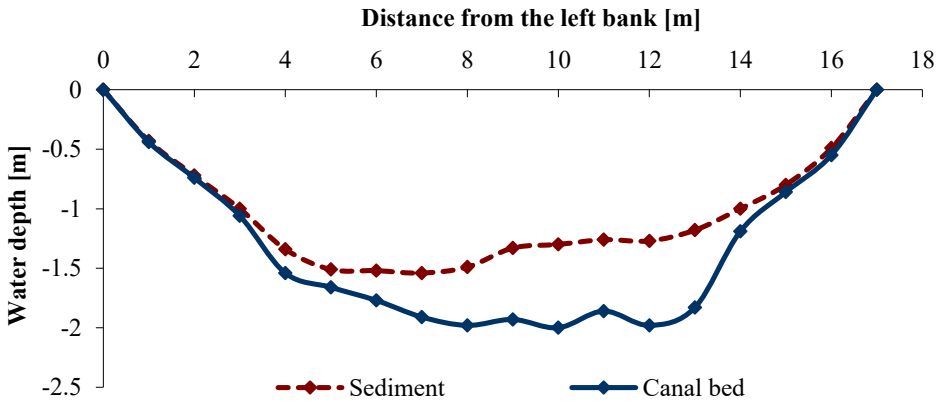

Fig. 4. Cross section and the sediment thickness in Gabčíkovo – Topoľníky canal, km 19.

Consequently, the resistance parameters of the canals were determined. The resistance of bed sediments is a variable that controls the duration of SW-GW exchange, and defines the travel time of water flow between the canal and the aquifer in days. The infiltration resistance is the resistance of bed sediments to water flow when the water is infiltrating from the canal to the aquifer; the drainage resistance is the resistance of bed sediments to water flow when the water is draining from the aquifer to the canal. In the study area, the average value of drainage resistance (*CD*) is 3 days and of infiltration resistance (*CI*) is 5 days. Generally, the values of *CI* are approximately 1.5-times higher than the values of *CD* in the analysed samples. Higher values of infiltration resistance are caused by little particles in the canal water, which are clogging the upper layer of sediments. Due to the combination of clogging and a sediments layer, the infiltration resistance is higher than the drainage resistance. Similar relation between infiltration and drainage resistance was described by Phernambucq (2015). This finding also correlates with the results of Baroková and Šoltész (2011), who analysed the impact of *CI* and *CD* on the travel time in SW – GW interactions. The calculated values of *CI* and *CD* are shown in Table 2.

Model calibration

Goodness-of-fit statistics for statical (spatial) and dynamic model predictions are given in Table 3 and evaluated according to Moriasi et al. (2015). NSE, R^2 and PBIAS are sensitive to the discrepancies between the observed and modelled data in different ways, PBIAS being a measure of the differences between the totals, R^2 that of the dynamics, whilst NSE incorporates both, but shows sensitivity for extremes.

The computed and observed GW heads for selected time periods at each monitoring well are shown in Figures 5 and 6. Similar graphs can be displayed for different time steps throughout the simulation period.

Table 2. Drainage resistance (*CD*) and infiltration resistance (*CI*) [day] of bed sediments in the Gabčíkovo – Topoľníky canal.

Distance from the estuary of canal GT and Klátovské branch [km]	1	12	14	19	23	23.5	26	28	Average
CI [day]	0.35	5.93	4.42	3.49	8.02	5.81	6.63	3.14	5.00
CD [day]	0.22	3.72	2.77	2.19	5.04	–	4.16	1.97	3.00

Table 3. Goodness-of-fit statistics for the static and dynamic model evaluations.

GW head	Type of the analysis			
	spatial, static		dynamic	
Illustration	high-flow	low-flow	Well 633	Well 7336
	Fig. 5	Fig. 6	Fig. 7	Fig. 8

GW head	Temporal resolution				Evaluation criteria (Moriasi et al., 2015)		
	not relevant		daily		very good***	good**	satisfactory*
R^2	0.98***	0.84**	0.94***	0.88***	> 85	$0.75 \leq R^2 < 0.85$	$0.60 \leq R^2 < 0.75$
NSE	not relevant		0.92***	0.69*	> 0.80	$0.70 \leq NSE < 0.80$	$0.50 \leq NSE < 0.70$
d	not relevant		0.98***	0.89**	> 0.90	$0.85 \leq d < 0.90$	$0.75 \leq d < 0.85$
PBIAS (%)	not relevant		–3.0***	+8.2**	> 5 %	$5 \leq PBIAS < 10$	$10 \leq PBIAS < 15$

R^2 = coefficient of determination, NSE = Nash-Sutcliffe efficiency/coefficient, d = index of agreement, PBIAS = percent bias/deviation

The TRIWACO model showed very good to fit between the observed and modelled GW heads. The model performed better for the high-flow conditions, R^2 being 0.98 for the high-flow case compared to 0.84 for the low-flow case, indicating very good and good model calibration results (Table 3), respectively. The values of R^2 were between 0.98–0.76 for all the cases, which means that significant amount of variance is explained and a good fit was achieved.

For visual illustration, computed and observed GW head (m a.s.l.) dynamics are shown in Figures 7 and 8 for selected monitoring wells. The model performed better for well number 633, showing a very slight underestimation of the GW heads mostly for the low-flow periods (Figure 7). Contrarily, for well number 7336 the GW heads were overestimated especially for the low-flow cases (Figure 8).

For dynamical evaluation (Figures 7 and 8), all the statistics showed very good or good calibration results except that of NSE for well 7336 (Table 3), which showed satisfactory simulation. As explained before, NSE is sensitive to dynamics and extremes, and incorporates the model weaknesses in an integrated way. Further studies would be needed to discover the reasons of very good (well 633) and good/satisfactory (well 7336) model performances within the study area.

Generally, the statistical evaluation of the TRIWACO model performance indicated that the model was successfully adapted to the study area and the obtained parameter set could be used for scenario analyses.

RESULTS OF MODEL SCENARIOS

The results of simulations for Scenario A, B and C are shown in Figs. 9, 10 and 11, respectively. The error in the water balance for the simulations was maximum 2%, what indicates that the conceptual model is good. In TRIWACO, the water balances show how well the conceptual model is and thus the model itself is. According to the TRIWACO User's Manual, for a good model the error in the water balance should be as small as possible.

It was shown that the groundwater flow direction and levels are similar for all the three simulated options, however the distribution is different. These results are confirming the canals influence on the groundwater regime in the region. Generally, the GW flow direction in the area is West-East, with groundwater level gradually decreasing following the topography, i.e. from the Danube River to the Small Danube River. Maximum levels are on the West (115.6 m a.s.l.) and minimum levels are on the East (109.2 m a.s.l.). These results correlate with the hydrogeological maps and other studies done in the region (e.g. https://apl.geology.sk/gibges/).

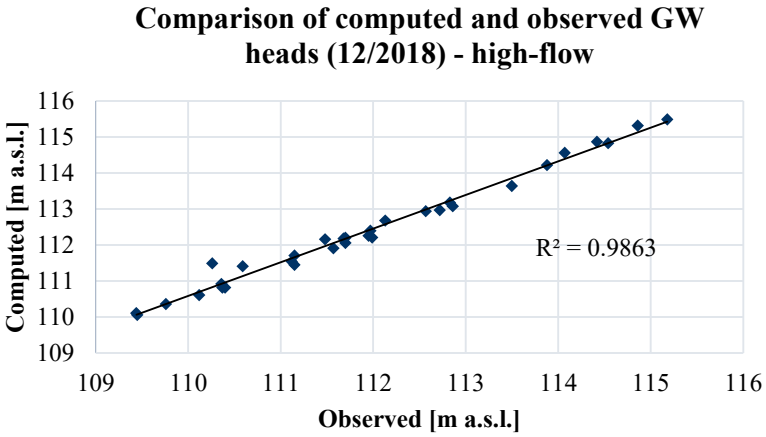

Fig. 5. Comparison of computed and observed GW heads [m a.s.l.] in high-flow conditions (12/2018) at each monitoring well.

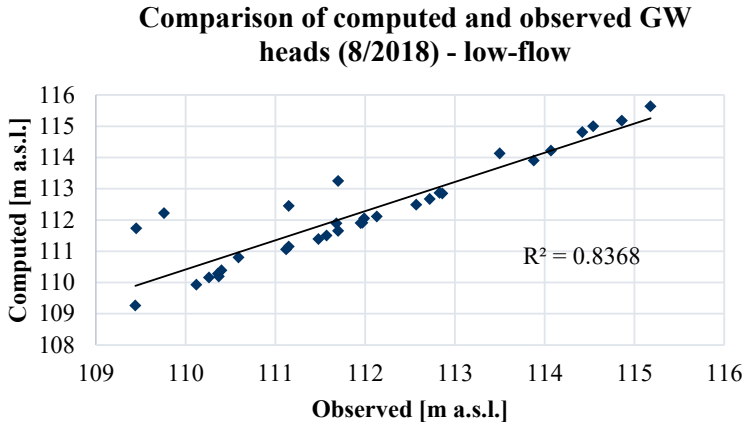

Fig. 6. Comparison of computed and observed GW heads [m a.s.l.] in low-flow conditions (8/2018) at each monitoring well.

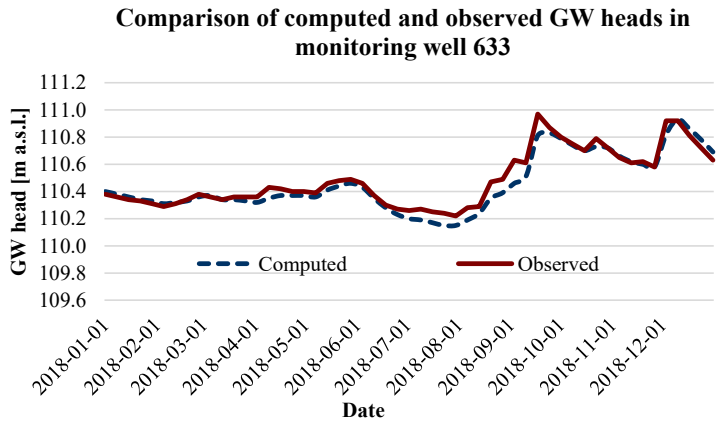

Fig. 7. The course of computed and observed GW heads [m a.s.l.] in monitoring well number 633.

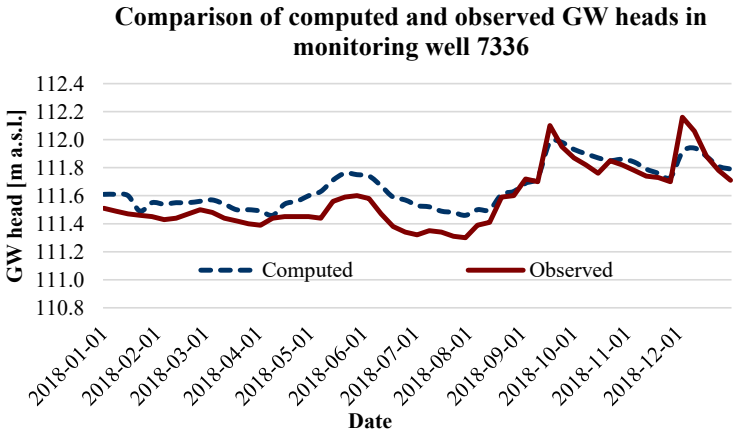

Fig. 8. The course of computed and observed GW heads [m a.s.l.] in monitoring well number 7336.

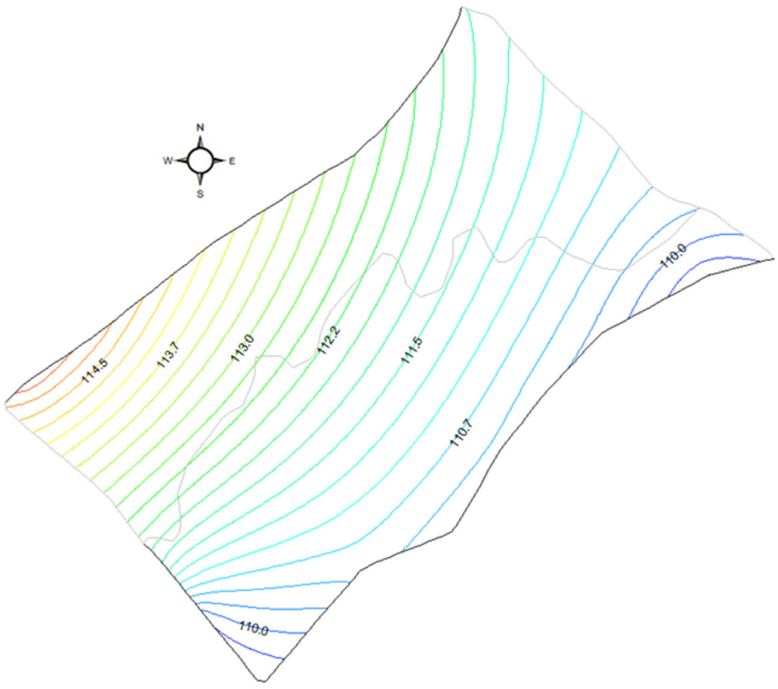

Fig. 9. Contour map of GW heads [m a.s.l.] for Scenario A - no hydraulic connection between the canal and the aquifer.

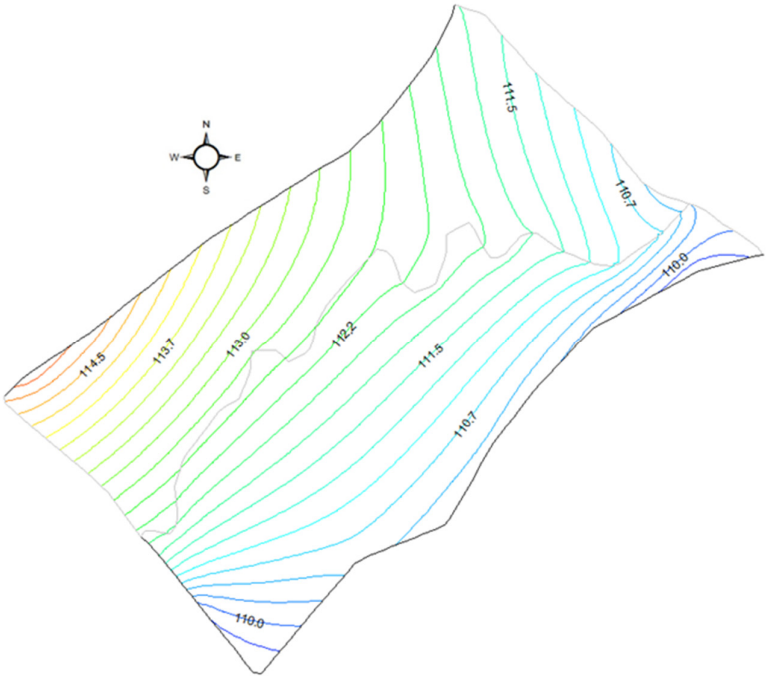

Fig. 10. Contour map of GW heads [m a.s.l.] for Scenario B - considering only Gabčíkovo – Topoľníky canal.

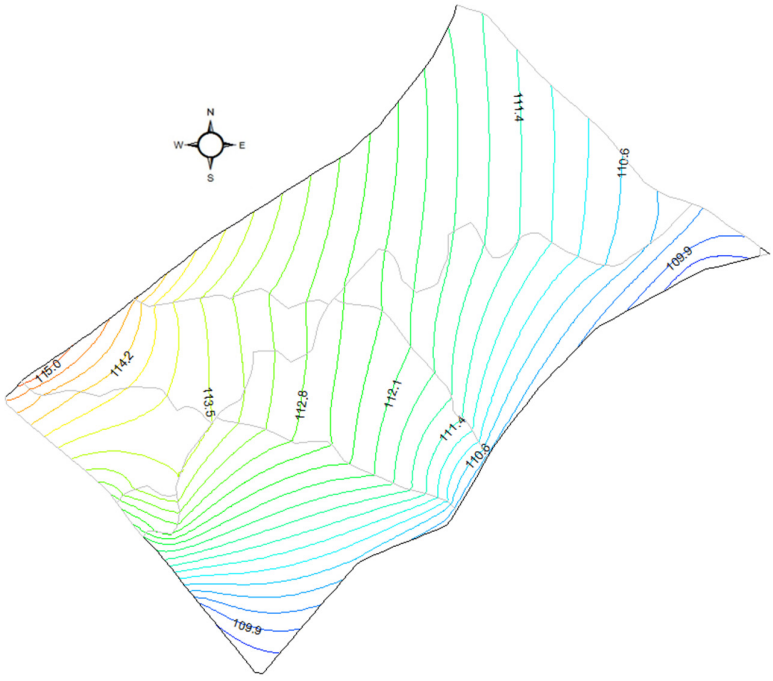

Fig. 11. Contour map of GW heads [m a.s.l.] for Scenario C - including the main and the side canals.

The contour maps of GW heads for different sediment layer thicknesses according to scenarios D-G are shown on Figures 12–15. The sediments change the GW flow direction only locally, near the canals. The modelled scenarios changed not only the values of GW heads, but also their spatial distribution in the modelled area in general. From the simulation outputs it is clear, that the canals have bigger influence on the GW flow direction when there are no or just thin layers of sediment deposits (Figure 12 and 13). In this case the GW flow direction is more affected by the water level and flow conditions in the canals. It was shown, that in the study area even 0.1 m of sediments layer affects the drainage and infiltration resistance parameters, and thus the interaction processes between GW and SW. The thicker the sediments layer, the less effect the canal has on the GW flow direction (Figures 14 and 15). Thick sediment deposits can almost entirely cut off the communication between the canals and the aquifer – the results are similar to simulations where no hydraulic connection between the canal and the aquifer was considered.

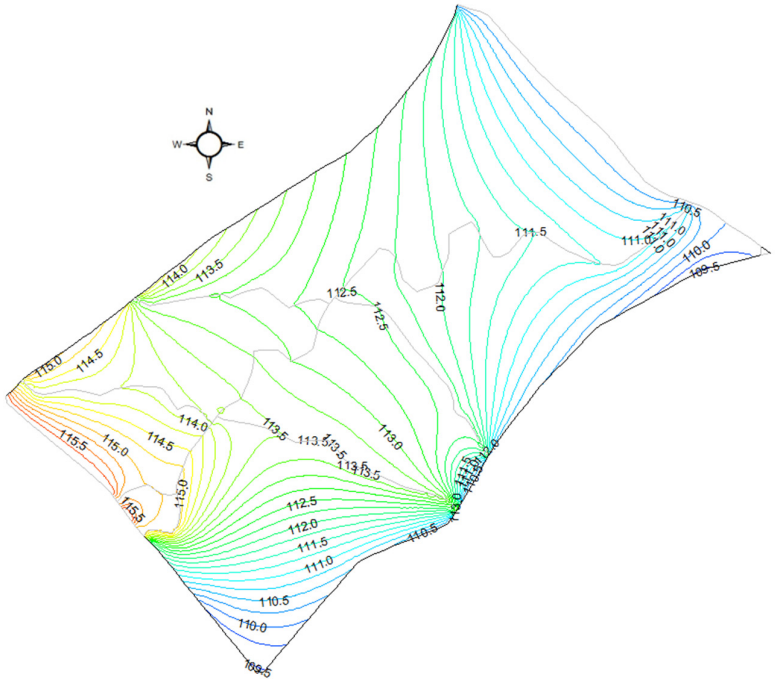

Fig. 12. Contour map of GW heads [m a.s.l.] for Scenario D - no sediment deposits; d_S = 0 m.

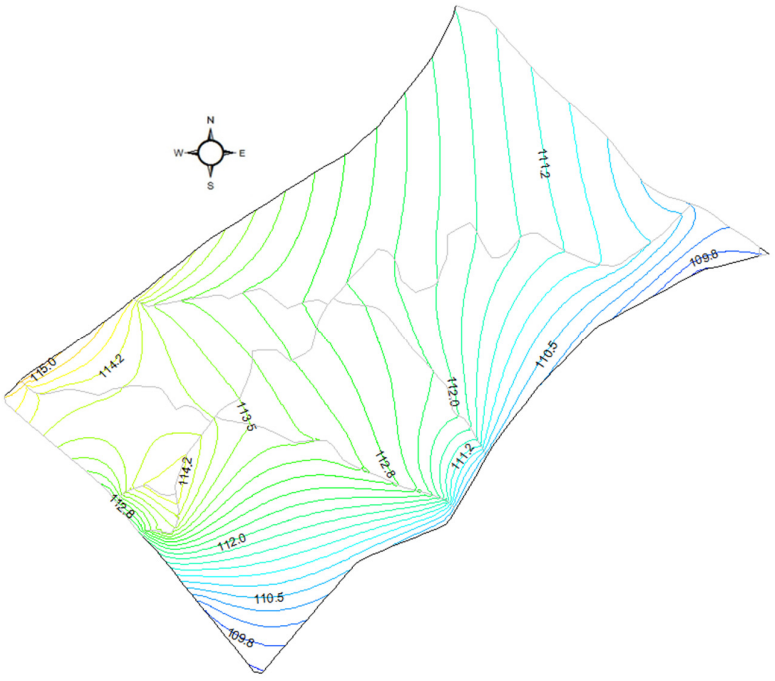

Fig. 13. Contour map of GW heads [m a.s.l.] for Scenario E - sediment layer thickness d_S = 0.1 m.

CONCLUSIONS

The aim of this study was to assess the bed silting of irrigation canals and its influence on the surrounding GW regime, and by this way enhance knowledge and allow better understanding of GW – SW water interaction processes in lowland areas. The TRIWACO model was used for the simulation of GW regime along the Gabčíkovo-Topoľníky canal at the Rye Island (Žitný Ostrov) in Slovakia. The bed sediments thickness measurements along the canal were used as input data to the model. Besides that, values of hydraulic conductivity computed from undisturbed samples of bed sediments, drainage resistance, infiltration resistance and other field data were used to parametrize the TRIWACO model. According to four different goodness-of-fit statistics, the model was calibrated successfully against the GW heads observed in 32 wells. GW heads were simulated for four different sediment layer thicknesses and canal resistance conditions.

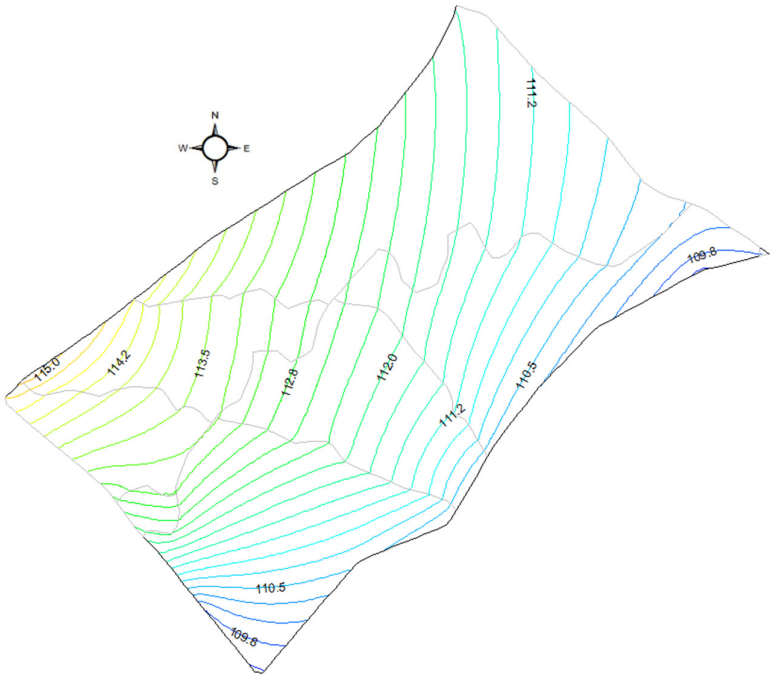

Fig. 14. Contour map of GW heads [m a.s.l.] for Scenario F - sediment layer thickness d_S =1 m.

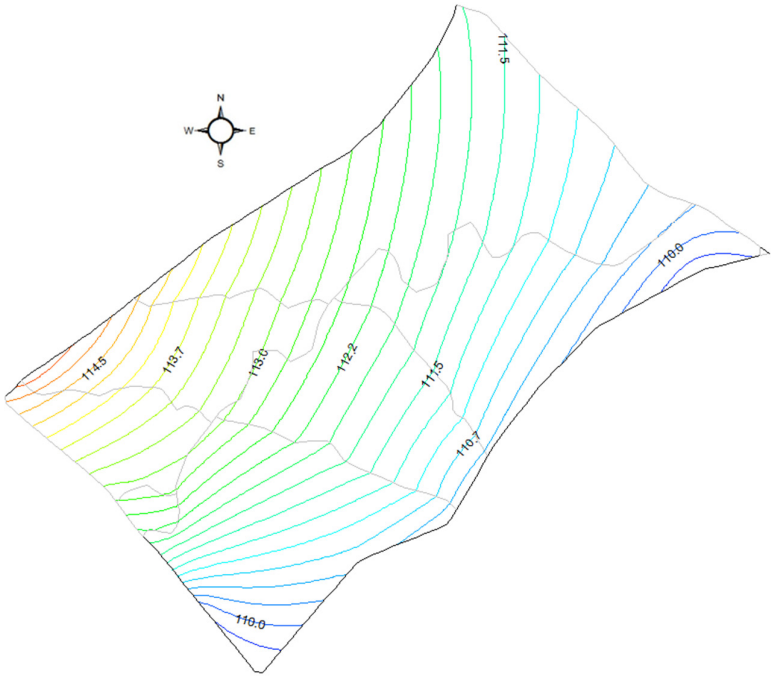

Fig. 15. Contour map of GW heads [m a.s.l.] for Scenario G – sediment layer thickness d_S = 2 m.

It was found out that the sediments distribution along the canals is rather variable, ranging from 0.09 to 0.74 m. The thickness is not increasing gradually, but thinner deposits are at the upper part (about 0.05–0.1 m) and at the lower part (0.1–0.2 m) of the canal. The numerical simulations confirmed the influence of sedimentation in the canals on GW – SW interaction. It was demonstrated, that even 0.1 m of sediments layer could significantly affect the infiltration and drainage resistance of the canals, extend the duration of GW – SW exchange and reduce the canals draining ability. Moreover, thicker sediment deposits (more than 0.5 m) would obstruct the canals function in a great extent, possibly even cut off the communication between the canals and the aquifer. The results for simulations with sediment deposits thicker than 1 m are similar to those where no hydraulic connection between the canals and the aquifer exists. Due to the geological structure of the Rye Island (mostly gravels with

high transmissivity/permeability) the bed sediments created by fine-grained material with low permeability have a high impact on the groundwater regime locally, however this impact is not significant in regional scale.

The model results suggest that the sediments should be regularly removed in the whole length of the canals. Despite the fact that canal maintenance and the removal of riverbed sediments is time-consuming and financially demanding, it is necessary to ensure the connection between the canals and aquifer and to guarantee the canals proper draining ability. Our results can support the planning of canal maintenance and the regulation of the canals operation.

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