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# Groundwater response to extreme flows in the Danube River

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The presented paper deals with the numerical modeling of groundwater response to the extreme hydrological situations in the Danube River. A 3-D numerical groundwater modeling is carried out using MODFLOW (McDonald and Harbaugh, 1998) and Groundwater Modeling System (AQUAVEO, 2021) simulation packages for available hydrological, geological, and hydro-geological parameters to study how the groundwater responded to the flood event in the Danube River that occurred in June 2013.

KEY WORDS: Danube River, groundwater head, groundwater-surface water interaction, GMS MODFLOW package

## Introduction

The Danube River is the main hydrological factor that controls the formation and hydrodynamics of groundwater along its course in Bratislava and downstream. There is a continuous dynamic interaction between the groundwater and the Danube River. The water level in the river is located above the groundwater table throughout the whole year, and it permanently replenishes the groundwater reservoir. After the construction of the Gabčíkovo hydropower plant, the effect of the backwater of the reservoir is extended upstream up to Bratislava, i.e., the water level in the Danube is increased so as the groundwater at the vicinity of the river (Mucha et al., 1999). In addition, the groundwater regime became more stable after the implementation of the structure (Jarabicová et al., 2014). The process of this interaction is mostly very complex to solve. The seepage between the river and the adjacent aquifer system occurs along their entire intersection and it depends on the river stage, hydraulic head in the groundwater system, and the riverbed conductance (Winter et al., 1998).

The presented paper deals with the numerical modeling of groundwater response to the extreme hydrological situations in the Danube River. A 3-D numerical groundwater modeling is carried out for saturated flow conditions using MODFLOW (McDonald and Harbaugh, 1998) and Groundwater Modeling System (GMS) (AQUAVEO, 2021) simulation packages for available hydrological, geological, and hydro-geological parameters to study how the groundwater responded to the flood event in the Danube River that occurred in June 2013. Since the portion of the subsurface above the water table is mainly composed of manmade ground, building constructions, and roads, saturated groundwater flow systems were considered for this specific work.

To calibrate the model parameters for both steady-state and transient flow including hydraulic conductivity and river conductance, observed groundwater heads in several boreholes of Slovak Hydrometeorological Institute (SHMI) were used (19 boreholes for steady state and 17 boreholes for transient flow). The results of the model are in good agreement with the observed data and therefore, the model can be used for studying and analyzing the changes and movements of the groundwater level in the aquifer in response to the extreme flow conditions in the Danube River. It could also be used as a base for further studies on pollutant movement from industrial and/or urban areas towards Rye Island along the Danube River. Specifically, the movements of pollutants from bombarded Apollo refinery could be the one that needs more attention as this region is currently accommodating construction of several high-rise buildings, where deep excavation takes place.

## Methodology

### *Mathematical background*

MODFLOW, which was developed by the United States Geological Survey (USGS), can be used to simulate both steady and transient flow systems in confined, unconfined, or a combination of a confined and unconfined aquifer. McDonald and Harbaugh (1998), who developed the MODFLOW program, used a finite difference version of Eq. (1) to describe three-dimensional incompressible groundwater flow in a heterogeneous and anisotropic medium, provided that the principal axes of the hydraulic conductivity are aligned with the coordinate directions.

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \qquad (1)$$

where

$K_{xx}$, $K_{yy}$, $K_{zz}$ – are values of hydraulic conductivity along the $x$, $y$ and $z$ coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity [L $T^{-1}$],

$h$ – is the potentiometric aquifer head [L],

$W$ – is a volumetric flux per unit volume and represents sources and/or sinks of water, $W<0.0$ for flow out of the groundwater system and $W>0.0$ for flow into the groundwater system [$T^{-1}$],

$S_s$ – is the specific storage of the porous medium [$L^{-1}$],

$t$ – is time [T].

The river conductance ($C$), which is a function of riverbed hydraulic conductivity and riverbed geometry, is calculated roughly based on Eq. 2. Below (Cousquer et al., 2017; Harbaugh, 2005). The concept of riverbed conductance was introduced in 1971 by Prickett and Lonnquist and it is well described in MODFLOW as a river package (Cousquer et al., 2017).

$$C=\frac{KLW}{M} \qquad (2)$$

where

C – is riverbed conductance [$L^2 T^{-1} L^{-1}$],

$K$ – is hydraulic conductivity of the riverbed material [L $T^{-1}$],

$L$ – is the length of the river reach within the grid cell [L],

$W$ – is the river width [L],

$M$ – is the riverbed thickness [L].

### *Study area*

The study region is a part of the Danubian Plain (Hreško et al., 2014) and it is located between the Danube River and the Little Carpathians. It includes different parts of Bratislava – bordered from the North by Little Carpathian, on Southwest by Danube River, on the Southeast by Little Danube, and on the Eastern side by Vajnory. The Danubian Plain is mainly known by a flat elevation which is created due to tectonic instability.

### *Hydrology and Meteorology*

The Danube River is the main hydrological factor that controls the hydrodynamics of groundwater in the major parts of the study area. There is a continuous dynamic interaction between the groundwater and the Danube River. Historic data about the water level of the Danube River at Bratislava gage is obtained from SHMI for the periods between 2002 and 2016. A minimum water level of 130.54 m a.s.l. was observed on 26.9.2004 at the Bratislava gauging station. However, a maximum water level of 138.65 m a.s.l. was observed on 6.6.2013. It is a historic record for the Bratislava gauging station. On the other hand, the average water level for the specified periods, 2002–2016, is 131.87 m a.s.l. as shown in Table 1 below.

On the other hand, mean annual precipitation of 720 mm is estimated by SHMI at Bratislava-Koliba and 580 mm at Bratislava-Airport for 2 002–2016. More than 60%

**Table 1. The minimum, maximum, and average water stage in the Danube River for the hydrologic year between 2003 and 2017 at Bratislava gage**

| Hydrologic year | Minimum [m a.s.l.] | Maximum [m a.s.l.] | Average [m a.s.l.] |
|---|---|---|---|
| 2003 | 130.84 | 134.54 | 131.82 |
| 2004 | 130.93 | 133.87 | 131.72 |
| 2005 | 130.54 | 135.55 | 131.89 |
| 2006 | 130.68 | 136.63 | 132.01 |
| 2007 | 130.87 | 136.17 | 131.66 |
| 2008 | 131.08 | 134.08 | 131.91 |
| 2009 | 130.92 | 136.85 | 132.04 |
| 2010 | 131.18 | 136.70 | 131.98 |
| 2011 | 131.01 | 135.95 | 131.68 |
| 2012 | 130.77 | 134.61 | 131.89 |
| 2013 | 131.07 | 138.65 | 132.26 |
| 2014 | 131.07 | 134.90 | 131.79 |
| 2015 | 131.07 | 134.57 | 131.77 |
| 2016 | 130.82 | 135.04 | 131.91 |
| 2017 | 130.88 | 134.25 | 131.73 |

of the precipitation falls between April and September.

### Geology and Hydrogeology

From the geological point of view, the study region is generally classified under Danube Plain. The subsoil is formed from Paleozoic, Neogene, and Quaternary sediments. The topmost layer is predominantly covered by made ground, which is mainly created due to anthropogenic activities. It is then followed by quaternary sediments, which appear to be chaotically arranged, and their composition changes horizontally over a very short distance.

The thickness of gravel-shaped fluvial sediments in the area ranges from 8 to 18 m. This part of the aquifer has high hydraulic conductivity ($10^{-4}$ to $2x10^{-2}$ m $s^{-1}$). Based on data about groundwater head from SHMI, the water table is located from 3 to 8 m below the terrain. There is no significant fluctuation in the groundwater level throughout the year. The groundwater in the study area has a free surface, and it is connected directly to the surface water. A large amount of groundwater reservoir in the study area is found in Quaternary Sediment, which is located a few meters below the terrain.

There is a clear hydraulic connection between groundwater and the Danube River. The groundwater level increases or decreases based on the water level in the Danube River. However, a study conducted by (Mucha et al., 1999) indicated that the level of groundwater increased in the study region since Gabčíkovo's water work was put into operation. Water from the river always (throughout the year) infiltrates to the groundwater reservoir which is bound to the Quaternary Sediment. The groundwater heads in selected SHMI observation wells which are located along the Danube River (the locations of each well can be seen in Fig. 3) for the 2013 flood events are shown in Fig. 1 below.

### Conceptual Model

The GMS MODFLOW package, which is used to solve the finite-difference equation of groundwater flow, requires many spatial and non-spatial data inputs. Therefore, input data collection, creation, and analysis will be an important component in this study. Most of the spatial data will be created from terrain analysis of the Digital Elevation Model (DEM) which is processed using different approaches. Then the stream networks and hillslopes are created from terrain analysis of the processed DEM. Archive data about groundwater hydrology for the period of 2002 to 2019 is obtained from the Slovak Hydrometeorological Institute. Based on the request, the SHMI institute also provided precipitation data from Bratislava-airport and Bratislava-Koliba stations. Specifically, weekly precipitation data is obtained from 2002 to 2016 to estimate the effective recharge rate. The thickness and values of horizontal hydraulic conductivities of the aquifer were collected from archive data of State Geological Institute of Dionýz Štúr (SGIDŠ).

### Model setup and Boundary Conditions

Construction of groundwater model consists of series of steps and requires several input data. For setting up a quality numerical model, the first and the most

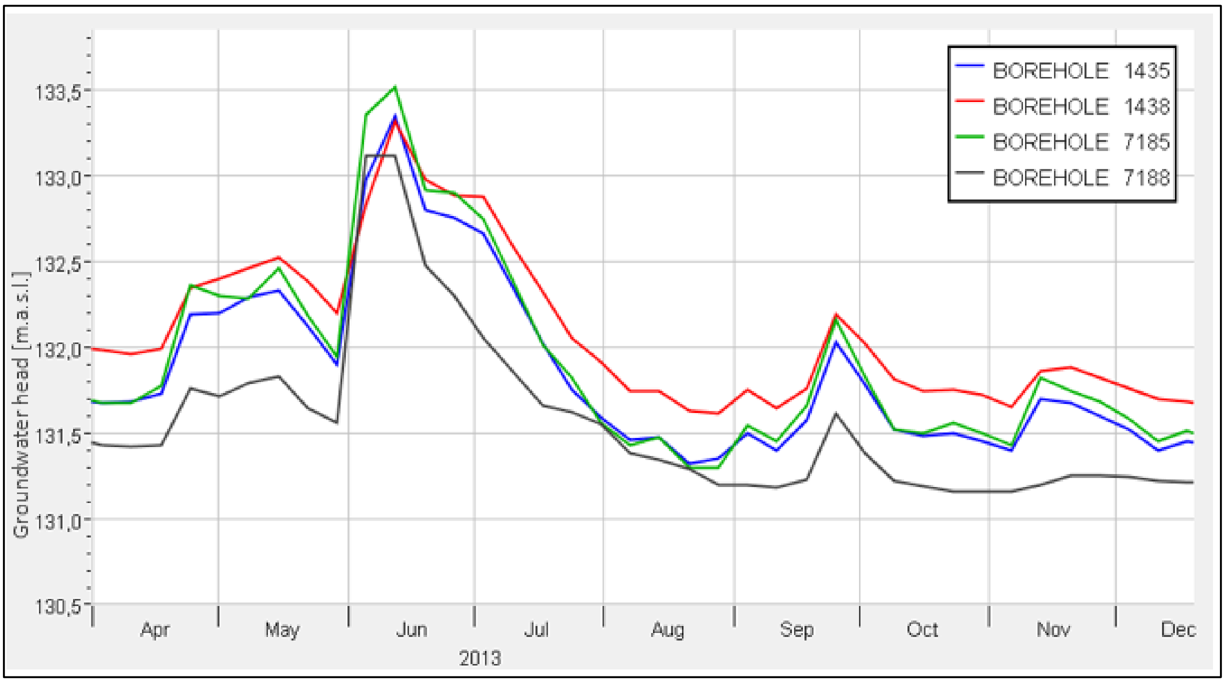

*Fig. 1. Groundwater head in selected SHMI observation wells for the 2013 flood events in m a.s.l.*

important step is developing a conceptual model that physically describes the natural groundwater water system. On the other hand, the mathematical model is used to describe the system using numerical procedures or mathematical algorithms.

The boundary of the model is created by considering surface water divides and the physical topography of the study area. The processed input data were used to create a conceptual model which is associated with calculation grids. Horizontally, finite-difference computation networks of 236 columns by 374 rows were discretized. Four model layers were created to divide the aquifer in the vertical direction.

The assigned boundary conditions for the steady state simulation include specified head for the Danube River on the western side, the artificial boundary condition of general head on the eastern side, general head in the Little Danube on the southern side, and flux to the boundary on the northern side of the boundary. As there is no significant change on the Danube River stage due to water exchange with the aquifer, the river is used as a specified head boundary. The specified heads at the nodes are determined by both interpolation and extrapolation of measured average stages (Devin and Bratislava stations) in the Danube River. There is no barrier to flow as the aquifer is directly connected to the river channel. The boundary condition along the Little Danube is assumed to be a general head that acts as an infinite sink for water to leave the boundary of the model. The flux to the boundary accounts for specified flow from Little Carpathian Mountain to the model area.

The transient simulations were carried out by considering the flood event in the Danube River at the Bratislava gauging station which occurred in June 2013. The water level in the Danube River was started to rise at the end of May and reached a peak level of 138.65 m a.s.l. with a culminated discharge of 10 641 $m^3 s^{-1}$ on June 6 (Pekárová et al., 2013). It was recognized as one of the historic records and the water level was above the 3rd level flood stage for a couple of days, see Fig. 2 below.

## Results

### *Steady state flow*

For study state flow, different input parameters were manually (trial-and-error method) calibrated to match the simulated and observed groundwater heads. Great attention is given to horizontal hydraulic conductivities, river conductance, and flux to the model. During calibration, the hydraulic head data of 16 SHMI observation wells were used. The horizontal hydraulic conductivities, which were obtained from SGIDŠ, were adjusted by trial-and-error method. The calibrated results were in the order of $10^1$ to $10^2$ m $day^{-1}$. Trial-and-error methods were chosen due to the fact that the hydraulic conductivities in the study area changes in a very short distance because of the complexity of the aquifer. Thus, it was difficult to use the common zonation method for automated parameter estimation. On the other hand, due to a lack of data about riverbed thickness and its hydraulic conductivity, the river conductance ($C$) was calculated roughly using Eq. 2. Then, the calculated riverbed conductance was adjusted by trial-and-error during the calibration process, as well.

In GMS MODFLOW, the quality of the calibration can be evaluated using some statistical indices like mean error, mean absolute error or mean root square error. The results after calibration show that there is good agreement between the simulated and observed groundwater head (±0.50 m), thus, the model can be used for further study as shown in Fig. 3 and Table 2 below.

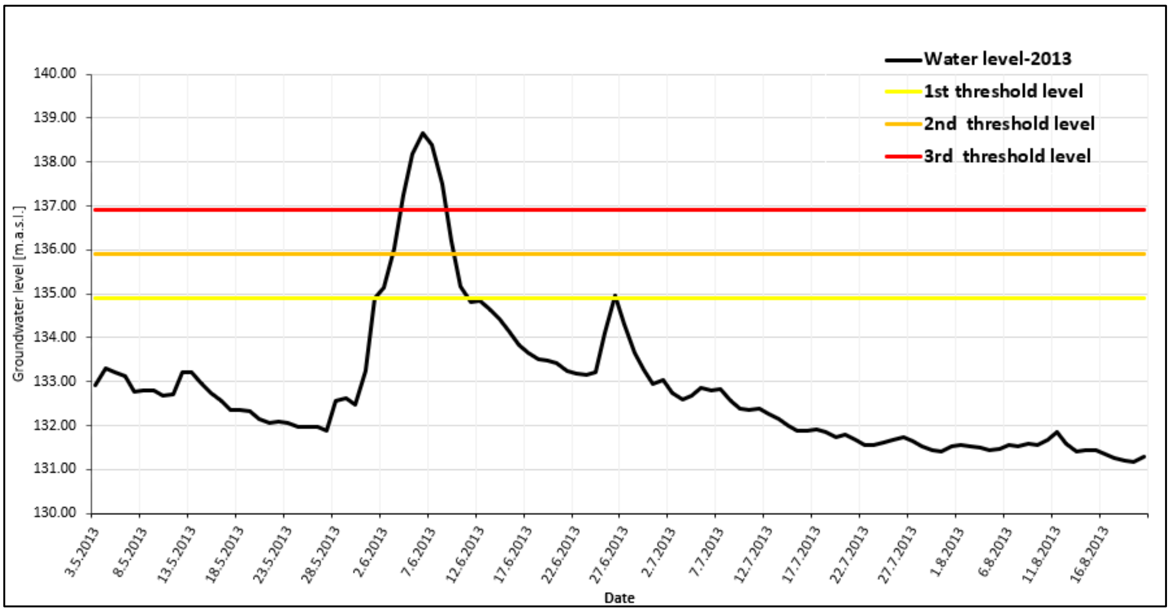

*Fig. 2. The water level in the Danube River at Bratislava gauging station during a flood event in 2013 and proposed flood threshold levels by SHMI.*

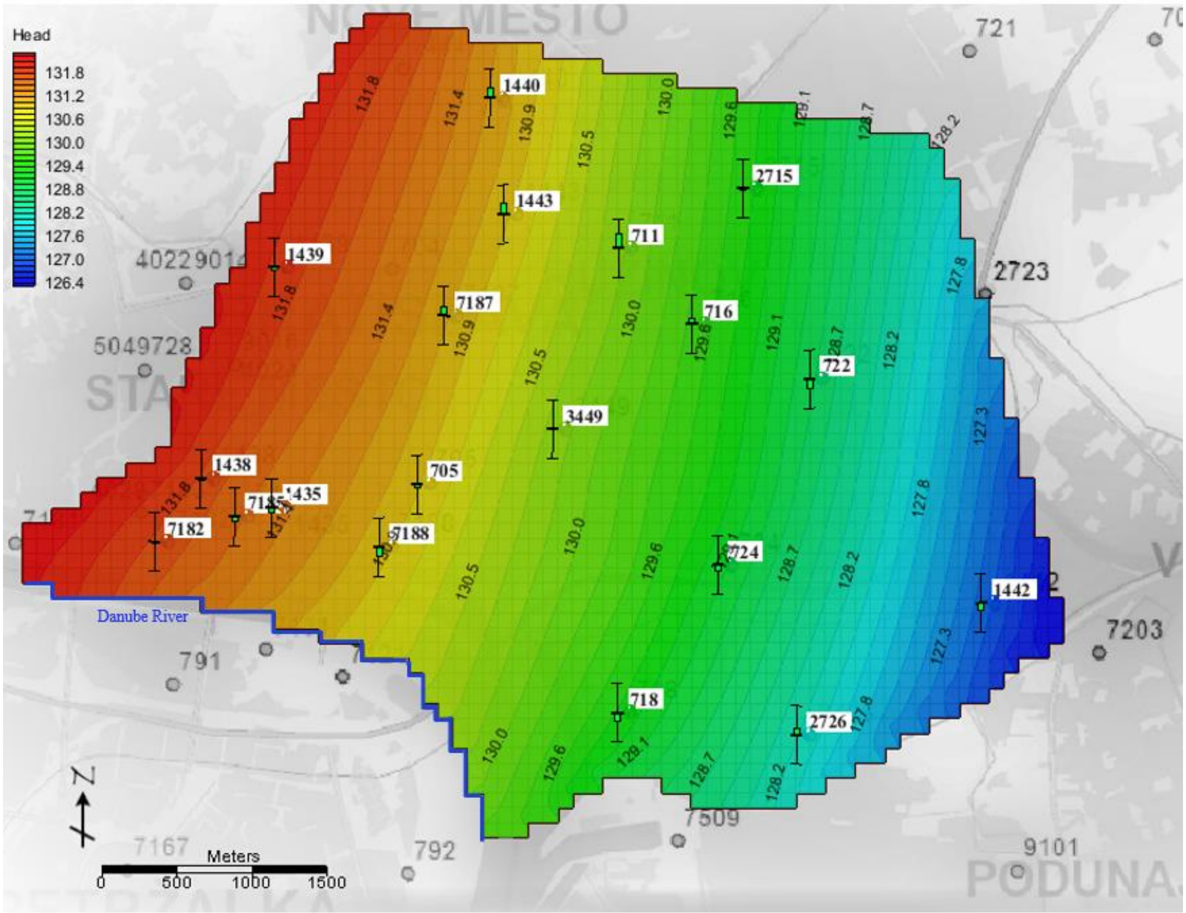

*Fig. 3. Simulation result that shows calibrated groundwater head as a contour map [m a.s.l.] and location of SHMI observation wells.*

**Table 2. Comparison between observed and calculated groundwater heads for the steady state flow condition**

| Borehole ID | Observed head [m.a.s.l.] | Simulated Head [m.a.s.l.] | Differences [m] |
|---|---|---|---|
| 705 | 130.95 | 130.86 | 0.10 |
| 711 | 129.62 | 130.11 | -0.49 |
| 716 | 129.41 | 129.59 | -0.18 |
| 718 | 129.61 | 129.31 | 0.30 |
| 722 | 129.07 | 128.75 | 0.32 |
| 724 | 129.30 | 129.09 | 0.21 |
| 1435 | 131.56 | 131.38 | 0.18 |
| 1438 | 131.77 | 131.72 | 0.05 |
| 1439 | 131.95 | 131.87 | 0.08 |
| 1440 | 130.74 | 131.11 | -0.37 |
| 1442 | 127.24 | 126.98 | 0.26 |
| 1443 | 130.50 | 130.86 | -0.36 |
| 2715 | 129.44 | 129.39 | 0.05 |
| 2726 | 127.92 | 128.13 | -0.21 |
| 3449 | 130.15 | 130.19 | -0.04 |
| 7182 | 131.80 | 131.73 | 0.07 |
| 7185 | 131.65 | 131.49 | 0.16 |
| 7187 | 130.69 | 131.01 | -0.32 |
| 7188 | 131.23 | 130.91 | 0.32 |

As it can be seen from Fig. 3 above and Table 2 below, the calibrated groundwater in the boreholes has shown a good match except borehole ID 711, where the difference between simulated and observed groundwater head was about -0.49 m. The negative sign indicates the computed groundwater head is greater than the observed groundwater head.

***Transient flow***

The transient simulation was carried out based on the hydrological situation in the Danube River. Specifically, the flood event which occurred in 2013 was the main period where detailed attention was given. The calibrated steady state, which was based on the average water level in the Danube River, was used as an initial condition or as starting head for the transient simulation. The transient calibration was carried out to adjust aquifer storage, specific yield, riverbed conductance, and hydraulic conductivities of the aquifers. The calibration was also carried out by the trial-and-error method. The calibrated values were as follows: specific yield = 0.22, specific storage = 0.00067 The increase in water level in the Danube River caused a significant change in groundwater level in the narrow adjacent area. However, the change in water level was insignificant (almost negligible) in the areas far from the banks of the river as shown in Fig. 4 and 5. This might indicate that there is a parallel flow of groundwater along the river during the transient state.

The simulation results also showed that the flow of the groundwater is towards the southwest of Slovakia, where Rye Island (Žitný Ostrov) is located. Rye Island, which is one of the biggest river islands in Europe, is located between the Danube, Little Danube, and Vah Rivers. The island is the biggest source of drinking water reservoirs and agricultural products in Slovakia (Michalko et al., 2015). The rise in the water table and groundwater flow towards this area could have positive and negative impacts. As a positive impact, groundwater around Rye Island could be recharged. As a negative impact, there might be movement of toxic contaminants from bombarded Appolo refinery, which is in Bratislava at the banks of the Danube River, along with groundwater flow during peak hydrological situations. This is because of the fact, that the groundwater in the region of Danubian Lowland is mainly recharged from the Danube River and the increase in the water level facilitates high movement of polluted groundwater. Additionally, the undergoing construction of several high-rise buildings around the bombarded Appolo refinery could disturb the accumulated refinery and facilitates pollutant movements along with the Danube River towards the Rye Islands.

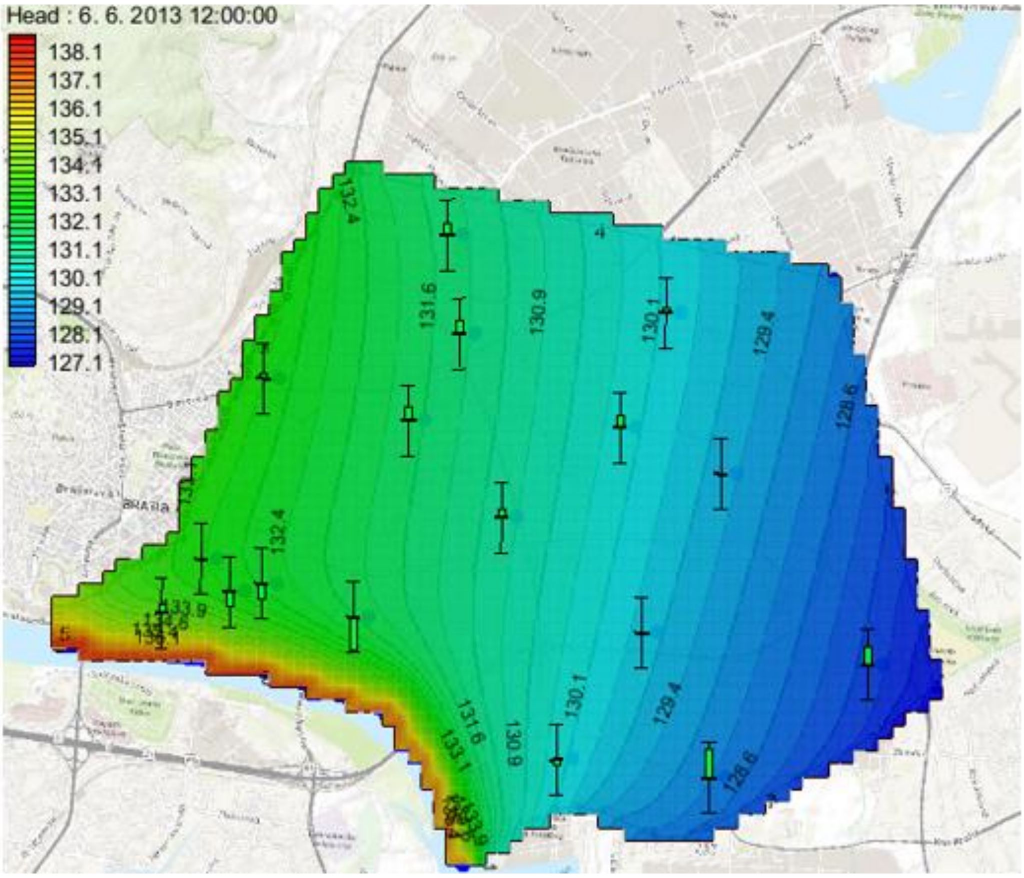

*Fig. 4. Course of simulated and observed groundwater head in borehole-7188, which is located close to Danube River, Appolo bridge (the weekly observed groundwater head is converted to daily observed head).*

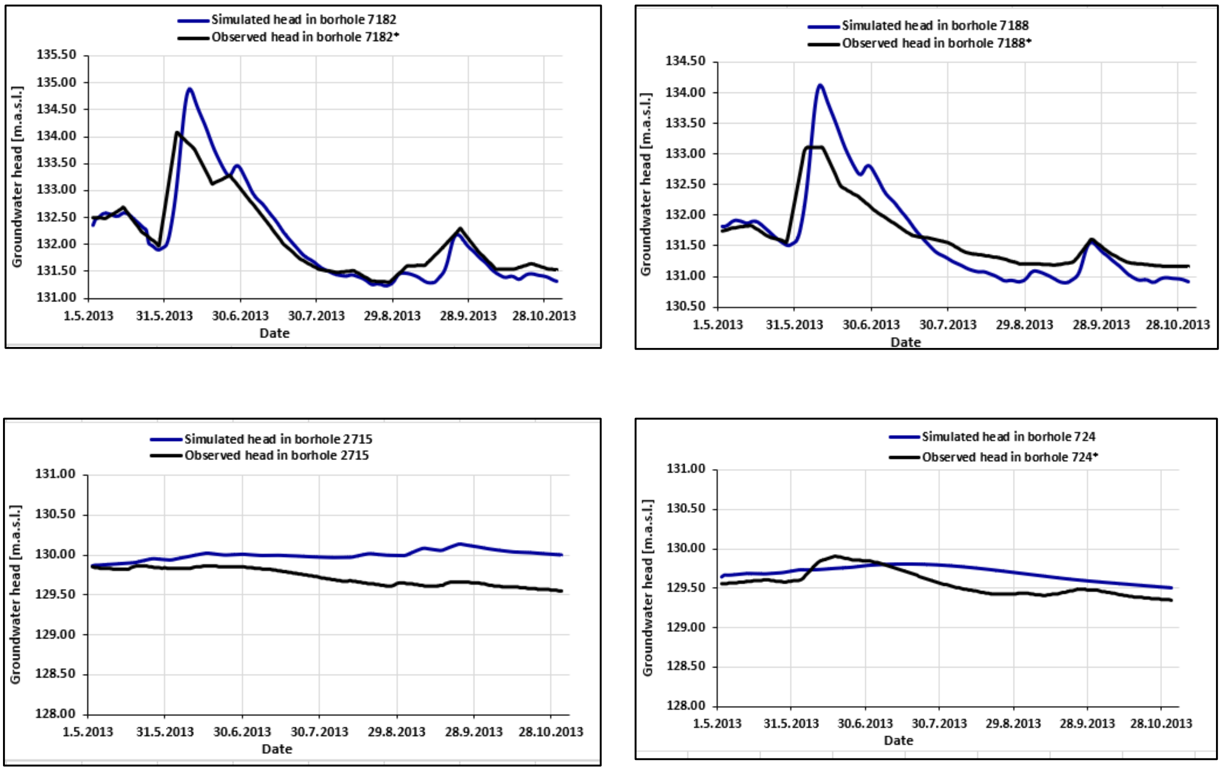

*Fig. 5. The course of simulated and observed groundwater head in selected boreholes (boreholes 7182 and 7188 are located very close to the Danube River and the others are relatively far). *Observed weekly data, which is obtained from SHMI is converted to daily data.*

## Conclusion

A 3-D groundwater flow was modeled to investigate the interaction between aquifer and river. The main analysis was focused on a transient flow for specific flood events that occurred in 2013. Even though most of the simulated transient heads matched the observed head in boreholes of SHMI during the flood events, certain lag time differences were observed in some of them (i.e., short lag time between observed and simulated peak heads). The obtained results could be used as relevant information for water resources planning and management. It could also be used as a base for further study on contaminant movement from Bratislava towards Rye Island along the Danube River. Specifically, the movements of pollutants from bombarded Apollo refinery could be the one that needs more attention as this region is currently accommodating construction of several high-rise buildings. Most of such construction requires deep excavation work (below groundwater level) and pumping of groundwater during and after construction. These activities may facilitate the movements of pollutants during peak flows in the adjacent river. Therefore, certain technical measures should be considered in this region to avoid or minimize movements of pollutants during flood events in the Danube River.

## Acknowledgments

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