ASSESSMENT OF THE IMPACT OF PROPOSED CUT-OFF WALLS ON GROUND-WATER LEVEL REGIME DURING EXTREME HYDROLOGICAL CONDITIONS

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The capacity of rivers Váh, Small Danube and the deviation of river Nitra, located in Slovakia, is sufficient in terms of transferring flood flow rates, however defects occur during long-lasting flood situations. If the problem is ignored, different processes may eventually endanger the adjacent territory or may lead to contamination of water and soil as a result of flooding a nearby sewage treatment plant. For these reasons an additional sealing of dykes was proposed. The article deals with the impacts of suspended cut-off walls on groundwater flow and level regime in a wider area for both steady and unsteady scenarios.

KEY WORDS: cut-off wall, numerical simulation, groundwater, flood, TRIWACO

Introduction

During long-lasting flood situations in Slovakia (e. g. in years 2006 and 2010) there were defects repeatedly seen on the downstream slopes of the flood protective dykes along rivers Váh, Small Danube and the deviation of river Nitra (Fig. 1, Fig. 2). These defects are mainly followed by leakage and seepage of water and waterlogging accompanied by leaching of fine-grained particles from the subsoil of the protective dykes. Seepage through dyke bodies can significantly reduce the stability of the dykes. At the same time, there were signs of lifting of the cover layers with the risk of breaking. The geological composition of the area as well as the occurrence of these phenomena indicates that there should probably be some preferred routes through the dyke bodies and also in the subsoil. If the problem is ignored, different processes may eventually endanger the adjacent territory with residential houses, infrastructure and agricultural land. Other negative impact (Julínek et al. 2020) could be the contamination of water and soil as a result of flooding a nearby wastewater treatment plant (WTP) located in Zemné (Fig. 2). For these reasons an additional sealing of the dykes using suspended cut-off walls (CW) was proposed (Šoltész at al., 2017). Cut-off walls, built from the top of the dykes, will eliminate the risk of suffosion and minimize the risk of breakage of the cover layers caused by buoyancy. These protective measures extend the leakage path and thereby greatly reduce the hydraulic gradient and, accordingly, leaching quantities (Krempa, et al., 2016; Hnidiak et al., 2016; Chládek and Kováčiková, 2016).

Before the application of proposed measures, it is necessary to verify the functionality of such a solution using the method of mathematical modelling. That is why the numerical simulation of the groundwater flow and groundwater level regime at a relatively steady state (steady flow model) as well as during flood event (transient flow model created for the flood wave based on Q_{100}) was elaborated (Grambličková et al., 2017). It also includes the impacts of the suspended cut-off walls on the groundwater flow and level regime in a wider area. The numerical model of the area of interest was created using Triwaco-Flairs software (Velstra, et al., 2014) simulating the groundwater flow using finite element method.

Material and methods

Creation of a numerical model requires knowledge of the area of interest. Therefore, it was necessary to conduct a field survey before the modelling process itself. It is also needed for subjective decision making during the phase of modelling. During the data preparation phase, all available data, information or background materials on geomorphology, geology, hydrogeology, hydrology as well as anthropogenic activity were collected, processed and evaluated. These data served to determine the parameters of the filtration area such as the hydraulic conductivity, storage coefficient, porosity and thickness of aquifers, aquifer interface, effective precipitation, etc. Based on collected data, it was possible to determine boundary conditions needed for steady and also initial conditions for unsteady flow simulations.

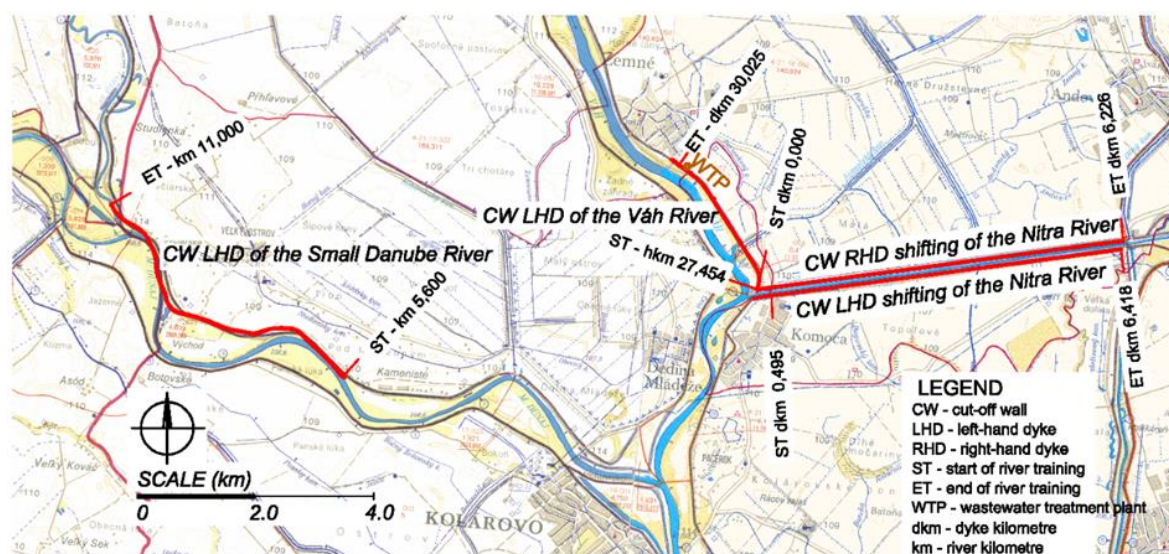*Fig. 1.   The location of the area of interest (source: mapy.atlas.sk).*

Fig. 2.   The situation of proposed cut-off walls (background: Water management map, 2003).

Description of the area of interest

The area of the proposed activity is a plane with a slope of less than 1°. The average altitude in the wider area is around 107–115 m a. s. l. (Miklos, 2002).

The geological structure of the area has led to the formation of two hydrogeological units – a neogene and a quaternary. Neogene sediments (neogene clay) arepractically impermeable (Pristaš et al., 1992).

There are two genetic types of quaternary sediments – fluvial represented by gravel, sandy gravel or sand with a thickness about 10–30 m (rarely 70–80 m) and eolian represented by silt and fine sands with a thickness about 2–6 m. Fluvial sediments form the first aquifer with phreatic conditions that is in interaction with surface water. In some places, the groundwater level may be moderately stressed (Pristaš et al., 1992).

From a hydrogeological point of view, the area of interest

is influenced by the hydrogeological conditions of the Rye Island (the area between the rivers Danube, Small Danube and Váh) which is one of the most important areas, both in terms of quantity and quality of groundwater. The hydraulic conductivity of Quaternary sediments varies from $k_f=10^{-4}$ to 10^{-5} m.s^{-1} (Pristaš et al., 1992).

For the simulation of groundwater flow it was necessary to determine:

- the surface water level course in the rivers Váh, Small Danube and in the deviation of river Nitra (Fig. 3) using 4 gauging stations of the Slovak Hydrometeorological Institute (SHMI) [SHMI];
- the surface water level course in adjacent drainage channels (Fig. 4) using measurements at 3 pumping stations (PS) of the Slovak Water Management Enterprise, state enterprise (SWME, s. e.) (PS Komoča, PS Kolárovo and PS Kráľov Brod) [SWME]; all drainage channels can be seen in Fig. 7;
- the groundwater level regime (Fig. 5) [SHMI];
- and the total precipitation in the location (Fig. 5) [SHMI].

Data used for calibration of the model and also for the prediction were from hydrological years 2009–2013. The reason is the fact that years 2010 and 2013 were rich in rainfall and therefore extreme flood situations occurred. These extreme flood situations were also the reason for designing the cut-off walls.

Developing a conceptual model of the system

The purpose of building a conceptual model is to simplify the field problem and organize the associated field data so that the system can be analysed. Simplification is necessary because a complete reconstruction of the field system is not feasible (Anderson and Woessner, 2002). The first step in formulating the conceptual model is to define the area of interest, i.e. to identify boundaries of the model (Fig. 6).

Numerical models also require inner and outer boundary conditions. Correct selection of boundary conditions is a critical step in model design (Anderson and Woessner, 2002). Along the whole outer boundary the Dirichlet boundary condition was used using the measurements of the groundwater level in monitoring boreholes [SHMI]. To simulate water level course in rivers and drainage channels (Dušek and Velísková, 2017) within the interior of the grid, the internal boundary condition was inserted (Fig. 7). This step was based on data described above.

Calibration of the numerical model

The purpose of calibration is to establish that the model can reproduce field-measured heads and flows. During calibration, a set of values for aquifer parameters and stresses that approximates field-measured heads and flows, was found (Anderson and Woessner, 2002). Calibration was performed under steady-state conditions and
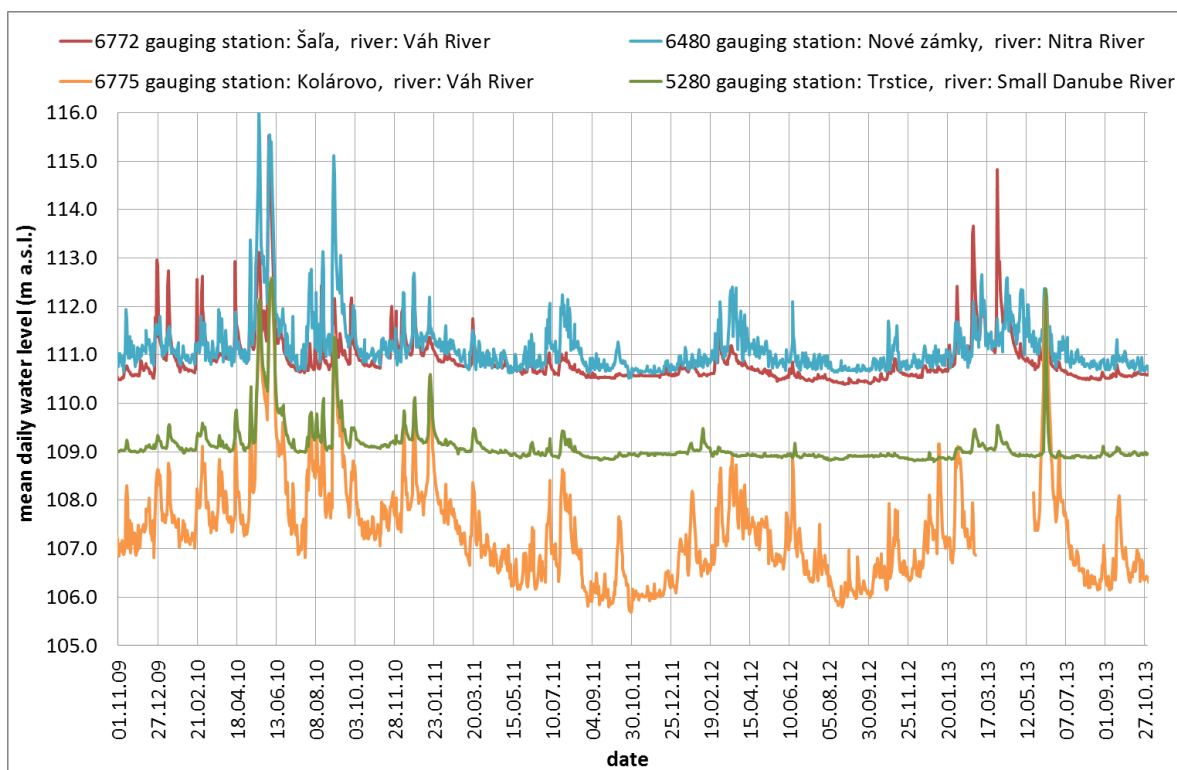

Fig. 3.   Water level course in gauging stations Šaľa, Kolárovo, Nové Zámky and Trstice [SHMI].
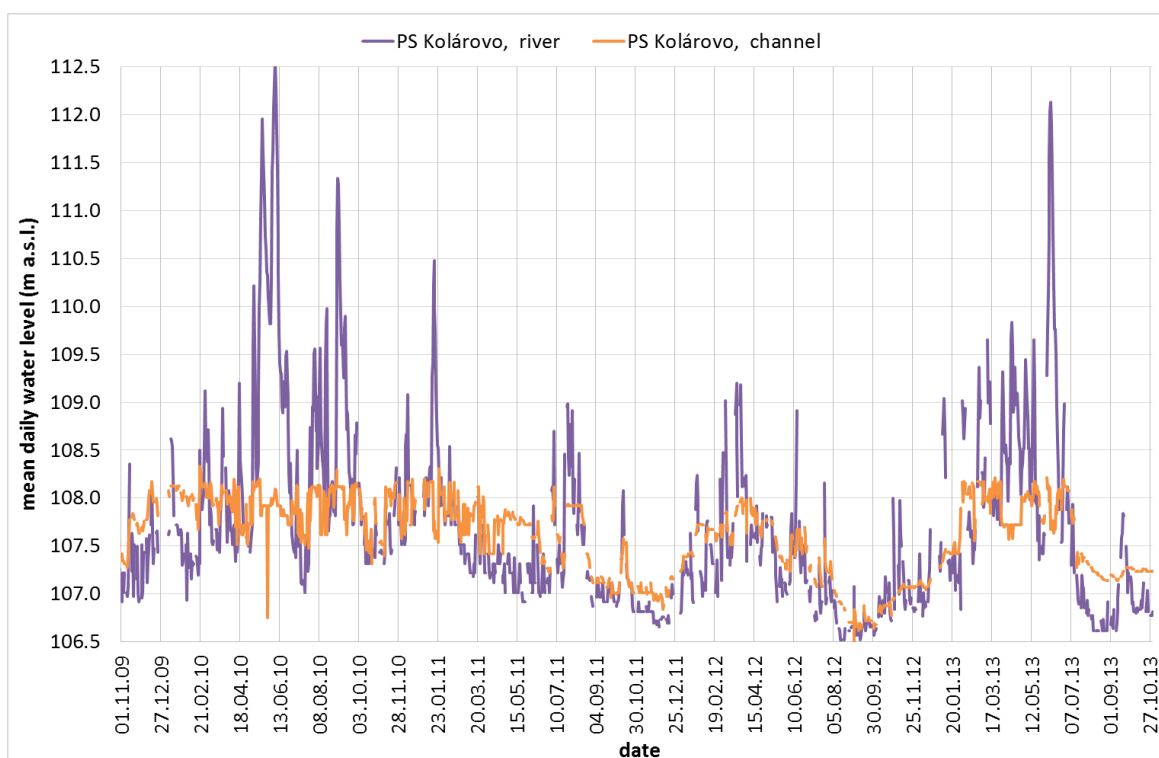
Fig. 4.   Water level course at the pumping station Kolárovo – channel and river [SWME].
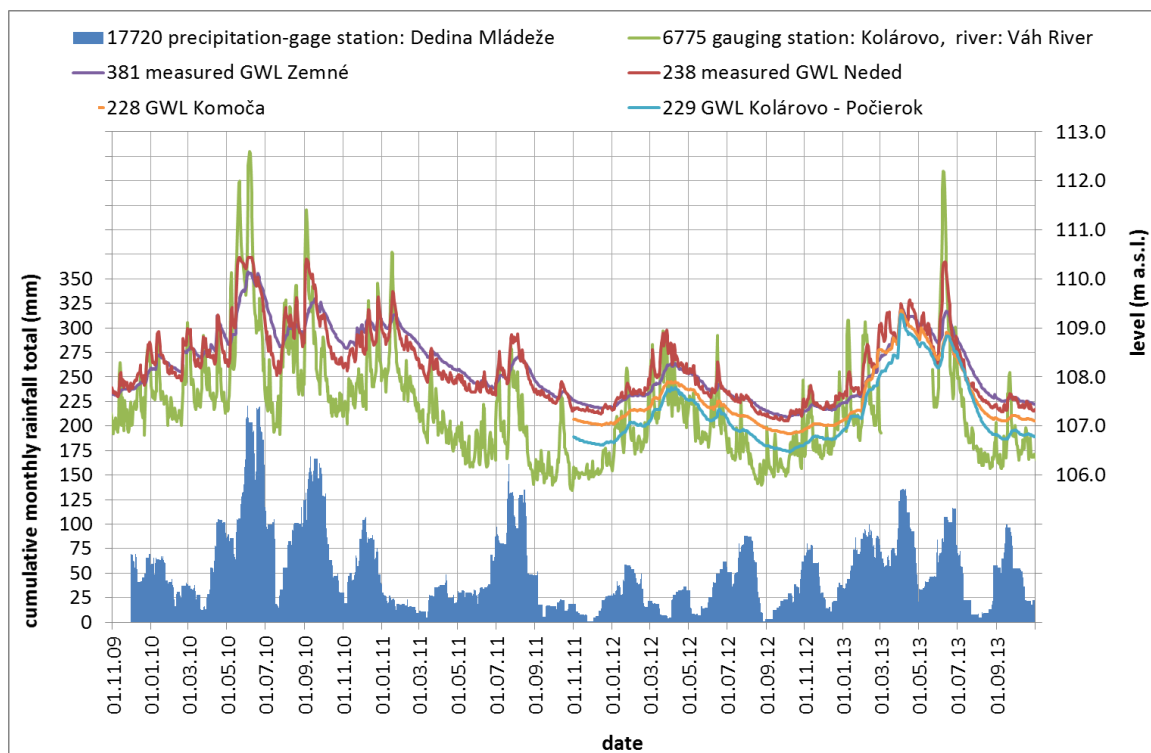
Fig. 5.   Groundwater levels in selected measuring stations (381, 238, 228, 229), water level course in gauging station Kolárovo and cumulative monthly rainfall total in precipitation-gage station Dedina Mládeže [SHMI].
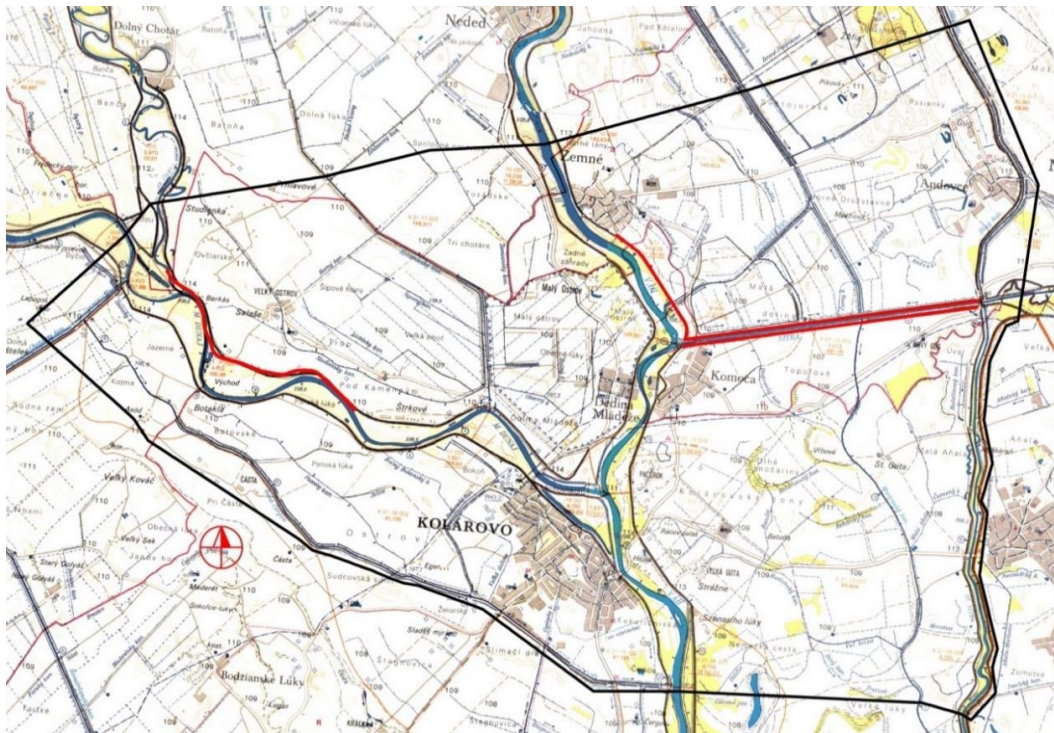
Fig. 6. The area of interest with the model boundary and proposed cut-off walls (legend: red – cut-off walls, blue – rivers and drainage channels, black – boundary of the model).

Fig. 7. Location of rivers and drainage channels. The inner boundary conditions – surface water elevation (m a. s. l.).

was done by trial-and-error adjustment of parameters such as hydraulic conductivity, storage coefficient, effective rainfalls and drainage and infiltration resistance (Dulovičová, 2013).

The calculated values of groundwater levels, respectively piezometric heads, were compared with existing field measurements in observation points (Fig. 8). Fig. 8 shows the differences between the simulated and measured piezometric heads in groundwater monitoring boreholes of SHMI. The value on the right is determined assuming zero effective rainfall, the value on the left assuming the average value of effective rainfall (Švasta

and Malík, 2006).

The effective rainfall is the part of precipitation totals, which is able to infiltrate into the soil. There are no strict and clear rules ensuring good calibration, except this one: the difference between the calculated and measured values considering the total piezometric head in observation points should be small. Assuming the groundwater levels fluctuation in monito-ring boreholes between 2 to 3 m, the results are sufficient for the prognosis of the development of piezometric heads after realization of underground sealing walls.

The results of simulation of the current state after calibration of the model taking into account effective rainfall can be seen in Figure 9.
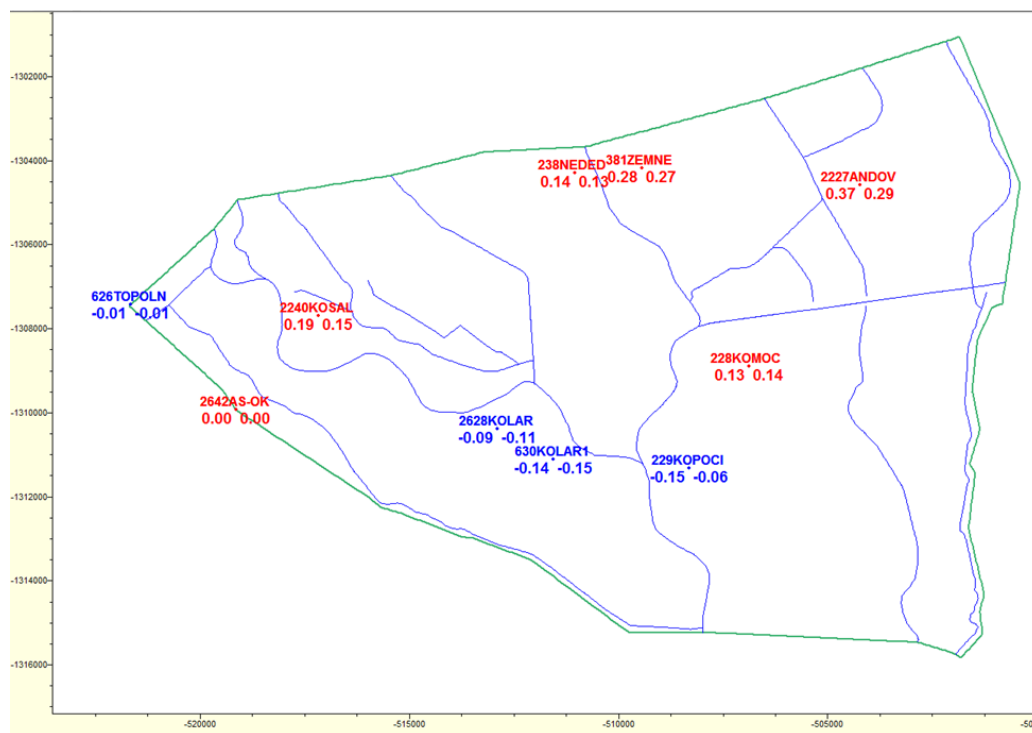

Fig. 8.   The differences between calculated and measured values of piezometric heads in observation points assuming zero effective rainfall (on the right) and also the average value of effective rainfall (on the left).
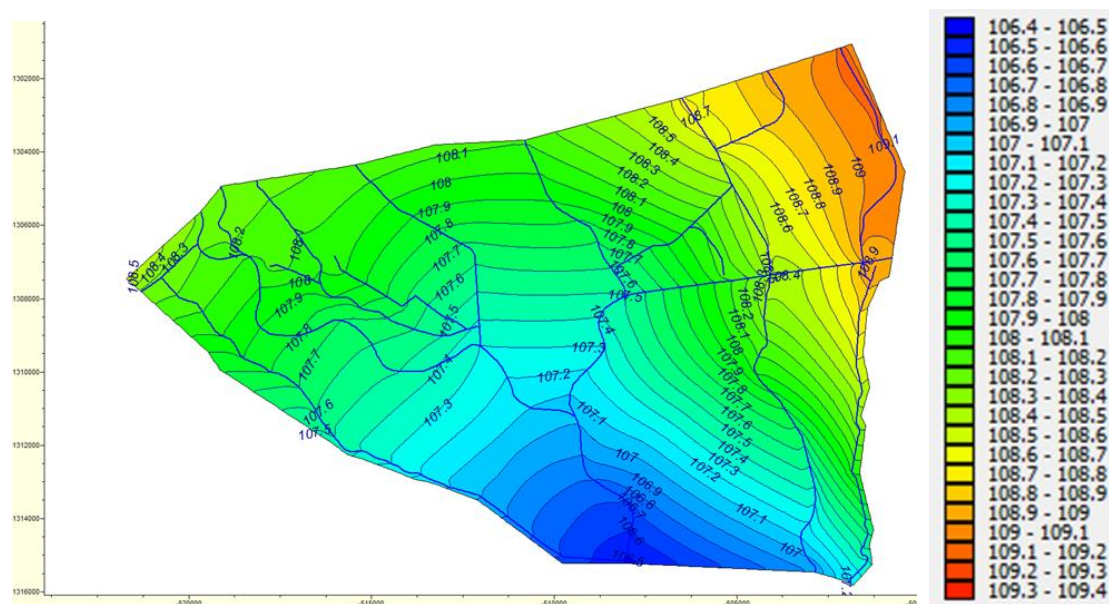

Fig. 9.   The contour map of the calculated piezometric head taking into account effective rainfall.

Results and discussion

Prediction using steady-state model

The aim of modelling is a simulation of the future events. However, if the prognosis serves for answering questions about changes due to anthropogenic interventions, i.e. to determine the effect of cut-off walls (CW) on the piezometric heads after realization of a wall embedded to a depth of 15 m from the dam crest, it is necessary to proceed to a modification of the model. The modification consists in the input of CW by a parameter expressing the permeability of the aquifer, i.e. by changing the values of the hydraulic conductivity, but only in certain parts of the aquifer.

For this purpose, it was necessary to divide the aquifer into two parts as shown in Fig. 10. The individual aquifers are separated by a fictitious semi-permeable layer. In the upper aquifer, it is then possible to enter the CW as a region of a very low permeability, i.e. as the area with hydraulic conductivity around 10^{-9} to 10^{-11} m s^{-1}. The lower part of the aquifer has the same properties as before.

The steady-state prognosis, created using the long-time mean values of hydrological conditions, shows that the situation after realization of CWs will not change in the future. In Fig. 11, you can see the vertical cross section of the model with the influence of the cut-off walls on the groundwater flow.

Predictions using unsteady-state model

The steady-state model is also an initial condition for the transient model simulation. In order to determine the impact of CWs on groundwater level regime, the most extreme three months from hydrological point of view, were selected for simulation. The 122-day period was characterized by high water level conditions in all rivers as well as by high precipitation. Such a situation occurred in the period from 1st April 2010 to 31st July 2010. For simulation of an unsteady flow it was necessary to specify time-dependent water level in rivers (Velísková et al, 2015).

This parameter was entered through a relative value, i.e. through a daily change in water levels (Fig. 12). This is a change considering the mean value of water levels
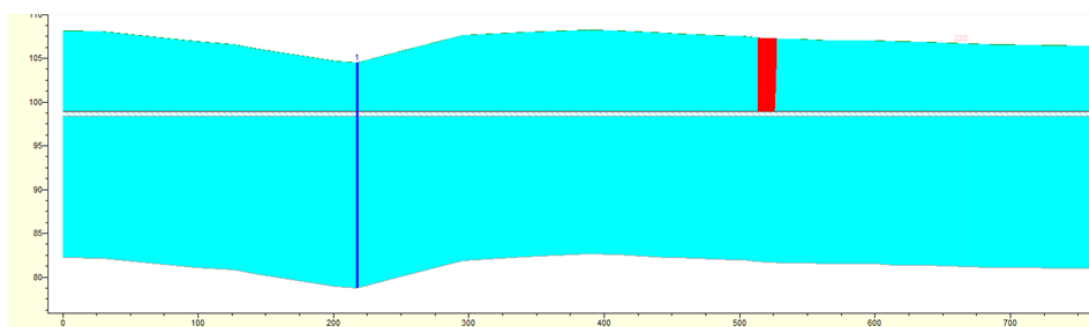

Fig. 10. *Division of the aquifer using fictitious semi-permeable layer (white). Section at km 29.400 of the left-hand side of the river Váh – (red) CW is embedded to a depth of 98.8 m a. s. l.*
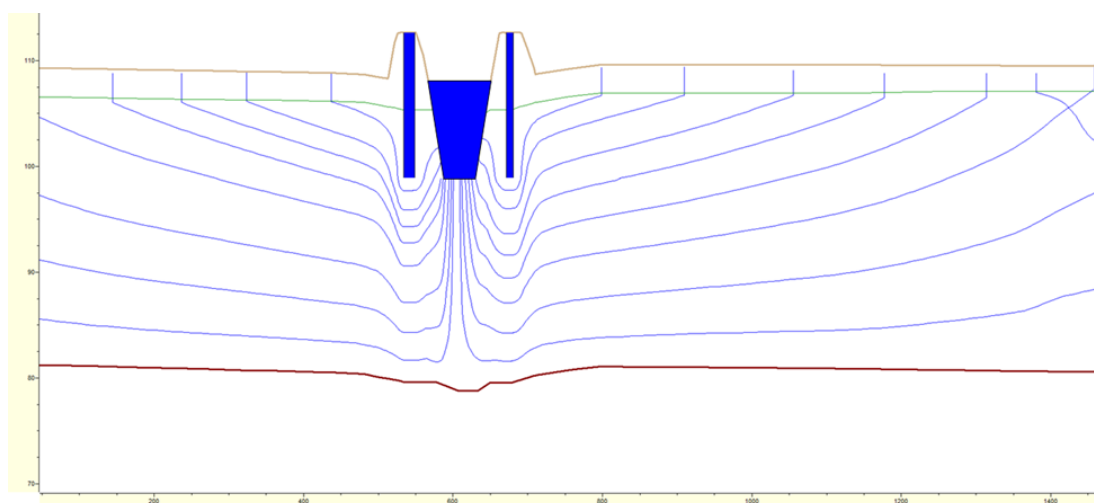

Fig. 11. *Influence of the cut-off walls on the groundwater flow – vertical cross section.*

(increase or decrease of water levels related to the mean value).

The results of the simulation of the unsteady flow is the difference in piezometric heads between the current state and the future scenario (assuming after realization of CWs) in specific days of the simulation:

- 20th May 2010 – 50th simulation day,
- 21st May 2010 – 51st simulation day,
- 4th Jun 2010 – 65th simulation day,

- 21st July 2010 – 112th simulation day.

Fig. 13 shows the calculated and also measured groundwater levels in two monitoring boreholes as well as total daily precipitation.

During extreme hydrological conditions the piezometric head in the wider area of interest may slightly change (in certain part it may drop by max. 0.6 m and rise by max. 0.4 m) (Fig. 14).
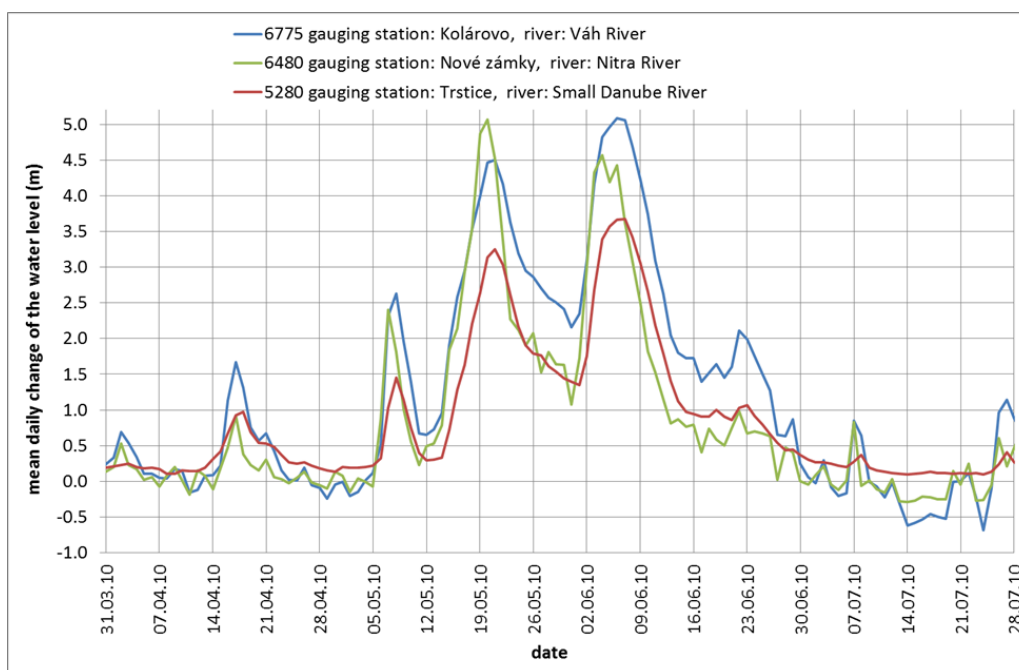

Fig. 12. The daily change of water levels in rivers Váh, Small Danube and Nitra.
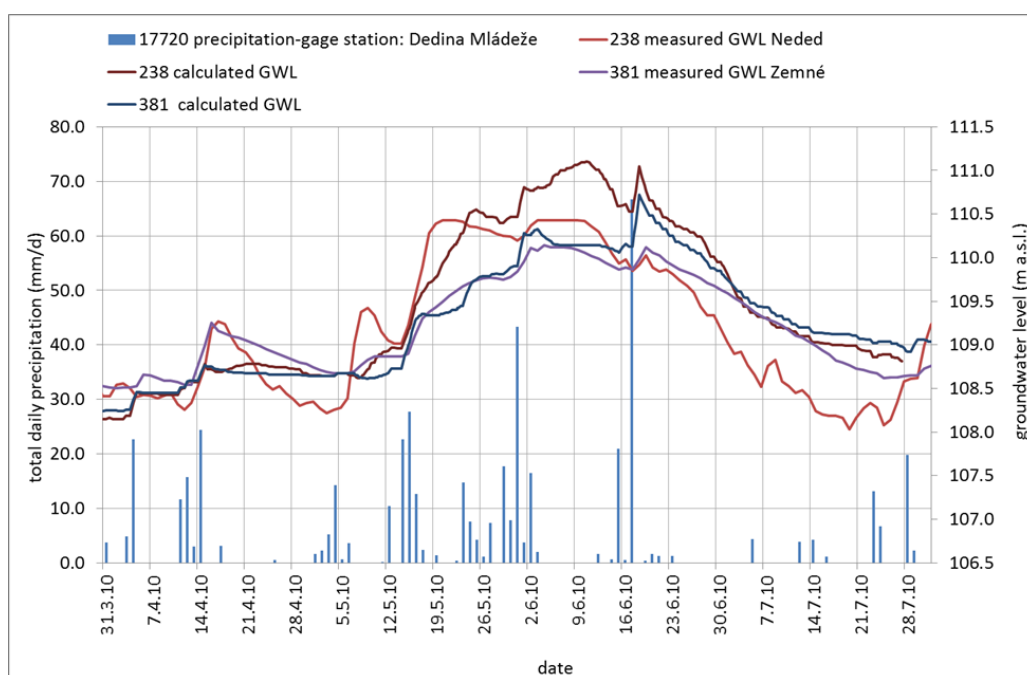

Fig. 13. Groundwater levels (calculated and measured) in two monitoring boreholes.
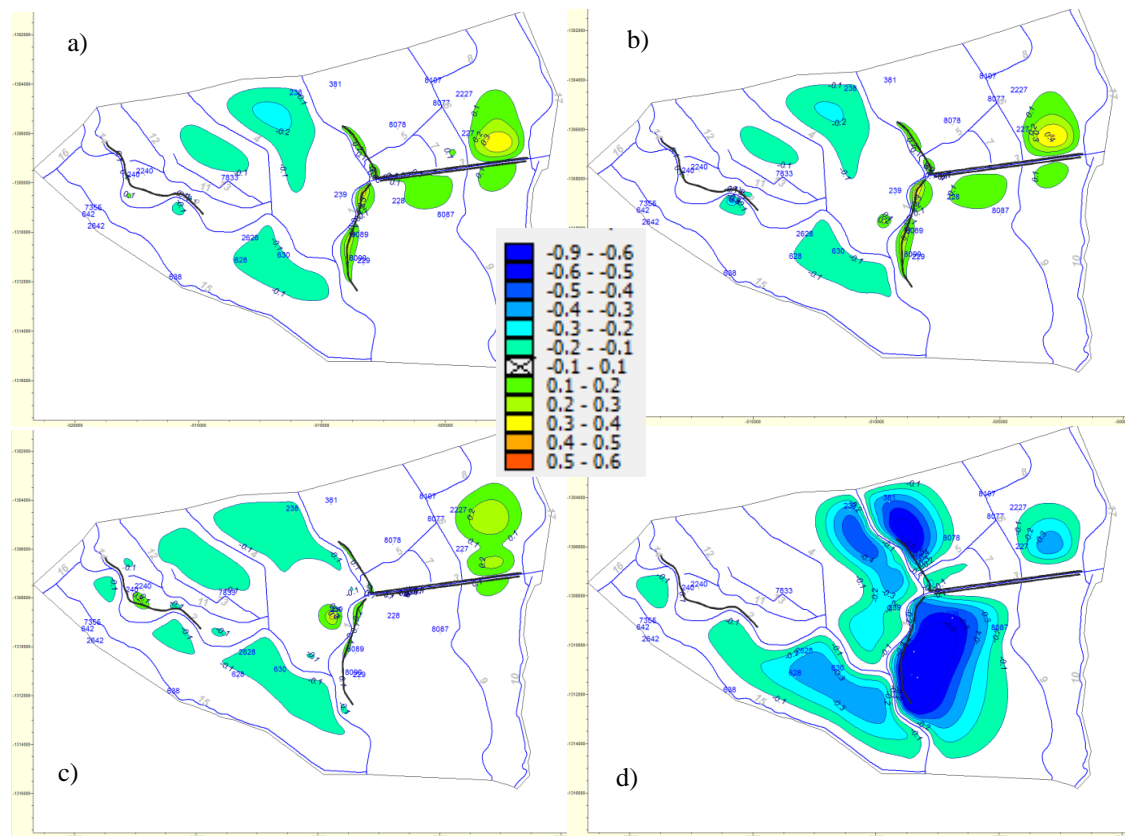
Fig. 14.   Prognosis of the difference in piezometric heads after and before the realization of CWs [m] – a) 50th, b) 51st, c) 65th day and d) 112th day of the simulation.

Conclusion

There were defects repeatedly seen on the downstream sides of the flood protective dykes along rivers Váh, Small Danube and the deviation of river Nitra. These defects can significantly reduce the stability of the dykes, which may lead to endangerment of the adjacent territory with residential houses, infrastructure and agricultural land, or to the contamination of water and soil as a result of flooding a nearby sewage treatment plant. Therefore, the additional sealing of dykes using suspended cut-off walls was proposed.

The aim of the paper was the verification of the functionality of the proposed cut-off walls using the method of mathematical modelling. The numerical simulation of the groundwater flow and groundwater level regime at steady state as well as during flood event was created. It includes also the impacts of the suspended cut-off walls on the groundwater flow and level regime in a wider area. The steady-state prediction, created using the long-time mean values of hydrological conditions, shows that the situation after realization of cut-off walls will not change after the realization of such a measure. The primary purpose of the cut-off walls is the elimination of the risk of suffusion and minimization of the risk of breakage of the cover layers caused by buoyancy. These protective measures extend the leakage path and thereby greatly reduce the hydraulic gradient and, accordingly, leaching quantities.

On the other hand, the piezometric head in the wider area of interest may slightly change during extreme hydrological conditions – in certain parts it may drop by max. 0.6 m and rise by max. 0.4 m.

Acknowledgements

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[SHMI] Source data from the Slovak Hydrometeorological Institute in electronic form.

[SWME] Source data from the Slovak Water Management Enterprise, s. e. in electronic form.

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