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Rye Island, 2010: Impact of the flooding on the groundwater level

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ABSTRACT

During the flood situations in May and June 2010, the culmination of the Váh River and the Danube River was accompanied by the groundwater level rising in the Rye Island, in some boreholes even to their maximum measured levels. The increased groundwater level caused major problems, e.g. flooded cellars and underground spaces, contaminated drinking water in wells, flooded railways and farmlands. As a part of the research concentrating on the groundwater flooding phenomena in the Rye Island, the flood situation from the year 2010 was reconstructed, establishing the basis for a construction of the flood hazard maps and flood risk management plans. The problem was solved with a MODFLOW numerical model using the Groundwater Modeling System.

KEYWORDS

2010 flood situation, groundwater modeling system, groundwater flooding, MODFLOW, numerical modeling, Rye Island

1. INTRODUCTION

Floods are natural phenomena, which cannot be prevented. However, some human activities e.g., increasing human settlements and economic assets in floodplains and the reduction of the natural water retention by land use and climate change contribute to an increase in the likelihood and adverse impacts of flood events [1]. In 2004, the European Commission initiated the development of a European action programme on flood risk management, including a possible future Floods Directive [2]. The purpose of this Directive is to establish a framework for the assessment and management of flood risks, aiming at the reduction of the adverse consequences for human health, the environment, cultural heritage, and economic activity associated with floods. This can be achieved by undertaken the preliminary flood risk assessment, preparation of flood hazard maps and flood risk maps and by establishment of flood risk management plans [1].

Although groundwater flood risk is, in general, less of a concern across Europe than fluvial, pluvial and coastal flood risk, it presents a significant local or regional hazard in some areas [3]. In Europe, in recent years, especially after the floods in Germany and neighboring countries, individual research institutions have dealt with the methodological development of damage estimation and integrated flood risk management. Flood events have shown that processes caused by groundwater dynamics may be responsible for a significant proportion of the damage caused. Therefore, in recent years there has been a better understanding of this risk and also its incorporation into national legislation.

Dresden scientists have developed a numerical model simulating the groundwater flow in Dresden and its vicinity, which is able to map the dynamics of groundwater during floods [4]. They also examined the factors influencing the extent of damage caused by high groundwater levels that occur during fluvial floods or due to extreme precipitation [5, 6].

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In response to the need for more information on groundwater flooding, British Geological Survey (BGS) has produced the first national dataset on the susceptibility of groundwater flooding, covering England, Wales, and Scotland. Based on geological and hydrogeological information, the digital data can be used to identify areas where geological conditions could enable groundwater flooding to occur and where groundwater may come close to the ground surface [7]. An early warning system [8] has been developed for groundwater flooding and trialed in the Patcham area of Brighton.

In Britain, the groundwater flooding is mainly connected with karst aquifers. Monitoring the karst aquifer water level fluctuation is also the aim of the research in Hungary [9].

Research from the Czech Republic [10] brought a new method of quantifying the hazard due to the potential uplift of the topsoil layer induced by rising groundwater level during a flood event. The scientific novelty lies in the fact that the problem is solved with an interdisciplinary approach that reconnects disciplines like Geographic Information System (GIS) analysis techniques and transient groundwater flow modeling while taking the relationship between surface water and groundwater into account as well as limit state application in soil mechanics.

In Slovakia, the flood risk assessment and management is mainly focused on fluvial floods, whereas mapping of flood risk from groundwater sources is in the background. One of the few researches dealing with the issue of flooding from rising groundwater levels is [11]. The paper evaluates the territory of the Rye Island in the period of the flood wave in 2013, especially the impact of the flood on the groundwater level and outlines the extent of the areas in which the groundwater level approached, respectively has reached ground level. The hydraulic relationship between surface water and groundwater in this region created legitimate assumptions for the possible flooding of large areas as a result of a significant rise in groundwater levels to or above ground level. However, these assumptions were not confirmed.

The article follows a research concentrating on the groundwater flooding phenomena in Slovakia carried out at the Department of Hydraulic Engineering of the Slovak University of Technology in Bratislava [12]. The studied part of the Rye Island is the area in which preliminary assessment of flood risk [13] evaluates the possibility for a negative phenomenon caused by rising groundwater levels or even a potentially significant flood risk. It is therefore the area in which the groundwater levels are at a shallow depth below the surface and which can be delimited by natural, geological, or hydrological boundaries. The investigated area is bordered (Fig. 1) on the north by the Chotárny channel, on the west and southwest by the Komárno channel, on the east by the Váh River and on the northeast by the Little Danube River. It is a lowland area, which is protected by dykes against direct flooding, with relatively small depths of groundwater level below the ground. However, dykes do not exclude the possibility of bank filtration into the subsoil in the adjacent area, which often causes its waterlogging, even flooding by groundwater. Therefore, a system of drainage channels and Pumping Stations (PS) was built to adjust the regime of internal waters and groundwater. On the other hand, it is a very favorable area for highly productive agricultural production [14, 15].

2. MATERIALS AND METHODS

2.1. Flood situation from the year 2010

Floods that occurred in Slovakia in May and June 2010 were exceptional from a hydrological point of view. Due to the meteorological situation in April and May, flood situations

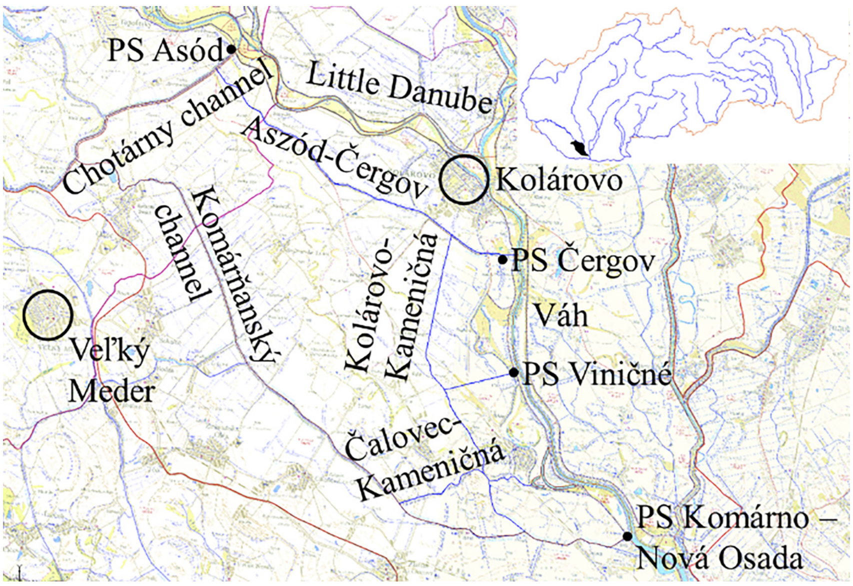

Fig. 1. The area of interest

occurred simultaneously in almost all river basins. Due to the saturation of the river basins from previous precipitation and their repetition, the retention capacity of river basins was very limited. The groundwater rose, causing major problems. These devastating, almost widespread floods caused ruptures of dykes, road-washing, landslides, destruction of bridges, demolition of houses or their partial destruction, flooded cellars and underground spaces (garages), contaminated drinking water in wells, flooded railways and farmlands. Five people lost their lives, and more than sixty were injured. Thousands lost their homes [16].

In the second half of May 2010, significant increases in water levels were recorded in the lower part of the Váh River (Figs 1 and 2), when the water level in Kolárovo reached the level of the 2nd degree of flood activity (Fig. 2). The next flood episode happened from June 2 to 7. The culmination in Kolárovo took place in the night of June 6–7 at a level corresponding to the 3rd degree of flood activity. In addition, the high-water level appeared in the Danube River as well. Almost 50-year flood discharge was achieved in Komárno on the Danube River what contributed to the increase in water levels in the lower part of the Váh River. The Váh River in Kolárovo and the Danube River in Komárno culminated at about the same time [16].

In the area of the lower part of the Rye Island, a gradual rise in the groundwater level has been recorded since the beginning of the hydrological year 2010 (Fig. 2), with a maximum groundwater level at the beginning of June. The groundwater level has been falling since the end of June with fluctuating increases in August and September. The reason was, on one hand, the exceptionally high precipitation totals recorded in May and June, as well as the high-water inflow from the Nitra River and the Little Danube River and high water levels on the Danube River [18]. In some groundwater level observation boreholes, the maximum measured groundwater levels were exceeded in 2010, while in others the measured heads approached the maximum levels observed for the entire observation period [17].

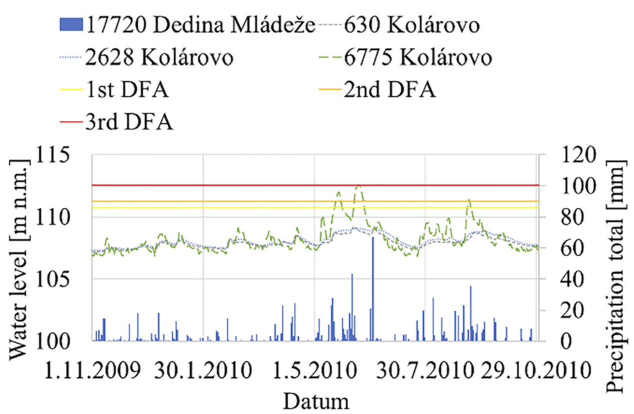

Fig. 2. The course of the groundwater levels in boreholes no. 630 and 2,628 in Kolárovo and the course of water level at the gauging station 6,775 Kolárovo (with the designation of the Degree of Flood Activity (DFA)); daily total precipitation in the rain gauging station 17,720 Dedina Mládeže - hydrological year 2010 (*Source*: with the permission of the Slovak Hydrometeorological Institute, [17])

2.2. Methodology

The impact of the flood situation from the 2010 on the groundwater level in the Rye Island, respectively the reconstruction of the mentioned flood, was solved using the MODFLOW numerical model in the Groundwater Modeling System (GMS) environment [19]. MODFLOW is a computer program that numerically solves the three-dimensional groundwater flow equation for a porous medium by using a finite-difference method. The three-dimensional movement of groundwater of constant density through porous earth material may be described by the partial-differential Eq. (1) [20]:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+ +\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_S\frac{\partial h}{\partial t}, \tag{1}$$

where K_{xx}, K_{yy} and 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 (Lt^{-1}); h is the potentiometric head (L); W is a volumetric flux per unit volume and represents sources and/or sinks of water (t^{-1}); S_S is the specific storage of the porous material (L^{-1}); and t is time (t).

Equation (1), together with specification of flow and/or head conditions at the boundaries of an aquifer system and specification of initial-head conditions, constitutes a mathematical representation of a ground-water flow system. A solution of Eq. (1), in an analytical sense, is an algebraic expression giving $h(x, y, z, t)$ such that, when the derivatives of h with respect to space and time are substituted into Eq. (1), the equation and its initial and boundary conditions are satisfied. Except for very simple systems, analytical solutions of Eq. (1) are rarely possible, so various numerical methods must be employed to obtain approximate solutions. One of the approaches is the finite-difference method, wherein the continuous system described by Eq. (1) is replaced by a finite set of discrete points in space and time, and the partial derivatives are replaced by terms calculated from the differences in head values at these points. The finite-difference analog of Eq. (1) may be derived by applying discretization conventions described in [20].

A modeling protocol, which was used for creation of the numerical model, is described in Fig. 3. During the conceptual model stage, the system boundaries were identified, field data describing geomorphological [21], geological [22], hydrogeological [22], hydrological [17, 23], and meteorological [17] conditions were assembled, and the model area was visited. After that, the conceptual model was mapped to the designed grid, the boundary and initial conditions were set and preliminary selection of values for aquifer parameters and hydrologic stresses was performed (model design). During the calibration stage, a set of values for aquifer

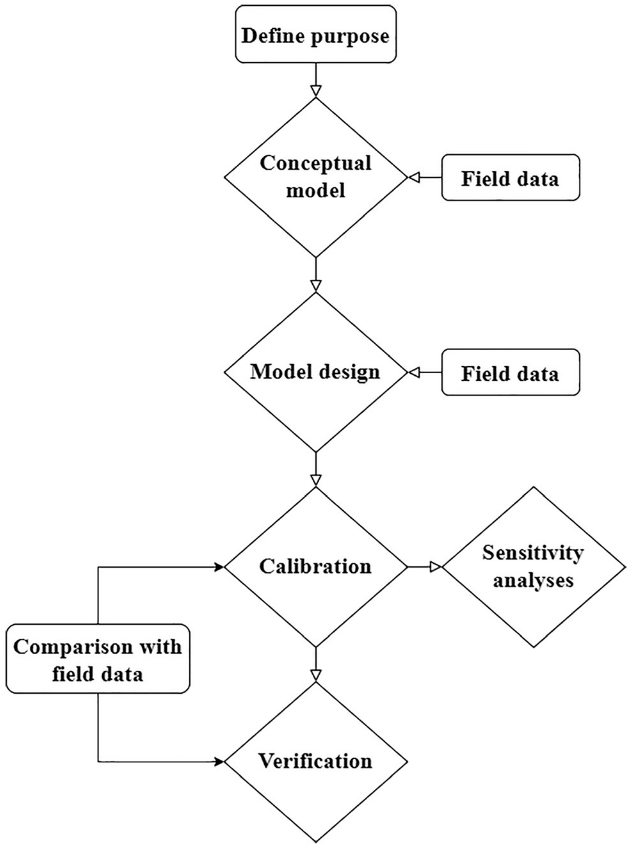

Fig. 3. Modeling protocol (adapted from [26])

parameters and stresses, that approximates field-measured heads and flows, was found. A sensitivity analysis, as a part of the calibration process, was done comparing different MODFLOW modules for the simulation of the river type boundary condition [24]. The calibration of hydraulic conductivity and conductance was performed on a steady-state model using data from the hydrological year 2008, specifically for the mean value of hydrological parameters in this hydrological year. The reason for choosing this period is that the hydrological year 2008 was “average” in terms of precipitation (100–109% of the long-term normal) for the regions of western Slovakia [25]. The calibration of the recharge values was performed using the relatively steady state (Fig. 2) before the flood in 2010 (the mean value of the hydrological parameters in the period from November 11, 2009 to March 31, 2010). This model served as an initial condition for the unsteady model. The unsteady state model, calibrated using the recharge values as calibration parameter, simulates the period from April 2010 to February 2011 (Fig. 2). The influence of the boundary condition on the solution was investigated within the sensitivity analysis. The calibration, as well as the sensitivity analysis, was done by trial-and-error adjustment of calibration parameters. At the end of the modeling phase, the verification of the model was done using the set of calibrated parameter values and stresses to reproduce a second set of field data (the mean value of the hydrological parameters in the period from April 1, 2010 to July 31, 2010).

3. RESULTS AND DISCUSSION

Figure 4 captures the contours of the calculated piezometric groundwater head for June 7, 2010 during the second flood wave culmination of the Váh River in Kolárovo and the culmination of the Danube River in Komárno at the same time. As can be seen in this figure, a large part of the area was either waterlogged, in the extreme case even flooded due to rising groundwater level, what can cause problems for buildings (and especially their foundations), civil structures (a major problem is caused by flooded sewage treatment plants), and this may also have a negative impact on agricultural production.

To illustrate the depth of the calculated groundwater level under the terrain, Fig. 5 was constructed. In addition to flooded areas (with a negative value of the depth), it is also

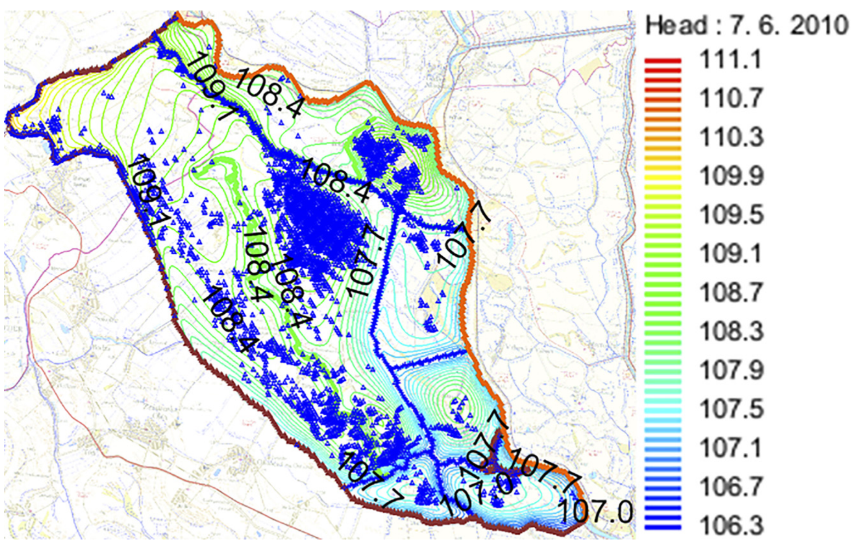

Fig. 4. Map of calculated piezometric groundwater head for June 7, 2010 [m a. s. l.] (Δ - flooded area)

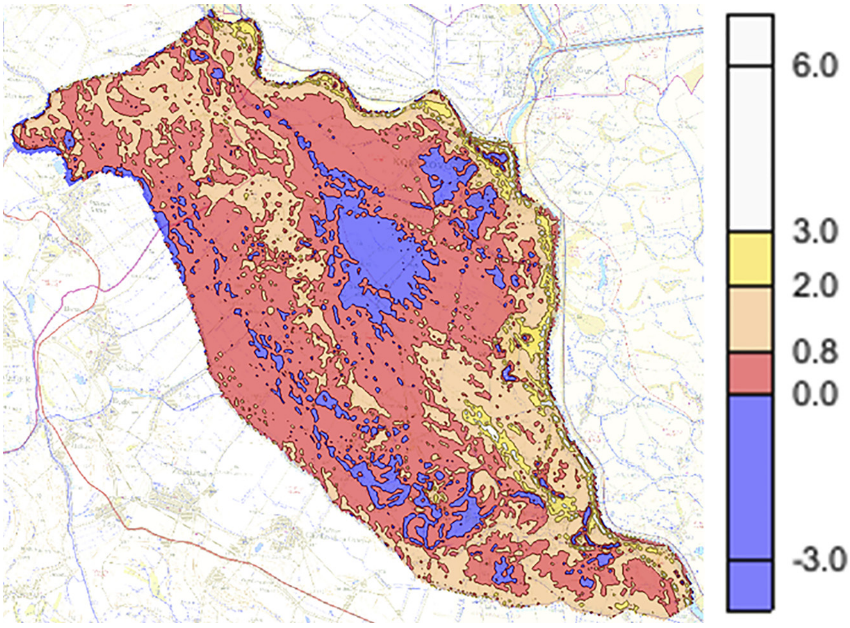

Fig. 5. Map showing the depth of the groundwater level under the terrain [m b. g. s.]

possible to see areas where the depth to groundwater table is less than 0.80 m below ground surface. The value 0.80 was not selected randomly; it represents the average depth of freezing in Slovakia [27]. It is therefore the depth in which the foundations of non-basement buildings are located.

4. CONCLUSION

The article presents results of the research concentrating on the groundwater flooding phenomena in the lower part of the Rye Island, especially on the reconstruction of the flood situation from 2010 and its consequences on the groundwater level in the studied locality. The investigated area was chosen on the basis of the preliminary flood risk assessment for the whole territory of the Rye Island. The modeling step concentrated mainly on the mentioned flood situation in 2010 when the exceptionally high precipitation totals were recorded in May and June, as well as the high water inflow from the Nitra River and the Little Danube River and high water levels on the Danube River, causing a gradual rise in the groundwater level.

The contours of the calculated piezometric groundwater head for June 7, 2010 during the second flood wave culmination of the Váh River in Kolárovo and the culmination of the Danube River in Komárno at the same time was illustrated defining a large flooded part of the area of interest due to rising groundwater level. This can have a lot of negative impacts, e.g. for the agricultural production, or even flooding of sewage treatment plants and contamination of drinking water in wells.

Also, the map showing the depth of the groundwater level under the terrain was constructed. Besides the flooded areas, it can be also seen the waterlogged areas where groundwater is at the depth less than 0.80 m. This value represents the mean depth of freezing in Slovakia, so the presence of groundwater at this depth can cause problems for buildings, especially their foundations. Taking building with basements into account, also the occurrence of groundwater in the depths of 0.80–3.0 m can be problematic.

The research establishes the basis for a construction of the flood hazard maps and flood risk management plans taking groundwater into account, which was in the background compared to the fluvial flooding.

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REFERENCES

[1] “Directive 2007/60/EC of the European parliament and of the Council of 23 October 2007 on the assessment and management of flood risks,” in *Official Journal of the European Union*, 2007, pp. L288/27–L288/34.

[2] “Vulnerability and adaptation to climate change,” in *European Environment Agency Briefing*, Copenhagen, Denmark, 2005.

[3] “Flood risks and environmental vulnerability. Exploring the synergies between floodplain restoration, water policies and thematic

policies," *European Environment Agency*, Copenhagen, Denmark, 2016.

[4] K. Ullrich and T. Sommer, "Effects of the 2002 flood on groundwater," Research paper (in German), Dresden: Landeshauptstadt Dresden, 2005.

[5] T. Sommer, "Development of multi-sequential precautionary strategies for urban habitats at risk of groundwater flooding ('MULTISURE')," Final report (in German), Dresdner Grundwasserforschungszentrum, Dresden, Germany, 2010.

[6] R. Schinke, M. Neubert, J. Hennersdorf, U. Stodolny, T. Sommer, and T. Naumann, "Damage estimation of subterranean building constructions due to groundwater inundation - The GIS-based model approach GRUWAD," *Nat. Hazards Earth Syst. Sci.*, vol. 12, no. 9, pp. 2865–2877, 2012.

[7] Groundwater data, information and services. [Online]. Available: https://www.bgs.ac.uk/research/groundwater/datainfo/home.html. Accessed: Nov. 26, 2019.

[8] B. Adams, J. P. Bloomfield, A. J. Gallagher, C. R. Jackson, H. K. Rutter, and A. T. Williams, "An early warning system for groundwater flooding in the Chalk," *Q. J. Eng. Geology. Hydrogeol.*, vol. 43, no. 2, pp. 185–193, 2010.

[9] M. Maller, A. Rehák, and G. Hajnal, "Water level fluctuation in karst aquifers in the Trandsanubian range (Hungary)," *Pollack Period.*, vol. 13, no. 3, pp. 151–162, 2018.

[10] T. Julínek, D. Duchan, and J. Říha, "Mapping of uplift hazard due to rising groundwater level during floods," *J. Flood Risk Manag.*, Spec. Issue, pp. 1–13, 2020.

[11] E. Kullman, J. Gavurník, B. Bodácz, and Z. Pal'ušová, "The historic Danubian flood in 2013 and its impact on groundwater levels" (in Slovak), in *Manažment Povodí a Povodňových Rizík*, Výskumný Ústav Vodného Hospodárstva, Bratislava, 2013, pp. 11–13.

[12] M. Červeňanská, D. Baroková, A. Šoltész, and A. Janík, "Preliminary assessment of flood risk due to increased groundwater levels in Slovakia," in *16th International Multidisciplinary Scientific GeoConference, Albena, Bulgaria*, Jun. 30–Jul. 6, 2016, 2016, pp. 223–228.

[13] M. Červeňanská, D. Baroková, and A. Šoltész, "Case study on groundwater flooding: the lower part of the Rye Island," *J. Landscape Manag.*, vol. 11, no. 2, pp. 7–11, 2020.

[14] D. Duba, *Groundwater Hydrology* (in Slovak). Bratislava: Vydavatel'stvo Slovenskej akadémie vied v Bratislave, 1968.

[15] A. Porubský, *Water Management Plan of the Slovak Socialist Republic. VII. Danube Basin. Map No. 5. Water Management-hydrogeological Map 1: 200 000. Text Explanations* (in Slovak). Bratislava: Geografický ústav SAV, 1976.

[16] A. Blahová, K. Matoková, P. Smrtník, M. Hazlinger, T. Masár, M. Bírová, P. Parditka, J. Pecho, D. Lešková, J. Poórová, M. Jarošová, J. Kozub, P. Škoda, P. Mráček, and V. Wendlová, *Flood Situation on the Streams of Western Slovakia in May and June 2010* (in Slovak). Bratislava: Slovenský hydrometeorologický ústav, Centrum predpovedí a výstrah, Odbor Hydrologické predpovede a výstrahy, 2010.

[17] Data provided from the Slovak Hydrometeorological Institute, 2020.

[18] Assessment of the hydrological year 2010 (in Slovak). [Online]. Available: http://www.shmu.sk/File/Hydrologia/Monitoring_PV_PzV/Monitoring_kvantity_PzV/KnPzV_2010/KnPzV_2010_hodnotenie.pdf. Accessed: Jan. 7, 2020.

[19] Groundwater modeling system. [Online]. Available: https://www.aquaveo.com/software/gms-groundwater-modeling-system-introduction. Accessed: May 2, 2020.

[20] M. G. Mcdonald and A. W. Harbaugh, *A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, Chapter A1*. US Gological Survey, 1988.

[21] Aeronautical laser scanning and DRM 5.0 (in Slovak). [Online]. Available: https://www.geoportal.sk/sk/udaje/lls-dmr/. Accessed: Feb. 14, 2020.

[22] Final reports and assessments of the Geofond digital archive (in Slovak). [Online]. Available: https://www.geology.sk/sluzby/digitalny-archiv/. Accessed: Dec. 12, 2019.

[23] Data provided from the Slovak Water Management Enterprise, 2020.

[24] P. Dušek and Y. Velísková, "Comparison of the MODFLOW modules for the simulation of the river type boundary condition," *Pollack Period.*, vol. 12, no. 3, pp. 3–13, 2017.

[25] Assessment of the hydrological year, 2008 (in Slovak). [Online]. Available: http://www.shmu.sk/File/Hydrologia/Monitoring_PV_PzV/Monitoring_kvantity_PzV/KnPzV_2008/KnPzV_2008_hodnotenie.pdf. Accessed: Jan. 7, 2020.

[26] M. P. Anderson and W. Woessner, *Applied Groundwater Modeling. Simulation of Flow and Advective Transport*, California: Academic press, 1992.

[27] *STN 73 1001:2010, Geotechnical Structures, Foundation of buildings* (in Slovak). Bratislava: Office for Standardization, Metrology and Testing of the Slovak Republic, Department of Technical Standardization, 2010.