Assessment of the influence of a building upon groundwater temperature pattern using numerical modelling

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Abstract: Nowadays, heat transport in an aquifer is a widely discussed topic. Groundwater temperature rise is the result of a variety of factors and a common phenomenon, especially in larger cities. Heating and cooling in buildings, infrastructure, even paved surfaces can accumulate solar energy and further emit heat into the subsurface, leading to an increase in temperature. The research of the issue of increased groundwater temperature is related to the potential use of heat as an energy source. Numerical modelling, which is based on the solution of partial differential equations, can be used to evaluate the given phenomenon. The Aupark shopping centre in Bratislava was selected for the model area, where the temperature in hydrogeological boreholes is monitored, and at the same time, multilevel monitoring of the rock environment temperature takes place. The evaluation of monitoring data was realised through the Groundwater Vistas 7 programme, where a hydraulic and transport model was compiled using MODFLOW and MT3DMS. The MT3DMS code is intended for the transport of dissolved substances; however, with the appropriate substitution of input parameters, it is also applicable for the transport of heat. The sensitivity of the input data and calibration of the model was evaluated through the PEST programme, where the goal was to achieve the highest possible correlation between the measured and modelled results. By analyzing the data from monitoring, it was possible to quantify the areal and depth impact of the Aupark shopping centre. Last but not least, the energy input from Aupark to the rock environment was determined, and ranges from 0.1 W·m^{-2} at a distance of 100 m to 12 W·m^{-2} immediately next to the building.

Key words: numerical modelling, temperature pattern, heat transport, urban heat island, MT3DMS, MODFLOW

1. INTRODUCTION

The temperature of groundwater and rock environment is increasing due to urban development. This is due to the fact that the urban development generates heat, which is gradually stored in the aquifer. This phenomenon can be defined by the term *urban heat island*, which means an area in a city that manifests significantly increased temperature values due to anthropogenic activity when compared to its surroundings. This process is most pronounced at the increased average air and surface temperature; after some time, at groundwater temperature as well (Fig. 1). Groundwater temperature is affected by reinjection of thermally used groundwater in heat pumps, too. Anthropogenic factors that affect the temperature regime of groundwater are: urbanization, utilities, heating basements, and heat transfer from the Earth's surface. The temperature is also increased by the influence of impermeable materials, such as asphalt and concrete, which absorb heat from solar energy and then radiate it into their subsoil (earth).

Among the first studies examining temperature differences in the city and surrounding rural areas were the studies done by Howard (1833); Oke (1974, 1979, 1982). The research associated with this topic is based mainly on the possibility of using elevated temperature as a possible source of thermal energy (Krčmář et al., 2017; Geletič, 2017; Epting et al., 2013a; Epting et al., 2017). The emergence of an urban heat island is also related to climate change, which has recently been intensively researched and discussed (Epting et al., 2011; Epting et al., 2013a; Ferguson and Woodbury, 2007). Current discussions also focus on issues, such as water resources being qualitatively affected by elevated air temperatures. The influence of elevated temperatures has an impact on the quality of groundwater, as well as on biological, chemical and physical processes. Urban areas with significant industrial pollution are becoming problematic, where an increase in water temperature can cause a change in microbial processes (Epting et al., 2013a). An increase in groundwater temperature also affects the solubility of gases and solids (Palmer et al., 1992). In addition, chemical reactions induced by temperature changes can lead to changes in the porosity and permeability of the aquifer (Saripalli et al., 2001).

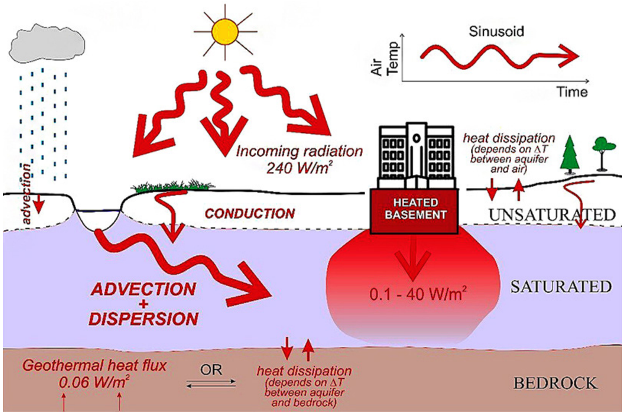

Fig. 1. Illustration of the heat exchange situation between the river, the Earth's surface, the basement of the building, and groundwater (modified according to Krčmář et al., 2019)

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The issue of an urban heat island is widely discussed by the scientific community. Zhu et al. (2015) evaluated the phenomenon of an urban heat island in the Cologne region of Germany. The investigation of the phenomenon was based on a numerical model of groundwater flow and heat transport, which described the hydraulic conditions and the development of thermal anomalies in the area. Tinti et al. (2017) evaluated the thermal behaviour of the underground affected by a building in Italy using three-dimensional modelling. By calculating the temperature field below the building, it was proven that variations in the urban geometry (size and number of green areas versus built-up areas) or materials of the building can significantly affect the subsurface temperature. Attard et al. (2016) present the results of three-dimensional modelling of heat transport in order to quantify the heat-affected zone in the Lyon area of France. The authors found that the most significant effect of the groundwater thermal impact is present in the city centre, where the influence of buildings is dominant. Elevated temperatures of more than 4.5 °C were locally demonstrated. Epting et al. (2013b) evaluated the urban heat island phenomenon in Basel, Switzerland. Thermal impacts in the investigated groundwater bodies were quantified by multi-level groundwater temperature monitoring, a combination of short-term and long-term data analysis, and 3D modelling of groundwater heat flow and transport. The publication by Dědeček et al. (2012) deals with the quantification of the influence of local anthropogenic factors and regional climate change on groundwater temperatures in the localities of Spořilov (Czech Republic) and Šempeter (Slovenia). Rivera et al. (2017) assess the increased groundwater temperatures in urban areas and their prospective energy potential usable for practical purposes. The contribution by Kolokotroni et al. (2007) discusses the urban heat island in London, UK, and the possibility of using it for heating purposes. For the last three decades, Akbari and Kolokotsa (2016) have been evaluating an urban heat island with emphasis on examining developments and evaluating options for mitigation.

The aim of the paper is to evaluate and interpret the data obtained through multilevel monitoring in the Aupark shopping centre in Bratislava. The evaluation was based on the compilation of a hydraulic and transport model in the MODFLOW and MT3DMS programme using a deeper analysis of the input parameters through automatic calibration. Subsequently, it was possible to determine the input of energy from the shopping centre into groundwater.

2. STUDY AREA

The investigated area, Aupark – Bratislava is located in the south-western part of the Slovak Republic. It is situated on the right bank of the river Danube, in the city district of Petržalka, between Einstein Street and Janko Kráľ Park. Due to the location of a large park between Aupark and the Danube river, it can be stated that the temperature regime of groundwater is affected to a minimal level without other heat sources from buildings. In terms of regional geomorphological division, according to Mazúr and Lukniš (1986), the investigated area belongs to the area of the Danubian lowland and the unit of the Danubian plain. The type of relief is flat with an average altitude of 135 m a s l. (Fig. 2).

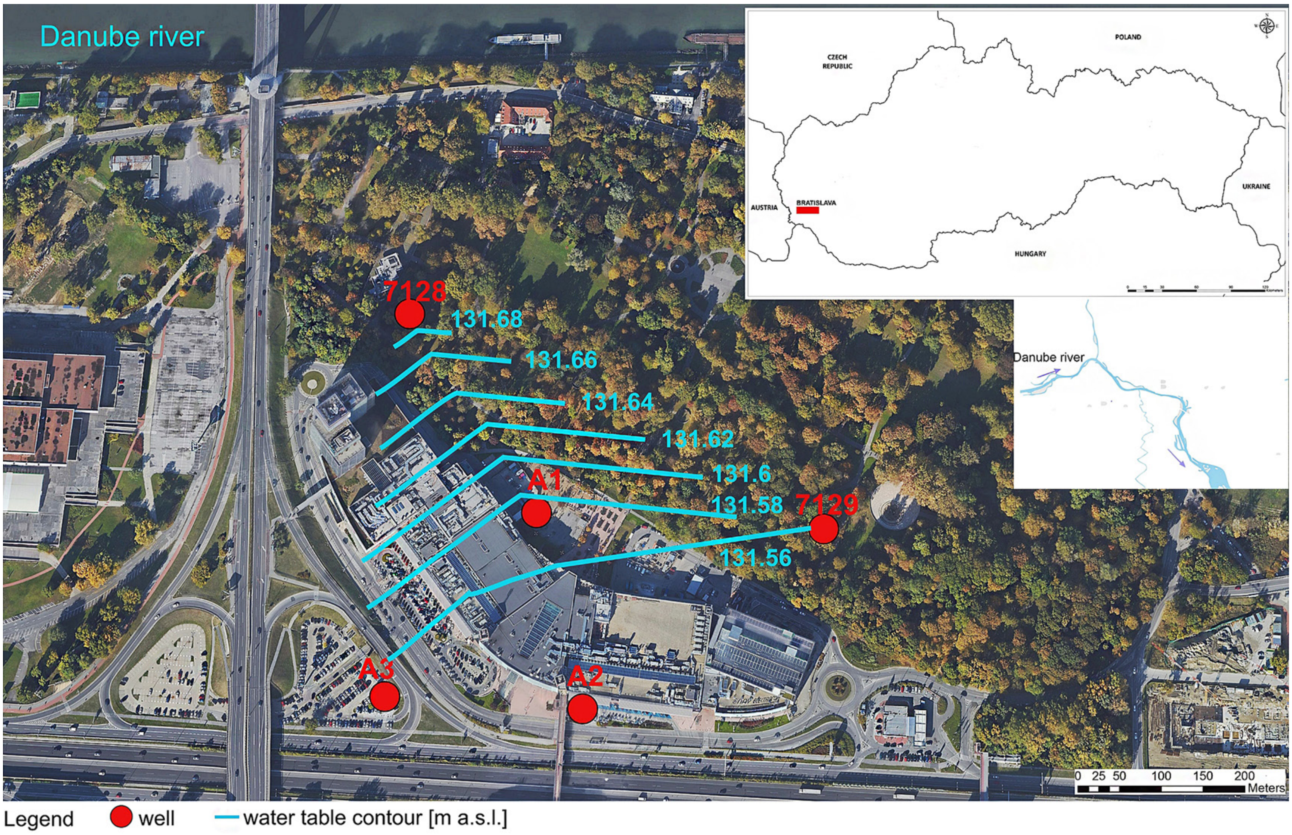

Fig. 2. Map of the territory of interest

The Aupark shopping centre was built in 2001 with an area of 44,000 m^2; during the second phase of construction, the area was expanded by 15,000 m^2 in 2007. The underground floor of Aupark is used as a parking garage, while the altitude of the foundations is 131.4 m above sea level (3.6 m below ground). In winter, the basement is heated to 20 °C. The surrounding terrain is flat with an average altitude of 135 m above sea level (Vlasko, 2005).

The investigated area based on the climatic zoning of Slovakia is characterized as warm, dry, with a mild winter. Based on the Map of climatographic types, the area is part of a lowland climate type with a characteristic inversion of temperatures (Kočický and Ivanič, 2011). More detailed climatological information is included in Tab. 1.

Tab. 1 Climatological characteristics of the territory (Atlas of Landscape SR, 2002)

Lower range of average January temperatures [°C]	–4
Upper range of average January temperatures [°C]	–1
Lower range of average July temperatures [°C]	19.5
Upper range of average July temperatures [°C]	20.5
Lower interval of annual total precipitation [mm]	530
Upper interval of annual precipitation level [mm]	650

From a geological point of view, the area is located in the marginal part of the Neogene basin consisting of Neogene and Quaternary sediments (Polák et al., 2012). The Neogene subsoil is formed by the Pannonian Formation in the lithological development of clays, sandy or silty clays, and fine-grained gravels. Within the study area, the Quaternary sediments are represented by fluvial deposits, which are made of gravelly sediments with a variable content of a sandy fraction with an irregular surface development.

This results in a relatively large inhomogeneity of sediments in the vertical and horizontal directions. The horizons of the gravels can be covered with a discontinuous layer of fluvial loams and sands with a thickness of 2 – 4 m. The topmost part of the study area is covered by anthropogenic sediments reaching variable thickness. The geological profile of monitoring wells A-1 to A-3 with the indication of the groundwater table, as well as the well completion (location of the well screen, PT100 thermocouples – red stripes and data loggers Solinst – blue stripes) is shown in Fig. 3. Distances of the monitoring wells from the Aupark shopping mall are 30 m (A1), 13 m (A2), and 88 m (A3), 59 m (7128), and 91 m (7129).

The Quaternary aquifer is built from gravel sands of the Danube alluvium with an average thickness of 18 m. From a hydrogeological point of view, the Danube River plays an important role in the given area. Due to the presence of the Danube, water infiltrates into permeable, gravelly alluvium. During the infiltration of water from Danube River, its chemical composition is changing, not only with contacts of sediments but specially effect of secondary factors, as are escape form city´s canalization, waste deposits, pollution from chemical industry and so on (Šulvová et al., 2009; Ženišová et al., 2000; 2018). The Danube forms the northern border of the investigated area and recharges groundwater reserves throughout the year. The general direction of groundwater flow is from north to south. The average groundwater level is 131.6 m above sea level. Hydraulic conductivity varies from $1 \cdot 10^{-3}$ to $1 \cdot 10^{-2}$ m · s^{-1}, the hydraulic gradient reaches $7 \cdot 10^{-4}$ (Vlasko, 2006; Hanzel et al., 2012).

3. MATERIALS AND METHODS

3.1. Monitoring

There are three exploratory-monitoring, narrow-diameter hydrogeological boreholes A-1 to A-3 in the study area, which are drilled up to the Neogene subsoil. The depth of each well is as follows: 16.30 m (A-1), 20.50 m (A-2) and 18.40 m (A-3). The wells were drilled by core-boring without drilling fluid (slurry) with percussion drilling bits (Fig. 4). The drilling bits used were ø 98 and 78 mm. Protective steel casings of ø 98 mm were used for temporary casing of boreholes. Each well consists of two separate polyethylene tubes (Fig. 5). The first tube (HDPE, diameter 50 mm) is installed to 6 m depth with a 3 m long screen at the bottom. A Solinst Junior data logger is located 0.5 m above the well bottom that measures groundwater head and temperature with a resolution of 0.1 °C. The second tube (HDPE, diameter 32 mm) has six cut ports, where PT100 thermocouples are located (Fig. 6). The ports are covered by a protective screen and the inner space of the tube between each port is filled with water-tight foam. Six thermocouples with a resolution of 0.01 °C are connected to a Fiedler Minilog T6 data logger. Monitoring of the surroundings of the shopping centre is supplemented by two SHMI wells marked 7128 and 7129. The wells have a steel casing of ø 100 mm with a screening interval along the entire thickness of the aquifer. The Solinst Junior data logger is installed 0.5 m above the well bottoms. Monitoring of the temperature and depth of the groundwater level in all wells was started in April

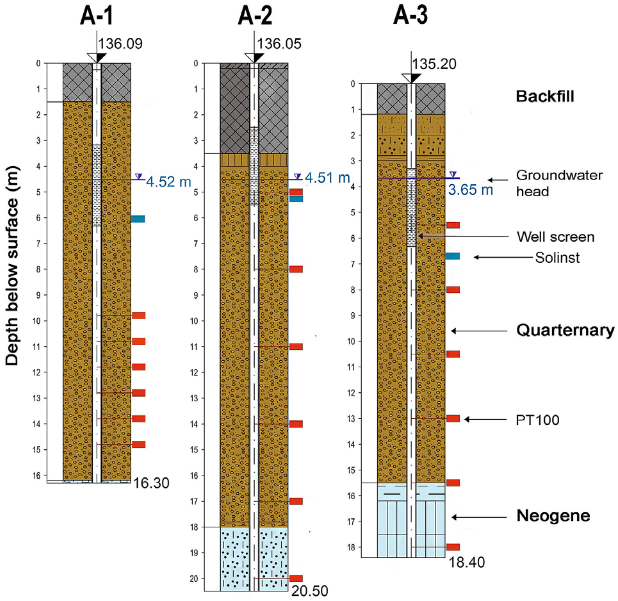

Fig. 3. Geological profile of monitoring wells

Fig. 4. Drilling of monitoring wells

20, 2018 and still continues, while data is regularly transferred from the installed data loggers to the PC (Fig. 7).

3.2. Hydraulic and transport model

To create a hydraulic and transport model, it was necessary to define the temperature and hydraulic parameters of the environment. These were entered during the initial compilation of the model on the basis of data from the literature, and these parameters were subsequently optimized using data from monitoring during the calibration of the model. The parameters required for the calculation of the hydraulic and transport model were: hydraulic conductivity, porosity, rock density, thermal diffusivity and longitudinal and transverse dispersibility (Hecht – Mendéz et al., 2008).

When compiling the hydraulic model, two possible situations in terms of flow can be solved; namely steady or transient flow (Anderson et al., 2015). In our case, we simplified the steady state flow, which represented the average water level of the Danube River over the period from April/ 2018 to June/2020. The transport model was entered as transient, meaning that the temperature changed over time. The simulation period was divided into stress periods, during which temperature values were entered. The definition of boundary conditions was also related to the above description. It was necessary to distinguish whether the groundwater table or groundwater temperature changed over time or remained constant. In our case, the boundary conditions *Constant Head and Transient Temperature* were applied.

The model of the area in question was created using the Groundwater Vistas 7 software package, which contains various hydraulic and transport tools. The MODFLOW code, was used to compile the hydraulic flow model. This programme was developed and is constantly being updated by the U.S. Geological Survey (Langevin et al., 2017).

The MT3DMS programme was used to solve the heat transport, where the heat transport is based on the advection – dispersion equation. MT3DMS (A Modular Three – Dimensional Multispecies Transport Model), which was developed at S.S. Papadopulos & Associates Ins., and contains a comprehensive set of options for simulating the processes of advection, dispersion or diffusion, and chemical reactions of contaminants in the groundwater flow

Fig. 5. Construction of monitoring well A-1: On the surface, there is a closable cap and a protective casing to a depth of 1 m. Inside the well are two HDPE tubes: a tube with a red plug (5 cm in diameter) is used to measure the depth of the groundwater level, the second tube (3.2 cm in diameter) with 6 ports is used to measure the temperature of the aquifer.

Fig. 6. PT100 thermistor port for temperature measurement (Krčmář et al., 2019)

Fig. 7. Groundwater sampling and recording of data from data loggers on groundwater temperature and table level in well A-3

system. It was originally designed to simulate the transport of solutes; however, with the appropriate substitution of transport parameters for temperature, it can be used to model heat transport (Zheng et al., 1999). Its disadvantage is that the possibilities of modelling processes in the unsaturated zone are limited, which in the solution of heat transport can cause problems, especially in the solution of heat transfer from the terrain towards the aquifer (or vice versa). This issue can be solved by connecting the analytical solution of vertical heat transport through the unsaturated zone with the transport model (Kupfersberger et al., 2017).

Calibration is a process in which selected model parameters are modified or optimized to a specified range of values (Droogers & Immerzeel, 2006). Model calibration is one of the most important and time-consuming components of modelling. In the case of the examined area, the possibility of automatic calibration using the PEST programme, which is available within the Groundwater Vistas 7 programme, was used.

The PEST algorithm for estimating model parameter is Gauss –Marquard-Levenberg. The input file of PEST is the control file (.pst). The file links to the hydraulic model and heat transport model by a batch file (.bat). PEST defines the optimal parameter by letting the model running many times as it needs. At the beginning of each iteration, the ratio between model parameters and observed parameters is linearized by defining Taylor expansion for the best parameter set. This means that derivatives of all observations with regard to all parameters must be calculated (Droogers & Immerzeel, 2006; Tum, 2017). The individual hydraulic and temperature parameters were adjusted to achieve the best possible match between the measured and modelled parameters. The calibration itself is preceded by a process in which the given monitoring objects (Calibration Targets) were entered into the model grid using the AE (Analytical Elements) tool. The calibration target is a point in space and time where one of the model dependent variables is measured. Calibration targets provide a means of assessing calibration quality because an error term, called a residual, is computed for each target location. A residual is computed as the field measurement minus the model-computed value. The range of errors helps to determine whether the quality of the calibration is sufficient (Droogers & Immerzeel, 2006). Using targets, the course of temperature development was characterized in time, which indeed corresponded to the measured data from monitoring. These were further compared using statistical methods with the modelled results. Subsequently, the values of the input parameters were adjusted to achieve the best possible results between the measured and modelled values (Batu, 2006).

4. RESULTS

4.1. Processing of monitoring data

There are two types of temperature measurements at the site. Firstly, groundwater temperature measurement in conventional hydrogeological wells (wells SHMI 7128 and 7129; wells A-1 to A-3) and multilevel temperature measurement of the geological environment using a special installation of wells with measuring ports at different depths (wells A-1 to A-3). The deepest temperature sensors were placed in the Neogene subsoil, and thus made it possible to study the heat transfer from the aquifer to the impermeable subsoil. In standard hydrogeological wells A-1 to A-3, the data loggers were at a depth of 5.5 meters below surface, which was approximately 1 meter below the groundwater table. The measurements manifest a seasonal change in temperature (sinusoidal course, Fig. 8) with a phase shift (maximum) of approximately 3 months (maximum air temperature is reached in August and groundwater in November). The phase shift and magnitude of the amplitude were the same in all three wells, indicating that the groundwater heat comes from the same source. In our case,

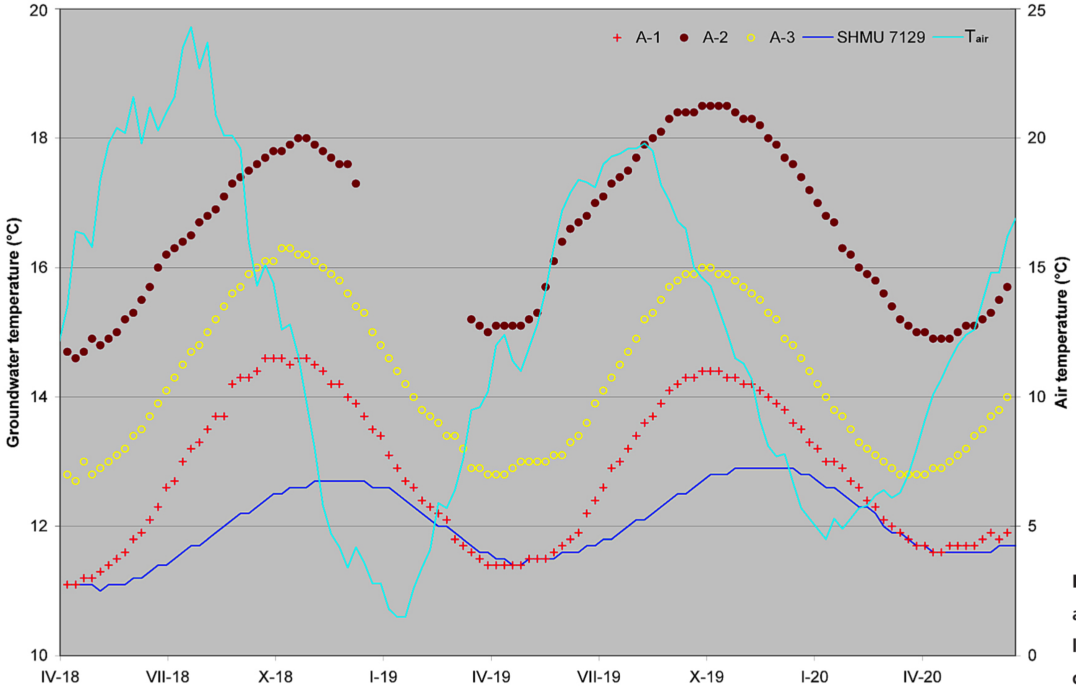

Fig. 8. Data measured in a standard hydrogeological well with Solinst data loggers

it can be said that the main source of heat for groundwater was heat transferring from the surface. The average value of individual temperatures was shifted by a constant value throughout the year, with the largest shift at the location of well A-2 and the smaller at the location of well A-3. This shift is caused by the heat source in the basement of Aupark shopping centre; with increasing distance its influence decreases, as reflected in the measurements.

Thanks to a special installation, it was also possible to monitor the temperature directly in the geological environment in conventional hydrogeological boreholes. At each well A-1 to A-3, 6 thermistors were installed at different depths to measure the groundwater temperature. The course of temperatures from individual sensors is shown in Fig. 9 and the change in temperature over time for the entire depth of the profile is shown in Fig. 10. At each temperature, attenuation of the amplitude and phase shift towards depth is visible. In the Neogene subsoil (at a depth of 19 meters below the ground), the temperature is nearly constant throughout the year at 14 °C.

Flowing groundwater disperses heat from the Aupark building. This was visible during monitoring of well A-2, which has a 13 m downgradient from the shopping centre at a depth of 17 m, where the temperature is 2° C higher. In our case, the groundwater flow velocity is $1 \cdot 10^{-6}\,\mathrm{m} \cdot \mathrm{s}^{-1}$. However, at well A-1, which has a 30 m upgradient along the flow line, no increase of temperature is visible. This shows the importance of groundwater flow velocity in the context of heat transport assessment.

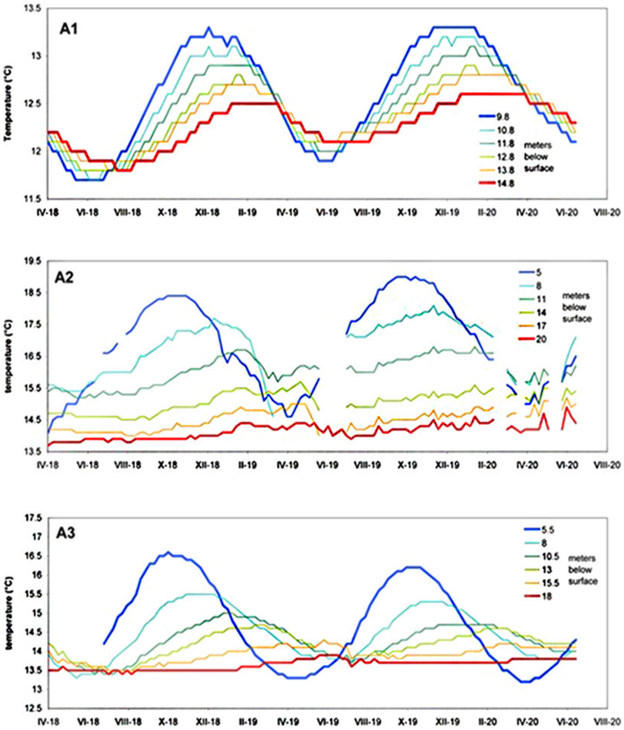

Fig. 9. Data measured directly in the geological environment using PT100 thermistors connected to a Fiedler data logger. Data from well A-2 is noisy, probably affected by operating a nearby electric vehicle charging station.

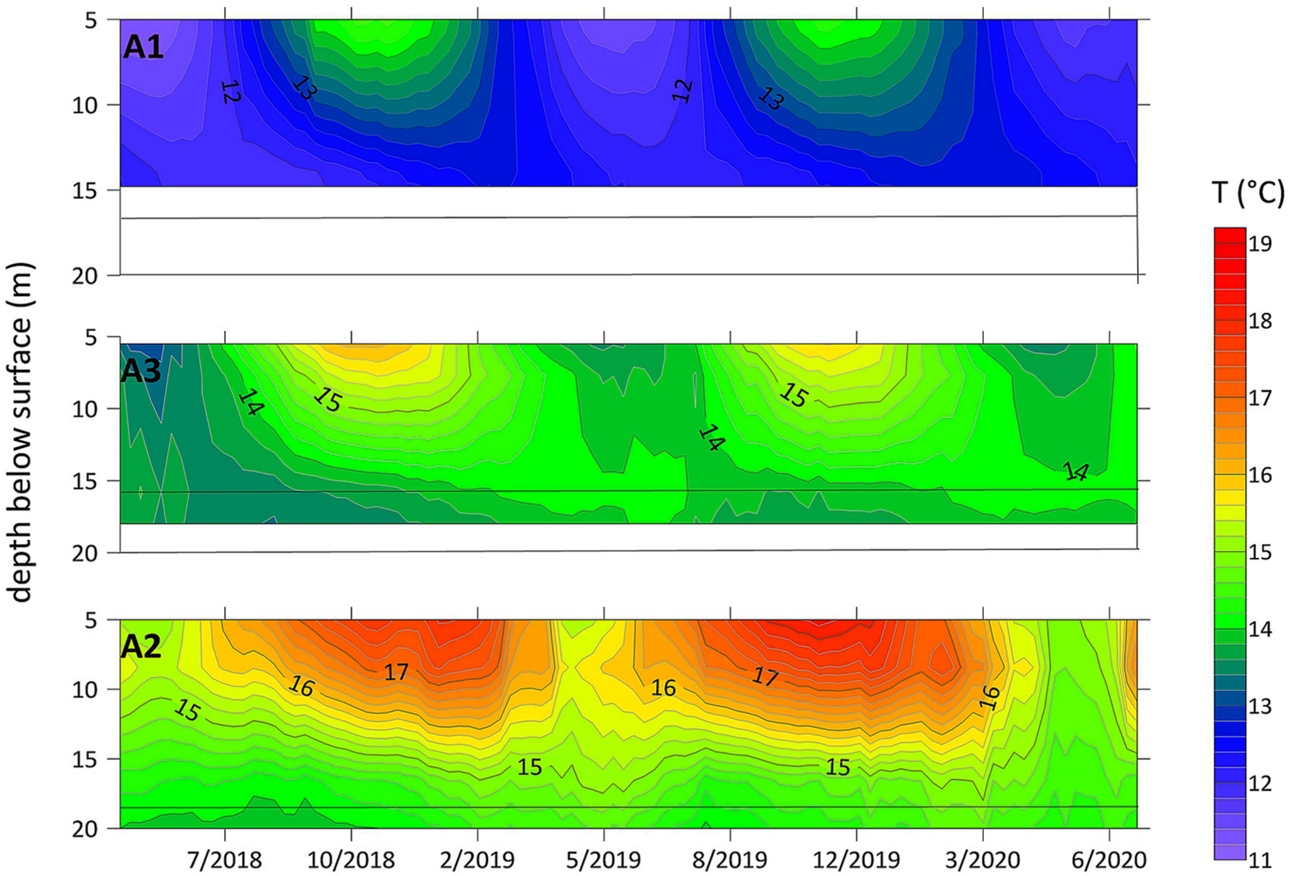

Fig. 10. Development of temperatures with depth in individual wells during monitoring, ranked from the least affected well A-1 to well A-2, which is most affected by the foundations of the Aupark shopping centre.

4.2. Hydraulic model

The size of the model was 1000 x 1000 m, with a basic cell size of 3x3 meters. The model area was divided vertically into 18 layers, of which 13 layers represented the aquifer and the remaining 5 layers represented the impermeable Neogene subsoil. The input parameters that were entered for the calculation of the hydraulic model are given in Tab. 2. The hydraulic model was built for steady flow conditions. In the north of the model area, the 1st type boundary condition H = constant was determined with a value of 131.5 m a.s.l., which represents the average water level in the Danube. In the south of the territory in question, a boundary condition of type 1 was defined with a value of 130.8 m a.s.l., which represented the average groundwater table level at the site. The results from the hydraulic model subsequently served as input for the creation of the transport model.

Tab. 2 Input parameters for calculating the hydraulic model using MODFLOW

parameter	value	unit
Hydraulic conductivity Kx	$1{\cdot}10^{-3}$	$m{\cdot}s^{-1}$
Hydraulic conductivity Kz	$1{\cdot}10^{-4}$	$m{\cdot}s^{-1}$
Hydraulic conductivity – Neogene Kx	$1{\cdot}10^{-6}$	$m{\cdot}s^{-1}$
Initial water table level	131.3	m asl

4.3 Transport model

The transport model of the solved area was processed using the MT3DMS code, which is part of the Groundwater Vistas 7 software. Input parameters for transport calculation are given in Tab. 3. To calculate the transport model, it was necessary to define the initial temperature, which in our case, was equal to the average air temperature.

Tab. 3 Input parameters for calculating the transport model using MT3DMS

parameter	value	unit
hydraulic conductivity Kx	$1{\cdot}10^{-3}$	$m{\cdot}s^{-1}$
hydraulic conductivity Ky	$1{\cdot}10^{-3}$	$m{\cdot}s^{-1}$
porosity	0.25	–
solid phase density	2650	$kg{\cdot}m^{-3}$
longitudinal dispersibility	0.5	m
transverse dispersibility	0.05	m
diffusion coefficient	0.16	$m^2{\cdot}s^{-1}$
distribution coefficient	$2.1 \cdot 10^{-3}$	–
initial temperature	12.3	°C

The transport model was defined as transient. This means that the temperature has changed over time; in our case, the length of the time step was 1 month, and the total transport time was 49 months. The 1st type boundary condition was entered into the first layer, where the average air temperatures for the given months were input. The average air temperature was equal to 12.3°C. Another marginal condition was the Aupark shopping centre, which directly affects the groundwater temperature. The boundary condition was defined as T = constant, i.e. not changing over time with a temperature value equal to 20 °C. This temperature is the average temperature inside the basement.

4.4 Calibration and model results

The accuracy of the transport model largely depends on the calibration process, where the input parameters are adjusted to achieve the best possible match among the measured and modelled values. There were five wells located in the study area equipped with data loggers, which provided us with information on the development of groundwater temperatures or the rock environment, and which served as a basis for model calibration. From the data, the average monthly values were calculated at the first step, and these were then inserted into the model (as so-called targets) and used to calibrate the model. Three calibration targets were set up in the model. The observed temperatures were determined for each target. In the Groundwater Vistas 7 environment, automatic calibration using the PEST programme was used. The calibrated parameters (e.g. hydraulic conductivity) and the range of values in which the parameter can occur were inputted into the programme. The software then changed the values of the calibrated parameters automatically and performed a model solution. Subsequently, using a set of statistical methods, it determined the difference among the measured data and the modelled data. Using statistical methods, a residual value (error) was determined in each monitoring object, which informs of a model error. The residual was computed by subtracting the modelled temperature values from the target values. The value of residual of the transport model was 0.25, which indicates a high quality result. The most accurate result was achieved in the well A-1, and the lower quality was on the well A-2. The sufficiency and efficiency of the calibration could be verified through a report in which the individual statistical indicators are evaluated. As an example, Tab. 4 is presented. The programme also determines the sensitivity of the parameter to the change of value, i.e. how the change of the parameter affects the error of the model. From the automatic calibration applied to the model, it was possible to conclude that the solution was

Tab. 4 Summary statistics for Targets

Target Statistics	value
Residual Mean	0.25
Residual Standard Deviation	0.85
Absolute Residual Mean	0.64
Sum of Squared Residuals	$6.92{\cdot}10^{2}$
Root Mean Square Error	0.89
Minimum Residual	−1.88
Maximum Residual	2.47
Range of Observations	6.57
Scaled Residual Standard Deviation	0.129
Scaled Absolute Mean	0.098
Scaled Root Mean Square	0.135
Number of Observations	882

largely influenced by the hydraulic conductivity. The hydraulic conductivity is a very sensitive parameter, and even with minor changes it has a great influence on the error (or accuracy) of the model. The resulting transport model of the study area is shown in Fig. 11. The heat transport model was set up using MT3DMS. Monitoring of wells A-1, A-2, and A-3, and the Aupark shopping mall are shown in the heat transport model as well. The transport model displays the effect of how the river decreases with distance, as well as how the heat input of the shopping mall from the surface is predominant.

5. DISCUSSION AND CONCLUSION

Rock environment and groundwater temperature change due to urban development is an increasingly discussed topic. This is generally referred to as an urban heat island. Numerical modelling is a sophisticated tool used for solving a given problem. Although the schematization of the natural environment is largely limited, the current technical equipment makes it possible to overcome more and more shortcomings.

In the subject area of Bratislava – Aupark shopping mall, it was possible to interpret the given issue appropriately. Multilevel monitoring of the temperature and depth of groundwater table levels in the area was implemented there. By using data from different depth levels of the area, it was possible to analyze the impact of the building on the increasing groundwater temperature relatively accurately. Multilevel monitoring for modelling purposes was introduced; for example, in the study by Mueller et al. (2018). The advantage of multilevel monitoring is that it allows us to define the boundary conditions for heat transport.

Based on the monitoring data, it is possible to state that the greatest impact of the building on the groundwater temperature can be seen in the well, A-2. The highest temperature reached 18.98 °C at a depth of 5 m below the ground. This is up to 5 °C higher than the average temperature in wells A-1 and A-2. The modelled temperature without the influence of the building is approximately 13.5 °C. The trend of increasing the temperature by up to 5 °C is also found in the contribution by Zhu et al. (2010), where the geothermal potential of urban heat islands is investigated. The course of groundwater temperatures was also influenced by the seasonality of the weather, with a phase shift of approximately 3 months (maximum temperature of groundwater was in the winter months).

Using the Groundwater Vistas 7 programme, a model was compiled, the aim of which was to determine the influence of individual input parameters on the sensitivity of the model results, as well as to determine the energy input from the Aupark shopping centre into the rock environment.

The transport model was built using the MT3DMS code. One of the disadvantages of this programme is that heat transport through the unsaturated zone is problematic. For the cells where there is no water, the MODFLOW marks them as dry. The MT3DMS omits these cells and transfers the concentration (temperature) down from the surface without change to the nearest active cell below the inactive cells. However, this is an inappropriate approximation because the temperature changes in depth (its amplitude decreases, and a phase shift occurs). This issue is already fixed in the programme MODFLOW – USG, which directly contains the transport module dealing with transport through the unsaturated zone (Falakdin, 2019).

Through automatic PEST calibration, it is possible to analyze the influence of input parameters on the final solution. The PEST is a relatively technically and time-consuming process; however, its application makes the resulting solution significantly more accurate.

The input energy from Aupark varied in the following values: 0.1 W·m^{-2} at a distance of 100 m to 12 W·m^{-2} immediately next

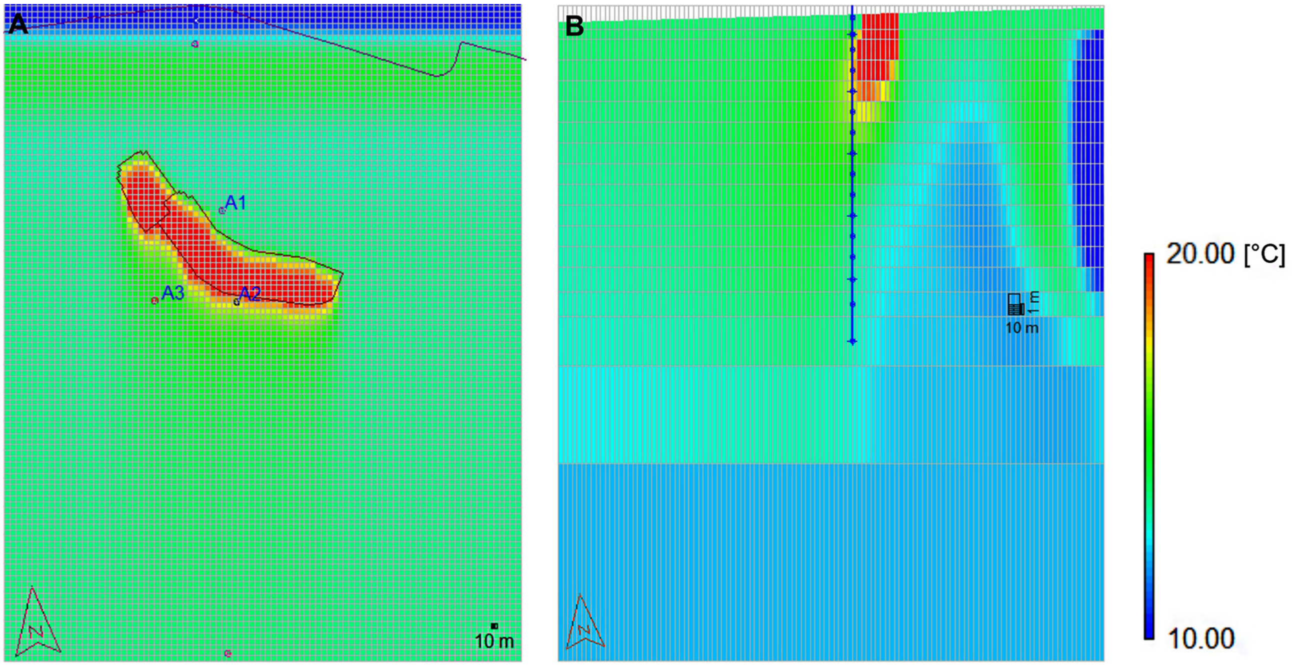

Fig. 11. Heat transport model compiled using MT3DMS: A – planar view, B – cross section

to the building, which is in line with the previous studies by Epting & Huggenberger, 2013a and Bidarmaghz et al., 2019. It can be stated that the heat input into the aquifer increases if the distance between the basement structure and the groundwater table decreases (Kupfersberger et al., 2017). The calculation of input energy is essential information for possible future planning of use of the temperature increase.

Evaluation of the heat transport through modelling is a time-consuming process, which, however, provides useful information about the interaction of the building with the natural environment. The use of modelling tools for simulation of natural processes with a wide range of input variables is becoming more and more important. As such, they can provide useful information on the impact of urban development on groundwater temperature changes.

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