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Hydrodynamic characteristics of water supply source of Kikinda (Serbia)

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ABSTRACT

For the purpose of simulation of groundwater exploitation on the public source of water supply of the city of Kikinda, hydrodynamic flow model of the groundwater regime was created. Made hydrodynamic model includes urban groundwater source of Kikinda (groundwater source „Šumice" and the well „Jezero") but also includes a wider area in which are the groundwater sources for water supplies for factories: "MSK", „TM" and „LŽT - Kikinda". Application of hydrodynamic modeling, based on numerical method of finite difference will show groundwater balance of sources of the wider area of Kikinda. Also, it will be shown the impact of the sources for the industry on the regime of the public water supply source. Radius of influence of groundwater source is determined by simulation of conservative particles for a period of 200 days.

KEYWORDS: water supply, groundwater source, hydrodynamic modeling, groundwater balance, particle tracking

INTRODUCTION

Municipality of Kikinda is located on the north-eastern part of Vojvodina, which occupies an area of 782 km^2. According to the latest census from 2002, it has 41935 inhabitants, with population growth of -5.7%. Geological and hydrogeological research in the past of few years was done in the in the wider area of the groundwater source of Kikinda aimed to provide the necessary amount of quality groundwater to water supply of citizens. This area belongs to the southern part of the Pannonian Basin, which is a lowland character and occupies the northern parts of the territory of Serbia (Fig. 1). City of Kikinda covers an area of 13.5 km^2 in a typical large Banat plain, where the highest elevation is 83 m, while the lowest is 76 m. Water supply source of Kikinda is tapping groundwater by 11 wells. Tapped water-bearing horizon is at a depth of about 250 m, formed in the Quaternary sands, thickness of about 50 m. In the surroundings there are also groundwater sources for the industry which have certain influence on the regime of the public water supply source.

Determination of the groundwater balance of groundwater sources was carried out by the method of hydrodynamic modeling. Also it was shown the impact of the industry groundwater source on the urban groundwater source. For determining the radius of influence of groundwater sources for a period of 200 days, a method of particle tracking [1] was used. Period of 200 days includes the area from which groundwater flows into the tapping objects of that period and represents the third and the widest sanitary protection [2]. The particle

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tracking can be used for different purposes. The backward particle tracking method with an uncertainty analysis concerning the porosity values, applying a Monte Carlo approach, coupled with the use of geographical information systems (GIS) can be used to delineate groundwater protection zones [3]. The particle tracking simulation can be used to determine travel times from recharge areas to discharge areas along the flowpaths identified [4]. Using a standard numerical flow and transport code and the technique based on adjoint theory and combines forward-in time and backward-in time transport modeling, can be determined the impact of potential contaminant sources at unknown locations within a well capture zone, including the expected times of arrival of a contaminant, the dispersion-related reduction in concentration, the time taken to breach a certain quality objective, and the corresponding exposure times [5].

GEOLOGY

Extensive geological research (structural exploration drilling, geophysical work, paleontological work) enabled a relatively good researched field of geological conditions [6]. Of the lithological units, there are sediments of Pliocene and Quaternary. The base of the Quaternary sediments are shallow-lacustrine sediments of Upper Pliocene. They are built of sandy siltstone, gravelly and sandy siltstone, dark gray siltstone and organogenic silty sands. In these sediments, carbonic interlayers and organic matter are regularly present. Color of sediments varies from dark gray to light gray and olive-gray. During the Quaternary, Pleistocene and Holocene deposits were abstracted. The earliest anthropogenic formations built river and lake sediments of the lower Pleistocene. The immediate sequel are river-marsh sediments of Mindel period whose continuity is extended during the Mindel-Riss interglacial period. Upper Pleistocene is built of river-marsh sediments of the riverbed facies and of the floodplain facies which constitute the deposit "Varoška terrace" of Wurm age. Sedimentological analysis showed that the river and lake sediments were made of sands, silty sands and of alevrites (sandy, rarely clay and gravelly), while the river and marsh sediments were composed of clay alevrites and alevrite sands with gravel.

Figure 1. Geographic position of study area

In the postglacial period during the Holocene, more units were abstracted: abandoned channel facies, floodplain facies, marsh sediments, alluvium, and the youngest unit which had been deposited from the Holocene to the present day - beach facies of the Tisa River. Sedimentological analysis showed that they were made mostly of alevrites, sand, gravel and loess.

HYDROGEOLOGICAL OVERVIEW

Large number of wells (Fig. 2) was drilled in the exploration area [7]. According to the type of porosity and hydrodynamic characteristics, in this region there are two types of aquifers: confined aquifer and unconfined aquifer, formed in the Quaternary sands.

Unconfined aquifer was formed in the Quaternary sands, in alluvial sediments of rivers. Sediments are dipping to a depth of about 30 m. Recharge of the aquifer is done by infiltration of precipitation directly from the surface waters, since there is a a good hydraulic connection between aquifer and the river. Drainage of the aquifer is done in a natural way at the time of the hydrological minimum, when due to the low water level, movement of groundwater is directed towards rivers and artificially - through drilled and dug wells.

Confined aquifer was formed within more water-bearing complexes of Quaternary sands. Although in the aforementioned aquifer there are more water-bearing layers, it was not possible to carry out their separation, by the geometry, the hydraulic relations and physical and chemical characteristics of the water. The reason for this is the history of terrain formation, or more precisely, these are the lake, marsh and river sediments for which there are no reliable data about the horizontal and vertical distribution and interlayers of the slightly permeable and impermeable layers. An important characteristic of these layers is the constant alternation of sands, slightly gravelly sands, with loessial clays, sandy clays, and clays (Figure 3). In the figure, it can be see that the lateral alternation and thinning of the impermeable layers and water-bearing layer is characteristic. The layers of sand, which can even be over 30 meters thick (although this number is typically under 10 m), represent the basis of certain polygenic packages. Over the sands are more microgranular sediments: loamy sand, loessial clays, clays, and sand clays. These transitions towards the more finely grained sediments are often quite gradual.

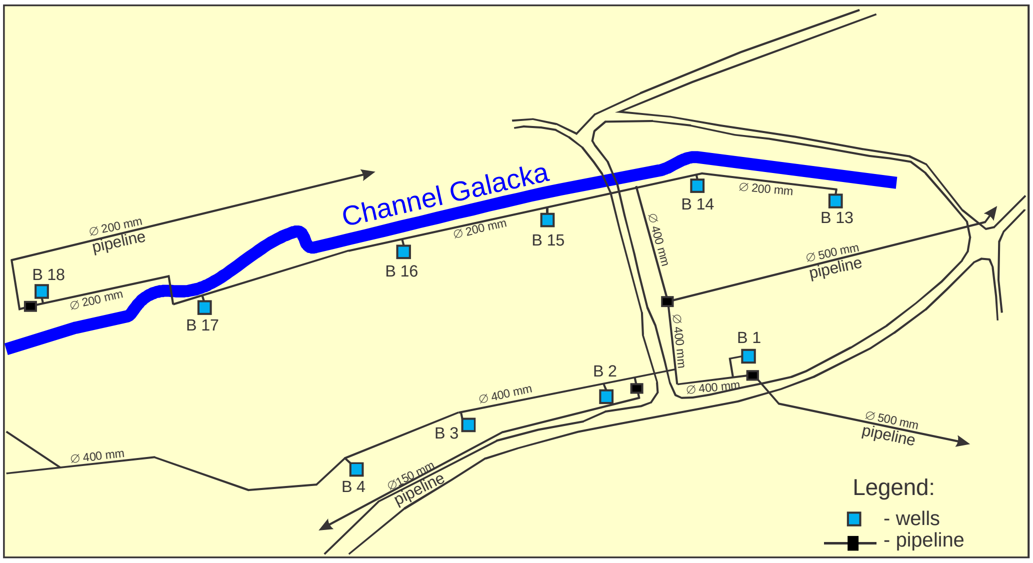

Figure 2. Map of well location at the groundwater source „Šumice”

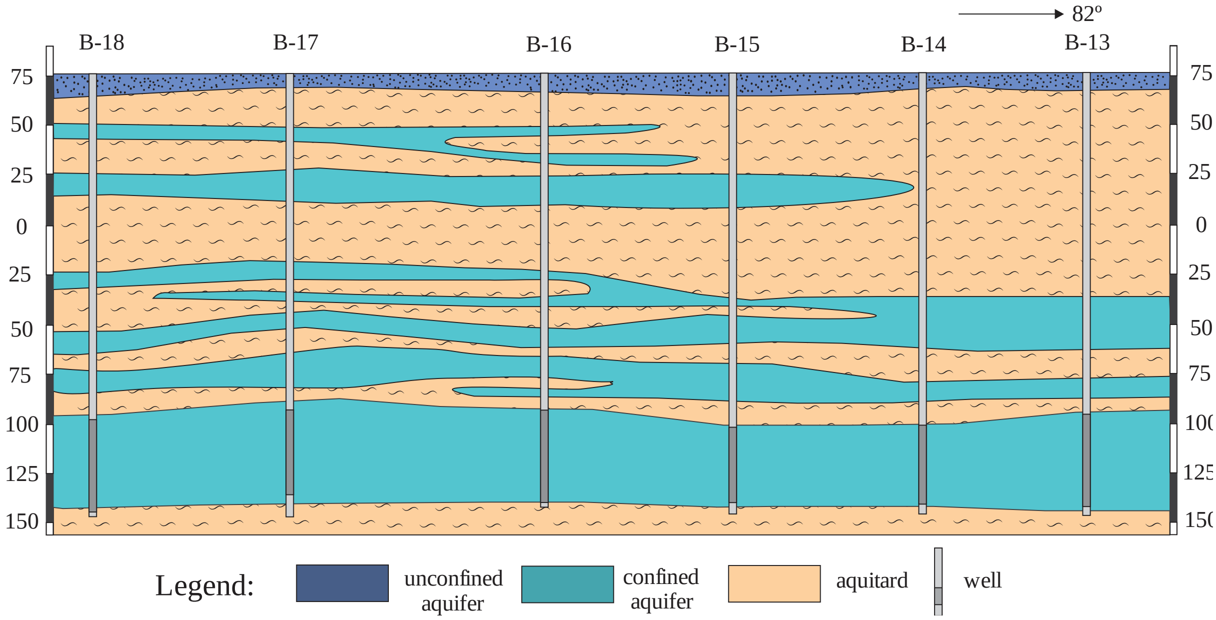

Figure 3. Hydrogeological sections of the groundwater source „Šumice"

Based on the results of grain size determination of the composition of materials contained in the water-bearing horizons, which also include the examined aquifer, we can say that the material of the water-bearing formation is represented by sands of fine and medium granulation (uniformity coefficient: d_{60}/d_{10}=2-3 with d_{50}=0,1-0,3 mm). Based on the data analysis from the pumping test, it can be conclude that, in the larger area of Kikinda, the transmissibility coefficient is within the range, depending on the locality between (2,5-10) x 10^{-2} m^2/s. The table 1 contains the values of the hydrogeological parameters that were determined in the previous period for the area of Kikinda [8]. The analysed aquifer extends beyond the studied area. The recharge of this aquifer is probably done on the slopes of the Carpathian Mountains, the Vršac Mountains, and Fruška Gora mountain (east of the research area). The aquifer is also recharged from the surface waters in the south-west part of the area, where the layers within which the aquifer was formed, subsided to smaller depths, which allowed the formation of the hydraulic connection between the river and the aquifer over the alluvial layers. The main forms of aquifer drainage are: the artificial drainage (through the groundwaters exploitation) and the leakage into overlying bed - less permeable layers (due to the confined aquifer), and from them into the top aquifer. In the lithological view, the aquitards are mostly represented with clays and sandy clays (Fig. 3).

Table 1. The values of hydrogeological parameters determined on the basis of previously performed field work

Wells	Transmissibility coefficient (m^2/s)	Hydraulic conductivity (m/s)	Year
„Šumice" (B-2)	(10-12) x 10^{-3}	-	1979
Toza Marković	(11-18) x 10^{-3}	-	1979
MSK	(3-7) x 10^{-3}	-	1978
MSK	(17-22) x 10^{-3}	-	1981
MSK	20.5 x 10^{-3}	8.5 x 10^{-3}	1995

CONCEPTUAL (HYDROGEOLOGICAL) MODEL

The conceptual model of the hydrogeological system is based on the geological information from boreholes (Fig. 2) and water-level fluctuation in observation wells. The conceptual model was designed according to the actual groundwater flow in the basin. It is simulated by three layers in the vertical section, one layered aquifer, where the horizontal and vertical flow among the simulated layers were considered. The model layers, downward from the ground surface, are given in Tab. 2.

Table 2. Corresponding layers of terrain and model layers

first confining stratum	clayey sediments with interbeds of sands
second water- bearing stratum	fine-grained and medium-grained sandy sediments
third confining stratum	clays and clayey sands

Made schematization is based on the existence of the slightly preamble sediments of overlying bed and underlying bed and the water-bearing horizon, tapped by the enumerated groundwater sources. This way, the influence of the possible hydraulic contact with the sandy water-bearing horizons in the bottom layer of the pumped horizon is avoided, because of the insufficient level of analysis, as well as the artificially created difficult conditions in the recovery of the groundwater reserves, which, of course, has to do with the safety of the water source's functioning. Geometrization of the layer contours, their transposition into the coordinate system of the model, is based on abundant data from boreholes all over the research area. The Figure 4 represents the three-dimensional hydrogeological model of the sectional view of the "Šumice" groundwater source. In the figure, the tapped water-bearing horizon is coloured in blue, and it contains screen constructions for the exploitation wells (coloured in green). As we mentioned before, the overlying bed and underlying bed of this water-bearing horizon consist of the slightly permeable and water impermeable sediments.

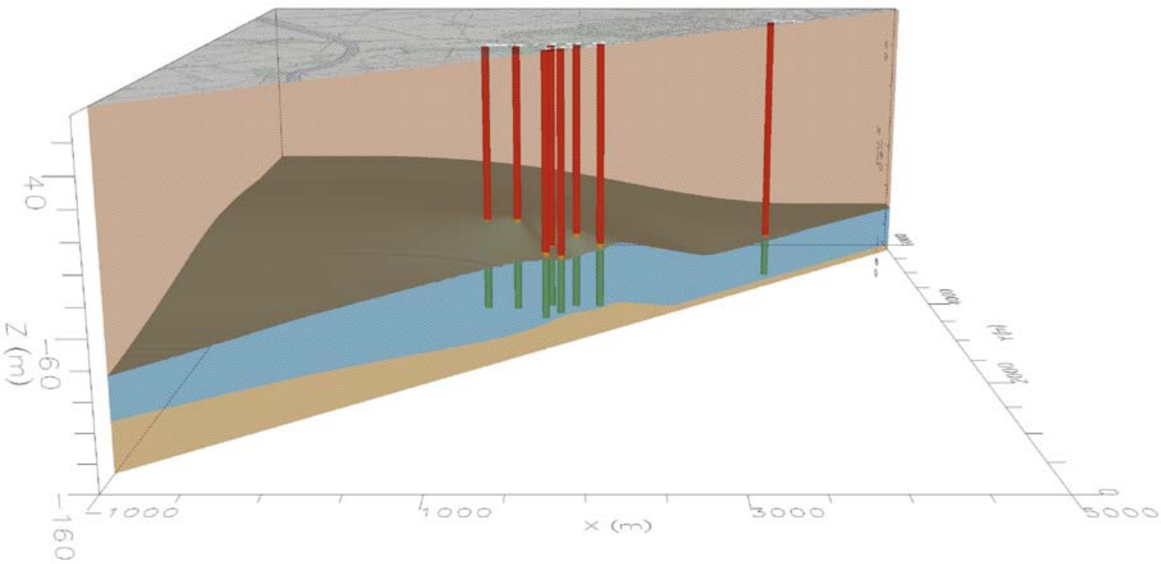

Figure 4. 3D hydrogeological model of the groundwater source „Šumice" – azimuth section 230^{o}

HYDRODYNAMIC MODEL

The entire concept for the development of the hydrodynamic model of the groundwater regime of sources for Kikinda’s water system is based on the simulation of the three-dimensional groundwater flow. The essential in the selection of the conception for the mathematical model of the aquifer were the natural factors, such as the type and characteristics of the represented geological units, distribution of water-bearing and impermeable units, seepage characteristics of porous media and mechanism and regime of groundwater flow, as well as the desired goal within the given assignment. During the selection of the main model characteristics, it has been proceeded to create a multi-layered model. The hydrodynamic model includes the urban groundwater source of Kikinda (the “Šumice” source and the well “Jezero”), but also a wider area which contains the groundwater sources for water supplies for factories: “MSK”, „TM”, and „LŽT - Kikinda”.

The tree-dimensional (3D) finite-difference numerical model for this study was developed using ModFlow [9] with Grounwater Vistas as graphical user interface [10]. The model domain 6 x 6 km and 300 m in depth. The domain is oriented north-south and discretized into 100 rows, 100 columns and 3 layers. Grid cells size is refined to 12.5 m x 12.5 m in the area of interest where the groundwater wells are dense and extraction rates are high (Fig. 5). As an illustration of the flow field discretization and the derived schematization of the geometric relations between the lithological elements in the research area, Figure 6 shows the result of the schematization that was made in the vertical profile.

Hydraulic parameters

Seepage characteristics of the schematized model layers were specified through the values of the hydraulic conductivity, storage coefficient, specific storage, and the effective porosity. These hydrogeological parameters were assigned as the representative values to each cell o discretization. As initial values of the hydraulic conductivity of the made model, values of this parameter, obtained during the testing of exploitation wells in previous period, were used. During the course of research, the pumping test were not performed on wells for the purpose of development of hydrodynamic models, given that there was a reduction in the water supply for both the population and the industry. The initial values of the storage coefficient, the specific storage, and the effective porosity were adopted based on the foreign experience [11, 12, 13, 14] related to the hydrogeological properties of sediments with similar characteristics.

Boundary conditions

In the hydrodynamic mode of the “Šumice” water source, the following boundary conditions were applied: head-dependent flux boundary condition (Cauchy or mixed conditions), boundary of prescribed flux (Neumann conditions) and specific head (Dirichlet boundary type).

Head-dependent flux boundary condition (Cauchy or mixed conditions) - the influences of the channel Galacka was simulated using this boundary condition. Given the depth of subsidance of the pumped aquifer at the source and a thick package of less permeable and impermeable sediments in its overlying bed, the surface stream have no influence on the groundwater regime in the tapped horizon. This boundary condition was allocated in the first layer at locations where the channel exist as the minimal mutliannual values, or 74.00 mnm for both channel. Widths of the channel is given according to a topographic map, elevation 0.5 m less than the minimum water level of the channel, and the thickness of the layer at the bottom of the channel 0.15 m with a value of hydraulic conductivity $1x10^{-6}$ m/s.

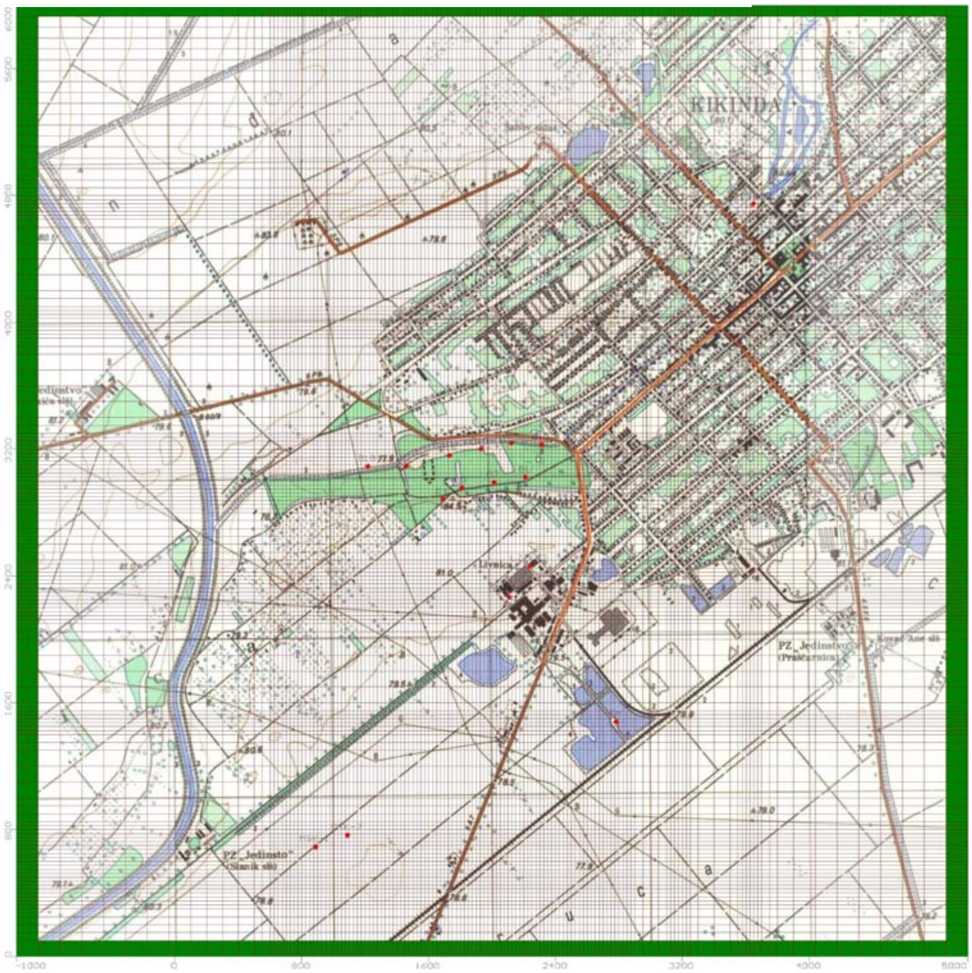

Figure 5. Survey of discretization and boundary conditions: red – wells, green contours – general head boundary

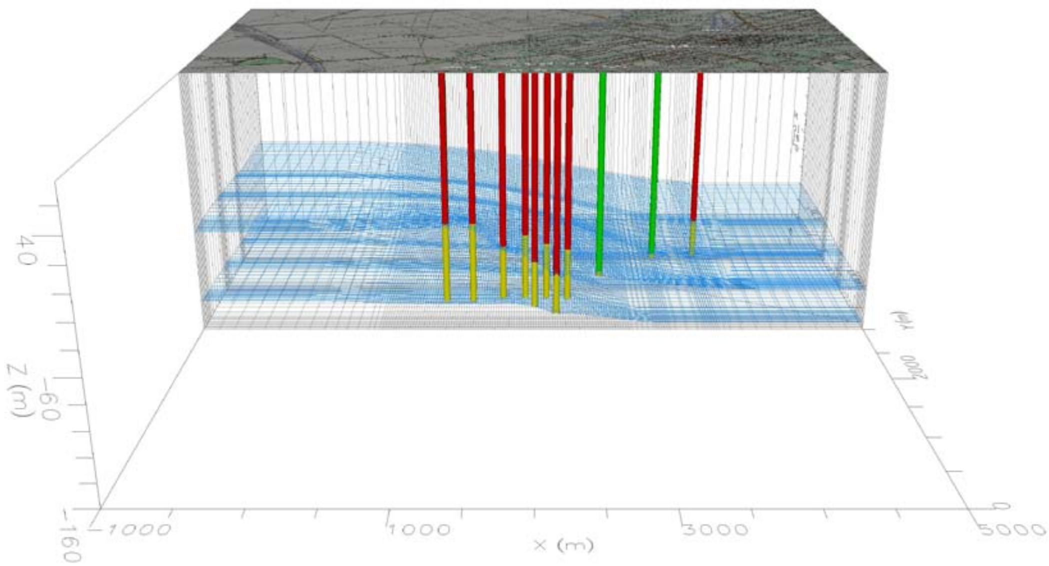

Figure 6. Discretization (cross-section west-east) Legend: blue network - aquifer

Under the same boundary condition, the head-dependent flux boundary condition, the effect of source recharge or drainage that is located outside of the area covered by the model, has been simulated. In the ModFlow code, which was used here, it was represented with the “*general head boundary”*. In the second model layer, the registered piezometric levels of the pumped water-bearing horizon in the local groundwater sources were set in this manner, given the remote locations where this horizon is recharged. The Figure 5 represents this type of boundary condition.

Boundary of prescribed flux (Neumann conditions) - The impact of wells on the groundwater source was simulated through the boundary with a specific flux. In this case, the flux was specified as a function of position and time. The Figure 5 presents the position of wells, whose functioning, in the model, is simulated with a specified boundary condition of the prescribed flux. For the purpose of hydrodynamic model, the values of the well capacities at the "Šumice" groundwater source were registered every seven days in the period between 02.01.2009 and 31.12.2009 (table 2). Figure 7 shows a well capacities diagram of the registered individual wells in the observed one-year period at the “Šumice” water source. The model shows the individual wells capacities at the “Šumice” groundwater source, assigned with consideration to the registered dynamics of the wells functioning and by taking into account the measured capacities of individual wells. The screen constructions of the wells are given with the real dimensions on which they were built. In the hydrodynamic model, the capacities of the exploitation wells in the surrounding water sources are set based on the existing technical documentation [15] as the constant values throughout the entire period. These are:

- “MSK” groundwater source, using two exploitation wells with a total capacity of 54 l/s
- „TM” groundwater source, using a single exploitation well with the capacity of 35 l/s
- “LŽT - Kikinda” groundwater source, using two exploitation wells with a total capacity of 50 l/s.

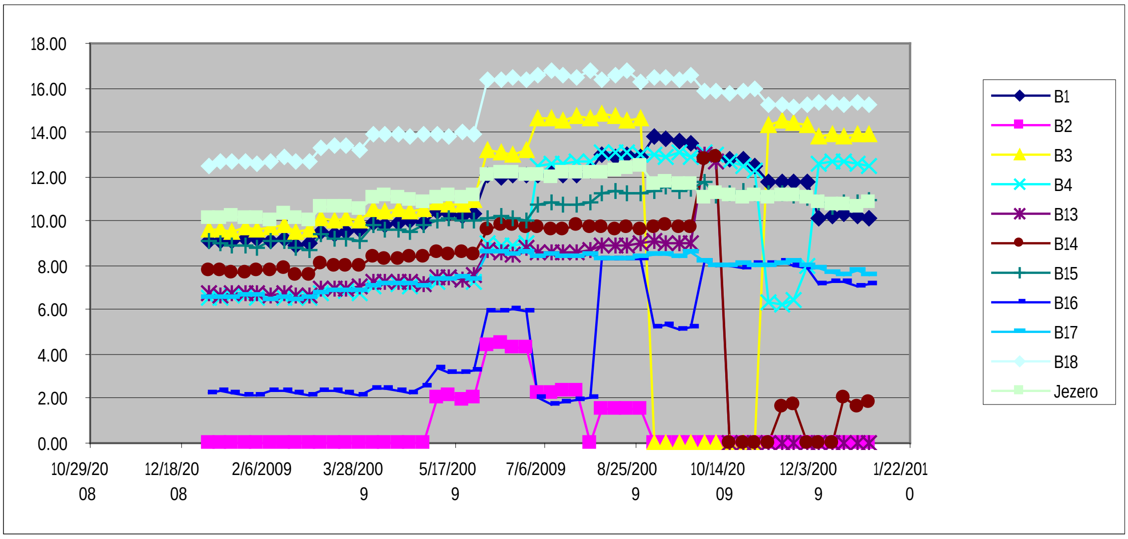

Figure 7. Diagram of the registered well capacities of individual wells in the period between 01.01.2009 – 31.12.2009

Effective infiltration - in the overall balance of the groundwater, for the reasons cited in the description of the boundary conditions of „rivers“, the, so-called, „vertical balance“ has no direct impact on the tapped water-bearing horizon. It was simulated through the first layer by variable flux Neumann boundary conditions. This value is made up of the sum of infiltrated precipitation and evapotranspiration. The depth to the groundwater table during the whole analyzed period (01.01.2009 – 31.12.2009) was several meters below the terrain surface (4-7.3 m). Bearing in mind that the top layer has low permeability, infiltration of rainfall has only a small impact on the groundwater regime. As an initial value of effective infiltration, a 10% precipitation value was used. The Figure 8 represents the mean monthly precipitation values for the period between 1996 - 2006.

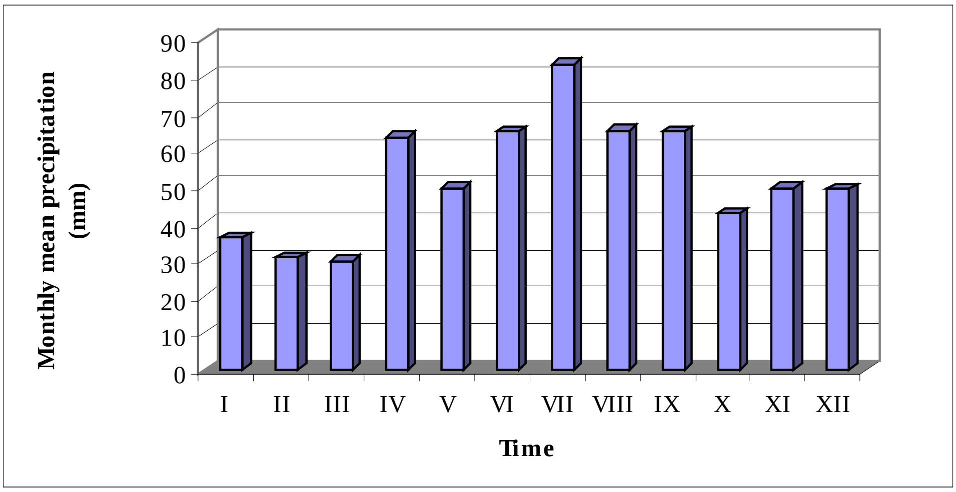

Figure 8. Monthly mean precipitation values for the period 1996-2006.

Model calibration

The calibration of the model was carried out under the conditions of transient flow, with a time step of seven days for the analysed period (01.01.2009 – 31.12.2009). The Figure 9 represents comparative review of the total capacity of the "Šumice" water source and the registered piezometric levels in the observation wells.

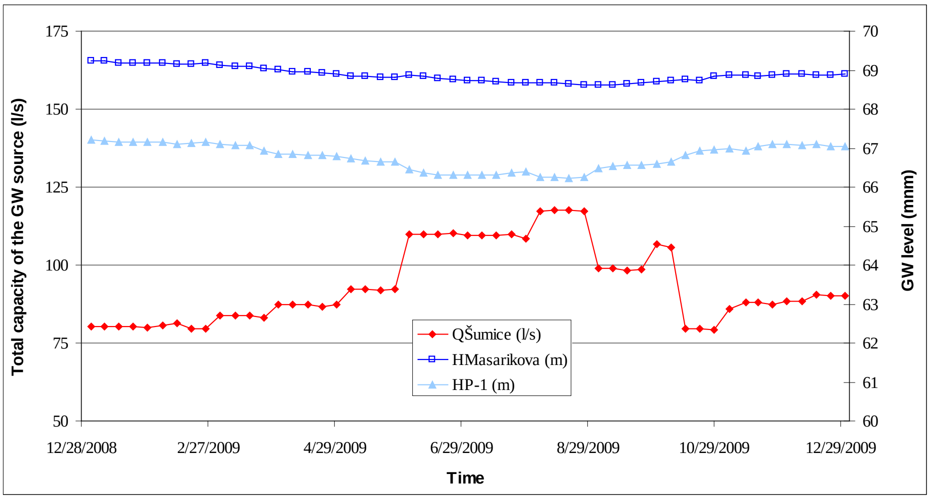

Figure 9: Diagram of the total capacity of the “Šumice” groundwater source and the piezometric levels in the observation wells (01.01.2009 – 31.12.2009)

The calibration of the model was completed when a satisfactory agreement between the registered aquifer levels and levels obtained by calculation was received. The Figure 10 presents the arrangement of the piezometric levels in the tapped water-bearing horizon for the maximum water tapping at the "Šumice" water source of 117,66 l/s (20.08.2009). The Figure 11 presents the groundwater levels registered at the observation wells and the figures obtained by calculation in the model calibration process (in the same observation wells). The agreement of registered and calibrated groundwater levels was fairly good.

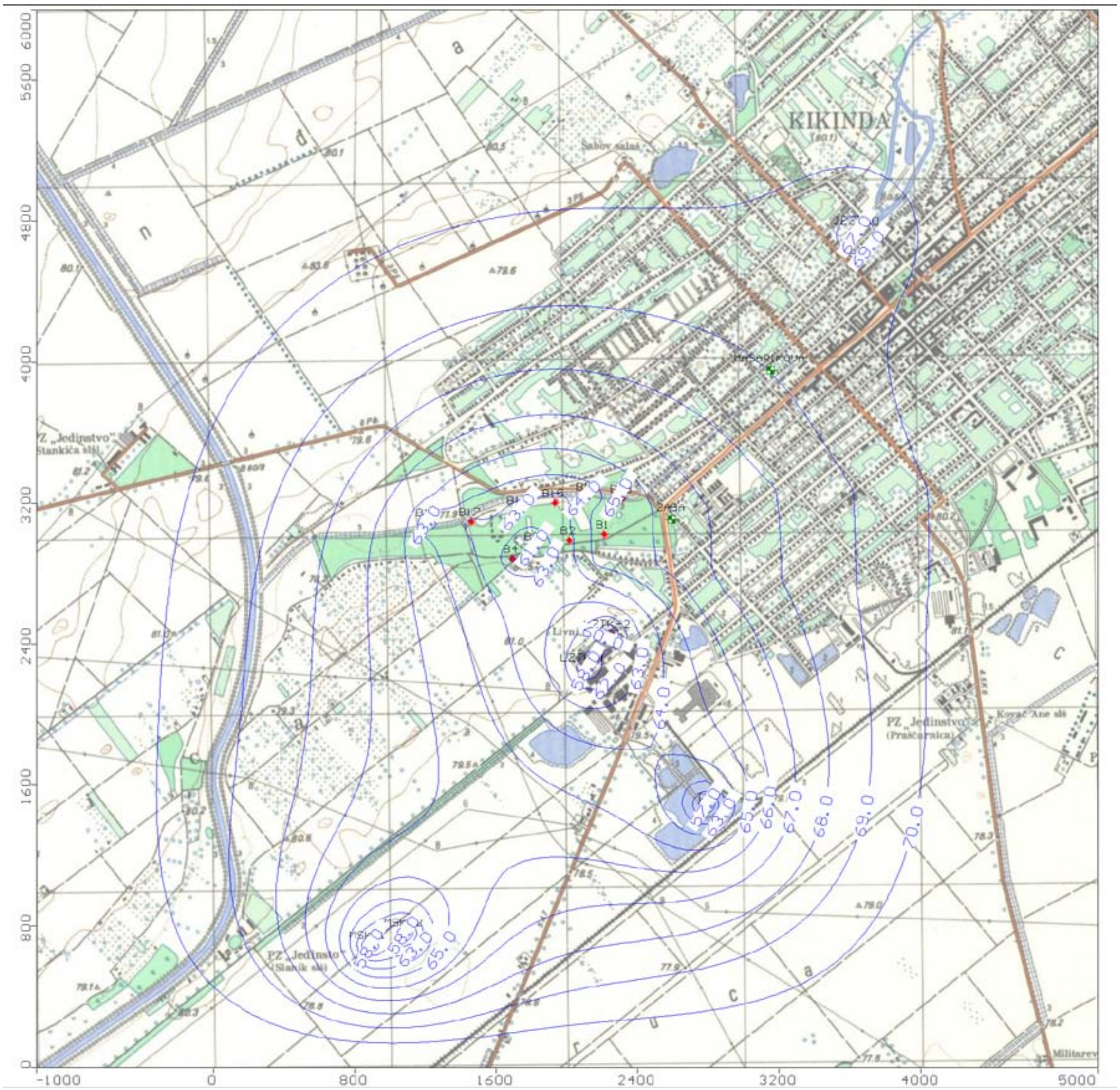

Figure 10: Map of head distributions in the surrounding area of the "Šumice" water source (20.08.2009) for its maximum capacity

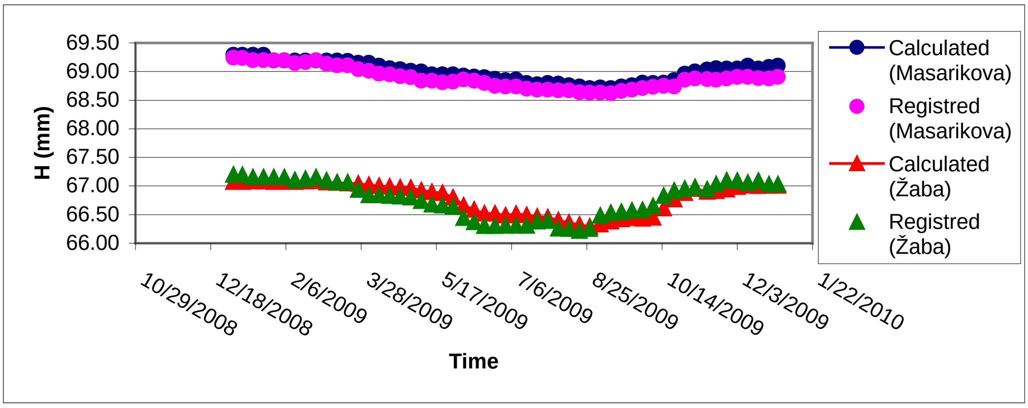

Figure 11: Groundwater levels in the P-1 piezometer („Žaba”) and the „Masarikova” well in the function of an observation well, registered and calculated during the process of model calibration

GROUNDWATER BALANCE

In the analysis of the groundwater balance in the area covered by the model, it was concluded that under the conditions which prevailed during the maximum groundwater pumping at the "Šumice" groundwater source, the most of the groundwater in the tapped water-bearing horizon comes from the South (35.23 %). The table 3 contains an overview of the inflow into the area covered by the model under the give conditions (20.08.2009) meaning. It contains the total balance of groundwater - of the urban groundwater source and groundwater sources for water supply of the industry.

Table 3: Elements of the groundwater balance of the wider area of the “Šumice” groundwater source for its maximum wells capacity of 117,66 l/s including the wells capacity of industry groundwater sources (139,00 l/s)

Model inflow (l/s)		Model outflow (wells) (l/s)
North	27,57	256,66
East	73,85	
South	90,38	
West	64,72	
Sum	**256,52**	**256,66**

RADIUS OF INFLUENCE OF GROUNDWATER SOURCE „ŠUMICE“

Modpath [2] was mostly used to simulate the conservative advection of dissolved phase contaminants or microbes within the groundwater system over the selected periods ignoring the effect of dispersion. It used hydraulic heads from Modflow [9] and computes porewater velocity using the hydraulic conductivity and porosity data. The use of the three-dimensional models easily allowed the consideration of layer heterogeneity and partial penetration of the well screens. As previously stated, the particle tracking can be used for different purposes. In this case, the code modpath was used for the determination of the radius of influence that wells of the "Šumice" water source have. It was determined the distance from the wells needed for water filtering during 200. The arrows on the currents lines that are geared towards extraction wells indicate the segment of 20 days of travel for the conservative particles. The aforementioned Figure 12 shows that the dimensions of the radius of influence of the "Šumice" groundwater source (blue contours) are 700-750 m and the radius of the well "Jezero" is 350 m.

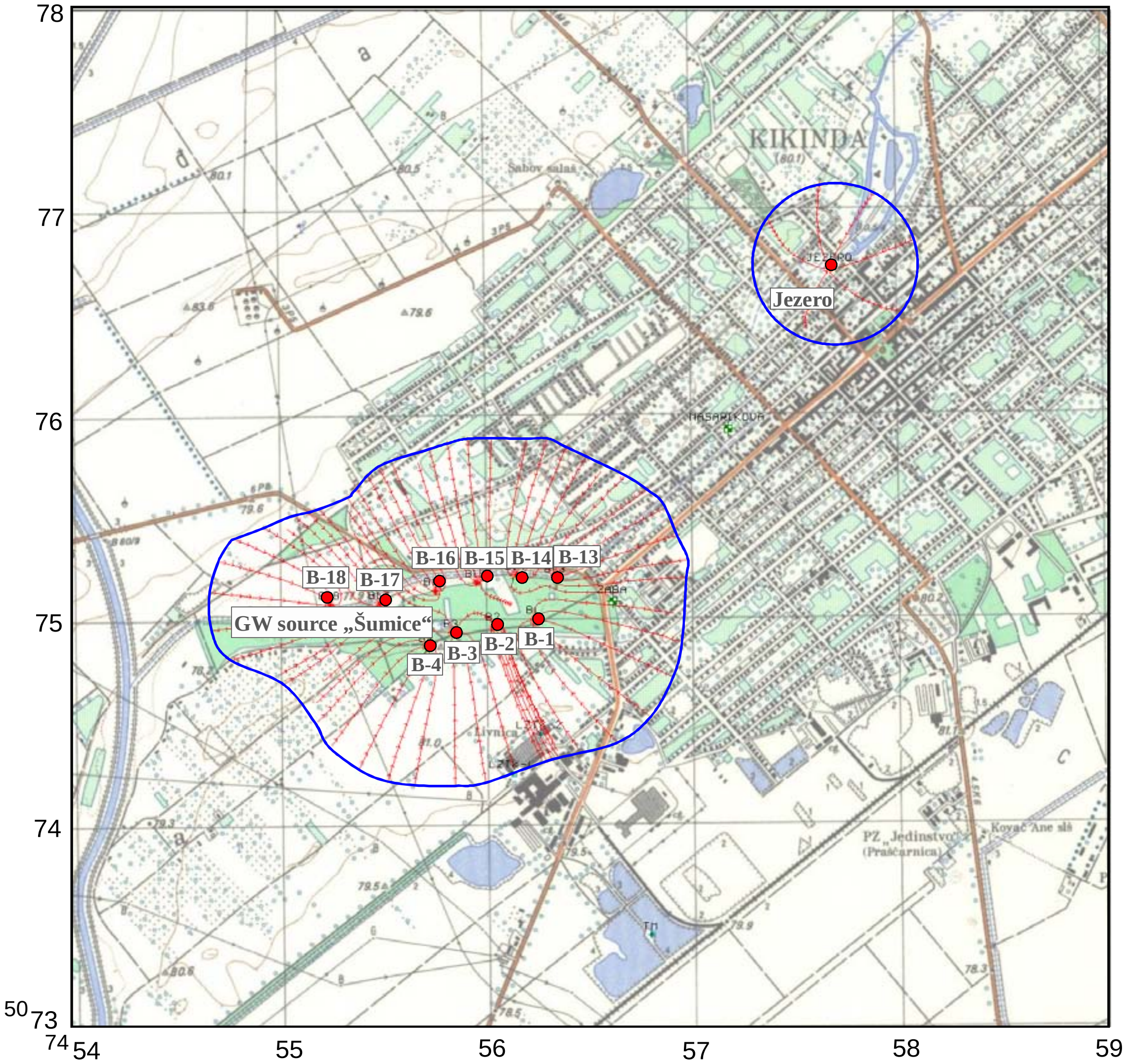

Figure 12: Arrangement of the streamlines around the exploitation wells at the "Šumice" groundwater source for the capacity of 117,66 l/s, which indicate the distance from the well needed for water filtering during 200 days

CONCLUSION

A groundwater flow model has been calibrated for the quaternary aquifer for unsteady-state conditions. The analysis of groundwater balance determined that the most of the groundwater to the water-bearing horizon of the "Šumice" source arrives from the South (35.23%). Assuming the occurrence of Darcian unsteady-state three-dimensional flow and the major assumptions of this method - the linear form of the sink term in the mass transfer equation and the negligible order of magnitude of the dispersion effects, presentation of the particle tracking method for the determination of the radius of influence of groundwater source is performed. Maximum wells capacity of source "Šumice" is 117.66 l/s and for these conditions, the dimensions of the radius of influence of the "Šumice" sources are about 700-750 m, while the radius of the well "Jezero" is 350 m.

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