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Hydrogeological and hydrodynamic characteristics of groundwater sources for the public water supply of Bečej (northern Serbia)

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Abstract. The existing groundwater source for the public water supply of Bečej City in Serbia is tapping groundwater from three water-bearing horizons over 15 wells with a summary capacity over 100 l/s. It is one of the characteristics of sources that several water-bearing layers are most frequently tapped simultaneously by wells. Two layers are tapped simultaneously by 12 wells; all three layers are tapped by ten wells, while one water-bearing layer is tapped by only three wells. The groundwater table at the source was recorded for a period of 30 years. In the conducted hydrodynamic analysis of the groundwater regime, it was concluded that in the mentioned period, a relatively low fall of the water table occurred, far lower than the previously predicted values. The results of a simulation of the exploitation regime of both the town and surrounding sources are presented in this paper for a period of more than two and a half years and the results of the identification of the basic hydrogeological parameters of the tapped water-bearing layers are presented in this paper. In addition, a balance for each element in the water-bearing layers exploited as sources of tapped water for the town are presented.

Key words: water-bearing layer, groundwater source, rheometric measurements, groundwater modeling, groundwater balance.

Апстракт. Постојеће извориште подземних вода за водоснабдевање становништва у Бечеју (Србија) захвата подземне воде из три водоносна слоја преко 15 бунара сумарног капацитета од преко 100 l/s. Једна од карактеристика изворишта је да су бунарима најчешће истовремено каптирано више водоносних слојева. Два слоја су истовремено каптирана на 12 бунара, сва три на 10, а три бунара каптирају само један водоносни слој. Током периода од 30 година регистрован је ниво подземних вода на изворишту. У спроведеној хидродинамичкој анализи режима подземних вода закључено је да је у поменутом периоду дошло до релативно малог опадања нивоа, далеко мање од раније прогнозираних вредности.У раду су презентирани резултати симулације експлоатационог режима градског и околних изворишта у периоду од преко две и по године и резултати идентификације основних хидрогеолошких параметара каптираних водоносних слојева. Такође, презентовани су елементи биланса градског изворишта на нивоу сваког каптираног водоносног слоја.

Кључне речи: водоносни слој, извориште подземних вода, реометријска мерења, моделирање подземних вода, биланс подземних вода.

Introduction

The studied terrain on which the public groundwater source lies is located west of Bečej, north of Novi Sad (Vojvodina). The terrain considered in the research and mathematical model takes the form of a rectangle with sides of 12.8 ×13.2 km and covers an area of 168.96 km^2 (Polomčić *et al*. 2011) (Fig. 1).

To meet the water supply requirements of the population and industry of the wider area of Bečej, the groundwater is tapped from three water-bearing layers located at depths from 60 to 13 meters. The town source of Bečej (Vodokanal–Bečej) comprises about 15 exploitation wells tapping the three mentioned water-bearing layers. The source is characterized by a relatively rapid ageing of the wells and relatively low

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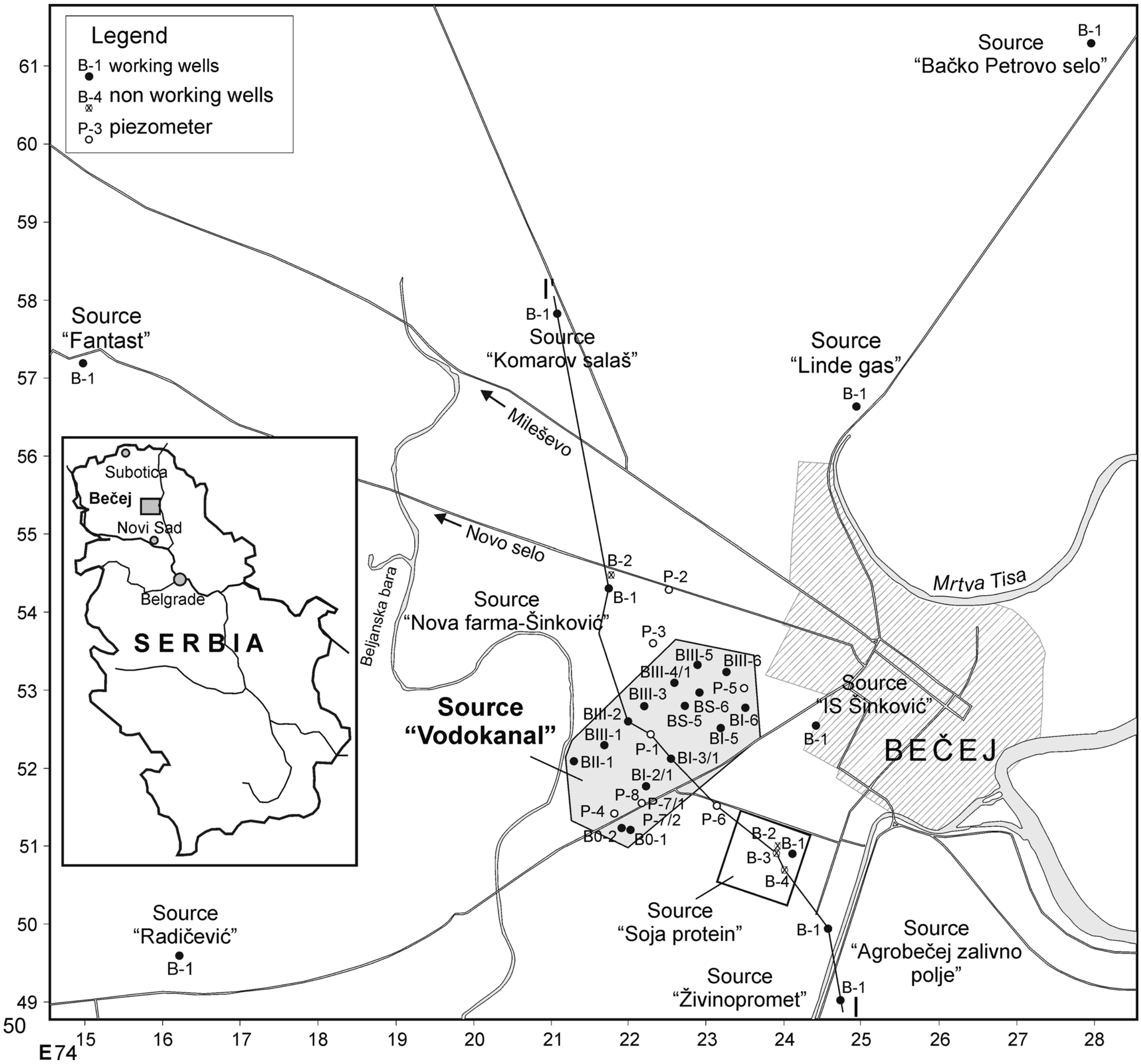


Fig. 1. Geographical location and positions of the groundwater sources.

head losses, being far lower than the predicted values. Several water-bearing layers are most frequently tapped by wells: two layers are tapped simultaneously by 12 wells, and all three by 10 wells, while one layer is tapped by three wells. In order to determine the hydrogeological parameters for each of the water-bearing layers, as well as the ground water balance of the Vodokanal–Bečej Source, a hydrodynamic model for each of the tapped water-bearing layers was developed. During the exploitation regime, a simulation of both the town and surrounding sources for a period of more than two and a half years and an identification of the basic parameters of the hydrogeological environment were performed and the balance of the groundwater elements was also determined.

Geologic setting of the wider surroundings of the Vodokanal–Bečej Source

From a geological point of view, the study area belongs to the large Pannonian Plain. The stratigraphical column in the study area is made of rocks of Precambrian–Palaeozoic, Mesozoic, Miocene, Pliocene and Quaternary age. The oldest rocks in the study area are comprised of crystalline shale, most likely of Precambrian–Palaeozoic age. The crystalline shale is found at depths between 1424 m and 1528 m in deep boreholes in Bečej itself and its surroundings. Discordant sediments of the Upper Jurassic and the Upper Cretaceous overlie the crystalline shale. Among the Mesozoic members, the Upper Cretaceous, comprised of carbonate and flysh sediments, is the most widely distributed. Upper Cretaceous formations in the Bečej area are found at depths from 1357 m to 1900 m.

The thickness of the overall Neogene series is about 1250 m. This series most frequently overlies transgressively Upper Cretaceous, Sennonian, flysh and carbonate formations. Sediments of Miocene age are represented by sandstone, reef limestone, marl, clayey marl, and Badenian conglomerates, while the formations of Pannonian age are comprised of clayey marl, marl, sandy–clayey marl and sandstone. Badenian sediments are not of high thickness but are very good aquifers in which a carbon dioxide deposit was discovered. Unlike them, Pannonian sediments are typical aquifuges. Sediments of Pliocene age are represented by Upper Pontian sandy–marly clay, marl, sandstone and clayey marl, and by Paludina deposits comprised of clay, sand, sandy coal-bearing clay and lignite. The thickness of the Upper Pontian sediments is estimated to be 400–450 m, and the thickness of sandy layers within them ranges from several meters to about 250–300 m. These layers are significant aquifers. It is thermo-mineral water with the presence of dissolved gases that occurs in the deep regions.

Quaternary deposits cover the whole surface of the study area. The thickness of the Quaternary deposits ranges from about 130–140 m. Generally, the Quaternary, in relation to Paludina deposits, is characterized by a higher content of the Psammite component and more frequent alternation of sand and clay. Tapped water-bearing layers in the Bečej town source belong to the Quaternary, predominantly the Upper and partly the Middle Pleistocene, deposited under river-lake and river-marsh conditions.

Hydrogeological characteristics of the wider area of Bečej town source

In the study area, there have been developed five water-bearing layers were developed in a vertical profile to a depth of about 170 m.

The shallowest water-bearing layer lies to a depth of 30 m (Fig. 2). Its horizontal distribution is significant. Lithologically, its composition is not homogenous. It is comprised of loess sediments in the upper part and fine-grained, locally clayey sand, in the lower one. An unconfined aquifer, the water of which is used neither for the public water supply nor for industrial needs, formed in these heterogeneous sediments.

Three deeper water-bearing layers lying at depths of 60 m to 130 m are comprised of fine-grained to medium-grained sand and are used for domestic and industrial water supplies. All three layers are distributed regionally extending beyond the study area. These three deeper water-bearing layers represent a hydrogeological complex formed under similar sedimentary river-lake and river-marsh conditions during the Lower and the Middle Pleistocene. From the surface of the terrain, these layers are marked by Roman numbers I, II

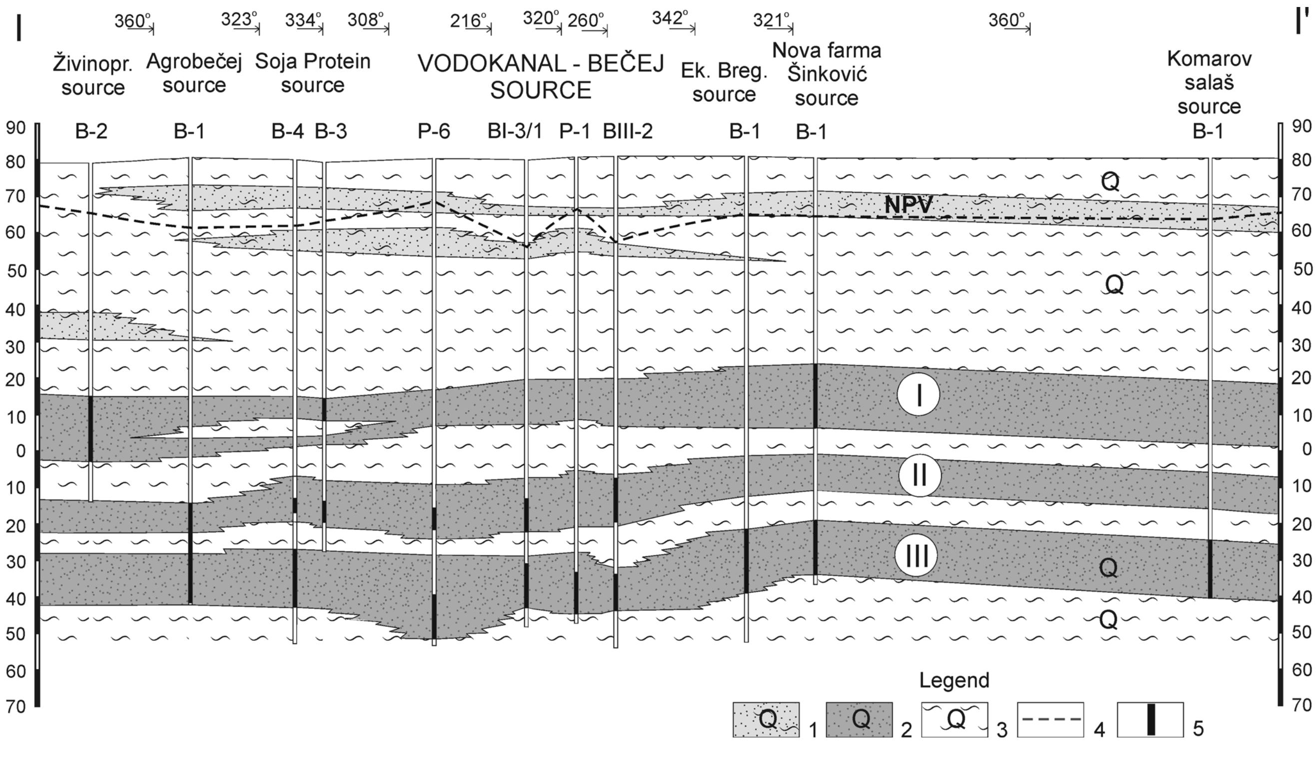


Fig. 2. Hydrogeological profile across the Vodokanal–Bečej Source. Legend: **1,** unconfined aquifer; **2,** confined aquifer; **3,** conditionally waterless sediments; **4,** head of the confined aquifer; **5.** position of the well screen.

and III (Fig. 2). The thickness and depth of some water-bearing layers were determined based on data obtained by well drilling and logging measurements in the majority of the wells and are presented in Table 1.

Table. 1. Thickness of water-bearing layers in wider study area.

Groundwater Source	Water- bearing layer		
	I Thickness (m)	II Thickness (m)	III Thickness (m)
"Vodokanal" - Bečej	9.1–16.1	6.6–18.1	7.0–23.0
"Soja Protein"	6.0–8.7	12.5–12.9	16.2–16.5
"Linde Gas"	23		14.6
"Nova farma - Šinković"	17.6	7.69	15
"Inkubatorska stanica - Šinković"	17	11	14.3
Komarov salaš	17.7	10	16
"Hotel Fantast"			
"Zalivno polje Agrobečej"	13.8	27.4	
Radičević	26	11	20
"Svinjogojstvo"	16.9	11.5	21
Bačko Petrovo Selo			
"Živinopromet"	18	10	14.6

The water-bearing layers I, II and III are separated by packages of clay and sandy clay with the thickness of 5–20 m. This insulation is not complete and allows partial hydraulic communication and the construction of an aquifer with the table under pressure. Additionally, northwest in the area of the Linde Gas Source, the water-bearing horizons of I and II merge into one. All this indicates a complex hydrodynamic whole.

It was perceived by analysis of logging diagrams that interlayers and lenses of clay material with a thickness of 2–6 m occur within some water-bearing layers (MILOSAVLJEVIĆ & POLOMČIĆ 2010). The distribution zones of the clayey interlayers in the water-bearing layers are presented in Figure 3. The significance of these intercalations of clay is that the thickness of the water-bearing layers of the city sources is really smaller, by the thickness of the clay intercalations. In order to simulate the real hydrogeological conditions in the exploratory area, these interbeds were later included in the hydrodynamic model, which resulted in increase of number of the model layers from 7 to 13.

The water-bearing layer IV, tapped under pressure only by the piezometer P7/1, was recorded in the underlying layer of the water-bearing layer III, at depths of about 149–155 m, and 161–167 m, but owing to the unfavorable quality of the groundwater, it is not used as a water supply.

The way of recharging the complex aquifer tapped in sources in the wider area of Bečej has not been studied especially and it can be discussed only based on general knowledge of the geological and hydrogeological features of the terrain and head loss analysis over a long period of time. The overlying layer of the water-bearing layer I is comprised of loess, sand, clayey sand and sandy clay. Partial precipitation infiltration into the water-bearing layer I is allowed by such a lithological composition. Infiltration certainly occurs very slowly and in complex ways. As the aquifer is distributed regionally, recharging occurs over a wider area where water permeable sediments prevail in the overlying layer or in zones where the aquifer communicates directly with the surface of the terrain or river flows.

The aquifer is drained by about 70 wells distributed over the area with a diameter of 15–20 km: by the town source in Bečej, Novi Bečej, Bačko Petrovo Selo, Veliko Gradište and other minor settlements, as well as by the factories: Sojaprotein, Linde–Gas, Agricultural Industrial Company Bečej and the companies: Agroprodukt Šinković, *etc*.

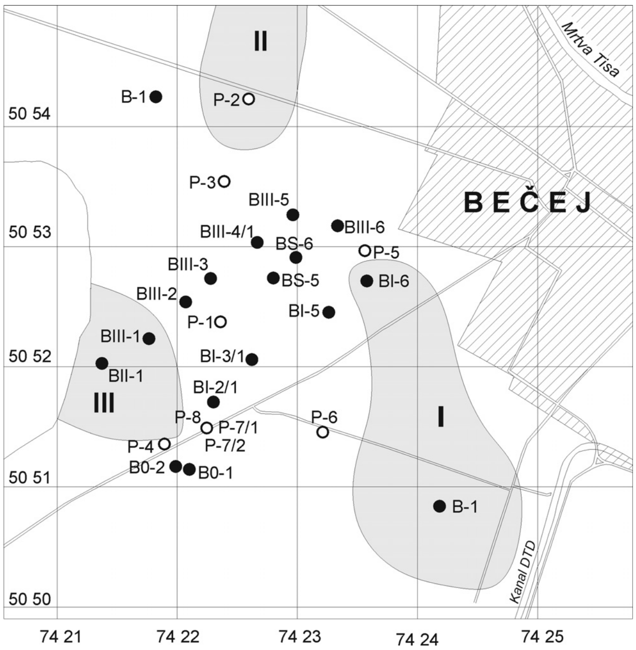


Fig. 3. Distribution of clayey interlayers (I to III) within the tapped water-bearing layers of the town source.

Physico-chemical characteristics of the groundwater

In the past, numerous chemical analyses of the town source were conducted in order to determine physico-chemical characteristics of the groundwater. As the largest number of wells tap water from two or three water-bearing layers simultaneously, only a common mixed water type could be determined. Only in a few cases were the conditions given for groundwater sampling from only one water-bearing layer (Table 2).

Table 2. Comparative analysis of physico-chemical characteristics of some water-bearing layers.

Parameter	Mark of water-bearing layer			
	II, III	I, II, III	III	IV
Electrical conductivity (μS/cm)	699–808	785–832	792	1.133
Evaporation residue (mg/l)	440–501	450–526	499	702.5
Total Hardness (°dH)	13.5	17.6–18.6	–	3.8
Consumption $KMnO_4$ (mg/l)	3.5–6.1	2.4–5.5	4.5	24.2
Ammonia (mg/l)	2.2-2.8	1.6–3.4	3.5	3.0
Sodium (mg/l)	86.1	83.9–108.1	–	243.0
Magnesium (mg/l)	36.5	43.3–50.0	–	13.1
Total Iron (mg/l)	0.4–0.8	0.2–0.5	0.4	0.1
Arsenic (mg/l)	0.035	0.001–0.005	–	0.076
Chlorides (mg/l)	6.0–6.9	6.0–10.1	5.7	18.6

Based on the analysis of a large number of groundwater samples taken from wells and piezometers in the period from the year 2004 to the year 2010, a mixed water type could be with certainty confirmed, but without the possibility of the analysis of some water-bearing layers (MILOSAVLJEVIĆ & POLOMČIĆ 2010).

According to the Alekin classification, the groundwater belongs to the hydrocarbonate class and the sodium–magnesium–calcium group. The chemical composition of the groundwater according to the classification of Kurlov can be expressed by the following formula:

$$M_{0,44-0,53}\frac{HCO^{3}{}_{95}}{(Na+K)_{39}Mg_{37}Ca_{24}}T_{16,9}$$

Concerning the groundwater of the town source in Bečej, the general evaluation from the point of view of the quality of the potable water is that the water is of a good quality after specific treatment in the water-processing factory. The, to some extent, increased content of ammonia is common for deeper water-bearing horizons. The increased iron content, recorded only in some samples, does not affect health but can affect the color and taste of the water. An increased arsenic content was recorded in only some samples; thus, there is no general increased presence of arsenic. Additionally, it has not been determined whether the arsenic occurrence in the water is organic or inorganic.

The head in the water-bearing layers I, II, and III, indicating to a hydraulic connection of these three water-bearing layers, was realized outside of the study area. In order to confirm this hypothesis, an analysis was performed and the physico-chemical characteristics of the water from some water-bearing horizons were determined. Comparing the content of some components of the chemical composition of the groundwater, it was confirmed that the contents of specific components from the water-bearing layers I, II and III are very similar and that, undoubtedly, one aquifer formed in the three water-bearing horizons with almost identical hydrodynamic and hydrochemical indicators (MILOSAVLJEVIĆ & POLOMČIĆ 2010) (Table 2).

The physico-chemical characteristics of the deeper water-bearing layer IV, tapped by the piezometer P-7/1, are essentially different from the nearest layer III. The difference can be seen in all parameters, which indicates that there is no, or very little, hydraulic connection between them.

Hydrodynamic characteristics of the Vodokanal–Bečej Source

In the past 30 years, from the year 1980 to the year 2010, about 25 wells were drilled in the Bečej Town Source, of which 15 are active, two out of use and eight are destroyed. Several layers were most frequently tapped simultaneously by wells: two layers were tapped simultaneously by 12 wells, all three layers were tapped by 10 wells simultaneously, and only one layer was tapped by three wells.

The filtration characteristics of the porous media in the Bečej Town Source were determined based on test pumping data, being partly the result of parameter identification from a hydrodynamic model of the source (CHENG & MOROHUNFOLA 1993). The tapped water-bearing layers with the values of their hydraulic conductivity are presented in Table 3.

In the period from the year 1980 to the year 2010, groundwater monitoring was realized at the source. The states of the head from the year 1980 to the year 2010 are presented in Figure 6. The groundwater table measured in the year 1980 was at almost at same depth in all three layers. To some extent, the higher differences in the head measured in the year 2010 are the consequence of the small distance from the wells

Table 3. Survey of water-bearing layers being tapped at Vodokanal–Bečej Source and surrounding sources with survey of hydraulic conductivity values.

Mark of well	Tapped water--bearing layer	Hydraulic conductivity (m/s)
VODOKANAL Source		
B0-1	II, III	1.90×10^{-4}
B0-2	I, II, III	1.21×10^{-4}
BI-2/1	II, III	1.46×10^{-4}
BI-3	I, II	5.00×10^{-4}
BI-3/1	I, II, III	1.21×10^{-4}
BI-4	I, II	5.50×10^{-4}
BIII-1	I, II, III	1.75×10^{-4}
BIII-1/a	I, II, III	1.42×10^{-4}
BIII-2	I, II, III	2.93×10^{-4}
BIII-3	I, II, III	3.19×10^{-4}
BIII-4	III	8.50×10^{-4}
BIII-4/1	I, II, III	1.90×10^{-4}
BIII-5	III	9.70×10^{-4}
BIII-6	II, III	1.90×10^{-4}
BS-5	I, II, III	3.98×10^{-4}
BS-6	I, II, III	3.33×10^{-4}
SOJA PROTEIN Source		
B-1	III	2.30×10^{-4}
B-4	II, III	2.04×10^{-4}
LINDE GAS Source		
B-1	I	6.18×10^{-4}

and the varied pumping intensity. The highest head losses were observed at the piezometers located in the central part of the source (P-1, P-4, P-6 and P-7/2), where pumping is the most intensive, while the lowest head losses were observed at the piezometers located at peripheral part of the source (P-2, P-3 and P-5). The recorded values of the groundwater table at the piezometers confirmed that these three water-bearing layers represent a unique hydrodynamic whole.

Based on the cross-section of the head states covering the span of 30 years (1980–2010) (MILOSAVLJEVIĆ & POLOMČIĆ 2010) (Fig. 4), it can be seen that the head loss was below all expectations and previously given prognoses.

A head loss of 3.04 m was recorded at the piezometer P-7/1, the filter of which is located in the water-bearing level IV, in the period of 1980 to 2010 years. As this water-bearing layer is not tapped by any wells in the vicinity, the only explanation is that the groundwater "pours off" into the nearest water-bearing layer III.

In order to determine the yield of the water-bearing layers, rheometric measurements were realized at 10 wells (Fig. 5) and the following results were obtained (MILOSAVLJEVIĆ & POLOMČIĆ 2010):

– at the wells where layers I and II are tapped (BO-2 and BI-3/1), layer I works with 86.5–90 % and layer II with only 10–13.5% of the total capacity,
– at wells where layers II and III are tapped (7 wells), the layers mainly gave unequal amounts of water and
– in case of water tapping from all three layers, measurements were performed at only one well (BIII-1), where the layers were also unequally active.

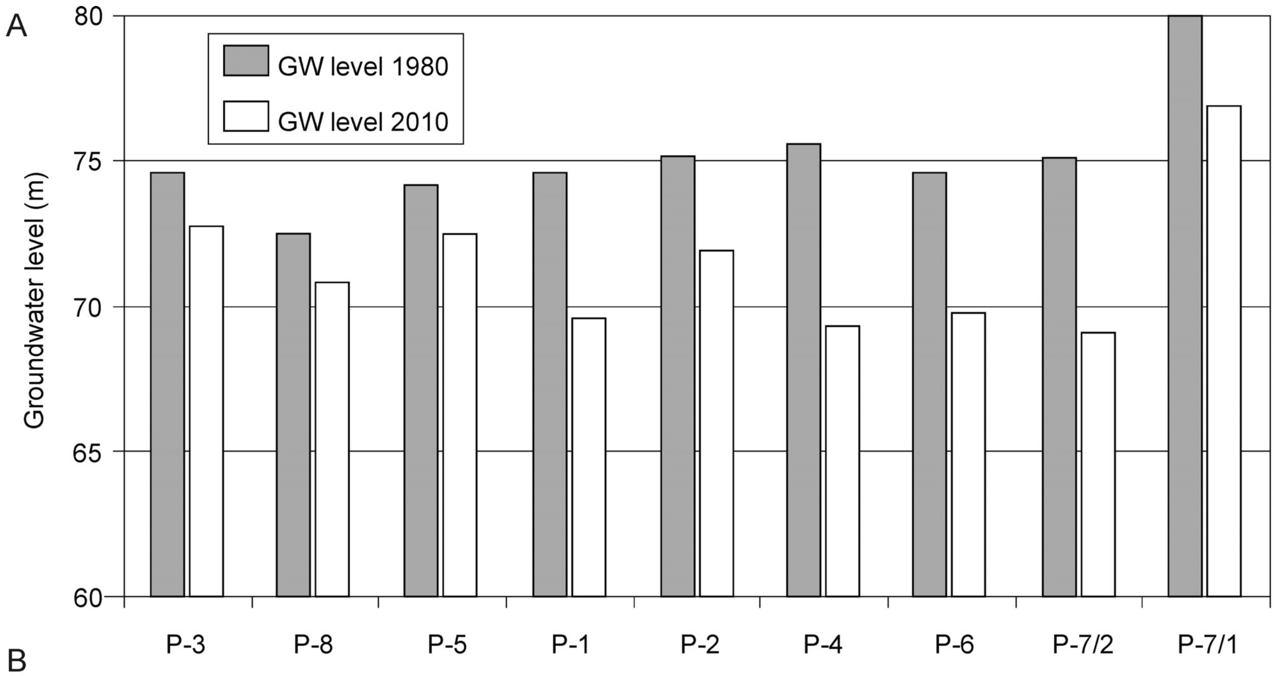
By having access to the well capacity, it can be seen that initial capacity of the wells was relatively high (17–37 l/s), and that it decreased rapidly with exploitation owing to fast ageing of the wells. Working age of wells according to past experience at the Bečej Town Source is, on average, 8 to 9 years (Fig. 6). Revitalizations were frequently performed; on average, one or two per well. After revitalization, the age of the wells was extended by two to five years.

Hydrodynamic model of wider area of the Vodokanal–Bečej Source

A hydrodynamic model was developed in order to simulate the current groundwater exploitation at the Vodokanal–Bečej Source and to determine the groundwater balance. The code selected to develop the numerical model was MODFLOW-2000; a modular, three-dimensional finite difference groundwater flow model developed by the US Geological Survey (HARBAUGH *et al.* 2000). The program Groundwater Vistas 5.33b (Environmental Simulations International, Ltd.) was used in the present study. The development concept of the groundwater source hydrodynamic model for the Bečej water supply is based on the simulation of three-dimensional finite difference groundwater flow. The development of this model included the steps from the basic interpretation of input data, the schematization of porous environment, flow field and flow conditions to the formation and calibration of the model. Natural factors, such as the type and characteristics of distributed geological members, the distribution of water-bearing layers and aquafuges, filtration characteristics of the porous environment, conditions, mechanism and the groundwater flow regime, as well as a the desired goal within the set assignment had decisive impacts on the selection of the basic characteristics of the mathematical model of the Vodokanal–Bečej Source (POLOMČIĆ 2001).

Flow field geometry and discretization of the wider area of the Vodokanal–Bečej Source

The developed hydrodynamic model includes the wider area of the Vodokanal–Bečej Source. Locations



B

Piezometer	P-3	P-8	P-5	P-1	P-2	P-4	P-6	P-7/2	P-7/1
Tapped water-bearing layer	I		II	III		II, III			IV
The average annual decline in the level (m)	0.06	0.06	0.06	0.17	0.11	0.21	0.16	0.20	0.10

Fig. 4. State of the head at Bečej Town Source measured between 1980 and 2010. **A,** Diagram of groundwater level in the piezometers; **B,** Table with average annual decline in the groundwater level observed in the pieozometers.

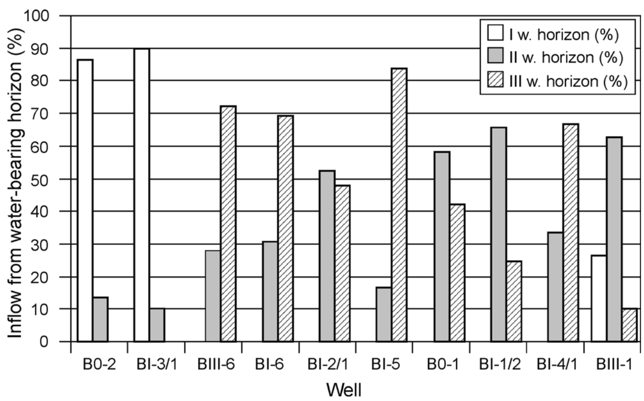


Fig. 5. Results of rheometric examinations at the Bečej Town Source.

of facilities in the area included in the model used for defining of spatial characteristics of isolated schematized lithological members are given in Fig. 1. The performed schematization of the hydrogeological environment is based on the existence of water impermeable overlying and underlying sediments, and the three water-bearing layers being separated by clayey sediments and clayey interlayers of limited distribution within each water-bearing layer (POLOMČIĆ 2002). To summarize, observed from the surface of the terrain, the corresponding model layers and terrain are presented in Table 4.

Although in total five water-bearing layers were recorded in the study area, only the tapped layers are included in the model. The shallowest water-bearing-layer, being neither in direct hydraulic connection with the lower layers nor used for water supply, is also in the first model layer. The water-bearing layer IV (not being used for water supply) is not included in the model.

The three-dimensional hydrogeological model in two cross-sections within the wider area of the Vodokanal–Bečej Source is shown in Figs. 7 and 8. The tapped water-bearing layers, in which filter constructions of the exploitation wells are placed, are marked in dark grey color. As stated before, the overlying layer, the underlying layer, and interlayer deposits are composed of poorly permeable and water impermeable sediments.

The distribution of all layers can be seen in the presented three-dimensional profiles, thereby the existence of clay interlayers in the water-bearing layers at particular localities and the merge of the first and second water-bearing layers (at the locality of the Linde Gas Source) are evident.

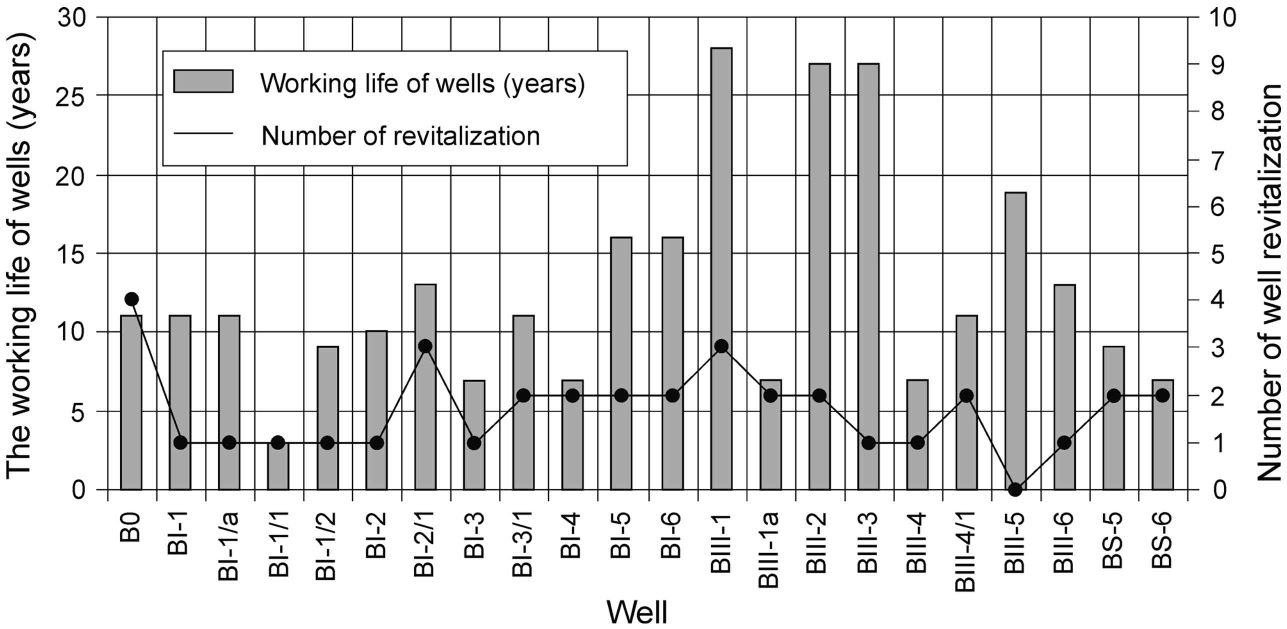


Fig. 6. Survey of working age and number of revitalizations of the wells of the Vodokanal Bečej Source.

Table 4. Lithological members and model layers of wider area of groundwater source Vodokanal–Bečej.

Complex of clayey and sandy overlying sediments	1	clayey and sandy sediments
I water-bearing layer with clay interlayer	2	overlying part of I water bearing layer
	3	clay interlayer grading laterally into sands of I water bearing layer
	4	underlying part of I water bearing layer
clayey sediments	5	clayey and sandy sediments
II water-bearing layer with clay interlayer	6	overlying part of II water bearing layer
	7	clay interlayer grading laterally into sands of II water bearing layer
	8	underlying part of II water bearing layer
clayey sediments	9	clayey sediments
III water-bearing layer with clay interlayer	10	overlying part of III water bearing layer
	11	clay interlayer grading laterally into sands of III water bearing layer
	12	underlying part of III water bearing layer
floor clayey sediments	13	clayey sediments

Basic dimensions of the matrix included in the study area are 12800 m × 13200 m, covering an area of 168.96 km^2. The discretization of the flow field in the plan was performed with a basic cell value of 400 m × 400 m, which is condensed in the source zone by a square net with dimensions of 25 m × 25 m (POLOMČIĆ 2004). The terrain included in the model is divided by a net of squares and rectangles with the dimensions of 322 rows × 197 columns and is comprised of 824 642 active model cells (POLOMČIĆ *et al.* 2011).

Boundary conditions

The following boundary conditions were applied in the hydrodynamic model of the Vodokanal–Bečej Source:

- "vertical balance", result (effective) infiltration, as a result of infiltration differences of precipitation and evapo-transpiration
- general head boundary
- boundary condition with a set flow – a discretization net cell ("inner contour").

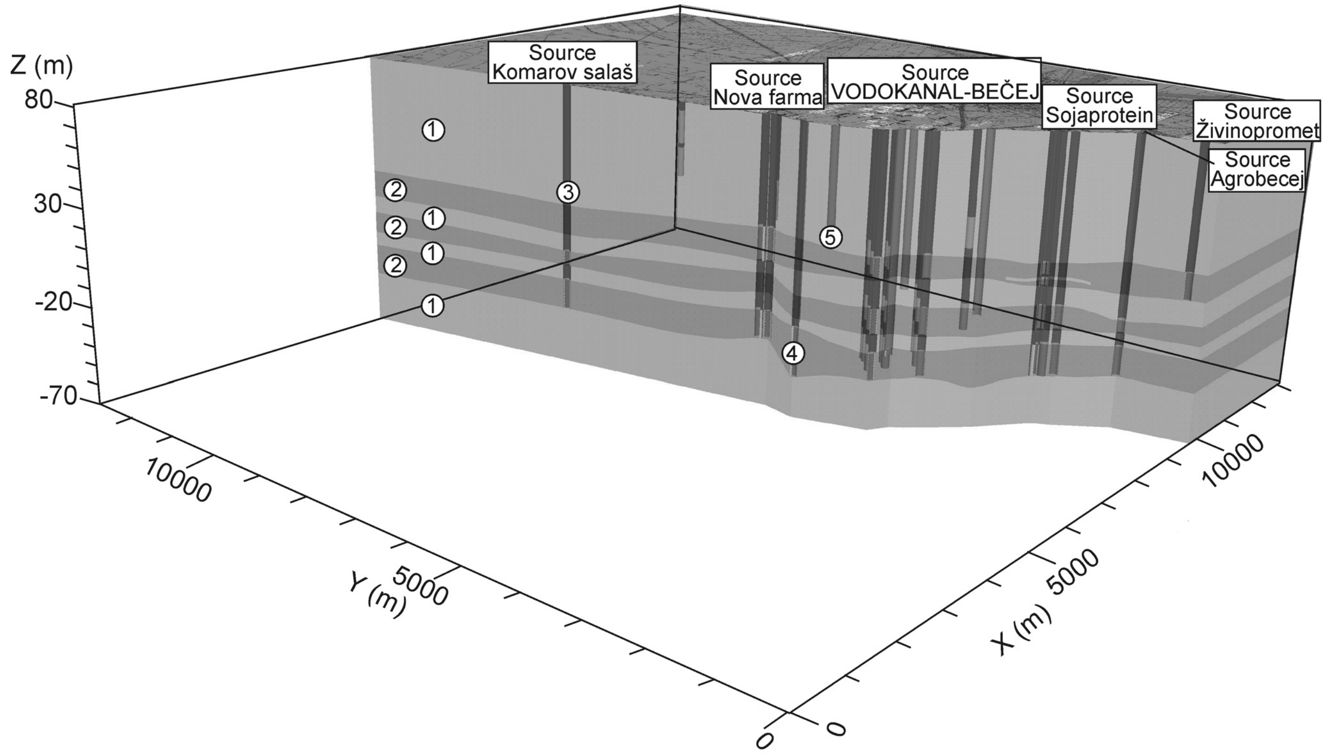


Fig. 7. 3D hydrogeological profile of the model of the town source: cross-section north–south. Legend: **1,** poorly permeable layer; **2,** water-bearing layer; **3,** well structure; **4,** well screen; **5,** piezometer.

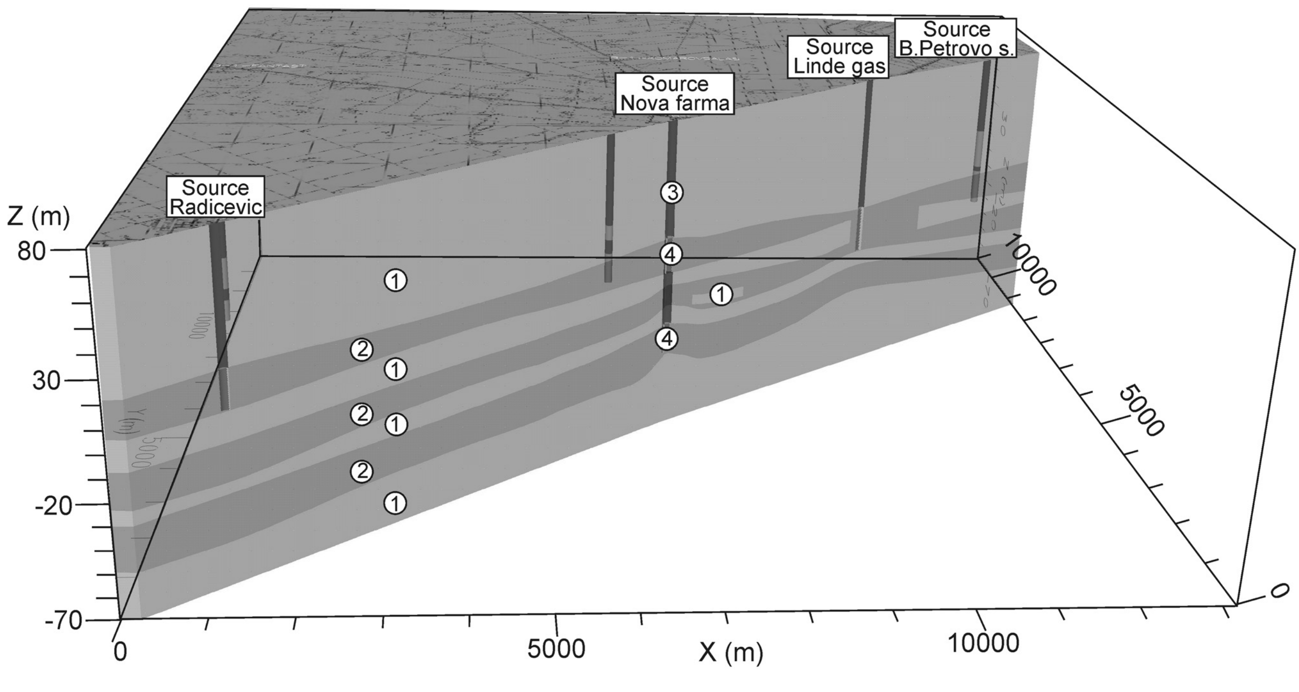


Fig. 8. 3D hydrogeological profile of the model of the town source: cross-section SW–NE. Legend: **1,** poorly permeable layer; **2,** water-bearing layer; **3,** well structure; **4,** well screen.

In the overall groundwater balance, the so-called "vertical balance" of the study area affects the tapped water-bearing layers to some extent. Here, the vertical balance implies the effective resultant infiltration (POLOMČIĆ 2008). This value is comprised of the sum of infiltration by precipitation, evaporation from groundwater and evapo-transpiration. Additionally, the depth to groundwater table, the state of humidity, as well as the lithological composition of the soil in the zone above the aquifer are highly significant. A precipitation value of 10 % was taken as the initial value of effective infiltration and this boundary condition was set only in the first layer of the model. Average monthly values of precipitations at the Bečej Meteo-

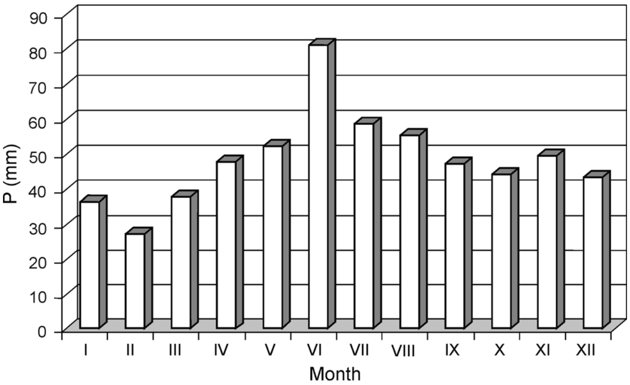


Fig. 9. Average monthly values of precipitations for period from 1978 to 2010 (M.S. Bečej).

rological Station for the period from 1978 to 2008 are shown in Fig. 9.

As stated before, there are several water-bearing layers at the wider area of the Vodokanal–Bečej Source, three of which are tapped for water supply. With regard to conditions of sedimentation and the development of these water-bearing layers, their sources of recharge are situated far from the study area. The impact of these distant recharge sources on the hydrodynamic model of the Vodokanal–Bečej Source was set *via* the boundary condition of the general head for each of the water-bearing layers.

A hydrodynamic analysis of the groundwater regime according to the recorded groundwater table was conducted in order to determine the value of the head to be set by this boundary condition for each water-bearing layer. Groundwater hydrographs at the piezometers of the Vodokanal–Bečej Source for the period from 1st August 2007 to 28th May 2010 are presented in Fig. 10.

The general conclusion from Fig. 10 is that identical fluctuation trends of the head were recorded at all piezometers, characterized by lower levels during the summer and early autumn months as a consequence of higher tapping of groundwater. In addition, from an analysis of the values of the hydraulic head registered at each piezometer separately, it can be concluded that all three water-bearing layers are in the hydraulic connection. In the exploratory area, the connection of the first and second water-bearing layers was registered in the area of the source "Linde Gas" (Fig. 8). The head oscillations in the piezometers indicate that the hydra-

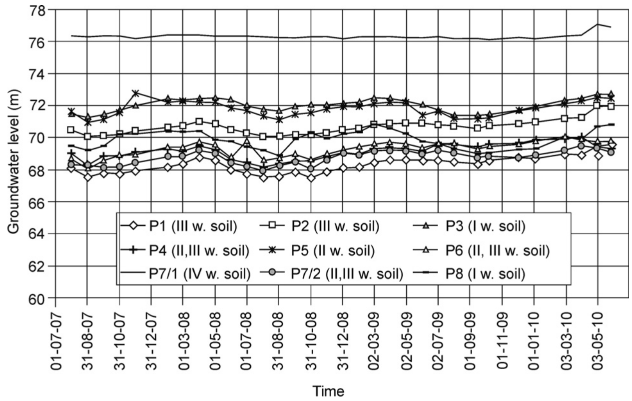


Fig. 10. Hydrographs of the head at the monitoring facilities of Vodokanal–Bečej Source in the period from 1st August 2007 to 28th May 2010.

ulic connection of the three water layers was realized outside the investigation area. The exception is the P-7/1 piezometer, the filter of which is located in the fourth water-bearing layer, which is not tapped by wells in the study area and is not included in the model.

The impact of the exploitation wells at the sources was simulated *via* the set flow boundary condition. The locations of wells in the area included in the model are shown in Figure 1. The values of well yield of and groundwater table in the wells at the Vodokanal–Bečej Source were recorded for the period from 1st August 2007 to 28th May 2010 (Fig. 11).

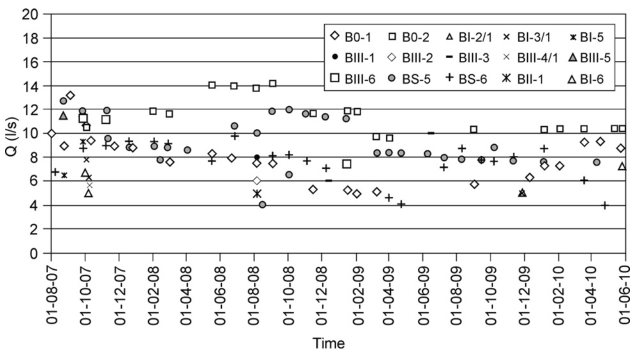


Fig. 11. Diagram of the recorded single well flows at the Vodokanal–Bečej Source in period from 1st August 2007 to 28th May 2010.

The capacity values of the remaining wells located at the other sources on the area included in the model were set at values recorded during exploitation of several years and range from 1.0–13.3 l/s (MILOSAVLJEVIĆ & POLOMČIĆ 2010). Well screens at the Vodokanal–Bečej Source and the remaining sources were set according to their real mounting position as multi-segmented ones in one, two or three water-bearing layers.

Results of the model calibration

The calibration of the model is realized under transient flow conditions with a time of one day for the analyzed period of time (1st August 2007 to 28th May 2010), being at the lowest level of the iterations divided into 10 parts of unequal duration (factor 1.2) (POLOMČIĆ 2004). The groundwater flow model was calculated and simulated as real flow under pressure or with a free table in each discretization cell individually, whereby the flow model conditions were changed with time in accordance with the real conditions.

The model calibration was completed when, according to the evaluation of the model author, satisfactory concordance between the recorded groundwater tables and those obtained in the calculations (Figs. 12, 13 and 14). The head layout in the tapped water-bearing layers at the end of the period for which the model was calibrated is shown in Figures 15–17 (28th May 2010).

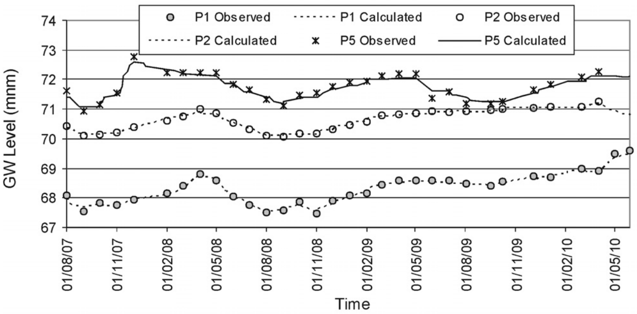


Fig. 12. Diagram of the observed and calculated heads in the piezometers which screened only in the second (P5), and in the third water-bearing layer (P1 and P2) for the whole model calibration period.

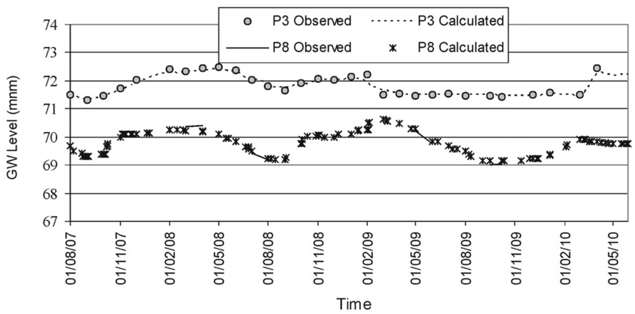


Fig. 13. Diagram of the observed and calculated heads in the piezometers which screened only the first water-bearing layer for the whole model calibration period.

The groundwater balance was analyzed for the Vodokanal–Bečej Source for each well. Respecting the results of the rheometric investigations (Fig. 5) and the performed simulation of the town source work, the average well capacities and inflows from the water-bearing layers for each the wells were obtained (Table 5).

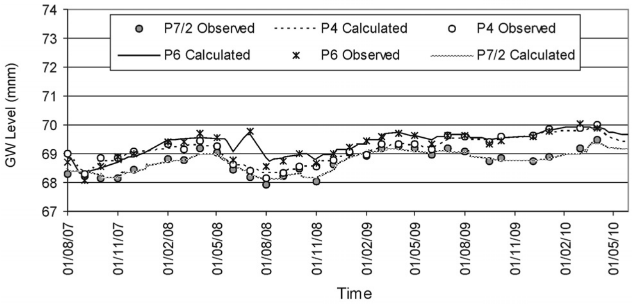


Fig. 14. Diagram of the observed and calculated heads in the piezometers which screened the second and third water-bearing layers for the whole model calibration period.

The largest amount of water flow up comes from water-bearing layer III (43.93 %) as a consequence of the largest number of wells tapping water from this layer. Then follows the inflow from layer II (33.4 %) and the least from water-bearing layer I (22.57 %).

Table 5. Groundwater balance at Vodokanal–Bečej Source.

Well	Well capacity (l/s)	Inflow from I water horizon (l/s)	Inflow from II water horizon (l/s)	Inflow from III water horizon (l/s)
B0-1	8.1	0.00	4.72	3.38
B0-2	11.5	9.95	1.55	0.00
BI-2/1	5.9	0.00	3.06	2.84
BI-3/1	6.4	5.76	0.64	0.00
BI-5	7.9	0.00	1.30	6.60
BI-6	5.3	0.00	1.63	3.67
BII-1	5.0	1.75	1.25	2.00
BIII-1	8.0	2.10	5.05	0.85
BIII-2	6.0	1.48	3.48	1.04
BIII-3	8.0	1.36	4.96	1.68
BIII-4/1	5.7	0.00	0.00	5.70
BIII-5	11.7	1.76	2.46	7.49
BIII-6	9.9	0.00	2.75	7.15
BS-5	9.5	1.14	3.52	4.85
BS-6	7.5	0.98	2.63	3.90
Total	116.4	26.3	39.0	51.1

Conclusions

Groundwater from three water-bearing layers comprising a unique hydrodynamic whole is used for domestic and industrial water supply to the wider area of Bečej. The stated layers are located at depths from 60 to 130 m. There are clayey interlayers within water-

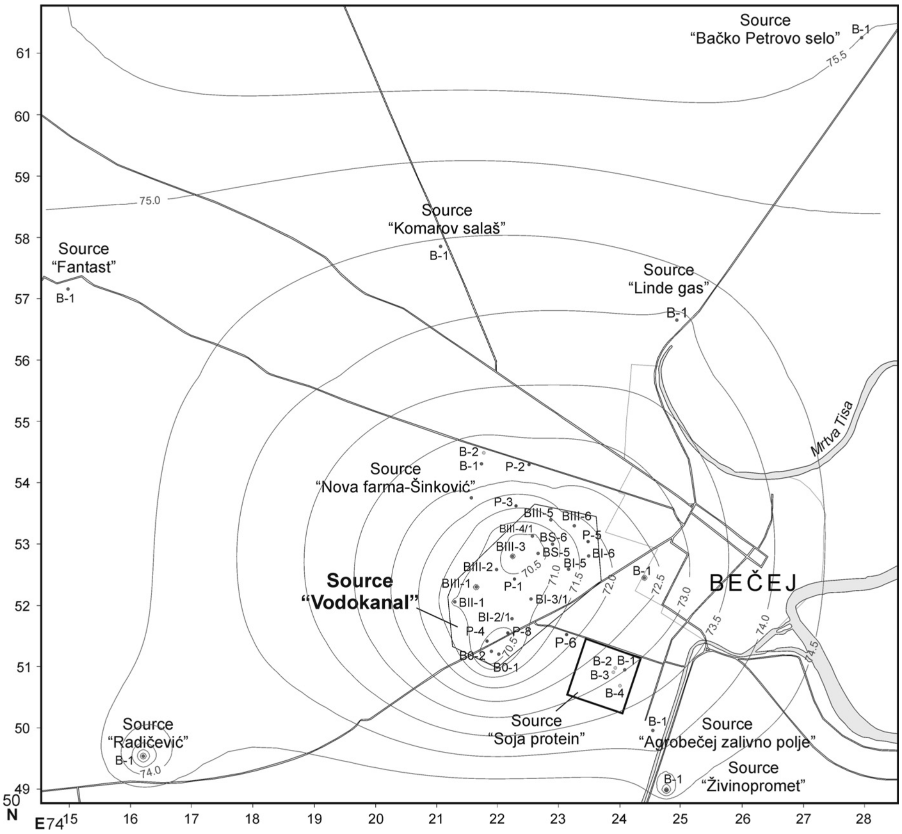


Fig. 15. Map of the head layout in water-bearing layer I in the wider surroundings of the Vodokanal–Bečej Source at the end of the model calibration period.

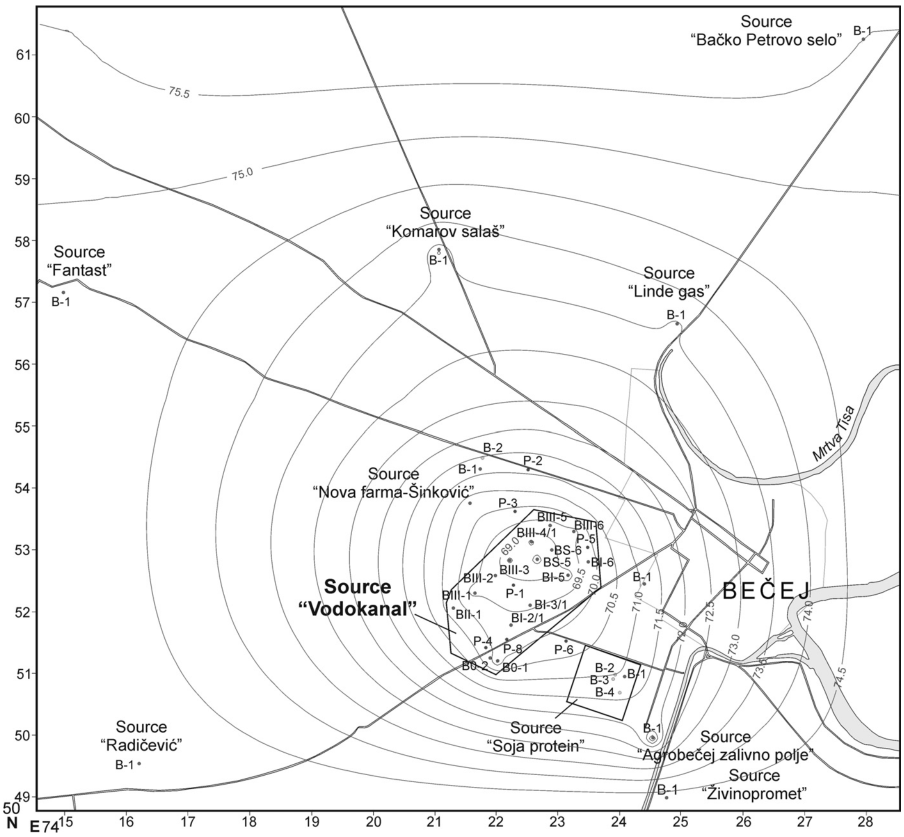


Fig. 16. Map of head layout in water-bearing layer II in the wider surroundings of Vodokanal–Bečej Source at the end of the model calibration period.

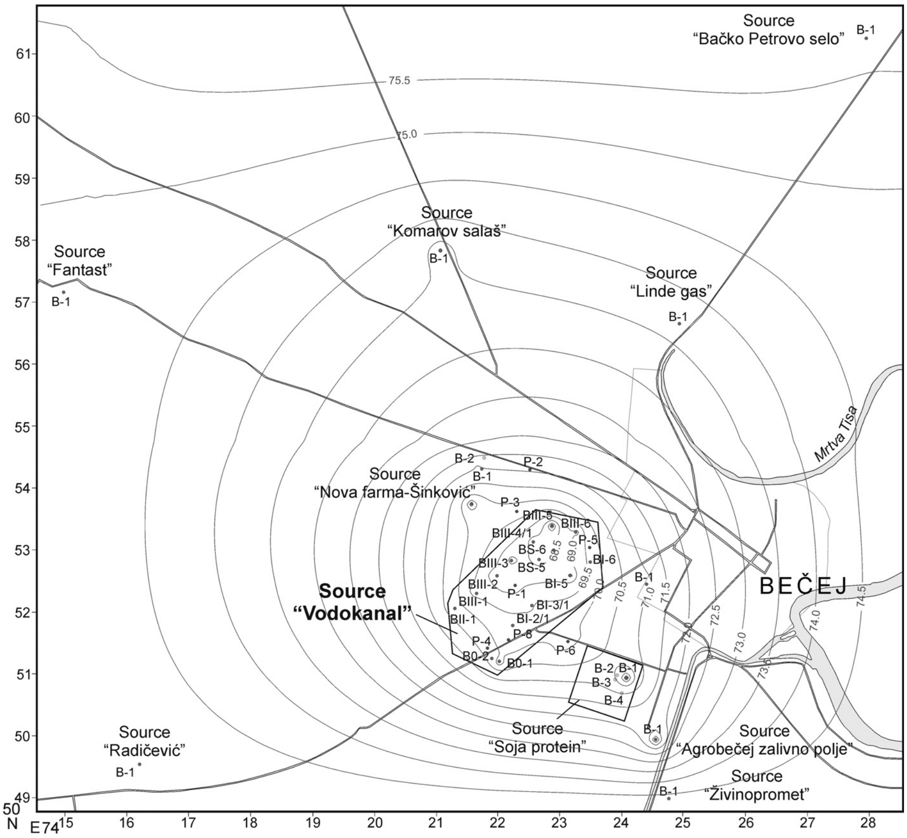


Fig. 17. Map of the head layout in water-bearing layer III in the wider surroundings of the Vodokanal–Bečej Source at the end of the model calibration period.

bearing layers at the Vodokanal–Bečej Source that serve for water supply to the population and industry of Bečej. The Source is comprised of 15 drilled wells the filter structures of which tap one or more water-bearing layers. The quality of the groundwater is burdened with an increased content of ammonia. Increased contents of arsenic and iron were recorded in some water samples. The water must be treated in the water treatment plant before usage. According to the Alekin classification, the groundwater belongs to the hydrocarbonate class, sodium–magnesium–calcium group.

Fast ageing of the wells is present at the Source. The average working life of wells at the town source is 8–9 years.

During past 30 years, groundwater table has been monitored. Recorded values of groundwater table at piezometers confirmed that the three tapped water-bearing layers represent a unique hydrodynamic whole. The results of hydrochemical examination additionally confirmed this statement.

A multilayer hydrodynamic model with overall 13 layers was developed for the determination of the groundwater balance at the Vodokanal–Bečej Source. The relatively large area included in the model and the numerous layers conditioned the existence of 824 642 active model cells. The model included the town and 11 surrounding groundwater sources. The simulation of the working of the sources was performed under non-stationary conditions for a period of over two and a half years.

The conducted hydrodynamic analysis of the groundwater regime at the Vodokanal–Bečej Source showed that the highest amount of water flow is from the water-bearing layer III (43.93 %), then from layer II (33.4 %), and the least from the water-bearing layer I (22.57 %).

The result of the performed investigations states indicate that it is possible to tap considerably higher amounts of groundwater than those being tapped presently.

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Резиме

Хидрогеолошке и хидродинамичке карактеристике изворишта подземних вода за јавно водоснабдевање Бечеја (северна Србија)

За потребе снабдевања водом становништва и индустрије на ширем подручју Бечеја, захватају се подземне воде из три водоносна слоја која се налазе на дубинама од 60 до 130 m. Градско извориште Бечеја („Водоканал–Бечеј") састоји се од 15 експлоатациоинх бунара који каптирају наведена три водоносна слоја. Извориште карактерише релативно брзо старење бунара, и релативно мало опадање пијезометарског нивоа. Бунарима је најчешће каптирано више водоносних слојева: на 12 бунара каптирана су истовремено два слоја, на 10 су каптирана сва три, а на 3 бунара је каптиран један слој.

На изучаваном терену у вертикалном профилу до дубине око 170 m развијено је пет водоносних слојева. Најплићи водоносни слој залеже до дубине око 30 m и има велико хоризонтално распрострањење. Изграђен је од лесоидних седимената у горњем и ситнозрних, местимично заглињених пескова у доњем делу. У овим хетерогеним седиментима формирана је издан са слободним нивоом чије се воде не користе за јавно водоснабдевање или за потребе индустрије.

Три дубља водоносна слоја, која леже на дубини од 60–130 m, изграђена су од ситнозрних до средњезрних пескова и користе се за водоснабдевање становништва и индустрије. Сва три слоја имају регионално распрострањење и представљају један хидрогеолошки комплекс стваран у сличним седиментолошким речно-језерским и речно-барским условима у току доњег и средњег плеистоцена. Каптирани водоносни слојеви (I, II и III) међусобно су раздвојени пакетима глине и песковите глине дебљине 5–20 m. Ова изолација није потпуна и омогућава делимичну хидрауличку повезаност. У регионалној размери, изграђују једну издан са нивоом под притиском. Поред тога, према североистоку у домену изворишта „Линде гас", I и II водоносни хоризонти се спајају у један. Све ово указује да се ради о једној сложеној хидродинамичкој целини.

Анализом каротажних дијаграма уочено је да се унутар појединих водоносних слојева јављају прослојци и сочива глиновитог материјала дебљине 2–6 m.

У подини каптираног III водоносног слоја на дубини од око 149–155 m и од око 161–167 m регистрован је IV водоносни слој под притиском који је захваћен једино пијезометром П7/1 и због неповољног квалитета подземних вода не користи се за водоснабдевање.

Пијезометарски нивои у каптираним водоносним слојевима I, II и III потврдили су да се ради о хидрауличкој повезаности ова три водоносна слоја која се остварује и ван изучаваног простора. Као додатна потврда повезаности ова три водоносна слоја су физичко-хемијске карактеристике вода из појединих водоносних хоризоната. Упоређењем садржаја појединих компоненти хемијског састава подземних вода утврђено је да су садржаји одређених компоненти из I, II и III водоносног слоја веома слични и да се неспорно ради о једној издани

формираној у три водоносна хоризонта са скоро истоветним хидродинамичким и хидрохемијским показатељима. Према класификацији Алекина подземне воде припадају хидрокарбонатној класи, натријумско-магнезијумско-калцијумској групи.

На основу пресека стања пијезометарских нивоа у распону од тридесет година (1980–2010) утврђено је да је пад пијезометарског нивоа испод свих очекивања и раније постављених прогноза, и да износи 6–21 cm годишње.

У циљу утврђивања издашности одређених водоносних слојева, вршена су реометријска мерења на 10 бунара. На основу ових мерења је утврђено је да су каптирани слојеви углавном давали неједнаке количине воде.

За потребе извођења симулације постојеће експлоатације подземних вода на изворишту „Водоканал–Бечеј“ и утврђивања биланса подземних вода формиран је хидродиамички модел. Концепција израде хидродинамичког модела заснива се на симулацији тродимензионалног струјања подземних вода применом методе коначних разлика. Терен обухваћен моделом је издељен мрежом квадрата и правоугаоника димензија 322 реда × 197 колоне и састоји се од 824.642 активних моделских ћелија, у 13 моделских слојева. Еталонирање модела је спроведено у нестационарним условима струјања, са временским кораком од једног дана за анализирани временски период (01. 08. 2007. – 28. 05. 2010. год.), који је на нижем нивоу итерација подељен на 10 делова, неједнаког трајања (фактор 1,2). Постигнуто је веома добро слагање регистрованих и прорачунатих вредности пијезометарских нивоа. Као резултат процеса калибрације модела, добијене су карте распореда пијезометарског нивоа за сваки водоносни слој и за сваки временски пресек (преко 1000 пресека). Такође, одређени су елементи биланса водоносних слојева на градском изворишту Бечеја. Највеће количине вода дотичу из III водоносног слоја (43,93 %) као последица највећег броја бунара који захватају воде из овог слоја. Потом следи дотицај из II (33,4 %), и на крају из I водоносног слоја (22,57 %).

Како резултат спроведених истраживања стоји да је могуће захватати и знатно веће количине подземних вода него што се данас захватају.