

A new approach to the definition of design criteria for radial collector wells in anoxic settings

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Abstract. The outcomes of a study on groundwater flow from a river to a radial collector well are presented in the paper. The considered well, RB-16, is part of a groundwater source that provides water supply to Belgrade (Serbia). The source relies on the alluvial aquifer of the Sava River. The groundwater is mildly anoxic ($Eh \sim 125$ mV, $Fe^{2+} = 0.46$ mg/L, $NO_3 \sim 0.24$ mgN/L, $O_2 \sim 0.1$ mg/L). The paper is specific in the sense that it presents a novel approach to the definition of water well susceptibility to iron incrustation in an anoxic alluvial setting. Maximum permissible screen entrance velocities, as well as the structural characteristics of the horizontal screens and the radial collector well itself, are determined based on correlations established between the rate of well incrustation, redox potential, iron concentration in groundwater, and screen entrance velocities. One of the criteria is that the hydraulic resistances, caused by the precipitation of iron on the horizontal screens, are being lower than specified. The correlations between maximum permissible screen entrance velocities (the velocities that still allow a lower-than-specified increase in local hydraulic resistances at the entrance to the screens) and biochemical indicators (Eh , Fe^{2+}) were taken from previous papers by the same authors and their associates. Original software was used for hydraulic analysis of the potential capacity of the location of well RB-16. The software supports 3D analysis, including boundary conditions, and was adapted for this particular purpose.

Key words: groundwater, anoxic conditions, rate of horizontal screen incrustation, new approach, definition of well elements, numerical modeling of groundwater, public water supply, Serbia.

Апстракт. У раду су приказани резултати студије струјања подземних вода од реке ка бунару са хоризонталним дренажима. Разматрани бунар РБ-16 се налази на изворишту подземних вода, које служи за водоснабдевање Београда (Србија). Извориште црпи воду из алувијалног аквифера реке Саве. Вода је благо аноксичних карактеристика ($Eh \sim 125$ mV, $Fe^{2+} \sim 0.46$ mg/L, $NO_3 \sim 0.24$ mgN/L, $O_2 \sim 0.1$ mg/L). Рад је специфичан, јер се по први пут приказује примена нове методе за дефинисање склоности бунара ка инкрустацији талозима гвожђа у условима аноксичне средине алувијалних седимената. На основу утврђене везе између кинетике колмирања бунара, редокс потенцијала и садржаја гвожђа подземних вода, као и улазних брзина воде у дренаже бунара, утврђене су максимално дозвољене улазне брзине, а затим и капацитет дренажа, као и самог бунара. Постављен је захтев да хидраулички отпори, изазвани таложењем гвожђа на филтрима дренажа, буду мањи од задатих. Веза између максимално дозвољених брзина уласка подземних вода у дренаже бунара (брзине које још увек омогућују да пораст локалних хидрауличких отпора на улазу воде у дрен буде мањи од задатих вредности) и биохемијских индикатора (Eh , Fe^{2+}), преузета је из претходних радова аутора овог чланка са сарадницима. Хидрауличка анализа потенцијалног капацитета локације бунара РБ-16 је рађена оригиналним софтвером, који омогућава 3Д анализу, са граничним условима прилагођеним за ову сврху.

Кључне речи: подземне воде, аноксични услови, кинетика колмирања дренажа бунара, нова метода, дефинисање елемената бунара, нумеричко моделирање подземних вода, снабдевање водом, Србија.

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Introduction

Urban agglomerations generally rely on the nearest water resource for their water supply. If the agglomeration is situated next to a river, it is natural to use groundwater from the alluvial aquifer. However, the configuration, development, and maintenance of such water supply sources are coupled with numerous and highly complex issues. Some of the drivers are: natural hydrogeologic conditions, type of abstraction (wells), required discharge capacity of the wells and the entire source, biochemical properties, groundwater regime, configuration of the source, distance from the urban agglomeration, and specific features related to well maintenance, water treatment, and transport. Numerous authors have studied groundwater source issues, which can be classified into several groups. Some of them are:

a) Establishment of a groundwater monitoring system, to characterize and manage the groundwater resource (e.g., ALLER et al., 1991; FRETWELL et al., 2006),

b) Assessment of conditions and selection and design of wells (ABRAMOV, 1952; JOHNSON, 1972; KOVACS & UJFALUDI, 1983; VUKOVIĆ & PUŠIĆ, 1992; DIMKIĆ & PUŠIĆ, 2008),

c) Study of well ageing processes, dependency on the natural setting, and rehabilitation (LANGELIER, 1936; RYZNAR, 1944; MANSUY, 1998; CULLIMORE, 1999; McLAUGHLAN, 2002; HOUBEN & TRESKATIS, 2007),

d) Study and definition of the correlation between hydraulic resistances due to iron incrustation of wells in anoxic conditions and biochemical indicators (Eh , Fe^{2+} , ...), (DIMKIĆ et al. 2011b, 2011c; DIMKIĆ & PUŠIĆ, 2014),

e) Assessment of the potential for source capacity increase by various engineering measures (BORCH et al., 1993; PYNE, 1995; PUŠIĆ et al., 1997; DIMKIĆ et al. 1997a, 1997b, 2007),

f) Modeling of groundwater flow to the wells under characteristic conditions (DIMKIĆ et al., 2007, 2008, 2009, 2010; VIDOVIĆ et al., 2014),

g) Regional-scale management of groundwater resources (DIMKIĆ et al., 2008; SINCLAIR KNIGHT MERZ, 2013),

h) Self-purification potential of aquifers (DIMKIĆ & KECKAREVIĆ, 1990; RAY et al., 2002; SCHMIDT et al., 2003; DE VET et al., 2010; DIMKIĆ et al., 2011a).

Alluvial formations are frequently characterized by alternating coarse and fine sediments, such that water-bearing (gravel, sand) strata are often vertically separated by semi-permeable, predominantly clay interbeds and lenses.

Analysis of the mechanical conditions of well screen stability (item b above) has been one of the initial areas of scientific and technical consideration of water well operation. Well ageing processes in anoxic

settings have mostly been studied at the end of the previous and beginning of the present century (item c above).

The authors of this paper and their associates have correlated anoxic aquifer conditions, iron concentration in groundwater, intensity and kinetics of screen incrustation and increase in hydraulic resistances at the screens, and also established functional relations between them (item d above).

As groundwater becomes anoxic, maximum permissible groundwater flow velocities (v_{perm}) are increasingly governed by biochemical parameters of the aquifer. The relationship

$$v_{perm} = f(Fe^{2+}) \quad (1)$$

$$v_{perm} = f(Eh) \quad (2)$$

has been defined for alluvial sources in Serbia, and this approach has for the first time on a global scale been reported by DIMKIĆ & PUŠIĆ (2014) and DIMKIĆ et al. (2011a, 2011b, 2011c).

The present paper is the first to describe a complex methodology for determining:

- the abstraction capacity of a certain location and a particular well; and

- the structural elements of the well (number of horizontal screens, entrance velocities), taking the characteristic biochemical properties of the anoxic aquifer as the starting point.

This new design approach has a considerable effect on the longevity and, in general, the operational economics of horizontal collector wells. Basically, the approach should also be applicable to other types of tapping structures (e.g. tube wells).

Setting, analyzed processes, and statement of the problem

Belgrade Groundwater Source (BGS) is situated along the Sava River, in part within the city fabric. This renders it vulnerable to urban pressures. Still, at first glance a multiple-decade time series shows a surprisingly high and stable quality of the abstracted groundwater.

The alluvial complex tapped by the horizontal screens (laterals) is characterized by multiple alternations of coarse (gravel) and fine (sand) sediments. The final sequences of sedimentation cycles are represented by fine, predominantly clay, particles which have hydrogeologically been modeled as semi-permeable interbeds (of which there is locally one or more). The horizontal screens have been installed in the lowest coarse-grain strata, such that the interbeds, along with the colmated riverbed, constitute the primary constraint of location and well capacities.

The greatest losses of energy (hydraulic resistances) during the course of groundwater flow occur at the

riverbed and the interbed, as modeled (Fig. 1). In the immediate vicinity of the horizontal screens of well RB-16, where the concentration of groundwater leakage through the interbed (interlayer) is the greatest, the piezometric head difference between the strata above and below is as large as ten meters. This has been established by a pair of piezometers near the said well (Fig. 2). The filtration characteristics and extent (continuity) of the interlayer directly affect the well discharge capacity and, as such, it is important to characterize the interlayer.

The accuracy of results depends on the number and locations of the required observation wells. In reality, more piezometer pairs should be put in place, which would tap the strata above and below the interbed. Their screens should not be long (about half a meter). Unfortunately, it is not possible to install piezometers where they are most needed: below the riverbed and along the directions of the horizontal screens towards the river.

In addition to the discharge capacity of the well and the location, it is necessary to determine the maximum

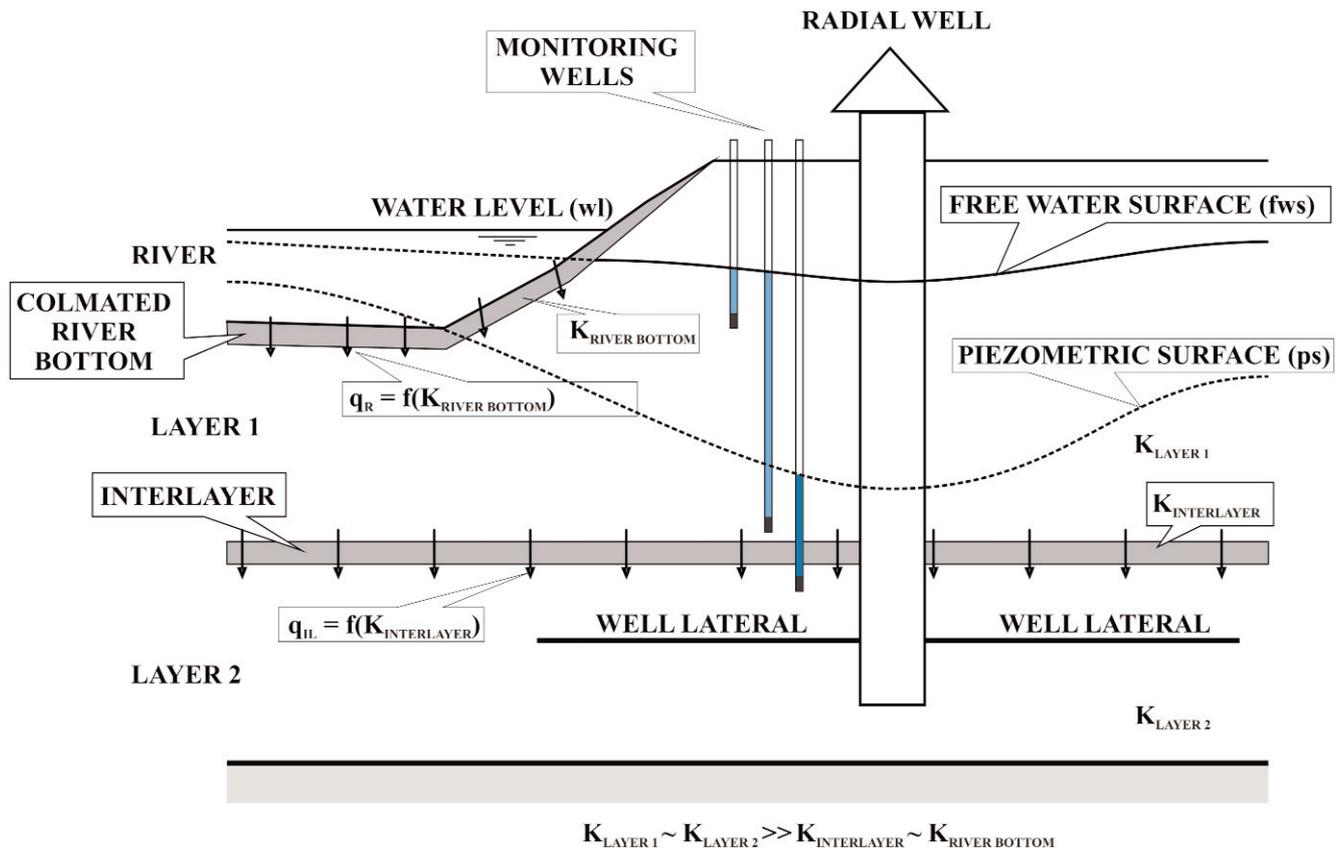


Fig. 1. Schematic representation of groundwater flow from the river to the radial collector well, where there is a semi-permeable interlayer.

Well RB-16 is located on the right bank of the Sava River, on a river island (Ada Ciganlija) close to downtown Belgrade. It is surrounded on all sides by other wells, roughly at a distance of 400 m. It has four relatively new horizontal screens (installed in 2007); the other screens have been shut-off and decommissioned (Fig. 2). The screens tap the lowest alluvial water-bearing stratum, at a depth of some 30 m.

Given its position in space, the recharge zone of well RB-16 is relatively constricted, primarily by the operation of neighboring wells. This limits its capacity even further.

The assessment and quantification of the discharge capacity of the well and, in hydraulic terms, the part of the aquifer to which it belongs, are in this case related to the previously-described conditions on the

screen entrance velocities, which in turn requires the quantification of the capacity of individual screens. The conductivity of a horizontal screen is defined via the coefficient of local hydraulic resistance (*LHR*), which may vary both along the length of the screen and over time.

Here the maximum (permissible) screen entrance velocities are related to two criteria:

The first criterion ensures filtration stability of the porous medium in the near-well region and is determined for site-specific conditions, generally based on experience.

The second criterion is much more complex and pertains to well ageing, in the present case study due to screen incrustation. The well ageing process is a set of different phenomena that occur simultaneously and

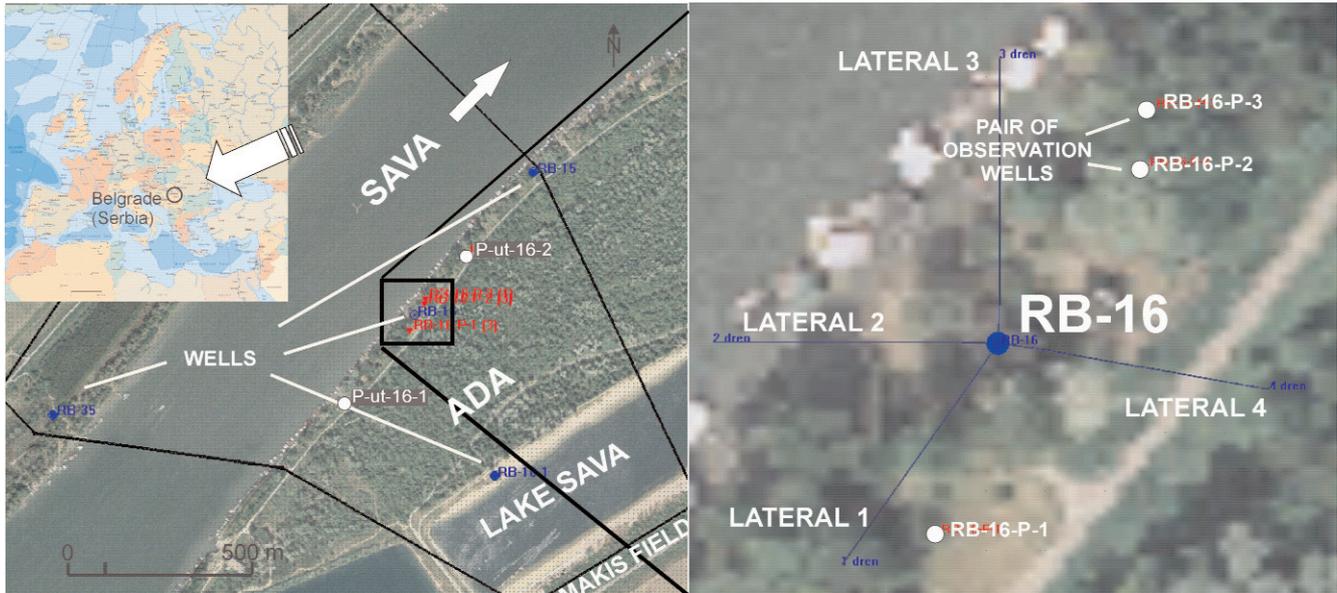


Fig. 2. Well RB-16 and its environs; map of a part of Belgrade Groundwater Source.

whose intensity differs over space and time. They depend on the composition of the porous medium (grain-size distribution, petrology, mineralogy, geochemistry) and of the groundwater (physical, chemical, biochemical and microbial parameters). Additionally, well ageing may depend on the operating mode of the well. Well ageing results in increasing LHR along the horizontal screen and decreasing conductivity, until the screen ultimately ceases to function.

Long-term research undertaken at BGS has revealed a distinct correlation between the previously-mentioned drivers and the well discharge capacity (or screen entrance velocities). With regard to two groundwater parameters: redox potential (Eh (mV)) and dissolved iron concentration (Fe^{2+} (mg/L)), identified as well ageing indicators, the correlation with permissible entrance velocities (v_{perm}) has been empirically quantified as a function of a given ageing rate (rate of LHR increase) (Dimkić & Pušić 2014):

$$v_{perm} = f(Eh, Fe^{2+}) \quad (3)$$

The second criterion is often more stringent and requires lower screen entrance velocities, resulting in a lower well discharge capacity, but it ensures longevity and requires less frequent rehabilitation of horizontal screens.

Groundwater flow is calculated applying the Richards equation, which describes flow through the vadose zone. This equation, as a function of the hydraulic potential, may be written as:

$$C(h) \frac{\partial h}{\partial t} - \nabla \cdot (k_r K \nabla h) = q \quad (4)$$

where: $C(h) \frac{\partial h}{\partial t}$ – specific moisture capacity,

K – filtration tensor (hydraulic conductivity),

k_r – relative conductivity, and

h – hydraulic potential (piezometric head).

Three approaches were followed to simulate boundary conditions: Neumann's, Dirichlet's, and Robin's.

The Neumann boundary condition applies to the part of the flow boundary at which the rate of discharge is known:

$$u \cdot n = g_N \quad (5)$$

where: u – Darcy's velocity, and n – external unit normal to the boundary. It is used to model the contour that represents the boundary streamline (in plan view, or surface in space, $g_N = 0$), the wells ($g_N \leq 0 \leq g_N$), precipitation ($g_N > 0$), and evaporation ($g_N < 0$).

The part of the boundary at which the hydraulic potential is known is modeled applying Dirichlet's boundary condition:

$$h = g_D \quad (6)$$

Dirichlet's condition is applicable to boundaries that represent water flow (rivers, lakes, channels, etc.), as well as to wells (without LHR) where the piezometric head is known.

Robin's condition is specified in the case of semi-permeable boundaries through which groundwater leaks:

$$u \cdot n = \Psi(h - g_R) \quad (7)$$

where: $\Psi = K_k/d$ – leakage coefficient, and K_k – hydraulic conductivity of the semi-permeable layer at

the boundary, and d – its thickness. A colmated riverbed, a radial well screen, and a tube-well screen are typical examples of Robin's condition (DOTLIĆ, 2015). Colmation is a process through which hydraulic resistances increase due to mechanical, biochemical and microbial processes (DIMKIĆ et al., 2008, 2011b, 2011c; DIMKIĆ & PUŠIĆ, 2014).

Methods

Spatial data related to well RB-16 were analyzed and organized to produce a hydrogeological model of the terrain and alluvial sediments, governed by the principle that a layer is the basic spatial and hydraulic unit: a hydrogeologic entity, a result of sedimentation, whose filtration characteristics are homogenous across the areal extent. Licensed software RockWorks by RockWare, Inc. was used for analysis and display.

The initial values of filtration parameters, as the starting point for the development of the hydrodynamic model, were determined applying a two-fold approach: based on the grain-size distribution of the material sampled at different borehole depths, and based on interpretation of multiple well pumping tests.

Well test data were entered and groundwater flow simulation calculations performed using an original solver – WODA (Well Outline and Design Aid), developed at Jaroslav Černi Institute for the Development of Water Resources, Numerical Analysis Group, Belgrade. WODA is a simulator of variably saturated well-driven groundwater flow in an anisotropic discontinuous environment with miscible displacements, heat transfer, variable density, sorption, degradation, etc. The mathematical groundwork was prepared and the solver programmed by VIDOVIĆ et al. (2014). At this time, WODA does not have its own graphical user interface, but it can work with groundwater models constructed using a Lizza interface.

Lizza was developed in cooperation with the Bioengineering Research and Development Center - BioIRC, Kragujevac, Serbia. It supports full 3D representation of the results of stationary and non-stationary modeling of groundwater flow within the aquifer and the vadose zone, as well as the results of calculations of mass and heat transport via groundwater.

Both software programs are open source and available at:

WODA – <http://www.sourceforge.net/projects/wodasolver/>

Lizza – <http://www.bioirc.ac.rs/index.php/groudwater-flow-software>

A special user-friendly feature of the software is ease of specifying the real cross-section of the river and radial well screens in the model (DIMKIĆ et al., 2009, 2010, 2011d).

Analysis and definition of model input data (schematization)

The study area was hydrogeologically schematized using available data: drilling data from 139 wells and several hundred grain-size distribution analyses of samples. The schematization was based on an assessment of descriptions of tapped units, grain-size distributions of samples, and photos of borehole cores.

Suitable software was used to generate a 3D hydrogeologic model of the sediments. The first attempt produced eight schematized layers.

Figure 3 shows how the layers in the immediate vicinity of well RB-16 were modeled. The blue rectangles on the left-hand side of the figure represent the average d_{10} (mm) of the samples collected from boreholes in the near-well region. Brown rectangles denote intervals of semi-permeable material, whose grain-size distribution was generally not analyzed. The intervals were identified as semi-permeable based on descriptions and relatively few data. As previously mentioned, the profile derived in this manner was compared to the corresponding profiles of neighboring wells in the study area, arriving at eight schematized layers.

Then, the elevations and lengths of the screens of available observations wells, and the piezometric head recorded while the wells were in operation, were analyzed to obtain an indication of the hydraulic relationships of the layers above and below layer packages 5, 6 and 7. In view of the problem addressed and data availability, it was concluded that a simpler hydrogeologic scheme (with fewer layers) could be adopted.

It should be noted that there was a pair of piezometers (RB-16-P-2, RB-16-P-3) with short screens (0.5 m) in the immediate vicinity of the well, a short-screen piezometer (RB-16-P-1) in the water-bearing layer, also in close proximity to the well, and two piezometers (P-ut-16-1, P-ut-16-2) with relatively long screens (5 m) in the upper layer package, half way to the neighboring wells. As concluded, the short screens virtually provided data on a point in space within the water-bearing layer, while the long screens, which covered several layers, provided the resulting piezometric head potential of the individual layers.

It should also be kept in mind that groundwater flow in the near-well region, around the horizontal screens, is distinctly spatial (3D) and that under such conditions short-screen observation wells provide a more realistic picture. As the distance from the well grew, groundwater flow became increasingly horizontal in nature, such that the screen length ceased to be of overriding importance for the veracity of the measured data.

As a simpler alternative, a hydrogeologic model comprised of three schematized layers was constructed (Fig. 3). Apart from the knowledge about the study area, the model in this case was a result of the number

and locations of available piezometric head data collection points: observation wells and their screen lengths.

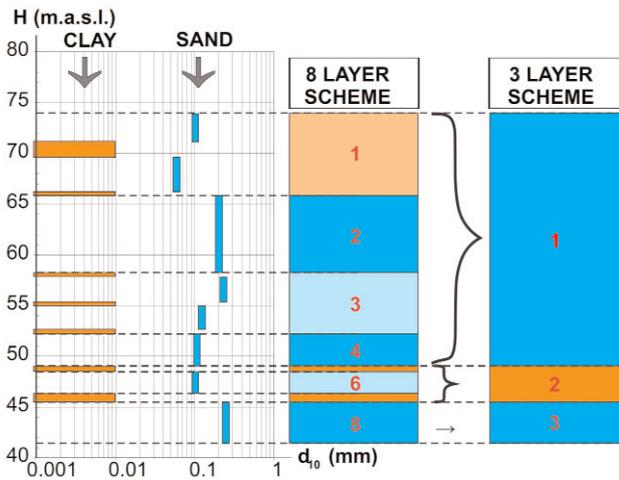


Fig. 3. Vertical distribution of grain d_{10} (synthesized well RB-16 location data), and switch from 8 to 3 layers.

Even though it is generally deemed that radial well screens are horizontal, that does not apply to well RB-16. Two of the four screens had a vertical bend, especially Lateral 1, whose curvature towards the ground surface was slightly less than 6 m.

Calibration of the model of the extended area of well RB-16 was based on well pumping tests. Datasets from three tests, conducted on 7 October 2007, 24 March 2011, and 22 July 2013, were used in the case study. The first test was undertaken immediately upon installation of new screens (the old screens were shut-off).

Groundwater model of well RB-16

Based on the hydrogeologic model, a hydrodynamic model of the groundwater flow on the location of well RB-16 was constructed. This model included schematized layers of the alluvial complex of the Sava River. The dominant directions of groundwater flow are from the Sava River, Lake Sava, and New Belgrade. The model output came via the wells within the model.

The model boundaries were defined on the basis of the analyzed flow pattern in this part of the groundwater source. The neighboring wells (RB-15, RB-16-1, RB-35), a segment of the Sava River, and a part of Lake Sava were also included in the model. Groundwater inflow from New Belgrade was the boundary on the left bank of the Sava River (Fig. 4).

Well RB-16 was modeled using actual data, including its (impervious) caisson and horizontal screens, whereas the other wells were tube wells, of the corresponding equivalent diameter.

The river and the lake were specified in the model based on their previously measured cross-sections.

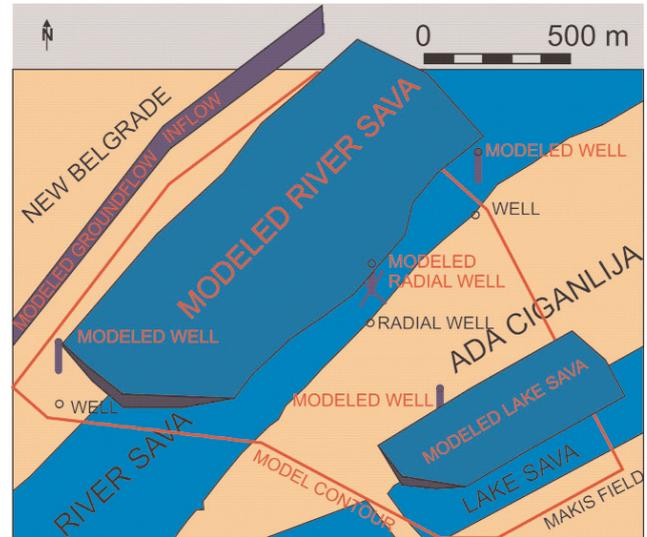


Fig. 4. Model contours and boundary conditions.

The software interpolated the intervals between the cross-sections, to produce a continuous river channel (whose geometry and filtration properties can vary).

The hydraulic conductivity of the colmated riverbed was specified at each cross-section inflection point. This boundary condition is specific in that the program recognizes the river width between banks, depending on the specified river stage. The width of the river was constrained by levees, or the maximum stage contour.

The existing observation wells were used as control points in groundwater level calculations for model calibration. The pair of piezometers above and below the semi-permeable interlayer is very important, in this specific case also for properly defining the well discharge capacity. The pair's piezometric head difference is a function of well discharge and uniquely determines the filtration parameters of the interlayer, which were derived from calibration. It would have been very useful to have piezometers in the water-bearing layer immediately below the riverbed but, unfortunately, that was not the case. Otherwise, it would be possible to come up with much better inputs for the quantification of riverbed conductivity.

Where there is a semi-permeable interlayer that constitutes a hydraulic barrier for groundwater flow to the well, it is extremely important and useful to have pairs of piezometers both close and at some distance from the well.

Model calibration – calculation results

Calibration of the model of the well RB-16 location was a huge and complex task, which involved several steps.

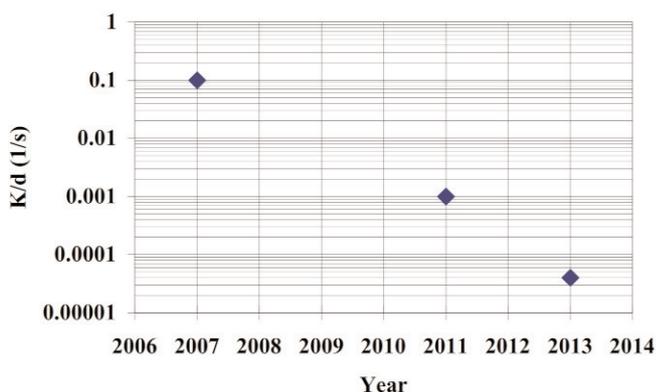
Datasets from three pumping tests (2007, 2011, and 2013) were used for calibration. The model was cali-

brated for the simulation of each test. The results were compared and analyzed. Finally, the 2011 test model was selected and, after minor boundary condition adjustments, the calculations were repeated for the other tests. This procedure was followed for both hydrogeologic model options: three and eight schematized layers.

At the end, a representative model of the well RB-16 location was adopted.

The simulation of well RB-16 tests provided the variation in horizontal screen conductivity over time (Fig. 5a). The conductivity parameter was K/d (K is the hydraulic conductivity of the clogged layer along the edge of the screen (m/s), and d is the adopted representative (unit) thickness, (m)). Figure 5b shows the variation in local hydraulic resistance, LHR , of the screen, based on information on all the tests, using data on well RB-16 and the so-called “close” piezometer (DIMKIĆ et al., 2011a, 2011b, 2011c; DIMKIĆ & PUŠIĆ, 2014).

The calculation results from both procedures yielded qualitatively similar results and corroborated well ageing due to biochemical incrustation.



parameters. The representative, average values of filtration parameters of the porous medium and riverbed conductivity in the case of the three-layer model are shown in Table 1.

Table 1. Model calibration results, average values of filtration parameters of schematized layers, riverbed, and lakebed.

	K_{horiz} (m/s)	K_{vert} (m/s)	S (m ⁻¹)	S_y (-)
Layer 1	3.35E-04	2.37E-06	7.E-05	1.5E-01
Layer 2	4.46E-04	3.00E-07	7.E-05	7.0E-02
Layer 3	6.65E-04	6.65E-04	7.E-05	1.2E-01
	K/d (1/s)			
Sava River	4.00E-07			
Lake Sava	3.00E-07			

Representative characteristics were also obtained for the Sava River and Lake Sava.

The effect of the interbed on groundwater flow was manifested through the piezometric head difference

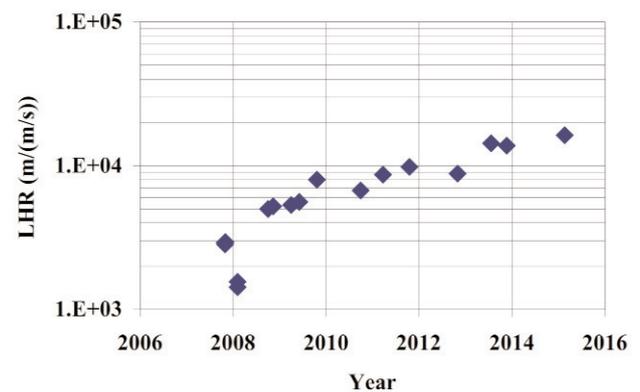


Fig. 5. a) Decrease in conductivity (K/d) of radial well screens, based on model simulation of selected pumping tests; b) increase in local hydraulic resistance (LHR) of the screens, based on analysis of all available pumping test data, via the so-called “close” piezometer.

Analysis and quantification of the components of groundwater flow to the well are important for assessing the effect of individual boundary conditions (recharge zones) on well discharge capacity and, indirectly, well water quality. Model tests revealed that the discharge capacity of well RB-16 was the sum of inflows from the Sava River (95%), Lake Sava (4%), and New Belgrade (1%). These proportions resulted from the simulation of the 2011 pumping test (similar results were obtained for different conditions).

Filtration parameters of the schematized layers were another outcome of model calibration. It was obvious that the schematized layers were a result of the synthesis of the geometry and filtration characteristics of corresponding real sediments, such that there was certain heterogeneity in plan view and anisotropy of

between the upper and lower water-bearing layers. The conclusion was that it is extremely important for the discharge capacity of the well, and the location as a whole, to determine the hydrogeologic characteristics of the interbed (position, spread, thickness, filtration parameters). Figure 6 shows the piezometric head difference between the upper and lower water-bearing layers, as a result of the presence of the schematized continuous interbed, under the operating conditions of well RB-16.

Analysis of the discharge capacity of well RB-16

In order to predict the achievable discharge capacity of a new or reconstructed well, the design needs to



Fig. 6. Piezometric head difference between the lower and upper layers (interbed floor and roof).

be based on the quantification of discharge under relevant conditions and an analysis of drivers (parameters). Of interest here is the determination of zones with different intensities of groundwater flow to the well. Depending on the specific case and as needed, these zones can be treated differently in terms of purpose.

Figure 7 shows the determined sizes of the zones of well RB-16. The lines delineate areas that contribute a certain percentage of the flow to the well. In the present case study, the basis was the calculation of unit vertical fluxes through the semi-permeable interbed.

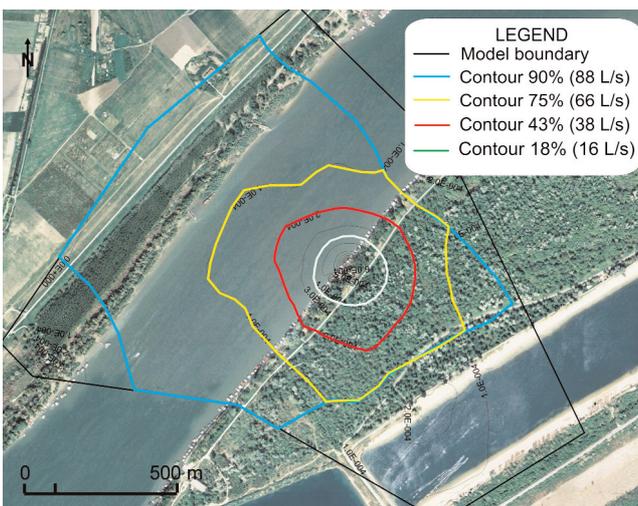


Fig. 7. Percent contributions of different zones to well discharge.

The time the groundwater takes to travel through the interbed can be calculated on the basis of the vertical flow velocity distribution and interbed thickness. Figure 8 shows the results of such calculations. The

first, roughly estimated average travel time through the interbed was 12 months (75% contour in Fig. 7, interbed thickness 4 m). Understandably, the travel time was much shorter within the zone of the horizontal screens (about 100 days for the 18% contour in Fig. 7, interbed thickness 3.5 m).



Fig. 8. Time zones of groundwater travel through the semi-permeable interbed (in months).

Model tests can also provide unit discharge capacities of the horizontal screens, as well as the distribution of entrance velocities along the screens. Figure 9 shows the results of calculations for a specified water level in the well caisson of 55 m above sea level (a.s.l.), corresponding to a discharge of 98.5 L/s. It is apparent that the discharge of Lateral 1 is low; it bends in the vertical direction (about 6 m). This horizontal screen penetrates the interbed and reaches the water-bearing layer above it. The low discharge can be attributed to the fact that this screen is rather encrusted, according to an underwater video.

The total capacity of a well location can be determined based on the calibrated model and set criteria (water level maintained inside and outside the well caisson). If the groundwater level is specified in the interval from 52 to 55 m a.s.l. and the water level in the well caisson at 5 m above the horizontal screens, the maximum discharge capacity of well RB-16 will be in the interval from 120 to 150 L/s.

Effect of riverbed conductivity

Riverbed conductivity is a key driver of the discharge capacity of a well and location. The colmating layer of the river varies over both space and time. It depends on the river discharge regime and the dominant type of groundwater flow. It is especially important where the operation of a bank-filtration type well

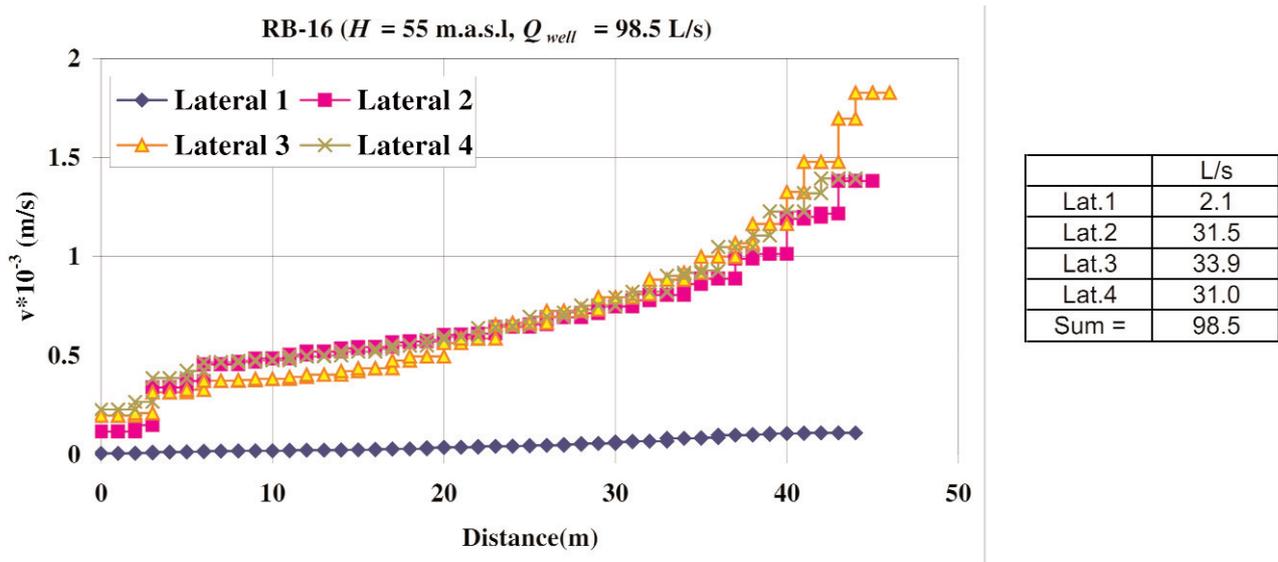


Fig. 9. Discharge capacities of individual horizontal screens and distribution of entrance velocities along the screens of well RB-16 (water level in the well caisson maintained at 55 m above sea level, $Q = 98.5$ L/s)

imposes one-way groundwater flow – constantly from the river to the aquifer.

Figure 10 illustrates to what extent riverbed conductivity can affect the flow pattern and the well discharge capacity. Black denotes the vadose zone.

Figure 10a shows the results of calculations that involve the river, from the calibrated model (three-layer scheme, 2011 pumping test).

In Fig. 10b the hydraulic conductivity of the riverbed is lower by a factor of 10. The changes are obvi-

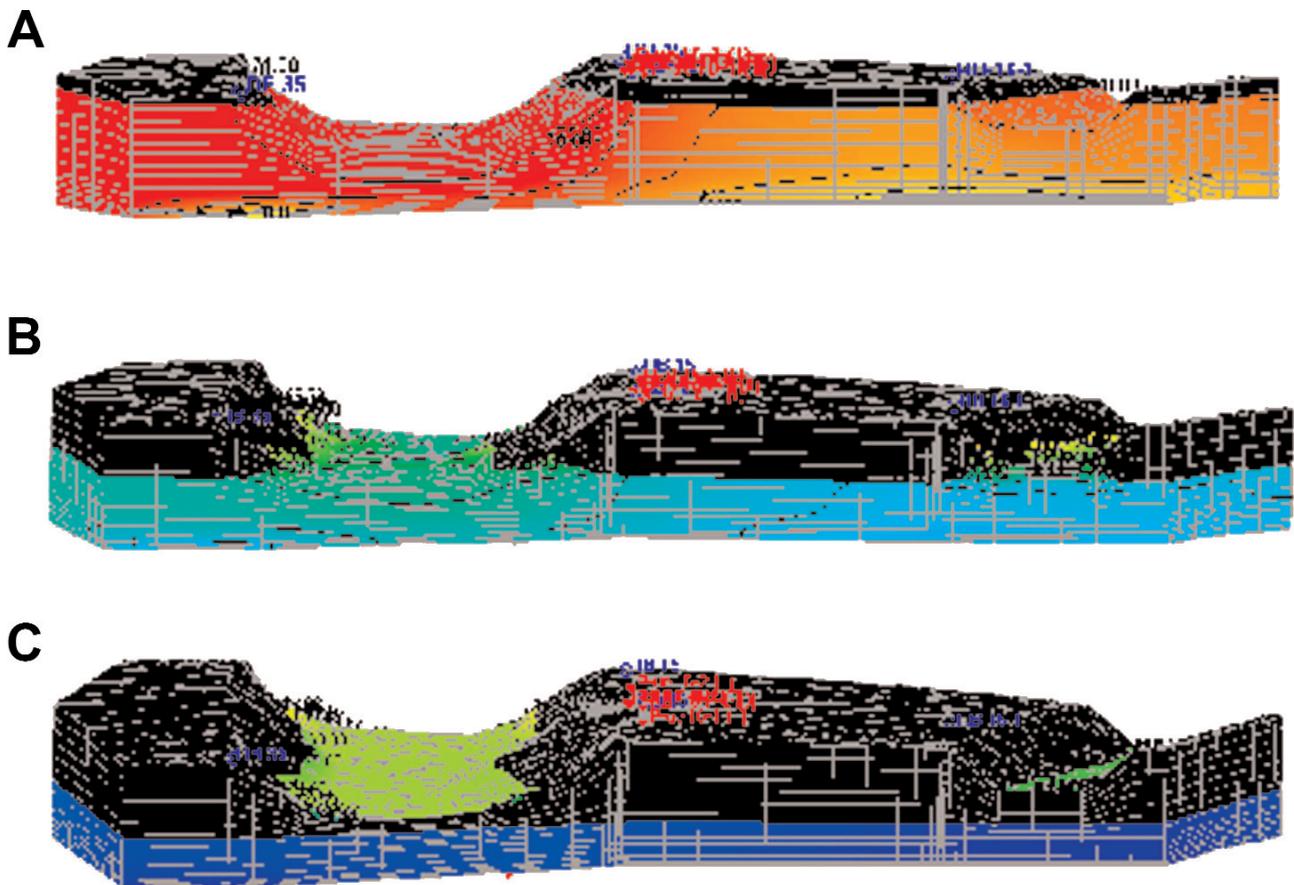


Fig. 10. Separation of the water table from the riverbed, at reduced riverbed conductivity. a) $S_{ava} = 1.5 \times 10^{-7}$ m/s; QRB-16 = 98.5 L/s; b) $S_{ava} = 1.5 \times 10^{-8}$ m/s; QRB-16 = 28 L/s; c) $S_{ava} = 1.5 \times 10^{-9}$ m/s; QRB-16 = 1 L/s.

ous, in terms of both flow pattern and well discharge capacity, which is lower by a factor of more than three.

Figure 10c shows the results of calculations for a riverbed conductivity decreased by a factor of 100. The outcome is dramatic – the river is virtually detached from the groundwater hydraulically (“perched” above it), and infiltration from the river is negligible. The well is dry! If this should actually occur (though unlikely), the well would receive water from beyond the left and right banks of the river, but the quantity would certainly be small.

The above analysis shows that a realistic determination of riverbed conductivity is of major importance for the quantification of the discharge capacity of the location and the well itself.

The travel time from the river to the well under “normal”, calibrated model conditions differs, depending on the path of travel, but is not shorter than two years. The travel time through only the upper water-bearing layer is of the order of 500 days, such that the shortest travel time through the semi-permeable interbed is about 200 days. Inherent in this fact is the answer to the question why the well water quality is consistently high, despite the variation in river water quality over time.

Effect of the semi-permeable interbed

In the case of well RB-16, the semi-permeable interbed causes vertical groundwater filtration from the upper to the lower (tapped) water-bearing layer. Its filtration properties can be so poor as to prevent the flow of water to the well. On the other hand, the interbed is extremely important for the conservation of high well-water quality. Slow and prolonged filtration facilitates complex biochemical processes, which reflect the self-purification potential of the aquifer.



Fig. 11. Piezometric head difference between the lower and upper layers (interbed floor and roof), at reduced interbed conductivity ($K_{vert} = 1 \times 10^{-9}$ m/s).

Figure 11 shows the piezometric head difference between the interbed floor and roof when the vertical conductivity is $K_{vert} = 1 \times 10^{-9}$ m/s. The difference in the near-well region can be even greater than 10 m, which is about three times more than under real conditions (Fig. 6).

The discharge of the well has dropped to a third of the realistic discharge (34 L/s vs. 98 L/s), at the minimal water level in the well caisson ($H = 55$ m a.s.l.). Under these conditions, the entire amount of the water in the well comes from the overbank area.

This is another illustration of the need for more pairs of piezometers, to track hydraulic losses through the semi-permeable interbed.

Rate of well ageing

In radial well design, sizing of the discharge capacity is not only a matter of initial permissible screen entrance velocities, but also of sustainable operation, which implies technically and economically viable service over a prolonged period of time.

The authors of this paper have for years been studying the conditions and well ageing processes at BGS (about 100 horizontal collector wells). A correlation has been established between well ageing and the biochemical properties of the groundwater. Based on maintenance practices and rehabilitation scheduling, the design rate of increase in local hydraulic resistance (LHR) is 0.35 m/year. This criterion determines the maximum permissible screen entrance velocities, depending on the redox potential (Eh) and concentration of bivalent iron (Fe^{2+}) in the groundwater (Fig. 12).

In the specific case, this means that the well discharge capacity that fulfills these criteria, guarantees a maximum increase in the local drawdown of about 3.5 m over 10 years, which is the preferred maintenance interval between two well rehabilitations.

The average groundwater parameters of well RB-16 are: $Eh \sim 137$ mV and $Fe^{2+} = 0.6$ mg/L, which, according to Fig. 20, correspond to a maximum allowable entrance velocity of $v = 3.15 \times 10^{-4}$ m/s relative to Eh and $v = 7.5 \times 10^{-4}$ m/s relative to Fe^{2+} . Considering the total length of the horizontal screens (four, diameter 0.4 m) of 240 m, the resulting discharge capacities of this well are $Q = 94$ L/s and $Q = 226$ L/s. Obviously the more stringent criterion needs to be fulfilled. If the well had six screens, it would be reasonable to expect a sustainable long-term discharge capacity of about 110 L/s.

Taking into account the maximum entrance velocity criteria and the maximum capacity of the location, eight horizontal screens would ensure long-term operation of the well at a capacity of 120 – 130 L/s. Based on these technical guidelines, the preferred solution becomes a matter of economics.

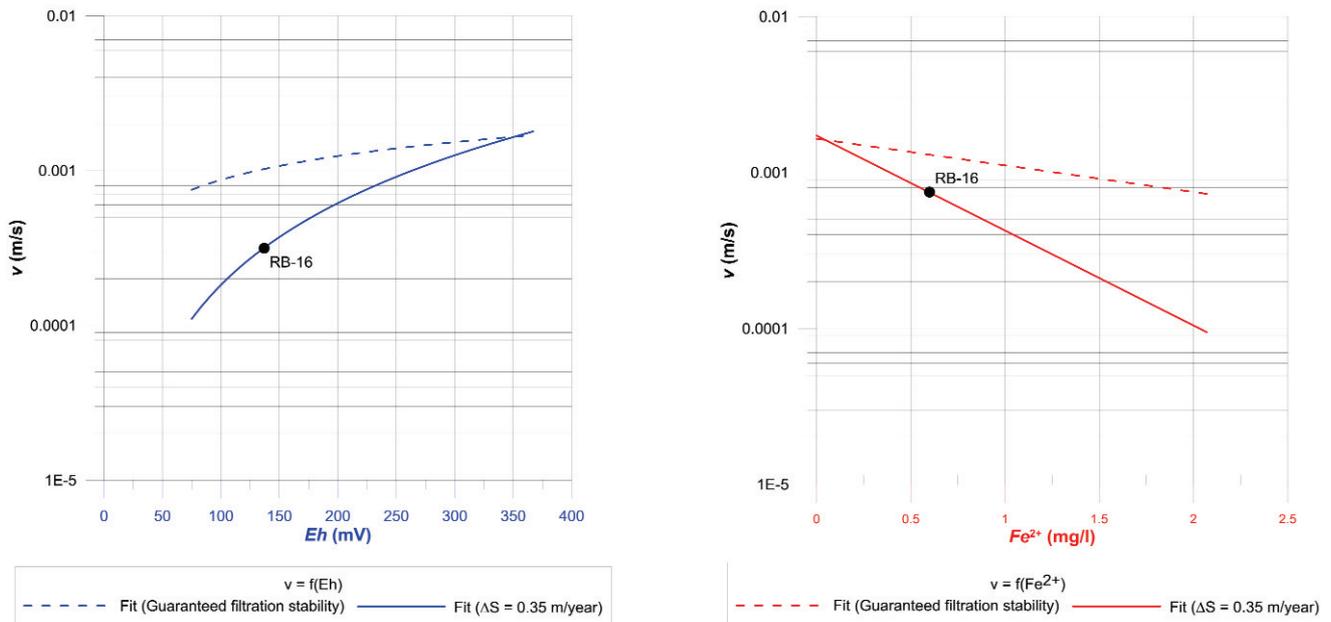


Fig. 12. Permissible horizontal screen entrance velocities as a function of Eh and Fe^{2+} .

Discussion and conclusions

When plans are made to build a well or improve the capacity of an existing well, there is a series of issues that need to be addressed in as precise a manner as possible.

There are several important reasons for using radial collector wells in alluvial aquifers of relatively large rivers to provide public water supply, generally for big agglomerations. These reasons are:

- Tapping of the most permeable alluvial strata (usually lower sediments);
- Utilization of the purification potential of semi-permeable interbeds; this potential can be harnessed more effectively by radial collector wells than tube wells;
- Easier groundwater source management due to high capacities of individual wells, such that fewer wells, pumps, etc. are needed.

Biochemical incrustation of wells tends to occur in anoxic alluvial aquifers, where there are sufficient amounts of iron. The correlation between the rate of increase in hydraulic resistance at horizontal screens and biochemical parameters (incrustation indicators Eh and Fe^{2+}) has already been discussed by the authors of this paper (in DIMKIĆ et al., 2011a, 2011b, 2011c, DIMKIĆ & PUŠIĆ, 2014). The correlation yields a maximum permissible horizontal screen entrance velocity function, depending on the considered indicator:

$$v_{\text{perm}} = f(Fe^{2+}); \quad v_{\text{perm}} = f(Eh). \quad (8)$$

The procedure presented here generally comprised four stages:

Stage 1: Monitoring of well-water quality and definition of biochemical conditions and rate of LHR increase.

Stage 2: Definition of the capacity of well RB-16 (in terms of its groundwater withdrawal potential), based on monitoring of its operation and changes in piezometric head in observation wells above and below the semi-permeable interbed. The horizontal screens of the considered well are below this interbed. The parameters relevant to the determination of the capacity of the location are: permeability of the aquifer strata, permeability and thickness of the semi-permeable interbed, quality of the hydraulic link between the river and the aquifer, and LHR at horizontal screens. A minimal but sufficient network of piezometers was available for achieving this objective.

Original software was used to create a 3D hydraulic model of groundwater flow. Its additional features include excellent modeling of links between rivers and aquifers, as well as horizontal screens and aquifers (BioIrc and Jaroslav Černi Institute, 2014; DIMKIĆ et al., 2007a, 2010; VIDOVIĆ et al., 2014).

Stage 3: Determination of critical velocities, depending on biochemical parameters. Under anoxic conditions, these velocities are lower or much lower than those derived from the aquifer's filtration characteristics in the region around the horizontal screens. The determination of critical velocities via biochemical parameters allows the capacity and number of horizontal screens to be defined in a way that prolongs their life cycle and reduces maintenance costs.

The confirmation and/or improvement of the presented relations, and the definition of the roles of individual species of iron bacteria in the well incrustation process, are challenging from a scientific perspective.

Stage 4: Monitoring of the operation of the well following rehabilitation or reconstruction (emplacement of new horizontal screens).

BGS is comprised of 99 radial wells and about 50 tube wells. The decline in source capacity, due to iron incrustation, has been substantial – about 200 L/s per year. The proposed method, along with appropriate monitoring, allows considerable well maintenance cost cuts and the selection of best locations for new wells. The method is believed to be a significant contributor to the engineering practice and calls for further scientific study.

Natural setting

Urban agglomerations around rivers generally rely on riparian water supply sources (bank filtration). Well screens are located in the lower part of the water-bearing complex, which is usually the best to be tapped. The hydraulic contact with the river and the filtration parameters of the aquifer are of primary importance. Alluvial sediments, from which groundwater is often abstracted, are characterized by sudden alternation of coarse- and fine-grain strata. Semi-permeable interbeds and lenses hinder groundwater flow to a well and limit its capacity. However, a prolonged groundwater travel time has a positive effect on groundwater quality transformation processes and the natural self-purification potential.

Well RB-16, which is the object of the present case study, relies on bank filtration. Within the aquifer system, above the horizontal screens, there are several semi-permeable interbeds.

In order to determine the optimal discharge capacity of a well (from a technoeconomic perspective), the discharge capacity of both the extended location and the well itself needs to be analyzed. It should be noted that well RB-16 is surrounded by other wells of the same groundwater source. The effect of the extent of riverbed colmation and the filtration parameters of the interbed were assessed, using a hydrodynamic model of the groundwater in the pertinent part of the groundwater source.

The number and distribution of observation wells from which data were used to calibrate the model governed the schematization of the aquifer system as a three-layer medium, with a single schematized interbed. This was a result of the presence of a pair of piezometers that registered water levels above and below the series of semi-permeable interbeds. It was noted that a suitable (larger) number of pairs of observation wells would be very useful for this type of analysis.

Based on the calibrated model, the conclusion was that the conductivity of the riverbed was of the order of 1.5×10^{-7} m/s. Any decrease in conductivity directly impacted the capacity of the location. A decrease by a factor of 100 resulted in total hydraulic separation of

the water table from the riverbed. Groundwater flow from the river to the aquifer was solely a function of the river stage and filtration parameters of the aquifer.

The conductivity of the semi-permeable interbed was analogous. In the case of well RB-16, while in service, it is not realistic (but in principle possible) for the piezometric level of the lower water-bearing stratum to drop below its roof and create a vadose zone near the horizontal screens. This would certainly have a considerable impact on the discharge capacity of the well, in particular the biochemical processes that take place in the groundwater.

Well ageing

Well ageing is a technoeconomic challenge because it affects well longevity and maintenance costs. Screen entrance velocities, which determine the discharge capacity of the well, need to also guarantee a pre-defined rate of well ageing (or the rate of discharge capacity decline). The initial water level maintained inside the well caisson, which ensures enough (pre-set) time before the next rehabilitation of the well, is defined accordingly.

A maximum permissible screen entrance velocity of $v = 3 \times 10^{-4}$ m/s was specified for the average ageing indicators of well RB-16 (Eh and Fe^{2+}); as the current number of screens is four, the resulting discharge capacity of the well is $Q = 72$ L/s. Given such a design and maintenance concept, any increase in discharge capacity needs to be sought in a larger number of screens. If the well had six screens, it would be reasonable to expect a sustainable long-term capacity of about 110 L/s.

In closing, the significance of this research lies in the simultaneous determination of the hydraulic capacity of the location of a radial collector well and the critical groundwater flow velocities to the horizontal screens. The discharge capacities of the location and the well were determined using a specially developed and highly sophisticated 3D model. The maximum permissible screen entrance velocities were established on the basis of the relevant biochemical relationship $v_{perm} = f(Fe^{2+}, Eh)$.

The approach outlined above is highly relevant to anoxic alluvial water supply sources, such as Belgrade Groundwater Source. The way the relationship $v_{perm} = f(Fe^{2+}, Eh)$ is included in the analysis is shown here for the first time.

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Резиме

Нови принцип дефинисања елемената радијалних бунара у аноксичним условима

У раду се по први пут приказује примена нове методе за дефинисање склоности бунара колмирању талозима гвожђа у издани, аноксичних услова. На основу утврђене везе између кинетике колмирања бунара, редокс потенцијалаа, садржаја гвожђа у води и улазних брзина у дренаже бунара, утврђене су максимално дозвољене брзине, а затим и капацитет дренажа и бунара.

Постављен је услов да хидрулички отпори, изазвани таложњем гвожђа на филтрима дренажа, буду мањи од задатих. Веза између максимално дозвољених брзина уласка подземних вода у дренаже бунара (брзине које још омогућују да пораст локалних хидрауличких отпора на улазу у дренажу буду мање од задатих) и биохемијских индикатора (Eh , Fe^{2+}), преузета је из претходних радова аутора овог чланка са сарадницима. Хидрауличка анализа потенцијалног капацитета локације бунара РБ-16 је рађена оригиналним софтвером, који омогућава 3Д анализу са граничним условима, прилагођеним за ову сврху.

У раду су приказани резултати студије текуће и потенцијалне експлоатације подземних вода бунаром са хоризонталним дренажима РБ-16. Бунар је лоциран на изворишту за снабдевање водом града Београда, у алувијалним седиментима реке Саве. Рад је специфичан, јер се по први пут приказује поступак одређивања основних елемената за процену стања дренажа и/или обнове бунара, утискивањем нових дренажа. Узимају се у обзир биохемијски параметри подземних вода, који утичу на брзину колмирања талозима гвожђа:

$$\begin{aligned} v_{dozv} &= v_{dozv} (Fe^{2+}) \\ v_{dozv} &= v_{dozv} (Eh) \end{aligned}$$

Максимално дозвољене брзине (v_{dozv}), које обезбеђују задату (дозвољену) кинетику пораста локалних хидрауличких отпора на дренажима бунара, по први пут су дефинисани радовима Dimkić et al. (2011a, 2011b, 2011c), Dimkić & Pušić (2014). Приказана је примена комплексне методологије којом се одређују:

- експлоатациони капацитет локације и самог бунара,
- конструктивни елементи бунара (број дренажа, улазне брзине), полазећи од карактеристичних биохемијских одлика аноксичне издани.

Примена оваквог, новог приступа пројектовању бунара има знатан утицај на трајање бунара са хоризонталним дренажним системима и уопште, на економичност њиховог рада. Овај принцип у основи треба да важи и за друге типове водозахватних објеката (на пример, за цевасте бунаре).

У раду су дати оквирни принципи на основу којих је израђен софтвер за решавање изразито 3Д проблема струјања подземних вода, какво се јавља у непосредној близини бунара. Такође су приказани резултати верификације прорачуна струјања ка бунару. Основни параметри који утичу на капацитет локације бунара су: рад осталог дела изворишта, пропусност речног дна, хидрогеолошке одли-

ке издани. Утврђен је капацитет локације бунара у износу од 120 до 150 L/s. На основу биохемијских параметара, утврђене су максимално дозвољене улазне брзине, као и капацитети појединачних дренажа. Резултат анализе указује на оптималне главне конструктивне карактеристике бунара (број и капацитет дренажа), које се могу ускладити са техничким и економским условима решавања изворишта у целини.

Сматрамо да је приказ овог рада значајан за инжењере и научнике, који се баве хидрауликом и процесима на бунарима, посебно имајући у виду оне у аноксичним условима, изложене колмирању талозима гвожђа.

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