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Comparative assessment of radial collector well elements with a new approach

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Abstract. In radial collector well design or rehabilitation it is extremely important to define the capacity of the location and the long-term sustainable discharge of the well. Where incrustation occurs, groundwater entrance velocities at horizontal screens also need to be determined. At Belgrade Groundwater Source, maximum permissible screen entrance velocities are correlated with the oxic state of the aquifer, expressed via the redox potential, and the concentration of bivalent iron in the groundwater. The entrance velocities limit the rate of screen incrustation and are based on the maximum permissible increase in local hydraulic resistance at the screens. This is a novel approach on a global scale. In the case of anoxic groundwater, the derived permissible entrance velocities are much lower than estimated by standard, commonly used methods. The new approach is believed to be a significant contribution to well design. Jaroslav Černi Institute for the Development of Water Resources (JCI) has developed software for estimating 3D groundwater flow, which relatively easily and realistically simulates horizontal screens and riverbed configuration and conductivity. The software is an effective tool for determining the capacity of the location and of the radial collector well itself. It is especially useful where the aquifer system comprises a semi-permeable interbed between the water-bearing layer, in which the screens are emplaced, and the overlying strata. A comparative hydrodynamic analysis of two wells at Belgrade Groundwater Source is presented in the paper. One of the wells (RB-16) clearly reflects the presence of a semi-permeable interbed, whereas the other (RB-46) does not.

Key words: groundwater, well discharge capacity, design.

Апстракт. Приликом пројектовања, или санације бунара са хоризонталним дреновима, значајно је да се дефинише капацитет локације, као и дуготрајно одрживи капацитет бунара. У условима присутног колмирања, потребно је одредити и улазне брзине у филтре дренова. Максимално дозвољене улазне брзине у дренове бунара су на београдском изворишту утврђене преко зависности са степеном оксичности аквифера, израженој преко редокс потенцијала и садржаја двовалентног гвожђа. Њима се ограничава брзина колмирања дренова, преко максимално дозвољеног годишњег пораста локалног хидрауличког отпора на дреновима. Ово представља нови поступак у светским оквирима. За аноксичне услове подземних вода, добијају се значајно мање дозвољене улазне брзине, него раније стандардно усвојеном методом, што је од великог значаја за пројектовање бунара. У Институту за водопривреду "Јарослав Черни" је развијен софтвер за прорачун 3Д струјања подземних вода, којим је могуће да се релативно лако и верно симулирају дренови радијалних бунара, као и конфигурација и пропусност речног дна. Овакав софтвер је успешна алатка за одређивање капацитета локације изворишта и самог бунара са хоризонталним дреновима. Ово је нарочито корисно у случају аквифера где постоји слабопропусни међуслој, који се налази између водоносног слоја у коме су дренови бунара и горњих слојева. Спроведена је упоредна хидродинамичка анализа на два бунара београдског изворишта. Код једног (РБ-16) је изражен слабопропусни међуслој, док код другог (РБ-46) он изостаје.

Кључне речи: подземне воде, капацитет бунара, пројектовање, Србија.

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Introduction

Radial collector wells are generally installed along rivers, in shallow alluvial sediments. Horizontal screens, which are sometimes longer than 50 m, enable high rates of groundwater extraction, low screen entrance velocities, low local hydraulic losses, and slower screen incrustation compared to tube wells in the same setting (WILLIAMS, 2005). At the design stage, much attention is devoted to determining the structural characteristics of horizontal screens (http://www.layne.com/en/solutions/construction/ranney-collector-wells.aspx; http://www.bhg-brechtel.com/ leistungen/horizontal-brunnenbau/) and estimating total well capacity.

In view of their origin, alluvial sediments often exhibit considerable differences over a relatively small area. This makes it difficult to conduct a proper and detailed analysis of the required well and screen parameters. Moreover, the horizontal screen emplacement technology does not enable full directional control during installation. As such, there is a high level of uncertainty that the outcome of screen emplacement will be favorable.

In the past, the characteristics of horizontal screens have been based on the results of exploration boring in the vicinity of future screens. Maintaining the filtration stability of the water-bearing medium had been the main sizing criterion (ABRAMOV, 1952; GAVRILKO, 1968; JOHNSON, 1972; KOVACS & UJFALUDI, 1983; VUKOVIĆ & PUŠIĆ, 1992). More recently, increasing use has been made of the results of research of well ageing, largely caused by iron incrustation (CULLIMORE, 1999; DIMKIĆ & PUŠIĆ, 2014; DIMKIĆ et al., 2011b, 2011c; HOUBEN & TRESKATIS, 2007; MANSUY, 1998; MCLAUGHLAN, 2002).

At Belgrade Groundwater Source (BGS), the maximum permissible screen entrance velocities have been defined as a function of the given (desirable) rate of incrustation. They are correlated with the oxic state of the aquifer (expressed via the redox potential, *Eh*) and the concentration of bivalent iron (DIMKIĆ et al., 2011a, 2011b, 2011c, DIMKIĆ & PUŠIĆ, 2014). This has resulted in screen entrance velocities that are lower than those derived solely on the basis of the filtration stability criterion, but which ensure slower well ageing and longer-term preservation of initial capacity (DIMKIĆ & PUŠIĆ, 2014).

Consistent with BGS well maintenance practices and rehabilitation scheduling, a rate of increase in local hydraulic resistance (*KLHR*) of 0.35 m/year has been specified (DIMKIĆ et al., 2011a, 2011b, 2011c, DIMKIĆ & PUŠIĆ, 2014). This criterion was used to derive maximum permissible screen entrance velocities, depending on the redox potential (*Eh*) and the concentration of bivalent iron (Fe^{2+}) in the groundwater (Fig. 1).

Polycyclic sedimentation is a specific feature of the BGS aquifer system, where each cycle is characterized by a decreasing grain size along the vertical. Often the final sequence of a cycle is dominated by fine-grain silty to clay particles that form semi-permeable layers. These layers, of local or extended spread, reduce well discharge capacity and prolong bank filtration. In view of their small thickness and because engineers had largely focused on finding strata of superior filtration properties, these layers often remained undetected.

Statement of the problem and methods

Two major problems have been identified after decades of BGS monitoring: declining well discharge and deteriorating condition of horizontal screens. While the deterioration of horizontal screens is attributed to corrosion due by poor-quality material, the capacity decline is a far more complex problem (DIMKIĆ et al., 2007). Apart from structural characteristics (number and length of horizontal screens, position within the aquifer, type and size of screen slots, etc.), the capacity of a well is defined by hydrogeological conditions and capacity decline is largely a result of incrustation processes.

Drawing on many years of experience, BGS researchers and well designers follow an approach comprised of three stages:

Determining the potential of the well location

The potential capacity of a well location can be interpreted differently, depending on the way it is considered. In the present case, the potential capacity of a well location is associated with actual BGS hydrogeological conditions and the assessment of a well also takes into account the actual operating mode. BGS wells are located along the banks of the Sava River, such that a certain part of the overbank "belongs" to each well. The capacity of such a location is quantified using a so-called "local" hydrodynamic model, which encompasses a part of the river, part of the overbank, and neighboring wells. In addition to riverbed conductivity, it is extremely important to identify the hydrogeological features of the captured medium. Another important factor is the presence of any semi-permeable interbed(s), because it or they can limit the capacity of the location to a significant extent. This identification is neither easy nor simple, so whenever exploration drilling indicates the existence of such a layer, a pair of piezometers are installed whose screens are above and below the interbed. Based on the piezometric head difference when the well is online, the filtration characteristics and the hydraulic role of the interbed can be determined with a relatively high degree of reliability.

Determining maximum permissible screen entrance velocities and screen capacities

Variations in local losses at BGS wells have systematically been monitored since 2005. More than

650 tests have been conducted, at virtually all the radial collector wells. The maximum permissible entrance velocities (expressed as Darcy velocity) have been defined based on analyses of test results (Fig. 1), taking into account the oxic state and bivalent iron concentration in the groundwater (Dimkić & Pušić, 2014).

The correlations are BGS-specific and cannot be generalized, but the approach itself is of universal significance. The recommended BGS screen entrance velocities are lower by a factor of 3 to 4 than the velocities based solely on the filtration stability criterion (at most of the wells, *Eh* is ~ 75–125 mV and bivalent iron concentration Fe^{2+} ~ 0.7–1.5 mg/L).

ria (Pušić et al., 2012). The specified water level in the well caisson, which defines the capacity of the well, is determined such that there is always a spare water column in the well caisson above the horizontal screens, which ensures long-term stable operation. Based on many years of experience, an initial water level in the well caisson of about 6 m above the horizontal screens has been specified for BGS radial collector wells.

Production programmed in this manner controls well incrustation, which, for the same discharge, requires lowering of the operating water level over time. Screen rehabilitation is undertaken when the water column falls below 3 m.

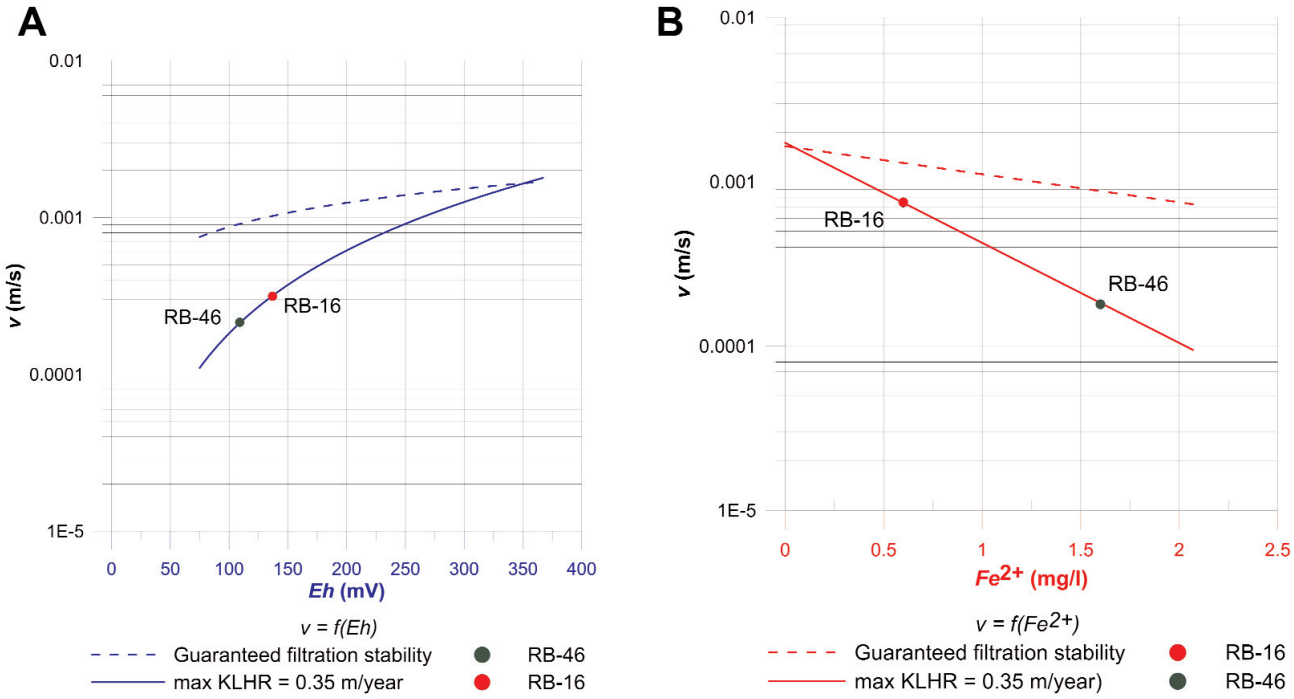

Fig. 1. Permissible horizontal screen entrance velocities as a function of a) *Eh* and b) Fe^{2+} (Dimkić & Pušić, 2014), including data points for wells RB-16 and RB-46, which defined the maximum screen entrance velocities.

Based on the maximum permissible entrance velocities, it is easy to compute the maximum permissible capacity of a single horizontal screen. In the specific case, it depends on the length and diameter of the screen. At BGS, the standard screen length is 50 m and the diameter 0.3 m.

Determining the hydraulic effect of well operation

A detailed analysis of the configuration of a well with new horizontal screens is conducted immediately after or in parallel with modeling of the capacity of the location. The analysis includes the number, length, position and elevation of emplacement of the horizontal screens, and the well capacity that meets set crite-

A lack of suitable commercial software had hindered complex hydrodynamic analyses of groundwater flow, as needed for the design of BGS wells. Consequently, JCI has developed software for estimating 3D groundwater flow, which supports hydraulic quantification of horizontal screen parameters (Kojić et al., 2007; Vidović et al., 2014; Dotlić, 2015). This software relatively easily and realistically simulates horizontal screens and riverbed configuration and conductivity.

Three-dimensional modeling to support the design of BGS radial collector wells is comprised of several steps.

The first step is the development and calibration of a model of the analyzed well and the respective part of the groundwater source (or aquifer system). Model

development begins with the schematization of aquifer layers, which is generally based on the results of boring in the extended zone of the well. The model is then calibrated by simulating periodic pumping tests under BGS standard operating conditions. While performing calibration, both boundary conditions (flows in wells, river water level, piezometric levels along the model boundaries in the coastal area) and the adopted porous medium geometry have not been altered. Calibration confirmation has been verified using the obtained satisfactory congruence of calculated and measured groundwater level values (measured in the existing piezometers).

The horizontal screens and riverbed configuration are specified in the model on the basis of *in situ* surveys, including filming of horizontal screens by an underwater camera; recording of screen length and vertical and horizontal displacement; and detection of the riverbed by an echo sounder or similar onboard instrument designed for that specific purpose.

The second step in the application of the 3D model is hydrodynamic analysis of the groundwater, under actual and design conditions. The ultimate goal is to define the capacity of the well and the natural and/or artificial limiting factors.

In the final step the capacity of the well is verified against or adjusted to permissible screen entrance velocities according to the plots shown in Fig. 1.

The present paper discusses the results of hydrodynamic analyses of two BGS wells whose characteristics differ: (i) well RB-16, with a relatively stable capacity of more than 80 L/s, even though there is a semi-permeable interbed at its location, and (ii) well RB-46, whose capacity is of the order of 20 L/s despite no notable interbed.

Characteristics of well RB-16 and RB-46

Belgrade Groundwater Source (BGS) is located along the lower course of the Sava River, ahead of its confluence with the Danube. Well RB-16 is situated near the edge of the river island Ada Ciganlija (Fig. 2), whereas well RB-46 is on the left bank of the Sava, upstream from the former well (DIMKIĆ et al., 2007b).

In hydrogeological terms, the two wells differ to a large extent, particularly with regard to the total thickness of the water-bearing sediments and the range and distribution of the aquifer grain sizes. Given that grain size d_{10} largely determines the filtration characteristics, the situation with regard to wells RB-16 and RB-46 is as follows: The average diameter of the d_{10} fraction at RB-16 is 0.2 mm and at RB-46 0.24 mm (Fig. 3). By considering only this information, the conclusion would be that the filtration characteristics of well RB-46 are better than those of RB-16. Corresponding well discharges would also be expected. However, they differ considerably; the discharge of well RB-16

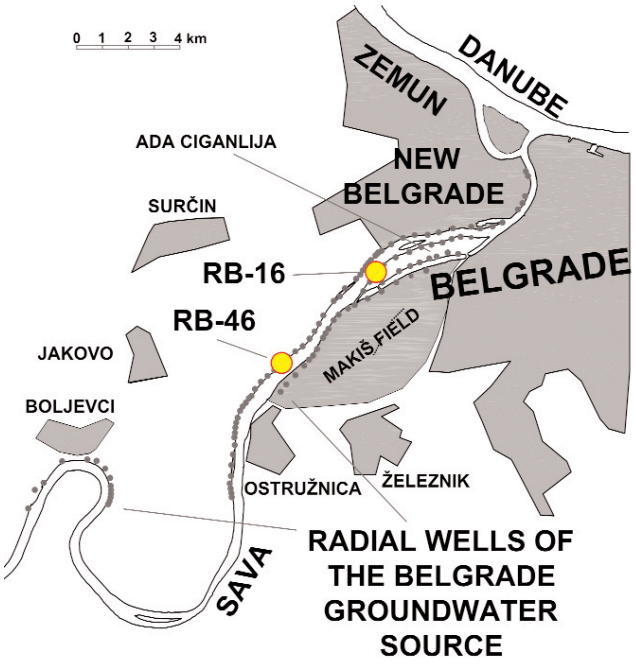

Fig. 2. Locations of Belgrade Groundwater Source and selected wells RB-16 and RB-46.

is about four to five times higher (Fig. 4) and depends on other factors as well. As such, additional information is needed to examine the reasons.

Figure 3 shows that the range of d_{10} values at RB-16 is much larger (generally from 0.014 mm to 2.5 mm) than at RB-46 (0.12 mm to 0.38 mm). Moreover, the largest grains are found in the zone of well screens (two samples, 1.6 and 2.5 mm, highlighted in Fig. 3).

At the two wells the thickness of the water-bearing sequence also differs. This has influenced the depths of the wells and the elevations of screen emplacement. The difference is more than 6 m (46.3 m above sea level at RB-16 and 52.4 m a.s.l. at RB-46).

Another difference between the two wells is that on the location of well RB-16 there is a clearly defined sequence of semi-permeable layers (final unit of the sedimentation cycle), which were modeled as a single semi-permeable interbed in the hydrodynamic analysis. It is between 50 and 55 m a.s.l. (note d_{85} in this zone). The interbed increases hydraulic resistances during vertical groundwater filtration, as corroborated by a piezometric head difference of about 10 meters recorded by two relatively close piezometers, whose screens are at different depths (Fig. 3). However, the presence of this interbed over the extended area has not been confirmed.

There is no such layering on the location of well RB-46, or at least it is not as distinct.

The times of drilling and the initial capacities of the two wells also differ (Fig. 4). Well RB-16 was built in 1967 and its initial capacity was greater than 200 L/s. This capacity declined over time to about 50 L/s, such

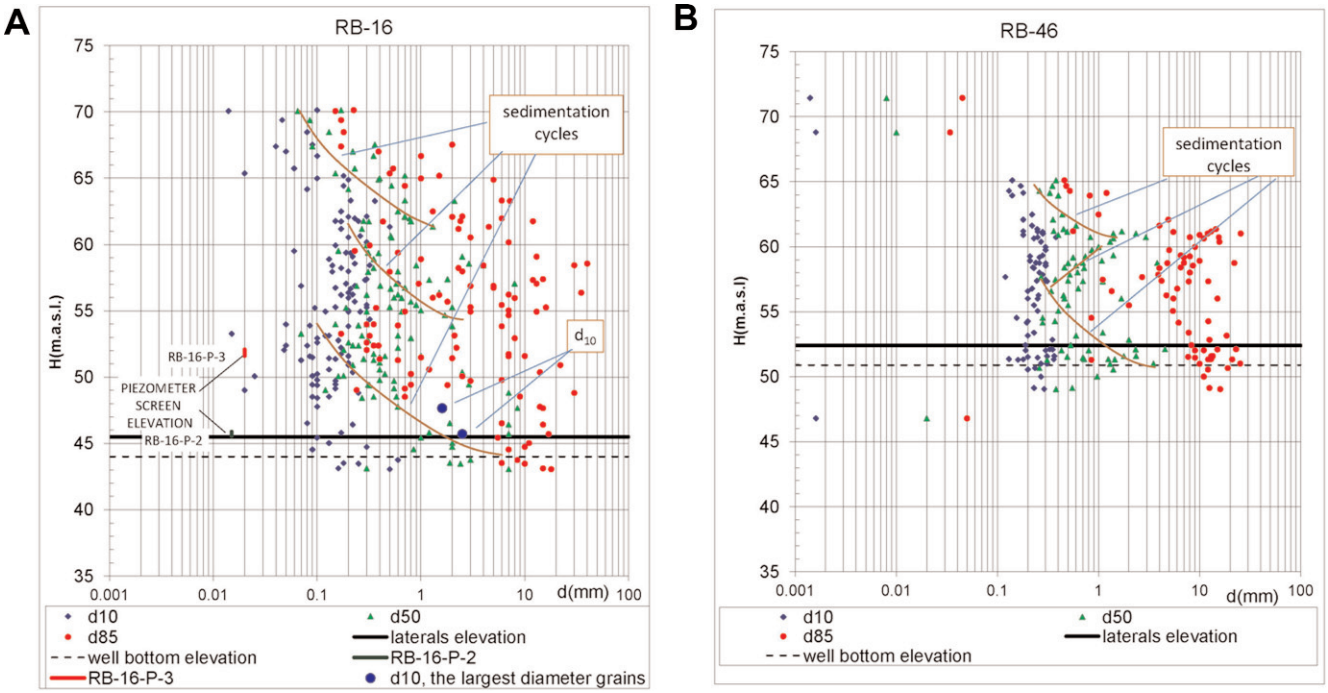

Fig. 3. Vertical sections of select grain-size fractions (d_{10}, d_{50} and d_{85}) in the areas of a) wells RB-16 and b) RB-46. The plot of well RB-16 also shows two piezometers, one above and the other below the modeled semi-permeable interbed.

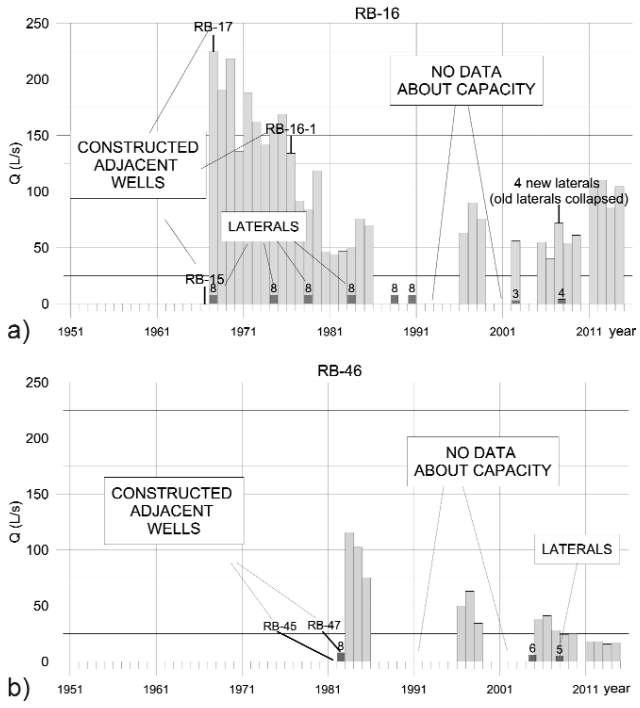

Fig. 4. Measured capacities of wells a) RB-16 and b) RB-46 as a function of time. The darker bars represent the number of active horizontal screens after rehabilitation.

that four new horizontal screens were installed in 2007. Well RB-46 was drilled much later (1983) and its initial capacity was modest compared to the former well. Today, only four horizontal screens out of the initial eight are active. The length of one of the screens is about 40 m and of the other three 20 m. The capacity of this well is about 20 L/s.

Yet another difference between the two wells pertains to well ageing, expressed via the increase in hydraulic resistance (*KLHR*) at the horizontal screens. The oxic state (redox potential) and bivalent iron concentrations also differ (Table 1). The data shown in the table are indicative of the reasons for different discharge capacities of the two wells.

Table 1. Parallel representation of several parameters of wells RB-16 and RB-46.

	Q [l./s]	KLHR [m/y]	*Eh* [mV]	$[Fe^{2+}]$ [mg/l]	Number of screens	Screen length [m]
RB-16	81	0.1	137	137	4	179
RB-46	22	2.3	109	109	5	101

Calculation results

The capacity of each well location was assessed by hydrodynamic analysis of groundwater flow using "local" models of the two wells. The models encompassed relevant parts of BGS in the hydraulic sense

and were bounded by neighboring wells and parts of the left and right overbanks of the Sava River. Simulations were undertaken for 4, 6 and 8 horizontal screens, each 50 m long. The well caisson water level was specified at 6 m above the elevation of emplacement of new horizontal screens. The model was previously calibrated, but calibration does not fall within the scope of this paper.

Location capacity, maximum permissible screen entrance velocity, and well capacity

The elevation of the horizontal screens of well RB-16 was set at 45 m a.s.l., so the operating water level in the well caisson was 51 m asl. The resulting discharges of 4, 6 and 8 horizontal screens were 150, 160 and 164 L/s, respectively.

The horizontal screens of well RB-46 were set at an elevation of 52 m a.s.l. Scenarios with 4, 6 and 8 screens were simulated and the water level in the well caisson was maintained at 58 m a.s.l. The resulting well capacities were 30, 33 and 35 L/s, respectively.

The three screen scenarios were also used to calculate well capacities at selected representative maximum permissible screen entrance velocities. The results of the capacity simulation are shown in Fig. 5, while those of the maximum permissible screen velocity simulation are presented numerically in Table 2 and graphically in Fig. 1.

Table 2. Resulting maximum permissible screen entrance velocities based on biochemical incrustation conditions (v min – selected representative value).

Well	Eh (mV)	v max. perm. (M/s)	Fe^{2+} (mg/L)	v max. perm. (M/s)	v min. (M/s)
RB-16	137	3.15E-04	0.6	7.50E-04	3.15E-04
RB-46	109	2.15E-04	1.6	1.80E-04	1.80E-04

As a remark, it can be stated that the increase of number of laterals above 8 does not contribute to the capacity increase of the well location. It is obvious that, in hydraulic sense, with the increase of number of laterals, the radial well is becoming more like a tubular well.

Based on Fig. 5, the capacity of the location of well RB-16 appears to be about 165 L/s. However, it is also apparent that this capacity exceeds by far the discharges based on the maximum permissible velocity criterion (where the maximum permissible discharge of a single horizontal screen is about 15 L/s). Theoretically, the capacity of the location could be reached by installing ten new screens. But it is up to the engineer to decide how to restore or improve the capacity of this well and select the number of new laterals.

The maximum permissible entrance velocity criterion was fulfilled by setting the operating water level in the well caisson at 58 m a.s.l. The other required well capacity characteristics were determined in parallel, including an average screen entrance velocity of $3 \cdot 10^{-4}$ m/s and an average discharge per screen of about 16 L/s. From a technical and economic perspective, the well can be reconstructed by installing 6 to 10 new horizontal screens, which would result in a well capacity of 98 to about 160 L/s.

With regard to well RB-46 and biochemical criteria, all calculation scenarios resulted in below-critical entrance velocities, as shown in Fig. 5. Installation of a large number of laterals in the case of this well is questionable, given the low capacities and the differences between them. In the four 50 m-long screens scenario, the average screen entrance velocity is

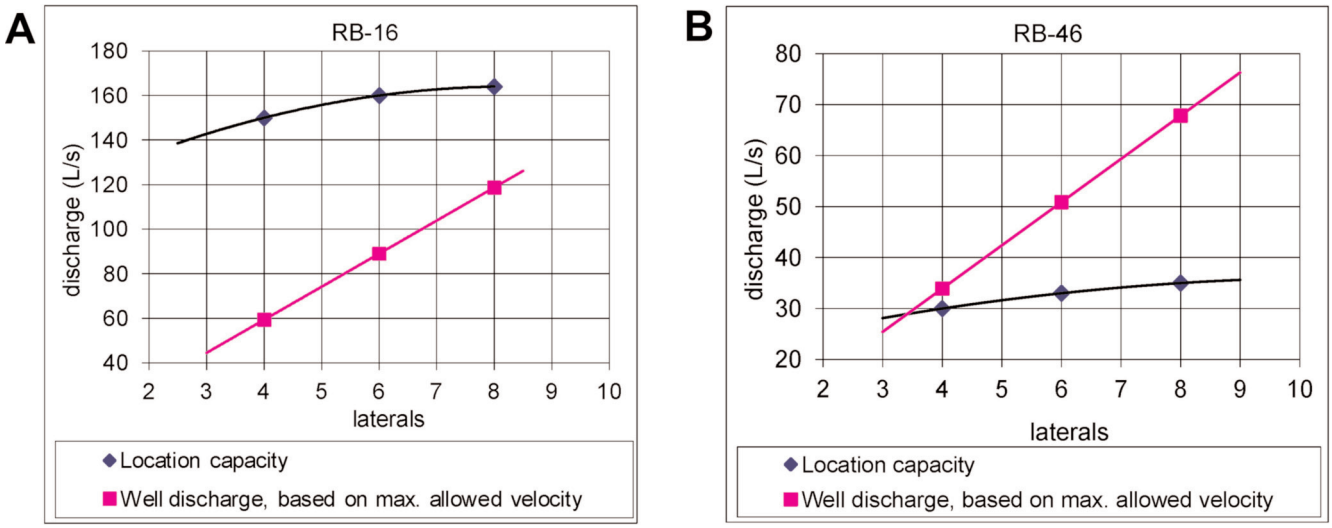

Fig. 5. Capacities of wells a) RB-16 and b) RB-46 based on simulations of location capacity and maximum permissible screen entrance velocities, as a function of the number of screens.

$1.6 \cdot 10^{-4}$ m/s and the average discharge per screen about 8 L/s. At the operating water level maintained at 58 m a.s.l., the discharge of the well with four screens will be about 30 L/s. The capacity of the location of well RB-46 is lower than that of well RB-16 because it is shallower and cannot produce more than 36 L/s. Due to poorer chemical and biochemical conditions, the maximum permissible entrance velocities are much lower. The analysis shows that this well hardly recommends for rehabilitation because of insufficient capacity of its location and poor biochemical conditions.

Flow distribution to the well, vertical travel time, and impact of interbed on well capacity

Different aspects of groundwater flow were analyzed based on calculations using local models of the two wells, primarily to assess the potential pollution threat. The spatial distributions of the flow to the wells are shown in Fig. 6. The lines represent the boundaries of zones that reflect percent fluxes relative to the total well discharge.

The different sizes and shapes of the flux zones of the two wells are a result of several factors, including overall hydrogeological (especially filtration) characteristics of the aquifer, well capacity, and number and positions of horizontal screens.

The travel time through the semi-permeable interbed is one of the important drivers of pollutant transformation on the way to the well. It is apparent from the interpretation of the calculation results shown in Fig. 7 that only the immediate vicinity of the well is potentially threatened by pollutants prone to transformation and degradation (primarily organic pollutants).

The assessment shows that a different approach to sanitary protection zoning might be warranted, compared to the method generally accepted in the past (estimation of travel distance and residence time of a

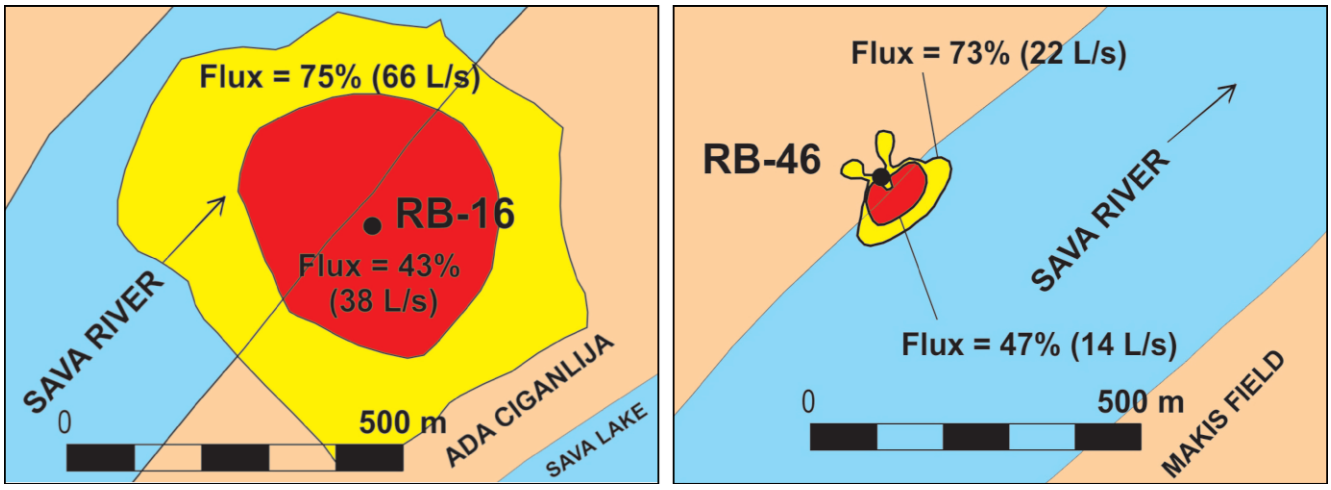

Fig. 6. Zones of different percent fluxes: a) well RB-16, and b) well RB-46.

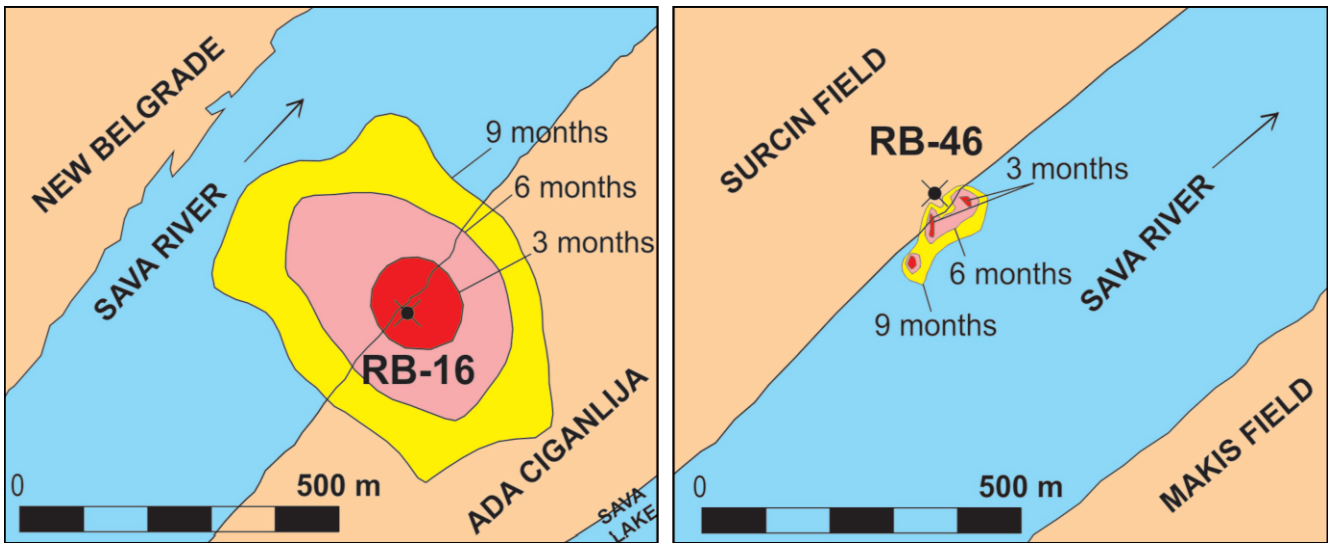

Fig. 7. Travel time (in months) through the semi-permeable interbed of the aquifer system: a) well RB-16, and b) well RB-46.

potential pollutant by particle tracking, whereby calculations assume that the pollutant is an ideal tracer).

The effect of the semi-permeable interbed was also reflected in the piezometric head difference between the upper and lower water-bearing layers. In the immediate vicinity of well RB-16, the pair of piezometers, with one screen above and the other below the interbed, registered a piezometric head difference of about 8 m. Model calibration yielded a vertical hydraulic conductivity of $3 \cdot 10^{-7}$ m/s. In order to analyze the impact of different hydraulic conductivities of the interbed on the groundwater flow pattern and well capacity, the vertical hydraulic conductivity of the semi-permeable layer was reduced by a factor of three on the model (from $3 \cdot 10^{-7}$ to $1 \cdot 10^{-7}$ m/s). This resulted in a well discharge of 73 L/s (compared to the previous 98 L/s), whereby the piezometric head difference was increased by 1.5 m (largely attributed to the layer above the interbed). This corroborated the fact that the piezometric head above and below the interbed was an excellent indicator of its filtration characteristics. The conclusion was that the semi-permeable interbed in the zone of RB-16 provides excellent protection from pathogens.

As in the case of well RB-16, there is a semi-permeable interbed in the vertical section at well RB-46, but it does not constitute a distinct hydraulic barrier for groundwater flow. The piezometric head difference between the layers above and below the interbed is of the order of 1 m, even though its thickness in the immediate zone of well RB-46 is from 10 to 13 m.

Conclusions

The case studies presented above, of two radial collector wells in an alluvial anoxic setting, demonstrated that the design and long-term operation of a well require that proper consideration be given to the capacity of the well location and that maximum/critical screen entrance velocities (and thus their capacity) be correctly defined.

Maximum/critical screen entrance velocities have been defined here according to the previously determined increase of local hydraulic resistances in a given wells, RB-16 and RB-46, bearing in mind the oxicity and the content of ferrous iron in groundwater.

The analyses showed that at the same groundwater source, the capacity of one well location (RB-16) was 4–5 times higher than that of another (RB-46). Also, the maximum permissible horizontal screen entrance velocities (per biochemical and hydraulic criteria) were several times higher in the case of well RB-16. This practically means that the analyses based on the proposed approach convincingly and decisively determine whether reconstruction of the studied wells would be justifiable. The same can be done for other radial collector wells at Belgrade Groundwater Source. The approach is also purposeful for other alluvial water supply sources that rely on anoxic aquifers.

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Резиме

Упоредно дефинисање елемената радијалних бунара применом нове методе

У односу на досадашњи начин пројектовања дренова радијалних бунара на београдском изворишту, приказан је оригинални методолошки поступак, којим се дефинише капацитет бунара. Овим поступком, којим се у суштини лимитира величина улазних брзина подземних вода у бунар, обезбеђује се дуготрајност рада и стабилност његовог капацитета. Поступак се састоји од три целине: 1) одређивања потенцијалног капацитета локације бунара, 2) одређивања максимално дозвољених улазних брзина подземних вода и капацитета дренова бунара, 3) прогнозе хидрауличких ефеката рада бунара у почетном периоду. Капацитет локације се одређује за деоницу реке и обале са залеђем, који хидраулички гравитира анализираном бунару. Од велике важности је познавање хидрогеолошких, филтрационих карактеристика порозне средине, пропусности речног дна, присуства слабопропусних слојева, као и техничких карактеристика бунара. На основу анализе протицаја бунара, колмирања дренова изазваног присутним гвожђем, као и степена оксичности аквифера на београдском изворишту, дефинисане су максимално дозвољене улазне брзине подземних вода у дренове бунара. Ове брзине обезбеђују стабилан капацитет бунара за усвојени критеријум дозвољене брзине колмирања дренова. Ове брзине су 2 до 5 пута мање од брзина, дефинисаних одржањем филтрационе стабилости прифилтарске зоне. Дуготрајност стабилног капацитета бунара се обезбеђује и величином почетног стуба воде у бунару изнад дренова, који за београдско изворише износи 6 m. На основу овако дефинисаног капацитета бунара, врши се хидрауличка анализа ефеката рада бунара: просторно дефинисање процентуалног учешћа дотицаја вода у бунар, као и врем задржавања током филтрације од реке до бунара. Ова методологија захтева и одговарајући софтвер за спровођење прорачуна, односно моделирање струјања подземних вода. Посебно је интересантно просторно задавање дренова бунара и приказ резултата прорачуна пијезометарских нивоа, као и распореда дотицаја дуж њих. Осим тога могуће је задавање просторне геометрије и филтрационих карактеристика корита реке и реална симулација њеног простирања у зависности од водостаја. На примеру у овом раду је показано да се на истом изворишту капацитет локације два бунара разликује и 4 до 5 пута. Слично је и са величином максимално дозвољених улазних брзина које узимају у обзир биохемијске критеријуме. Анализа капацитета два бунара, овде приказаном методологијом, даје опредељење њихове реконструкције, што је применљиво и на остале радијалне бунаре београдског изворишта. Приказана метода је применљива и за друга изворишта у алувијалним аноксичним условима издани.

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