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Hydraulic characterization of laterals as applied to selected radial collector wells at Belgrade Groundwater Source

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Abstract: The paper examines the possibility of hydraulic characterization of radial well laterals in a manner that does not require prior hydrodynamic analysis by simulating groundwater extraction conditions on a numerical model. The first step of the proposed approach is to assess the groundwater level regime formed in the capture zone when the well is operating, which is indicative of the functional condition of the laterals and the aquifer potential in terms of groundwater availability. Then the efficiency of the laterals is examined through the hydraulic function of the skin zone, depending on its filtration properties. An expression for groundwater flow from the aquifer to the laterals (commonly used to simulate laterals on a hydrodynamic model) is employed to define representative values of the conductance coefficient of the skin zone (as an indicator of colmation), and then applied to several wells at Belgrade Groundwater Source. The present research shows that a conductance coefficient of $[K_s/d_s]=1.0\times10^{-4}\ s^{-1}$ can be considered as the threshold value in relation to which the effects of colmation of well laterals are exhibited, which is consistent with the results reported by researchers who studied the effect of skin zone conductance on the occurrence and nature of the so–called early drawdown at radial collector wells. In addition to gaining insight into the present condition of the laterals, the proposed approach can be used to study the progress of colmation at different points in time and to quantify the effectiveness of regeneration of laterals.

Key words: radial collector well, groundwater level regime, skin zone, conductance coefficient.

Апстракт: Циљ рада је сагледавање могућности дефинисања хидрауличких карактеристика дренова на начин који не подразумева претходну израду хидродинамичке анализе симулацијом услова експлоатације подземних вода на нумеричком моделу. Први корак у предложеном приступу представља анализа режима нивоа подземних вода који се формира у непосредној зони и под утицајем рада бунара, а који указује на функционално стање дренова и потенцијал водоносне средине у погледу расположивих количина подземних вода. У наставку се анализира ефикасност дренова преко хидрауличке функције прифилтерске зоне, у зависности од њених филтрационих својстава. Преко израза за дотицај воде из издани у дренове (којим се најчешће симулирају дренови на хидродинамичким моделима), дефинисане су репрезентативне вредности коефицијента пропусности прифилтерске зоне (као показатеља њихове колмираности) на примеру више анализираних бунара београдског изворишта подземних вода. Спроведено истраживање указује да се вредност коефицијента пропусности дренова од $[K_{приф}/d]=1,0\times10^{-4}\ s^{-1}$ може сматрати граничном вредношћу у односу на коју се испољавају ефекти колмираности дренова, што је у сагласности са резултатима истраживања аутора који су испитивали утицај пропусности прифилтерске зоне на појаву и карактер тзв. раног снижења код хоризонталних бунара. Осим упознавања актуелног стања дренова, представљеним приступом се може пратити напредовање процеса колмирања дренова у различитим временским тренуцима, као и квантификовати ефекти регенерације дренова.

Кључне речи: бунар са хоризонталним дреновима, режим нивоа подземних вода, прифилтерска зона, коефицијент пропусности дрена.

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Introduction (present condition of the wells and current extraction rate)

Belgrade Groundwater Source (BGWS, Fig. 1) is currently comprised of 99 radial collector wells and 47 tube wells. The radial collector wells contribute more than 90% to the BGWS output.

Well ageing is a process that has accompanied groundwater extraction since the very beginning, from the early 1950s (DIMKIĆ *et al.* 2011a, DIMKIĆ *et al.* 2011b, POLOMČIĆ 2000). Over time, the condition of the laterals of the radial collector wells has deteriorated and reduced well discharge. The needed amount of drinking water has been provided by continuous lowering of the water level inside the well caissons (i.e. by intensifying production). Occasional mechanical regenerations of the laterals were undertaken in an attempt to decelerate the discharge decline. In the past decade, despite regenerations, a sustained downward trend has been about 100 l/s per year.

Fig. 1. Geographic location of Belgrade Groundwater Source.

During a period of low flows of the Sava River (from mid-July to mid-August 2015), the river stages were generally below an elevation of 70 m above sea level (at a Belgrade gauging station near the confluence of the Sava and the Danube), which is a stage of 95% exceedance probability. These hydrologic conditions resulted in a record low rate of groundwater extraction by the radial collector wells – only about 3 m^3/s. Consequently, the water levels inside the caissons were extremely low and in the 96 active wells they were 4.75 m above the laterals, on average. The greatest drawdown was recorded in the caisson of well RB–28, where the water column was only 1.0 m above the laterals.

During the period of low flows of the Sava River, the average discharge of the wells was about 30 l/s. The discharge of 20% of the wells was less than 10 l/s and that of another 20% greater than 60 l/s. The discharge of only three wells was above 100 l/s.

The condition of the laterals is such that out of about 800 laterals in place, one–third had been out of commission for a relatively long time due to major damage to the screen pipes and loss of the water capture function. One third of the laterals had been shortened, damaged, filled with material from the near-screen zone and vertically displaced. As a result, the length of only one third of all the laterals is close to the initial length. The condition of these laterals was considered good, despite the fact that some of them were colmated (i.e. clogged). The lowered capture capability had been addressed by regeneration.

The condition of the wells and the rate of groundwater extraction, as described above, necessitate systematic rehabilitation of the BGWS wells, which would need to include nearly half of the wells in the immediate future. Objectively, 4–5 wells can be revitalized per year, such that rehabilitation would take an entire decade. In the meantime, the condition of a number of wells whose current discharge capacity is above average would deteriorate and they, too, would require replacement of laterals. As such, similar to past regenerations, replacement of laterals might become an ongoing activity in the future, to ensure a consistent water supply.

Criteria for selecting wells to be rehabilitated

The selection and ranking of "candidate" wells for rehabilitation cannot be based solely on the current condition of their laterals. The conclusion that the laterals of a well are not functioning and that there is a dramatic loss of discharge does not constitute a sufficient basis for undertaking the design of the installation of new laterals and procuring the needed funding.

In addition to knowing the condition of a well, it is essential to understand the main natural features and aquifer recharge conditions in the capture zone. Only such an approach is warranted for addressing the present state of affairs at BGWS and selecting wells where it would be justifiable, in technical and economic terms, to emplace new laterals and ranking the wells based on the expected increase in discharge capacity.

Even when a well is properly designed and built, if the potential of the well site is modest, new laterals will not bring about significant improvement in terms of capacity increase (ΔQ in the design). Another well will have to be revitalized to ensure a sufficient amount of drinking water. In other words, even though the money spent will only partially justify the outcome, spending will have to be repeated (i.e. doubled).

Past rehabilitations of laterals at BGWS (six wells in 2005–2009 and one well in early 2016) have shown that this activity requires considerable funding and that the spending per well is generally the same. In view of the fact that the BGWS aquifer is highly heterogeneous in terms of groundwater availability at different well sites, the outcomes of laterals replacement can result in diverse well discharges (as corroborated by experience).

BGWS well rehabilitation priority needs to be given to the wells and sites with a high potential for achieving significant discharge capacities. The approach is based on two objectives: (i) to first halt the downward production trend (already quite alarming), and (ii) to then increase and maintain the rate of groundwater extraction at the needed level.

The most important information needed for well rehabilitation design is as follows:

– Well: elevation of emplacement, number and condition of active laterals; operational history and effectiveness; operating water levels; and effects of any past rehabilitations;

– Geologic framework and hydrogeological features: lithostratigraphic composition and grain–size distribution of the deposited clastic sediments; groundwater flow characteristics; and geometry of riverbed incision into the aquifer;

– Hydrodynamic conditions: quality of hydraulic contact between the river and the aquifer; rates of recharge from the river and the hinterland; aquifer regime; and local hydraulic losses at the lateral screens (according to DIMKIĆ *et al.* 2011b, DIMKIĆ & PUŠIĆ 2014);

– Hydrochemical and microbial composition of the groundwater: iron and dissolved oxygen concentrations; redox potential; and activity of certain bacterial species.

Such information is collected by means of various types of investigations and analyses.

The amount of groundwater captured by a well is a function of the permeability of the sediments (all lithostratigraphic layers in the vertical section of Quaternary sediments, not only that or those in which the laterals are installed), recharge conditions of the medium through which groundwater flows under the influence of the operating well, technical characteristics, the condition of the water–capturing parts of the well, the operating mode, and the like.

Regardless of the current capacity of a radial collector well, production causes the formation of a certain dynamic groundwater level in the zone of influence. The surface of the groundwater level in the capture zone is typically three-dimensional. Given the present number and condition of the laterals, the groundwater levels in the vicinity of BGWS wells exhibit a distinct spatial irregularity.

Gauging of well discharge and water levels in the caisson, ascertaining of the current condition of the laterals (by underwater video recording, including determination of vertical displacement), analyses of the chemical and microbial composition of a number of parameters, and installation of 2–3 suitably located piezometers, along with regular groundwater level monitoring, constitute an adequate scope of investigations for gaining insight into the status of each well and the potential of the well site. Once wells are selected in this manner for the rehabilitation of laterals, subsequent investigations (hydrodynamic simulation of regime conditions monitored over a longer period of time) will provide more detailed insight into pertinent conditions.

The approach outlined above improves the efficiency of the investigations, as well as cost–effectiveness, given that each activity of this type requires funding which, in reality, is not always easy to procure. Uniform BGWS coverage by these investigations is equally important, in view of the fact that the information required for the rehabilitation design for some wells has been available for years, while for others the lithological composition of the setting or the piezometric head is still unknown.

Assessment of the groundwater level regime as a criterion for prioritizing well rehabilitation

Assessment of the groundwater level regime provides needed information, for example, whether the potential capacity of the well site is modest or considerable and if the filtration characteristics of the water–bearing medium are relatively unfavorable, sound or very good. For a preliminary selection of wells, it is not necessary to know whether a modest potential is a result of the lithologic stratification, presence of semi-permeable interbeds, anisotropy, reduced recharge from the direction of the river, influence of neighboring wells, or the like. These details are explored through subsequent investigations, in the well rehabilitation design phase (and after all the wells that have a greater potential for achieving high discharge rates have been revitalized). Or, to select the wells to be rehabilitated, it is enough to know whether the laterals are incrusted and, of so, to what extent. Subsequent activities will determine whether the encrustations are largely mechanical or biochemical in nature.

An integrated functional analysis of the radial collector well and the water–bearing medium will constitute a basis for:

– decision-making regarding the activities that need to be undertaken to improve the condition of the well and the entire groundwater source,

– ensuring that the selection allows for the considerable funding needed to first be spent on wells where high discharge rates are achievable, to halt the downward production trend and provide proper water supply for Belgrade, and then tackle the other wells where satisfactory and consistent discharges can be achieved (in other words, reduce the risk of limited or negative results),

– a preliminary but objective assessment of the site/groundwater resource, and prediction of the effectiveness of new laterals (post–rehabilitation discharge capacity, assuming that the work is done properly), and

– defining local hydraulic resistances at the laterals, as well as hydraulic characteristics of existing laterals (skin zone).

Hydraulic characterization of laterals

The conductance coefficient of a lateral, or its resistance coefficient, $[K_s/d_s]$, is an extremely important parameter for assessing operating conditions of a radial collector well. It indicates the effectiveness of the lateral and the extent of its hydraulic function (which enables groundwater extraction), or if it is closed due to colmation, improper emplacement or development, or the characteristics of the screen pipe and gravel pack (which actively hinder its function). In this regard, the hydraulic role of the skin zone, or the so–called *skin effect* (Feng & Zhan 2016, Yeh & Chang 2013, Pasandi *et al.* 2008, Yeh & Yang 2006, Barrash *et al.* 2006, Kawecki 2000), can either be negative or positive.

The conductance coefficient of a lateral is obtained by defining the filtration characteristics of the skin zone (representative hydraulic conductivity), even though it in essence reflects the extent of the hydraulic resistances at the lateral screen and its skin zone. Quantification of this parameter over time demonstrates the progress of well ageing.

A precondition for defining the conductance coefficient of a lateral, as an indicator of its efficiency, is the presence of a piezometer (with a short screen, up to 1 m, installed at the same depth as the lateral), which should be located as close as possible to the lateral (at a distance of up to 1 m). Clearly, piezometer bores need to be drilled very carefully, so as not to damage the lateral (as a rule, the horizontal displacement of a lateral is unknown but reasonably assumed to exist).

It is desirable to perform measurements to determine the capacities of individual laterals in operation (by placing a current meter at the beginning of the lateral), as this method can be used to determine the conductance coefficient for each of the active laterals of a radial collector well. Otherwise, approximate capacities of the laterals can be derived from the correlation between well discharge and the number of functional laterals, along with an analysis of the groundwater level as an indicator of the rate of groundwater extraction.

If an adequate observation well is in place, the conductance coefficient of a lateral can be determined from the expression used for simulating the boundary condition "radial well lateral" in contemporary hydrodynamic analyses, or by mathematical modeling of groundwater flow under the influence of a radial collector well (Božović *et al.* 2015, Dimkić *et al.* 2011c, Lee *et al.* 2010, Mohamed & Rushton 2006, Bakker *et al.* 2005, Park & Zhan 2002):

$$q = 2r\pi L\ [K_s/d_s](H_{NP} - H_{RW})\ [1]$$

where:

$$2r\pi L = \omega \ \text{ and } \ [K_s/d_s](H_{NP} - H_{RW}) = v$$

and where:

q is the flow to a single lateral (m^3/s);

r is the flow to a single lateral (m^3/s);

L is the actual or assumed length of the lateral (m);

K_S is the hydraulic conductivity of the skin zone (m/s);

d_s is the thickness of the skin (colmated) zone (m);

H_{NP} is the groundwater level at the neighboring piezometer (m.a.s.l.);
H_{RW} is the water level in the caisson (m.a.s.l.);
ω is the surface area of the screen pipe (m^2); and
v entrance velocity to the lateral (or approach velocity; occurs at the contact/contour between the skin zone and the screen (m/s)

Note: The approach velocity is Darcy's velocity, not the actual groundwater flow velocity in the analyzed zone adjacent to the screen. The actual groundwater flow velocity in the skin zone (generally assumed and calculated as the mean linear velocity), is obtained from the relation of inflow rate into the lateral and the porosity of the skin.

It is evident that hydraulic characterization of a lateral involves defining of the hydrogeological function of the skin zone, or the measure in which it acts as a barrier to the infiltration of groundwater from the aquifer into the lateral. According to Darcy's law, the intensity of groundwater exchange between the aquifer and a lateral (of certain length and diameter), contrary to the difference in piezometric head between the inside and the immediate outside of the lateral, is a function of skin zone conductance. The piezometric head difference along the way through the skin zone can be defined as local drawdown, or local hydraulic resistance (Dimkić & Pušić 2014).

The hydraulic "origin" and function of the skin zone sediments are analogous to those of the riverbed deposits, which determine the rate of aquifer recharge on account of infiltration of surface water, and whose filtration properties are poorer than those of the aquifer sediments with which they are in physical contact (Lee *et al* 2010, Sun & Zhan 2006, Polomčić 2001). As a result, the formation of a skin zone around the laterals, whose filtration properties are poorer, as a rule, has an adverse effect on the operation of the well.

Presented below is the definition of the conductance coefficients of the laterals of the representative wells selected for analysis of characteristic groundwater level regimes in the BGWS well region, as well as a comparison of the results to the outputs of detailed hydrodynamic models (Božović *et al.* 2016).

The first example is well RB–7m (hydrogeological cross-section in the vicinity of the well is presented in figure 2), which has four open laterals whose condition is rather poor (damaged screens filled with aquifer material). They are also colmated, as evidenced by a low discharge capacity, low/reduced operating water level in the caisson and high groundwater level in the zone of the laterals. The lateral which is practically filled–up over its entire cross-section at the caisson wall can be assumed not to take part in groundwater extraction. Based on groundwater level regime analysis, a uniform drawdown at the piezometers in the well zone suggests that the individual capacities of the laterals are nearly the same. Their common feature – poor condition – supports the assumption of equivalent capacity.

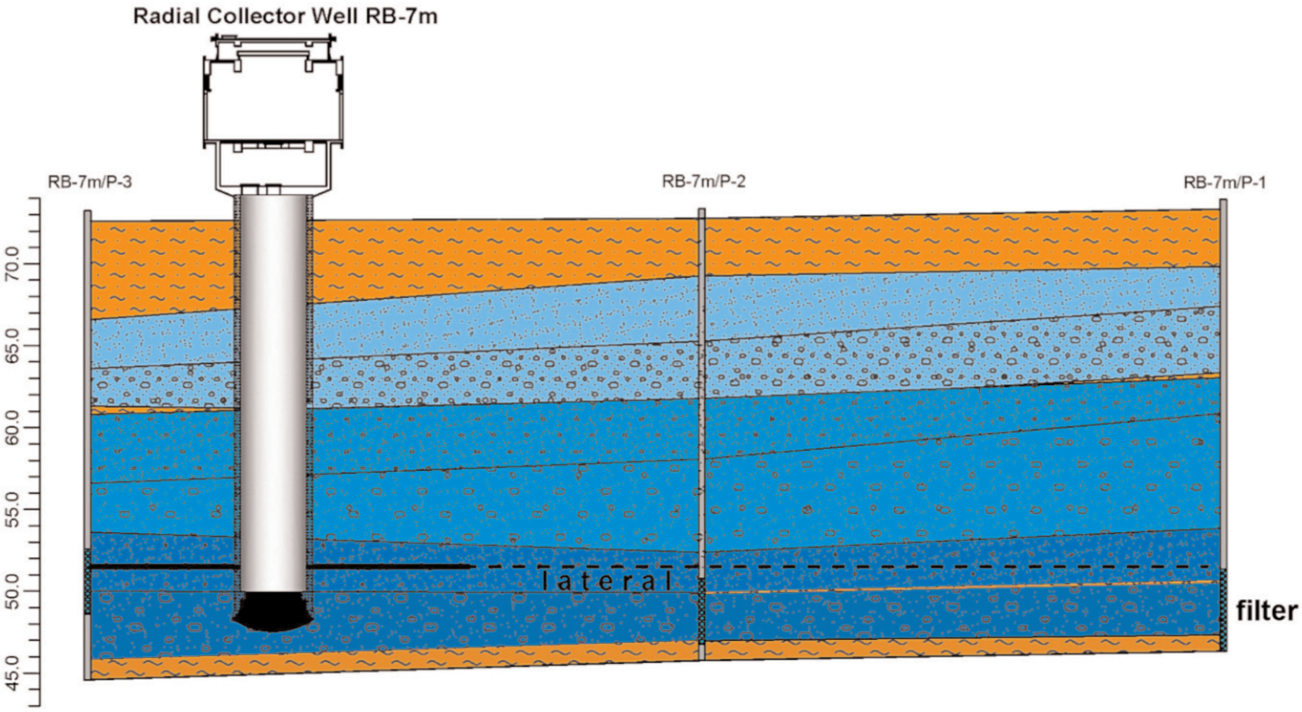

Fig. 2. Hydrogeological cross-section in the vicinity of the well RB-7m.

Applying Eq. [1] to the regime conditions that existed on 27 February 2014, for example, when the gauged capacity of the well was Q=20 l/s (q≈6.65 l/s), the water level in the caisson H_{RW}=55.88 m.a.s.l. and the groundwater level at piezometer RB-7m/P-3 (located between active laterals 1 and 2) at H_{NP}=68.15 m.a.s.l., assuming that the laterals had retained most of their initial length, the resulting hydraulic conductance was $[K_s/d_s]=2.6\times10^{-5}$ s^{-1}. The value obtained in this manner was similar to that derived by simulating groundwater extraction conditions on a detailed hydrodynamic model (BOŽOVIĆ *et al.* 2016): $[K_s/d_s]=2.5\times10^{-5}$ s^{-1}.

Given that in many cases it is not possible to determine the length of the laterals, their hydraulically–active lengths need to be assumed. This means that calculations are based not only on an assumed capacity of the lateral, but also its assumed length, which increases the error of the results. In such a case it is more reasonable to follow a different approach and define the representative value of all active laterals via the known capacity of the well, rather than for each of the laterals. This approach is applicable only if the piezometers record roughly equal dynamic groundwater levels of the aquifer. Therefore, Eq. [1] acquires the form:

$$Q = 2r\pi L_{tot}\,[K_{r.s}/d_s](H_{NP} - H_{RW}) \quad [2]$$

where ω becomes: $2r\pi L_{tot} = \omega_{tot}$

and where:
Q is the discharge capacity of the well (m^3/s);
L_{tot} is the total length of active laterals (m);
$K_{r.s}$ is the representative hydraulic conductivity of the skin zone of the active laterals (m/s); and
ω_{tot} is the total capture surface of the active laterals (m^2).

The second example is well RB-42, which has been exhibiting the effects of colmation in the past dozen years, since the last rehabilitation of its laterals in 2004. Unfavorable hydrochemical conditions and the production and maintenance history of this well indicate that its capacity has steadily declined since it was placed online. Given that the laterals were exposed to incrustation, the effects of this phenomenon in terms of a declining conductance coefficient of the skin zone were analyzed at two points in time, three years apart.

At the beginning of November 2011, the water level in the caisson was at H_{RW}=53.80 m.a.s.l., which resulted in a discharge capacity of Q=21.6 l/s. Due to operation in this mode, the groundwater level at piezometer Prb-42-1 was at H_{NP}=62.23 m.a.s.l. The total length of three laterals, which had retained most of their initial lengths, was L_{tot}=125 m. Under such conditions, the conductance coefficient of the laterals (conductance of the skin or the coefficient of colmation of the laterals), was $[K_{r.s}/d_s]=3.25\times10^{-5}$ s^{-1}.

Three years later, at the end of October 2014, the following was established: well discharge capacity Q=13.6 l/s, water level in the caisson H_{RW}=55.49 m.a.s.l., groundwater level at piezometer Prb-42-1 H_{NP}=67.06 m.a.s.l., and the length of the laterals unchanged. The capture capability of the laterals during the analyzed period dropped to $[K_{r.s}/d_s]=1.50\times10^{-5}$ s^{-1}. As such, the change in the conductance coefficient of the laterals corroborated that the discharge capacity of the well declined as a result of colmation and, consequently, the groundwater levels in the well zone rose.

This approach of comparing calculated values at two points in time is also applicable to assessments of the effectiveness of mechanical rehabilitation of laterals.

Hydraulic losses at the laterals are only one (time-variable) part of the total losses during groundwater flow influenced by the operation of a well (from the contour at a certain distance from the well, where the impact of production ceases, to the point of entry into the screen pipe). Analyses of the groundwater level regime in the zone of the BGWS well laterals showed that if the filtration characteristics of the lateral skin zone did not differ considerably from the representative hydraulic conductivity of the lithostratigraphic layer in which the laterals were emplaced, the losses in the skin zone had no major effect on the occurrence of additional resistances and, as such, they had no substantial effect on the operating conditions of the well. This meant that the skin zone, as a thin layer which hydraulically separates the lateral from the water-bearing layer and whose conductance coefficient is lower, according to PARK & ZHAN (2002), essentially did not exist. Such conditions are present initially, after a successful mechanical regeneration of old laterals, when the characteristics of the new laterals are well suited to the porous medium, as well as in the case of existing laterals with no visible signs of incrustation.

PARK & ZHAN (2002) proposed a certain threshold value, based on a sensitivity analysis of drawdown (so–called early drawdown, immediately after the well is placed online), depending on the conductance coefficient of the skin zone on a hypothetical model. Their research showed that at a hydraulic conductivity of the skin zone greater than $[K_s/d_s]=1{,}0\times10^{-4}$ s^{-1}, the skin effect may be disregarded.

To assess the performance of wells under real BGWS conditions, it is important to determine whether the said value is appropriate and if Eqs. [1] and [2] can be used to establish the hydraulic conductivity of the porous, water-bearing medium. Hydraulic characterization of the laterals that are not (or not considerably) exposed to colmation is presented using wells RB-46 and RB-8m as examples.

The analysis of hydraulic characteristics of well RB-46 was conducted under the conditions that existed in April 2012. The conditions were: well discharge capacity Q=21.0 l/s, water level in the caisson H_{RW}=55.22 m.a.s.l., groundwater level at piezometer RB-46/P-1 (which registers the lowest levels) at H_{NP}=59.94 m.a.s.l., and assumed length of the screen section of lateral No. 8 L=20 m. In these conditions, the conductance coefficient of the studied lateral was $[K_s/d_s]=1.35\times10^{-4}$ s^{-1}. It is similar to the value obtained from hydrodynamic model tests: $[K_s/d_s]=1.25\times10^{-4}$ s^{-1} (Božović *et al.* 2015). The representative hydraulic conductivity of the layer in which the laterals are emplaced in the zone of well RB-46 was calibrated on the model to $K=1.0\times10^{-4}$ m/s.

The last example is well RB-8m. The water level in the caisson has for years been maintained at about 53.20 m.a.s.l. (Fig. 3), meaning 4 m above the laterals. It was evident that the operating water level in the caisson was very low and that the well was under stress. As a result, the achieved well discharge has been 35–40 l/s (Fig. 4). After regeneration in January 2012, four open laterals remained. Underwater filming revealed that the length of the screen pipes was 165 m (i.e. that the original length was retained). The condition of the screens was found to be rather poor.

When the water level in the caisson was low, the groundwater levels in the vicinity of the well, monitored by three piezometers, were at different depths (Fig. 3). Of course, the registered groundwater levels are a function of the distance between the piezometers and the laterals, as are the capture rates of the laterals.

Figure 3 shows that at the end of 2012, as the stages of the Sava River increased, the conditions were such that the structural properties of the laterals were affected to the extent that they could not withstand them and collapsed. As expected, this reduced the discharge capacity of the well, which has since been on the decline. This was the reason for selecting October 2012 for the conductance coefficient analysis, given that it was the last time the conditions were representative before the regime changed.

The piezometric head at observation well RB-8m/P-1, which registered the lowest levels and which was located adjacent to lateral No. 3, had fluctuated over a long period of time between 55 and 56 m.a.s.l. As a result of the ultimate phase of degradation of the lateral, which began at the end of 2012, the groundwater level steadily rose (up to 62.5 m.a.s.l.).

Under the October 2012 conditions, the 2 m difference between the water level at piezometer RB-8m/P-1 and that in the caisson indicated that the lateral was hydraulically open (i.e. not very colmated). Otherwise, it would not have been able to achieve such a large drawdown relative to the quasi-static level (about 12 m), and could not have been a notable contributor to the summary discharge of the well. That the lateral was not colmated was corroborated by the fact that the piezometric head at the well site had not substantially changed (< 1 m), nor did the discharge capacity of the well ($\Delta Q\approx5$ l/s at the same operating water level).

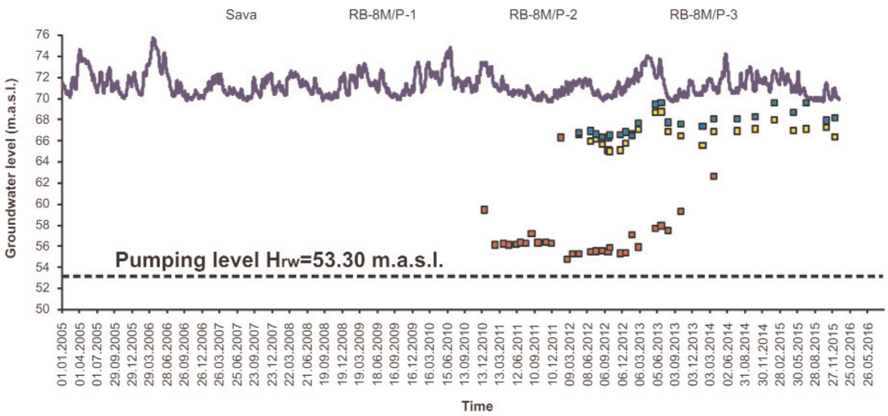

Fig. 3. Groundwater levels in the zone of well RB-8m.

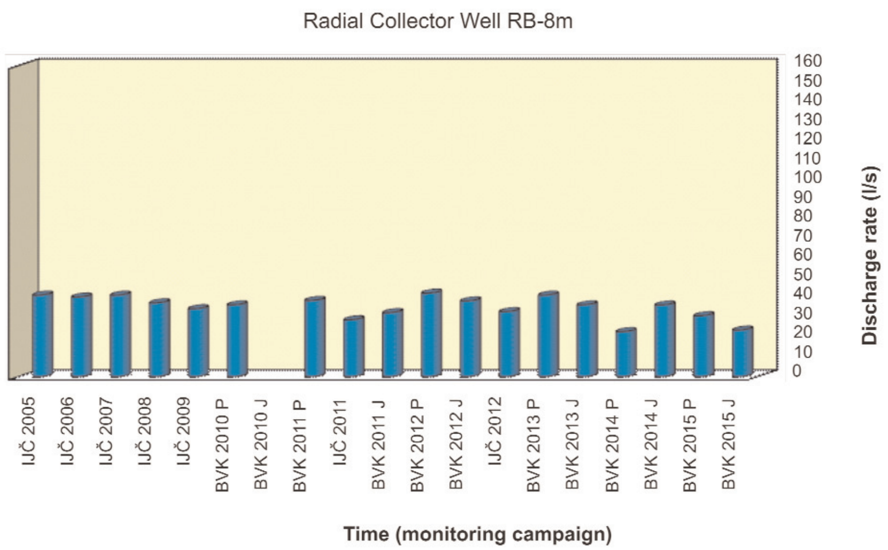

Fig. 4. Discharge capacity of well RB-8m.

The calculation parameters were: Q=39.0 l/s, caisson water level H_{RW}=53.30 m.a.s.l., groundwater level at piezometer RB-8m/P-1 H_{NP}=55.30 m.a.s.l., length of screen section of lateral #3 L=45.6 m, and discharge capacity of the lateral unknown and therefore assumed.

The status at the other piezometers was analyzed to estimate the discharge capacity of the lateral. The groundwater level at piezometer RB-8m/P-2, which is located adjacent to the very edge of the river and between open laterals #1 and #2, indicated that their post-regeneration discharge capacity had not considerably altered. The groundwater level at piezometer RB-8m/P-3, located immediately beyond the well caisson, indicated that it was the least affected by production (recorded the highest levels).

For hydraulic characterization of lateral #3, it was assumed that its contribution to the overall gauged well discharge was q≈15 l/s. The conductance coefficient of this lateral was therefore $[K_s/d_s]=2.6\times10^{-4}$ s^{-1}.

In view of the supposed discharge capacity of the lateral, it was assumed that the representative hydraulic conductivity of the medium in the well zone was not greater than $K=4.0\times10^{-4}$ m/s. Otherwise, there could not have been considerable lowering of the groundwater level, which was present on the contour of the lateral as a result of groundwater filtration through the porous medium of modest filtration characteristics.

Conclusions

The actual condition of the wells at Belgrade Groundwater Source is such that the discharge capacity of half of the radial collector wells can only be recovered by installing new laterals and it is therefore extremely important to prioritize the order of rehabilitation.

The groundwater level regime in the zone of the well is an indicator of the functional condition of the laterals and the potential of the water-bearing medium in terms of groundwater resources. Analysis of the regime is a prerequisite for gaining insight into the condition of the laterals, by defining the hydraulic function of the skin zone.

The results obtained using the proposed approach, compared to the results of previous research on detailed hydrodynamic models, indicate that the hydraulic characteristics of the laterals can be quantified with a degree of reliability sufficient to analyze and monitor the actual condition to the wells, as well as to make a preliminary selection of wells to be rehabilitated.

It was established that by defining the conductance coefficients of the laterals at different points in time, it is possible to monitor the progress of colmation, which is a basis for predicting any further decline in capacity or estimating conditions that will require maintenance (e.g. regeneration of laterals). In addition, the value of this parameter before and after regeneration can serve as a suitable indicator for a quantitative assessment of the effectiveness of regeneration.

The results showed that there was a good match between the threshold value of the horizontal well skin conductance of $[K_s/d_s]=1.0\times10^{-4}$ s^{-1}, proposed by PARK and ZHAN (2002), and coefficient of colmation of laterals of the BGWS radial wells, and that it can therefore be accepted. In cases where the conductance coefficient of the skin zone was less than the declared value (e.g. wells RB-7m and RB-42), the effects of incrustation were evident. Where the filtration properties of the skin zone were better than proposed (e.g. wells RB-46 and RB-8m), their impact on the operation of the wells and groundwater extraction were practically negligible. In that case, the hydraulic conductivity of the water-bearing medium (the lithostratigraphic layer in which the laterals are emplaced) can in principle be considered equivalent to the hydraulic conductivity of the skin zone.

The obtained values need to be verified and the hydraulic efficiency of the laterals analyzed further in the design of an optimal solution for the rehabilitation of the laterals of the selected wells. This will be accomplished by developing a detailed hydrodynamic model, to verify or additionally calibrate the initial hydraulic conductivity of the medium, estimated on a preliminary basis via the hydraulic characteristics of non-colmated laterals.

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Резиме

Дефинисање хидрауличких карактеристика дренова на примерима бунара београдског изворишта подземних вода

Функционално стање дренова данас има доминантан утицај на капацитет бунара београдског изворишта подземних вода. Стање филтерских цеви и хидрауличке карактеристике прифилтерске зоне су основни разлог значајног снижења нивоа у шахтовима бунара и скромних капацитета бунара. Узрок оваквог стања је процес старења, који представља појаву која прати експлоатацију подземних вода на изворишту од самог почетка изградње овог типа водозахватних објеката, почетком педесетих година прошлог века.

Током времена експлоатације, на већини бунара се, у мањој или већој мери, одвијало пропадање дренова услед корозије филтерских цеви и биохемијског колмирања дренова. Производња потребних количина пијаћих вода се и даље обезбеђује значајним снижењем нивоа воде у шахтовима (тј. све интензивнијим режимом експлоатације), што подразумева услове који доприносе даљој деградацији и искључењу дренова из експлоатације.

У протеклој деценији, смањење експлоатације подземних вода је имало константан тренд од око 100 l/s годишње, упркос мерама регенерације. Тренутно стање је такво да је просечан капацитет бунара са хоризонталним дреновима око 30 l/s, док је укупна експлоатација преко 96 активних бунара свега око 3 m^3/s (на нивоу на ком је била пре 45 година).

Овакво стање објеката и експлоатације подземних вода указује да је неопходно приступити систематској санацији бунара на београдском изворишту, којом би већ сада била обухваћена готово половина од укупног броја изграђених бунара. Адекватан избор и рангирање бунара који су кандидати за санацију представља најважнији услов за успешно решавање питања стања водозахватних објеката на изворишту и обезбеђења стабилног водоснабдевања Београда.

Без обзира на актуелни капацитет бунара, експлоатација се манифестује формирањем одређеног динамичког нивоа подземних вода у зони утицаја. Површина нивоа подземних вода у зони бунара са хоризонталним дреновима има по правилу карактеристичан тродимензионалан изглед. Из разлога актуелног броја и стања дренова, као и хетерогеног литолошког састава и филтрационих одлика седимената водоносне средине, нивои издани у окружењу бунара београдског изворишта имају изразито просторно неправилне површине.

Управо је режим нивоа издани у непосредној зони бунара индикативан показатељ потенцијала водоносне средине у погледу расположивих количина подземних вода. Анализа режима нивоа уједно представља претходни корак у упознавању функционалног стања дренова, преко дефинисања коефицијента њихове пропусности.

Дефинисањем вредности коефицијента пропусности се може сагледати ефикасност дренова, односно утврдити у којој мери су они хидраулички функционални (чиме омогућавају експлоатацију подземних вода) или затворени процесом колмирања, неадекватним извођењем радова на утиски-

вању и разради дренова, карактеристикама филтерских цеви и засипа (чиме је активно спречавају). Евидентно је да се у случају дефинисања хидрауличких карактеристика дренова заправо ради о дефинисању хидрогеолошке функције прифилтерске зоне, односно мере у којој она представља баријеру инфилтрацији подземних вода из издани у дренове.

У случају да непосредно уз дрен постоји изграђен адекватан осматрачки објекат, вредност овог хидрауличког параметра се може одредити према изразу који се користи за симулацију граничног услова „дрен" у савременој хидродинамичкој анализи, тј. математичком моделирању кретања подземних вода под утицајем бунара са хоризонталним дреновима. Израз је заснован на Дарсијевом закону, према ком интензитет размене подземних вода између водоносне средине и дрена (одређене дужине и пречника), за разлику у пијезометарским нивоима унутар дрена и непосредно са његове спољашње стране представља функцију водопропусности прифилтерске зоне.

Квантификацијом и поређењем вредности коефицијента пропусности дренова за различите временске пресеке, може се пратити напредовање процеса колмирања на неком бунару, што представља основу за изношење прогноза у погледу даљег пада капацитета или процене услова када ће на бунару бити потребно применити мере одржавања, односно регенерације дренова. Додатно, дефинисање вредности овог параметра пре и после спроведене регенерације, може служити као квантитативан показатељ реалне оцене њених ефеката.

Резултати спроведених прорачуна указују да гранична вредност пропусности прифилтерске зоне хоризонталног бунара предложена од стране аутора PARK & ZHAN (2002) од $[K_{prif}/d]=1,0\times10^{-4}$ s^{-1}, показује добру сагласност са коефицијентом колмираности дренова у случају анализираних бунара београдског изворишта, због чега се као таква може прихватити.

У условима када прифилтерска зона има коефицијент пропусности мањи од наведене вредности (примери бунара РБ-7м и РБ-42), ефекти колмирања су сасвим евидентни. Када прифилтерска зона има повољнија филтрациона својства од декларисане вредности (примери бунара РБ-46 и РБ-8м), њени ефекти на рад бунара и експлоатацију подземних вода су практично занемарљиви. У том случају се коефицијент филтрације водоносне средине (литостратиграфског слоја у ком су утиснути дренови) начелно може сматрати еквивалентним са вредношћу коефицијента филтрације прифилтерске зоне.

Проверу добијених вредности и даљу анализу хидрауличке ефикасности дренова треба вршити у фази пројектовања оптималног решења санације дренова на одабраним бунарима. Она треба бити реализована израдом детаљног хидродинамичког модела. На овај начин биће верификована или додатно калибрисана почетна вредност коефицијента филтрације прифилтерске зоне, претходно оријентационо одређена представљеним изразом за дефинисање хидрауличких карактеристика дренова.