Groundwater management by riverbank filtration and an infiltration channel: the case of Obrenovac, Serbia

Dušan Polomčić · Bojan Hajdin · Zoran Stevanović · Dragoljub Bajić · Katarina Hajdin

Abstract The Vić Bare groundwater source is used to supply water to the population and industry of Obrenovac, one of the municipalities of Belgrade (the capital of Serbia). It is a typical riverbank filtration site; exploitation is performed through 30 drilled wells and two radial wells located in the meander of the Sava River. The established hydraulic connection between the river and tapped aquifer is so great that the river regime has a dominant influence on the aquifer. As a consequence of this, water-delivery reduction occurs in the dry months (summer–autumn), when the population needs water the most. Based on the data associated with the river's gauges, precipitation, quantity of pumped water and groundwater-level fluctuation, a simulation of the groundwater regime for non-steady-state flow conditions has been undertaken through a numerical model. To overcome problems of water shortage during the dry season, the possibility of artificial recharge using an infiltration channel, made up of two connected parts, was analyzed. During the dry months, 80% of the wells receive water partly from the infiltration channel. In this way, possibilities for extracting additional water are created. The application of this concept is discussed.

Keywords Groundwater management · Riverbank filtration · Sustainable water supply · Serbia

Introduction

Riverbank filtration is a commonly used method of tapping water for supply to the population and for industry. Besides securing additional reserves through induced river-water infiltration, the microbiological and hydrochemical quality of infiltrating river water improves (Kühn and Müller 2000). This method of water extraction has been widely applied along rivers throughout Europe in the past few decades. In the Republic of Slovakia, it is employed in 50 % of the potable supply systems, and in Hungary 45 % (Grischek et al. 2005). In Germany, more than 300 water works use bank filtration and roughly 50 plants are based on artificial groundwater recharge (Schmidt et al. 2003). Riverbank filtration in the Netherlands provides annually 80×10^6 m^3 to the national drinking-water supply, through a total of 26 well fields (Stuyfzand et al. 2006). In Serbia alone, 56 % of the abstracted water for the population and industry is groundwater from alluvial aquifers, i.e. from bank filtration sources, of which almost one half is tapped for the water supply of the capital, Belgrade (Dimkić et al. 2007; Polomčić et al. 2011). In the last few years the application has increased in the USA and Asia (Sontheimer 1980; Ray et al. 2002a, b; Chang et al. 2011).

When compared with direct river-water extraction, exploiting infiltrated river water from aquifers secures waters of a biologically and chemically higher quality, with a more stable temperature regime and better organoleptic characteristics (Schmidt and Brauch 2008). It uses the natural biological and sorption potentials of the minerals of the water-bearing environment in cleaning infiltrated river water. It is a well-known fact that riverbank filtration significantly lowers the presence of organic matter and pathogenic microorganisms (Hiscock and Grischek 2002; Grünheid et al. 2005). With regard to the quality (degree of pollution) and final purpose of tapped water, treatment of these waters can be performed on a smaller scale than with directly abstracted river water (Polomčić 2001). Systems based on river-water infiltration can be viewed as a pre-treatment in raising the water quality, or, under favourable conditions, as the final treatment before disinfection (Ray et al. 2002a, b).

Although most of the sources along the banks of rivers are supplied through river-water infiltration, in some cases, the tapped waters represent a mixture of infiltrated river water and water from the alluvial catchment of intake structures, which can have different chemical compositions (Shankar et al. 2009, Stauder et al. 2012). The quality of alluvial groundwater depends on the mineral composition of rocks and soil as well as land usage (urbanization, agriculture, industry), while the quality of infiltrated river water depends on the quality of the

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water from the surface flow and efficiency of the self-purification mechanism of the water-bearing environment (Kühn and Müller 2000; Eckert and Irmscher 2006).

The main aim of this work is to determine the relationship between infiltrated river water and the groundwater, as well as the distribution of certain river-water infiltration zones based on non-steady-state flow conditions, during a 4-year period. Also, a hydrodynamic analysis has been performed to assess the possibility of securing a more stable extraction of water from the aquifer during low water levels in the dry season. Done through a simulation of a virtual infiltration channel, should the results be positive, construction of such a channel would be advised for the already formed source.

Site description

The investigated terrain that is the subject of this study encompasses an area in which the Vić Bare groundwater source is used for the water supply of the 41,000 residents of Obrenovac, one of the largest Belgrade municipalities, and its associated industry and agriculture. It is located on the alluvial plain of the Sava River, 4 km from the city of Obrenovac, and 35 km southwest of Belgrade (Fig. 1). The size of the Sava River has allowed for the sustainable use of riverbank filtration for the last 50 years, with its current contribution of 320 l/s for Obrenovac, as well as for bank filtration downriver at the Belgrade source, where over 100 radial wells tap around 4,700 l/s. Water demand for Obrenovac's population, industry and agriculture is estimated at approximately 500 l/s.

Tapping groundwater at the Vić Bare is performed via the alluvium of the Sava River using 30 drilled wells and two radial wells. At the investigation area of the Vić Bare source, sandy-gravelly alluvial Quaternary sediments are present (Fig. 1) and form the porous aquifer, which is underlain by an aquitard formed by the alluvial clays and marly-clayey of the Pliocene. The top layer is made up of silty sands of low permeability and clays 4–6 m thick. The main aquifer layer is made up of an upper (sandy) and lower (gravelly) part (Fig. 2). The thickness of this layer in the source area varies from 5 to 15 m. It is thinnest in the southern part, while in the central part of the study area, it is 10–12 m thick. In the northern zone near the Sava River, where the largest number of wells is located, the thickness of these deposits exceeds 15 m, locally. The underlying stratum is made up of clayey sediments of Pliocene age (Hajdin et al. 2007).

In the water-bearing sands, the value of the hydraulic conductivity fluctuates in the range of 2×10^{-5} to 8×10^{-5} m/s, and in the water-bearing gravel of 8.4×10^{-4}–1.8×10^{-2} m/s. The hydraulic conductivity of the top layer is between 1×10^{-8} and 7×10^{-7} m/s, while the underlying Pliocene clays have a value lower than 1×10^{-8} m/s.

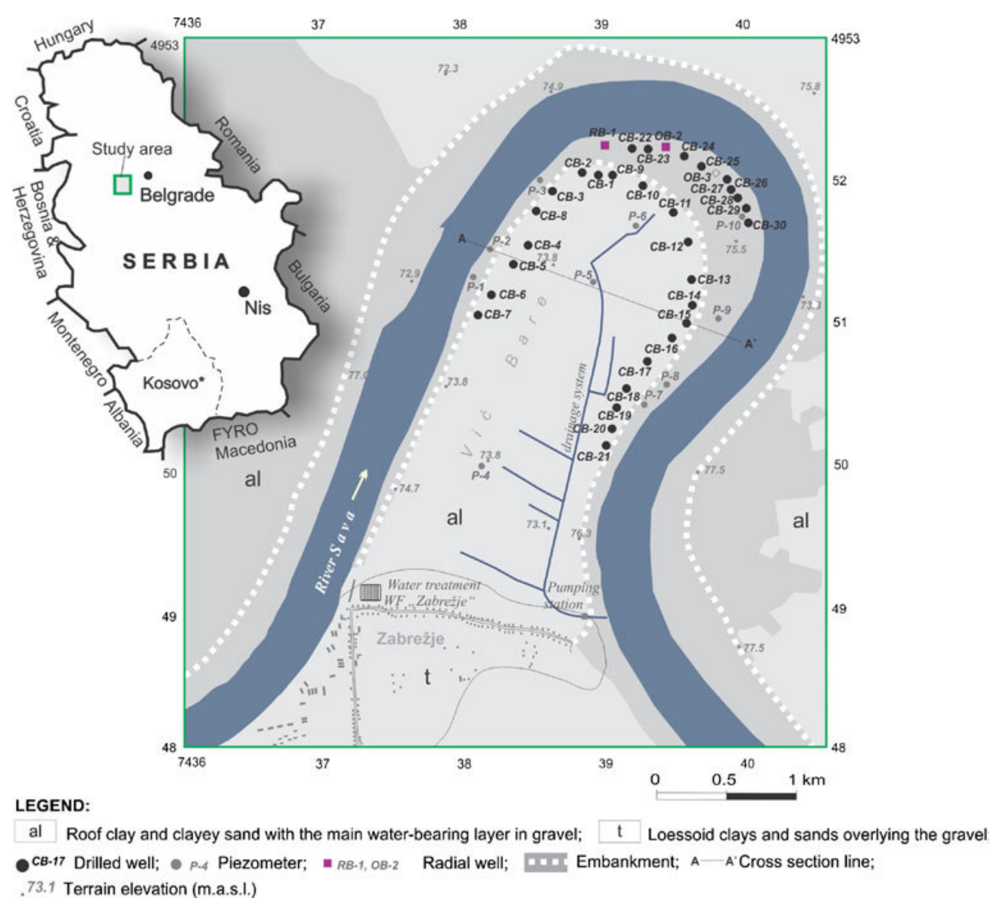

Fig. 1 Geographical position of the study area and positioning of wells at the Vić Bare source

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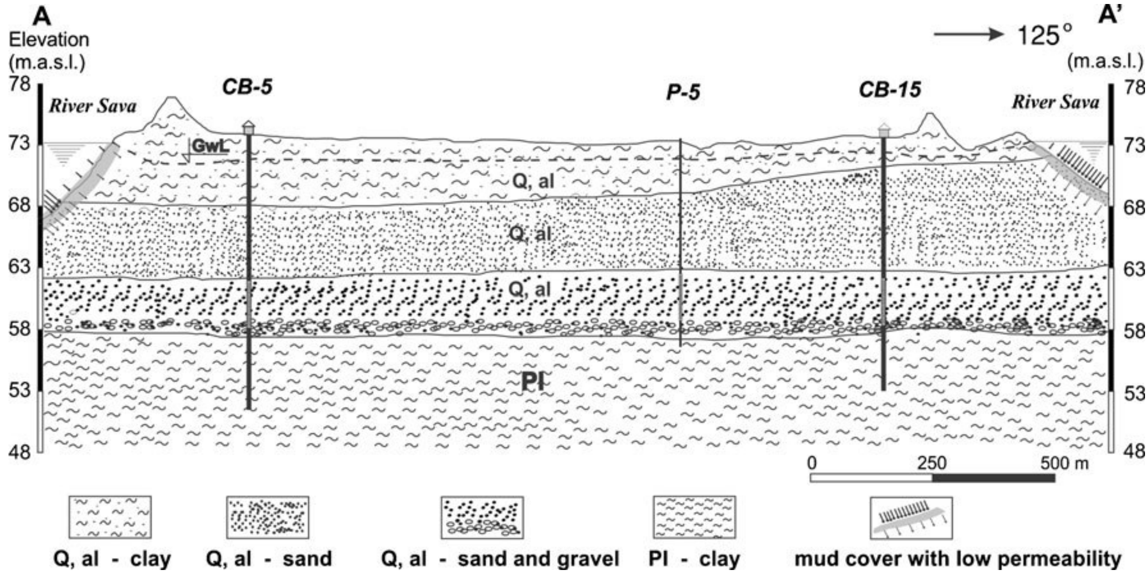

Fig. 2 Hydrogeological profile

The Sava riverbed was carved in sandy layers of the alluvial aquifer as shown in Fig. 2. However, clogging of the river bottom could restrict infiltration of Sava River waters in some sections. The relatively low water velocity of this large river stimulates sedimentation in a whole section from the study area to the confluence of the Sava and the Danube River, located some 30 km downstream.

Groundwater regime

The groundwater regime depends on the Sava River's regime, especially in the riverbank area; towards the central part of the Vić Bare site this influence is weaker. The aquifer is also recharged through precipitation, but to a lesser extent. Groundwater extraction at Vić Bare occurs mainly through wells, but in periods of low water level of the Sava River, discharge of groundwater into the river also takes place. Finally, a part of the water is "lost" naturally, through evapotranspiration.

In order to analyze the impact of the river on the groundwater regime, data concerning the river-water level and groundwater level during two time intervals, 6 July 2007–5 July 2008 and 16 November 2010–31 May 2011, were collected and evaluated. Figure 3 shows the dependence of the groundwater level at Vić Bare on the water level of the Sava River and on daily precipitation. During 2007–2008 ten piezometers were permanently observed, while for period 2010–2011, groundwater level was monitored in five piezometers (Fig. 4).

Figures 3 and 4 show the dominant impact of the Sava River on the groundwater regime, while the influence of rainfall can be considered as minor. This is due to the high permeability of the gravel and sandy layers hydraulically connected with the Sava River.

A rapid change in groundwater levels concurrent with the changes in the Sava River water level was

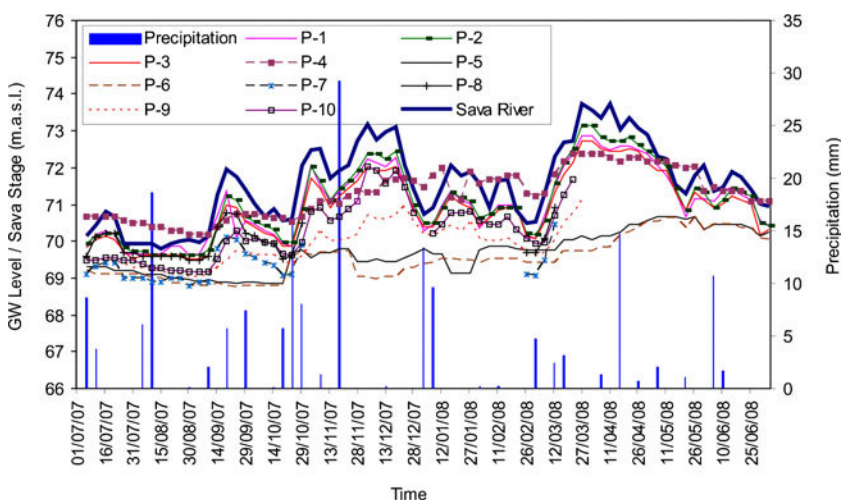

Fig. 3 Groundwater-level fluctuation, Sava River water-level oscillation, and daily precipitation values from 6 July 2007 to 5 July 2008

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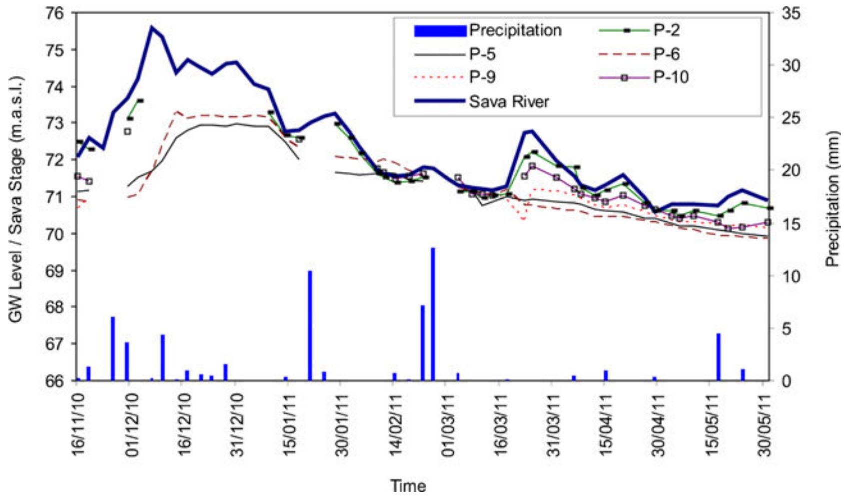

Fig. 4 Groundwater-level fluctuation, Sava River water-level oscillation, and daily precipitation values from 16 November 2010 to 31 May 2011

noted in the piezometers, which indicates a strong hydraulic connection between the surface water and groundwater. Away from the river, towards the central part of the Vić Bare site, the river impact is apparent, seen by following the groundwater level in piezometer P-4 located in the middle part of the meander. The groundwater levels in the other two piezometers located in the central part (P-5 and P-6) are lower and stable in relation to the other piezometers, a consequence of being surrounded by exploitation wells.

The wells age as a result of the process of incrustation due to heightened concentrations of iron and manganese in the groundwater. The reduction of well discharge over time follows the reduction of the total groundwater source discharge (Mayr et al. 2011). In the last 10 years, the waterworks service has made several attempts to solve this problem by applying physical-chemical regeneration methods to the wells. Because of the intensity of the incrustation process, more wells are regenerated per year (12 wells, on average). Previous groundwater extraction at Vić Bare was dependent on gauges of the Sava River. During the dry season, when there is a decline in groundwater levels, the individual capacity of wells must be reduced in order to obtain a functional condition of the source.

Figure 5 presents the mean values of the Sava's water levels as well as the mean monthly values of the Vić Bare groundwater source capacities during the dry season (August, September, October) in the period 2001–2011.

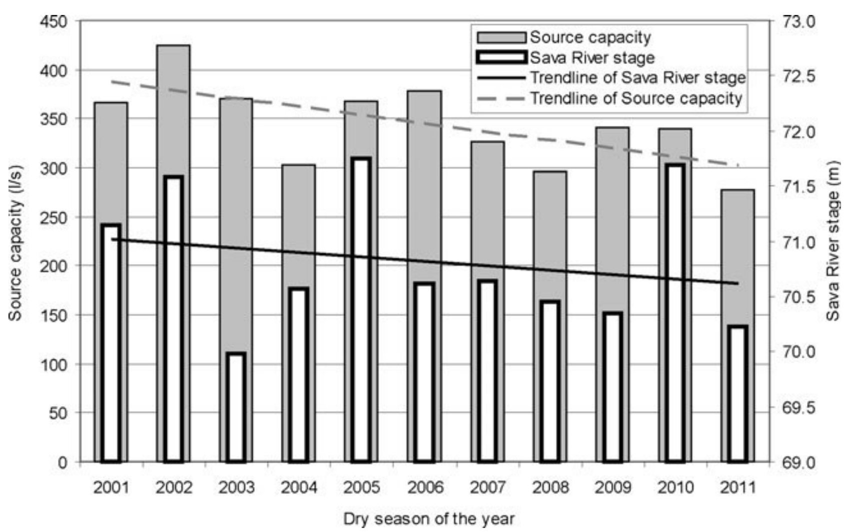

Fig. 5 Mean monthly values of the Sava River water level and capacity of the Vić Bare groundwater source during the dry season (August, September, October) in the period 2001–2011

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Source discharges during the low-water periods, which coincide with late summer and early autumn months (August, September, October), are defined as the averaged and summarized pumping rates of all operational wells. Certain higher values of the source capacity (e.g. 2002, 2005 and 2006) are a consequence of the completion of new wells and the regeneration of a good number of existing wells. However, upon the performed interventions or well replacement, the groundwater exploitation rate again drops quickly and noticeably. Also, this figure presents the trend lines that generally show a continual decline in the Sava River's water level over the last 11 years. Because of the great hydraulic connection, the groundwater level has simultaneously fallen, causing also a reduction in the capacities of the exploitation wells.

Numerical model

In order to determine the different hydraulic components of riverbank filtration, the water balance and the groundwater reserves, numerical modelling was performed. The input data for the model are the result of numerous field investigations (well pumping tests, sieve analyses), hydrometeorological and hydrological data, groundwater extraction data and groundwater-level data obtained during the two representative periods of 2007–2008 and 2010–2011.

The applied numerical model was MODFLOW-2000, a modular, three-dimensional (3D) finite-difference groundwater-flow model developed by the US Geological Survey (Harbaugh et al. 2000). The software used is Groundwater Vistas 5.33b (Environmental Simulations International, Ltd.).

The Vić Bare numerical model has been conceived and produced as a multi-layered model, with a total of four layers in the vertical profile. Determination of "geometric" properties of the layers' contours and their transfer to the model's coordinate system was performed based on the available lithological data obtained from drilling of exploitation and observation wells.

The basic matrix dimensions which encompass the studied terrain are 3,500 m × 4,000 m, in an area of approx. 14 km^2. The flow field is delineated by a basic cell size of 100 m × 100 m, strengthened in the zone of the extraction wells with a net of squares whose dimensions are 12.5 m × 12.5 m.

Boundary conditions

In the case of the Vić Bare hydrodynamic model, the following boundary conditions were applied: head-dependent flux boundary condition and boundary of prescribed flux (Fig. 6).

1. Head-dependent flux boundary condition (Cauchy or mixed conditions): The influence of the Sava River was simulated using this boundary condition which is independent of the state of the alluvial aquifer, with observed water levels in terms of absolute elevation (m.a.s.l.). As there are no data to estimate the river conductance, an arbitrary mean value is used which describes a relatively good contact between the river and the aquifer. This boundary condition was allocated in the first or second layer

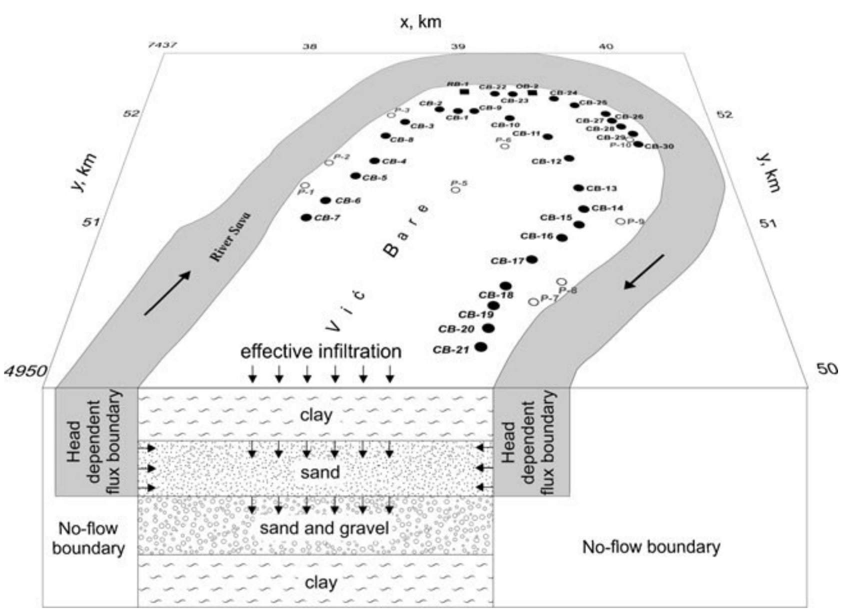

Fig. 6 Hydrogeological conceptual model

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depending on the elevation and position of the underlying stratum.

2. Boundary of prescribed flux (Neumann conditions): The impact of exploitation wells on the groundwater source was simulated through the boundary with a specific flux. In this case, the flux was specified as a function of position and time. The individual well discharges were appointed into the model in accordance with observed well performance and dynamics. A specific case is the impermeable border, which represents the border that demarcates the spreading of the water-bearing environment, without any inflow from the background. This boundary was chosen for the left bank of the Sava River.

Effective infiltration, percolation as a "vertical" component in the groundwater balance, has no pronounced impact, as can be seen from Figs. 3 and 4. It was simulated through the first layer by variable flux Neumann boundary conditions. This value is made up of the sum of infiltrated precipitation and evapotranspiration. The groundwater level during the whole analyzed period (2007–2008 and 2010–2011) was several meters below the terrain surface (2–6 m). Bearing in mind that the top layer has low permeability, infiltration of rainfall has only a small impact on the groundwater regime. As an initial value of effective infiltration, a 10 % precipitation value was used.

Model calibration and verification

Model calibration was performed in non-steady-state flow conditions, with time intervals of 1 day for the analyzed time period 6 July 2007–5 July 2008. Figure 7 shows the correlation dependence of the observed and calculated groundwater level values for all ten piezometers in the period for which the model was calibrated.The mathematical simulation results of the groundwater level regime are generally well coordinated with the observed groundwater levels in the investigation area (±10 cm accuracy on average).

The observed data of the groundwater regime, as well as observation of the Sava River and precipitation, have enabled model verification for the period 2010–2011, which was performed with the same time steps as model calibration. The results of model verification indicated a relatively good match between the observed and calculated groundwater levels. The residual values are somewhat lower than those obtained in the model calibration process.

Results: determining the river-water infiltration zones and groundwater budget analysis

The river-water infiltration zones and the groundwater budget are analyzed for the conditions of the Sava River's minimum water levels and the minimum or maximum groundwater extraction from wells. The calculations were performed for steady-state flow conditions of groundwater filtration. Using particle-tracking analyses, border flow lines were determined and have an exclusively limiting character for the river-water infiltration zones.

Figures 8 and 9 show the flow images for the extreme conditions as well as the flow images that separate three river-water infiltration zones. When minimum river water levels occur and also cause the

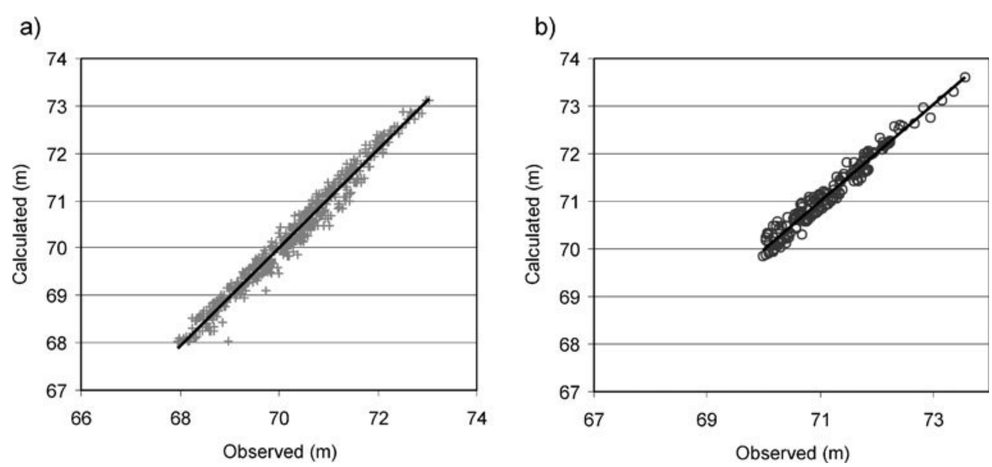

Fig. 7 Correlation dependence of the observed and calculated groundwater level values for **a** ten piezometers in the 6 July 2007–5 July 2008 period (model calibration), and **b** five piezometers in the 16 November 2010–31 May 2011 period (model verification)

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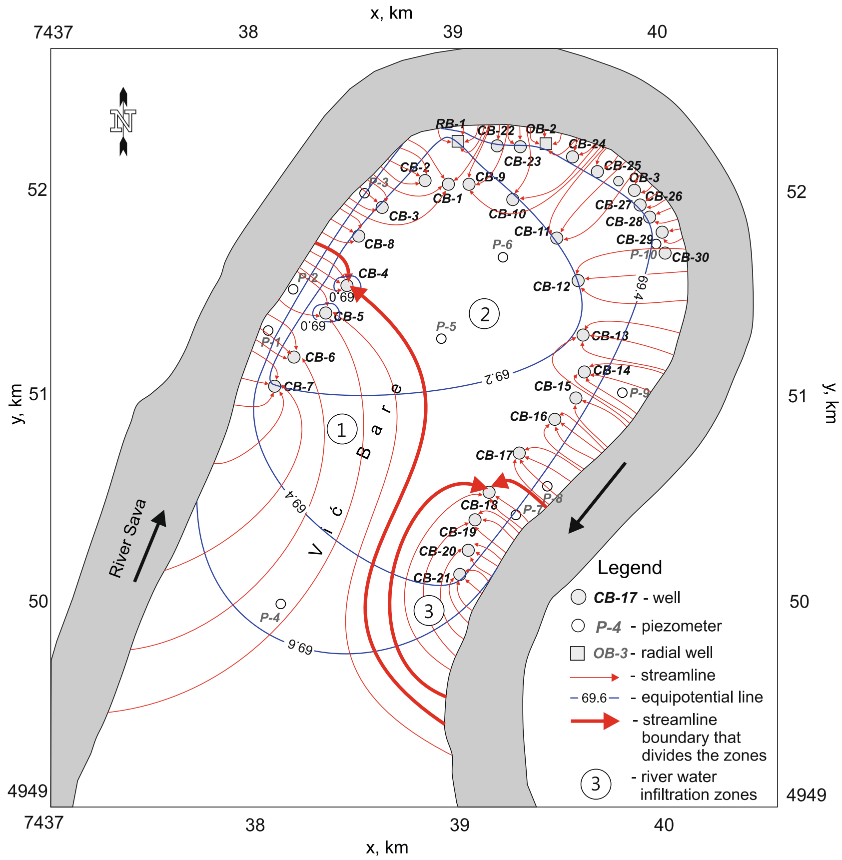

Fig. 8 The flow pattern during minimum water level (69.80 m.a.s.l.) of the Sava River and minimum groundwater extraction (210 l/s) with a view of the riverbank infiltration zones. Labels *1, 2* and *3* are zones described in the text

lowest observed groundwater source capacity, zone 1 is extended in the western part of the meander comprising well CB-7, the area of wells CB-4 to CB-7, and the area downstream of well CB-21 on the eastern side of the meander. In these conditions, zone 2, as the largest zone, contains 22 drilled and 2 collector wells (Fig. 8), while zone 3 has the smallest area and is tied to the area around wells CB-18 to CB-21. However, according to these wells, river water from the western side of the meander, upstream from zone 1, gravitate to the existing exploitation zone.

The groundwater budget was calculated for Sava River minimal gauges and for groundwater extraction of 350 l/s. As a consequence of the variation of an individual well's discharge, the flow pattern rearranges within the studied meander: the separate river-water infiltration zones do not coincide with those under the conditions of the lowest observed summary capacity of wells. This flow rearrangement is not the consequence of the proximity of Sava River, or the values of hydraulic conductivity and thickness of water-bearing sands and gravel, that are identical in both scenarios. This is the result of variable pumping rates of the wells. Zone 1 encompasses the area from well CB-7 to well CB-25 in the western and northern part of the meander. This zone contains the largest number of wells, 14 vertical and 2 collector wells. Zone 2 in the north-eastern part of the study area contains 13 vertical wells. The third zone encompasses the smallest area and contains only wells from CB-18 to CB-21.

The groundwater budget (or balance) of a groundwater system can be determined by calculating the inputs and outputs of water, and the storage changes of the groundwater system. For the study area, the major inputs of water are the infiltration of the river's water and precipitation, while the major outputs from a groundwater system are groundwater pumping and, to a significantly lesser extent, evapotranspiration. Table 1 shows the aquifer water budget in the meander for the analyzed cases of maximum and minimum water level in the Sava River and appropriate groundwater exploitation rates.

The impact of the Sava River on the extracted alluvial-aquifer budget elements and regime is very high, as shown in Figs. 3 and 4. Under the conditions

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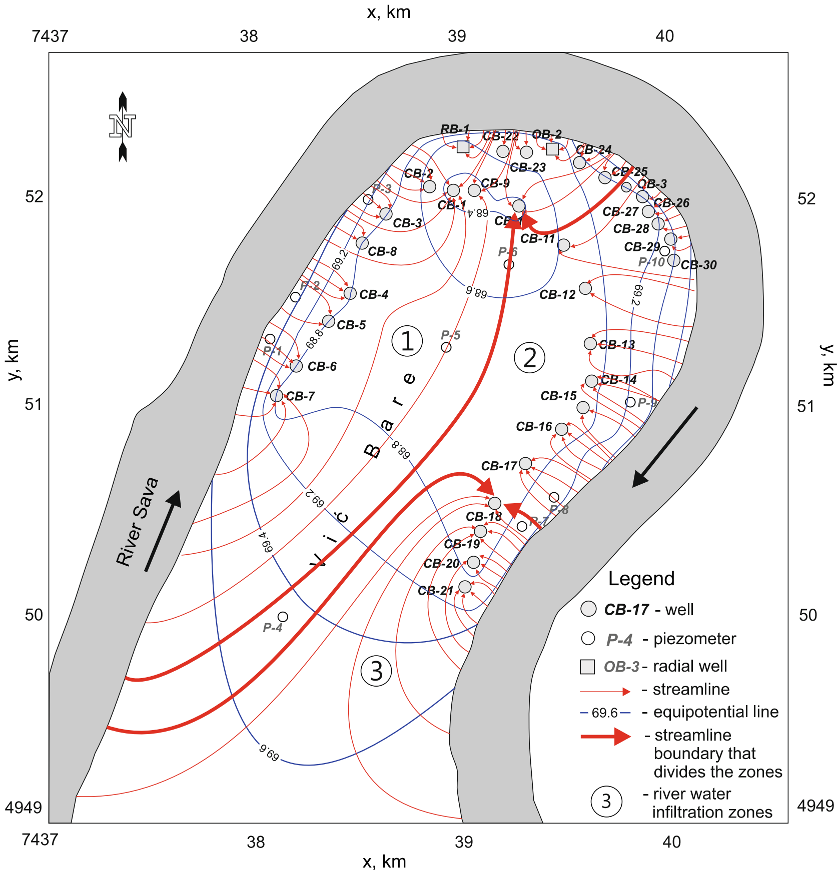

Fig. 9 The flow pattern during minimum water level (69.80 m.a.s.l.) of the Sava River and maximum groundwater extraction (350 l/s) with a view of the riverbank infiltration zones, Labels *1, 2* and *3* are zones described in the text

of minimum water level and groundwater extraction with a total capacity of 210 l/s, river water contributes 99.52 %. In terms of separate zones, the contribution of river-water infiltration is as follows: zone 1, 13.33 %; zone 2, 74.76 %; zone 3, 11.43 %. Under the conditions of minimum water level of the Sava River too, and maximum groundwater exploitation with a total capacity of 350 l/s, riverbank filtration contributes 99.68 % in the securing of exploitation reserves for the groundwater source. In terms of zones, the contribution by percentage is as follows: zone 1, 61.55 %; zone 2, 27.83 %; zone 3, 10.30 %.

Discussion: alternative with artificial recharge

Due to the lowered piezometric level in the aquifer when the Sava River is at its minimum level, the capacity of the Vić Bare groundwater source declines. Although characterized by relatively large river flow, the Sava's bed is covered by a clogging layer which reduces the infiltration rate particularly during low water periods. This is the period of greatest need for water for both the population and industry, but the lowered capacity of the groundwater source leaves the consumer's needs unsatisfied and a reduction in water supply is not infrequent.

Table 1 The aquifer water budget in the meander for the analyzed cases of minimum and maximum possible groundwater extraction for minimum water level in the Sava River

Location	Minimum extraction of groundwater		Maximum extraction of groundwater	
	Inflow (l/s)	Outflow (l/s)	Inflow (l/s)	Outflow (l/s)
Sava River zone 1	28.40		215.27	
Sava River zone 2	156.00		97.33	
Sava River zone 3	23.73		36.04	
Wells		210.00		340.31
Effective infiltration	1.10		1.10	
Total	209.23	210.00	349.74	350.00

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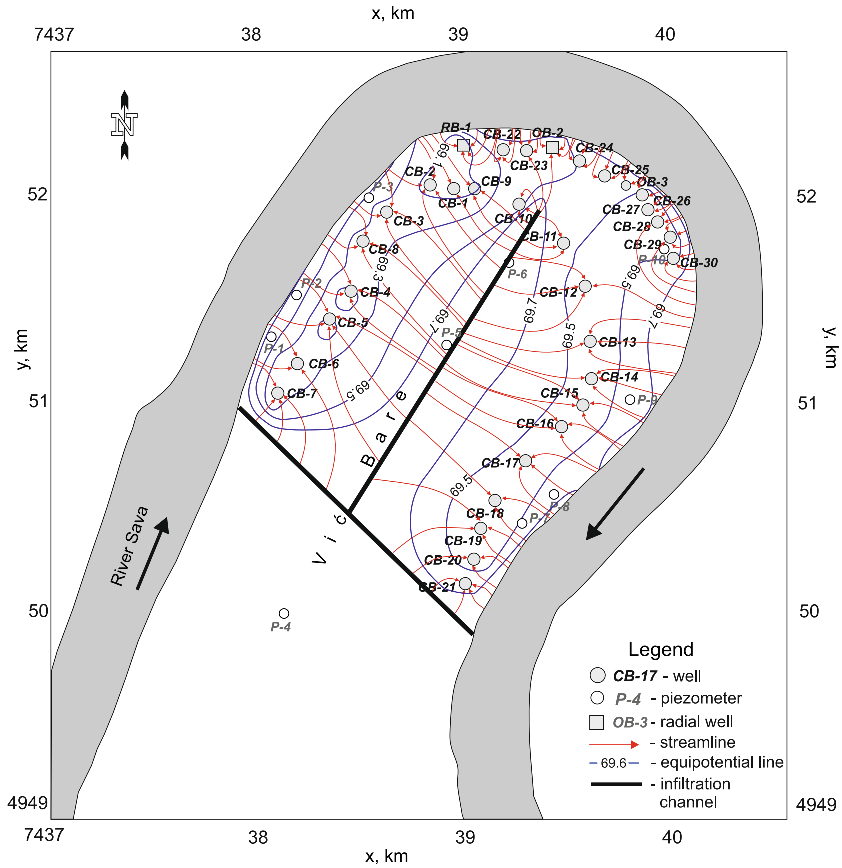

Fig. 10 The flow pattern under the conditions of an infiltration channel for the minimum Sava River water level (69.80 m.a.s.l.) and minimum groundwater extraction (210 l/s)

The effects of introducing artificial recharge through building an infiltration channel, made up of two parts, were analyzed. The conceptual design considers the first part of the channel which cuts the meander south of the wells and connects the western and eastern meander banks. The second part is located in the central part of the meander, in the catchment of the wells, and connects with the first part of the channel in the south (Figs. 10 and 11). The channel would be 2 m wide and its bottom would coincide with the sandy water-bearing layer (second model layer), up to a maximum depth of 6 m. The water level in the channel was assigned the same values as those of the Sava River's water levels. The infiltration channel in the model was assigned through the head-dependent flux boundary condition with the same hydraulic characteristics as the Sava River.

The two options were analyzed, identical with those applied for the groundwater budget analysis: minimum Sava River levels and the appropriate groundwater exploitation rates. The calculations were performed for steady-state conditions. Figures 10 and 11 show groundwater flow patterning for the minimal gauges of the Sava River and minimal and maximal groundwater extraction values. The forecast includes the proposed infiltration channel.

When the Sava River is at minimum level and for minimum groundwater extraction (210 l/s), the largest rise in groundwater level (0.6 m) occurs in the central part of the meander in the zone of piezometers P-5 and P-6. The infiltrated water of the channel gravitates to a total of 23 wells, or 80 % of the total number. The inflow of groundwater towards the wells is "cut" south of the channel (parts of the recharge of zones 1 and 3), taking into account that the infiltration channel represents a watershed between the well groups.

To estimate maximal groundwater extraction from the Vić Bare source, the main criteria included limited general drawdown to an elevation not below 68 m.a.s.l. Such a level still ensures sustainable hydraulic conditions in the source. For minimal Sava gauges and the anticipated infiltration channel, which contributes to the recharge of 23 existing wells, the model results showed groundwater extraction which should not exceed 435 l/s. For that pumping rate, resulting groundwater levels are 68.2–68.4 m.a.s.l., which is 1 m lower than, for instance, when groundwater extraction is 210 l/s. In the central part of the meander near the infiltration channel the groundwater level remains at 69.8 m.a.s.l., while the

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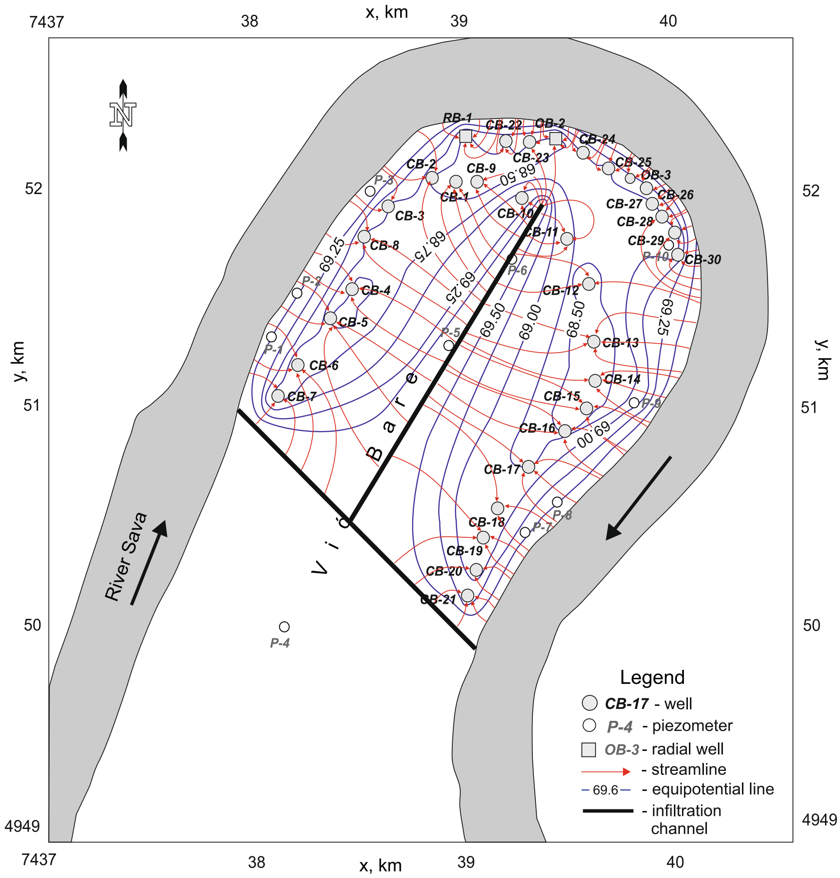

Fig. 11 The flow pattern under the conditions of an infiltration channel for the minimum Sava River water level (69.80 m.a.s.l.) and maximum possible groundwater extraction (435 l/s)

gradient is steeper towards the eastern and western parts of the meander. The groundwater budget under the conditions of an infiltration channel has been analyzed for the conditions of minimum water levels of the Sava River and the channel, and is presented in Table 2.

Figure 12 shows the relationship between maximal source capacity and Sava River stage (from gauges), with and without an infiltration channel. Calculation is made for steady-state flow while an individual pumping rate for each well was restricted to maximal local drawdown, not to be below an elevation of 68 m.a.s.l.

When a channel is absent, maximal source capacity is in the range of 350–442 l/s, while an infiltration channel enables capacities of 435–710 l/s. Therefore, for the minimal stage of Sava waters, a channel supports an additional 85 l/s, whereas for the maximal stage, 268 l/s of "new" water could be pumped out. The yield enlargement is not linear; when the river-water level is low the capacity cannot be significantly supplemented even with a fully operational channel. The channel then contributes some 24 % of the total yield (Sava level at 69.8 m.a.s.l.) but the contribution could reach 60 % when the Sava level is 6 m higher (76 m.a.s.l.).

Table 2 Elements of groundwater budget in the Vić Bare groundwater source area for the minimum water levels of the Sava River in the case of a simulated infiltration channel

Elements of groundwater budget	Minimum extraction of groundwater		Maximum extraction of groundwater	
	Inflow (l/s)	Outflow (l/s)	Inflow (l/s)	Outflow (l/s)
Sava River	136.84		309.83	
South Channel	29.18		45.46	
Central Channel	43.11		78.39	
Wells		210.00		435.00
Effective infiltration	1.10		1.10	
Total	210.23	210.00	434.78	435.00

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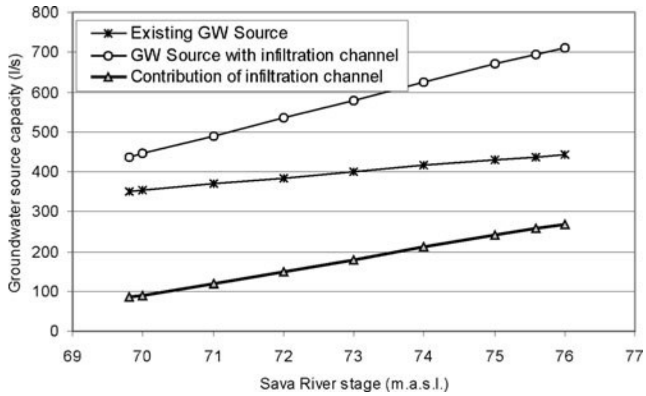

Fig. 12 Maximal source capacity vs. Sava River stage

Water-quality aspects

The problems of initial river-water quality, and the clogging and maintenance of the proposed channel, are considered to be very important for the success of proposed artificial recharge structure. Generally, Sava River water has low mineralization, total dissolved solids (TDS) up to 300 mg/l, and turbidity in the range of 10–40 NTU, while organic components could reach 25 mg/l of $KMnO_4$. Such initial river-water quality is, however, satisfactory for the existing bank filtration since current groundwater treatment (which includes aeration, filtration and chlorination) results in water suitable for drinking according to national and international standards. Bank-filtered Sava River water is utilized in a similar way in the largest national source for the Serbian capital Belgrade, while there is direct treatment of the river water (capacity 0.2 m^3/s) for the small city of Baric, located between Obrenovac and Belgrade.

The problem of clogging regularly accompanies artificial recharge structures (Plotnikov and Kaden 1979; Huisman and Olsthoorn 1983; Jury and Roth 1990). Pre-treatment of infiltrated water commonly reduces clogging intensity (Huisman and Van Haaren 1966; Schmidt 1996). In the case of the Vić Bare source, the construction of a small system for pre-treatment of Sava water, consisting of two small basins and small cascades between them, is suggested. In this way, river water would pass through stabilization, sedimentation, aeration and filtration before entering the infiltration channel (Fig. 13). In addition, during periods of high waters, which commonly result in the poorest river-water quality, the gate of the channel will be closed. During these periods, productivity of the wells is, however, greatest and artificial recharge should be cancelled to allow seasonal maintenance of the channel. The calculated channel gradient is 0.0017 and will be emptied by gravity flow and, if required, by pumping; after which ploughing and harrowing of the channel bottom will be applied.

To ensure suitable drinking-water quality, plans to broaden the final treatment of extracted groundwater to include pre-ozonation and coagulation with flocculation have already been made by the Obrenovac water authority. The capacity of the treatment plant for the raw groundwater would be easily adapted to these new processes. After this preliminary assessment and before construction of the infiltration channel and water-treatment plant extension, further detailed study on water technology and its feasibility will take place.

Conclusion

The groundwater of the Vić Bare site has great hydraulic connection with the water of the Sava River, creating a typical riverbank filtration situation. The river-water regime is even more influential on the groundwater-level fluctuation than the work of other nearby exploitation wells. A simulation of the groundwater regime with a numerical model, used for the analysis of the streamlines and water-budget elements of the tapped alluvial aquifer, confirmed that river-water infiltration contributes 99 % to the total groundwater reserves.

To overcome the problem of the lowering capacity of the groundwater source during the dry months (summer–autumn) construction of an infiltration channel has been proposed, through which river water would be transported from the western toward the eastern part of the meander. The virtual channel, up to 6 m deep with an open bottom situated in the water-bearing sands, was positioned in the southern and central parts of the groundwater source. The effects of artificial recharge have been simulated on the same numerical model and the following results obtained:

- In general, an infiltration channel would enable more intensive infiltration of surface water into the aquifer in every stage of operation.
- The performed hydrodynamic analysis for the maximum and minimum river-water levels and appropriate groundwater-extraction rates indicated that the

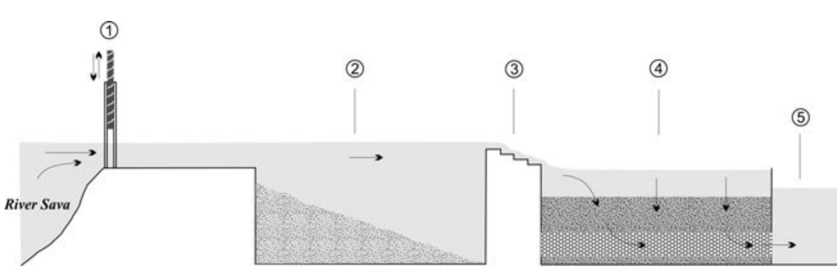

Fig. 13 The pre-treatment scheme for river water before channelling. *1* gate; *2* sedimentation basin; *3* cascade aeration; *4* sand filter; *5* channel

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infiltration channel has a significant impact on the groundwater level and budget of the aquifer.

- This impact is more prominent in the dry period when 23 exploitation wells receive part of their water from the channel. The average rise in groundwater level under the conditions of minimum river water level is 0.3 m.
- An assessed additional yield resulting from an infiltration channel depends on the level of the Sava River. For the minimal stage of Sava waters, a channel could support the pumping of 85 l/s, while for the maximal stage of river water, pumping of 268 l/s of "new" water would be possible according to the model.
- Such a result, of combining riverbank filtration and artificial recharge via a channel, would enable groundwater to be extracted to a greater capacity and to satisfy the water needs of the 41,000 residents and industry during the critical summer and autumn months.
- It is thus recommended that the design and construction of an infiltration channel be completed, which does not require a great financial investment.

As is common when such an artificial recharge structure is proposed, the problems of initial river-water quality, clogging of the channel and its maintenance have to be studied in detail. At this stage, pre-treatment of the Sava River is suggested and should include water stabilization, aeration and fast filtration before it flows to the channel, while a gate at its beginning would enable manipulation: opening when infiltration is needed as well as closing for seasonal cleaning from clogging materials.

Lastly, it can be concluded that the creation and testing of a hydrodynamic numerical model is an essential tool for this kind of preliminary analysis and assessment of the feasibility of a proposed intervention at the groundwater source. In the Vić Bare case, a hydrodynamic model opens the way toward system optimization and sustainable source development.

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