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A comparison of the efficiency of riverbank filtration treatments in different types of wells

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Abstract

In the paper, a comparison of the efficiency of riverbank treatments is outlined for the Krajkowo well field, where different methods of water abstraction are used. The water is extracted from 29 vertical wells that are located at a distance of 60–80 m from the channel of the River Warta and from a horizontal well with radial drains located 5 m below the bottom of the river. The results of a two-year water-quality investigation indicate that the water quality in both types of abstraction system is influenced by the quality of river water. The water quality observed in the horizontal well is closely similar to that of the river water, with similar concentrations of sulphates, nitrates and micropollutants, but a reduction in bacteriological contamination and plankton is clearly seen. The reduction in contaminants is mainly the result of physical processes, such as mechanical entrapment of suspended material and colloids as well as bacteria and plankton. In the vertical wells, the influence of contamination from river water is also visible, but the reduction in contamination is more significant, especially in cases of bacteria, plankton, micropollutants and nitrates, and is determined by both physical and chemical processes, such as sorption, dissolution, red-ox processes and denitrification. The present research shows that river water treatment is more effective in the case of vertical wells. The most favourable distance of a well from the channel of the river, from the perspective of water quality, is 150–200 m, which corresponds to a residence time of about six months.

Keywords: groundwater and surface water contamination, riverbank filtration, horizontal well

1. Introduction

Managed of Aquifer Recharge (MAR) is often used to support groundwater recharge, especially in the supply of relatively large cities or communities (Dillon, 2005). One of the MAR methods is recharge through riverbank/riverbed filtration (RBF). In cases of polluted river water filtration into the groundwater, the RBF system must remove contaminants from the source river water, and therefore, this system must be properly designed and operated to maximise the removal of contaminants (Ray et al., 2003). The RBF is used as a pretreatment step to improve the quality of surface water for drinking (Hiscock & Grischek, 2002; Ghodeif et al., 2016). The infiltration process through river bottom sediments and then through aquifer sediments causes natural purification and improvement of water quality along the flow path. Surface water, after infiltration from the river, becomes subjected to combined physical, biological and chemical processes, such as sorption, dissolution, red-ox processes, denitrification and biodegradation (Hiscock & Grischek, 2002; Ghodeif et al., 2018; Paufler et al., 2018). The influence of these processes causes the surface water to acquire features of groundwater.

There are many types of riverbank/riverbed filtration systems (Ray et al., 2003), one of these is the location of vertical wells close to river bank. In such a case groundwater withdrawal creates a cone of depression that enables infiltration and movement of surface water towards the wells. Another method involves the use of horizontal well (HW) with drains located below the bottom of the river.

In the present study, a comparison of the efficiency of river water treatments is presented for the Krajkowo well field that supplies the city of Poznań (Poland), where both methods of water abstraction are used, i.e., a vertical well located close to the river and HW with drains below the bottom of the river. The main goal of research was to document changes in water quality during the passage between river and aquifer, and to demonstrate advantages and limitations of each water extraction system from the point of view of water quality.

2. Site description

The Krajkowo well field is located on Krajkowska Island in the valley of the River Warta (Fig. 1), 30 km south of the city of Poznań, where two Main Groundwater Basins (MGB) are situated – the Wielkopolska Burried Valley (WBV) aquifer and the Warszawa-Berlin Ice Marginal Valley (WBIMV) aquifer. The well field is located in the region where sediments that form these aquifers overlap (Przybyłek et al., 2017), thereby creating good conditions for water exploitation (fluvio-glacial and fluvial sand and gravel deposits with a thickness of 30–40 m).

The lithology of the upper aquifer (WBIMV) shows a predominance of fine- and medium-grained sands of fluvial origin (to a depth of ~10 m) and by coarse sands and gravels of fluvio-glacial origin in the deeper portions (to a depth of ~20 m) (Fig. 2). The deeper aquifer (WBV) is also composed of fluvial fine- and medium-grained sands in the upper part (to a depth of 25–30 m) and by coarse-grained fluvio-glacial sands and gravels in the deepest part of the aquifer. Locally, these two aquifers are isolated by glacial tills (with a thickness of ~10 m). The static water level occurs approximately 3–5 m below the surface. In periods of droughts, a decrease in water level is visible to a depth in excess of 10 m (Fig. 2).

Two different systems are used for water extraction (Fig. 1):

- A gallery of RBF wells located on the left side of the River Warta on the flood plain – 29 wells are located at a distance of 60–80 m from the river channel. The total length of the wells gallery is 1,980 m. The wells are protected against flooding by embankments (Fig. 3).
- HW with drains placed 5 m below the bottom of the river. The positions of the well drains in relation to the bottom of the River Warta are shown in Figure 3. The drains were installed by excavation of riverbed sediments.

3. Materials and methods

Investigations of water quality were performed in the River Warta by utilising seven monitoring points, including an HW and four vertical wells located on the left bank of the river (Fig. 1; Table 1).

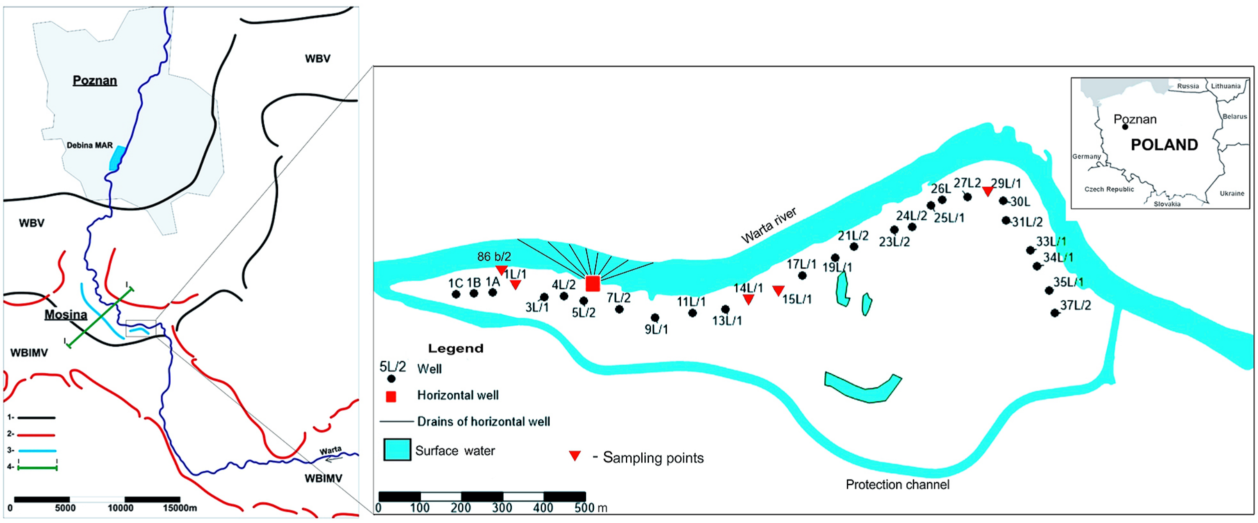

Fig. 1. Scheme presenting location of the Krajkowo well field and Major Groundwater Basins (MGB): 1 – Wielkopolska Buried Valley aquifer (WBV); 2 – Warszawa–Berlin Ice-Marginal Valley aquifer (WBIMV); 3 – well galleries; 4 – line of hydrogeological cross section (Fig. 2).

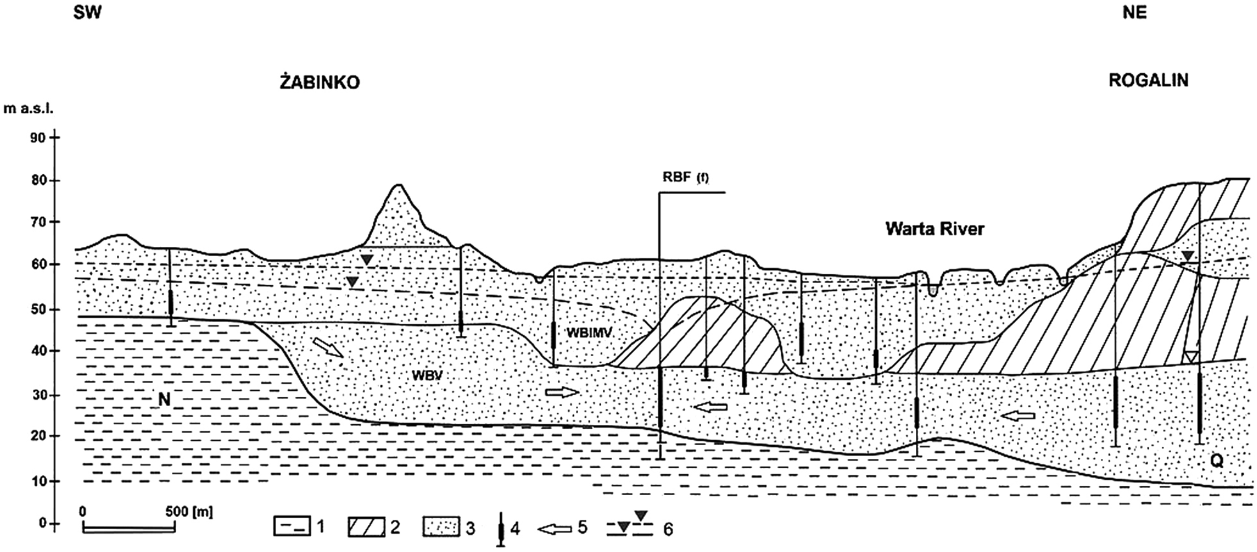

Fig. 2. Hydrogeological cross section I–I′ (line of cross section shown in Fig. 1): 1 – clays; 2 – glacial tills; 3 – sands and gravels; 4 – well screen location; 5 – main groundwater flow directions; 6 – water level (static and dynamic); RBF – Riverbank filtration; MBIMV – Warszawa–Berlin Ice Marginal Valley; WBV – Wielkopolska Buried Valley; Q – Quaternary; N – Neogene (modified after Przybyłek et al., 2017).

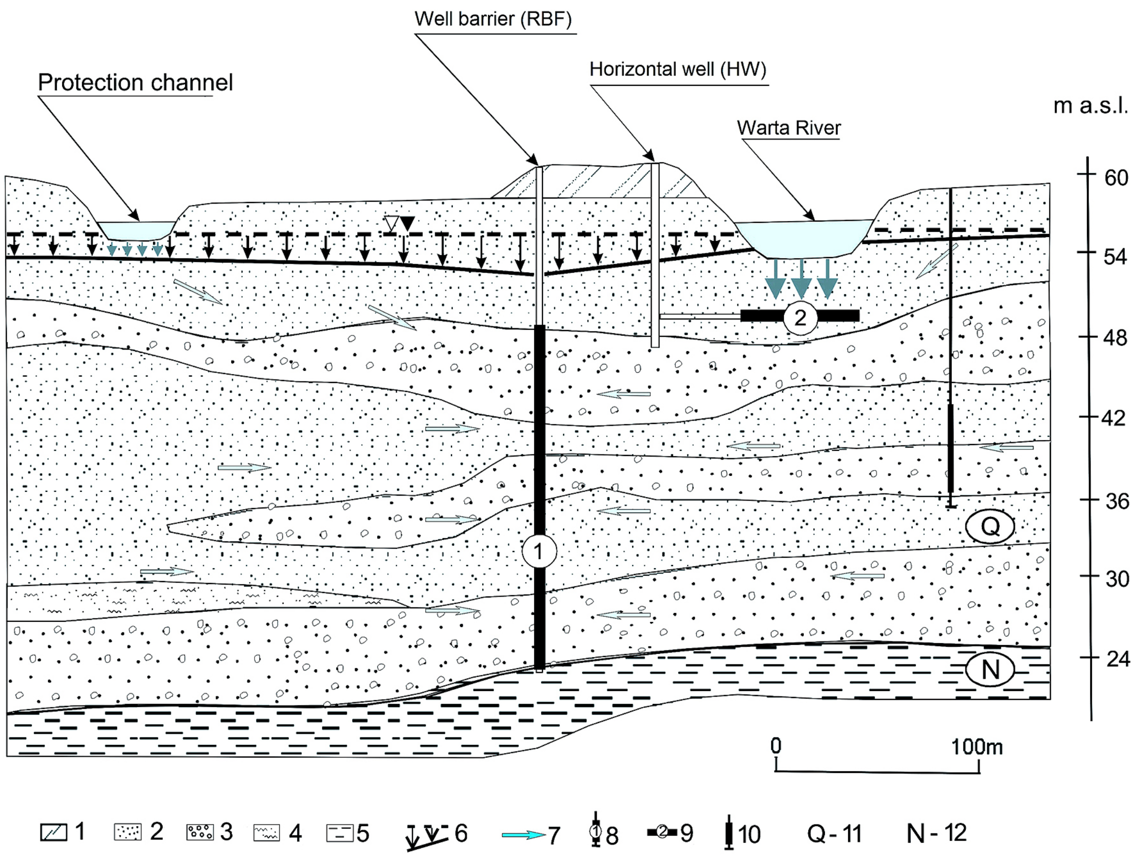

Fig. 3. Scheme presenting location of horizontal well drains (HW) and positions of RBF wells: 1 – embankment; 2 – sands; 3 – gravels; 4 – silts; 5 – clays; 6 – static and dynamic water level; 7 – groundwater flow directions; 8 – position of RBF well screen; 9 – position of HW drains; 10 – other observation wells; 11 – Quaternary; 12 – Neogene (modified after Przybyłek et al., 2017).

Table 1. Characterisation of the Krajkowo well field.

Investigated points	Morphology	Distance from the river bank (m)	Depth of the well screen (m)	Contribution of river water in total water balance in well (%)	Residence time
Warta River	–	–	–	–	–
Horizontal well (HW)	Drains under river bottom	0	5 m below river bottom	100	a few hours
Observation well no. 86b/2	Flood plain	30	6.0–10.0	100	a few weeks
Vertical wells (RBF)	Flood plain	60–80	15.8–35.8	65–85	1–3 months
Observation well no. 78b/s	Higher terrace	250	18.0–28.0	60	6 months

As part of the investigation, two piezometers were also included: one located between the channel of the River Warta and the wells gallery, close (30 m) to the river channel, and the other located at a greater distance (250 m) from that (Fig. 1). This piezometer also received water from bank filtration during exploitation of the wells located on the higher terrace (Górski & Przybyłek, 2005; Górski, 2011).

The water quality investigation was conducted during a 2-year period between October 1996 and June 1998, with sampling performed every three months. The research included:

- Physico-chemical analyses of temperature, colour, pH, NH_4, NO_2, NO_3, Fe, Mn, Cl, SO_4, total hardness, COD_{Mn}, COD_{Cr}, alkalinity, O_2, BOD_5, TOC, PO_4, Na, K, Mg, Ca, N_{org}, H_2S, dry residue phenols, detergents, Pb, Zn, Cd, Cr, and Ni and, in selected analyses, dichloromethane, chloroform, 1,2-dichloroethane, carbon tetrachloride, trichloroethylene, 1,2-trichloroethane, tetrachloroethylene, hexachlorobenzene, lindan, heptachlor and its epoxide, DDT, etaxichlor, pentachlorophenol, PAH, aromatic and aliphatic hydrocarbons.
- Microbiological analyses of the range of coliform bacteria and amount of bacterial cultures at temperatures of 37 °C and 20 °C.
- Hydrobiological analyses of plankton.

The analytical measurements were performed by the laboratory of the Department of Water Treatment Technology, Faculty of Chemistry, Adam Mickiewicz University in Poznań.

4. Results and discussion

The results show a strict dependence between water quality in the River Warta and in the HW, as well as in observation well no. 86b/2 (Table 2).

The contamination level, in case of nitrate compounds, detergents, bacteriological contamination and plankton occurrence in HW, is similar to water from the River Warta. Periodically, specific micropollutants were also detected (Table 3). A significant

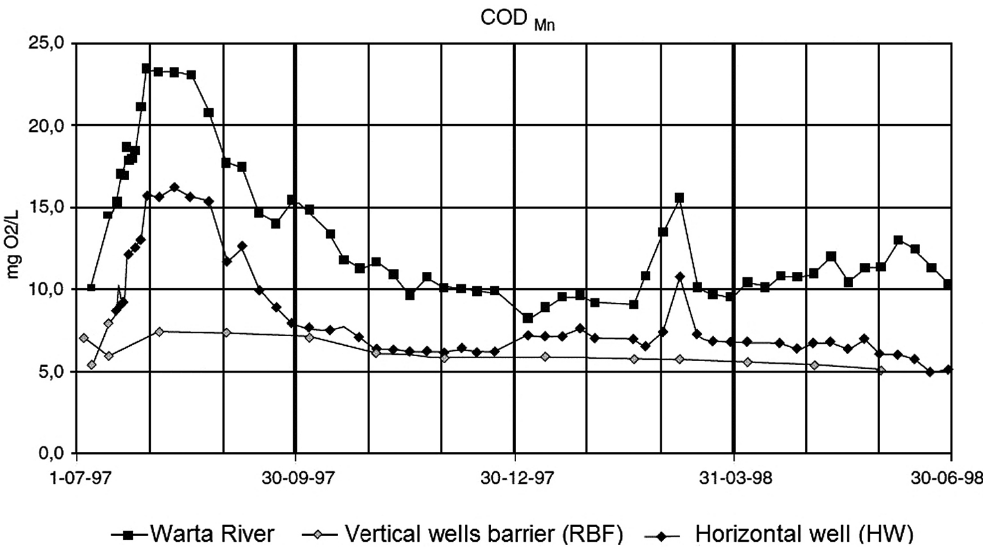

Fig. 4. Temporary changes of COD during and after the flood in July 1997.

Table 2. Changes of water chemistry and content of micro-organisms during bank filtration (*n* = 8).

A

Investigated points	TOC		COD_{Mn}		COD_{Cr}	
	mg/L	% of decrease*	mgO_2/L	% of decrease*	mgO_2/L	% of decrease*
Warta River	14.25		10.4		22.7	
Horizontal well (HW)	10.58	25.7	6.2	40.4	14.9	34.4
Observation well no. 86b/2	13.03	8.6	6.1	41.3	23.4	103.1
Vertical wells (RBF)	11.07	22.3	5.5	47.1	20	11.9
Observation well no. 78b/s	7	50.9	4.7	54.8	15.3	32.6

* – decrease or increase of concentration in relations to the Warta River.

B

Investigated points	NO_3		NH_4		Total hardness		$Fe_{(tot)}$		Mn	
	mg/L	% of decrease*	mg/L	% of decrease*	mval/L	% of decrease*	mg/L	% of decrease*	mg/L	% of decrease*
Warta River	11.6		0.42		4.8		0.55		0.14	
Horizontal well (HW)	10.6	8.0	0.28	33.3	4.7	0.83	0.15	72.3	0.18	128.6
Observation well no. 86b/2	8.7	24.2	0.28	33.3	4.9	102.1	0.12	78.2	0.48	342.8
Vertical wells (RBF)	2.6	77.4	0.28	57.1	5.31	110.6	0.92	167.3	0.52	371.4
Observation well no. 78b/s	0.3	97.3	0.18	57,2	4.9	102.7	1.31	238.2	0.61	435.7

* – decrease or increase of concentration in relations to the Warta River

C

Investigated points	Detergents[3]			Coliform bacteria*			Plankton**
	mg/L max	% of decrease***	%[1]	max	% of decrease***	%[1]	
Warta River	0.3		61	700,000		100	very numerous
Horizontal well (HW)	0.15	50	17	1,670	99.7	52	a few
Observation well no. 86b/2	0.2	33.3	33	398	99.9	75	14
Vertical wells (RBF)	0.2	33.3	50	5	99.9	40	a few/to 64[2]
Observation well no. 78b/s	0.	100.0	0	0	100.0	0	a few[2]

[1] – % percentage of the analyses with detected contamination.
[2] – only after the flood.
[3] – anionics.
* – number of bacteria in 100 mL of water.
** – number of organisms in 1 mL of water.
*** – decrease or increase of concentration in relations to the Warta River.

influence of summer flooding on the water quality from the HW was observed. This was visible mainly in the temporal changes of COD, which indicate the presence of organic matter in the water. The clear peak after the summer flood in 1997 is visible on the graph in both the River Warta and HW (Fig. 4).

The correlation with the Warta River water quality is also seen in the case of the RBF wells, where periodical occurrence of bacteriological contamination and plankton, specific micropollutants, nitrate, organic matter (TOC and COD) and detergents are apparent (Tables 2 and 3). These wells are less sensitive to changes in surface water quality. The deterioration of water quality after the flood is also visible, but the temporal changes of COD are smaller than in the HW (Fig. 4). Water from observation well no. 78b/s shows no bacteriological contamination, a lower COD, a lack of detergents and a low concentration of nitrates. The water quality is similar to that of groundwater with no distinct influence of nitrates and micropollutants. However, remains of plankton were found.

Table 3. Specific micropollutant concentrations (*n* = 8).

Investigated points	Dichloromethane (µg/L)	Chloroform (µg/L)
Warta River	n.d.	n.d.
Horizontal well (HW)	n.d.	n.d.
Observation well no. 86b/2	n.d. – 9.71	n.d. – 1.22
Vertical wells (RBF)	n.d. – 11.67	n.d. – 0.67
Observation well no. 78b/s	n.d.	n.d.

n.d. – not detected.

Changes in groundwater chemistry collected in the HW and in observation well 86b/2 are controlled mainly by physical processes, such as mechanical retention of suspended material, colloids, bacteria and plankton. In addition, a disadvantage of water from the HW is the large variability in water temperature (between 0 and 25 °C). Water quality of the RBF is determined by the processes of mechanical suspension, colloids and plankton retention, as well as the influence of sorption, solution and red-ox processes. These processes contribute to the improvement of surface water quality, not only in the range of turbidity, organic matter and bacteria but also in ammonia and nitrates.

4.1. Advantages and limitations of different types of water withdrawal

The greatest advantage of the HW is the relatively large production of water. The maximum well yield is 15,000 m^3/d, comparable to the total yield of 10–15 vertical wells. Another positive feature is the good quality in terms of Fe and Mn. This is the reason for the specific location of HW on Krajkowska Island (simultaneous exploitation of both RBF and HW well-field components) because the HW is recharged almost exclusively from river water infiltration. This also explains the high efficiency and relative longevity of the well operation, with the well working without meaningful modernisation for almost 26 years (1991–2017).

The disadvantage of the HW is water quality. The water quality extracted from the HW is strictly dependent on the quality of the river water. The locations of horizontal drains 5 m below the bottom of the river (Fig. 3) determine a travel time that is too short for water quality treatments. This is the reason for periodic occurrence of poor water quality. This well is also sensitive to extreme weather conditions (flood and droughts). For this reason, high nitrate concentrations, specific micropollutants, bacterial contamination and plankton appear periodically. In fact, the HW was disconnected periodically because of poor water quality. The disadvantage of HW is the wide range in water temperature (between 0 and 25°C), which depends on that in the River Warta.

The advantage of vertical wells lies in their much better water quality. The distance of 60–80 m from the river channel ensures a travel time of 50–100 days (Przybyłek & Kasztelan, 2017), which is long enough for river water treatment. Thus, after infiltration and movement in the aquifer river water acquires features typical of groundwater. The variation in temperature in RBF wells is smaller than that in HW (between 5 and 15°C). The RBF wells are also less sensitive to extreme weather conditions and fluctuations in river water quality. However, in such wells, bacterial contamination and high nitrate concentrations appear periodically. The disadvantage of vertical wells is relatively short well longevity (no more than 10 years) due to clogging of well screens. This explains the mixing of surface water (rich in oxygen) with groundwater rich in Fe (2–3 mg/l) and Mn (0.2–0.3 mg/l).

5. Conclusions

A comparison of changes in water quality during riverbank/riverbed filtration in vertical wells located close to the riverbank and in HW with drains situated below the bottom of the river in the Krajkowo well field shows different efficiency of levels of treatment.

The investigations have demonstrated that HW, with drains located 5 m below the bottom of the river, does not ensure a good level of water treatment. The water quality is strictly dependent on surface water quality. The short travel distance of water causes periodical poor water quality, as a result of elevated concentrations of nitrate compounds and detergents as well as bacteriological contamination and occurrence of plankton. This type of well is also sensitive to extreme weather conditions (flood and droughts). However, the advantages of this type of well are the relatively large production of water (well yields of 15,000 m^3/d) and a relatively greater well longevity.

A higher level of water treatment is achieved with vertical wells located along riverbank. A distance of 60–80 m from the river channel ensures a travel time of between 50 and 100 days, which is long enough for river water treatment, and has water acquire features typical of groundwater. The RBF vertical wells are also less sensitive to extreme weather conditions and fluctuations in river water quality. However, in such wells, bacterial contamination and high nitrate concentrations appear periodically.

Water quality from a well situated at 250 m from the river channel shows a small influence in river water quality. Features of the water are similar to those of groundwater.

It has been found that in the study area, wells should be placed at a distance of 150–200 m from the river channel in order to obtain satisfactory water quality. Such distance assures residence time in aquifer of at least six months.

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