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Assessment of river water infiltration conditions based on both chloride mass-balance and hydrogeological setting: the Krajkowo riverbank filtration site (Poland)

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Abstract

In the present work measurements of chloride concentrations were used to assess the variability of infiltration conditions and contributions of surface water and local groundwater to the discharge of wells at Krajkowo riverbank filtration site (western Poland). Tests were performed on samples from 26 wells located in a well gallery close to the River Warta. Due to higher chloride concentrations in river water in comparison with local groundwater, significant differences in concentrations in samples from individual wells were noted. In particular, lower chloride concentrations in 11 wells were recorded, which can be linked to the local occurrence of low-permeability deposits in the superficial zone; a locally higher degree of riverbed sediment clogging in the highly convex meandering zone, where strong erosion of the riverbed occurred, which in turn led to increased clogging; the occurrence of a more intensive groundwater inflow into the river valley due to water infiltration from a smaller river entering the River Warta valley, as well as unfavourable conditions for the infiltration of surface water to the lower part of the aquifer with a greater thickness. Differences in chloride concentrations observed were also used to quantify approximately river water contribution to the well production. The average contribution of the River Warta to the recharge of the entire well gallery was estimated at 59.8%.

Key words: riverbank filtration, water balance, water travel time, natural tracers

1. Introduction

Wells located near rivers or lakes can be recharged from surface water as a result of induced bank filtration, as well as by local groundwater. The contribution of river water to the recharge of wells depends on many environmental and technical factors (Gollnitz, 2003; Grischek et al., 2003). Environmental factors can be divided into external (related to river hydrology) and internal factors (related to aquifers). Hydrological phenomena refer to factors that are variable in time, such as river flow rate and water level and hydrological conditions (droughts and floods). The type of riverbed sediment and geometry, as well as the process of clogging of riverbed sediments are also important (Przybyłek et al., 2017). Internal factors are related to the diversity of aquifers and, in particular, to their lithology and permeability. Technical factors concern the location of the well in relation to the riverbed and its construction (Umar et al., 2017). In addition to these factors, which are often highly variable in time and space, groundwater inflow variation to particular sections of the river under natural conditions may be important. This factor is especially relevant for river sections where the inflow of groundwater is increased by water infiltration from a smaller tributary river or stream. In such a case, it is more difficult to ensure a high contribution of river water to the supply of the wells.

Approximate assessments of the bank filtrate proportion in productive wells can be made on the basis of mathematical modelling, balance methods using natural chemical tracers, usually chloride (Trettin et al., 1999; Ghodeif et al., 2016), or on the isotopic composition of the water. The isotope method is most often used to differentiate hydrogen and oxygen isotopes in river water and local groundwater (Maloszewski et al., 2002; Forizs et al., 2005; Clark, 2015).

The present paper discusses the impact of various factors on riverbank filtration (RBF) conditions on the basis of results of hydrochemical testing of 26 wells in the well gallery located at Krajkowo, which supply water to the city of Poznań (Poland). We attempted also to quantify the contribution of river water to the total water balance based on the differentiation of chloride concentrations in river water, local groundwater and water pumped from wells.

2. Site description

The Krajkowo riverbank filtration site is situated 20 km south of Poznań (Fig. 1) in the Warsaw-Berlin ice-marginal valley on the left bank of the River Warta. The well gallery comprises 29 wells located on the floodplain of that river (RBF (c)) (Figs. 1, 2). The protection of the wells against flooding ensures their location on the flood embankments. The distance from the wells to the river is mainly 60–80 m. Operation of the wells was started at the turn of the years 1982/1983. In 1992, a horizontal well (HW) with drains located 5 m below the river bottom was constructed (Górski et al., 2018). Southwest of the RBF (c) gallery, at a distance of 700 m, there are wells on the upper terrace of the valley of the River Warta (RBF (f)).

The Krajkowo riverbank filtration site is located in the zone of water-bearing sediments with a thickness of approximately 40 m (Fig. 3). This complex consists of fluvioglacial and fluvial strata of the Warsaw-Berlin ice-marginal valley (WB). The lower part of the aquifer is associated with the Wielkopolska Buried Valley (WBV). In the upper part of the WB, alluvial fine- and medium-grained sands occur; their thickness attains several metres. Within these sands, there are local accumulations of mud and peat (Fig. 3). Below, a series of fluvioglacial sediments (sand with gravel and pebbles) is found.

The lower sedimentary buried valley series (WBV) is thinner, and its upper layer consists of fine- and medium-grained sands and local deposits of mud and clay. Below a few metres, fluvioglacial sediments occur; these usually are coarse sands and gravels. At the bottom of the aquifer, Neogene clays occur (Dragon et al., 2019; Kruć et al., 2019).

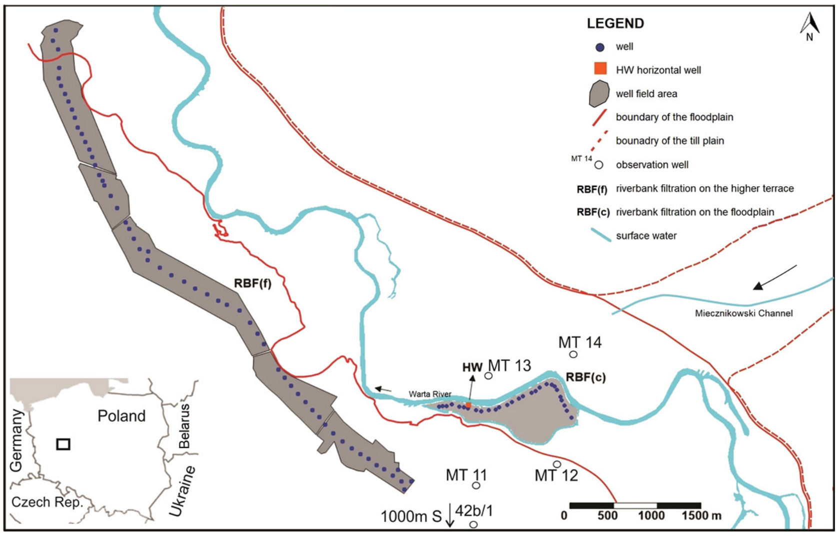

Fig. 1. Map of the Krajkowo well field (Poznań area, western Poland).

The conditions of the infiltration of river water are determined by the series of Holocene sands at the surface, which are a few metres thick. Within these deposits, a buried oxbow lake was documented; this consists of mud and peat (Fig. 3). Such local sediments (e.g., in the area of wells no. 13 L, 14 L and 15 L; see Fig. 3) occur directly below the riverbed, which is, on average, situated at an elevation of 54.8 m a.s.l. In this situation, the infiltration of river water is impeded. The upper edges of the well screens are located at depths of 12–16 m b.g.l. The hydraulic conductivity determined from the wells pumping tests varies widely between 19.0 and 249 m/d (average 84 m/d).

Water travel time from the river to the wells was estimated based on temperature measurements. This research showed that in summer the water travel time passing the aquifer oscillates within 1–1.5 months, while during the winter it is approximately 3 months (Przybyłek & Kasztelan, 2017).

3. Material and methods

We here use the results of a hydrochemical sampling of all 26 productive wells which was done between June 29 and July 4, 2005. Water analyses were performed by Aquanet S.A., the administrator of the

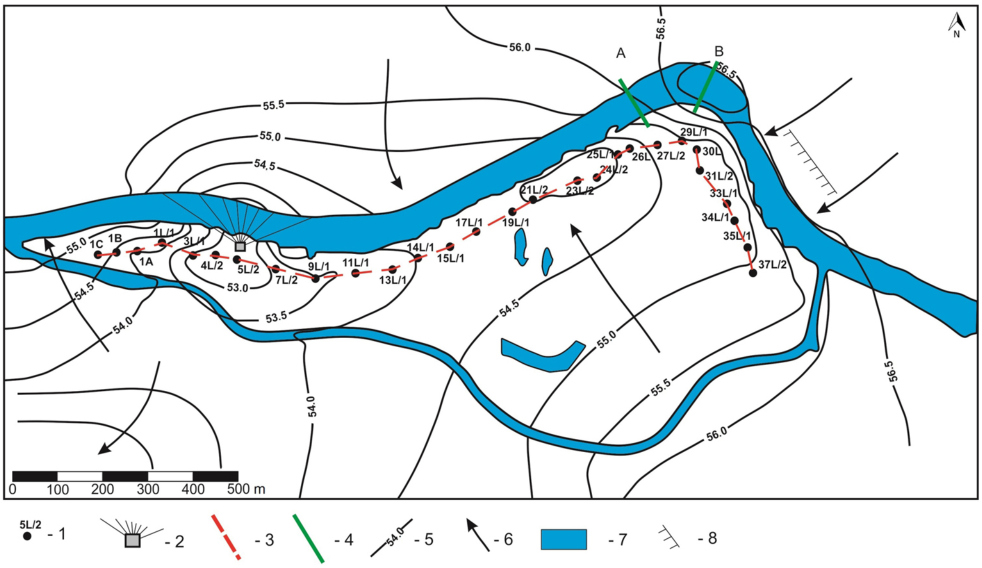

Fig. 2. Piezometric countour map of Krajkowo Island and surroundings; 1 – well; 2 – horizontal well; 3 – line of hydrogeological cross section (see Fig. 3); 4 – cross-section of the Warta riverbed (see Fig. 6); 5 – piezometric countours according to a mathematical model (Kostecki, 1998); 6 – groundwater flow directions; 7 – surface water; 8 – zone of enhanced groundwater flow to well gallery.

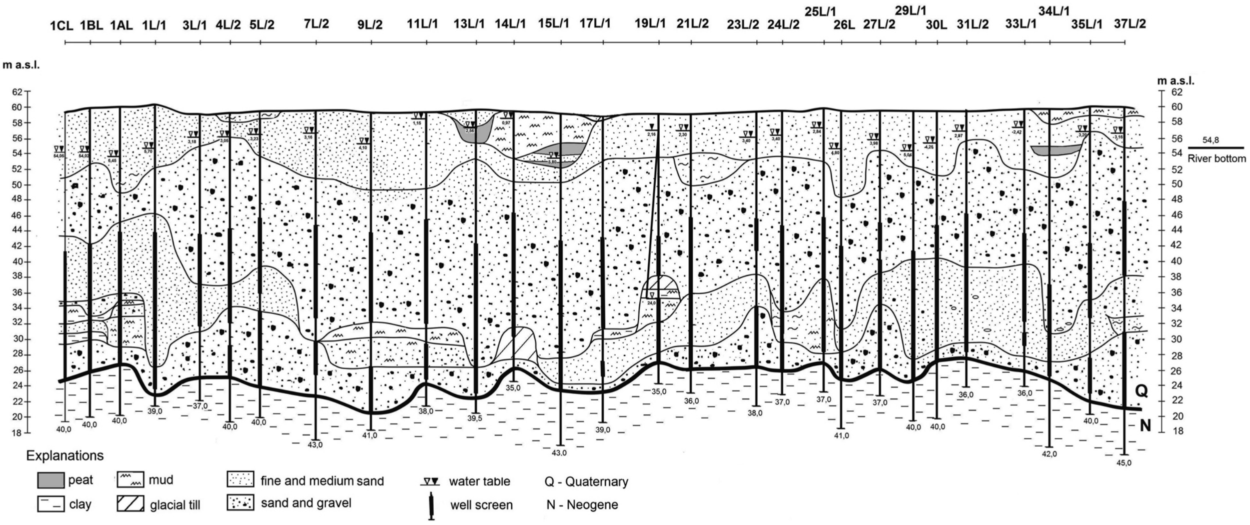

Fig. 3. Hydrogeological cross section.

waterworks. Sampling of the water from the wells was performed directly from the tap attached to the well head. Besides, the results of chloride analyses of water from the River Warta and groundwater sampled from observation wells of the local monitoring net were used. This research was also carried out by Aquanet S.A. The water analyses were conducted using ion chromatography (DX-120, Dionex, USA and Metrohm 881 Compact IC Pro, Switzerland).

In order to determine the percentage share of river water and groundwater using chloride concentrations as an conservative contaminant, the formula for the mixing of water with two different concentrations was applied (Clark, 2015):

$$\% \text{ of river water} = \frac{C_s - C_s}{C_{sw} - C_g} \times 100\%$$

where:

- C_s – concentration of chlorides in well water [mg/l];
- C_{sw} – concentration of chlorides in river water [mg/l];
- C_g – concentration of chlorides in groundwater [mg/l].

4. Results

4.1. Assessment of infiltration conditions

Infiltration conditions were assessed on the basis of variations in chloride concentrations in the water from individual wells (Fig. 4). Previous research had revealed that the average chloride concentrations in the vicinity of the well gallery were higher in river water than in groundwater. An investigation of chloride concentrations in the river prior to well testing showed a high variability in the range of 33–61 mg/l, but we should take into consideration chloride data from before the start of April, when chloride concentration was higher in the river than in wells (Fig. 5). According to these data, the infiltration of river water into the aquifer had to have occurred before the beginning of April. In April–June, the chloride concentration was relatively stable, on average approximately 35 mg/l, and did not exceed 40 mg/l, while in the majority of the wells the concentration was 44–46 mg/l. Unfortunately, in March there was a high variability of concentrations. Only three chloride measurements in this period were available (March 5 – 55.0 mg/l; March 14 – 51.7 mg/l; March 20 – 46.0 mg/l). With regard to chloride concentrations in the wells, it was assumed that the March 14 concentrations (51.7 mg/l) should be taken into account, which would give a travel time of 105 days. Such a time of water flow at winter temperatures is realistic, taking into account the data from temperature observations (Przybyłek and Kasztelan, 2017). The concentration of chlorides in local groundwater was assessed on the basis of sampling performed in a network of observation wells (MT11, MT12, MT13, MT14 and 42G) located around the well gallery (Fig. 1). In 2005 and 2006, the average chloride concentration in groundwater was 23.7 mg/l. Data from wells on RBF(f) gallery where out of contamination sources, chloride concentrations were in the range of 20–25 mg/l, confirm this value. Despite the rough approximation of chloride concentrations in the river and groundwater, the data reveal the variability of river water infiltration conditions.

The lowest value measured in the river was 33 mg/l. Changes in chloride concentrations in wells (Fig. 4) show that in 15 of these, concentrations are in a narrow range of 43.8–46.6 mg/l. However, lower concentrations were found in 11 wells; this is likely due to higher contribution of groundwater in total water balance.

Reductions in concentrations to 32–35 mg/l were noted in wells 13 L, 14 L and 15 L, which can be linked to the presence of a buried ox-bow lake that is filled with poorly permeable sediments at the

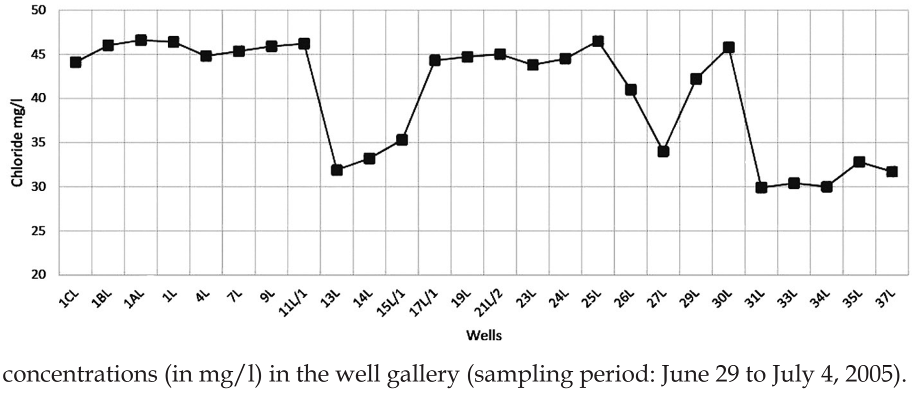

Fig. 4. Chloride concentrations (in mg/l) in the well gallery (sampling period: June 29 to July 4, 2005).

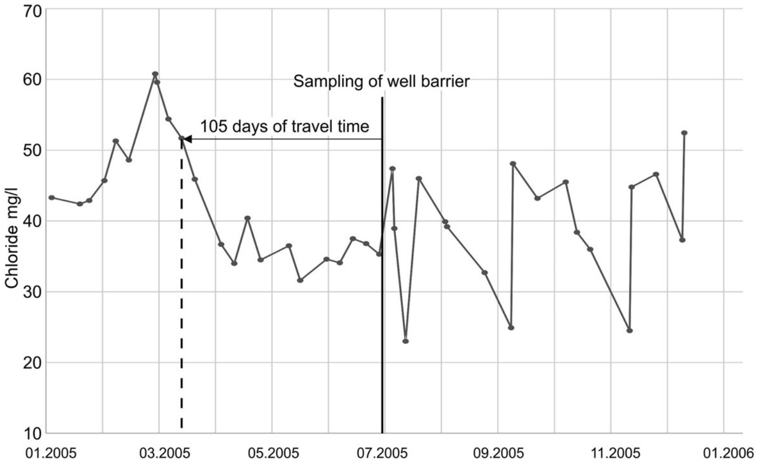

Fig. 5. Chloride concentrations in the River Warta in 2005.

bottom of the riverbed (Fig. 3). Lower chloride values were also found in wells 27 L, 26 L and 29 L, as well as in 31–37 L.

In the case of wells 26 L, 27 L and 29 L, the lower contribution of river water is likely influenced by the location of these wells in a strong river bend. Under natural conditions, highly favourable conditions occurred for groundwater contact with the river at the convex eroded right bank. However, in the nineteenth century, concrete blocks were emplaced in order to reduce the lateral erosion in the curves of meanders. Under these conditions, deep erosion of the riverbed developed to an elevation of approximately 51 m a.s.l., some 4 metres deeper than the average elevation of the bottom of the river (Fig. 6). As a result of the deep erosion of the riverbed, fine-grained sand and, subsequently, gravel sand grains were removed.

In this way, the river came into contact with coarse-grained sediments (Fig. 3). Therefore, in the first period of well operation within the meandering zone, conditions for river water infiltration were favourable. This is the characteristic influence of river geometry on riverbank filtration facilities (Umar et al., 2017). Simultaneously, the operation of the well created favourable conditions for the penetration of suspended matter into the aquifer and the development of deep clogging of the riverbed and aquifer sediments below the riverbed (Przybyłek et al., 2017). As a result, contact with the river in the meandering zone is currently hampered, which leads to increased groundwater contribution to well recharge. However, it is likely that the lower values of chloride concentrations in the wells from 31L to 37L can be attributed mainly to the favourable conditions of natural groundwater inflow to this part of the valley of the River Warta. This section of the river is situated perpendicular to the main groundwater flow, formed by inflow from the Miecznikowski Channel, which recharges groundwater in this valley. This situation is illustrated in Figure 2, which presents a groundwater piezometric level contour map. This map was obtained as a result of the mathematical modelling of groundwater and reflected the well field's state of operation in 1992 (Kostecki, 1998). This year saw a hydrological state

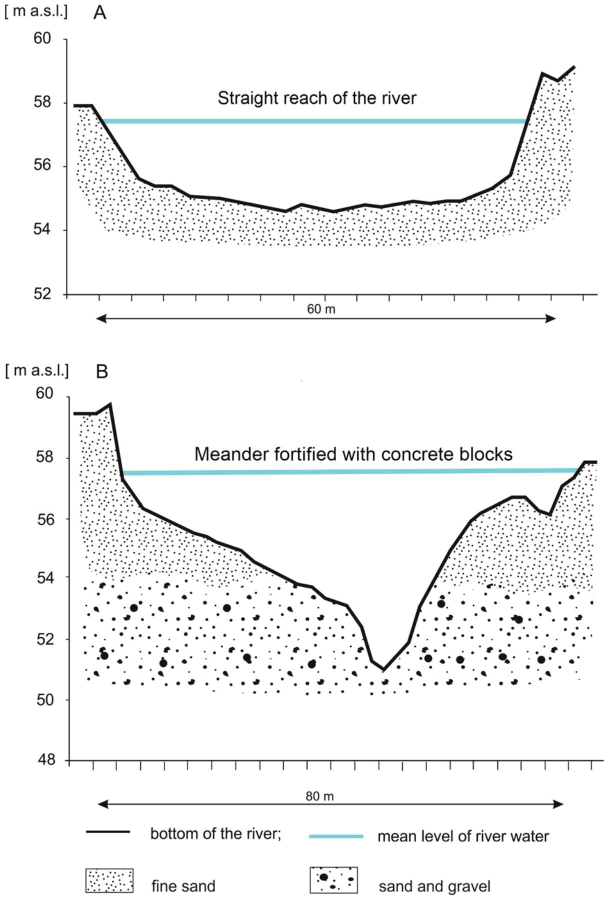

Fig. 6. Cross section of the riverbed near Krajkowo Island (see Fig. 2 for location).

that was comparable to that in 2005 (hydrological long-term drought; see Górski et al., 2019). The increased contributions of groundwater to wells 35 L and 37 L may also be due to the greater thickness of the aquifer, with the lower layer partially isolated by a series of poorly permeable, fine-grained sands and silty sands (Fig. 3).

4.2. Assessment of contributions of river water and groundwater to the recharge balance of wells

Data on chloride concentrations in river water, local groundwater and water pumped from wells allow an evaluation of the balance of supply of each well. Based on data discussed above, we assume that chloride concentration in river water was 51.7 mg/l (i.e., during the period when river water infiltrated to the aquifer) and that in groundwater was 23.7 mg/l. The water balance calculation data are presented in Table 1. The average portion of river water in wells is 59.8%. The highest participation of river water in the total water balance is observed in wells where the highest chloride concentration was noted (e.g., well 1AL – 85.3%). These wells are recharged by local groundwater to a lesser extent (19.3% on average), while the lowest river water contribution is observed in wells that are characterised by the lowest chloride concentrations (e.g., well 31L – 22%). These wells are recharged by local groundwater more intensively (63.8% on average).

An assessment of the contribution of river water to the total water balance was also performed based on mathematical modelling studies (Kostecki, 1998). These data reflect the situation in 1992, when the contribution of riverbank filtrate water was about 75%.

5. Conclusions

An assessment of infiltration conditions and the contribution of river water to the recharge of the Krajkowo riverbank filtration site was performed on the basis of the chloride mass balance (chloride concentration in river water, local groundwater and water pumped from wells). There was a significant difference in chloride concentrations in each well of the well gallery, indicating varying proportions of river water and groundwater in their recharge.

It was concluded from the hydrogeological setting and a graphical interpretation that less favourable conditions of river water infiltration are related to the local occurrence of a buried oxbow lake that is filled with poorly permeable deposits. Less favourable conditions of infiltration were also found in wells located at the inner curvature of a strongly convex meander, where concrete blocks were constructed so as to prevent lateral erosion. This change resulted in the development of deep erosion of the riverbed, followed by intensified development of clogging in this part of the River Warta. In addition, smaller proportions of surface waters occur where under natural conditions the inflow of groundwater was favourable to the part of the river valley. In this part, water infiltration from the smaller river proceeds into the valley area of the River Warta.

Based on chloride concentrations in surface water, groundwater and the water pumped from each well, the contribution of surface water was determined to be 59.8% on average, and the variation of this value in individual wells was estimated to be between 22.0 and 82%. It should be noted that these data were obtained during a period of relatively low flow, in connection with a long-term drought between 2003 and 2006. The calculations of the share of river waters in the wells supply are undoubtedly subject to certain errors that result from the high variability of chloride concentrations in the river and difficulties in determining the concentrations in local groundwater. However, the results obtained allowed for a proper identification of the factors that influence the variability of infiltration conditions.

In short, these results underline the suitability of the method used for assessment of important factors that influence surface water infiltration, which should be considered when designing riverbank fil-

Table 1. Balance of well recharge based on chloride concentrations.

	Concentration of chloride [mg/l]	Portion of river water [%]	Portion of groundwater [%]
The entire well gallery – mixed water from 26 wells	40.5	59.8	40.2
The highest chloride concentration (well 1AL)	46.6	85.3	14.7
The lowest chloride concentration (well 31 L)	29.9	22.0	78.0
15 wells with high chloride concentration	45.3	80.7	19.3
11 wells with lower chloride concentration	33.8	36.2	63.8

tration sites. Surface water infiltration rate is also an important factor to be reckoned with in investigations of contaminant removal during riverbank filtration.

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