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Natural attenuation potential of the urban hyporheic zone: field experiment set-up, baseline monitoring and modeling for extraction test design

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Abstract

In order to investigate the natural attenuation potential in the hyporheic zone, a study of the relationship between the hydraulic conditions and the chemical reactions within the hyporheic zone is being undertaken. To understand the process interactions, the groundwater-surface water flow exchanges within the hyporheic zone will be controlled by careful groundwater extraction from the aquifer beneath the river. A field experimental site has now been established on the River Tame – Birmingham aquifer system, in an urban environment regionally contaminated by VOCs and heavy metals. The site comprises a single bank-side extraction well (now operational) that will be used for a long-term pumping test, during which hydraulic and chemical conditions within the hyporheic zone will be carefully monitored. A dense riverbed monitoring network comprising multilevel sampling points and piezometers for head measurements within the riverbed has been established along the adjacent 200 m long reach. A major water quality sampling round has recently been undertaken with analytical data pending, and preliminary data show a *c*.15 cm thick surface water-groundwater mixing zone with some evidence of locally deeper mixing zones with greater temporal variability. Spatial variability in hydraulic heads and hydraulic conductivities is also evident. An optimum extraction rate between 100 and 150 m^3/d is suggested from preliminary simulations investigating the sensitivity of hydraulic gradient to various hydraulic conductivities and extraction rates. The long-term extraction test is expected to begin in early 2008. By inducing a decrease in hydraulic gradients, it will increase the residence time within the hyporheic zone and may therefore enhance the attenuation potential.

Keywords: Groundwater – surface-water interactions, urban, water quality, forced gradient field test

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1 Introduction

The hyporheic zone, defined herein as the zone of active groundwater - surface-water exchanges (Rouch *et al.*, 1997), presents great opportunities for management of urban water problems, and equally great challenges due to its complexity. Biogeochemical processes may be prominent within the uppermost tens of centimeters of the riverbed sediments and may have a profound effect on chemical water quality (Sophocleous, 2002) as they may actively contribute to the degradation of contaminants present (Fraser *et al.*, 1996; Conant *et al.*, 2004; Ellis and Rivett, 2007). Such natural attenuation (NA) processes may mitigate the impact of urban groundwater contaminant plumes. Our objective is to better understand how hydrodynamic conditions, both natural and engineered, influence the microbial and chemical activity present in the hyporheic zone and how the NA properties of that zone may be better engineered as an urban water quality management tool.

The City of Birmingham (UK) has a long industrial heritage and as such significant potential to impact both surface water quality, for example of the River Tame that drains the greater West Midlands conurbation, and the underlying Birmingham Triassic Sandstone. Previous work has shown that both are sporadically contaminated to some degree by for example volatile organic compounds (VOCs) and heavy metals (Shepherd *et al.*, 2006) with baseflow of contaminated groundwaters causing some impact on surface water quality (Ellis *et al.*, 2007). The field experiment site described herein is located on the River Tame – Birmingham system. The field site comprises a specifically installed bankside extraction well located immediately adjacent to a riverbed monitoring network. The extraction well allows controlled perturbation of the riverbed hyporheic zone and hence examination of that zone's NA properties at the fieldscale under dynamic, but known, conditions.

In this paper, we overview the chemical and physical conditions observed at the River Tame (Birmingham, UK) field site (analytical data are pending), preliminary hydrogeological modeling results examining the hydrodynamic response to various extraction conditions and outline the field experiment design of the upcoming extraction tests.

2 Field experiment design

The field experiment set-up is shown schematically in Figure 1 (note monitoring equally extends downstream). Central to the experiment is the 16.5 m deep extraction well set back 5 m from the river bank. The well is screened over 10.5 – 16.5 m depth within the Triassic Sandstone immediately underlying 9 m of mixed superficial deposits. The River Tame is about 1 m deep with the river level around 2 m below the ground elevation of the extraction well. The well has been fitted with a mains-powered submersible pump with an associated discharge point remote downstream. The extraction well is undergoing licensing via the regulatory authorities.

A riverbed hyporheic zone monitoring network has been installed over 200 m of adjacent river reach extending equally up and downstream. It comprises an array of 22 novel hybrid multilevel sampler (MLS) - piezometer drivepoint devices that have a 1 cm diameter central piezometer tube for recording hydraulic head surrounded by up to 10 multilevel Teflon® sampling tubes (3.2 mm OD, 1.6 mm ID) used for sampling water quality. The latter are located at 10 cm depth intervals below the riverbed. The MLS-piezometer drivepoints are distributed in eight transects containing two or three devices in each transect. Eight bespoke devices for automatic head measurements on 12 available points have been specifically developed for the study (and represent a monitoring tool advance), one Diver®

pressure transducer within the extraction well, and one other within the river permit a continuous temporal record of the hydraulic conditions.

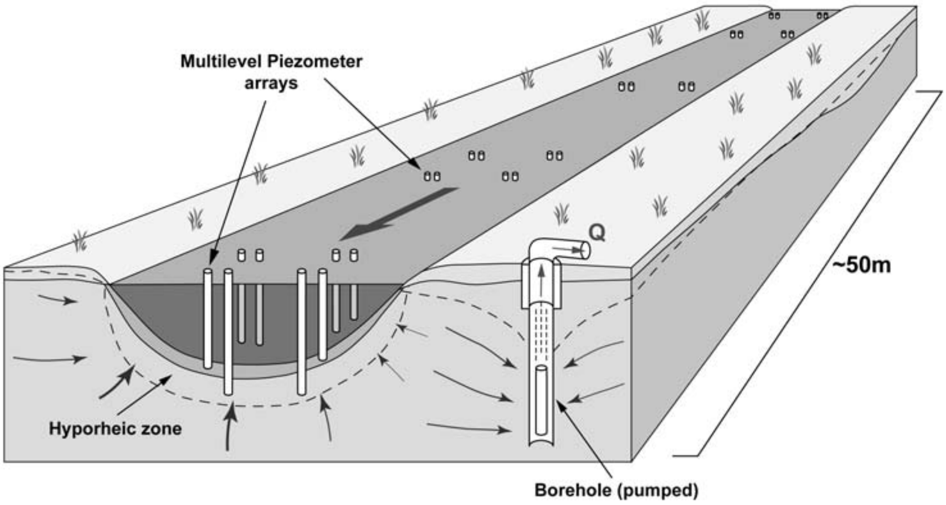

Figure 1. Schematic view of the experimental design

The programme of initial activity comprises: (i) an initial period of baseline riverbed network monitoring of chemical and hydraulic conditions pre-extraction test (currently on-going); (ii) the determination of bulk aquifer properties and hydrodynamic response via a short-term (<4 day) pumping test. These initial data, combined with our numerical modeling (see later) will be used to optimize long-term pumping rates to achieve the desired pattern of head declines in the riverbed for the main extraction field tests in 2008. These will last several months and will allow a controlled evaluation of dynamic flow and hydrochemical conditions under various hydraulic gradient conditions. The latter will permit flow rates and hence residence times within the hyporheic zone to vary, i.e. be perturbed thus allowing insight into the zone's dynamic natural attenuation capacity and associated controlling factors. The data will be quantitatively interpreted by numerical modeling. The early data are expected to lead to a refinement of the riverbed monitoring network and an optimized sampling strategy for the main tests.

3 Observed riverbed profiles under natural conditions

Detailed geochemical analytical data covering the entire riverbed network are pending and will be available shortly. These include sampling of 110 tubes on 22 MLS-points. Field measurements of pH, temperature and conductivity were made and lab analysis of major ions, metals and VOCs were undertaken. Previous data collected from Tame transects in the near vicinity are reported below to provide some initial chemical context.

3.1 Hydrochemical data

Profiles of chloride, sulphate, nitrate and dissolved oxygen are presented in Figure 2. The chloride profile shows high concentrations at the upper surface of the riverbed, *c.* 150 mg/l, corresponding to the river chloride concentrations, and lower concentrations at depth, *c.* 60 mg/l. The inverse is observed for sulphate, with the higher concentrations (300 mg/l) at depth declining to *c.*150 mg/L near the riverbed and is ascribed to the dilution of comparatively sulphate rich groundwater. The chloride profiles in particular imply that the mixing zone is thin (15-20 cm) and, in the shown profile, temporally stable over the summer. However, there are some nearby profiles where transient invasion has been observed for chloride and sulphate to >70 cm and ascribed to flood event related invasion of surface water to the riverbed and deeper mixing with the groundwater. The nitrate and dissolved oxygen (DO) profiles (Figure 2) indicate more complex behavior (on other profiles too, not shown), with temporal variations more obvious that may relate to possible consumptive reactions as electron acceptors within the riverbed of these more reactive solutes.

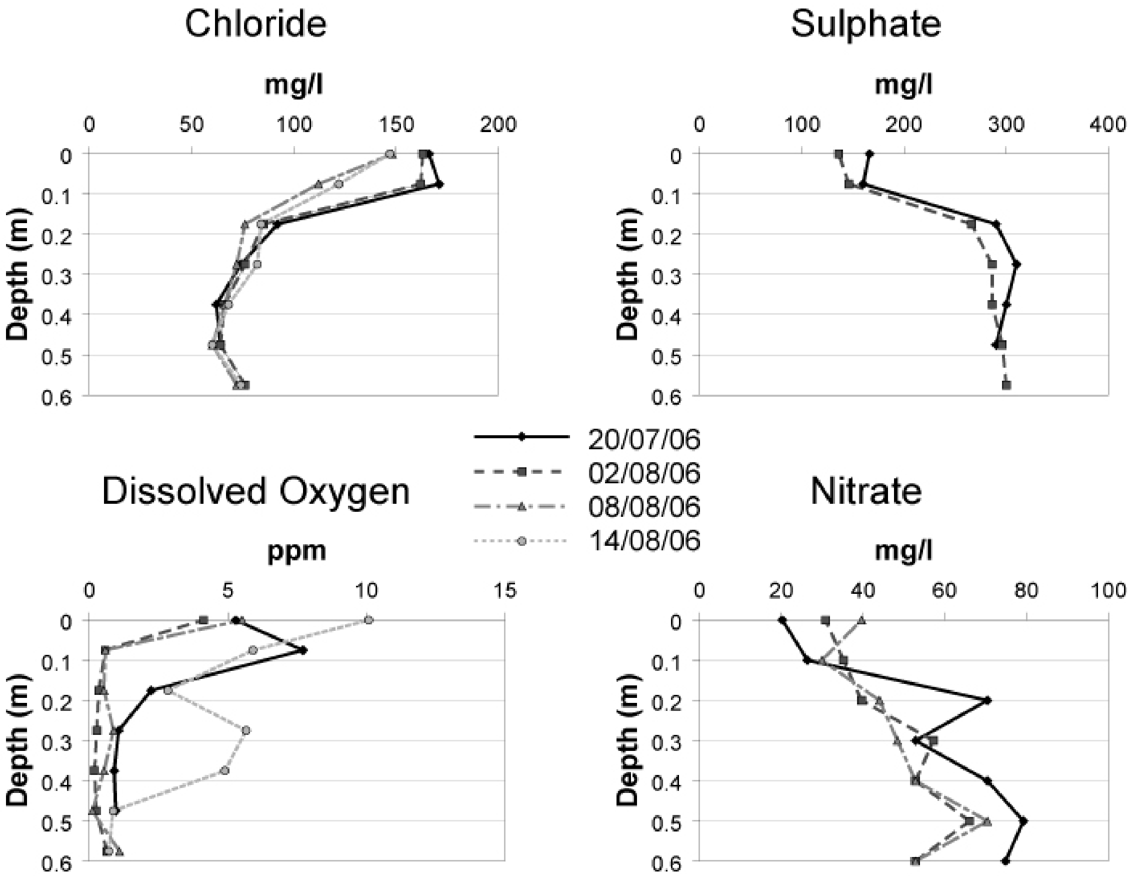

Figure 2. Chemical riverbed profiles obtained in the River Tame close to the field experiment reach

Electrical conductivity (EC) data from part of the recent sampling of the test experiment network (Figure 3) show cross-transect variation: the eastern MLS profiles (square symbols) are located closest to the extraction well on the east bankside and exhibit the highest EC with depth. Although there is some dilution with depth of these profiles from the elevated surface water (0 m) values, it is less than the mid-stream and western profiles that have profiles reminiscent of the chloride data of Figure 2. Those latter profiles appear to again support a limited thickness mixing zone of c. 15 cm. The profiles closer to the extraction well, however, either suggest greater surface water mixing to depth and relate to the geologic heterogeneity of the riverbed or hydraulic river conditions, and/or groundwater discharging from that bankside of slightly higher EC. Further data are required to understand this variability.

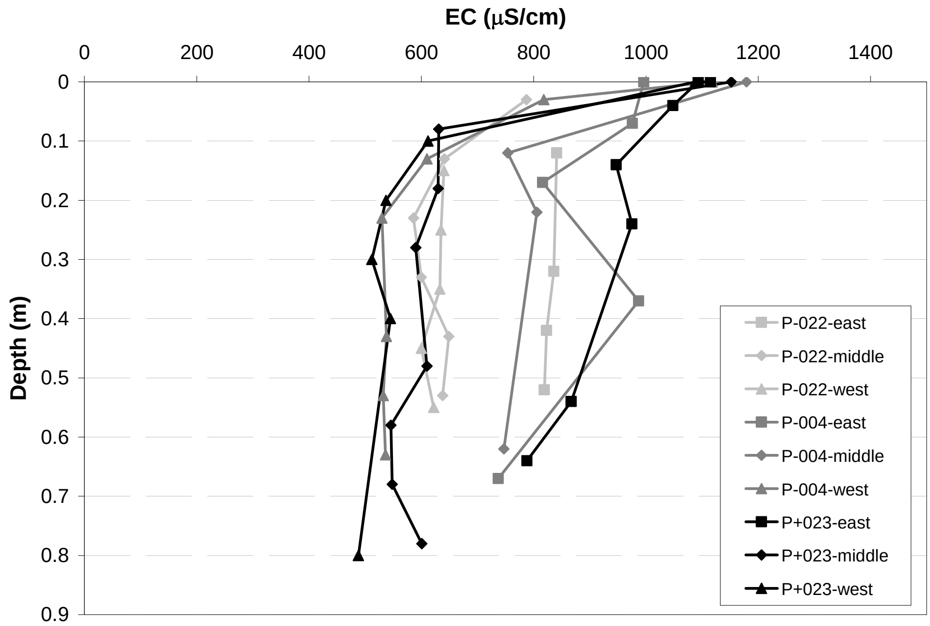

Figure 3. E-W trend recently observed in the conductivity profiles in the transects located 22 m and 4 m upstream and 23 m downstream from the extraction well located on the east bank

3.2 Hydraulic head data

The piezometers in the riverbed allow head measurements and hence indication of vertical flow exchanges between surface-water and groundwater. Figure 4 plots (left) groundwater – surface-water differential hydraulic head data with depth for a cross-river transect. The positive relationship between depth and differential head obtained confirm a water flux from the aquifer towards the river, i.e. a baseflow condition. The right plot in Figure 4 plots the hydraulic gradient with depth. The gradient decreases generally with depth. It can indicate either flow convergence at the river bed, or else longitudinal flow components along the river flow direction that cannot be resolved by the present piezometer network. The precise explanation at this stage is hence unknown but may be potentially clarified from the extract well tests.

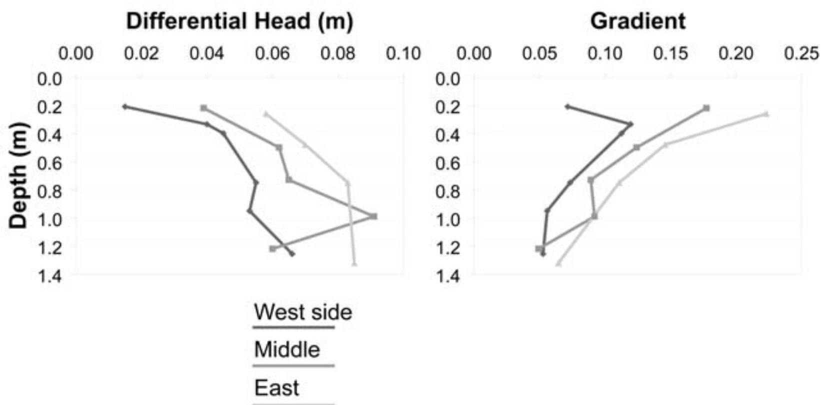

Figure 4. Hydraulic head data obtained from a cross-river transect

The above data are supplemented by recent data taken along the extraction well test reach (Figure 5). Slug tests on piezometers suggest moderate heterogeneity in hydraulic conductivities (Figure 5a) of the riverbed with K varying from 0.1 to 6 m/d. Hydraulic gradients (Figure 5b) are likewise spatially variable, ranging over -0.1 to 0.3. Together these data suggest that flow exchanges between the river and the hyporheic zone are both spatially and temporally complex. Some reverse flows (from the river to the aquifer) are observed towards the downstream, southern end of the monitored reach (Transect P+110).

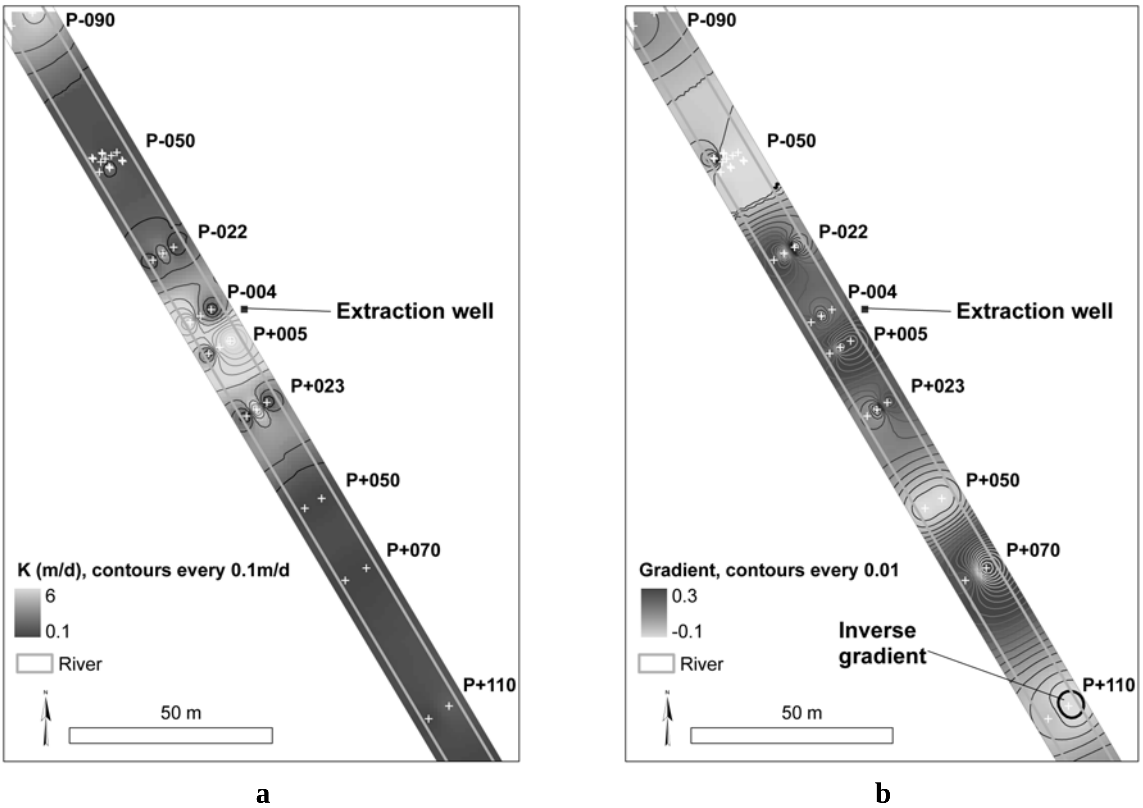

Figure 5. New hydrodynamic data obtained on various points.
a: Hydraulic conductivity data; b: gradient data

4 Preliminary flow simulations

In order to predict the influence of a long-term pumping test on the riverbed hydraulic gradients, a hydrogeological model was built. MODFLOW (Harbaugh and McDonald, 1996) was chosen for ease of use and because only approximate behavior of the water table was required for these scoping simulations. To capture the major vertical flow components during well extraction, a 58 layer model was constructed to cover a total effective depth of 100 m (approximate sandstone aquifer thickness). Three principal lithologic layers can be identified on this site: the riverbed, < 1m thick, the alluvial deposits, *c.* 10 m thick, and the underlying Triassic sandstone bedrock. Extraction is from the upper layers of the sandstone unit. Simulations allowed relationship and sensitivity to be established between extraction rate, aquifer properties (e.g., K) of the three units and drawdown or hydraulic gradient changes in the riverbed and river channel vicinity.

Three extraction rates were tested, 50, 100 and 150 m^3/d. For each one, different values of K were chosen for each of the three principal units corresponding to the range of values observed from other pumping tests in the region. Figure 6 shows some example results and indicates the various K values assumed. The calculated drawdowns are expressed in terms of modified hydraulic gradients from an assumed initial state in the riverbed, this being the average obtained in Figure 4. As the extraction reduces the contribution of groundwater flow from the aquifer to river baseflow, the simulated gradients during a pumping test all exhibit lower gradients than the reference initial state. The influence of the extraction is understandably greater as the discharge increases. At a discharge of 150 m^3/d, the gradient was predicted to reverse (below zero) causing river flow to the aquifer. The changes to the gradients were found to be very sensitive to the K values assumed for the different layers, especially in the riverbed, which illustrates the potentially important role of the highly heterogeneous properties of the river bed layer on the flow paths. Likewise the extraction rate that will cause flow reversal is sensitive to the assumptions on K, particularly of the riverbed value.

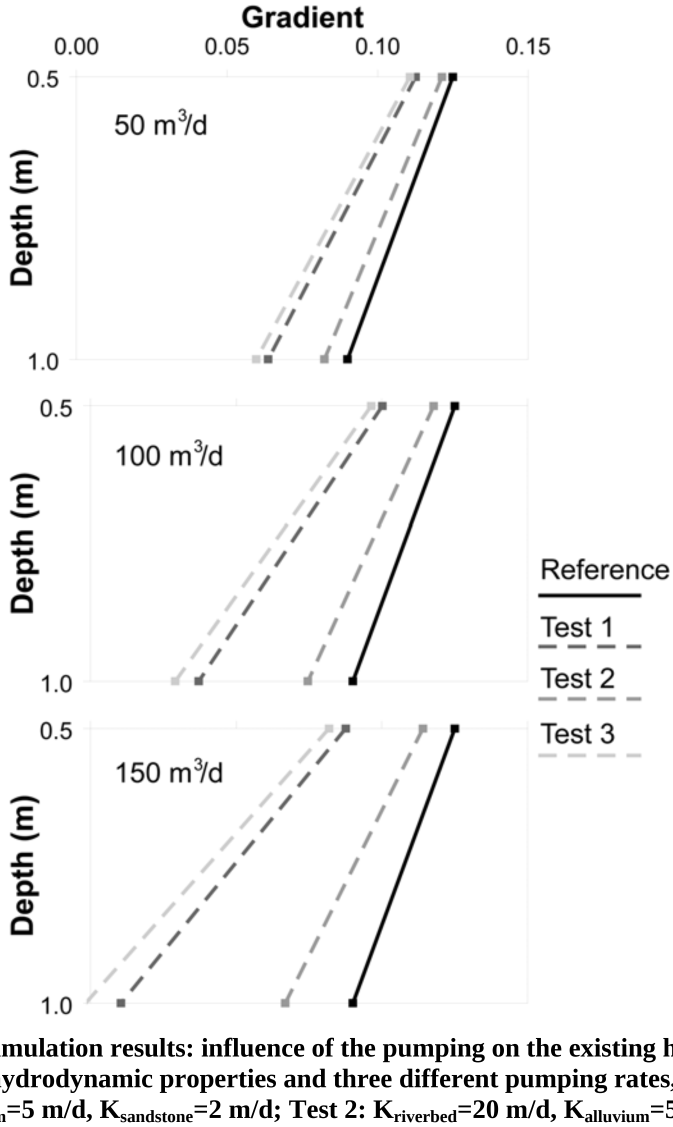

Figure 6. Preliminary simulation results: influence of the pumping on the existing hydraulic gradient with various hypotheses of hydrodynamic properties and three different pumping rates, 50, 100 and 150 m^3/d. Test 1: $K_{riverbed}$=$K_{alluvium}$=5 m/d, $K_{sandstone}$=2 m/d; Test 2: $K_{riverbed}$=20 m/d, $K_{alluvium}$=5 m/d, $K_{sandstone}$=2 m/d; Test 3: $K_{riverbed}$=$K_{alluvium}$=5 m/d, $K_{sandstone}$=1 m/d

5 Conclusions

The chosen field experiment site on the River Tame – Birmingham aquifer system has now been established. It comprises a single bankside extraction well which is now operational and going through the licensing process. Additionally, a riverbed monitoring network has been established along the adjacent 200 m long reach comprising 11 cross river transects with a total of 22 riverbed multilevel-points with 148 tubes available for water quality sampling and 33 piezometers for hydraulic head measurement that are supplemented by 12 transducer monitoring points using developed bespoke devices to provide a continuous temporal record. Early chemical data indicate a *c.*15 cm thick surface-water groundwater mixing zone with some evidence of locally deeper mixing zones with greater temporal variability. The recently completed sampling campaign of the entire array shows cross-transect variation of conductivity in the vicinity of the extraction well, possibly due to lithologic variation. This trend needs to be further analyzed using the pending analytical data. Measurements of hydraulic gradients and hydraulic conductivities in the piezometers highlight a significant spatial variability in hydraulic conditions within the reach. The preliminary simulations show a good sensitivity of gradients to hydraulic conductivities, and indicate that the optimum discharge rate may lie between 100 and 150 m^3/d, in order to obtain a clear influence of the extraction without risking a reversal of the exchange flows between the river and the aquifer in the area to be monitored during the long-term test. Extraction tests are anticipated to commence in early 2008. They will comprise a short-term pumping test (four days) to allow a better understanding of aquifer properties, which will lead to the choice of the final discharge rate for the long-term pumping test (several months). During the latter test, gradients from the aquifer to the river will be reduced, resulting in an increased residence time within the hyporheic zone. This will allow potentially greater opportunity for contaminant attenuation which will be monitored thanks to the established sampling network.

6 References

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