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Natural attenuation potential of the urban hyporheic zone: Foundational studies to the River Tame (Birmingham, UK) dipole field experiments

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Abstract
The urban hyporheic zone (riverbed) represents an important natural system for water self purification that may mitigate the impact of urban landuse-derived groundwater contaminant plumes on receiving water courses where baseflow is important. The attenuation capacity of the hyporheic zone is significant as microbiological and chemical activity may be high causing contaminant degradation or sorption. Our research (under 5.3 of SWITCH) proposes to use 'dipole' field experiments involving extraction and injection well pairs immediately adjacent to a river to perturb the natural groundwater – surface-water exchanges in a controlled manner. The transport of solutes/contaminants naturally present and injected tracers will be monitored through a series of field experiments to yield insight into the potential of the urban hyporheic zone to naturally attenuate water contamination. The field experiment site is to be located on an urbanised reach of the River Tame that receives groundwater baseflow from the sandstone aquifer underlying the City of Birmingham, UK. Field and modelling studies conducted on the River Tame – Birmingham aquifer system are reported that have evaluated controls on urban baseflow contaminant fluxes as well as more recent studies that have focused upon the sub-reach around the proposed dipole experiment site. These studies have examined the extent of the groundwater – surface water mixing zone observing chloride-rich surface water to decimetre depths into the riverbed as well as undertaking physical-hydrogeological chracterisation of the riverbed and numerical modelling to produce a first design of the dipole experiment set-up that is currently being iterated for implementation at the chosen field site.

Keywords: hyporheic zone, urban water, groundwater – surface water interactions, natural attenuation

1 Introduction

Rivers are hydraulically connected to groundwater in most landscapes. The River Tame, for example in north Birmingham is the natural groundwater discharge point for the sandstone aquifer underlying the city (Ellis and Rivett, *in press*). This hydraulic interchange may result in the transfer of both water and contaminants between the two systems. Urban contaminated land present in cities with a long

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industrial presence such as Birmingham may hence pose risks to surface waters already potentially stressed by poor quality run-off water, pipe discharges, storm-sewer overflows etc. The surface water-groundwater interface or 'hyporheic zone' (HZ) is the final geological zone through which groundwater discharges as baseflow into surface water. Dynamic solute exchange, active groundwater-surface-water mixing, steep geochemical gradients may occur within the 0.1-<2 m thick HZ. Hydraulic residence time in the HZ is generally much shorter (hours/days) than in the underlying aquifer. The HZ contaminant attenuation capacity may, however, be significant. Elevated organic carbon content, microbial activity and mixing of waters may cause enhanced contaminant attenuation via (bio)degradation and sorption and lead to mitigation of surface water impacts (Lorah et al., 2005). The EU Water Framework Directive requiring integrated management of groundwater and surface water bodies provides a strong regulatory driver for understanding such processes.

The urban HZ hence represents an important natural system for water self purification, i.e., 'Task 4' under the EC SWITCH (Sustainable Water (management) Improves Tomorrows' Cities' Health) programme. Our research (under 5.3 of SWITCH) proposes to use 'dipole' field experiments involving extraction and injection well pairs immediately adjacent to a river to perturb the natural groundwater – surface-water exchanges in a controlled manner. The transport of solutes/contaminants naturally present and injected tracers will be monitored through a series of field tests to yield insight into the potential of the urban hyporheic zone to naturally attenuate contamination and its engineered enhancement. The field experiment site is currently being developed on an urbanised reach of the River Tame in Birmingham and builds upon a long history of field-based research within the city. Study of solute/contaminant transport in the underlying Triassic sandstone aquifer has continued since at least the 1980s, including studies on rebounding groundwater levels (Knipe et al., 1993), inorganic geochemistry/contaminants (Jackson and Lloyd, 1983; Ford and Tellam, 1994), organic contaminants (Rivett et al., 1990a,b, 2005), recharge and contaminant flux (Thomas and Tellam, 2006) and integrated contaminated land and water assessment (Shepherd et al., 2006). Since around 2000, our research group has been studying the hyporheic zone for the Tame – Birmingham system. The aim of this paper is to briefly summarise the studies that are foundational to the proposed dipole experiment including: (i) studies conducted at the 'city-scale' covering the 7.4 km long unconfined aquifer reach (Ellis, 2003; Ellis et al., 2002, 2004; Ellis and Rivett, *in press*); (ii) modelling-based studies examining river-aquifer fluid exchange processes at various scales (Ellis et al., *in press*; Ellis, 2003); (iii) recent studies that have focused on the sub-reach local to the proposed dipole experiment site (Conran, 2006; Lydon, 2006); and, (iv) an outline of the dipole experiment concept and design (Conran, 2006).

2 Overview of hyporheic zone studies at the city scale

Ellis (2003) installed 100 riverbed piezometers in 19 river channel transects covering the groundwater-effluent 7 km reach of the Tame traversing the Birmingham unconfined sandstone aquifer (Fig. 1). The study is believed to be one of the first to assess the impact of urban groundwater on river-water quality at the city scale. Birmingham groundwater has long been recognised to contain chlorinated volatile organic compounds ($_{Cl}$VOCs) that are persistent due to the recalcitrance of such compounds and persistent DNAPL (dense nonaqueous-phase liquid) sources (Rivett et al., 1990, 2005). $_{Cl}$VOC-contaminated baseflow was widespread along the reach with trichloroethene (TCE) dominant displaying concentrations in riverbed piezometers around 0.1-100 μg/l with typical regulatory limits occasionally exceeded by an order of magnitude. Anaerobic biodegradation products such as cis-dichloroethene (cDCE) were widespread, however, for the most part, these may have not formed in the generally aerobic riverbed, rather in the more reducing parts of the aquifer and source areas up-gradient. The lack of anaerobic conditions was ascribed to insufficient accumulation of low-permeability, organic-carbon rich riverbed sediments in this medium-high energy river. On-going

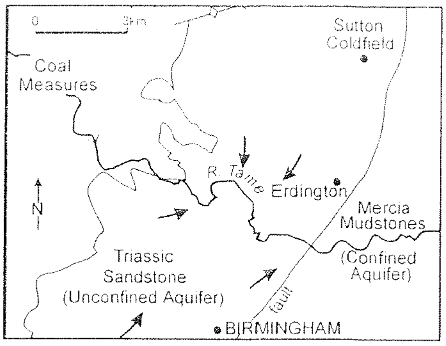

Figure 1: Birmingham aquifer – River Tame study area

local sub-reach studies have shown TCE biodegradation in some silty, organic carbon rich areas. Surface-water quality impacts were low with in-river TCE increasing by just 2 μg/l over the 7-km reach. The presence of non-chlorinated VOCs in the urban baseflow was limited and ascribed to their more ready attenuation (biodegradation) in the main aquifer. The presence of other organic contaminants in baseflows has not been evaluated and hence their fluxes remain unknown.

Inorganic/metal chemical quality of baseflow is influenced by both natural, i.e. rock dissolution, and anthropogenic processes. Data for a wide range of determinants are reported by Ellis (2003) with specific discussion of sulphate, calcium and nickel data within Ellis et al. (2004). Key contaminants detected in baseflow were copper, nickel, sulphate and nitrate, with some localized occurrence of aluminium, chloride and fluoride. Such occurrence data reasonably accord with either generally elevated or sporadic high concentrations detected in the aquifer and land contamination (Ford and Tellam, 1994; Shepherd et al., 2006). Baseflow concentrations were generally lower than might be expected for such an urban setting. For some determinants, for example chloride, the quality of baseflow was actually better than the surface water quality that has been classified as E/F (poor/bad) (1999 classification, Environment Agency). Such poor quality is due to a host of other urban pressures.

'First pass' baseflow contaminant/solute flux estimates at the urban city scale have been obtained; improved estimation methods and greater monitoring densities are still warranted. Agreement of flux estimates from five flow-concentration product methods was achieved to within an order of magnitude for TCE at 22-200 kg/yr of contaminant discharging to the 7-km reach (0.8–7.5 mg/d per m^2 of riverbed) (Ellis and Rivett, *in press*). Major ion baseflow mass fluxes to the Tame reach can be expected to be in the low 10^6 kg/yr range (Ellis et al., 2004); e.g., sulphate flux was estimated at 0.86 – 2.20 10^6 kg/yr that was only ~1% of an estimate of atmospheric fallout on the city aquifer. Minor ion/metal baseflow fluxes were lower, e.g., nickel was in the range 140-360 kg/yr, however, specific sub-reaches could dominate these fluxes suggesting significant local impacts were possible.

3 Modelling-based studies examining river-aquifer fluid exchange

Data from Ellis (2003) have been used to examine river - aquifer fluid exchanges via numerical modelling at various spatial and temporal scales (Ellis et al., *in subm.*). The goal was to quantify spatial and temporal flow distributions governing mixing processes at the river-aquifer interface affecting HZ attenuation (taking the HZ here to be defined as the zone of physical mixing of river and aquifer water). Modelling was conducted with FAT3D-UNSAT, a 3-D saturated-unsaturated flow and transport code (Mackay, 2004), and a momentum exchange code (Ellis et al., *in press*). To test the hypothesis that flow directions are variable with depth for the Tame, groundwater flows adjacent to the

3.8 km major meander (Fig. 1) were calibrated against field data to assess flows at the regional scale (Ellis et al., *in subm.*). The results illustrated that the shallow groundwater flow adjacent to the river is nearly orthogonal but the deeper groundwater flow entering the mid-section of the channel is almost parallel to the river at a key field transect studied. Interpretation of chemical distributions at depth along a transect orthogonal to the river may hence lead to false indications of remedial processes close to the river as the flows/plume are diverted downstream. Modelling also demonstrated accretion along the reach is highly variable and the proportion of flows from opposite river banks highly variable with significant underflows at depth below the river bed. Occasional local groundwater abstractions could also lead to local flow reversals, i.e., influent surface waters.

Urban rivers such as the Tame respond rapidly to rainfall events. Rapid rises in river water level can create opportunities for flow reversal, leading to enhanced HZ thickness in a river otherwise solely receiving groundwater. To test the significance of this process on mixing, a calibrated transect model was developed to examine flow patterns during storm events at a transect where transient hydrogeological data were available (Ellis et al., *in subm.*). Results of this bank storage model showed the likely variation in discharge rates across the bed confirming the dominance of the lateral flows in to the river through the river sides below the river water level and where a seepage zone forms above the river stage, e.g. the central 50% of the river bed contributes only 25 % of the total baseflow. Several general points emerged: (i) river water entering the river bed during the passage of the flood wave occurs only for very short times (<10 mins) and in negligible quantities - aquifer head changes derive mostly from damming of water entering the river rather than flow reversal; (ii) after passage of the flood wave a persistent (rather than large short-term) release of groundwater occurs as the stored water progressively drains to the river; (iii) vertical pressure gradients through the bed of the river are higher at the river channel edge than near the centre; (iv) the local scale geological heterogeneity (particularly clay lenses) substantially influences the flow geometry beneath the river.

The above (homogeneous material based) modelling indicated that the flow distributions lead to positive flows from the aquifer to the river at all points for nearly all times. Field chloride and thermal gradient data have, however, lead to conclusions that some surface water mixing must be occurring within the river bed. Previous authors have hypothesised that local-scale mixing can be explained by bed material heterogeneity and undulations in bed form (Conant, 2004). This issue was evaluated with a 10-m reach model populated with slug test hydraulic conductivity data. The modelling indicated that: (i) a laterally persistent shallow HZ of less than 10 cm only should exist; (ii) where flows are concentrated, e.g., near river edges, HZ existence is very unlikely; (iii) the HZ is physically created if the bed material is protected from significant vertical flow. These results are not entirely consistent with field-observed deeper mixing zones on occasion up to ~30 cm (Ellis, 2003). The discrepancies require further study but may be due to: (i) low permeability structures deeper in the profile are having a significant influence in generating the apparently high hydraulic gradients; (ii) other processes are operative, e.g. in the summer aquatic plants are more common and may induce locally steeper river gradients; (iii) upper layer material structure is radically different to that modelled, e.g. due to bioturbation or more likely river reworking during the commonly observed armouring process leading to the winnowing of fine material in the near riverbed surface.

Impacts on the local mixing in the river bed may occur due to flow variations arising from rapid pressure perturbations at the base of the river caused by turbulent eddies and surface wave forms (with time periods on the order of a second). Penetration of pressure transients to reasonable depth (up to 0.5 m) in the river bed on these timescales may be hypothesized and that enhanced chemical diffusion may operate in this zone as a consequence of fluctuating velocity induced mixing. Whether such pressure transients can operate at levels that may cause enhanced diffusion and thereby enhance the depth of penetration of the stream aquifer mixing zone was evaluated my momentum exchange modelling (Ellis et al., *in press*). The results confirmed that the momentum exchange increases the depth of penetration of reverse flows into the river bed although the magnitudes are lower. The flow reversals extend to a depth of 50 cm for the same system with momentum suggesting that enhanced diffusive mixing into the river bed profile could occur against a general upflow. This does lend support to the concept that small scale pressure transients could be influential in increasing the mixing at depth which when combined with flow mixing created through the heterogeneity patterns in the river bed may explain HZ (mixing zone) thicknesses that are observed to be much greater than ~10 cm.

4 Studies local to the dipole experiment site

Recent studies (Conran, 2006; Lydon, 2006) have focused on the ~500 m sub-reach local to the dipole experiment site within the large meander of the Tame (Fig. 1). A plate of this sub reach and part of the riverbed network installed at 12 transect locations totalling 37 piezometers and 11 multilevel (6 point) samplers are shown in Fig. 2. Head data from summer 2006 indicated a groundwater effluent condition with slug test (Hvorslev) hydraulic conductivity estimates (n=27) ranging from 0.4-7.9 m/d with deep and shallow riverbed geometric means of 1.4 and 5.3 m/d respectively.

Chloride data (Fig. 3) obtained from multilevel samplers in transects 8 and 11 (Conran, 2006), the latter being adjacent to the proposed dipole experiment (Fig. 2). Chloride concentrations in the surface water are elevated due to upstream sources (direct pipe discharges, run-off etc) at typically 150–220 mg/l with high concentrations associated with greater flows. Chloride hence provides a convenient surface water marker as groundwater concentrations, unless polluted are typically in the 50 –75 mg/l range, i.e., deeper points in most of the Fig. 3 profiles. Both transect 11 depth profiles and the transect 8 ML3 profile show stable profiles over the 3-4 occasions monitored over a 2-3 week period under summer low flow conditions. Elevated concentrations occur at 10 cm below the riverbed, but by 20 cm concentrations are lower and remain fairly constant with depth suggesting surface water mixing is occurring to 10-15 cm depths. This accords with the predictions of the 10-m reach model described earlier. Profile T8-ML1, however, shows time-variant behaviour with variable riverbed penetration of high chloride between 10 – 50 cm. The profile is located in more permeable deposits, with slightly greater and turbulent surface water flow on the inside of the further upstream bend. Attempts have been made to correlate the behaviour with temporal changes in stage and precipitation over the period (variable with several mm on wetter days), however, this proved inconclusive and pointed to the need for higher resolution (automated) temporal data. Other data on dissolved oxygen, pH, redox, nitrate, sulphate, fluorescence (an indicator of organic matter type) are discussed in Conran (2006).

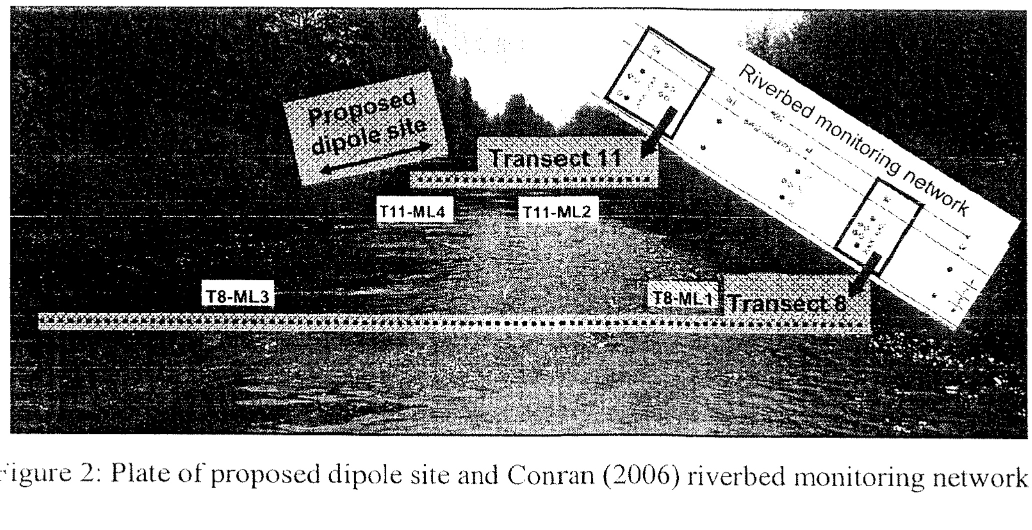

Figure 2: Plate of proposed dipole site and Conran (2006) riverbed monitoring network

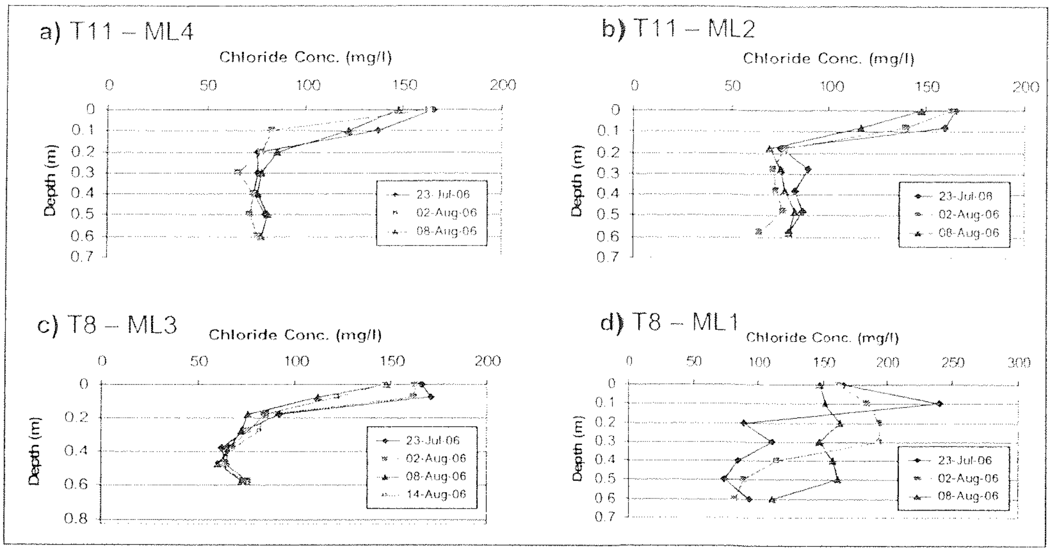

Figure 3: Riverbed chloride depth profiles at transect 8 (T8) and transect T11 (Conran, 2006)

5 Outline of the dipole experiment concept and design

The dipole experiment concept and a working design of the field experiment setup is provided by Lydon (2006) and is based upon the hydrogeological data collected for the sub-reach and surroundings shown in Fig. 2. Although there is some 7 km of the River Tame crossing the unconfined aquifer, our walkover inspection indicated very few sub-reaches were suitable candidates for hosting the dipole experiment due. Key constraints were: provision of power supply, suitable river conditions for in-river monitoring works (i.e., not too deep or fast flowing), access for drilling rigs, supportive land (riparian) owner(s), a reasonably uniform river channel. The site selected was the best available option. The design of extraction and injection wells and their configuration is currently being iterated for implementation in 2007 and is briefly indicated below. A conceptualisation of the proposed dipole field experiment is shown in Fig. 4. Three wells are proposed so as to provide flexibility of dipole spacing and will be located within ~6 m of the riverbank spaced along a 90 m long and 9 m wide river reach (Fig. 4). Wells will be bored via rotary drilling to a depth of approximately 15 m. The holes will be cased from the surface to just below the consolidated sandstone with the remainder screened. Well spacings are dictated by the need to produce sufficiently separated portions of the river to achieve discrete influent and effluent surface-water – groundwater conditions. Numerical groundwater flow modelling (Lydon, 2006) indicates extraction rates need to be of the order 1-4 l/s for wells positioned at 30-50 m spacing. Rates are sensitive to the riverbed hydraulic conductivity values used in the modelling currently derived from point piezometer slug tests. It is proposed that wells are drilled in two stages to allow a pump test of the first well such that the derived bulk hydraulic properties may be used in conjunction with modelling to best derive the borehole spacings.

Additional riverbed monitoring facilities (i.e., multilevel samplers, piezometers, pressure transducers etc.) to those already installed by Conran (2006) and Lydon (2006) will occur in parallel with the drilling of the main extraction/injection wells. Most monitoring is to be located in the surface-water influent reaches in order to observe the extraction-induced deeper mixing zone via monitoring of the natural water quality present and tracers injected in riverbed piezometers. Having two extraction wells

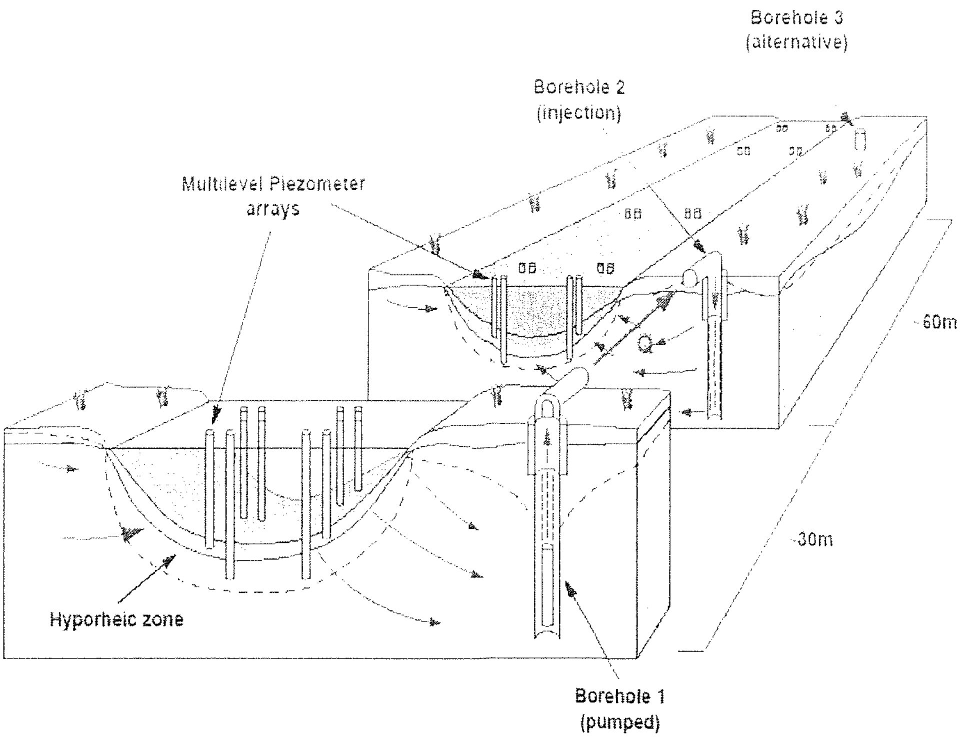

Figure 4: Conceptualisation of the proposed dipole field experiment

allows examination of contrasting riverbed locations. The testing will be designed to enhance understanding of natural attenuation capacity and its temporal and dynamic variability. To create adequate time to adjust and stabilise the mixing depths, each test is likely to exceed 120 days. A period of 18 months will allow four full scale teats to be completed and analysed. Ellis (2003) indicates groundwater from 50 cm below the riverbed near to the site has the following composition: moderate conductivity of 500 μS/cm, pH 7.6, Eh 400 mV and D.O. 3 mg/l (i.e. oxic), major ion chemistry of Cl 45 mg/l, NO_3, 70 mg/l, SO_4 165 mg/l, alkalinity 210 mg/l - $CaCO_3$, Ca 110 mg/l, K 10 mg/l, Mg 18 mg/l, Na 22 mg/l, minor ions PO_4 1.9 mg/l, F 0. 6 mg/l, Si 5 mg/l, low metals, Mn 1.3 mg/l, Fe 1 mg/l, Sr 0.3 mg/l, Ba 0.1 mg/l, Pb 1 μg/l, Hg 0.03 μg/l, Cd 1.7 μg/l, Cr 1 μg/l, As 1.4 μg/l, Cu 4 μg/l, Zn 50 μg/l, Ni 13 μg/l with all VOCs below low μg/l detection limits. A period of natural flow monitoring will be conducted ahead of the main extraction-injection tests to further establish the natural temporal/ spatial variability of the HZ flow regime and chemistry in proximity to the extraction/injection wells.

The controlled dipole tests will allow research advances in several areas. These include: confirmation of relationships between river and groundwater gradients; evaluation of mixing depth extents and dynamic controls; assessment of redox dynamics / electron acceptor transport (key to biodegradation); and, elucidate controls on contaminant attenuation capacity. Such process-based understanding will underpin opportunities for engineering of bed forms to proactively remediate contamination present.

6 Conclusions

The wealth of previous research on the Birmingham aquifer – River Tame system has provided an excellent foundation for the proposed dipole experiments. The numerical modeling studies conducted to assess mixing zone (HZ) thickness and associated controls are particularly instructive. It is anticipated that the controlled perturbation dipole experiments will provide novel insights into the attenuation properties of urban hyporheic zones and their potential for engineered enhancement.

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References

Conant Jr., B., 2004. Delineating and quantifying ground-water discharge using streambed temperatures. *Ground Water* **42**(2), 243 – 257.

Conran, D.J., 2006. Assessment of groundwater-surface water mixing zone transients: Birmingham – River Tame study. MSc thesis (unpublished) School of Geography, Earth & Environmental Sciences, University of Birmingham, UK.

Ellis, P.A., 2003. The impact of urban groundwater upon surface water quality: Birmingham – River Tame study, UK. PhD thesis, School of Geography, Earth & Environmental Sciences, University of Birmingham, UK, 360 pp.

Ellis, P.A., Mackay, R. and Rivett, M.O., *in press*. Quantitative modelling of urban groundwater river exchanges – A case study on the Tame river, Birmingham, UK. *J. Contam. Hydrol.*

Ellis, P.A. and Rivett, M.O., *in press*. Assessing the impact of VOC-contaminated groundwater on surface-water quality at the conurbation scale. *J. Contam. Hydrol.*

Ellis, P.A., Rivett, M.O., Henstock, J, Dowle., Mackay, R., Ward, R. and Harris, R., 2002. Impacts of contaminated groundwater on urban river quality – Birmingham, UK. In: *Groundwater quality: Natural and enhanced restoration of groundwater pollution*. IAHS publication No. **275**, 71-77.

Ellis, P.A., Rivett, M.O. and Mackay, R. 2004. Estimation of groundwater-contaminant fluxes to urban rivers. In: *Hydrology: Science & Practice for the 21st Century*, British Hydrological Society (Publ.) 272-279.

Ford, M. and Tellam, J.H., 1994. Source type and extent of inorganic contamination within the Birmingham urban aquifer system, UK. *J. Hydrol.* **156**, 101-135.

Jackson, D., Lloyd, J.W., 1983. Groundwater chemistry of the Birmingham Triassic Sandstone aquifer and its relation to structure. *Quart. J. Eng. Geol.* **16**, 135-142.

Knipe, C.V., Lloyd, J.W., Lerner, D.N. and Gresswell, R., 1993. Rising groundwater levels in Birmingham and the engineering implications. *CIRIA (London). Spec. Publ.* **92**, 114pp.

Lorah, M.M., Burris, D.R. and Dyer, L.J., 2005. Natural Attenuation of chlorinated solvent ground-water plumes discharging into wetlands: *U.S. Geological Survey Scientific Investigations Report* **2004-5220**.

Lydon, C., 2006. Design for the Hyporheic Zone Dipole Setup. MSc thesis (unpublished) School of Geography, Earth & Environmental Sciences, University of Birmingham, UK.

Mackay, R., 2004. FAT3D-UNSAT: a computer program for saturated-unsaturated flow in 3-dimensions. An Hydrogeology Research Group working report, School of Geography, Earth & Environmental Sciences, University of Birmingham, UK.

Rivett, M.O., Lerner, D.N., Lloyd, J.W. and Clark, L. 1990. Organic contamination of the Birmingham aquifer, U.K. *J. Hydrol.* **113**, 307-323.

Rivett, M.O., Shepherd, K.A., Keeys, L., Brennan, A.E., 2005. Chlorinated Solvents in the Birmingham Aquifer, UK: 1986 – 2001. *Quart. J. Eng. Geol. & Hydrogeol.* **38**(4), 337-350.

Shepherd, K.A., Ellis, P.A. and Rivett, M.O., 2006. Integrated understanding of urban land, groundwater, baseflow and surface-water quality – The City of Birmingham, UK. *Sci. Tot. Environ.* **360**, 180-195.

Thomas, A., Tellam, J.H., 2006. Modelling of recharge and pollutant fluxes to urban groundwaters. *Sci. Tot. Environ.* **360**, 158-179.