018530 - SWITCH

Sustainable Water Management in the City of the Future

Integrated Project

Global Change and Ecosystems

Development of the Hyporheic Zone Test Site and Experimental Design

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Executive Summary

The urban hyporheic zone (HZ), the zone of groundwater – surface–water mixing beneath a river, represents an important natural system for water self purification. The University of Birmingham is undertaking research to better understand and exploit the urban HZ system as part of the *EC Framework 6 SWITCH* (Sustainable Water (management) Improves Tomorrows' Cities' Health) research programme (WP 5.3). Co-funding for the HZ research is provided by the Environment Agency (for England and Wales). The research is field based and set within the 'SWITCH Demonstration City' of Birmingham, UK. This progress report covers the project period up to *c.* May 2008. It outlines the project aims and underlying rationale, reviews the underpinning background research, and describes the development and experiment design of the hyporheic zone test site ('HZ Site'). The upcoming programme of research is outlined.

The overarching research aim is to learn enough about the dynamic behaviour of the urban hyporheic zone to confirm the continuous spatial and temporal attenuation capacity of the zone and to develop appropriate concepts that can be employed as part of any river restoration project for the purposes of minimising future potential risks from contaminated groundwater discharges to the river. Key objectives are to investigate groundwater – surface-water mixing processes and their importance within the HZ; provide insights into the dynamic behaviour of the HZ including its temporal persistence; investigate chemical attenuation potential of the HZ and spatial relationships between attenuation capacity and flow patterns; and, based on these, establish, descriptions of the HZ through modelling that can contribute to river restoration design.

Central to the project is the development of the *HZ Site*, a novel urban river based experimental test facility that can be used to dynamically modify the interactions between the aquifer and river in order to meet the identified research objectives above. The HZ Site has been established on the river Tame in Birmingham and builds on significant water-based research conducted in the city. The Site was specifically developed as part of the SWITCH programme and comprises an installed groundwater extraction well immediately adjacent to the river and an installed high density network of riverbed HZ monitoring points to measure the groundwater – surface-water flow and chemical exchange processes in the HZ. Operation of the extraction well allows the hydraulic gradients across the HZ to be modified and perturbed groundwater – surface-water interactions and chemical solute/contaminant attenuation behaviour that may be studied. The establishment and design of the HZ Site facility is described herein and includes support numerical modelling work that contributed to the test design.

Establishment of the HZ Site has required liaison with land owners to obtain necessary permissions for land access and research facilitation and with the Environment Agency to secure other necessary regulatory permissions. These aspects are not covered in detail herein, however, their all important progression is indicated. A 'Section 32' consent to drill and test-pump the extraction well was acquired and both operations successfully completed through 2007-08. Operation of the extraction well for the research programme duration has been authorised by the Agency under a consent arrangement. Application was also made to the Agency for a formal 'discharge consent' required to dispose of the extracted water to the river Tame. This, the final permission needed, was acquired in May 2008 and allows the proposed HZ Site extraction tests to proceed.

Baseline monitoring of the HZ Site has been conducted via the installed HZ monitoring network with hydraulic head (flow) and chemical water quality data being obtained in Autumn 2007 and late Spring 2008. Some enhancement of the network was undertaken for the later sampling round. Interpretation of those data is still on-going and will be provided in conjunction with the extraction test data that it critically underpins in future reporting. This work and previous work in adjacent areas along the river Tame has demonstrated that the river bed is weakly contaminated within the HZ Test Site reach, but with sufficiently contrasting water-quality conditions existing between groundwater and surface-water to address the research objectives.

The upcoming extraction tests are the primary focus of the outlined 2008 research programme. These tests are to commence imminently (July 2008) and comprise 3 pump tests at differing borehole extraction rates to allow understanding of a low, medium and high perturbation of the hyporheic zone flows. Test 1 will be conducted at the maximum rate, ~ 1.5 l/s, to induce a high perturbation test regime with following tests at reduced flows. Tests are proposed to comprise up to a 2-month extraction period followed by up to a 1-month recovery period (no extraction). The exact duration of tests (and numbers of tests allowed) will, however, depend on the observed hydraulic and water quality responses. Along side the interpretation of data arising from these tests, supporting work on momentum exchange is proposed to further elaborate groundwater – surface-water mixing processes.

The ultimate study goal is to determine the extent to which risks from groundwater pollution can be mitigated by sustaining the natural functioning of urban rivers and by appropriate design linked to any restoration proposals that may be considered as part of the regeneration of the urban landscape. Modelling will form a key tool in the development of a quantified picture of the HZ Test Site and its extension to urban restoration design.

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1 Introduction

Rivers are hydraulically connected to the underlying groundwater systems in most landscapes, including urban settings. This hydraulic connection will permit the transfer of chemical solutes/contaminants in addition to water across the interface. Thus, one particular concern for development of urban rivers and the adjacent lands for recreation and public amenity is the potential for long-term pollution entering the river from the aquifer and the corresponding risks to public and environmental health. This is of particular significance for industrialized cities, where historic or on-going activities have generated significant ground contamination. Pollutants can migrate to the underlying groundwater over time and posing risks to adjacent receiving surface waters already potentially stressed by poor quality run-off, pipe discharges, and storm-sewer overflows.

The River Tame in the SWITCH Demonstration City, Birmingham, drains the West Midlands conurbation and receives natural groundwater discharge from the sandstone aquifer underlying the city centre and the industrialized areas to the north and, thus, also receives part of the historical groundwater contamination that has arisen from the industrial activity in the city as well as from the whole of the conurbation upstream. The chemical quality of the River Tame flowing through North Birmingham is generally poor as a consequence of the urbanization of the catchment.

While pollution from groundwater sources is a potential problem for river development, many industrialized cities are undergoing regeneration of their infrastructure that includes restoring the natural amenity of the river corridors. This is leading to opportunities to mitigate the pollution risks from groundwater borne contamination through appropriate restoration approaches. Therefore, determining the extent to which groundwater contamination is a problem for a receiving water body and the extent to which any problem found can be mitigated by appropriate development of the river corridor during restoration is a highly worthwhile aim. The EU Water Framework Directive (WFD) requires integrated management of groundwater and surface water bodies and provides a strong regulatory driver for understanding such processes. The present research is focused on the near-river zone as this can be potentially modified as part of any river restoration.

The riverbed 'hyporheic zone' (HZ) is the final geological zone through which groundwater flows before discharging to a river. Depending on the relative head conditions, there is a potential for effluent and/or influent conditions. Moreover,

dynamic solute exchange, active groundwater-surface-water mixing, and steep geochemical gradients may all occur within the HZ. In UK rivers, this zone is typically 0.1 to 2 m thick although greater thicknesses are observed in other river systems around the world. The hydraulic residence time in the HZ is generally much shorter (hours/days) than in the main aquifer through which contaminant transport occurs. Nevertheless, contaminant attenuation capacity in the HZ can still be significant. Elevated organic carbon content, microbial activity and mixing of chemically distinct waters can individually and collectively enhance contaminant attenuation via (bio)degradation and sorption and lead to mitigation of groundwater pollution impacts to surface water. Attenuation of pollutants in poor-quality surface water discharging to groundwater can also be achieved where the dominant flow is from the river to the aquifer across the HZ. This aspect is being investigated as part of the studies of Bank filtration and is not being addressed in the present research. Nevertheless there are clear links between the two research issues.

The urban HZ represents an important natural system for water self purification; and understanding this system and its exploitation as part of an IUWM plan lies within the remit of Work Package 5.3 of the SWITCH (Sustainable Water (management) Improves Tomorrows' Cities' Health) integrated project. The planned research will use groundwater extraction experiments, involving an extraction well immediately adjacent to the Tame river, to perturb the natural groundwater – surface-water exchanges in a controlled manner. The migration of naturally-present solutes/contaminants and artificial tracers will be monitored during a series of extraction controlled field tests to gain insight into: (i) the potential of the urban hyporheic zone to naturally attenuate contamination; and, (ii) the potential for engineered enhancement of the HZ and its attenuation capacity within the scope of a river restoration scheme. The field experiments will focus on the former, the latter will be derived from modelling and the data analysis.

The hyporheic zone test site, 'HZ Site', has been developed on the River Tame in north Birmingham. The site was selected because of the knowledge base that has been accumulated on the Birmingham aquifer and the River Tame system over recent decades through the research programme of the Hydrogeology Research Group at the University of Birmingham. Past studies include: rebounding groundwater levels (Knipe et al., 1993); inorganic geochemistry/contaminants (Jackson & Lloyd, 1983; Ford & Tellam, 1994); organic contaminants (Rivett et al., 1990a,b,c 2005); recharge and contaminant flux (Thomas & Tellam, 2006); integrated contaminated land and water assessment (Shepherd et al., 2006); and, groundwater – surface-water interactions (Ellis et al., 2002, 2004, 2007; Ellis and Rivett, 2007; Rivett et al., 2008).

2 Aims and objectives

The overarching aim of the research is to learn enough about the dynamic behaviour of the hyporheic zone to confirm the continuous spatial and temporal attenuation capacity of the zone and to develop appropriate concepts that can be employed as part of any river restoration project for the purposes of minimising future potential risks from contaminated groundwater discharges to the river.

The key objectives are to

- Confirm or reject the concepts derived from previous hyporheic investigations concerning the mixing processes and their importance within the body of the hyporheic zone
- Provide new insights into the dynamic behaviour of the hyporheic zone to confirm the temporal persistence of the zone.
- Develop new insights into the chemical attenuation potential of this zone and the spatial relationship between the chemical attenuation capacity and groundwater-surface water flow patterns.
- Establish, after achieving the previous objectives, descriptions of the hyporheic zone through modelling that can contribute to river restoration design.

These objectives will be accomplished via the following activities:

- Assimilation of recent research knowledge generated and published as part of ongoing international actions related to the hyporheic zone.
- Development of an urban river based experimental test facility that can be used to dynamically modify the interactions between the aquifer and river and so determine the hydraulic controls governing the thickness of the hyporheic zone.
- Characterisation, chemically and physically, of the river reach forming part of the experimental facility prior to any modification of flow conditions and to quantify the extent and thickness of the hyporheic zone under natural conditions.
- Completion of a suite of long-term flow experiments to resolve the impact of pumping on the river-groundwater mixing in the hyporheic zone and any related chemical effects.

- Development of a numerical model for the river reach that describes the flow and chemical responses in the hyporheic zone to the different field experiments and to use the model to explore alternative concepts for exploiting the attenuation capacity of the hyporheic zone as part of a river restoration scheme.
- Elucidation of the data requirements to quantify the conditions beneath a river as part of any future assessment of its restoration potential.

3 The Field Site

This chapter describes the field site setting on the river Tame. Background hydraulic and chemical data obtained through previous studies and during the preliminary testing of the field site are presented. The latter primarily includes the sampling results to meet the regulatory requirements of the Environment Agency for the acceptance of the proposed experimental programme. Testing to support the groundwater abstraction consent-licence and the discharge to the river consent to dispose of the abstracted water have been performed. This section, hence, serves to provide background context to the field test programme described in Section 4.

The 'HZ Test Site', was identified to allow the construction of a small borehole extending c. 10 m below riverbed into the underlying shallow Triassic Sandstone beneath the superficial deposits and within 5 m of the river bank. Agreement for the installation of measurement points to provide detailed recording of the perturbations caused in the riverbed, both under natural flow and borehole extraction tests was also essential. Indicative modelling indicated that monitoring of the hyporheic zone would require instrumentation along a c. 200 m reach centred upon the extraction borehole: comprising a network of riverbed piezometers, multilevel samplers (as described by Rivett et al., 2008) and automated pressure transducers arranged to measure hydraulic head and chemical quality in detail within the HZ. A reach length of 200 m delimits the extent of the HZ Test Site.

3.1 Location

The HZ Test Site is located in an industrial area of north Birmingham. There is a net groundwater discharge to the river at the site due to its location along the 7 km river section draining the unconfined Triassic sandstone aquifer underlying the city. This

complete 7 km section on the Triassic Sandstone has been the subject of significant previous investigation by the University and is identified as the boxed 'Study area' in Figure 1 (Ellis *et al.*, 2007; Ellis and Rivett, 2007; Rivett *et al.*, 2008).

To operate long-term groundwater extraction tests coupled with in-river monitoring and instrumentation, the specification for the HZ Test Site included: (1) access to a permanent, secure electricity supply, ease of site access for the borehole construction, ease of in river monitoring; access conditions to allow safe working; agreement of the landowner(s) and minimal risk of enhanced pollution potential arising from the operation of the experiments. These constraints reduced considerably the available options along the 7 km section. Following exploration of all options along the river, the best site that addressed all requirements was located in Witton, 10 km north of the University of Birmingham (Figure 1) near the mid point of the 7km river section. The site is located on a near-straight river reach that should assist understanding of the observations from the tests.

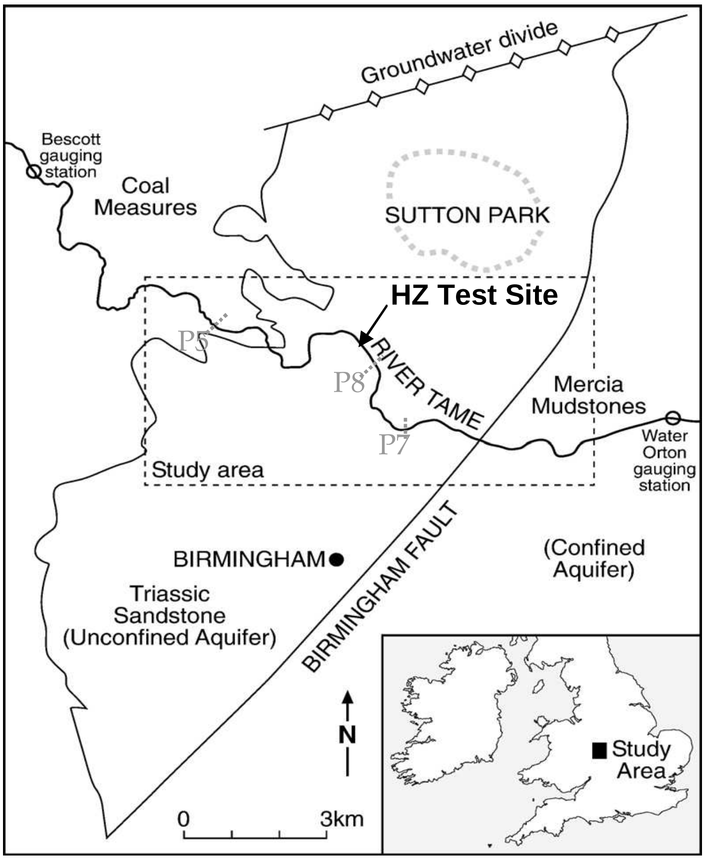

Figure 1. Location of the HZ Test Site set within the 7-km long unconfined aquifer River Tame reach study area researched by Ellis & Rivett (2007) (boxed area). Locations of transects P5, P7 and P8 used in previous research and discussed herein are also indicated.

Legal agreements were established between the University of Birmingham and the two land owners whose land intersects the HZ Test Site. Land access was granted by the land owners, subject to strict conditions, for the duration of the SWITCH project.

3.2 Geology and Hydrogeology

The HZ Test Site is located on the Birmingham Triassic Sandstone aquifer. Regional groundwater flow in the aquifer drains toward the river Tame, the regional topographic low. The site is underlain by approximately 7 m of river-terrace and alluvial deposits and 100 m thickness of the Kidderminster Formation (Figure 2). The river banks comprise of Made Ground, reflecting the industrial heritage of the location. The river course at this location has been modified from its original location and is partly channelized with Gabions used to reinforce the river banks. Bunds arise on both banks to retain flood flows. Originally, this area would have been predominantly marshland, but the reclamation of the land for industrial development altered the landscape significantly to develop the current conditions observed at the site. The Triassic Sandstone thins westward and deepens eastward towards the Birmingham Fault, a major discontinuity that is characterised at ground surface by a sharp transition from the Triassic Sandstone to the very low permeability Mercia Mudstone On the east side of the Birmingham fault, the sandstone aquifer is confined by the Mercia mudstones. The Triassic Sandstones are generally fine to medium-grained, and contain predominantly horizontal (bedding plane) fractures resulting in some dual-porosity (Jackson & Lloyd, 1983). Typical aquifer parameter values are hydraulic conductivity ~2 md^{-1}, specific yield ~0.1-0.15 and porosity ~0.27 (Knipe *et al*. 1993; Ford & Tellam 1994). The overlying superficial river-terrace and alluvial deposits in the area are heterogeneous mix of gravels, sands and fine grained clay-silt deposits with a wide range in hydraulic conductivity typical of such near-river environments.

Groundwater has generally been exploited only for industrial use and to augment the extensive canal network within Birmingham. Considerable depletion of the aquifer took place during the heavy industrial activity up to 1960-70s with considerable declines in groundwater level and in the subsurface flows to the River Tame. Surface drainage will have increased during the same period due to significant increases in the impermeable cover draped over the urban landscape and increases in the effluent discharges. Birmingham's public water supply has been largely derived from upland surface-water reservoirs in Wales (some 80 miles north west of Birmingham) since the 1900s (a scheme developed amid fears of local water contamination in the city). Steady decline in industrial abstractions from the aquifer

over the past 40 years has resulted in regionally rising groundwater levels (Knipe *et al*., 1993). Groundwater recovery is nearly complete at the present day.

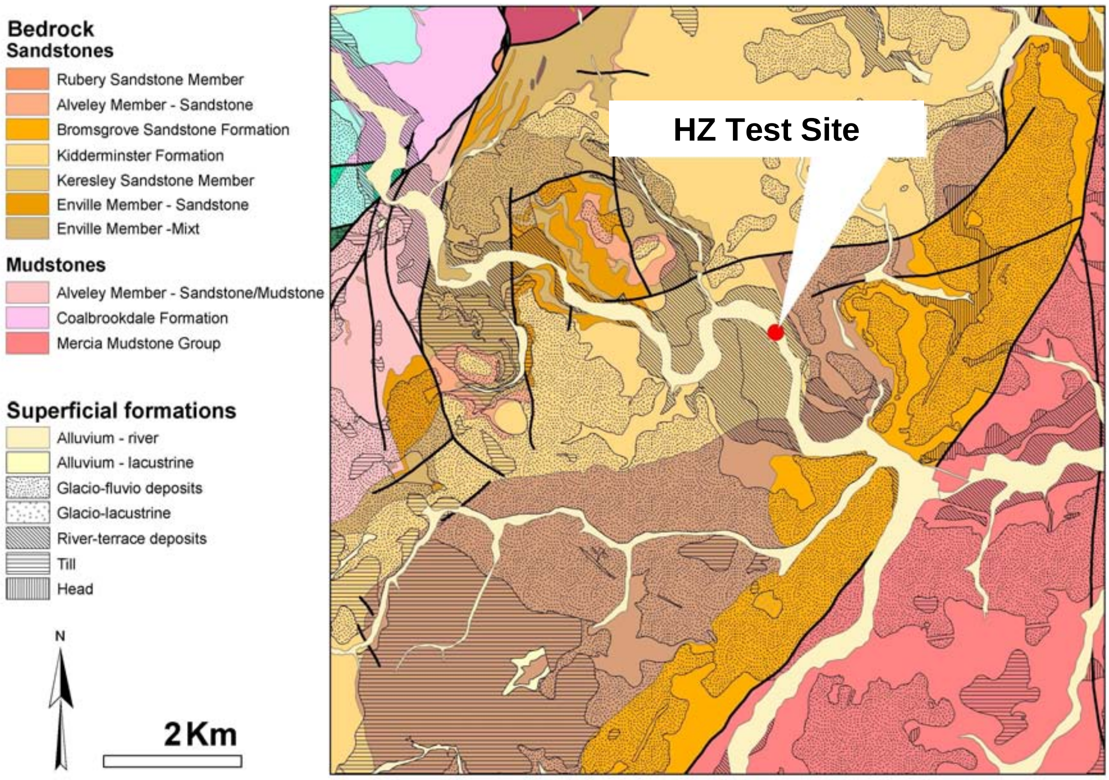

Figure 2. Geology map of the studied site (from http://edina.ed.ac.uk/digimap/).

3.3 *River Flows*

The river Tame's catchment area increases from 170 km² at the Bescot gauging station to 400 km² at Water Orton gauging station (Figure 1). The flows of the River Tame vary between 0.3 and 47 m³/s at Bescot 11.4 km upstream of the HZ Test Site, and between 2 and 106 m³/s at Water Orton 9.7 km downstream of the site (Table 1). The specific mean flow is about 14.5 l/s/km² at both stations. The continuous discharges at both stations during 1999 are presented on Figure 3.

The catchment is heavily urbanised and drainage to the river Tame is relatively efficient. The Tame hydrograph is characteristic of a 'flashy' urban river responding rapidly to rainfall events. Flood hydrographs are typically of short duration (< 1 day). Consequently, the Tame river serves to rapidly drain the West Midlands conurbation. The river stage at the HZ Test Site responds to upstream precipitation rather than to the local groundwater conditions. As a consequence the river can

become influent to groundwater for brief periods during the rising limb of any river hydrograph but this is of short duration as river bank groundwater levels rise rapidly in response to the damning effect of the river stage, given the limited storage capacity of the adjacent made ground. Under most conditions, however, groundwater is predominantly effluent to the reach of the Tame overlying the unconfined Birmingham aquifer unit (Ellis, 2003; Ellis et al., 2007).

Table 1. Observed flow at the Bescot and Water Orton gauging stations during the year 1999 (Environment Agency data, from Ellis, 2003).

Gauging Station	Catchment Area (km^2)	Mean flow (m^3/s)	Specific mean flow ($l/s/km^2$)	Median flow (m^3/s)	Max flow (m^3/s)	Min flow (m^3/s)
Bescot	169	2.46	14.6	1.71	46.76	0.31
Water Orton	408	5.86	14.4	3.91	105.9	2.08

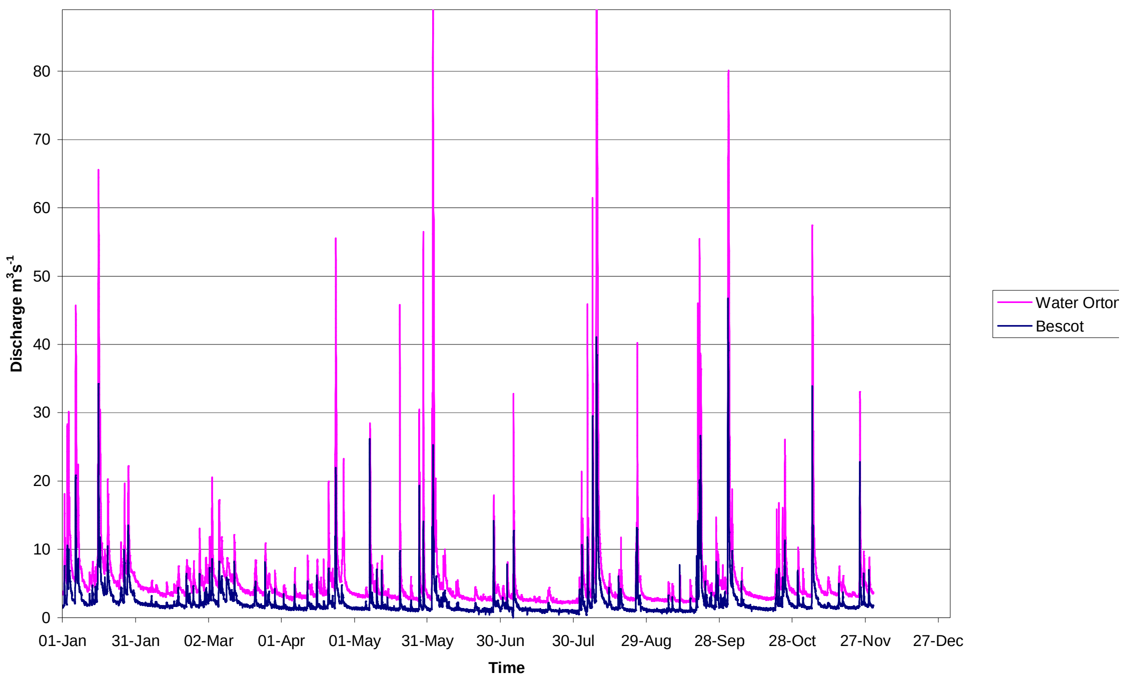

Figure 3. Observed river Tame discharges at Bescot and Water Orton stations during 1999 (Environment Agency data, from Ellis 2003).

3.4 *Water Quality*

The Environment Agency holds a database of chemical water-quality records for the river Tame. These comprise high frequency (automated) monitoring of a limited set of determinants at the Bescot and Water Orton gauging stations as well as much lower temporal density spot-sampling of the river at several other locations. The University of Birmingham has undertaken surface-water quality sampling, the majority of which is reported in the PhD study of Ellis (2003). These data are not reported here, but will be used to support the research to characterise the chemical signature of the river and its variability. Chloride levels are elevated in the Tame river flows due to the discharge of upstream treated sewage effluents and are distinctly higher than the groundwater chloride typically encountered. Chloride therefore provides a useful marker for the determination of the extent of groundwater/surface water mixing within the HZ. However, continuous monitoring of chloride will be expensive and it is proposed that, the relationship of chloride to electrical conductivity is established to see if the lower cost option of automated electrical conductivity monitoring can be used as an alternative indicator of surface-groundwater mixing in the HZ.

The most recent surface-water quality data at the request of the Environment Agency with respect to applications for the borehole groundwater license (consent) application and associated discharge consent to surface water ((obtained as part of the SWITCH HZ study) are presented here. Chemical sampling was undertaken for both the groundwater discharged from the HZ Site extraction borehole installed (see later) and the river water taken from a point in midstream adjacent to the borehole. Chemical analysis of the samples was carried out using independent accredited commercial laboratories. Tables 2 and 3 show the results for the determinants requested by the Agency.

VOCs (volatile organic compounds) and acid herbicides concentrations were below maximum concentration of European Drinking Directive and English freshwater Environmental Quality Standards (EQS) in the surface water and groundwater (http://www.environment-agency.gov.uk/yourenv/eff/1190084/water/213902/290690/290939/290981/). Most analytes were below the detection limits with the exception of the following detections in surface water: mecoprop, pentachlorphenol and chlorthal. VOCs were below the detection limits in both water types.

For metals/inorganics, the surface water contains Ni, Zn, Fe and B that are more elevated than the groundwater, with Cu vice versa. The EQS values are hardness related (see website above). The total hardness for both the river and groundwater is > 250 mg/l $CaCO_3$, i.e., within the top band thus allowing higher EQS metal values. EQS annual averages are hence Ni – 200 μg/l, Cu – 28 μg/l, Zn – 125 μg/l and EQS

95th percentiles are Cu – 112 μg/l and Zn – 500 μg/l. Thus all river and groundwater values fall within the EQS annual average for these determinants and very comfortably within the EQS 95th percentiles.

Table 2. Principal chemical characteristics of the water in the borehole and of the river.

Determination	Element	Groundwater	River Tame
General elements			
	pH	7.8	7.4
	Suspended Solids (mg/l)	10	18
	Total Hardness as CaCO3 (mg/l)	326	327
	Total Hardness as Ca (mg/l)	131	131
	Phenol Index as C6H5OH (mg/l)	0.9	0.8
Cations (mg/l)			
	Calcium (Ca)	102	97.5
	Magnesium (Mg)	17.3	20.3
	Iron (Fe)	0.05	0.13
	Manganese (Mn)	0.007	0.004
	Boron (Bo)	0.15	0.52
	Cadmium (Cd)	<0.0001	0.0001
	Chromium (Cr)	0.001	0.003
	Nickel (Ni)	<0.001	0.029
	Copper (Cu)	0.024	0.008
	Lead (Pb)	<0.001	0.002
	Zinc (Zn)	<0.002	0.036
	Ammoniacal Nitrogen as N	0.01	0.04
Acid Herbicides (ng/l)			
	2,4-D	<11	<11
	2,4-DB	<10	<10
	Benazolin	<9	<9
	Bentazone	<8	<8
	Bromoxynil	<10	<10
	Chlorthal	<12	15
	Clopyralid	<19	<19
	Dicamba	<13	<13
	Dichlorprop	<11	<11
	Fenoprop	<10	<10
	Fluroxypyr	<10	<10
	Ioxynil	<8	<8
	MCPA	<9	<9
	MCPB	<11	<11
	Mecoprop	<10	54
	Pentachlorophenol	<9	12
	Picloram	<9	<9
	Triclopyr	<15	<15

Table 3. VOCs in the extraction borehole and river Tame (µg/l).

Element	Groundwater	River Tame
Dichlorodifluoromethane	<1	<1
Chloromethane	<1	<1
Vinyl Chloride	<1	<1
Bromomethane	<5	<5
Chloroethane	<5	<5
Trichlorofluoromethane	<1	<1
1,1-Dichloroethene	<1	<1
trans 1,2-Dichloroethene	<1	<1
1,1-Dichloroethane	<1	<1
2,2-Dichloropropane	<1	<1
cis 1,2-Dichloroethene	<1	<1
Bromochloromethane	<1	<1
Chloroform	<5	<5
1,1,1-Trichloroethane	<1	<1
Carbon Tetrachloride	<1	<1
1,1-Dichloropropene	<1	<1
Benzene	<1	<1
1,2-Dichloroethane	<1	<1
Trichloroethene	<5	<5
1,2-Dichloropropane	<1	<1
Dibromomethane	<1	<1
Bromodichloromethane	<1	<1
cis 1,3-Dichloropropene	<1	<1
Toluene	<1	<1
Trans1,3-	<1	<1
1,1,2-Trichloroethane	<1	<1
Tetrachloroethene	<5	<5
1,3-Dichloropropane	<1	<1
Dibromochloromethane	<1	<1
1,2-Dibromoethane	<1	<1
Chlorobenzene	<1	<1
Ethylbenzene	<1	<1
1,1,1,2-Tetrachloroethane	<1	<1
m and p-Xylene	<1	<1
o-Xylene	<1	<1
Styrene	<1	<1
Bromoform	<1	<1
iso-Propylbenzene	<1	<1
1,1,2,2-Tetrachloroethane	<1	<1
Propylbenzene	<1	<1
Bromobenzene	<1	<1
1,2,3-Trichloropropane	<1	<1
2-Chlorotoluene	<1	<1
1,3,5-Trimethylbenzene	<1	<1
4-Chlorotoluene	<1	<1

3.5 *Groundwater – surface-water interactions*

Groundwater – surface-water interaction data have been primarily collected through sampling of the riverbed sediments and the installation of riverbed piezometers and multilevel samplers using the methods described in Rivett *et al.* (2008). The Environment Agency does not hold riverbed data, nor do they routinely collect such data. In this section both the available flow/head and chemical water quality data are presented to give an overview of groundwater – surface water interactions occurring at the HZ Test Site and vicinity. These data are drawn from work completed during the current study, previous studies including the PhD by Ellis (2003), several unpublished MSc Hydrogeology (University of Birmingham) theses and associated publications (Ellis *et al.*, 2002, 2004, 2007; Ellis and Rivett, 2007; Rivett *et al.*, 2008; Shepherd *et al.*, 2006). Data presented below (by those researchers) are from the 7 km reach study area indicated in Figure 1. The SWITCH HZ site is located around the centre of that study area.

Flow measurements at various locations spanning the Birmingham aquifer recorded during summer base flow conditions (Figure 4) show increased discharges downstream. Ellis (2003) analyses the various inputs to surface water over the reach and estimated that baseflow from the unconfined aquifer to the river Tame accounts for 7% of total discharge in the Tame with a minimum flow of around 180 Ml day^{-1}. Head data from throughout the unconfined aquifer reach indicate groundwater is predominantly effluent to the river with only a few localised exceptions. Historically, this is not anticipated to have always been the case. Although head data are not available to quantify the historical groundwater – surface-water interactions occurring at the local River Tame scale, the regional head data from the aquifer prior to c. 1970-80s suggest flow conditions local to the river may well have been reversed, i.e. influent, in parts of the reach as the high industrial abstractions, many in the Tame valley, were extensively drawing down the groundwater table (Knipe et al., 1993).

Temperature measurements within the riverbed sediments reveal a gradient with depth (Figure 5) and spatial variations following the river temperature (Figure 6). These data demonstrate that the groundwater fluxes to the river are not so large that thermal fluxes from the river to the aquifer are negligible. They also indicate that the thermal flux to the aquifer is non-negligible but less than might be anticipated for a static groundwater condition. It may be possible therefore to use these data to provide additional constraints on the magnitude of the groundwater flows within and below the hyporheic zone.

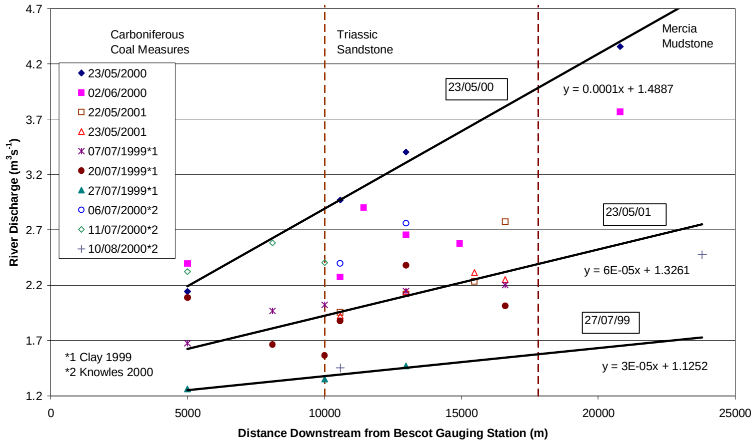

Figure 4. Flow measurements at various locations on the River Tame (Ellis, 2003).

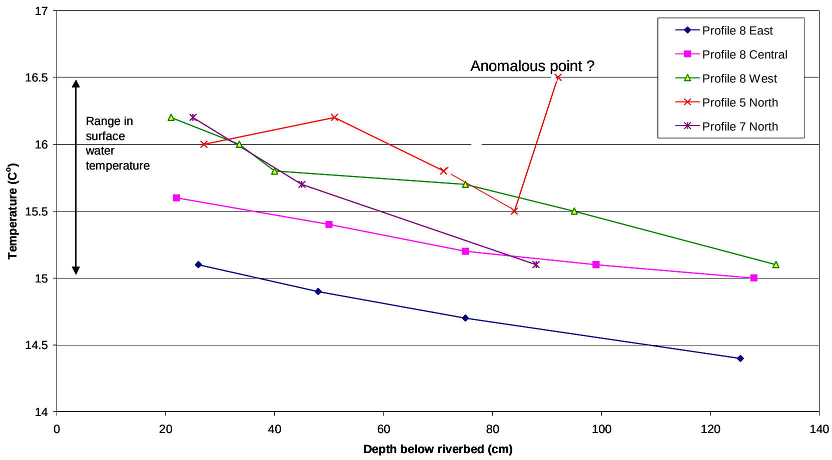

Figure 5. Vertical temperature profiles through the riverbed in 2000 (Ellis, 2003)

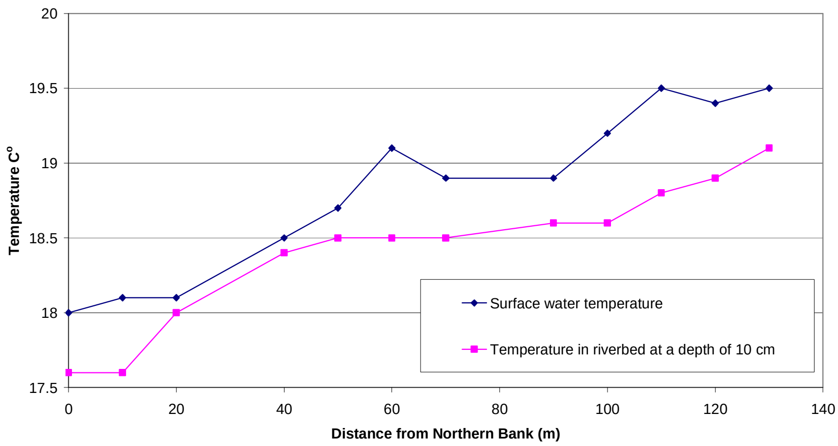

Figure 6. Longitudinal temperature variations in surface water and 10 cm below the riverbed going downstream from Profile 5 (Ellis, 2003).

The riverbed piezometer network installed by previous workers and this study allow head measurement to be taken and hence indications of flow exchanges between surface-water and groundwater. Figure 7a plots 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. Figure 7b plots the hydraulic gradient with depth below riverbed and indicates the gradient decreases generally with depth. It indicates flow convergence at the river bed, but this does not preclude additional longitudinal flow components along the river flow direction that cannot be resolved by the present piezometer network. The precise description of the flows in the riverbed is hence unknown but will be potentially clarified by the monitoring of the head perturbations observed during the extraction tests.

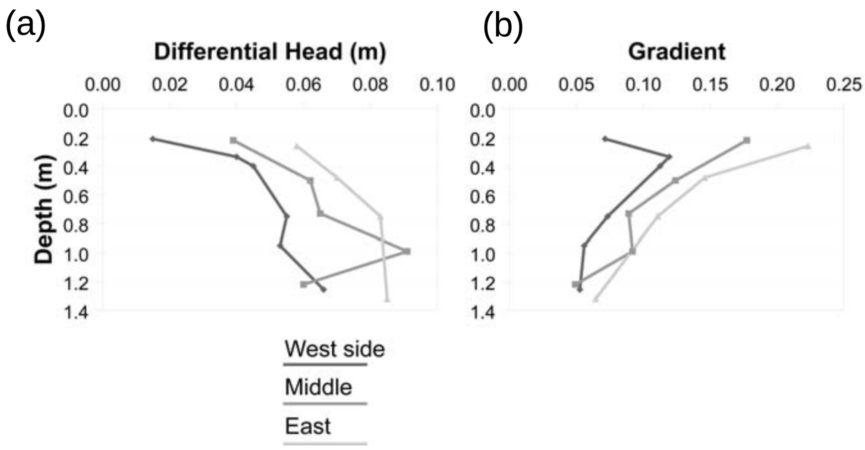

Figure 7. Differential heads between riverbed and river (a), and correspondent hydraulic gradients (b) on Profile 8 for various depths.

Measurements of hydraulic conductivity (*K*) on the riverbed piezometers (Figure 8) obtained via falling head tests provide an indication of the spatial heterogeneity of the riverbed sediments. The observed values ranged over two orders of magnitude, between 0.1 and 30 m/d. These values were recorded in *c.* 1 cm diameter and 10 cm screen length piezometer wells in deposits that were amenable to installations. The hydraulic conductivity range in practice is likely greater as for example, thin low permeability bands may be missed or not discerned if more permeable deposits are immediately adjacent and gravel-boulder areas are less easily instrumented.

Riverbed profiles of chloride, sulphate, nitrate and dissolved oxygen are presented in Figure 9 from the HZ Test Site area and vicinity. These are key example determinants that are illustrative of both conservative and electron acceptor species behaviour.

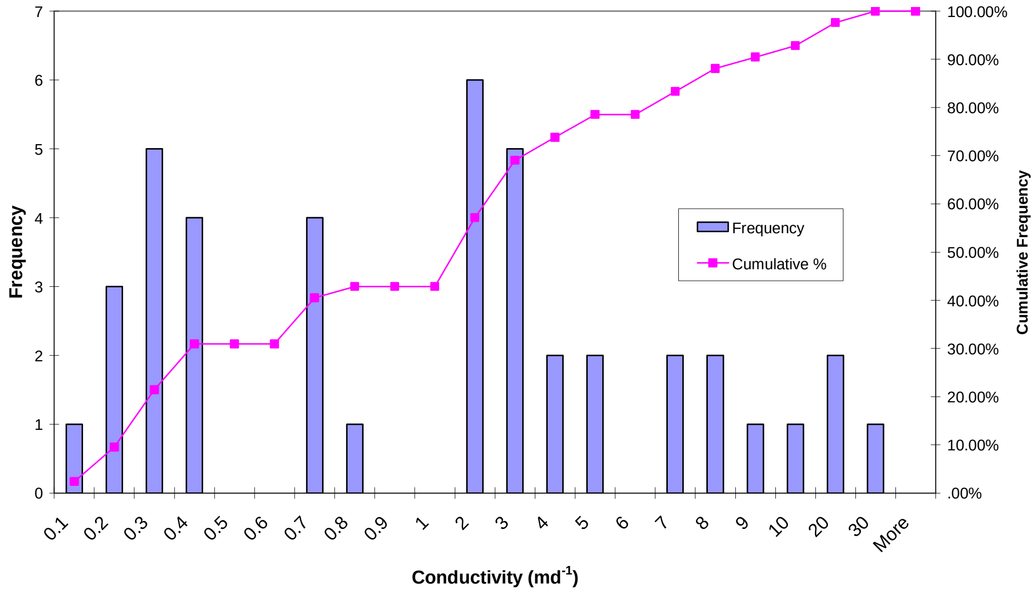

Figure 8. Frequency distribution of hydraulic conductivity in the Tame riverbed.

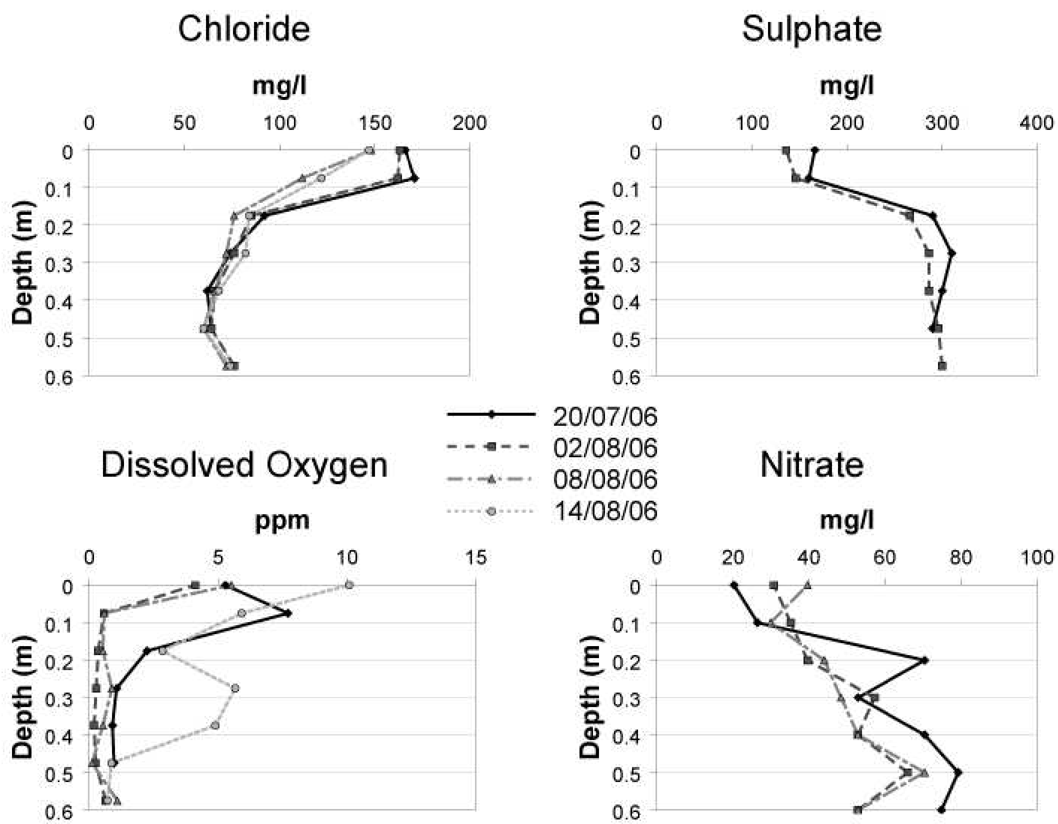

Figure 9. Typical chemical profiles within the riverbed sediments, River Tame study area.

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. Chloride behaves conservatively, i.e. it is neither sorbed nor degraded, and the declining profiles with depth can be ascribed to the invasion of chloride-rich surface water into the hyporheic zone. In the absence of contamination-source chloride plumes discharging with the groundwater to the river, the chloride provides a useful signature of surface-water and the surface-water –groundwater mixing process in the River Tame system. The chloride profiles generally indicate that the mixing zone is thin (15-20 cm) and at some sites temporally stable, at least over the summer period. Not all profiles are stable with some locations (see Rivett *et al.*, 2008) showing a more dynamic behaviour and significant chloride riverbed penetration to > *c.* 0.6 m. Higher resolution temporal data are required to investigate temporal mixing relationships. Nevertheless, such data do illustrate the potential for greater groundwater – surface-water mixing locally. Processes controlling surface-water – groundwater mixing are discussed by Ellis et al. (2007) in more detail for the River Tame system with numerical modelling undertaken at various scales to support interpretations made. Most of the previous results were concerned with steady conditions or the impact of very short term transients and therefore cannot determine the seasonal and annual scale temporal changes that are relevant to the evaluation of the attenuation potential of the HZ. The present HZ project is specifically designed to develop understanding in this area.

The approximate inverse relationship to chloride is observed for sulphate (Figure 9), with the higher concentrations (300 mg/l) at depth declining to *c.* 150 mg/l close to the riverbed surface. This is ascribed to the dilution of comparatively sulphate-rich groundwater. Sulphate will generally behave conservatively under the observed field conditions unless conditions are particularly anaerobic allowing bacteria-mediated sulphate reduction by sulphate-reducers. Although such anaerobic zones have not been generally detected to date, there is potential for such niche activity and micro-zones (and larger) developing where conditions promote such reaction, i.e. presence of an organic carbon donor, depletion of other electron acceptors and the presence of low permeability silts/clays restricting flow and the local development of low redox conditions.

Dissolved oxygen (DO) profiles (Figure 9) indicate more complex behavior with temporal variations more obvious that may relate to possible consumptive reactions as an electron acceptor in biotic reactions. DO is solubility limited to *c.* 8-12 mg/l (ppm) (temperature dependent) and may be readily consumed in aerobic degradation of organic contaminants or natural organic matter. Surface water may be replenished with DO, particularly where riverflow is turbulent, which is not the case for discharging groundwater. DO concentrations in the latter may vary

depending on the history of the groundwater pathway and contact with biodegradable organic chemical pollutant sources and plumes that may have depleted DO where anaerobic plume conditions occur. The observed DO concentrations generally declined with depth as expected with distance from the oxygenated surface-water interface, but still showed significant variability over the 0.1 – 0.5 m depth below riverbed. Monitoring of DO will be important in the extraction tests.

Nitrate may likewise be used as an electron acceptor and consumed in bacteria-mediated denitrification reactions. It may be elevated in both groundwater and surface waters with both urban and rural point and diffuse anthropogenic sources of nitrate widely present in the environment. The shown data (Figure 9) indicate a greater presence in the discharging groundwater with a general decline in concentration toward the riverbed surface. Temporal variability is not as significant as DO, but more significant than the sulphate and chloride. This is not unexpected as general biotic activity may be anticipated to occur in the order DO > nitrate > sulphate > chloride. Relative comparison of profiles suggest that groundwater – surface water mixing dilution is in part responsible for the declining trends of nitrate towards the riverbed surface, but with potential for some denitrification occurring particularly where DO has become low, 1-2 mg/l (rather than complete absence of DO) may be a threshold for denitrification observed elsewhere. Monitoring of nitrate will be important in the extraction tests.

Background HZ riverbed monitoring is on-going and databases actively populated for a wide range of anions, cations, metals and organics. All the baseline chemical data will be reported with the analyses of the experimental results from the planned test programme. Previous data obtained from piezometers near to the HZ Test Site indicate the following for groundwater taken 0.5 m below the riverbed (Ellis, 2003): 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. These values indicate a reasonable quality urban water with only low level contamination present with concentrations below EQS standards. Other parts of the 7-km unconfined aquifer reach of the Tame have locally shown more significant contamination in riverbed piezometers (Ellis et al., 2002, 2004, 2007; Ellis & Rivett, 2007; Rivett et al., 2008).

4 Experimental Arrangement

4.1 Background

The hydraulic conditions will have some influence on the biogeochemical processes that govern pollutant attenuation within the hyporheic zone. It is proposed that controlled (hence known) perturbation of hydraulic conditions may permit greater insight into attenuation controls as the hydraulic condition is manipulated. The proposal is to apply artificial hydraulic conditions through a bankside extraction well located adjacent to the hyporheic zone under evaluation. For a groundwater-effluent natural condition, extraction by that well will lead to modified hydraulic gradient conditions across the HZ and a reduction of the discharging baseflow groundwater component to the river. Although groundwater may still discharge to the river, as hydraulic gradients are not completely reversed, the residence time within the HZ will be increased due to the lower vertical gradients. As extraction rates are increased, HZ gradients decline and residence times increase leading potentially to greater opportunity for attenuation. With yet higher extraction rates and, or a particularly permeable connective strata existing between the well-screen and the river, the surface water may become influent to groundwater. The aim, however, is to achieve modified effluent conditions, rather than influent, but recognising natural flood events may lead to temporal influent conditions arising.

Bank-side extraction tests, lasting between 1 and 3 months will be used with extraction at different, but constant, rates for each test to reduce baseflow from the aquifer to the river. It is anticipated there will be several affects, including: a slower migration of groundwater through the HZ and greater time for reaction and formation of attenuation products; increased surface-water - groundwater mixing depths within the riverbed sediments; movement of geochemical boundaries, e.g. oxic-anoxic boundary of other Eh redox boundary lines; increased entry to the river bed of DO, nutrients, DOC from the surface water. The geochemical conditions will be monitored within the hyporheic zone in parallel to measurements of hydrodynamic conditions to understand the influence of the extraction tests. A network of bespoke installed mini-drivepoint piezometers and, or multilevel samplers will be installed manually in the riverbed sediments within the radius of influence area of the extraction borehole to allow vertical profile and 2-D/3-D temporal data to be collected on water quality changes in the HZ.

4.2 Borehole configuration

The extraction borehole was installed in July 2007 at the HZ Site following signing of agreement with the site owner and the granting of a Water Resources Act Section 32

groundwater investigation consent (E/UT/28/09/0082; E/UT/28/08/0161) from the Environment Agency that allowed both drilling and test pumping of the extraction borehole. The borehole is located on the east bank of the River Tame (5 m from the bankside) in Witton, Birmingham (Figure 10).

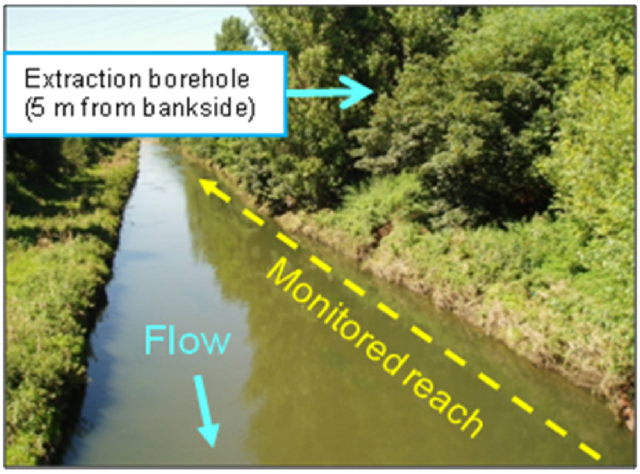

Figure 10. Plate showing the location of the SWITCH HZ Test Site reach.

The first attempt to install the extraction well was undertaken using a Dando rig with the intention of installing 200mm steel drill-casing to consolidated rock followed by open hole drilling to the final depth. The casing installation was done in conjunction with the use of an 8″ tri-cone bit for reaming and a down-hole hammer to break up the many large pebbles that repeatedly prevented the penetration of the casing into the free-flowing gravels and cobbles. At approximately 7.5m bgl a band of very large pebbles was encountered which could not be passed. To complete the well, a larger Techno drill was mobilized and a 12″ hollow stem auger used to successfully penetrate the fluvial sands and gravels and enter the weathered sandstone at approximately 9m bgl. The remaining borehole was drilled to the final depth with an 8″ tri-cone bit. The borehole log and completion details are shown in Figure 11. The borehole was ultimately completed at a diameter of 150 mm throughout to a depth of 16.5 m below ground. The successive lithologic layers (as measured by drill cuttings, rather than core) were top soil, made ground, sands and gravel, weathered sandstone and Triassic sandstone at the bottom. The borehole was completed with plain casing from surface to 10 m below ground, with slotted UPVC casing of 3 mm slot-size extending from 10 m to the base of the hole and hence screening the Triassic sandstone encountered (Figure 11). A gravel pack was installed over the screened interval. The borehole was complete at surface with a block-built concrete sump and cast-iron plate cover. As the ground surface at the borehole extraction site at 95 m aod was located *c.* 4 m above riverbed, the well screen was located c. 6-12 m below riverbed.

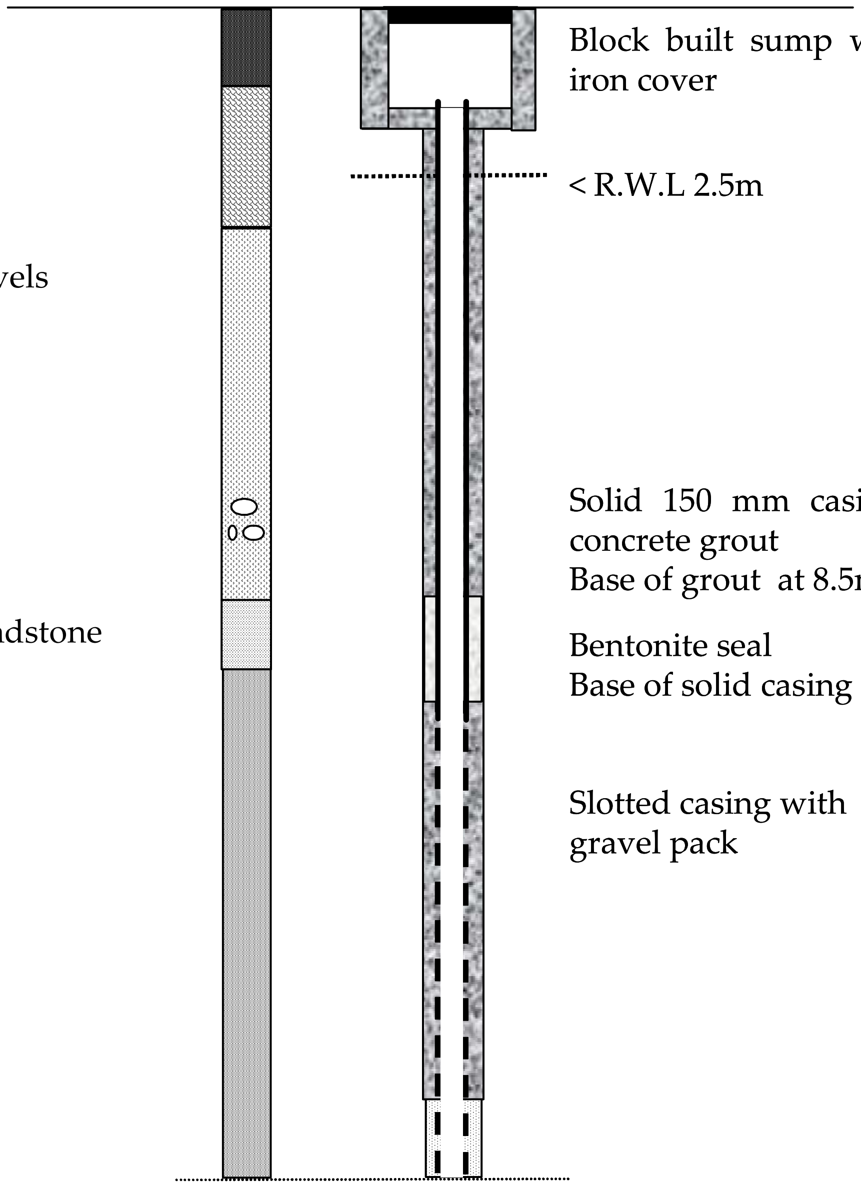

Figure 11. HZ Site extraction borehole completion and geological log (m below ground surface).

4.3 *Riverbed hyporheic zone monitoring network*

The initial riverbed HZ monitoring network was installed in July 2007 to monitor hydraulic and water quality conditions in the *c.* 200 m reach centred around the extraction borehole. Installation methods and design were similar to other river Tame studies described by Rivett et al. (2008). Installations used manual drive point methods causing minimal disturbance of the riverbed. The network comprised:

- Piezometers: comprising 29 drivepoint piezometers (9 mm ID, 12 mm OD HDPE) for measurement of head
- Combined piezometer-multilevel samplers (Figure 13): comprising 22 drivepoint piezometer (as above) with 5-10 multilevel chemical sampling tubes (1.6 mm ID, 3.2 mm OD Teflon® tubes) surrounding the piezometer tube and with the sample points spaced at 0.1 m depth intervals; the multilevel samplers provide the access points to collect water quality data to determine the HZ depth quality profiles.
- Transducer-piezometers: comprising 8 drivepoint piezometers (4 mm ID, 5 mm OD Nylon) furnished with bespoke automated head monitoring transducer devices (Figure 14).

The sample points are distributed in cross-sections along the river reach. For record keeping sample point names correspond to the distance from the extraction borehole (Figure 12). The negative distances indicate upstream cross-sections, up to 90 m upstream of the borehole, and the positive distances indicate downstream cross-sections, up to 110 m downstream of the borehole, i.e. the network covered 200 m of reach. The distance between successive cross-sections is less in the vicinity of the extraction borehole allowing higher resolution monitoring in this area (Figure 12). Piezometers penetrate to different depths across the network. The shallowest is set at 0.15 m and the deepest at 1 m with a mean depth of 0.4 m. The piezometers with automated head monitoring measure pressures relative to river stage using a bespoke transducer developed by the University. The transducers used permit measurements of water levels with an accuracy of 3-4 mm and time intervals can be set from one second between measurements and 12 h as an upper limit. The loggers can record up to 44000 measurements before being down loaded. The standard period for measurement interval was initially set to 5 minutes, giving the period between downloads and any maintenance of 30 days. The river water levels are recorded automatically by a Diver sonde (Figure 12).

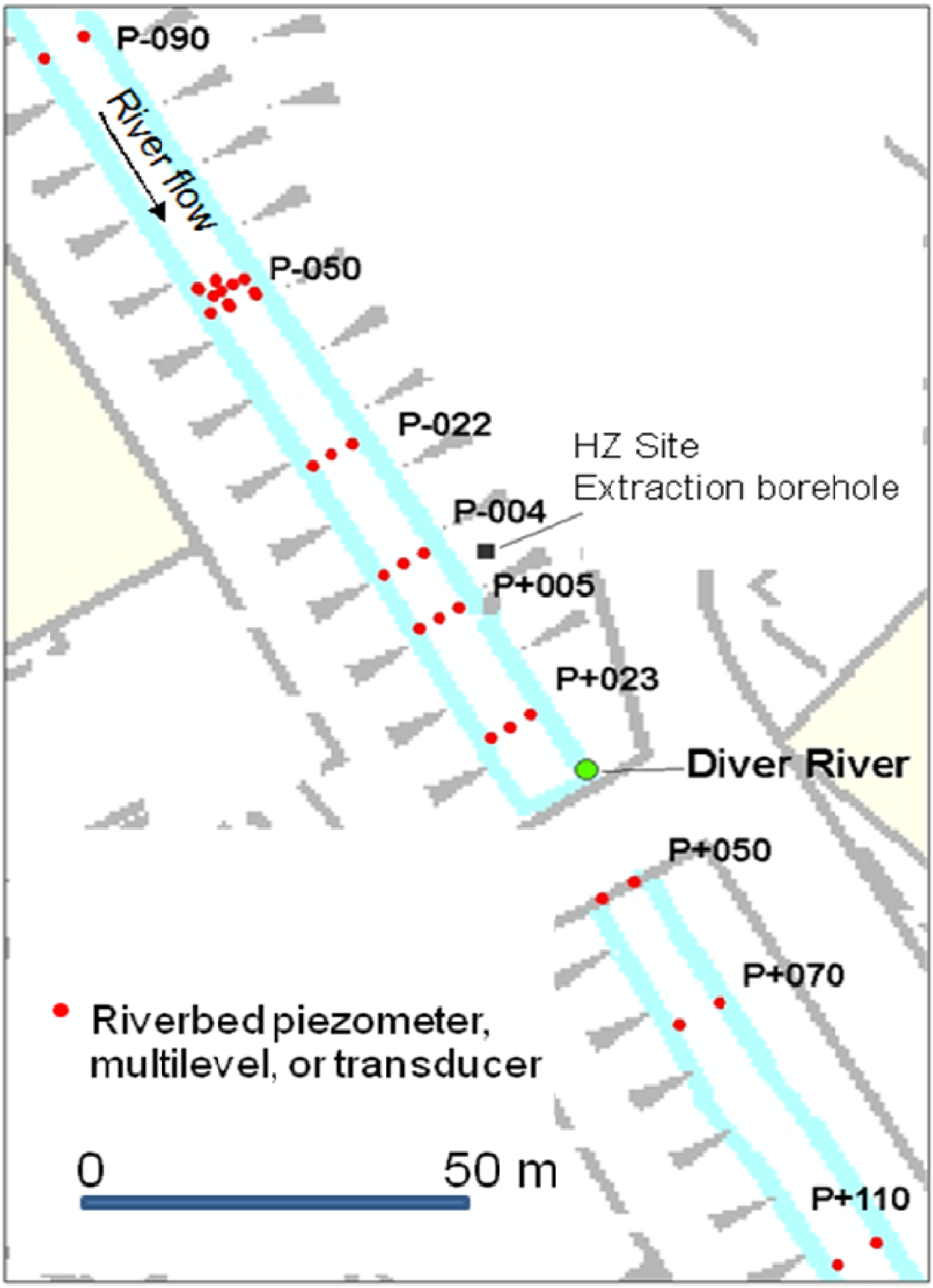

Figure 12. Location of HZ Site riverbed monitoring network points (phase 1, July 2007 installation) adjacent to the HZ Site extraction "borehole". The network points (type not differentiated) comprises piezometers (29), combined multilevel-piezometers (22), transducer-piezometers (8) and a Diver sonde (1) for river-head monitoring and cover a 200-m long reach. The Figure 10 plate was taken looking upstream from the bridge marked.

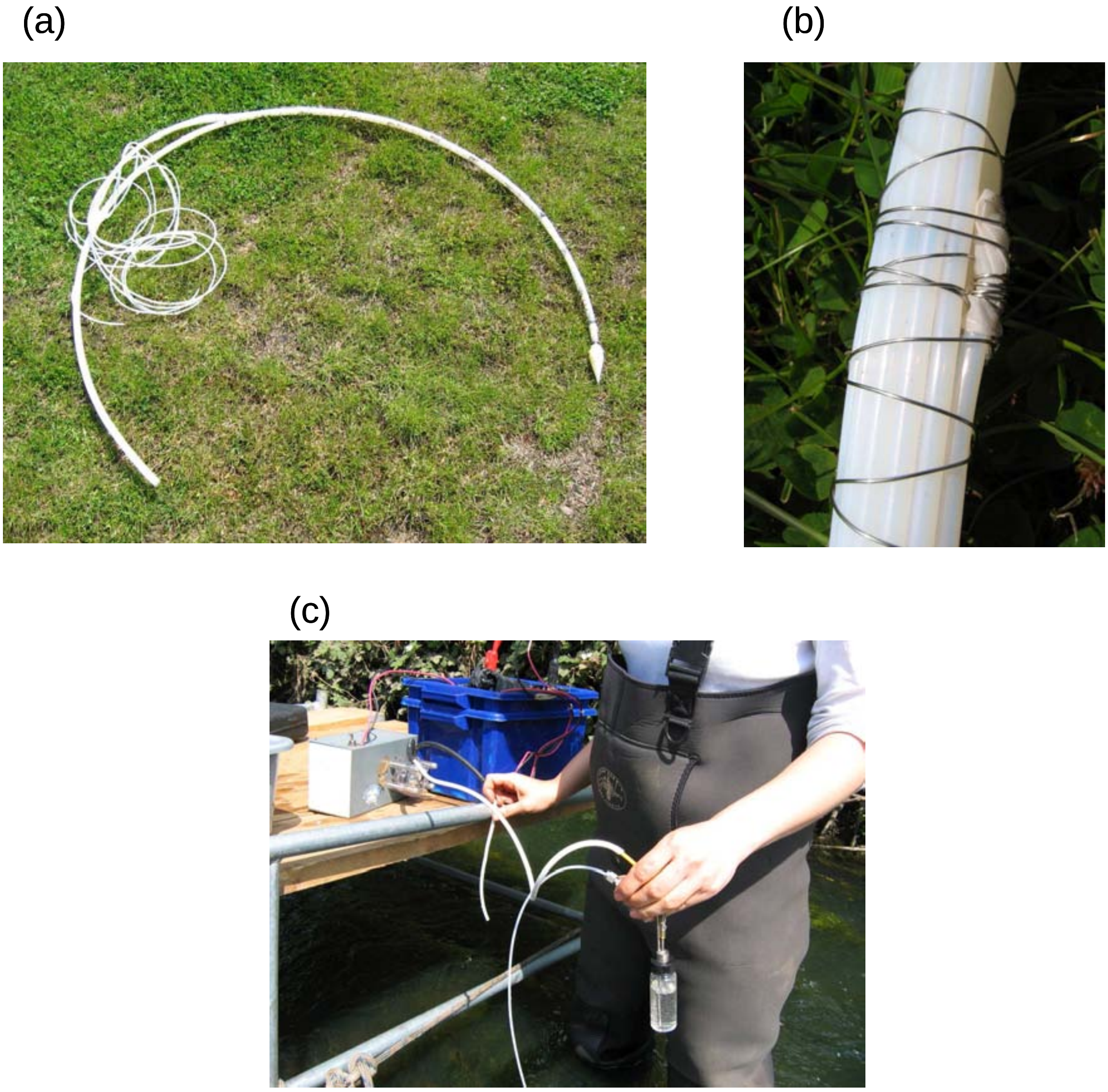

Figure 13. Plates of the combined piezometer-multilevel samplers showing: (a) the complete sampling device; (b) close-up of a monitoring point for water quality sampling; and (c) sampling being undertaken with a peristaltic pump – sample-head setup.

For the manually monitored piezometers, or combined piezometer-multilevel samplers the following sampling methods were adopted (in brief). Heads were measured in the wider diameter piezometer tubes manually, either visually or with a narrow coaxial cable dipper. Sampling of the multilevel sampler ports for chemical water quality was undertaken with a peristaltic pump connected to either a sample head fitted to glass vials or plastic sample bottles or a flow-through (Sheffield®) cell for well-head field determinants such as pH, Eh.

The transducer piezometers combined with the river-head Diver device allowed a continuous record of differential heads between the river and the hyporheic zone to be collected. The small piezometric tubes were connected to automatic pressure transducers within impervious boxes located on the riverbed (Figure 14) that were periodically downloaded.

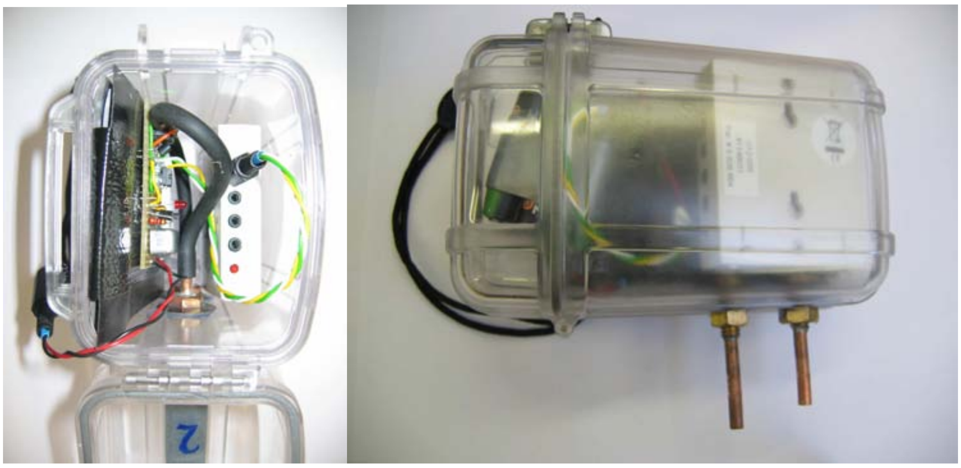

Figure 14. Automatic pressure transducers devices and logging equipment in impervious box connected to a piezometer tube and to the river

5 Experimental Programme

5.1 *Initial set up*

Before beginning the pumping test, it was necessary to know the baseline conditions within the riverbed, both in terms of hydraulic and chemical properties. Due to the on-going nature of data collection, lab analysis and interpretation, aspects of these are only briefly indicated here. The complete datasets and their interpretation will be presented more fully in future reporting in conjunction with the extraction test data.

5.1.1 Preliminary hydraulic testing

Some slug tests on each piezometer were performed in Autumn 2007 to determine the local hydraulic conductivity of the river bed materials. At the same time, the piezometric head differences between the observed piezometric level and the river water level were also measured and converted to gradients by dividing the head differences by the depth from the river bed to the piezometer mid point. The results are shown on two maps (Figure 15) and illustrate a high spatial heterogeneity with varying groundwater-effluent or river-influent conditions indicated. Continued temporal monitoring (manual and transducer) over the baseline (up to May 2007)

indicates most monitored locations are groundwater effluent with groundwater heads close to or a few cm above river level. Some monitored sites exhibited anomalously high gradients that were potentially related to mal-functioning devices, e.g. blocked screen piezometers, incorrectly installed/recording transducers. Further piezometers were later inserted at some of these sites to evaluate measurement reliability.

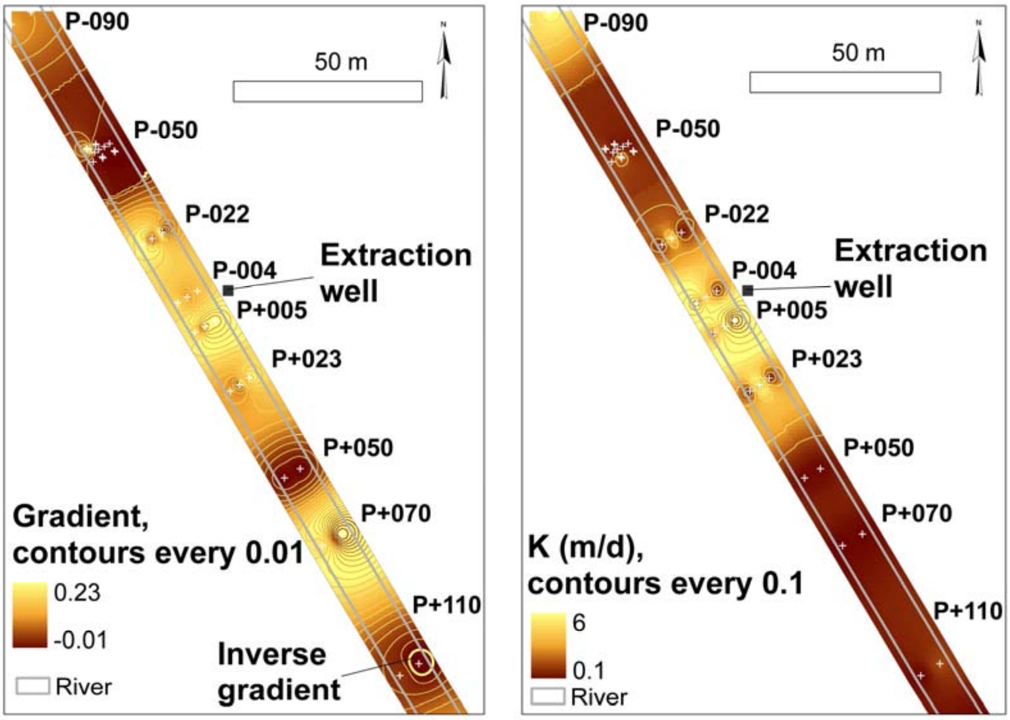

Figure 15. Example baseline hydraulic gradient (positive gradients correspond to groundwater discharge to the river) and hydraulic conductivity data from an initial hydraulic survey of the riverbed.

5.1.2 Baseline chemical water-quality analysis

A survey of the water quality sampling points on the combined multilevel-piezometer samplers was undertaken in Autumn 2007 with a follow up survey conducted in late Spring 2008 shortly before the first HZ Site extraction 'Test 1'. Some surface water samples were also obtained to characterise the quality of the river Tame. Sampling of the extraction well was undertaken for the Agency as part of the borehole licensing and discharge consent regulatory process. Those data have already been reported on in Section 3.4. It was apparent for the initial survey that not all of the multilevel sampler points yielded water, i.e. some sample points were blocked or potentially resided adjacent to very low permeability materials yielding little flow. Some further monitoring points were hence installed towards the end of

the baseline period (Spring 2008) to duplicate or provide new points in the vicinity of the extraction well. Determinant suites in the baseline have included conventional field parameters (pH, Eh, DO etc.), major/minor ions (by IC), metals (by ICP-MS), TOC/DOC and VOCs. The initial baseline survey indicated an absence of significant VOCs in the groundwater and sampling for that suite is to be dropped from future monitoring campaigns.

The water quality data are to be fully reported in conjunction with the extraction test data in later reports. Example EC (electrical conductivity) are reported here (Figure 16). The values of EC are relatively low and notably lower than the overlying river water EC. This suggests that the discharging groundwater is generally of a better quality in relation to total major/minor ions (EC being a measure of TDS (total dissolved solids)) than the river water. There is an E-W (east – west) trend in EC within the riverbed water in the vicinity of the extraction borehole with EC measured on the east side, closer to the borehole, slightly higher and approaching river values (Figure 16). This may reflect both different sources of groundwater, i.e. flows from groundwater units on opposing sides of the river, and, or contrasting mixing of surface water with groundwater. Certainly temporal data from elsewhere on the Tame indicates quite a dynamic exchange of surface-water and groundwater with surface water (as signified by chloride) penetrating to 0.5 – 1 m (Rivett et al., 2008).

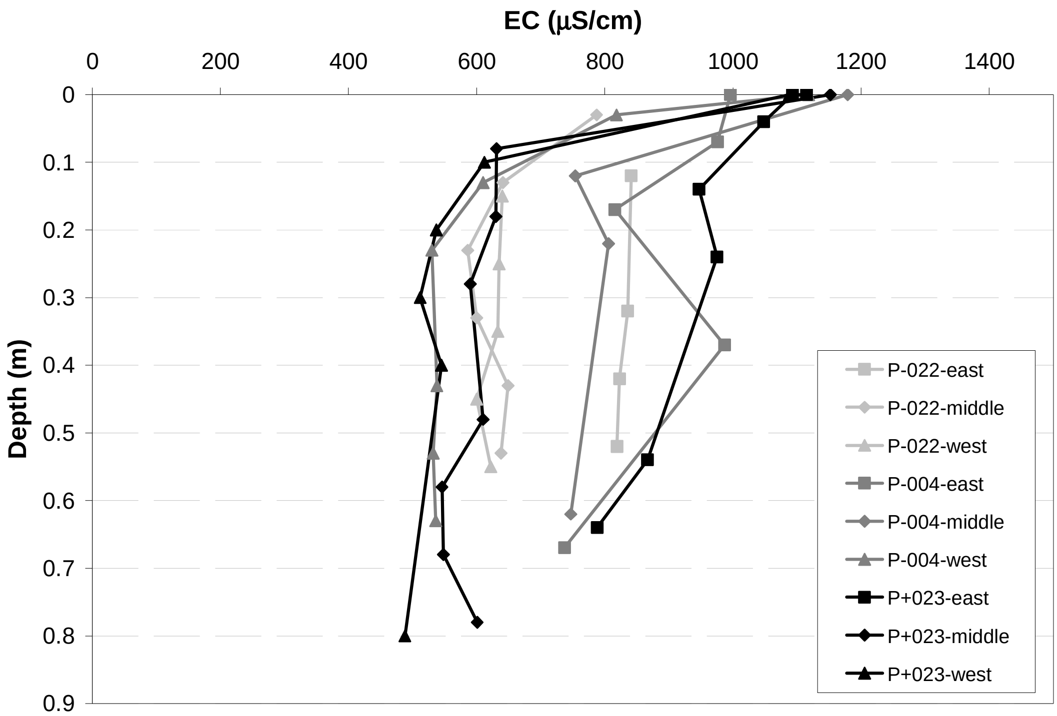

Figure 16. Electrical Conductivity (EC) values from riverbed network multilevel samplers located on three cross-sections close to the extraction borehole.

5.1.3 River bed survey

In order to develop a detailed model of the HZ Test Site, the precise positions of each measurement point were obtained using basic surveying to reference the site elevation to the National Grid reference Eastings and Northings.

5.1.4 Testing in support of regulatory licence applications

Conduction of the proposed HZ Site extraction tests not only required the permissions of the relevant landowners, but also permissions from the Environment Agency. These related to: (i) the drilling of the extraction borehole and extraction of groundwater; and (ii) the discharge of the extracted groundwater to the river. Aspect (i) required a 'Section 32' consent to drill and test pump the extraction borehole and would potentially leading to a full extraction license. Aspect (ii) required a 'discharge consent' to be granted from the Agency. Much time and effort has been put into securing both of these during 2007 and the first quarter of 2008. This included the obtaining of relevant background data, e.g. water features survey and the conduction of field work, notably the formal pump test and associated monitoring of both the HZ site monitoring infrastructure and nearly of-site wells. Quality sampling was also undertaken in relation to the discharge consent.

Reports and documentation associated with both of the above were submitted to the Agency in early 2008 (not included here) with permissions successfully obtained in the second quarter of 2008. Neither application raised undue concern with the Agency and were not expected to based on: (i) the groundwater extraction was sufficiently low volume and remote from other abstractors or sensitive water features to have detectable influences; and (ii) the quality of groundwater extracted was generally good and its volume small compared to the flow in the receiving water, i.e., River Tame. In summary, the Agency's decision was to not progress the groundwater extraction to a full license, rather authorise the test extractions to be conducted under an extended consent. A full discharge consent was, however, granted to the University of Birmingham (Discharge consent NPSWQD001206, May 2008) for the discharge of the borehole effluent to the river at a location *c.* 20 m downstream of the extraction well. The consent stipulates monitoring of the borehole effluent discharge volumes to the river (up to a maximum of 180 m^3/day and chemical quality monitoring for just suspended solids (to remain < 40 mg/l) and pH (to remain in the range 6 - 9) required. Breaching of these quality criteria throughout the HZ Site extraction tests is considered unlikely.

5.2 *Preliminary simulations*

To predict the influence of a long-term pumping test on the riverbed hydraulic gradients, a basic 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 (the 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, the aquifer properties 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 (hydraulic conductivity) were chosen for each of the three principal units corresponding to the range of values observed from other pumping tests in the region. Figure 17 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 18. As the pumping 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 about K, particularly of the riverbed value. The simulations do show that for the expected range of values of K for each of the formations that the pumping rate from a 16m deep well should yield the desired reduction in the baseflow components over a significant region of the HZ Test Site.

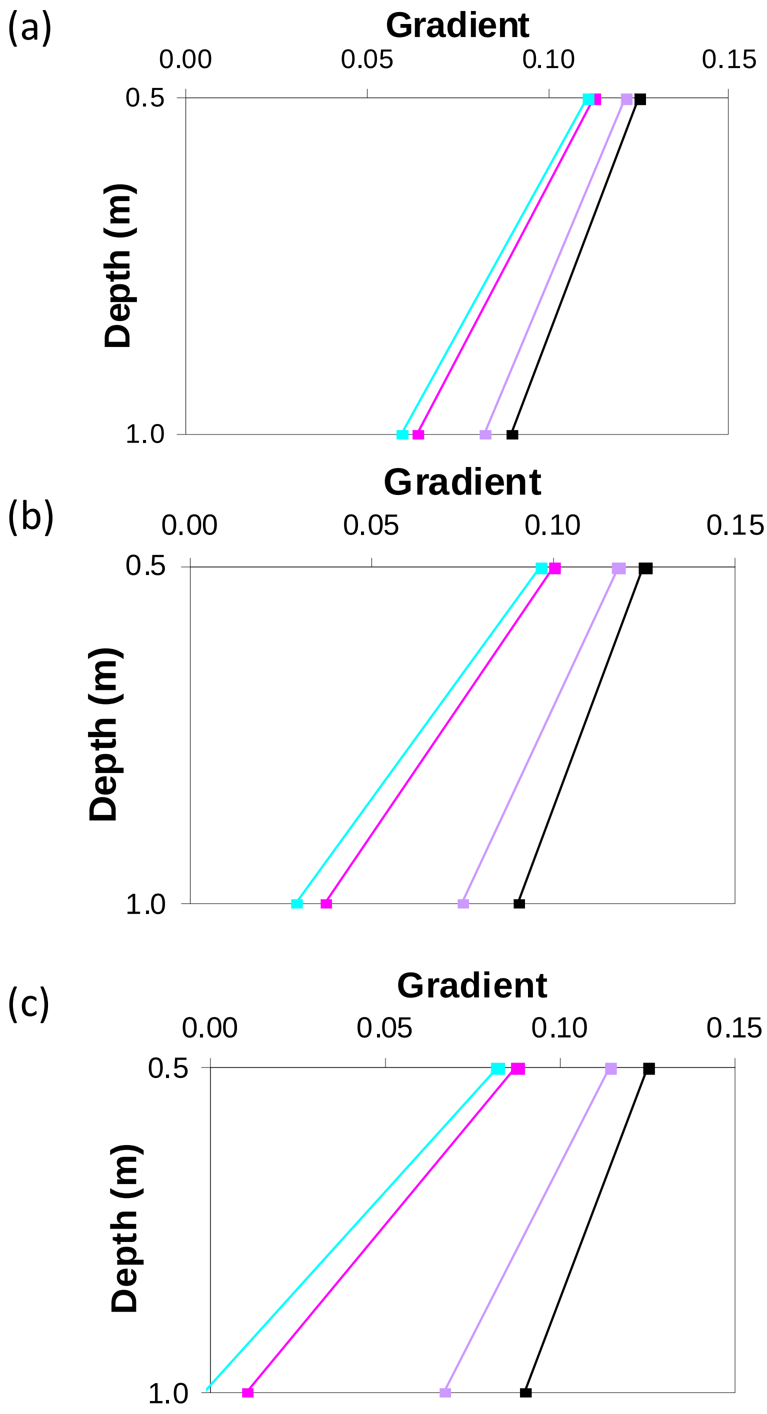

Figure 17. Simulated variation in hydraulic gradients within the sediment in P1 location under the influence of extraction from the aquifer calculated for different sets of hydraulic conductivities (set 1 in purple, set 2 in pink and set 3 in light blue) and different discharge rates (a: 50 m^3/d; b: 100 m^3/d; c: 150 m^3/d) compared to the observed natural hydraulic gradient in black.

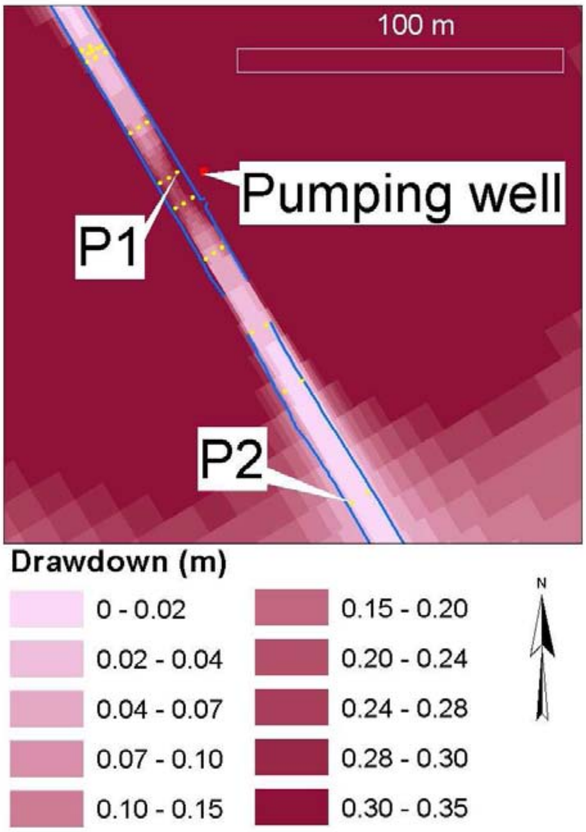

Figure 18. Simulated drawdown 50 cm below the riverbed under the influence of a 150 m^3/d extraction rate.

5.3 Experimental Plan

The experimental plan covering 2008 and the first quarter of 2009 is summarised in the Gantt chart (Figure 19). Five main areas of activity are proposed: (i) Meeting regulatory requirements; (ii) Baseline monitoring / site characterisation; (iii) Test 1; (iv) Test 2; (v) Test 3. Reporting is included in the chart as the final item for completeness. Critical to the plan was the gaining of Environment Agency licenses and consents in a timely manner; any delays in such will force a compression of the programme and cancellation of Test 3. These were ultimately granted (as noted above) in the second quarter of 2008 (i.e. recently) which has lead to a slight compression of the test programme and a (non-serious) 1-2 month slippage of the extraction Test 1 start date outlined in the 2008 plan.

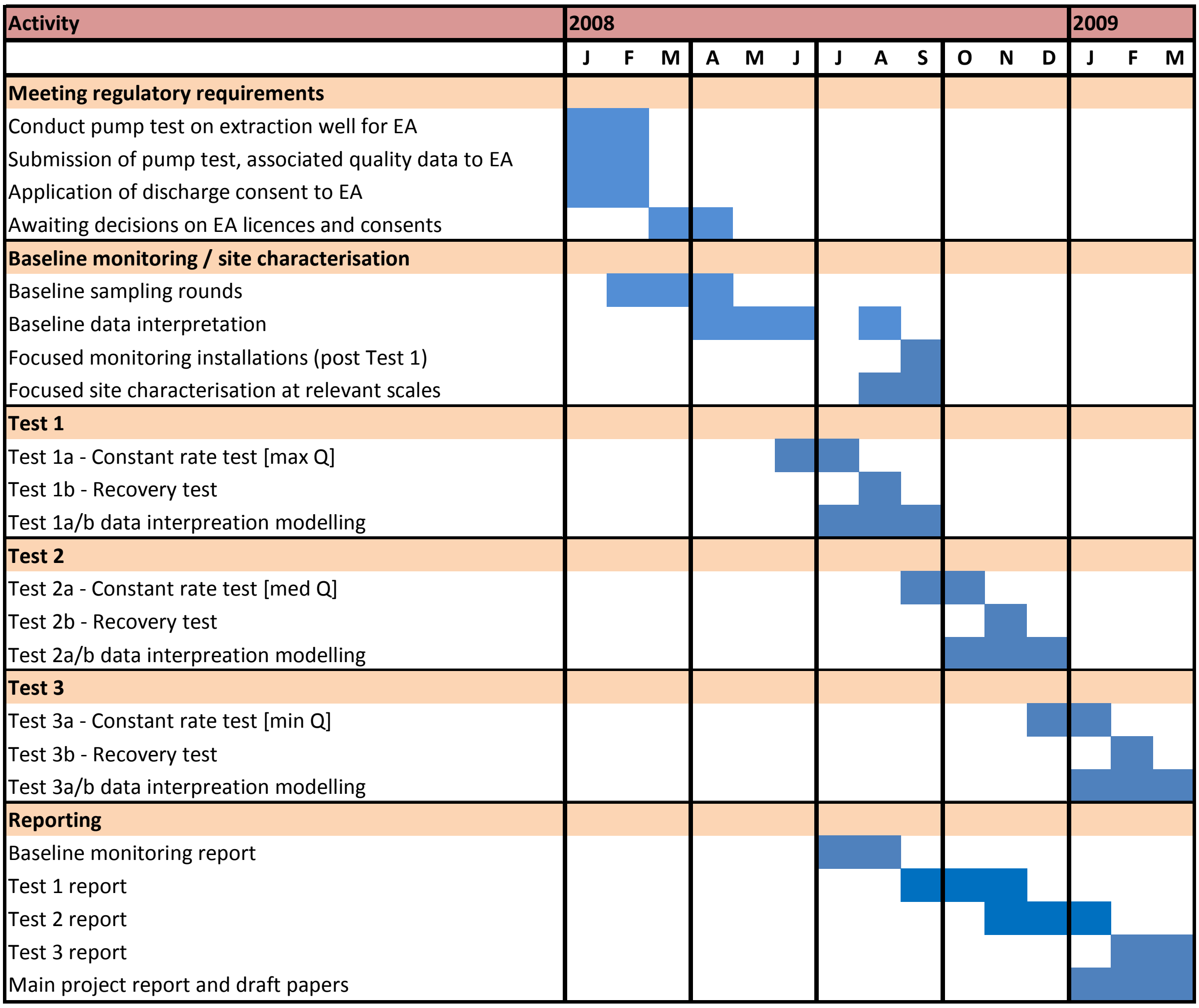

Figure 19. Gantt chart for 2008-09 activities.

Three pump tests at differing borehole extraction rates are proposed to allow understanding of a low, medium and high perturbation of the hyporheic zone flows. Test 1 will be conducted at the maximum rate, ~ 1.5 l/s, to induce a high perturbation test regime. The following tests will then be reduced in flow rate, rates being chosen based on the Test 1 influence. All tests are proposed to comprise a 2-month extraction period followed by a 1-month recovery period (no extraction). Again, this is a best estimate based on the field-conditioned model simulations and may well be modified depending upon observed effects during Test 1. Time reduction or lengthening of the tests are both possible, the latter will, however, necessitate 2 rather than 3 tests being ultimately conducted. Key activities during each test will be: water-quality sampling of the HZ Site monitoring network; associated lab analysis of water samples; hydraulic head measurement (manual and transducer); data assimilation; and data interpretation with support modelling as appropriate. The focus of the data

interpretation will be the understanding of surface water – groundwater mixing and changes in hyporheic zone attenuation behaviour observed under the various test hydraulic conditions per the initial three objectives set out in Section 2.

To date significant site characterisation and baseline-period monitoring has already been undertaken with interpretation on-going. Additional site characterisation focused to the scales of interest (indicated by the regulatory compliance pump test and Test 1) will be undertaken throughout 2008. There may also be a need to install further optimised riverbed monitoring following Test 1.

5.4 Other investigations

5.4.1 Momentum exchange

One of the issues that has arisen in previous investigations of the hyporheic zone is why there appears to be mixing of river and groundwaters at apparently all points beneath the river bed. Such conditions would not be expected where hydrodynamic mixing alone contributed to the presence of the zone (Ellis et al., 2007). One possibility is that additional mixing is facilitated by an enhancement to the diffusive mixing in the river bed and that this mixing is a result of velocity perturbations within the bed sediments that are associated with pressure perturbations in the river caused by the turbulent mixing in the river. The potential for velocity perturbations at depth in the bed sediment has been demonstrated previously (Ellis et al, 2007). However, no previous research has been found that has demonstrated that such variations in velocity can lead to enhanced diffusion. Therefore, as part of the present research, this concept will be tested through a series of laboratory and field experiments.

The field experiments will include the following:

1. Determination of the pressure fluctuation spectra from direct measurements at the bed of the river to yield the magnitude of the pressure fluctuation and the frequency distribution of the fluctuations.
2. Evaluation of the relationship between the pressure fluctuations and location within the river bed.

The laboratory experiments will include:

1. Design of an experimental rig for the determination of enhanced diffusion potential.
2. Determination of the impact of pressure fluctuations at the surface of a sand column on diffusive mixing magnitudes at different depths and for different amplitudes and frequencies of pressure perturbation at the top of the column.

3. Evaluation of the impact of material hydraulic properties on the depth of velocity perturbation.
4. Development of a model describing the diffusion response and the construction of a constitutive relationship for this response if it is determined to be significant.

The results of this process study will be introduced into the full model for the HZ Test Site to be developed as a significant product from the main test programme identified in Section 5.3.

5.4.2 Simulation modelling of HZ processes for river restoration

The model developed to describe the HZ Test Site will be used to explore alternative designs for river bed geometry and plan form geometry of a river reach to achieve maximum opportunity for development of an HZ and the protection offered through the natural attenuation processes that are observed to take place (contributing to the fourth objective in Section 2). The framework for this modelling will depend on the generalisation of the results of the simulation modelling under the preceding investigations through the development of general representations of the following elements: bed form versus HZ mixing; pressure fluctuations versus plan view geometry; biogeochemical process descriptions for the key natural attenuation processes for typical contaminants; hydraulic characterisation of typical bed materials and descriptions of typical stable bed material distributions based on geomorphologic knowledge of river beds. The extent to which each of these generalised components will be validated remains uncertain at this stage. However, account for the residual uncertainties will be made in the determination of potential benefits from the inclusion of a natural attenuation contribution to river restoration proposals and options and in the development of design guidelines for exploitation of the HZ.

6 Summary

An extended time period has been required to perform the baseline construction of the HZ Test Site and its initial testing. The development of the research programme has been completed and the main experimental phase is underway. Both previous and recent knowledge of the site and adjacent areas along the river Tame has demonstrated that the river bed is only weakly contaminated within the reach of the HZ Test Site and that investigations of the natural attenuation capacity of the system will be limited to a detailed evaluation of the potential for attenuation based on the determined mixing characteristics and the temporal evolution of the hyporheic zone as evidenced by the results from the different field tests. Initial sampling networks

have been installed at the site and these will be refined as each test progresses as required. Key to understanding the value of the HZ as a natural attenuation buffer between polluted groundwaters and the through flowing river water will be to quantify the spatial and temporal variability of the HZ. The experimental programme has been designed to achieve improved measurements that will quantify both forms of variation. A suite of additional tests are also proposed that will elaborate the processes and the component interactions between different parts of the river and the river-aquifer interface that affect the natural attenuation potential of the HZ.

The ultimate goal for the study will be to determine the extent to which risks from groundwater pollution can be mitigated by sustaining the natural functioning of urban rivers and by appropriate design linked to any restoration proposals that may be considered as part of the regeneration of the urban landscape. Modelling will form a key tool in the development of a quantified picture of the HZ Test Site and the controls governing the existence and performance of the HZ.

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