



Urban groundwater baseflow influence upon inorganic river-water quality: The River Tame headwaters catchment in the City of Birmingham, UK

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SUMMARY

Understanding the linkage between urban land, groundwater, baseflow and river contamination at the city scale is lacking. This study evaluates the influence of inorganic (major/minor ions and metals) groundwater contamination in the Triassic sandstone–Quaternary deposits aquifer system underlying the City of Birmingham, UK upon the baseflow and water quality of the river Tame. Baseflow water-quality data have been collected from a riverbed piezometer network installed in the 7.4 km reach crossing the effluent unconfined sandstone aquifer and compared to river and aquifer water-quality data. Overall, the inorganic chemical quality of the baseflow was not as poor as potentially surmised from the urbanisation present. Baseflow impact upon river-water quality was also low. These conclusions were underpinned by evidences of: limited river-water quality changes along the reach; some river concentrations being diluted by better quality baseflow; only occasional breaching of water-quality criteria; limited impact upon river-reach quality local to elevated baseflow discharges; natural attenuation occurrence within the riverbed; and, modest, albeit somewhat uncertain, baseflow mass fluxes. Baseflow fluxes to the reach were in the ranges 100–3500 t/yr for major ions, 1–50 t/yr for minor ions and 1–500 kg/yr for toxic metals with zinc and nickel most prominent. The sporadic occurrence of elevated baseflow concentrations was ascribed to discrete groundwater plume discharges. More detailed sub-reach studies would be required to fully resolve discrete plume baseflow contributions and improve mass flux estimates. Not uncommonly, the urban river studied was already contaminated and hence persistent baseflow fluxes may assume more importance if the river became cleaner through other control measures. Future research should hence consider the emergent significance of urban baseflows. There are needs to: conduct similar studies to investigate if city-scale baseflow impacts are comparable elsewhere; research the importance of spatially and temporally dynamic attenuation in the riverbed; and, develop improved baseflow mass flux estimation methods.

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1. Introduction

Many urbanised areas have developed across aquifer systems in hydraulic connectivity with river systems. Industrial and urban activity, often spanning decades to centuries, may result in chemical contamination of the land and underlying groundwater that may pose attendant risks to surface waters in receipt of groundwater baseflow (EA, 2009). Surface-water quality improvements achieved by control of industrial effluent pipe discharges, urban drainage programmes, or industrial closure, may ultimately be limited by the longer term release of contaminants from urban land. Timeframes between an original pollution event, percolation through the unsaturated zone, transport in groundwater, and eventual baseflow discharge to a receiving river may be years to dec-

ades later and depend upon the pathways and distances involved, groundwater velocities and capacity for natural attenuation of a pollutant in the subsurface.

There have been many studies of both urban groundwater pollution underlying cities (Graber et al., 2008; Hiscock et al., 2002; Rivett et al., 1990; Somasundaram et al., 1993; Tellam et al., 2006) and urban river-water quality (Erikssona et al., 2007; Gordon et al., 2005; Horowitz et al., 2008; Hudak and Banks, 2006; Karn and Harada, 2001; Peters, 2009; Tong and Chen, 2002). The link between contaminated urban groundwater and receiving rivers has, however, received comparatively little attention. Most recent work has been undertaken at the individual site scale (Conant et al., 2004; Westbrook et al., 2005) often driven by environmental liability assessment. Many sites may exist. For example, some 51% of the 1218 hazardous waste sites on the early 1990s US National Priorities List were estimated to impact surface water (USEPA, 1991). The cumulative impact of many industrial spill and waste disposal sites and other sources of urban groundwater pollution such as leaking

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sewers, storage tanks or drainage to ground from transportation routes may prove significant at the urban catchment or city scale.

Studies that link urban groundwater contamination with water quality in receiving river systems at the city/catchment scale are lacking. Available studies have tended to not directly measure riverbed baseflow discharges, but rather observe the river itself under baseflow conditions (Barber et al., 2006; Hur et al., 2007). Integrated studies are required to implement legislation such as the European Community Water Framework Directive (CEC, 2000) that is based upon groundwater–surface-water management at larger catchment, or conurbation/city scales. This larger scale understanding is underpinned by the expanding process-based research into contaminant natural attenuation in the riverbed hyporheic zone (taken herein to mean the zone of groundwater–surface-water mixing (Smith, 2005)). Sorption and degradation (Chapman et al., 2007; Smith and Lerner, 2008) and the influences of riverbed heterogeneity and hydraulic transients (Cardenas and Wilson, 2007; Cardenas et al., 2004; Kalbus et al., 2008) require increased understanding. This is important as attenuation may be enhanced in a nutrient-rich, redox-variable hyporheic zone compared to the proceeding aquifer and cause reduced groundwater impacts to a surface water.

Our research on the Birmingham aquifer–River Tame system contributes to the above needs. Integrated studies of the City of Birmingham's contaminated land, groundwater, baseflow and river-water quality have provided understanding of the city's groundwater baseflow impact upon the Tame, its primary river (Ellis, 2003; Shepherd et al., 2006). Our aim herein is to understand the influence of the long-established city upon the inorganic chemical quality of its groundwater baseflow that contributes to the city's main draining river and the associated impact upon river-water quality at the city scale. This has been realised through field study of the 7.4 km long Tame reach that receives effluent groundwater flow from the unconfined Birmingham aquifer underlying the city (Fig. 1). Our wider research programme on Birmingham includes study of volatile organic compounds (VOCs) in the aquifer groundwater and baseflow discharged to the Tame (Ellis and Rivett, 2007; Rivett et al., 2005) and flow and attenuation processes in the hyporheic zone (Ellis et al., 2007; Roche et al., 2008; Cuthbert et al., 2010).

2. Study setting

2.1. Urbanisation

Birmingham is the UK's second largest city set within the West Midlands conurbation and upper Tame headwaters – arguably the UK's most urbanised catchment (Lawler et al., 2006). The Tame rises in the urbanised Black Country and then flows through the city close to the principal north-south arterial motorway (M6). Most of Birmingham is underlain by the Triassic sandstone aquifer that has provided water primarily to its industry over the past century and longer. Earliest settlements located close to the present city centre and River Rea tributary date from the 12th century. This area is close to the Birmingham fault that separates the unconfined sandstones to the west from the Mercia mudstone confined, down-thrown sandstones to the east (Fig. 1). The industrial revolution saw the city develop into a major centre for metals and engineering manufacturing. Industrialisation had spread to the Tame valley by the early twentieth century (Fig. 1; Thomas and Tellam, 2006) with supporting coal and iron-ore extraction and smelting industries located upstream in the Black Country since the 17th century. Non-industrial areas in Fig. 1 predominantly comprise residential suburbs and a national hub of transportation networks. Open parkland is also present including Perry fields adjacent to the Tame in the upstream study reach.

2.2. Hydrology and hydrogeology

The study focuses upon the 7.4-km Tame reach crossing the unconfined Birmingham Sandstone aquifer (Fig. 1) (Wills, 1976). Annual rainfall is 650–800 mm with predominant surface and groundwater drainage from western high-ground towards the Tame to which groundwater is now effluent (Ellis, 2003). The Tame is 8–12 m wide and 0.2–2 m deep with natural and engineered sections, both predominantly of natural riverbed deposits. Minimum flow on the Tame (at Water Orton; Fig. 1) is ~180 Ml/d, but increases over an order of magnitude when in flood (later Fig. 3). The river efficiently drains the West Midlands and displays a relatively flashy hydrograph with quite steep recession segments spanning 1–3 d (later Fig. 3; Lawler et al., 2006). The Tame up and downstream of the study reach receives significant discharge from sewage treatment plants. Industrial discharge effluents have declined with only a few, low volume direct discharges occurring to the reach. During the decade prior to our study, it was estimated that >80% of dry-weather flow in the upper Tame was effluent discharge (NRA, 1996).

Quaternary deposits of alluvial and glacial origin cover the Triassic sandstone to depths of up to 40 m, but are only 1–5 m thick in the Tame valley (Powell et al., 2000). Alluvial gravel/sand/clay deposits occur in the valley bottoms and flood-plain deposits extend up to 1 km across the valley. Anthropogenic deposits (mine spoil, sand/gravels, ash, and rubble) up to 1–5 m thickness are extensive particularly on previously marshy ground. Our riverbed monitoring was located in the above deposits and the uppermost surface of weathered – unconsolidated Triassic sandstone. The study reach contained a range of poorly sorted sand–gravel–stones with more fine-grained sand and silt locally. The riverbed surface was often armoured with an upper stony surface. Significant macrophyte stands with extensive foliage (*Ranunculus* spp.) facilitate seasonal sediment accumulation in the riverbed. Our falling head tests on riverbed piezometers ($n = 44$) yielded an arithmetic mean hydraulic conductivity of 3.13 m/d and range of 0.08–23 m/d with geometric mean and medians of 1.26 m/d and 1.34 m/d respectively. Hydraulic gradients across 0.2–2 m of the riverbed ranged from –0.03 to 0.28 (+ indicates baseflow discharge to river) with a mean of 0.056 ± 0.06 .

The city-wide hydrogeology of the Triassic sandstone aquifer has been described by Land (1966), Jackson and Lloyd (1983) and Knipe et al. (1993) with Taylor et al. (2003) locally describing the Tame valley and Allen et al. (1997) the wider West Midlands Permo-Triassic sandstone. The aquifer comprises Kidderminster, Wildmoor and Bromsgrove sandstones that reflect different arid-climate deposition periods (Powell et al., 2000). Sandstones are predominantly fine- to medium-grained with occasional mudstone intercalations and may also contain bedding-plane fractures. They are considered a single hydrogeological unit, albeit with significant contrast in geological and hydraulic properties apparent between and within formations. Allen et al. (1997) have summarised hydraulic data for these sandstones across the West Midlands indicating median porosities of 25.7–27.4%, median core-based hydraulic conductivities (K) of 0.73–1.48 m/d and bulk (pump test) K medians ranging over 1.6–12.1 m/d, the increased values being attributed to fracture flow contributions.

Regional groundwater flow velocities based on a 0.004 regional hydraulic gradient (Rivett et al., 2005; Fig. 1) and the median core K data above would be 4.1–8.0 m/yr with greater velocities manifest where fracture flow is important. The multi-level borehole of Taylor et al. (2003) in the Kidderminster unit, 450 m from the river and central to the study reach, provided evidence of both upward and downward flows. Their data indicate the magnitude of vertical head gradients (e.g., 0.01–0.04 upwards) and the importance of geological low permeability layering in reducing vertical flows and transmis-

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