Natural attenuation potential of the urban hyporheic zone

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Abstract

Urban groundwater contaminant plumes may potentially discharge as baseflow to surface waters. So-called plume 'day-lighting' poses threats to surface-water quality and associated ecological environments. Incidences may lead to expensive remediation works. The use of monitored natural attenuation (MNA) strategies to manage groundwater plumes in aquifers in preference to engineered remedial measures has seen significant growth in recent decades (Rivett & Thornton, 2008). MNA is underpinned by the recognition that contaminant plumes may undergo natural attenuation (NA) in the geologic subsurface due to naturally occurring processes of dispersion, sorption and reaction – either abiotic chemical reactions, or bacterially mediated biodegradation. In recent years there has been emergent interest in NA potentially occurring within the riverbed – hyporheic zone (HZ) (EA, 2009). Interests are driven by legislation such as the EC Water Framework Directive that mandates integrated understanding of groundwater – surface-water systems and the anticipation that HZ conditions in gaining rivers may be more conducive to NA occurrence than those found in the preceding aquifer pathway. Increased NA potential is ascribed to greater availability of organic matter, nutrients, electron donors/acceptors and steep redox, or biogeochemical gradients that may promote attenuation (EA, 2009). Potential downsides are, however, the typically short path-length of the HZ and residence time for attenuation, and the immediate proximity of the HZ to the surface-water receptor. The aim of our SWITCH project work package has been to assess the NA potential of the urban hyporheic zone thereby contributing to a wider research agenda to evaluate the use of natural systems for self purification in the urban water cycle.

Our approach has centered upon the SWITCH HZ research site – an instrumented field site we have specifically developed under SWITCH on an industrial urbanised 200 m reach of the River Tame in Birmingham, the UK's second largest city and a 'SWITCH Demonstration City'

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(Cuthbert et al., 2009, 2010; Durand et al., 2007). Work on the SWITCH (HZ) Site has been additionally supported by continued parallel urban HZ research activity on the surrounding 7 km urban reach to which the Birmingham sandstone aquifer naturally discharges as baseflow and additional sub-reaches that have involved studies of specific groundwater plume discharges, for example involving contaminants not encountered at the SWITCH site (Rivett et al., *in subm.*; Roche et al., 2008; Ellis & Rivett, 2007; Ellis et al., 2007). We have also recently begun to assess the HZ attenuation potential at a further Birmingham site where a stream in receipt of motorway runoff leaks to the underlying sandstone aquifer (Rivett et al., 2010). These field sites have promoted development of monitoring technologies for the (urban) HZ (Greswell et al., 2009; Rivett et al., 2008). The interpretation of the various HZ field data sets has been supported by numerical modelling works. This assemblage of Birmingham sites has thus allowed us to assess the NA potential of the urban HZ, specifically for the Birmingham system and to comment more generally on urban systems.

A selection of key advancements and findings made at the SWITCH HZ and other Birmingham sites include the following.

- Baseflow fluxes to the 7 km urban reach were in the ranges 100 – 3500 t/yr (tonnes per year) for major ions, 1 – 50 t/yr for minor ions and 1 – 500 kg/yr for toxic metals and chlorinated volatile organic compounds (VOCs).
- Generally, chemical baseflow quality was not as poor as potentially surmised from the degree of urbanisation present. However, sporadic high-concentration groundwater plume baseflow discharges where found and subject to varied NA.
- Local sub-reach scale spatial variability in plume discharges and NA were evident – VOC plumes showed evidence of biodegradation (dechlorination) in lower permeability, higher organic carbon, more vegetated areas adjacent to zones with fewer of these features where plumes discharged to the river with limited NA apparent.
- The surface-water – groundwater mixing zone, that may provide an important source of river-derived nutrients / reactants for NA, or cause movement of biogeochemical NA reaction zones or redox fronts, was generally restricted to <0.2 m invasion depths. However, there were some evidences of deeper transient penetration into the HZ. Modelling and field observation indicated gas accumulation and storage in the HZ, possibly due to denitrification, may assist such deeper invasions.
- Flow reversals causing increased surface water invasion and temporary suppression of baseflows, increased plume residence time and NA potential were observed to be transient phenomena occurring for a few hours around storm event hydrograph peaks. It was difficult to induce flow reversals via a bankside extraction well that were significantly greater than induced by the natural urban river-stage temporal variability.
- The HZ was often weakly oxic with evidences of denitrification activity and some iron/manganese reducing conditions. More strongly reducing conditions, sulphate-reducing or methanogenic, were not generally obvious.
- Rapid contaminant concentration changes could occur through the HZ, that could not always be solely ascribed to surface water mixing dilution for various metals and VOCs and were taken to provide evidence of NA, particularly when corroborated by supporting redox, pH and other geochemical changes.
- There was some evidence of unwanted baseflow quality declines in passage through the HZ – this was attributed to historically contaminated sediments, most likely from accumulation of urban riverine sediments and prior influent conditions.

- Monitoring advancements were made, however, the need for techniques that can achieve higher spatial and temporal resolution, are automated and provide direct measurement of contaminant mass fluxes in the HZ is highlighted.

Overall, although the urban HZ offers some NA potential, this potential is spatially and temporally variable and contaminant specific. In general, NA potential is expected to be greatest in the lower permeability, finer grained and higher organic matter zones of the riverbed. Unfortunately, the bulk of baseflow is potentially transmitted through the higher permeability, lower NA potential zones thereby short-circuiting the best NA potential zones. The potential for NA of a plume will be site specific and require site specific evaluations and a typical line-of-evidence MNA approach, modified for the HZ. A regulatory preferred position may, however, perhaps be to primarily implement a bankside monitoring well compliance point, but recognize the HZ may offer some additional protective benefit. At most significant groundwater plume discharge sites, achievement of complete NA in the HZ would require engineered enhancement, for example through direct amendment additions to the HZ or, the installation of a permeable reactive barrier technology at the bankside that may promote reactions in the barrier or down-gradient in the HZ from barrier reagent dosing.

References

Cuthbert, M.O., Durand, V., Aller, M-.F., Greswell, R.B., Rivett, M.O., Mackay, R., 2009. River Tame hyporheic zone test site – data report. *Environment Agency Science Report* SC050070/SR. Publ.: Environment Agency, Bristol, UK.

Cuthbert, M., Mackay, R., Durand, V., Aller, M.-F., Greswell, R.B., Rivett, M.O., 2010. Impacts of river-bed gas on the hydraulic and thermal dynamics of the hyporheic zone. *Adv. Water Resour.* 33(11), 1347-1358.

Durand, V., Aller M., Greswell, R.B., et al. 2007. Investigation of the urban groundwater – surface-water interface via bank-side extraction well field tests: Concept and natural site conditions. Proc. of the 6th International IAHS GQ07 Conference, Fremantle, Australia, 2-7 December 2007, 286P, 61.

Greswell R, Ellis P, Cuthbert M, White R, Durand V., 2009. The design and application of an inexpensive pressure monitoring system for shallow water level measurement, tensiometry and piezometry. *J. Hydrol.*, 373, 416–425.

Ellis, P.A., Mackay, R., Rivett, M.O., 2007. Quantifying urban river–aquifer fluid exchange processes: A multi-scale problem. *J. Contam. Hydrol.* 91, 51-80.

Ellis, P.A., Rivett, M.O., 2007. Assessing the impact of VOC-contaminated groundwater on surface-water at the city scale. *J. Contam. Hydrol.* 91, 107-127.

Environment Agency (EA), 2009. The Hyporheic Handbook - A handbook on the groundwater–surface water interface and hyporheic zone for environment managers. Environment Agency Science report: SC050070. Environment Agency, Bristol, UK.

Rivett, M.O., Cuthbert, M.O., Simpson, D., Pearson, A., Shepley, M., 2010. Evaluation of winter motorway salting: impacts of surface water and groundwater, Battlefield Brook, West

Midlands. In: Urban Rivers: Emerging ideas and management implications. British Hydrological Society national meeting, 22 September, 2010, Birmingham, UK.

Rivett, M.O., Ellis, P.A., Greswell, R.B. et al., 2008. Cost-effective mini drive-point piezometers and multilevel samplers for monitoring the hyporheic zone. *Q. J. Eng. Geol. Hydrogeol.* 41, 49-60.

Rivett, M.O., Ellis, P.A., Mackay, R., *in subm*. Urban groundwater baseflow influence upon inorganic river-water quality: the River Tame headwaters catchment in the City of Birmingham, UK. In subm. *J. Hydrol.*

Rivett, M.O., Thornton, S.F., 2008. Monitored natural attenuation of organic contaminants in groundwater: principles and application. *Water Management*, 161(6), 381-392.

Roche, R.S., Rivett, M.O., Tellam, J.H., et al. 2008. Natural attenuation of a TCE plume at the groundwater – surface water interface: spatial and temporal variability in a 50 m reach. IAHS Publ. 324, 475 – 482.