HYDROLOGICAL PROCESSES
Hydrol. Process. **23**, 2103–2107 (2009)
Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/hyp.7366

Preface

Hyporheic hydrology: interactions at the groundwater-surface water interface

This special issue comprises papers on hyporheic hydrology given in an oral and poster session (HS7·4) titled 'Hydroecology of riparian zones: hyporheic controls at the groundwater-surface water interface' at the European Geosciences Union (EGU) General Assembly held in Vienna, 14–18 April 2008, as well as a selection of invited articles on recent advances in hyporheic zone (HZ) research.

The HZ is an interface that derives its physical, chemical and biological characteristics from active mixing of groundwater and surface water. Several investigations have shown that HZ properties may differ significantly from its surrounding groundwater and surface water environments (Bencala, 1984; Triska *et al*., 1989a,b; Findlay, 1995). For example, the HZ is frequently characterised by sharp chemical gradients in redox potential and dissolved oxygen (Boulton *et al*., 1998; Chafiq *et al*., 1999). This groundwater-surface water (GW-SW) interface may be very active biogeochemically, with hyporheic passage often resulting in conversion of nutrients and attenuation of pollutants (Grimm and Fisher, 1984; Triska *et al*., 1989a,b, 1993; Hill, 1996; Boulton *et al*., 1998; Hill and Lymburner, 1998). Furthermore, the HZ creates a unique environment, which hosts some highly specialised organisms that provide specific ecosystem functions and services (Stanford and Ward, 1988; Findlay, 1995; Brunke and Gonser, 1997). The HZ has been identified as an important habitat and refugium for a range of species (Brunke and Gonser, 1997; Dole-Olivier *et al*., 1997; Malcolm *et al*., 2004) and a 'hotspot' for biogeochemical cycling (Worman *et al*., 2002; Storey *et al*., 2004; Kasahara and Hill, 2006; Krause *et al*., 2009). Given this context, the EGU session solicited papers with a focus on:

(1) Development and application of novel experimental methods to investigate physical and chemical conditions and fluxes within the HZ.
(2) The role of hyporheic processes in retention and natural attenuation of nutrients and pollutants, and related implications for both surface water and groundwater quality.
(3) New hydrological, chemical and ecological models that include hyporheic exchanges.
(4) Impact studies of hyporheic controls on riparian and surface water biogeochemistry and ecology at different scales.
(5) The importance of GW-SW interactions for management and risk assessment in the context of the European Water Framework Directive.

The HZ can be viewed from a range of perspectives with different research questions resulting in different spatial and temporal scales of investigation. Hence, our EGU session also aimed to promote scientific exchange between often disparate disciplines (hydrology, biogeochemistry, ecology) and to identify current knowledge gaps in the field of HZ research. Therefore, we adopt a broader and more integrative definition of the HZ as: *the saturated transition zone between surface water and groundwater bodies that derives its specific physical (e.g. water temperature) and biogeochemical (e.g. steep chemical gradients) characteristics from active mixing of surface and groundwater to provide a habitat and refugia for obligate and facultative species*.

The primary rationale for this EGU session, and the emergent special issue, has been the rapidly increasing interest in HZ processes over the last three decades. A plethora of case studies on GW-SW interactions and HZ processes has been presented in the recent literature, ranging from sub-arctic (e.g. Gooseff *et al*., 2003, 2006; McKnight *et al*., 1999) to alpine (e.g. Hoehn and Cirpka, 2006; Brown and Hannah, 2007; Cadbury *et al*., 2008) to temperate (Harvey and Bencala, 1993; Kasahara and Wondzell, 2003; Kasahara and Hill, 2006) to semi-arid (Butturini *et al*., 2002; Fleckenstein *et al*., 2006) environments. Figure 1 illustrates the associated upsurge in publications listed in the ISI *Web of Knowledge* database using the term *hyporheic* (in the title, keywords or abstract) over the last decade. This bibliographic search may only represent the 'tip of an iceberg' because other papers may be hidden that consider GW-SW interaction and the hyporheic environment but do not use the term hyporheic, or that are published in non-ISI-listed outlets. Because the HZ represents an interface between groundwater and surface water environments and also between different science disciplines, publications cover a broad range of subject areas that span hydrology, hydrogeology, biogeochemistry, hydroecology and microbiology. The importance of HZ process dynamics has been recognized increasingly across the applied environmental sciences, which is demonstrated by growing citation numbers of *hyporheic* publications (Figure 2).

Initial publications in the 1980s comprised case studies of the HZ that were reported either in core hydrology

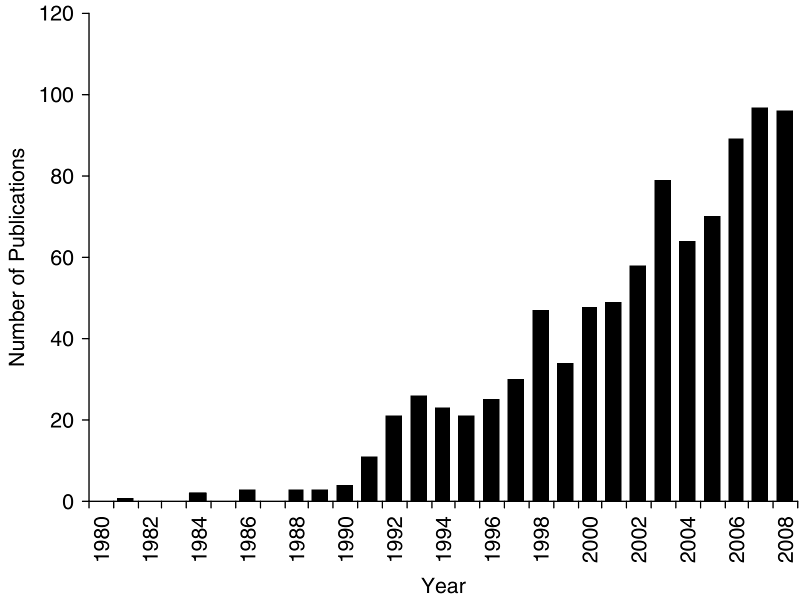

Figure 1. Number of peer-reviewed journals articles using the term "hyporheic" (1980–2008), as archived on ISI Web of Knowledge (http://wok.mimas.ac.uk)

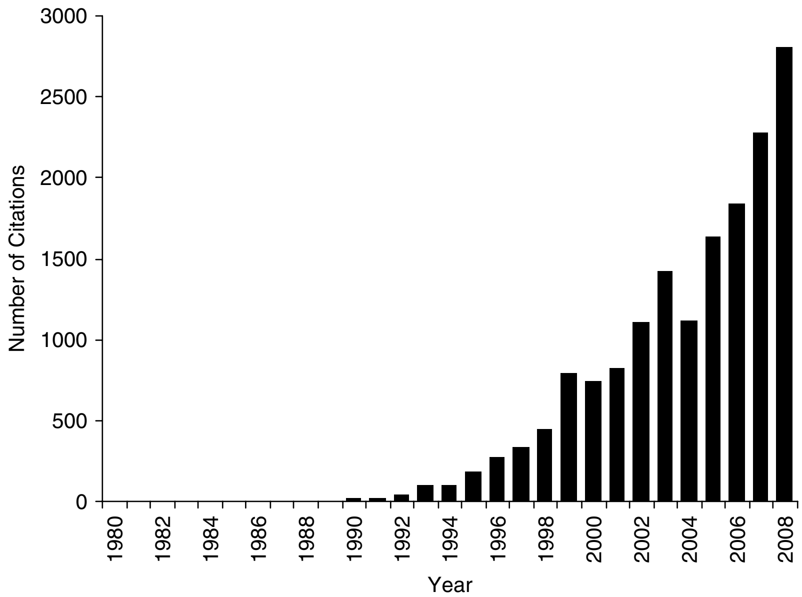

Figure 2. Number of citations of peer-reviewed journals that use the term "hyporheic" (1980–2008), as archived on ISI Web of Knowledge (http://wok.mimas.ac.uk)

or ecology journals (Bencala, 1984; Grimm and Fisher, 1984; Stanford and Ward, 1988; Triska *et al.*, 1989b; Boulton, 1989; Ward, 1989; Boulton *et al.*, 1998). In recent years, there has been progress in enhancing interdisciplinary knowledge transfer between hydrological, hydrogeological, biogeochemical, (hydro)ecological and microbiological research on the HZ. However, there is still a critical lack of knowledge transfer between disciplines and between academics and end-users (Hannah *et al.*, 2007). To foster greater exchange, a UK Natural Environment Research Council (NERC) knowledge transfer network on GW-SW interactions and HZ processes was funded from 2007 to 2009 (HZNet; http://www.hyporheic.net). The HZNet aims to provide a forum for presentation and discussion of new research, for users of research to communicate directly their priorities for future research to the academic community, and for dissemination of research from the academic community to users to aid in regulatory, management and policy decision-making processes. Although the HZNet is a UK funded activity, it outreached to continental European and other overseas research communities, and served as a catalyst for initiation of similar initiatives in other countries (e.g. Germany). This special issue is a contribution to the NERC HZNet.

To the Guest Editors' best knowledge, this is the first special issue that combines research on HZ hydrological, hydrogeological, hydroecological, biogeochemical and microbial processes. In 2003, *Advances in Water Resources* published a special issue on *Modelling Hyporheic Zone Processes* (Runkel *et al*., 2003) with papers focussing predominantly on transient storage model applications in hydrogeology. Runkel *et al*. (2003) captured the state-of-the-art in modelling of HZ flow; but this field has moved on considerably since then.

This special issue contains 12 research papers and one *HP-Today* invited commentary that, individually and collectively, showcase recent advances, challenges and perspectives on hyporheic (1) hydrology, exchange fluxes and thermal dynamics (2) biogeochemistry and (3) hydroecology.

With respect to investigations of *hyporheic exchange fluxes*, Boano *et al*. analyse, in their multi-scale model-based study of a hypothetical simplified stream-aquifer system, the extent to which regional groundwater discharge has an influence on local, bedform-induced hyporheic exchange. A coupled stream-aquifer model is applied to quantify exchange fluxes between streams and aquifers in nested flow systems. Their results show clearly that river–aquifer exchange at larger scales has significant impacts on exchange flows at smaller scales.

Drivers of water level fluctuations and hydrological exchange between groundwater and surface water in the floodplain of a lowland GW-SW system are investigated by Lewandowski *et al*. in an experimental study of an oxbow of the River Spree, Germany. Principal components analysis is applied to identify two major processes controlling water level fluctuations in the aquifer. The first component (representing dampening and delay of fluctuations of the river gauge spreading into the aquifer) explains about 70% of the observed fluctuations; while the second component (indicating groundwater recharge due to precipitation events) is responsible for about 20% of the fluctuations. Their study highlights that short-term water level fluctuations in the aquifer are not necessarily indicative of fast exchange flow velocities.

The effects of frequent river stage fluctuations caused by dam operation on the spatial extent and the thermal and biogeochemical characteristics of the HZ are investigated by Sawyer *et al*. They use an analytical solution for the propagation of stage changes into a semi-infinite aquifer together with fast Fourier transforms to estimate volumetric flow rates across the bank per unit river length for a gaining reach of the Colorado River, Texas, USA. Spatial extent of the HZ is estimated using particle tracking. Up to 1% of the total discharge in the channel passes through the HZ as a result of the dam-induced stage fluctuations. Depending on whether a hydraulic (all flow paths that start and end in the channel) or chemical (at least 10% surface water) definition is used, the HZ extends about 2 m or more than 5 m into the alluvial aquifer, respectively. They conclude that the artificially induced HZ exchange may have significant implications for near channel biogeochemical and thermal conditions as well as for the thermal regime in the water column with ramifications for nutrient transformations and in-stream habitat.

In an experimental study of multiple-scale subsurface flow in streambeds, Käser *et al*. investigate spatial and temporal patterns of vertical hydraulic gradients (VHGs), hydraulic conductivity and subsurface fluxes over riffle-step-pool sequences. VHGs are observed for a piezometer network. Point-dilution tests were carried out for piezometers to identify spatio-temporal variability in the streambed hydraulic conductivity and to test the reliability of VHG for predicting subsurface fluxes. Results indicate that, although VHGs vary significantly and even change their directions within the riffle-step-pool sequence, vertical fluxes appear more spatially homogeneous than VHGs. It is concluded that VHG may be a poor indicator of the intensity of HZ exchange.

In the context of *hyporheic temperature dynamics*, Brookfield *et al*. extend the fully integrated surface/subsurface water flow model *HydroGeoSphere* to simulation of thermal transport. The new heat transport routines are tested and validated by comparing model results with observations from a groundwater thermal injection study for a well characterised reach of the Pine River, Ontario, Canada. Spatial temperature and surface-subsurface exchange patterns in the streambed are reproduced successfully by the model. This study demonstrates the powerful capabilities of integrated numerical models, such as *HydroGeoSphere*, to provide quantitative assessment and also guidance toward supporting and maintaining healthy, functioning hyporheice cosystems.

Anibas *et el.* investigate the use of observed vertical temperature profiles in the HZ to invert exchange flux rates using analytical and numerical solutions to coupled water and heat flow. They conclude that during winter and summer the steady state assumption required for the much simpler analytical solution is usually valid and it can provide acceptable flux estimates. Their approach provides a relatively inexpensive, fast method to evaluate exchange patterns and quantify flux rates in GW-SW systems.

Seasonal hyporheic temperature dynamics over riffles are explored by Hannah *et al*. in a field study of a lowland UK river basin underlain by sandstone. Riverbed temperature is shown to vary temporally across (head, crest and tail) and between riffles. Bed thermal patterns are identified to be driven by hydroclimatological controls on river and groundwater temperature; and hydrological, local morphological and sedimentary controls on surface water and groundwater flux. This research demonstrates the utility of depth-related riverbed temperature time-series in understanding HZ processes and GW-SW interactions.

Biogeochemical process dynamics in the HZ are the focus of a study by Krause *et al*. of the fate of nitrate in upwelling groundwater along the hyporheic flow path. Field experiments are conducted during baseflow conditions for two reaches of a small UK river. Nitrate concentrations observed in the streambed pore water vary markedly in space and time, with the magnitude of variations being governed by the streambed sediment structure and physico-chemical characteristics. This study provides evidence that changes in pore water nitrate concentrations and increased hyporheic redox status may occur at greater depths than surface water infiltrates into the streambed and points toward the need for reconceptualisation of hyporheic nutrient transformations.

Robinson *et al.* investigate the hydrochemistry and sulphur isotope hydrology of an active glacial outwash plain (Skeiðarársandur, Iceland) to yield insights into weathering processes and the role of GW-SW contributions. Different sampling locations produce contrasting results, which reflect differences in sulphur sources and processes operating in the respective environments. For example, groundwater-fed kettle-hole lakes are shown to be important ecological niches within an otherwise relatively barren region; and they have the lowest recorded $\delta^{34}S_{-SO4}$ values, attributed to bacterially-mediated sulphide oxidation and coupled to carbonate and possibly silicate dissolution. Also of note, the hydrochemistry of other groundwaters are influenced by a hydrothermal source of reduced sulphate from the Grímsvötn caldera or an area of geothermal springs. Significant rock-derived and geothermal sulphate contributions are shown to buffer basin hydrochemistry and isotope hydrology from reductions in anthropogenic sulphur emissions.

In a paper that spans hyporheic biogeochemical processes and *hydroecology*, Trimmer *et al.* report on an experimental field study of accumulation and cycling of carbon and nitrogen beneath *Ranunculus* plants in a UK lowland chalk river. They show that the annual gross primary production by *Ranunculus,* its biofilm and the microphytobenthos can account for 26% of the accumulated carbon; the remainder is attributed to organic carbon in suspended particulate matter (57%) and associated with sands saltating along the bottom (17%). The results of this investigation indicate a significant contribution to carbon oxidation from the subsurface, and some oxidation by alternative electron acceptors. The observed ratio of carbon oxidation to total organic carbon accumulation suggests that 19% of the organic matter deposited is re-mineralised on an annual basis with peaks of 58% in June. For nitrogen, the observed efflux of NH_4^+ accounts for 11% of the mineralised N in the sediment, whereas, the remainder is accounted for by the N demand from primary production (67% macrophytes and biofilm; 36% phytobenthos).

Heppel *et al.* explore the role of aquatic vegetation in trapping fine sediment in two lowland UK catchments with contrasting hydrologic regimes. They observe distinct spatial and temporal patterns of sediment storage and release in the shallow HZ that were closely linked to vegetation and flow dynamics. In addition to cyclical patterns in time caused by vegetation growth and senescence, sediment storage on time-scales exceeding a year is observed. Spatial distribution of aquatic plant species, and resulting retention and storage of sediment, shows seasonal shifts from channel margins to mid-channel. Differences in sediment texture and composition (e.g. organic matter content) between more densely vegetated channel margins and mid-channel may affect the capacity for sorption of organic contaminants (e.g. pesticides) and, hence, their fate and transport in the riverine system.

Stubbington *et al.* investigate surface and hyporheic macroinvertebrate communities responses to supra-seasonal drought. Long-term data are presented for a UK chalk river on interannual variability in river flow and benthic communities (1992–1999) along with hyporheic samples taken during the 2006 groundwater drought. During low flows, reductions are observed in riverine macroinvertebrate species richness and number of individuals per sample. The hyporheic community shows a relatively homogeneous composition during severe low flow, with short-term excursions associated with water temperature fluctuations. New conceptual models are proposed of the mechanisms influencing both benthic and hyporheic invertebrates under drought conditions; these models highlight the hydroecological importance of the HZ and GW-SW linkages.

The *HP-Today* article, by Learner and Tellam, discusses the current status and requirements of management tools for river–aquifer interfaces. This commentary is based on debates and ideas developed during a joint workshop of the NERC, HZNet and the UK Groundwater Modeller's Forum. The paper evaluates the importance of river–aquifer interfaces for hydrological and hydrochemical processes; provides a review of river–aquifer interactions representation in current modelling approaches, suggests management requirements, and considers future perspectives.

The breadth of contributions and findings reported in this special issue reflects the truly trans-disciplinary nature of current hyporheic research. The intricate interplay and feedback between various hydrological, hydrogeological, biogeochemical, ecological and microbial variables that characterises process dynamics in the HZ necessitates researchers to think outside a single discipline's box. The research papers presented here take a step in that direction and we hope that this special issue can stimulate further, and foster fruitful discussions across disciplines that will advance our understanding of the HZ.

In putting together this special issue, the Guest Editors wish to acknowledge help and support of several people. We are grateful to the organizers of the EGU General Assembly in 2008 for granting our oral and poster session, and to the authors for preparing their papers under a tight deadline. We would also like to thank the many manuscript reviewers for their important contribution in enhancing the quality of this issue and for working so expeditiously. Last, but not least, we are very grateful for the support and efforts of Sue Amesbury at the *Hydrological Processes* Editorial Office at all stages in the preparation of this issue.

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S. Krause
(Keele University, UK)

D. M. Hannah
(University of Birmingham, UK)

J. H. Fleckenstein
(University of Bayreuth, Germany)