Groundwater–surface-water interactions: current research directions

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The interfaces between rivers and aquifers are characterized by high spatial and temporal variation in water flow, heat exchange, biogeochemical activity, and microbial and metazoan communities. Scientific studies of these interfaces are collectively referred to as groundwater–surface-water (GW-SW) interactions research. This nebulous term is appropriate, given the range of basic and applied issues that have been investigated in river–aquifer interfaces. These issues include contaminant remediation (Ren and Packman 2004), evolutionary change (Van Damme et al. 2009), rare-species conservation (DiStefano et al. 2009), military history (Younger 2012), and the potential existence and nature of life on Mars (Gooseff et al. 2010). The papers in this special issue encompass a substantial part of that range, while omitting some of the extremes.

Modern GW-SW science is an amalgamation of hydrogeology, biogeochemistry, landscape ecology, and other disciplines, many of which are themselves amalgamations of traditional science disciplines, such as microbiology and fluid mechanics (Robertson and Wood 2010, Krause et al. 2011). New branches of GW-SW science grow rapidly as the tools and perspectives of different disciplines are brought to bear on emerging research problems. Recent examples include nanobiotechnology (Sharma et al. 2012) and geomicrobiology (Gault et al. 2011). One consequence of the rapid diversification of GW-SW science is high research productivity. The publication rate in this field has grown exponentially for at least a decade (Wondzell 2015). GW-SW studies are often held up as models of multidisciplinary science (Danielopol and Griebler 2008, Krause et al. 2011). However, staying current with the state of knowledge in this prolific and expanding field is demanding.

Our primary aim for this special issue was to intrigue and challenge readers who might otherwise focus on papers from within their own disciplines. We cast our net widely when inviting contributions to the issue, and we received papers about hydrological dynamics, biogeography, instrumentation, habitat restoration, and ecosystem services, among other topics. We recognize that some of these issues are outside of the usual scope of *Freshwater Science*, and that different issues are in the domains of different research communities, each with distinct concepts, tools, and terminology. In the spirit of life-long learning, we invite readers to read papers within and far outside of their specialties.

We have grouped the 21 papers in this issue into 3 broad categories to provide some structure to the collection. The categories are hydrology and hydrodynamics, geochemistry and biogeochemistry, and ecology and biogeography. Within these categories, the papers report the results of field experiments, large-scale observational studies, and model development and testing. In each category, a synthesis paper provides a review of the state of knowledge and guidance for future research. The papers are summarized below.

HYDROLOGY AND HYDRODYNAMICS

A tenet of GW-SW science is that variation in the direction and magnitude of flow through flow-path networks generates spatial and temporal heterogeneity in water temperature and chemistry. This view is based on numerous stream and river studies. Recent technological advances, particularly fiber-optic distributed temperature sensors (FO-DTS), have facilitated comparable studies in lakes, es-

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tuaries, ocean beaches and wetlands. **Tristram et al.** (2015) used FO-DTS surveys to map groundwater discharge through the bed of an internally drained proglacial lake in Iceland. They combined the surveys with vertical temperature profiles at 3 locations, which were used to calculate rates of groundwater flow through the lake bed. The temperature maps indicated zones of persistent groundwater upwelling. Rates of groundwater inflow varied over time in response to rainfall. The dynamic responses of the GW-SW exchange rates suggest that proglacial lakes may be sensitive to long-term changes in precipitation inputs in response to climate change.

Cold-water patches in otherwise warm rivers can be thermal refugia for salmonids and other cold-water taxa. Cold-water patches occur at many perennial tributary confluences, and at confluences with intermittent tributaries where upwelling hyporheic water is cooler than mainstem surface water. **Ebersole et al.** (2015) predicted that the occurrence of cold-water patches at confluences would be a function of geomorphic and hydrologic factors, particularly those that govern water surplus and residence time in tributary basins. They used random-forest models to investigate relationships between cold-water patches and multiple catchment variables. The models correctly classified 71% of survey sites, and the variables that best predicted cold-water patches were water surplus, aspect, median gradient, and topographic index. Predicted sites of cold-water patches should be considered for protective management because of their beneficial effects as thermal refugia.

In most GW-SW studies, mean or median values are used to represent the bulk hydraulic conductivity. However, heterogeneity in hydraulic conductivity may be too great to be reasonably captured by spatial averaging. **Menichino et al.** (2015) surveyed macropores along the banks of 2^{nd}- and 3^{rd}-order streams. Large macropores were common in all surveyed streams and modeling with the Hydrologic Engineering Centers River Analysis System showed they would be inundated frequently by high flows. A tracer experiment comparing a reach before and after the addition of artificial macropores provided some evidence that macropores can influence solute transport during storms by facilitating bank storage. However, artificial macropores may not function like natural macropores if they are not connected to larger flow-path networks.

Considerable progress has been made in developing new methods to measure and model GW-SW interactions, but an overall synthesis is lacking because different methods operate at different scales. To facilitate the cross-application of new methods, **González-Pinzón et al.** (2015) carried out a field study that combined conservative and non-conservative tracer injections, in-stream and subsurface tracer measurements, distributed and local temperature profiles, and electrical resistivity imaging. The data set was analyzed using models for heat and mass transport at multiple scales. Characterizations of GW-SW interactions at different spatial scales (e.g., local vertical profiles, channel-units, reaches) yielded broadly consistent interpretations of hyporheic exchange fluxes and patterns. Furthermore, analysis of large-scale patterns helped inform interpretations of fine-scale observations, and fine-scale observations were useful for constraining estimates of local fluxes. Using multiple methods to achieve both high-resolution and large spatial coverage is a challenge in GW-SW studies, but the cross-comparison reported here indicates that this approach can provide robust assessments of hyporheic exchange.

GEOCHEMISTRY AND BIOGEOCHEMISTRY

Stelzer et al. (2015) used a manipulative field experiment to investigate the direct and indirect effects of buried particulate organic C (POC) on denitrification. The manipulation consisted of POC (conditioned maple leaves) additions to streambed sediments in a reach with upwelling, oxic groundwater. The POC additions reduced porewater dissolved O_2 (DO) concentrations and increased dissolved organic C (DOC) production and in situ denitrification rates. NO_3^- retention in treatments with added POC was ~50× greater than in controls. This experiment provided evidence of a dual role for allochthonous C in N cycling. The POC addition enhanced heterotrophic metabolism, which reduced DO concentrations in ground water to the levels required for rapid denitrification. The POC also produced DOC needed for assimilatory and dissimilatory NO_3^- reduction. By extension, the experiment illustrates the interdependence of riparian forests, streams, and aquifers. Buried riparian litter fuels the microbial processes that can reduce stream N loads in areas with NO_3^--rich ground water.

Zarnetske et al. (2015) investigated hyporheic denitrification and NO_3^- uptake at 2 spatial scales: the channel-unit scale (a 6.1-m-long gravel bar) and the reach scale (a 303-m-long stream reach). Salt and $^{15}NO_3^-$ injections and solute transport and groundwater-flow models were used to quantify NO_3^- uptake, denitrification, advection, diffusion, transient storage, and hyporheic exchange flows. These parameters were used to estimate the contribution of hyporheic NO_3^- uptake and denitrification to whole-reach NO_3^- removal. Bar-scale hyporheic NO_3^- removal, almost all of which was denitrification, accounted for ~17% of the total-reach NO_3^- uptake and ~32% of total-reach denitrification. Reach-scale observations from traditional stream injections mask heterogeneity in transport and biogeochemical processes. Conversely, local observations within hyporheic zones have limited coverage and may underestimate reach-scale variability. Despite combining reach-scale and channel-unit scale analysis, Zarnetske et al. (2015) concluded that most estimates of the contribution of hyporheic NO_3^- removal to whole-reach removal, including their own, are underestimates because most transport models exclude the slowest hyporheic exchange. The authors recommended more explicit quantification of the scales associated with different measurements and increased efforts to characterize the full range of spatial and temporal scales that influence solute dynamics.

GW-SW interactions are associated primarily with rivers, but they also play an important role in structuring marshes. GW-SW exchange and associated biogeochemical processes are difficult to measure in marshes because of complex landscape morphology, which is in turn influenced by flow patterns, vegetation growth, evapotranspiration, sediment deposition, and nutrient dynamics. **Larsen et al.** (2015) used reactive-transport models and landscape-scale pattern-formation models to assess the effects of these factors on P dynamics and the development of ridge-and-slough marshes in the Everglades. They found that high rates of GW-SW exchange homogenized river and slough pore waters during wet periods, but ridges were hydrologically disconnected from sloughs during dry periods, leading to P accumulation under ridges. Differential hydrologic exchange between ridges and sloughs, which facilitates P accumulation and vegetation growth in ridges, appears to be the primary control on landscape patterns in the modern Everglades. Particulate nutrient redistribution probably was more important under historically higher river flows. More generally, marsh landscape patterns reflect a combination of GW-SW exchange, particle redistribution, and evapotranspiration focusing.

The effects of solute input from hyporheic zones on stream surface-water chemistry are studied frequently, but these studies rarely distinguish between advective solute input along hydraulic gradients and solute diffusion along concentration gradients. **Kurz et al.** (2015) quantified chemical and hydraulic gradients and hydrologic dilution in a spring-fed karst stream in Florida to assess the effects of advective and diffusive transport from the hyporheic zone on the stream solute balance. The results indicated that advective hyporheic exchange and groundwater seepage rates were low and contributed little to stream solute loads. However, steep concentration gradients of several solutes extended from the hyporheic zone into the water column, and the hyporheic zone was a major source of dissolved Fe and Mn and soluble reactive P (SRP). In the case of Fe, diffusion from the hyporheic zone produced an order-of-magnitude greater flux than the 6 major source springs along the stream. This study demonstrated that solute diffusion from hyporheic zones can exceed advective input from underlying aquifers and can offset solute removal from the water column.

Soil organic C in Arctic and boreal watersheds is a major contributor to the global riverine DOC pool and the atmospheric CO_2 pool. DOC from boreal soils is stored, transformed, and released in hyporheic, surface, and riparian zones of headwater streams. DOC processing in these zones must be better understood to predict effects of permafrost thawing associated with climatic warming on DOC fluxes. **Rinehart et al.** (2015) used push–pull slug tests with acetate to investigate the effects of GW-SW interactions on DOC processing in the riparian zone of a boreal catchment. The rate constants for DOC processing did not appear to be related to preinjection water chemistry. Rather, the subsurface fluid velocity in the region of the well was most closely correlated with acetate uptake and CO_2 production. These results suggest that hydrological conditions control biogeochemical processes in the shallow riparian aquifer, perhaps by regulating the delivery of dissolved constituents to the microbiological communities.

ECOLOGY AND BIOGEOGRAPHY

Unregulated rivers and their floodplains have been described as shifting habitat mosaics in reference to their characteristically high spatial and temporal variability. This structural variability leads to variation in types and rates of ecological processes. Research focused on relationships between habitat dynamics and ecological processes in surface zones has a long history. Comparable relationships probably exist in the ecological dynamics of groundwater zones, but those relationships are rarely investigated. **Caldwell et al.** (2015) explored groundwater-ecology links along a habitat gradient from frequently scoured parafluvial zones to infrequently scoured orthofluvial zones in the Nyack floodplain. Groundwater discharge, fine sediment, woody debris, particulate organic matter, algal biomass, and areal NO_3^- uptake rates all increased along this gradient. Orthofluvial springbrooks were characterized by high, positive vertical hydraulic gradients (VHGs) and parafluvial springbrooks by negative VHGs. These patterns suggest that predictable relationships exist between hydrogeological structure and ecological processes across groundwater-dominated habitats. Conceptual models of structure–process relationships in river corridors should incorporate fine-scale variability generated by groundwater-dominated habitat dynamics.

Separate management of groundwater and surface-water resources is rapidly giving way to integrated GW-SW management. Meeting the flow requirements of both river and groundwater ecosystems is a primary aim of integrated management. To achieve this aim, managers need information about 2 issues: the effects of groundwater input on river ecosystems and the effects of surface-water input on groundwater ecosystems. The 1st issue has been studied for decades in groundwater-dominated rivers, but a persistent shortage of information exists about groundwater ecosystems. **Larned et al.** (2015) addressed that shortage with a study of groundwater-ecosystem responses to river-flow variation along an alluvial river. The authors compiled groundwater and surface-water hydrological, chemical, and biological data for 5 y from losing, variable, and gaining river reaches. Physicochemical conditions in losing-reach aquifers were dominated by hillslope runoff and surface-water infiltration, whereas gaining-reach aquifers were dominated by groundwater inflow from up-gradient aquifers. Groundwater organic C concentrations, bacterial densities, and invertebrate densities and taxon richness varied predictably in response to river flow and groundwater-level fluctuations. Hydrology–groundwater ecology relationships are prerequisites for identifying the river-flow requirements for healthy groundwater ecosystems.

Mediterranean streams are highly dynamic, with hydrological variability resulting from seasonal variation in precipitation and evapotranspiration, episodic storm flows, and flow intermittence. Despite this variability, most studies of GW-SW interactions in the Mediterranean region encompass a narrow range of hydrologic conditions. **Vazquez et al.** (2015) examined the distribution and composition of dissolved organic matter (DOM) in a seasonally intermittent Mediterranean stream. They focused on qualitative and quantitative changes in several molecular-weight classes of dissolved organic N (DON) and DOC in the surface and riparian groundwater zones during drying and rewetting periods. During the drying period, the composition of DOM in surface and ground water was similar and appeared to be dominated by old ground water moving from the hill slope to the channel via a relatively unreactive riparian zone. During the rewetting period, the flux direction reversed, and the groundwater zone was flushed with DON- and labile-DOC-rich surface water. In this period, the riparian interface was more active, as indicated by marked reductions in high molecular-weight DOC and all molecular-weight fractions of DON. Based on a synthesis of these results with prior findings, the authors developed a conceptual model in which the primary DOM source, DOC and DON composition and concentration, and DOM bioavailability vary in response to hydrological shifts between the drying, fragmentation, rewetting, and sustained-flow phases.

Streams in tectonically active, volcanic landscapes are characterized by complex GW-SW interactions that include interbasin transfers of ground water. Ground water in these landscapes may be chemically modified by geothermal processes, e.g., P enrichment from basalt and andesite dissolution. In turn, nutrient-enriched groundwater inflows can dominate nutrient fluxes at whole-catchment scales. **Ganong et al.** (2015) used a paired-catchment study in Costa Rica to compare nutrient fluxes controlled solely by locally generated stream flow with those influenced by interbasin transfers of geothermally modified ground water. Average annual surface-water fluxes of SRP, dissolved inorganic N, DON, and DOC were far higher in the catchment receiving geothermal water than in the catchment with only locally generated stream flow. These differences resulted from a combination of higher solute concentrations and higher groundwater input rates in the catchment receiving geothermal water. The results of this study suggest that nutrient fluxes are generally high in streams dominated by geothermally modified groundwater, but that temporal variation in fluxes and concentrations is low because groundwater discharge dampens fluctuations in flow and solute loads.

Enhanced GW-SW exchange is a common goal in river-restoration projects, but pre- and post-restoration comparisons of exchange flows are rare, and assessments of long-term effectiveness are even rarer. **Zimmer and Lautz** (2015) identified long-term effects of river-restoration structures on hyporheic flow and biogeochemistry in a stream reach before restoration and 1 y after restoration. The restoration project consisted of the installation of a cross-vane and engineered rock-riffle in a sand-and-gravel-bed stream. These structures caused localized increases in hyporheic exchange, particularly downwelling immediately adjacent to the structures, and upwelling downstream. The restoration structures also altered spatial patterns in some solutes. Dissolved O_2 and NO_3^- concentrations increased in the newly formed shallow hyporheic flow paths, whereas underlying ground water was O_2- and NO_3^--depleted. This bimodal pattern was attributed to the high-permeability sediment used to build the structures and the compaction of underlying streambed sediment, which restricted the vertical penetration of hyporheic flow. Despite the increase in local hyporheic exchange, the restoration project did not enhance NO_3^- removal. Restoring biogeochemical functionality with in-stream structures, such as cross-vanes and log jams remains a challenge, and further work is needed to develop engineering approaches that can substantially improve water quality.

Aubeneau et al. (2015) developed a new numerical model for conservative and reactive solute transport and biogeochemical reactions in streams. The model accounts for transport and reactions in the water column, benthic, and hyporheic zones. Their use of a continuous-time random-walk (stochastic) approach to characterize residence times in each zone provided exceptional flexibility in modeling solute transport. The model was used with a synthetic data set to evaluate the effects of sorption and uptake in different zones on downstream solute transport, and breakthrough curves were used to represent solute concentration dynamics. The simulations indicated that processes occurring in the water column affect water-column solute concentrations at all time scales. In contrast, benthic and hyporheic processes affect water-column concentrations only at the time-scales of benthic and hyporheic storage. As a result, information on benthic and hyporheic processes appears primarily in the tails of breakthrough curves. Comparisons of conservative and reactive solute concentrations in these tails provide an estimate of whole-stream benthic and hyporheic processing rates.

Dispersal barriers and low fecundity have led to high levels of endemism and small populations of obligate and facultative groundwater animals (stygobites and stygophiles, respectively). As with rare and endemic above-ground species, conservation of groundwater species requires an understanding of their distributions and habitat requirements.

Unlike above-ground species, the distributions and requirements of most groundwater species are unknown. **Johns et al.** (2015) analyzed the distributions of groundwater fauna in southwestern UK and evaluated associations between distributions and environmental conditions. Faunal and water-chemistry data were compiled from wells, bores, and springs across 5 hydro-units (geographic classes based on geology, permeability, and flow mode). Stygobite abundance and diversity were higher in carbonate and metamorphic/igneous hydro-units than in sedimentary hydro-units, but stygophile abundance and diversity did not differ significantly among hydro-units. Stygobite presence was associated with high NO_3^- and Ca concentrations, and stygophile presence with high DO. Relatively little variation in species occurrence and abundance was explained by geology and water chemistry, which suggested that distributions also are governed by biotic interactions and as-yet unidentified dispersal barriers.

Groundwater invertebrate and microbial communities vary in response to multiple environmental factors over a wide range of spatial scales. Associations between groundwater communities and different environmental factors have been assessed in regional and continental studies that used aquifers, geological formations, and other large structures as sampling units. The environment–community correlations revealed by these studies are very coarse grained. **Korbel and Hose** (2015) used wells in a single alluvial aquifer in Australia to identify associations between invertebrate and microbial communities and a suite of environmental factors that exhibit small-scale variability (e.g., sediment grain size, water chemistry). The wells were sampled during and after a severe drought to provide additional information about the effects of climatic variation. Dissimilar sets of environmental factors were correlated with invertebrate and microbial community structure, reflecting broad differences in the environmental requirements of these 2 groups. Microbial communities were primarily correlated with water-chemistry and climatic conditions, and invertebrate communities were primarily correlated with physical-habitat conditions.

The role of hyporheic zones as refugia for benthic invertebrates from physical disturbances is frequently presumed without thorough testing. The results of many field studies of hyporheic refugia are equivocal because of the absence of synoptic samples from hyporheic and benthic zones during and after disturbances. **Stubbington et al.** (2015) used a supraseasonal drought and severe heat wave as a prolonged disturbance to assess invertebrate–community responses in the benthic and hyporheic zones of a groundwater-fed stream. As the drought intensified, benthic taxon richness declined and spatial variability in benthic communities increased compared with hyporheic communities. Benthic and hyporheic community structure converged at the peak of the heat wave as some epigean and hypogean species migrated to the hyporheic zone, presumably for thermal and O_2 refugia. When flows resumed, the structures of benthic and hyporheic communities diverged, which may reflect postdisturbance redevelopment of distinctive communities in each zone. These results provide supporting evidence for the hyporheic refuge hypothesis.

Natural environmental systems supply society with a multitude of ecosystem services. The basis of the ecosystem-services approach is that our reliance on these services provides a framework for resource management. The application of this approach to groundwater ecosystems is at an early stage of development. Some core ecosystem services have been identified (e.g., water purification) and a subset of those have been assigned monetary values. Among the major steps remaining are a more comprehensive account of groundwater ecosystem services and predictions of changes in those services in response to groundwater use and degradation, climate change, and other anthropogenic modifications. **Griebler and Avramov** (2015) addressed these gaps in their review of groundwater ecosystem services. In addition to core services, the authors explored several poorly recognized ecosystem services, including recreation, natural products, and biodiversity. Attributing biodiversity per se with the qualities of an ecosystem service is controversial, but the authors give several compelling reasons for doing so: 1) high biodiversity increases redundancy in ecosystem services, which reduces the risk of lost services following perturbations; 2) high biodiversity increases the chances that species are present that can respond beneficially to future changes (e.g., species that metabolize emerging contaminants); 3) groundwater biodiversity is directly related to the diversity of natural products and biochemical processes, some of which are used in medicine and industry, while others are as yet undiscovered.

In 1993, 8 papers on hyporheic-zone science were published in a special section of the *Journal of the North American Benthological Society*. These papers served several purposes: they presented testable conceptual models about ecological processes in hyporheic zones, they identified knowledge gaps that were impeding progress, and they advised researchers to focus on hyporheic hydrology to maximize progress. In the concluding paper of our 2015 series, **Wondzell** (2015) assessed the current state of GW-SW science (as represented by the papers in our special series) in terms of the concepts, gaps, and advice set out in the 1993 series. The 2 collections of papers are quite different. In some ways, the scope of the 2015 series is broader because it covers more modes and locations of GW-SW exchange than the 1993 series, which was narrowly focused on advective flow through the hyporheic zone. This range extension is most obvious in the inclusion of studies of deep aquifers in the 2015 series. In other ways, the 2015 series has a narrower scope. Most of the hyporheic-zone papers in the 2015 series are reports of empirical studies carried out at channel-unit-to-reach scales. In the 1993 series, several authors proposed conceptual models that characterized the roles of hyporheic zones across stream networks. These conceptual models have not yet been explicitly tested. Despite that, the "fact" that GW-SW interactions are important throughout stream networks is now widely accepted, and claims of this importance are rarely questioned. Wondzell (2015) concluded that a critical need still exists to develop a holistic understanding of how GW-SW interactions vary among streams types and sizes and with changes in discharge over seasons or during storm events. This knowledge would help us understand where, when, and how GW-SW interactions influence (or do not influence) the ecology of surface waters and ground waters.

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