113: Hyporheic Exchange Flows

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Water having entered a stream channel from the surrounding catchment may continue to have connections with the catchment. In the stream's hyporheic zone, water "in the channel" exchanges with "groundwater" in the bed of the stream. Hyporheic exchange flows typically occur at scales small relative to the length and volumetric transport characteristics of the stream. Nevertheless, it is well documented that hyporheic exchange flows significantly influence nutrient dynamics. Additionally, there is evidence of hyporheic exchange flows similarly influencing the processes establishing the concentrations of major-ions and metals in stream-catchment systems. It is within the contexts of (i) solute transport and (ii) the continuing connections of streams to their catchments that the hydrologic aspects of hyporheic exchange flows are studied. The Transient Storage Model (TSM), a pseudo-two-dimensional representation of stream and hyporheic zone solute transport, is used to identify characteristics of hyporheic zone, physical size, and solute residence times. The TSM is further extended to simulations of reactive solute transport to understand and interpret the biogeochemical processes of streams influencing the solute dynamics of catchments. Active hydrologic research continues to advance the process basis from which quantitative assessments of the role of hyporheic exchange flows will be made.

INTRODUCTION

Hyporheic exchange flows are one of several mechanisms of the interaction of the groundwater and surface water (Winter *et al.*, 1998, *see* **Chapter 145, Groundwater as an Element in the Hydrological Cycle, Volume 4**). In the *hyporheic zones* of streams, water that is flowing in the stream channel flows into the subsurface materials of the streambed and then returns to the stream. Hyporheic zones function as continuing points of connection between the transport of water and solutes in the stream channel and the stream's catchment (Bencala, 1993).

Hyporheic zones are significant in the dynamics of nutrients within the stream-catchment system (*see* **Chapter 96, Nutrient Cycling, Volume 3**) and in the processes establishing the concentrations of major-ions and metals. The influence of hyporheic exchange upon the transport and transformation of solutes occurs in the environments where hydrologic and biogeochemical processes are dynamic and highly heterogeneous. Documenting the biogeochemical function of hyporheic exchange has thus been primarily accomplished in detailed high-sampling-intensity research studies. In spite of the inherent difficulties in isolating the function of hyporheic exchange amidst many other stream and catchment processes, it is clear that hyporheic exchange can be quantified as influencing the establishment of major-ion chemistry and the ongoing transformation of reactive constituents. Numerous investigators have completed extensive field studies documenting the biogeochemical processes active in the hyporheic zones of individual streams. An overview of a small sample of these studies forms the first sections of this article. The understanding of biogeochemical processes within hyporheic zones has further value when utilized in the context of quantitative assessment of solute transport and solute residence within the stream channel and the stream-catchment system. One approach to providing this context, the Transient Storage Model, is discussed below along with current research directions, suggesting that much work remains in interpreting the basic hydrologic mechanisms by which streams and their catchments are connected.

NUTRIENT DYNAMICS

The substantial body of empirical evidence establishing that surface-subsurface exchange significantly influences

nutrient dynamics in stream ecosystems is presented in the review article of Mulholland and DeAngelis (2000). As these writers state, "the expectation [of this exchange influence] is based on two factors: (1) high ratios of surface area of sediments to volume of water within sediments should result in large effects of microbial processes on subsurface water, and (2) relatively slow advective flow of water within the subsurface zone retards the downstream movement of soluble materials compared with the surface environment." Using a simple "nutrient spiraling" model, Mulholland and DeAngelis (2000) go on to demonstrate conceptually that the size of the subsurface zone and the rates of water exchange between surface and subsurface zones have substantial effects on nutrient dynamics and uptake lengths in stream ecosystems.

The influences of surface-subsurface exchange upon nutrient dynamics are recognized as being spatially heterogeneous and temporally variable. Butturini *et al.* (2003) present detailed data from a 2-year study of stream-aquifer hydrology and nitrate removal in which they observe a "riparian groundwater system characterized by drastic hydrological changes and by mixing of stream water with hillslope groundwater". In part due to the hydrologic change throughout the year, both nitrate removal and nitrate release are observed within the studied riparian system. The variability in hyporheic zone processes is further evident when considering the range of ecosystems now being studied. Butturini *et al.* (2003) studied an intermittent Mediterranean stream. Edwardson *et al.* (2003) studied Arctic tundra streams. The frank conclusions of Edwardson *et al.* (2003) highlight the difficulty in drawing sweeping inferences about the specific function of hyporheic zone processes. Edwardson *et al.* (2003) conclude: "...we expected that the presence of continuous permafrost in [the] Arctic environment would limit the importance of hyporheic processes, either physically (i.e., through the presence of a restricting thaw bulb in the permafrost) or biogeochemically (i.e., through low temperatures). Instead, we found that biogeochemical processes in the hyporheic zone of [the] Arctic streams are at least as important as it is in similar temperate stream ecosystems".

In addition to the numerous field studies of nutrient dynamics in hyporheic zones, experimental laboratory work has also been reported. Using sediment perfusion cores to study nitrogen transformations, Sheibley *et al.* (2003a,b) have measured the rates of nitrogen transformations in river-bed sediments. These laboratory studies integrate the hydrology of hyporheic exchange with the study of biological transformations to verify that groundwater-surface mixing controls the nitrification–denitrification coupling occurring in the river-bed sediments.

PROCESSES ESTABLISHING THE CONCENTRATIONS OF MAJOR-IONS AND METALS

In addition to influencing the nutrient dynamics of stream-catchment systems, hyporheic exchange flows similarly influence the processes establishing the concentrations of major-ions and metals in streams. The role of hyporheic exchange has been documented in pristine systems as well as in those with a high level of anthropogenic impacts.

Working in a glacial meltwater stream in Antarctica, Gooseff *et al.* (2002) studied the contribution of primary weathering to the in-stream concentrations of silica and potassium. The study of weathering in these streams represents an extreme example of a hydrologic situation in which there were no hillslope processes occurring to influence stream chemistry. Their analysis suggested that the continuous saturation and rapid flushing of the streambed sediment due to hyporheic exchange did facilitate chemical weathering.

Harvey and Fuller (1998), working in a drainage basin in Arizona contaminated through copper mining, found that manganese distributed in the stream–groundwater system affected the transport of trace metals. The cumulative effect of hyporheic exchange in the basin was to remove approximately 20% of the dissolved manganese flowing out of the drainage basin. Their further studies (Fuller and Harvey, 2000) demonstrated that decreased loading of trace metals in the stream was attributable to uptake of the trace metals by manganese oxides in the hyporheic zone that is enhanced by the ongoing manganese oxide formation.

Because the hyporheic zone is an interface between surface and subsurface waters, gradients may exist in oxidation/reduction conditions. For arsenic, the toxicity of this metal can be significantly different for the different oxidation states. Nagorski and Moore (1999) have demonstrated that this gradient has an influence on the form of arsenic mobilized in the hyporheic zone of a contaminated stream in Montana. The continual flux of the reduced form of arsenic to the stream maintains higher concentration of this form than would otherwise be expected in oxygenated surface water.

TRANSPORT MODELING – TRANSIENT STORAGE

The biogeochemical functions of the hyporheic zone occur in the context of solute transport along the stream. Solute transport models are a tool used in conjunction with field data to analyze, and interpret, exchange processes. Models of the transport processes of the interactions of streams and hyporheic zone have been developed over a wide range in physical complexity (Packman and Bencala, 2000). The relatively simple concept of "transient storage", which

has been used by several investigators, is included in the US Geological Survey modeling code OTIS (One-dimensional Transport with Inflow and Storage) (Runkel, 1998). The code and applications information are available at **http://co.water.usgs.gov/otis/.** The Transient Storage Model (TSM) builds upon the standard convection-dispersion model of one-dimensional solute transport down the length of the stream. To the convection-dispersion model, the TSM adds fixed-volume solute storage "boxes" along the stream channel. Solute exchange between the open stream channel and the storage boxes is modeled as controlled through first-order mass-transfer. The storage boxes are effectively the simplest attempt to model the influence that the hyporheic zone has on the transport of solutes; that is, solutes are continually being exchanged between the open stream channel and the storage boxes.

The TSM results in a pseudo-two-dimensional representation of stream and hyporheic zone solute transport; solute transport is one-dimensional (longitudinal) in the stream channel with the storage zones adding a limited second (lateral) dimension. In discussing the TSM, as it is implemented in the OTIS code, Harvey and Wagner (2000) explain both the degree to which the TSM can be used to characterize solute transport in the hyporheic zone and the limitations inherent to this simple representation of complex processes. Harvey *et al.* (1996) present detailed field hydrometric data showing that analysis of solute transport using the TSM leads to a bias in only characterizing the most rapid components of hyporheic exchanges. Wagner and Harvey (1997) then develop guidance for assessing the reliability of TSM characterizations. Scott *et al.* (2003) and Gooseff *et al.* (2005) have recently demonstrated the significance in using objective parameter estimation techniques as part of the application of OTIS to stream tracer data sets.

A further issue in the use of the TSM has been the comparison of results between stream systems. Runkel (2002) discussed several of the comparisons that have been proposed and developed a metric specifically for comparing, stream-to-stream, the significance of transient storage. The TSM can also be implemented to characterize solute transport and storage in terms of temporal moments of concentration–time distributions. Schmid (2003) discusses the development of this approach by several investigators. Wörman (2000) and Schmid (2004) compared the temporal characteristics of TSM solutions to other transport model formulations. Jonsson *et al.* (2004) extended the temporal moments approach to consideration of sorption behavior and long-term retention of reactive solutes in hyporheic zones. In analysis of their field studies, "the method of temporal moments was found to be inadequate for parameter determination, whereas fitting versus the entire tracer breakthrough curves with special emphasis on the tail indicates that [their] proposed model could

be used to represent both conservative and reactive transport".

RESIDENCE TIME AND CONNECTION TO THE CATCHMENT

The hyporheic zone influences stream biogeochemistry by increasing solute residence time within the stream-catchment system. The influence of the increased residence time may be enhanced in cases in which the overall biogeochemistry and extent of contact with sediment is distinct within the hyporheic zone compared to the adjacent open stream channel. A variety of approaches are being taken in identifying characteristic solute residence time in hyporheic zones as a significant factor in the connections of streams to their catchments. Harvey *et al.* (2003) used an analysis based on OTIS simulations of five stream tracer experiments to "conclude that relatively simple measurements of channel friction are useful for predicting the response of hydrologic retention in streams to major adjustments in channel morphology as well as changes in streamflow". Identifying characteristic storage zone residence time with a TSM was a step in the work of Thomas *et al.* (2003) to estimating the proportion of reactive nitrogen solute uptake occurring within hyporheic zones.

Although OTIS is used by several investigators and it is the implementation of the TSM that is the context for most of the discussion in this article, the TSM is a highly idealized representation of the function of hyporheic zones. A consequence of an analysis based on OTIS is that a hyporheic zone is characterized by a single residence time distribution. (The single residence time distribution is of exponential form. See Harvey *et al.* (1996) for discussion of this distribution form. The analysis is well beyond the scope of this article to show that a single form is indeed an implicit assumption of the TSM.) Haggerty *et al.* (2002) studied a power-law residence time distribution showing that "the hyporheic zone has a very large range of timescales". Gooseff *et al.* (2003) continued this line of work with analysis of three tracer experiments using a General Residence Time Distribution (RTD) model that is not bound by the implicit assumption of an exponential distribution. The basic result of the analysis is that the General RTD model allowed for a more accurate characterization of longer solute residence times compared to the characterization from OTIS. Gooseff *et al.* (2003) conclude: "Consequently the two models will result in different views of the hyporheic zone and its role in stream ecosystem processes." Haggerty *et al.* (2002) and Gooseff *et al.* (2003) have identified a significant aspect (significant for the understanding of solute transport and transformation in streams) of the complexity of hyporheic zone processes that the TSM's simplicity does not represent.

Residence time in the hyporheic zone is typically considered, as in the discussion above, in the framework of in-stream solute transport. Chanat and Hornberger (2003) use the concept of a "near-stream zone" to develop an analysis showing that mixing in this zone of chemically distinct catchment waters influences the timing of the solute balance flowing into a stream. Although they are using a different terminology for a somewhat different conceptualization of stream-catchment connections, the results of Chanat and Hornberger suggest that residence in the hyporheic zone can also be a factor in catchment-scale transport to a stream.

STREAMS TO RIVERS AND AQUIFERS

Most research papers written on hyporheic zones are undoubtedly about work done in streams, most often low-order, high-gradient streams. A few investigators have started working in the hyporheic zones of higher-order streams or rivers. Paralleling the main discussion above, the listing of a small sample of papers is given here in the sequence: solutes observed in monitoring river hyporheic zones, TSM applications to solute transport in rivers, and investigation of the function of hyporheic zones in connecting streams to aquifers.

Cox *et al.* (2003) completed a tracer experiment in the Upper Santa Clara River (Los Angeles and Ventura Counties, California; 645 square-mile basin) in which tracer added to the surface water was measured in several hyporheic zone sampling locations. In the Willamette River (Oregon; 12 000 square-mile basin) Hinkle *et al.* (2001) demonstrated nitrate reduction occurring along hyporheic flowpaths.

In nine rivers in the Willamette Basin (Oregon), Laenen and Bencala (2001) used OTIS to characterize the transient storage that occurred in 20 tracer additions to surface water. The tracer additions were conducted for other study purposes and there was no direct sampling in likely areas of hyporheic exchange. Thus, the influence of hyporheic exchange could only be inferred from the modeling exercise. However, Fernald *et al.* (2001) completed a study focused upon hyporheic exchange in the Willamette River. Their work included tracer additions, tracer sampling in the subsurface, and modeling analysis with OTIS. They concluded that "significant amounts of water follow flow paths with 0.2–30 hour transient storage zone residence times".

In addition to increasing the scale of studies of hyporheic zones to river systems, the scale can also be increased in the sense of linking hyporheic processes into conjunctive stream-aquifer modeling. Two such model development efforts were presented by Lin and Medina (2003) and Fox and Durnford (2003). Development of these new models will potentially be significant in providing tools for analysis in systems in which the geohydrologic framework is on spatial scales larger than typical for low-order, high-gradient streams.

HYDROLOGIC PROCESSES

The significant environmental influences of hyporheic zones are definitely upon biogeochemical processes. In order to understand these processes, the hydrologic processes that determine the characteristics of hyporheic flow need to also be investigated and understood. Harvey and Bencala (1993) made field measurements of the topography of a streambed. They concluded that solute transport occurred along well-defined subsurface flow paths. They observed hyporheic flow paths as determined by meter-to-meter scale topography, with the flow paths beginning at the transition from pools to steeper channel units. Cardenas and Zlotnik (2003) used ground-penetrating radar to develop a three-dimensional model of channel deposits. The channel deposits were clearly heterogeneous and nonisotropic. Their measurements document that it is an oversimplification to characterize a streambed by a constant width and thickness.

Cardenas *et al.* (2004) took their work further to show that heterogeneity causes significant additional hyporheic zone flux. The presence of heterogeneity can either decrease or increase residence times in the hyporheic zone. Salehin *et al.* (2004) concluded that (when compared to hyporheic exchange in homogeneous streambeds) "the structural heterogeneity of the streambed sediments produces more spatially limited hyporheic exchange that occurs with greater spatial variability and at a higher overall rate".

Solute transport in the hyporheic zone has been predominantly investigated as an adjunct to solute transport in the open stream channel. A groundwater focus has also been taken by a few investigators. Kasahara and Wondzell (2003) used groundwater flow models to investigate the morphologic features that controlled hyporheic exchange flow. Their interpretations are consistent with other studies in finding that surface-visible channel morphologic features controlled the development of the hyporheic zones. Also using groundwater flow models, Storey *et al.* (2003) conclude that the key factors controlling exchange flow within the alluvial (hyporheic) zone were (i) hydraulic conductivity of the alluvium, (ii) the hydraulic gradient between upstream and downstream ends of the riffle, and (iii) the flux of groundwater entering the alluvium from the sides and beneath.

Work to study the environmental fluid mechanics of hyporheic flows has been carried out through experimental tests in recirculating flumes. Bedforms are one control of the rate of solute delivery from the stream to the streambed. Further, bedform-induced pumping can be produced in a

flume to be the dominant exchange mechanism. Marion *et al.* (2002) demonstrate the effects on solute exchange of the longitudinal dimension of bedforms. Zaramella *et al.* (2003) show that the TSM can represent advective exchange with shallow beds that have a defined exchange layer restricted by the presence of an impermeable boundary. However, the TSM does not represent well exchange with a relatively deep sediment bed, where flow along different advective paths in the bed yields a wide distribution of exchange timescale. Clogging of the streambed surface will often isolate deeper regions of the bed from the streamflow. Laboratory flume experiments reported by Packman and MacKay (2003) show kaolinite clay deposition in a sand bed and the resulting alteration of hyporheic exchange flows. Ren and Packman (2004) observed that "reactive colloids can substantially mediate the stream-subsurface exchange of contaminants and the colloid deposition can provide a mechanism of contaminant immobilization that is generally not considered in field studies ...".

Transient storage of solutes may occur due to features of a stream (e.g. vegetation) that are unrelated to hyporheic flows. In one example of work on this issue, Salehin *et al.* (2003) studied solute transport and hyporheic exchange in vegetated and unvegetated stream reaches. Their work demonstrates the considerable inherent difficulties in trying to differentiate the effects of multiple individual processes from solute breakthrough curves.

CONTINUING WORK

This article focuses upon the hydrologic processes influencing solute transport. The process hydrology of hyporheic exchange flows continues as an area of active investigation. Hyporheic zones have an ecological role in the life cycle of stream organisms. For example, Malcolm *et al.* (2004) have studied the implications for salmon egg survival of hydrological influences on hyporheic water quality. In considering the ecological role of hyporheic waters, it is found that the transport of heat is also influenced. Malcolm *et al.* (2004) observed that "the amplitude of surface water temperature signals was damped considerably with depth into the hyporheic zone". Several authors have provided discussions of the open issues and potential directions for research. Again listed in parallel with the themes of this chapter, examples of these discussions are: (i) Stanley and Jones (2000); potential directions for hydrologic studies needed to support research on the biogeochemistry of hyporheic zones, (ii) Runkel *et al.* (2003); potential directions for development of solute transport modeling in the hyporheic zone, and (iii) Bencala (2000); potential directions for research to understand the hydrological framework of which hyporheic zones are a critical linkage element.

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