Preface

Modeling hyporheic zone processes

1. Introduction

Stream biogeochemistry is influenced by the physical and chemical processes that occur in the surrounding watershed. These processes include the mass loading of solutes from terrestrial and atmospheric sources, the physical transport of solutes within the watershed, and the transformation of solutes due to biogeochemical reactions. Research over the last two decades has identified the hyporheic zone as an important part of the stream system in which these processes occur. The hyporheic zone may be loosely defined as the porous areas of the stream bed and stream bank in which stream water mixes with shallow groundwater. Exchange of water and solutes between the stream proper and the hyporheic zone has many biogeochemical implications, due to differences in the chemical composition of surface and groundwater. For example, surface waters are typically oxidized environments with relatively high dissolved oxygen concentrations. In contrast, reducing conditions are often present in groundwater systems leading to low dissolved oxygen concentrations. Further, microbial oxidation of organic materials in groundwater leads to supersaturated concentrations of dissolved carbon dioxide relative to the atmosphere. Differences in surface and groundwater pH and temperature are also common. The hyporheic zone is therefore a mixing zone in which there are gradients in the concentrations of dissolved gases, the concentrations of oxidized and reduced species, pH, and temperature. These gradients lead to biogeochemical reactions that ultimately affect stream water quality. Due to the complexity of these natural systems, modeling techniques are frequently employed to quantify process dynamics.

This special issue of Advances in Water Resources presents recent research on the modeling of hyporheic zone processes. To begin this preface, a brief history on modeling hyporheic zone processes is presented. This background information is by no means complete; additional information may be found in Streams and Groundwaters [17] and the references therein. The preface concludes with an overview of current research needs and a summary of the articles in the special issue.

2. Background

Twenty years ago, Bencala and Walters [1] analyzed the results of a stream tracer experiment using a transient storage solute transport model (also known as a ‘dead zone’ model, e.g. [32]). Subsequent work by Bencala, Jackman, McKnight, and coworkers [2,3,16,20] established the use of stream tracers and the transient storage model as a standard approach to quantifying small stream hydrodynamics. In its simplest form, the transient storage solute transport model consists of a one-dimensional advection–dispersion equation [24] with an additional term to account for transient storage. Transient storage is defined as the movement of solutes from the free-flowing main channel into zones of stagnant water, temporary retention in the stagnant zones, and the subsequent movement of solute mass back into the main channel. Stagnant zones include both surface features (pools and eddies) and water within the hyporheic zone. These stagnant zones are lumped together as a conceptual storage zone within the transient storage model. Exchange of solute mass between the main channel and the transient storage zone is controlled by an exchange coefficient, $\alpha$, and the cross-sectional area of the storage zone, $A_s$.

Concurrent with the establishment of the transient storage paradigm, researchers began to recognize the ecological importance of the hyporheic zone and the effects of groundwater/surface water interaction on biogeochemical reactions. In particular, studies of nutrient cycling [12,23,34] illustrated the close coupling between hydrologic transport and biogeochemical processes. The transient storage solute transport model provided a means to quantify this coupling, with the transient storage parameters ($\alpha$ and $A_s$) providing a means of quantifying hyporheic exchange [30]. In addition, the use of conservative stream tracers allowed researchers to distinguish between the effects of hydrologic and biogeochemical processes. Since the time of the
Stream Solute workshop [30], numerous applications of stream tracers and the transient storage model have appeared in the literature [4,5,8,9,14,18,21,22,26,35]. In addition, advances have been made in regard to field techniques and modeling tools, e.g. [6,25].

3. Areas of research

Although much progress has been made in modeling hyporheic zone processes, many challenges remain. Three areas of research relevant to this special issue are described here. As discussed by Bencala and Walters [1], the transient storage model is an empirical approach that does not attempt to model exchange in a mechanistic manner. Further, surface storage and hyporheic exchange are lumped together in a single storage zone. Although it is sometimes possible to rule out one of the mechanisms (e.g., a reach affected by beaver dams may be dominated by surface storage, whereas a shallow reach with a well defined channel and porous streambed may be dominated by hyporheic exchange), it is often difficult to distinguish between surface and subsurface storage. This distinction is of paramount importance given the differences in surface and groundwater biogeochemistry noted earlier and the ultimate goal of studying stream water quality. On one hand it may seem trivial to formulate model equations for multiple storage zones, but it is quite another matter to develop practical field techniques to correctly parameterize such a model. The existing stream tracer approach [1] is unlikely to provide sufficient information for the separation of surface storage and hyporheic exchange.

A second research issue is that of scale. Harvey et al. [15] conclude that the standard modeling approach is only capable of identifying hyporheic exchange over relatively short-time scales (minutes to hours). Exchange processes at longer time scales (tens of hours to days), while important chemically, may not be properly identified using stream tracer data. Characterization of long time scale exchange has important implications as solutes entering long hyporheic flow paths have extended contact with reactive surfaces and attached microorganisms that conceivably lead to enhanced biogeochemical transformation. In addition to the issue of temporal scale, further work is needed to identify the spatial scales at which hyporheic exchange is important. With some notable exceptions [9,18], most investigations of hyporheic exchange have been conducted in low-order streams. The importance of exchange in these small systems is presently clear, e.g. [22]. Additional research in higher-order streams will be needed before similar conclusions can be drawn at larger spatial scales.

The final research issue discussed here is the need for improved field and modeling techniques to more accurately quantify biogeochemical processes. Biogeochemically reactive solutes may undergo transformation in the main channel and/or storage zone and the rates of transformation may vary considerably given the biogeochemical gradients noted above. Although separation of main channel and storage zone processes is possible using first-order rate coefficients [25], further refinement in quantifying process dynamics remains a challenge due to the possible range of storage zone microenvironments. Processes and rates in surface storage zones may be significantly different than those associated with the hyporheic zone, and the residence time (and thus reaction time) of solutes undergoing short-time scale hyporheic exchange may be considerably less than that for solutes entering longer hyporheic flow paths. As noted above, multiple storage zone models may be formulated, but estimation of the physical and biogeochemical parameters for each storage zone may not be tractable using existing tracer techniques. At the other extreme, lumping the multiple hydrologic and biogeochemical processes into a single storage zone with average, aggregate properties may not provide meaningful results for heterogeneous systems.

4. Overview of the special issue

The papers in this special issue address many areas of needed research. With respect to the issues raised above, several comments are in order. First, the papers of Gooseff et al. [11] and Salehin et al. [27] employ alternate models of transient storage that may provide a means of distinguishing between surface storage and hyporheic exchange. Second, the papers of Fox and Durnford [10] and Lin and Medina [19] present approaches that more accurately describe the groundwater system; these approaches may allow for the consideration of hyporheic exchange at longer temporal and larger spatial scales. Third, Thomas et al. [33] present a technique for distinguishing between main channel and storage zone nutrient uptake, while Sheibley et al. [29] present a modeling approach for the transformation of nitrogen in hyporheic sediments. Additional details on all of the papers in the special issue are provided below.

Edwardson et al. [7] quantified hyporheic zone interactions in seven streams, ranging from first to fifth order, in the Alaskan tundra. Despite the constraints of cold temperatures and permafrost, they found that hyporheic zone interactions were substantial from a hydrologic and biogeochemical perspective. The hypo-
The hyporheic zone was a zone of degradation of dissolved organic nitrogen and a source of nitrate, carbon dioxide, and ammonium in upwelling areas. Concurrent sampling of interstitial waters indicated that parts of the hyporheic zone did not fully equilibrate with the injected stream tracer during the duration of the experiment.

Fox and Durnford [10] investigated the occurrence of partially saturated conditions within the hyporheic zone that occur when the water table in the aquifer drops below the stream bed. Stream–aquifer interaction was analyzed and the stream depletion rate was quantified for three types of partially saturated conditions. Stream depletion rates were incorporated into an analytical solution of a pumping well adjacent to a stream, resulting in partially saturated conditions beneath the stream. The transient solution tracked the length along the stream over which perched conditions develop. Unsaturated conditions within the hyporheic zone may lead to higher dissolved oxygen concentrations, limiting transformation processes that are favored under anaerobic conditions.

Gooseff et al. [11] characterized hyporheic exchange processes in three reaches of Lookout Creek (Oregon, USA). Parameters describing storage and exchange were estimated using tracer data and two transport models: a transient storage model with an exponential residence time distribution and an alternate model based on a general power-law residence time distribution. Results suggest that the transient storage model fit the short-time tracer response adequately, but not the longer-term behavior. The long tails in the tracer response were fit reasonably well by the generalized residence time distribution model, except at very late times, when the observed concentrations drop off steeply in contrast to the model predictions.

Harvey et al. [13] analyzed changes in hydrologic retention by the hyporheic zone in a small desert stream. During a five year period, growth of aquatic macrophytes resulted in a decreased flow rate and average velocity and an increase in stream width. These hydrologic changes were associated with an order of magnitude increase in hydrologic retention. Temporal changes in hydrologic retention in this desert stream and in other streams were shown to correlate well with the Darcy–Weisbach friction factor, providing a potential guide for evaluating changes in hyporheic zone characteristics over time or at other locations.

Lin and Medina [19] developed a conjunctive stream–aquifer model that couples the transient storage equations with modules for groundwater flow, groundwater transport, and unsteady streamflow routing. The resultant modeling framework considers the large-scale exchange of solute between the stream and the underlying aquifer and the effects of flood waves on groundwater/surface water interaction. The coupled model was used to illustrate the potential contamination of the groundwater system during high flow events, and the subsequent release of solutes back into the stream during recession of a flood wave.

Salehin et al. [27] compared solute transport and hyporheic exchange in vegetated and unvegetated reaches of an agricultural stream using tracer data and the advective storage path model. The stream reaches analyzed were subject to extreme variations in vegetation and morphology due to seasonal effects and channel excavation. Variation of solute storage time in non-excavated reaches was attributable to differences in stream flow depth, velocity, and hydraulic conductivity of the streambed. Excavation altered stream channel geometry, increasing the storage time and reducing the effective exchange rate. Reach comparisons were facilitated by scaling model exchange parameters.

Schmid [28] developed analytical expressions for the temporal moments of the transient storage equations, for the case of an arbitrary upstream boundary condition. Whereas previous expressions for the temporal moments were developed for the case of an instantaneous slug release, the new expressions allow for the specification of any concentration-versus-time distribution at the upstream boundary. Given the upstream boundary conditions, the temporal moments may be routed downstream for comparison with field data or as a check on the accuracy of numerical models.

Sheibley et al. [29] modeled nitrogen transformations in sediment perfusion cores from the Shingobee River in Minnesota over an annual cycle. Their results indicate that ammonium concentrations in the river were controlled by nitrification of ammonium from groundwater in hyporheic sediments, and that the rate of this process was strongly temperature dependent. This study shows that hyporheic zone biogeochemical processes can change in potentially predictable ways due to seasonal shifts in temperature, as well as hydrology.

Supriyasilp et al. [31] developed a statistical technique for the calibration of water quality models. The technique, known as quantitatively directed exploration (QDE), uses the variance of model input parameters to identify the parameters and sampling locations that produce the most uncertainty in model results. QDE was applied to a hypothetical problem using a model that considers advection, chemical reaction, settling, and hyporheic exchange. Statistical results were used to determine which parameters result in the largest variance in predicted concentration; these parameters were identified as the focus of additional data collection efforts.

Thomas et al. [33] developed the regression partitioning method (RPM), a method for estimating the
portion of solute uptake occurring within the transient storage zone. Under RPM, whole stream uptake is determined from the spatial pattern of plateau tracer concentrations and main channel uptake is determined using data from the rising limb of the tracer profile. Storage zone uptake is then determined by difference. The method was demonstrated using data from two tracer additions, where 44–48% of the nitrate uptake occurred within the storage zone.

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References


