Environ. Sci. Technol. **XXXX,** *xxx,* 000–000

Environmental Science & Technology
Feature

Moving Beyond the Banks: Hyporheic Restoration Is Fundamental to Restoring Ecological Services and Functions of Streams

ERICH T. HESTER*
Virginia Tech, Blacksburg, Virginia

MICHAEL N. GOOSEFF
Pennsylvania State University, University Park, Pennsylvania

Stream restoration needs to consider the hyporheic zone just as much as the surface and benthic regions.

W. BRECK BOWDEN AND MICHAEL N. GOOSEFF

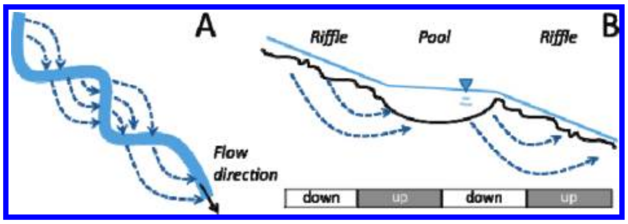

FIGURE 1. Idealized representations of hyporheic exchange in (A) plan view (lateral exchange) and (B) vertical cross-section (vertical exchange). In panel B, sections of channel that are upwelling (water moving from the bed into the channel) are noted by the gray bars and downwelling sections (water moving from the channel into the bed) are noted by the white bars.

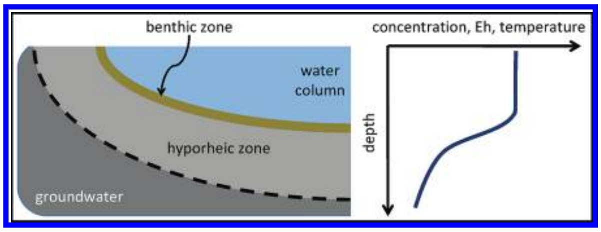

FIGURE 2. Conceptual cross-section of a stream system, made up of water column, benthic zone, and hyporheic zone. Associated typical gradients of redox state, dissolved oxygen (DO) concentration, and temperature variability are represented.

Hyporheic zones are aquifers beneath and adjacent to stream and river channels through which surface water exchanges and mixes with groundwater (Figure 1) (*1*). Hyporheic zones are intimately connected to the water column and benthic zones (Figure 2), and underpin stream ecosystem function through important contributions to biogeochemical cycling and biological habitat. Specifically, the movement of streamwater into the subsurface provides a vector for dissolved constituents (oxygen, nutrients, and pollutants) to come into direct contact with entrained carbon sources, microbial communities occupying the extensive surface area of sediment grains, and a unique array of biogeochemical conditions (e.g., both oxidative and highly reducing zones). Additionally, hyporheic exchange of water buffers surface water temperatures by facilitating heat exchange with relatively constant temperature groundwater. Thus the hyporheic zone contains gradients of physical, chemical, and thermal conditions; the water column and deeper groundwater are end members (Figure 2). The hyporheic zone therefore represents an ecotone between surface (stream) and groundwater ecosystems, is an important habitat for certain macroinvertebrates (*2*), and can be uniquely reactive relative to both surface water and deeper groundwater (e.g., denitrification (*1*)). Hyporheic zones are therefore important components of stream systems, and, similar to other stream habitats, have suffered degradation as a consequence of human activity. Deleterious human actions are diverse, ranging from direct channel and floodplain modifications to conversion of land to urban and agricultural uses both in the riparian zone (stream/riverbank) and in the larger watershed. Examples of the former are dam construction and channelization, while latter activities include deforestation and silt runoff from construction (*3*).

With increased recognition of their degradation, restoration of streams has become an increasingly popular activity (*4*). Common restoration goals include in-channel habitat recreation, riparian restoration, and in-stream species management (*5*). Coincidentally there is a desire to restore stream ecosystems and their associated functions (*6*). However, we currently lack restoration strategies that specifically address these broader, synergistic functions of streams (i.e., nutrient cycling and organic matter decomposition). Stream restoration activities have largely focused on modifying the form of the stream. For example, efforts like changing channel width and/or planform manipulate the spatial distribution of hydraulic energy on the bed and banks. Channel structures modify the distribution of hydraulic conditions in three dimensions, which may be important to reduce local erosion and impact available habitat. Nevertheless, there has been little study of how these structures might also influence

---

*

10.1021/es902988n

hyporheic exchange and associated stream ecosystem function (but see *7, 8*).

Despite its importance, the hyporheic zone heretofore has generally been overlooked in stream restoration design. We propose that one key step toward restoring stream ecosystems and associated functions is to incorporate channel elements that promote hyporheic exchange. We thus outline the needs and potential ways forward for restoring hyporheic zones in restoration projects. Nevertheless, while we focus here on channel manipulation projects that have become very common in recent decades, we also recognize that long-term and sustainable correction of stream impairment, including hyporheic impairment, requires altering the impact of human activities on a watershed scale. We therefore conclude with a discussion of watershed context.

Hyporheic Exchange and Associated Functions

Hyporheic exchange of water is controlled primarily by hydraulic head gradients between surface and subsurface water and the permeability of the sediments. Channel morphology dictates the spatial patterns of hydraulic head in the channel that drive local hyporheic exchange patterns (*9, 10*) (Figure 1). In particular, features such as pools, riffles, steps, debris dams, large wood, bars, meander bends, and side channels drive hyporheic exchange by increasing the local streambed gradient, creating obstacles in the flow which induce backwater and form drag, and create channel planform complexity (*11*−*13*). However, high hydraulic head in near-channel groundwater in highly gaining streams can limit the overall volume of hyporheic exchange (*14*). Finally, sediment permeability affects hyporheic exchange not only by controlling the overall range of hydraulic conductivities and therefore bulk flow rates through sediment (*15*), but also via spatial heterogeneity of conductivity which can drive exchange even in the absence of morphologic features (*16*).

Habitat. Biologists have identified a variety of hyporheic organisms (i.e., hyporheos) that spend either part or all of their lives in the hyporheic zone. In fact, the hyporheic zone was originally identified by biologists who found macroinvertebrates in the subsurface that were known to prefer surface water conditions (e.g., *17*), in some cases more than 1 km from the river (*18*). For other invertebrates, hyporheic zones are refugia during high flow events (e.g., *19*). Hyporheic exchange is also a key determinant of fish egg and embryo survival in benthic sediments. For example, bull trout (*20*) and Chinook salmon (*21*) spawning locations have been found to be linked to hyporheic downwelling and upwelling locations (i.e., where hyporheic water enters the subsurface and re-enters the channel, respectively). The occurrence of redds (fish spawning nests) in locations of localized hyporheic upwelling water is thought to take advantage of consistent temperatures and potentially nutrient rich water (*21*); redds in downwelling locations should experience conditions of relatively high dissolved oxygen (*20*).

Nutrient Cycling. Movement of water and associated dissolved nutrients into the hyporheic zone promotes the growth of extensive microbial communities in streambed and riparian sediments. These microbial communities fuel rapid and extensive biogeochemical cycling of stream-borne nutrients and also act to retard downstream pollutant transport (*22*). The increased residence time of water and solutes in the porous media of the hyporheic zone increases the opportunity for microbially mediated biogeochemical reactions relative to water in the channel. Hyporheic zones are thus locations of intense cycling of nitrogen (N), phosphorus (P), and carbon (C). Studies have identified hyporheic zones to be locations of denitrification (*23*), N mineralization (*24*), nitrification (*25*), and ammonification (*26*). As such, they also contribute to whole stream respiration (*27*), influencing stream ecosystem oxygen (O_2) and energy cycles as well.

The hyporheic zone can act as both a source and a sink of dissolved organic matter (DOM) (*28*). The hyporheic zone has more often been found to be a sink for DOM, because it is consumed and transformed by the extensive microbial communities therein. For example, *29* found that injected acetate fueled microbial respiration, denitrification, iron (Fe) and sulfur (S) reduction, and methanogenesis in the hyporheic zone. Hyporheic processes have also been found to encourage the rapid oxidation of reduced fulvic acids, suggesting that hyporheic zones may play an important role in watershed-scale energy flow (*30*). Microbes in hyporheic zones are poised to take advantage of DOM that comes from the degradation of particulate OM that is entrained on streambeds, as well as OM that becomes buried during sediment transport events.

Pollutant Buffering. Due to redox gradients and entrained C, the hyporheic zone can attenuate dissolved metals through retardation and precipitation (e.g., acid mine/rock drainage, (*31*)) and hydrocarbons through retardation and mineralization (*32*). Because hyporheic zones act as an intermediate between surface water and groundwater, they can retard pollutant transport from either source. The hyporheic zone has been identified as a sink for dissolved As from streamwater (*33*), dissolved Mn, Zn, and Co from inflowing groundwater (*34*), and dissolved chlorinated solvents (*35*). Nevertheless, the proportion of pollutant loads from upstream surface water subject to buffering—unlike those from groundwater—should decrease as the proportion of surface flow moving through the hyporheic zone decreases during storm events.

Temperature Regulation. Hyporheic exchange helps to moderate surface water temperature over daily and annual cycles primarily by removing exchanging water from exposure to direct solar radiation—the largest natural contributor to surface energy balances on clear days—and mixing with more constant temperature groundwater (*36, 37*). The significance of this effect can vary considerably depending on factors such as sediment texture and position within the stream system (e.g., benthic layer vs water column (*38*)). This temperature dynamic is an important driver of habitat heterogeneity in streams: it has direct influence on macroinvertebrate and fish survival during low flow, and is an important influence on the thermodynamic constraints of biogeochemical reactions (*1*).

Restoration Process and Hyporheic Assessment

As hyporheic exchange contributes to many stream ecosystem functions, and hyporheic exchange and function degrade as channels degrade (*3*), hyporheic restoration is a critical step toward restoration of stream ecosystems. Establishing clear goals is important for project success. Potential design goals include simply restoring hyporheic exchange of water itself and also any of the hyporheic functions discussed above. If goals include restoring preimpairment hyporheic conditions, it is necessary to quantify hyporheic deficiencies, defined here as any human induced reductions in exchange or function. It is important that this occurs in both degraded and restored systems to properly set and check restoration targets.

As there is no single established protocol, we list a range of example assessment techniques. At the qualitative screening level, the complexity of existing streambed topography (and hence hydraulic gradients) can be compared to historical photographs or reference reaches to infer the magnitude of lost hyporheic exchange. More quantitatively, shallow pits or wells can be sampled for natural or introduced tracers to determine whether sampled locations are connected to the stream (*39*). Within such locations, dissolved conservative tracers (e.g., NaCl) could be released to determine local subsurface flow rates. A more sophisticated approach entails reach-scale stream tracer experiments to determine the changes in residence time distributions of streamwater traveling along the reach: these are expected to shift toward long time scales if hyporheic exchange is occurring. Tracer analysis may or may not be accompanied by stream solute transport modeling to estimate rates of exchange (*40*). Finally, groundwater flow models of the hyporheic zone can be developed and informed by channel topography, channel hydraulics, and estimates of subsurface hydraulic conductivity (*10*). This approach could be directly integrated into the restoration design process.

Hyporheic Restoration Techniques

A variety of stream restoration design elements can promote the goal of restoring hyporheic exchange, mainly by enhancing surface−groundwater hydraulic gradients, increasing hydraulic conductivity of sediments, and/or providing sources of C to hyporheic sediments. This section presents some examples of these techniques. Other factors that control hyporheic exchange or function such as the broader groundwater setting or stream discharge are less amenable to engineering control. Additionally, certain common stream restoration strategies, such as floodplain reconnection, could enhance hyporheic exchange by incorporating many of the following elements.

Morphologic Features. Pools, riffles, log dams, steps, and meander bends are commonly installed in stream restoration projects to benefit geomorphic stability, aquatic habitat, and aesthetics (*5*). These features may also promote hyporheic exchange by creating slope breaks or backwater in the channel, thereby setting up hydraulic gradients between surface and groundwater. Some morphologic features may also retain OM (e.g., trap leaves) that could provide C sources and create the redox gradients necessary for certain functions. While the hyporheic benefits of ongoing installation of morphologic features may be considerable, to our knowledge they are not currently included as project design goals. Accordingly, we recommend adding the hyporheic benefits of existing installations as an explicit design goal where appropriate, modifying the design parameters of such features to maximize benefit as possible, and considering additional features explicitly for hyporheic benefit. Further benefits may come from adjusting feature location within a reach or even the larger stream network.

Large Wood. Large wood is often installed in stream restoration projects for stabilizing the bed and banks, and enhancing habitat for aquatic organisms. These benefits are similar to many morphologic features described above, and indeed, construction of many morphologic features utilizes large wood. In some cases, large wood may also serve as a C source.

Enhanced hyporheic exchange from morphologic features and large wood—parameters such as flow and residence time (*41*)—can be estimated using existing groundwater flow modeling tools (*42*). Such models would also form the basis for evaluating hyporheic functions. Furthermore, the hyporheic exchange of water induced by particular features can be informed by many existing studies, some of which include explicit "design curves" that relate restoration design parameters (e.g., feature size) to induced hyporheic exchange (e.g., *10, 12, 13, 43*). Similarly, a few studies quantify the impact of restoration features on hyporheic function (e.g., *7, 44*), including design curves (e.g., *38*). Nevertheless, there are large gaps in our knowledge about how morphologic features impact hyporheic function, and studies with specific design criteria are particularly rare.

Sediment Coarsening. Introduction of coarse sediment is a common stream restoration practice that generally has goals of increasing sediment stability, improving benthic conditions for fish eggs (*45*), and even thermal buffering from hyporheic exchange (*46*). This is typically accomplished by placement of coarser sediment brought from outside the stream system. Sediment coarsening has also been accomplished by removing fine sediment in place (*47*). The effort enhances surficial sediment permeability with the potential to enhance hyporheic exchange and possibly function. These hyporheic benefits, particularly the hydrologic component, can be estimated by modeling, by reference to design curves, or from examples in the literature (e.g., *13, 48*).

Riparian Planting. Floodplain reforestation is a common stream restoration technique, used to stabilize banks, provide shade to reduce peak stream temperatures, and improve aesthetics. It also provides a source of particulate (and with degradation, dissolved) OM, which can be entrained into streambed sediments during bedload movement. This has the potential to benefit hyporheic functions that require C sources or redox gradients. However, while many studies have demonstrated the link between C sources and hyporheic function, we are not aware of studies that have either quantified the applied value of riparian restoration for benefiting such functions or how such benefits vary with riparian planting techniques.

Spatial and Temporal Context

While typical stream restoration practice focuses on individual stream reaches, sustainably reversing stream impairment, including impairment of hyporheic function, requires a three-tiered watershed perspective. First, channel manipulation projects with hyporheic restoration goals must account for upstream watershed conditions that impact hyporheic conditions. Fluxes of water, nutrients, pollutants, and organisms from upstream may all impact restoration success. However, the most important upstream flux for hyporheic restoration is fine sediment which is often significant in agricultural or urbanizing areas, with the potential to eliminate hyporheic enhancement by filling sediment interstices and cutting off flow (*15*). Second, stream restoration projects, including those that target the hyporheic zone, should be coordinated at the watershed scale. For example, hyporheic restoration sites can be located within the stream network for optimal benefit. Finally, the ultimate solution to hyporheic impairment is recreating watershed conditions that naturally sustain hyporheic zones. In particular, any of the elements presented above as hyporheic restoration techniques could be promoted at the watershed scale as well. For example, rather than directly installing in-stream structures such as large wood or log dams to promote hyporheic exchange, riparian corridors, or even whole watersheds, could be reforested to create a source of large wood to the channel.

Restoration efforts must also consider the temporal context on at least two time scales. First, stream restoration projects that entail direct intervention (e.g., remeandering), represent short-term disturbances to aquatic, benthic, and riparian ecosystems (*49*), even if they offer long-term benefit. There will thus always be a recovery trajectory as organisms and communities re-establish after construction ceases. Second, and perhaps more importantly for hyporheic restoration, constructed morphologic features will evolve over time and/or fail due to sediment movement and rotting of large wood. Explicit planning for the failure of constructed features entails specifying a design life, which can be somewhat controlled by structural configuration and the materials used. In urbanized areas with little tolerance for channel or large wood movement, "threshold" channels may be used where bedforms are designed to not move; eventual structural failure might simply be acknowledged and designs modified to minimize liability. In natural settings, where channels are in dynamic equilibrium with their floodplains and where riparian vegetation is intact, these natural failure processes are balanced by natural creation of morphologic features (e.g., by a large log falling across a stream). Therefore, in areas where broader stream corridor restoration can occur, a more self-sustaining cycle of feature creation and destruction might be possible.

In summary, we propose that "hyporheic restoration" be considered as a goal of stream ecosystem restoration projects. Hyporheic restoration may not be appropriate or feasible in all settings. The value of restoration hinges on the nature and degree of hyporheic deficiencies as well as the watershed context. Nevertheless, the importance of the hyporheic zone underscores the need to at least evaluate hyporheic deficiencies and estimate the effects of any restorative effort. Many existing stream restoration techniques may have hyporheic benefits such as increasing head gradients between surface and groundwater, increasing hydraulic conductivity of sediments, or addition of C sources. Thus incorporation of hyporheic goals can potentially be a straightforward modification of traditional stream restoration techniques.

However, a more holistic and sustainable approach that couples direct intervention in stream channels with planning and restoration at the watershed level is recommended to realize maximal benefit. The multifaceted nature of the hyporheic zone poses a challenge to developing successful restoration strategies, and necessitates continued research of an increasingly interdisciplinary nature. Particularly, quantification of the effects of various restoration techniques on hyporheic functions, such as C benefits of riparian planting and the impact of morphologic features on pollutant attenuation, is needed. Such a greater understanding could further aid other efforts such as pollution mitigation and ecosystem service provision at the watershed level. Thus proper consideration of the hyporheic zone can shore up an important pillar of holistic environmental management.

Dr. Erich Hester is an assistant professor in the Department of Civil and Environmental Engineering at Virginia Tech. His expertise centers on how hydrology, hydraulics, and geomorphology influence ecological health and water quality in streams, rivers, and wetlands; key focuses include surface water groundwater interactions and ecological restoration of aquatic systems. Dr. Hester's research ultimately aims to allow better informed restoration design, ecosystem preservation, pollutant attenuation by natural processes, and watershed planning. Dr. Michael Gooseff is a Hartz Family Professor in the Department of Civil and Environmental Engineering at Penn State University. His research interests are focused on hydrologic and ecosystem responses to changing climate, hydrologic influences on ecosystem processes in terrestrial and aquatic systems, and in particular, stream−groundwater interactions. His field research spans from the Arctic to the Antarctic, and some other sites closer to home. Please address correspondence regarding this manuscript to ehester@vt.edu.

Literature Cited

(1) Brunke, M.; Gonser, T. The ecological significance of exchange processes between rivers and groundwater. *Freshwater Biol.* **1997**, *37*, 1–33.

(2) Hynes, H. B. N. *The Ecology of Running Waters*; University of Toronto Press: Toronto, 1970; p 555.

(3) Hancock, P. J. Human impacts on the stream-groundwater exchange zone. *Environ. Manage.* **2002**, *29*, 763–781.

(4) Bernhardt, E. S.; Palmer, M. A.; Allan, J. D.; Alexander, G.; Barnas, K.; Brooks, S.; Carr, J.; Clayton, S.; Dahm, C. N.; Follstad-Shah, J. Synthesizing U.S. river restoration efforts. *Science* **2005**, *308* (5722), 636–637.

(5) Bernhardt, E. S.; Sudduth, E. B.; Palmer, M. A.; Allan, J. D.; Meyer, J. L.; Alexander, G.; Follastad-Shah, J.; Hassett, B.; Jenkinson, R.; Lave, R. Restoring rivers one reach at a time: Results from a survey of U.S. river restoration practitioners. *Restor. Ecol.* **2007**, *15* (3), 482–493.

(6) Gore, J. A. *The Restoration of Rivers and Streams: Theories and Experience*; Butterworth-Heinemann Ltd.: Stoneham, MA, 1985; p 350.

(7) Kasahara, T.; Hill, A. R. Hyporheic exchange flows induced by constructed riffles and steps in lowland streams in southern Ontario, Canada. *Hydrol. Proc.* **2006**, *20* (20), 4287–4305.

(8) Lautz, L. K.; Fanelli, R. M. Seasonal biogeochemical hotspots in the streambed around restoration structures. *Biogeochemistry* **2008**, *91* (1), 85–104.

(9) Harvey, J. W.; Bencala, K. E. The effect of streambed topography on surface-subsurface water exchange in mountain catchments. *Water Resour. Res.* **1993**, *29* (1), 89–98.

(10) Kasahara, T.; Wondzell, S. M. Geomorphic controls on hyporheic exchange flow in mountain streams. *Water Resour. Res.* **2003**, *39* (1), 10.1029/2002WR001386.

(11) Cardenas, M. B.; Wilson, J. L.; Zlotnik, V. A. Impact of heterogeneity, bed forms, and stream curvature on subchannel hyporheic exchange. *Water Resour. Res.* **2004**, *40*, W08307; doi: 10.1029/2004WR003008.

(12) Gooseff, M. N.; Anderson, J. K.; Wondzell, S. M.; LaNier, J.; Haggerty, R. A modelling study of hyporheic exchange pattern and the sequence, size, and spacing of stream bedforms in mountain stream networks, Oregon, USA. *Hydrol. Proc.* **2006**, *20* (11), 2443–2457.

(13) Hester, E. T.; Doyle, M. W. In-stream geomorphic structures as drivers of hyporheic exchange. *Water Resour. Res.* **2008**, *44*, W03417; doi:10.1029/2006WR005810.

(14) Cardenas, M. B.; Wilson, J. L. Exchange across a sediment-water interface with ambient groundwater discharge. *J. Hydrol.* **2007**, *346* (3−4), 69–80.

(15) Rehg, K. J.; Packman, A. I.; Ren, J. Effects of suspended sediment characteristics and bed sediment transport on streambed clogging. *Hydrol. Proc.* **2005**, *19* (2), 413–427.

(16) Vaux, W. G. Intragravel flow and interchange of water in a streambed. *Fish. B.-NOAA* **1968**, *66* (3), 479–489.

(17) Stanford, J. A.; Gaufin, A. R. Hyporheic communities of two Montana rivers. *Science* **1974**, *185*, 700–702.

(18) Stanford, J. A.; Ward, J. V. The hyporheic habitat of river ecosystems. *Nature* **1988**, *335*, 64–66.

(19) Olsen, D. A.; Townsend, C. R. Flood effects on invertebrates, sediments and particulate organic matter in the hyporheic zone of a gravel-bed stream. *Freshwater Biol.* **2005**, *50* (5), 839–853.

(20) Baxter, C. V.; Hauer, F. R. Geomorphology, hyporheic exchange, and selection of spawning habitat by bull trout (*Salvelinus confluentus*). *Can. J. Fish. Aquat. Sci.* **2000**, *57*, 1470–1481.

(21) Geist, D. R. Hyporheic discharge of river water into fall chinook salmon (*Oncorhynchus tshawytscha*) spawning areas in the Hanford Reach, Columbia River. *Can. J. Fish. Aquat. Sci.* **2000**, *57* (8), 1647–1656.

(22) Fischer, H.; Kloep, F.; Wilzcek, S.; Pusch, M. A river's liver - Microbial processes within the hyporheic zone of a large lowland river. *Biogeochemistry* **2005**, *76* (2), 349–371.

(23) Duff, J. H.; Triska, F. J. Denitrification in sediments from the hyporheic zone adjacent to a small forested stream. *Can. J. Fish. Aquat. Sci.* **1990**, *47* (6), 1140–1147.

(24) Hill, A. R.; Labadia, C. F.; Sanmugadas, K. Hyporheic zone hydrology and nitrogen dynamics in relation to the streambed topography of a N-rich stream. *Biogeochemistry* **1998**, *42* (3), 285–310.

(25) Jones, J. B.; Fisher, S. G.; Grimm, N. B. Nitrification in the hyporheic zone of a desert stream ecosystem. *J. N. Am. Benthol. Soc.* **1995**, *14*, 249–258.

(26) Coleman, R. L.; Dahm, C. N. Stream geomorphology: Effects on periphyton standing crop and primary production. *J. N. Am. Benthol. Soc.* **1990**, *9* (4), 293–302.

(27) Mulholland, P. J.; Marzolf, E. R.; Webster, J. R.; Hart, D. R.; Hendricks, S. P. Evidence that hyporheic zones increase heterotrophic metabolism and phosphorus uptake in forest streams. *Limnol. Oceanogr.* **1997**, *42* (3), 443–451.

(28) Schindler, J. E.; Krabbenhoft, D. P. The hyporheic zone as a source of dissolved organic carbon and carbon gases to a temperate forested stream. *Biogeochemistry* **1998**, *43* (2), 157–174.

(29) Baker, M. A.; Dahm, C. N.; Valett, H. M. Acetate retention and metabolism in the hyporheic zone of a mountain stream. *Limnol. Oceanogr.* **1999**, *44* (6), 1530–1539.

(30) Miller, M. P.; McKnight, D. M.; Cory, R. M.; Williams, M. W.; Runkel, R. L. Hyporheic exchange and fulvic acid redox reactions in an alpine stream/wetland ecosystem, Colorado Front Range. *Environ. Sci. Technol.* **2006**, *40* (19), 5943–5949.

(31) Gandy, C. J.; Smith, J. W. N.; Jarvis, A. P. Attenuation of mining-derived pollutants in the hyporheic zone: A review. *Sci. Total Environ.* **2007**, *373* (2−3), 435–446.

(32) Smith, J. W. N.; Lerner, D. N. Geomorphologic control on pollutant retardation at the groundwater-surface water interface. *Hydrol. Proc.* **2008**, *22*, 4679–4694.

(33) Brown, B. V.; Valett, H. M.; Schreiber, M. E. Arsenic transport in groundwater, surface water, and the hyporheic zone of a mine-influenced stream-aquifer system. *Water Resour. Res.* **2007**, *43* (11), W11404; doi:10.1029/2006WR005687.

(34) Fuller, C. C.; Harvey, J. W. Reactive uptake of trace metals in the hyporheic zone of a mining-contaminated stream, Pinal Creek, Arizona. *Environ. Sci. Technol.* **2000**, *34*, 1150–1155.

(35) Conant, B.; Cherry, J. A.; Gillham, R. W. A PCE groundwater plume discharging to a river: influence of the streambed and near-river zone on contaminant distributions. *J. Contam. Hydrol.* **2004**, *73* (1−4), 249–279.

(36) Arrigoni, A. S.; Poole, G. C.; Mertes, L. A. K.; O'Daniel, S. J.; Woessner, W. W.; Thomas, S. A. Buffered, lagged, or cooled? Disentangling hyporheic influences on temperature cycles in stream channels. *Water Resour. Res.* **2008**, *44*, W09418; doi: 10.1029/2007WR006480.

(37) Hannah, D. M.; Malcolm, I. A.; Bradley, C. Seasonal hyporheic temperature dynamics over riffle bedforms. *Hydrol. Proc.* **2009**, *23* (15), 2178–2194.

(38) Hester, E. T.; Doyle, M. W.; Poole, G. C. The influence of in-stream structures on summer water temperatures via induced hyporheic exchange. *Limnol. Oceanogr.* **2009**, *54* (1), 355–367.

(39) Triska, F. J.; Kennedy, V. C.; Avanzino, R. J.; Zellweger, G. W.; Bencala, K. E. Retention and transport of nutrients in a third-order stream in northwest California: hyporheic processes. *Ecology* **1989**, *70* (6), 1893–1905.

(40) Runkel, R. L. A new metric for determining the importance of transient storage. *J. N. Am. Benthol. Soc.* **2002**, *21* (4), 529–543.

(41) Mutz, M.; Kalbus, E.; Meinecke, S. Effect of instream wood on vertical water flux in low-energy sand bed flume experiments. *Water Resour. Res.* **2007**, *43* (10), doi:10.1029/2006WR005676.

(42) Wondzell, S. M.; LaNier, J.; Haggerty, R. Evaluation of alternative groundwater flow models for simulating hyporheic exchange in a small mountain stream. *J. Hydrol.* **2009**, *364* (1−2), 142–151.

(43) Cardenas, M. B. Stream-aquifer interactions and hyporheic exchange in gaining and losing sinuous streams. *Water Resour. Res.* **2009**, *45*, W06429; doi:10.1029/2008WR007651.

(44) Crispell, J. K.; Endreny, T. A. Hyporheic exchange flow around constructed in-channel structures and implications for restoration design. *Hydrol. Proc.* **2009**, *23* (8), 1158–1168.

(45) NRCS. *Stream Restoration Design*; USDA National Resources Conservation Service: 2007.

(46) Grant, G. E.; Haggerty, R.; Lewis, S.; Burkholder, B. K.; Wampler, P. J. *Potential effects of gravel augmentation on temperature in the Clackamas River, Oregon*; General Electric: Portland, OR, 2006.

(47) Meyer, E. I.; Niepagenkemper, O.; Molls, F.; Spanhoff, B. An experimental assessment of the effectiveness of gravel cleaning operations in improving hyporheic water quality in potential salmonid spawning areas. *River Res. Appl.* **2008**, *24*, 119–131.

(48) Kasahara, T.; Hill, A. R. Modeling the effects of lowland stream restoration projects on stream-subsurface water exchange. *Ecol. Eng.* **2008**, *32* (4), 310–319.

(49) Tikkanen, P.; Laasonen, P.; Muotka, T.; Huhta, A.; Kuusela, K. Short-term recovery of benthos following disturbance from stream habitat rehabilitation. *Hydrobiologia* **1994**, *273*, 121–130.

ES902988N