Groundwater–surface-water interactions: perspectives on the development of the science over the last 20 years

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Abstract: Freshwater Science published a special series of papers on groundwater–surface-water (GW-SW) interactions in this issue (2015), marking the anniversary of an earlier special series of papers on the hyporheic zone published in 1993. In this concluding paper, I compare the 2 special series of papers and use this comparison to examine the development of the science in the years between 1993 and 2015. The 1993 papers marked the beginning of a period of exponential growth in the study of, and publication of, papers on GW-SW interactions. The 1993 papers tended to be forward looking, proposing conceptual models of GW-SW interactions across stream networks and identifying critical gaps. The 2015 special series of papers contrasts sharply with that of 1993. Broad issue papers are mostly lacking from the current special series. Instead, the special series is dominated by papers focusing on process-based or descriptive studies using empirical approaches. This difference probably stems from major methodological advancements over the past 2 decades that make it possible to study GW-SW interactions with ever greater detail and, thus, allows more complete understanding of specific processes. In contrast, the authors of the 1993 special series were acutely aware of the paucity of GW-SW studies and, thus, posed their conceptual models as hypotheses. Surprisingly, these hypotheses have not been rigorously tested in the decades since their publication. Perhaps it is time to re-examine such broad conceptual models. There remains a critical need for a holistic understanding of how GW-SW interactions vary among streams types and sizes and with changes in discharge among seasons or over storm events and how these GW-SW interactions influence stream ecosystem processes.

Key words: hyporheic, groundwater, streams, conceptual models, literature review

Hyporheic science has grown dramatically since the concept was defined by Orghidan (1955; from the English translation by D. Käser 2010). Early hyporheic studies were relatively few and tended to focus primarily on the biota inhabiting the shallow stream bed. The signature characteristic of the hyporheic zone—as an ecotone where stream water and ground water met and mixed—slowly gained recognition in aquatic ecology, and in the mid- to late-1980s, several landmark papers refocused attention on the potential effects of the hyporheic zone on broader stream ecological processes. Grimm and Fisher (1984) published a seminal work showing that metabolism in hyporheic sediment was large enough that a stream previously thought to be autotrophic was actually heterotrophic. Stanford and Ward (1988) described the importance of hyporheic habitats to stream-dwelling macroinvertebrates at lateral distances of several kilometers from the stream, a spatial scale never previously imagined for below (hypo) stream (rheos) processes. Triska et al. (1989a, b) showed that the hyporheic zone played a critical role in the transport and retention of nutrients in streams. These papers are the most highly cited early publications on the hyporheic zone (Scopus citation search, May 2014; Scopus, Elsevier, The Netherlands). These papers built on a history of previous research, much of which did not explicitly use the word “hyporheic” (e.g., Vaux 1962, Thackston and Schnelle 1970, Chatarpaul and Robinson 1979) and served as landmarks in the development of a new subdiscipline in hydrology and stream ecology. In 1993, the Journal of the North American Benthological Society (J-NABS) published a special series of papers on hyporheic science that further established it as a subdiscipline. The papers that made up that special series articulated needs and future directions for hyporheic research.

The growth rate of the number of papers published in the subdiscipline of hyporheic research and the more gen-
eral discipline of groundwater–surface-water (GW-SW) interactions has been approximately exponential since the mid-1980s (Fig. 1A). From its first use through the end of 1993, Scopus lists a cumulative total of only 55 citations using the word “hyporheic” in the title, abstract, or list of key words. As of May 2014, a cumulative total of 1200 citations, of which 135 were published in 2013 alone, was found by searching on “hyporheic” as a key word (Fig. 1B). Furthermore, the rate of growth in the number of publications in these fields has been 1.6 and 1.3× greater, respectively, than the growth of publications in the Scopus database at large (Fig. 1A). An examination of the titles of papers in this literature search indicates that early hyporheic research tended to be somewhat narrowly focused on stream–shallow groundwater interactions. Publications in the larger field of GW-SW interactions began to appear

Figure 1. A.—Semilog plot of the number of papers published each year including the word “hyporheic” in the title, abstract, or keywords (all hyporheic) vs those including either “hyporheic” or “surface water AND groundwater AND (interaction OR interactions)” compared to the growth in the number of papers published in the Scopus database at large. Linear regressions fit these lines with all $r^2 > 0.92$. Slopes are 0.086 (hyporheic), 0.070 (groundwater–surface-water [GW-SW], and hyporheic), and 0.053 (all Scopus citations). B.—Total number of papers published each year in 3 subdisciplines of hydrology.
in the Scopus database at approximately the same time as those reporting hyporheic research, but the GW-SW publications tended to focus on interactions between rivers and groundwater aquifers at larger scales more relevant to human social and economic systems. Only recently has the scope of research in stream ecology and hyporheic processes broadened to examine the full catchment continuum (Bencala et al. 2011) that influences the hydrology and ecology of streams, hyporheic zones, and both shallow near-stream unconstrained aquifers and larger regional aquifers. This expansion of the science is reflected in the descriptive terminology, with the phrase “stream-water–groundwater interactions” increasingly replacing “hyporheic” in the literature (Fig. 1B).

The 1993 special series

The 1993 special series of papers (J-NABS, volume 12, issue 1) was published immediately before the explosion of hyporheic research (Fig. 1B), and thus, was timely. Perhaps the tone of the special series was described best by David White who reflected on the relative newness of hyporheic research and wrote: “... there is danger in making sweeping generalizations with so few hyporheic zones having been examined comparatively. However, perhaps one of the most exciting times in any endeavor is when we are still at liberty to make some proposals” (White 1993, p. 61). To that end, the collected papers of the 1993 special series provided an important conceptual context from which to begin building a more comprehensive understanding of the hydrological and ecological processes that occur in the hyporheic zone and the importance of those processes to stream ecosystems. Furthermore, authors of papers in this collection raised critical unanswered questions in hopes that they would guide future research. As a consequence, many of the papers in the 1993 special series have become widely cited.

Bencala (1993) challenged common hydrologic perceptions of unidirectional flow of water into and down streams, which likens them to simple pipes, and instead recognized the importance of bidirectional exchange in which stream water can move repeatedly from the stream, into the subsurface, and back into the stream. The simple statement, “the stream is not a pipe”, reflected a major shift in the prevailing conceptual models of ecology and hydrology in the 1980s, but it did little to predict the relative importance of hyporheic exchange flows to stream ecosystems nor did it help answer the questions about where, when, and under what conditions hyporheic exchange flows occur.

Stanford and Ward (1993) and White (1993) endeavored to build conceptual models describing the relative importance of the hyporheic zone in stream ecosystem processes along the longitudinal corridor of alluvial rivers, from headwaters through large mainstem reaches. These efforts clearly complemented the river continuum concept (Vane note et al. 1980), which described a systematic progression in processes linked to location and size of the river. However, Stanford and Ward (1993) and White (1993) also recognized that spatial heterogeneity in the hydro-geomorphic factors that control the expression of the hyporheic zone would control the relative importance of specific hyporheic processes across scales ranging from the channel unit to stream networks. White (1993) emphasized the importance of developing a common, interdisciplinary framework to support comparisons of hyporheic processes among different river systems and across scales. Stanford and Ward’s (1993) conceptual model was heavily influenced by their work in large, unconstrained reaches of coarse-bedded mountain rivers, whereas White’s (1993) conceptual model drew heavily from his work on low-gradient mid-order streams. As a consequence, their conceptual models were somewhat different. For example, White (1993) hypothesized that little hyporheic exchange would occur in headwater reaches, which would be dominated by lateral inputs of ground water, whereas Stanford and Ward (1993) hypothesized that interstitial exchange in headwaters might be small in absolute terms, but potentially large relative to surface discharge. Both White (1993) and Stanford and Ward (1993) hypothesized that hyporheic exchange would be maximal relative to stream discharge in mid-order reaches and that the alluvial floodplains of larger rivers might well be dominated by hyporheic waters.

The papers by Hendricks (1993) and Stanley and Boulton (1993) examined spatial patterning of the hyporheic zone caused by characteristic hydrological flow paths through pool–riffle sequences and point bars and the resulting boundaries between ground water and hyporheic water. Hendricks’ (1993) paper summarized several years of published and unpublished research and provided one of the first multidisciplinary summaries of hyporheic processes including the density of invertebrates, microbial biomass and production, microenvironmental gradients in water chemistry, and basic geochemical processes in both aerobic and anaerobic zones. Stanley and Boulton (1993) showed that spatial patterns of subsurface invertebrates were closely related to patterns of groundwater upwelling and hyporheic downwelling in a mesic temperate river and an intermittent desert river and that temporal variations in these patterns caused by spates or drying also could be explained by hydrologic patterns. Together, these papers demonstrated the fundamental control that hydrology exerts on hyporheic processes and the importance of spatial heterogeneity from the microscale of biofilms on sediment surfaces to the channel-unit scale at which hyporheic upwelling and downwelling were organized.

Authors of papers in the 1993 special series also identified a number of unresolved issues that limited understanding of hyporheic processes and their influences on stream ecosystems. For example, Palmer (1993) identified
major obstacles limiting research on the hyporheic zone and attempted to suggest approaches that could break through these obstacles, leading to major advances in the understanding of hyporheic processes. These included: 1) embracing the intersite heterogeneity of the hyporheic zone and working to understand the factors that control hyporheic processes among different sizes and types of streams; 2) developing better sampling tools and methods; 3) considering the role of bed movement, sediment transport, and infrequent hydrologic events; 4) measuring subsurface flow velocities; and 5) quantifying the magnitude and direction of fluxes between surface stream, hyporheic zone, and groundwater environments.

**The 2015 special series**

The collection of papers in this 2015 special series provides a stark contrast to those published in 1993. Perhaps the most obvious difference is the absence of broad-issue papers. A number of potential reasons exist to explain this difference. Foremost among these is that the contributing authors were not specifically asked to address broad issues, such as the current state of the science, or to identify critical unresolved issues. At the same time, the collection of papers in the 2015 special series provides a broad sampling of current research into GW-SW interactions. Thus, comparisons to the collection of papers from 1993 may prove informative.

Undoubtedly, the newness of hyporheic science in 1993 enabled authors to build initial conceptual models around which individual studies could be organized to develop a more holistic understanding of the role of the hyporheic zone in stream ecosystem processes. The increased maturity of the field today creates a different publication environment, but also provides opportunities to evaluate the current state of knowledge and reassess topics that are important for future research. Several recent literature reviews (e.g., Sophocleous 2002, Boulton et al. 2010, Krause et al. 2011) fill this need, but I suspect that the content of the papers in the 2015 special series broadly reflects developments in the field over the past few decades, i.e., a strong focus on process-based research. This focus on process-based research arose, at least in part, from development and increasing accessibility of better technological approaches, e.g., fiber-optic distributed temperature-sensing technology (Selker et al. 2006), stable-isotope approaches (Böhlke et al. 2004), and computational capacity that makes numerical modeling with computational fluid dynamics models relatively accessible (Cardenas et al. 2004). These developments allow in-depth investigation into the mechanisms of hydrological and biogeochemical processes at relatively fine spatial and temporal scales, but larger-scale questions, many of which were raised in the 1993 special series, have received less attention.

Papers in the 2015 series can be broadly divided into 3 groups: 1) empirical, process-based studies of stream–groundwater interactions, 2) descriptive studies of the distribution of groundwater fauna, and 3) methods papers (Table 1).

The first group of papers, consisting of the process-based studies of stream–groundwater interactions, clearly follow the conceptual approaches put forth in the 1993 special series. Authors of these papers tended to focus at the reach-scale (8 of 10 papers; study topic = S or S/G in Table 1) and studied relatively small streams (median watershed size is 42 km²; Table 1) at low discharge (Q; median of both low and high Q = 65 L/s; Table 1). Temporal scales were more broadly represented, and studies addressed changes occurring over hours, days, seasons, and even between years. Two-thirds of these papers explored hydrological processes, sometimes alone but also in association with studies of biogeochemical processes (Table 1). Biogeochemical studies were focused primarily on N and C, but the advent of reliable and relatively inexpensive data-logging multisensors led to temperature, electrical conductivity, pH, and dissolved O₂ becoming common metrics in study-site descriptions or covariates in analyses. Notably absent from this subset of the 2015 papers are studies at the scales of sediment grains and biofilms, and only 1 study was conducted at the multi-reach to network scale. Although many authors in the series addressed biogeochemical processes, only 1 author attempted to develop budgets of mass fluxes at reach or larger scales (Zarnetske et al. 2015).

Unlike the 1993 special series, ~1/3 of the papers in the 2015 special series focused on groundwater fauna and the ecological relationships in larger aquifer systems (study topic = G, Table 1). This 2nd group of papers signifies the increased emphasis on the full complement of ecohydrologic systems that compose GW-SW interactions. In 1993, the hyporheic zone was so novel that the special series focused solely on those small spatial and short temporal scales at which stream water flowed through the stream bed, into subjacent sediment, and would soon return to the stream. The field has grown to recognize the importance of larger groundwater systems that need to be included as part of the continuum of these interactions. Groundwater-related studies in the 2015 special series range over spatial scales from local streamside aquifers to regional aquifers (Table 1). For example, seepage through the beds of rivers can recharge large aquifers so that distance from the river may be a primary influence on groundwater chemistry and the distribution of organisms found in these groundwater systems (e.g., Larned et al. 2015). Conversely, aquifer recharge may be dominated by precipitation so that spatial patterns in the overlying soils and regional geology may determine the distribution of organisms found in groundwater systems (Johns et al. 2015, Korbel and Hose 2015).
Table 1. A summary of the papers in this special series (2015). X denotes a primary focus of the study, and x denotes a secondary focus. Papers are categorized by dominant study topic (S = stream, G = ground water, W = wetland, M = methods), spatial scale, temporal scale, and topic or variables studied. Studies are identified as focused primarily on hyporheic or groundwater systems and as empirical or simulation studies. A few papers address narrow topics (as listed). Physical attributes of the study sites are summarized for the papers that reported them.

The percentage of the 20 papers in a category is given in the top row, except for the last 4 columns where median values of physical attributes for stream-focused studies are reported. Not all papers were easily categorized, and many studies spanned >1 category or did not fit any category. Q = discharge and EC = electrical conductivity.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Study topic</th>
<th>Spatial scale</th>
<th>Temporal scale</th>
<th>Special topic</th>
<th>Type of study</th>
<th>Topic or variables studied</th>
<th>Physical attributes of stream studies</th>
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<td>Caldwell et al.</td>
<td>S/G</td>
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<td>Ebersole et al.</td>
<td>S/G</td>
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<td>Gonzales-Pinzon et al.</td>
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<td>Menichino et al.</td>
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<td>Rinehart et al.</td>
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<td>Zimmer and Lutz</td>
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<td>Griebler and Avramov</td>
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<td>Korbel and Hose</td>
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<td>Stelzer et al.</td>
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<td>Aubeneau et al.</td>
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Discharge of long-residence-time ground waters from regional aquifers into streams can have major influences on stream ecosystem processes (e.g., Kurz et al. 2015), and of course, biogeochemical processes in these large groundwater systems influence water quality for anthropogenic uses and, thus, represent an environmental service (Griebler and Avramov 2015). Studies at the scales of large floodplain aquifers to regional aquifers are difficult because access to these systems requires deep wells. As a consequence, such studies are relatively rare and those published here are mostly descriptive (Johns et al. 2015, Korbel and Hose 2015, Larned et al. 2015).

Several authors in the 2015 special series explored methodological approaches to studying GW-SW interactions (study topic = M or S/M, Table 1). These papers are quite different in approach than the methods paper in the 1993 special series (Palmer 1993), which was forward looking and attempted to identify methods developments needed to make progress in the newly developing field. Authors of the subset of methods papers in the 2015 special series tended to examine existing methodological approaches and the limitations of these approaches. Tracer studies have been a mainstay of hyporheic research since their introduction to the stream ecology community by Bencala and Walters (1983) and the Stream Solute Workshop (1990). Modified 1-dimensional advection–dispersion models were initially developed by engineers to describe flow and transport in pipes (Taylor 1954, as cited by Thackston and Schnelle 1970), but when applied to streams, they failed to capture the shape of the breakthrough curve and, thus, were modified by adding a transient-storage component. The same models were further modified to include 1st-order reactions to describe the transport, retention, and transformation of reactive solutes. Transient-storage modeling has been used widely since the early 1990s. However, over the last few years, several authors have begun to question the applicability of these methods for understanding GW-SW interactions, especially at the time- and space-scales that are captured in such tracer tests (e.g., Zarnetske et al. 2015). Aubeneau et al. (2015) provided an in-depth analysis of the shape of hypothetical breakthrough curves, based on continuous-time, random-walk models, to examine the influence of a variety of benthic and hyporheic processes. González-Pinzón et al. (2015) reported the results of a multi-investigator, multitechnique analysis of GW-SW interactions conducted as a part of a workshop. Their study was unique in that they field-tested and compared multiple techniques simultaneously in a single stream reach, and they discussed the advantages and limitations of each technique. Many methodological improvements have occurred in the field since the 1993 special series, but it remains difficult to work across scales. Specifically, linking local point measurements or channel-unit measurements to describe reach-scale processes or to scale-up reach-scale measurement to the whole-stream network is challenging (e.g., Zarnetske et al. 2015).

Unaddressed issues and future directions

Hakenkamp et al. (1993) summarized the collection of papers in the 1993 special series and identified a number of important questions for future research. When one considers the 1993 special series more broadly, the authors of the collected papers clearly were acutely aware of the paucity of hyporheic studies and, thus, posed their conceptual models as hypotheses based on their own observations at one or a few sites or, in some cases, a comparison of their results with a small number of similar studies. It is interesting to look at the research accomplished in the intervening years and ask which of those conceptual models found strong support in the literature, which have been revised or modified on the basis of new results, which areas have seen substantial progress, and which have seen relatively little progress.

Many hyporheic processes are controlled by interactions between water flowing through individual pores and biogeochemical processes occurring in biofilms coating particles of hyporheic sediment. Hendricks (1993) studied finescale organismal processes, especially those mediated by microbial biofilms that explained the outcomes of GW-SW interactions at reach and larger scales. However, since then studies at the pore or biofilm scale have been relatively uncommon. The ecological and physical processes occurring at these fine spatial scales simply cannot be resolved by the methods most frequently used in the field. Subsurface environments are heterogeneous, and preferential flow might be a critical determinant of the actual influence that exchange flows exert. Improved computing power allows ever more powerful models to be run at finer and finer spatial resolution, but the ability to incorporate spatial heterogeneity into these models is limited by at least 2 factors. First, spatial properties do not scale continuously from micro to macro scales. Thus, grid/mesh spacing will become smaller than the size of the clasts that compose the dominant physical framework of the porous medium through which both surface stream water and ground water flow. Second, the spatial heterogeneity of the subsurface cannot be measured at the range of spatial scales relevant to understanding biological and hydrological processes. Thus, representing these processes in models, regardless how fine-grained the model, is challenging.

Investigators are beginning to explore alternative approaches. For example, relatively immobile domains within the subsurface, where solute transport is controlled by molecular-scale diffusion (Hadley and Newell 2014) rather than advection–dispersion processes, may be critically important to understanding solute transport. The influence of these relatively immobile domains on solute transport also is being explored with dual-domain mass-transfer
models (Haws et al. 2004) and versions of these models have been applied to flow-through porous media as influenced by biofilms (Seifert and Engesgaard 2007, Orgogozo et al. 2013), but these models have not been applied to studies of GW-SW interactions. Other modeling approaches are beginning to be used to explore the turbulence structures that develop with flow through pores between idealized spherical grains (e.g., Finn and Apte 2013). However, these models do not yet simulate the presences of biofilms coating mixtures of sediment grains with a heterogeneous distribution of sizes, factors that would be critically important to understanding the delivery of solutes to biofilms. Nevertheless, these are the scales at which many of the processes of interest are occurring. The range of spatial and temporal scales involved in these processes create significant challenges for investigators attempting to accurately characterize processes at the scale of cells and biofilms and to upscale these processes to predict system responses at whole-watershed or regional-aquifer scales.

White (1993) and Stanford and Ward (1993) began developing conceptual foundations on which to frame our understanding of stream–groundwater interactions and from which the potential role of surface–groundwater exchanges could be evaluated at the scale of whole stream networks. Geomorphic classification of streams, such as that published by Montgomery and Buffington (1998), would provide a reasonable starting point for developing such a framework. The geomorphic classification has proven useful for understanding fluvial-process domains (Montgomery 1999) and how they influence biologically important attributes (Buffington et al. 2004). Little progress has been made in developing a similar framework to organize conceptual models of processes controlling GW-SW interactions and their influence on stream and groundwater ecosystems. This problem is well illustrated in the 2015 special issue. None of the authors provided a comparative study of how geomorphic factors, especially channel morphology, influence GW-SW interactions. In fact, the authors generally did not describe the physical setting of the streams they studied. This omission makes it difficult to draw broad generalizations about the importance of different processes among stream types. The organizers of the 1993 special series stated that “each hyporheic system is unique, but cross-system comparisons may be possible …” (Hakenkamp et al. 1993, p. 97). A critical need exists to develop a rigorous taxonomic system within which the results of the many reach-scale studies can be organized conceptually so that broader generalizations can be made.

The 1993 special series was a watershed event in the field—one highlighted by Bencala’s figure challenging conventional wisdom that “a stream is not a pipe”. Today, this idea is so deeply entrenched that statements that GW-SW interactions are important in stream ecosystem processes are accepted as common knowledge and, thus, seldom receive critical examination. However, evidence is increasing that, in some stream reaches under some conditions and for some processes of interest, GW-SW exchanges have little-to-no influence on the properties of the bulk of stream water (Burkholder et al. 2008, Wondzell 2011). Under such conditions, streams serve primarily to convey water, solutes, and suspended materials downstream. The conceptual ideas presented by Bencala (1993), Stanford and Ward (1993), and White (1993) all deserve critical examination: When and where are streams not pipes? When and where do they really function as pipes, and for what materials or processes? The conceptual models presented by Stanford and Ward (1993) or White (1993) deserve to be critically tested.

Geomorphology, hydrology, biogeochemistry, and ecology can provide a descriptive framework within which understanding the relative importance of stream–groundwater interactions among the types of streams and across the range of flow conditions that occur in these streams might be possible. However, building such a framework will not be simple. Moreover, the stream reach provides a tractable scale for small research groups involved in studies of one to a few years duration, but such studies do not appear to have been sufficient to build or test such a framework. I see a few possible ways forward. The first would be akin to a meta-analysis approach in which smaller individual studies could be summarized across broad spatial scales for a more holistic understanding. However, such an approach would require that the smaller studies provide sufficient information and use sufficiently comparable techniques that reasonable comparative analyses could be conducted. Alternatively, resources for studies of stream–groundwater interactions could be invested in larger, multi-investigator, multisite, and multidisciplinary studies that could use a systematic approach in a manner akin to the Lotic Intersite Nitrogen eXperiments (LINX I and II; Webster et al. 2003, Mulholland et al. 2008, Dodds et al. 2014). In any event, growth in our understanding of GW-SW interactions will require new, holistic approaches that supersede the approaches used to date.

The science of hyporheic processes, and more broadly, GW-SW interactions, has progressed substantially over the last 20 y as evidenced by the growth in the published literature (Fig. 1A, B) and the comparison between the 1993 and the 2015 special series. Despite this progress, many of the larger issues posed by the authors of the 1993 special series remain as critical challenges for the study of GW-SW interactions. Answering these questions would help develop a holistic understanding of how GW-SW interactions vary among stream types and sizes and with changes in discharge among seasons or over storm events and would enable a deeper understanding of the role that GW-SW interactions play in the ecology of surface and ground waters.
**LITERATURE CITED**

Papers from the 1993 special series are denoted with an asterisk. Papers from the 2015 special series are in bold.


*Ebersole, J. L., P. J. Wigington, S. G. Leibowitz, R. L. Comeleo, and J. Van Sickle.* 2015. Predicting the occurrence of cold-water patches at intermittent and ephemeral tributary confluences with warm rivers. Freshwater Science 34:XXX–XXX.


along stream channels and the effects of artificially constructed large macro pores on transient storage. Freshwater Science 34:XXX–XXX.


