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INVITED COMMENTARY

Adding our leaves: A community-wide perspective on research directions in ecohydrology

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1 | INTRODUCTION

Ecohydrology encompasses ideas and processes at the interface of hydrology and ecology acknowledging couplings and feedbacks between biology and water-related processes across a broad range of spatial and temporal scales. It is inherently interdisciplinary, involving not only the environmental sciences but increasingly social science. The maturation of ecohydrology saw entire journals dedicated to the subject and the establishment of American Geophysical Union (AGU) Ecohydrology Technical Committee (TC) in 2008. Concurrent with the timing of the AGU Centennial, AGU Hydrologic Sciences leadership set out to identify the three “biggest science questions” in the hydrologic subdisciplines. Through collective brainstorming and an informal survey, the AGU Ecohydrology TC arrived at the following (AGU Hydrology Section Newsletter, July 2018):

Q1. How will changes in climate and atmospheric composition influence biota-water resources interactions, and when/where will we go beyond historic variability?

Q2. How do the impacts of multiple stressors including land cover changes, disturbances, climate change and atmospheric composition on biota interact to change the water cycle?

Q3. How does biota adapt in response to water availability—across time and spatial scales—from minutes to a century and from cell to continental scales?

These questions reflect key societal concerns about the impacts of climate change and agricultural and industrial pollutants (Q1) and a progression from studying pristine landscapes to landscapes where human impacts and disturbance play a key role (Q2). The questions also reflect the bidirectional nature of ecohydrology—examining not only how ecology influences the water cycle but also how ecology responds to changes in water availability. Big questions in ecohydrology are moving beyond thinking of ecosystems as static components and towards accounting for how they adapt to changing conditions, including water availability and quality (Q3).

The “big questions” proposed by our diverse community are necessarily broad. However, many researchers are also motivated by more specific questions, some of which may be initially compelling for a subset of the community. Although there are advantages to offering some “big community” questions, it is perhaps the questions that we do not yet even know to ask that are most critical. The diversity of the ecohydrology community is in many ways its strength and leads to an ever evolving set of “little” to “big” questions. To go beyond these big questions and learn more about current directions within the ecohydrology community, we utilized the information from an informal blog the AGU Ecohydrology TC initiated in 2018 (https://www.aguecohydrology.org/blog-adding-our-leaves).

2 | A BRIEF HISTORY OF THE ECOHYDROLOGY “LEAF BLOG”

On December 11, 2017 at 6:45 am, over 25 enthusiastic individuals crammed in to a small conference room of New Orleans' Hilton Riverside for what would be a transformational annual in-person meeting of the AGU Ecohydrology TC. This was the TC's first meeting following the “more the merrier” guiding principle of then AGU Hydrology Section President Jeffrey McDonnell. Attendance ranged from veteran members to those completely new to the TC arena with interests varying from the urban to tropical to dryland ecohydrology. It was evident that we all had very different perspectives, yet the energy in the room was contagious and seemed to evolve from a common interest in broadening the scope of ecohydrology to open the doors to more self-identified ecohydrologists. We saw ecohydrology as a tree, rooted in sciences but branching out with unique leaves, each with their own story. We wanted to know more about the various ways the interdisciplinary science of ecohydrology was being viewed by a community that includes academics and professionals. We decided that it would be informative to build an ecohydrology community of practice, by featuring an ecohydrologist each week as a “leaf” on our website in a blog forum. Building on AGU's centennial theme—both looking back at what we have learned and looking ahead to what we want to achieve—we ask each of our featured “meet a leaf” researchers the same set of questions, including two designed to help us learn more about our community's direction: “Do you have a favorite ecohydrology paper?” and “What do you see as an important emerging area of ecohydrology?” Since April 2018, we have featured perspectives on ecohydrology in our blog from over 75 researchers (hereafter referred to “meet a leaf researchers” [MLRs]). Between April 2018 and July 2019, MLRs were comprised of roughly one third (21) senior (tenured) professors, 11 assistant professors (or lecturers), nine government or industry scientists, six postdoctoral fellows, and three graduate students. The blog has generated a rich dataset highlighting the types of problems and topics that self-identified ecohydrologists are interested in and how they have gotten there. This community-based approach is a timely and complementary perspective to recent review pieces reflecting on what ecohydrology is, and where it is going (e.g., Blöschl et al., 2019; Mackay, 2019).

3 | INFLUENTIAL PAPERS IN ECOHYDROLOGY

As a complement to the blog dataset, we also examined recent highly cited papers to identify important concepts in ecohydrology that are gaining momentum. Using the Clarivate Analytics Web of Science scientific citations database, we considered the 20 most cited papers published between 2000 and 2015 with “ecohydrology” in the title or listed as a subject. We acknowledge that recent highly cited papers do not account for the enduring influence of certain papers written even decades before the present time. However, to gage new directions and focus on where we are going, we restrict papers to the post-2000 period. Mackay (2019) offers a longer term perspective of the most highly cited papers through time. We summarized 69 influential papers (Table S1); 19 of these came from our Web of Science highly cited recent papers, and the rest were “favorite papers” identified by researchers between April 2018 and July 2019. These papers covered a wider time span than the highly cited papers. We note that many of these leaf blog “favorite papers” are pre-2000 and represent papers that continue to influence ecohydrology. We include both sets (leaf blog and recently highly cited) in our analysis of influential papers.

Of these 69 influential papers, 22 were review papers (15 from leaf blog, seven from highly cited). Several influential papers (four to five) were vision or opinion papers whose focus was commenting on rather than summarizing or reviewing an area in ecohydrology. Most influential papers that address specific research directions (or “little” questions) were terrestrially focused (56), with six focused on aquatic systems (and six on “both” aquatic and terrestrial ecosystems). Similarly, the “eco” in most of these papers referred to vegetation (tree, grass, or shrub), with only four focused on aquatic organisms and two on microbes. All spatial scales (reach/plot to global) and timescales (subdaily to evolutionary) were included (Figure 1). All Köppen climate classes were included except polar. Semiarid or water-limited environments, however, tended to dominate among the most highly cited papers (9 of 19). A small number of papers focused specifically on urban systems (five). Many of the influential papers considered human impacts (24), and a substantial number looked at climate change (20). Overall, there was a strong focus on drought (25 papers) and much less on other disturbances (eight included floods, two included hurricane/wind, two included geomorphic/landslides, and two included fire). Several papers (four) considered multiple disturbances types.

Figure 2 shows a summary of the type of disturbances that each paper studied. Drought and climate change were the most commonly

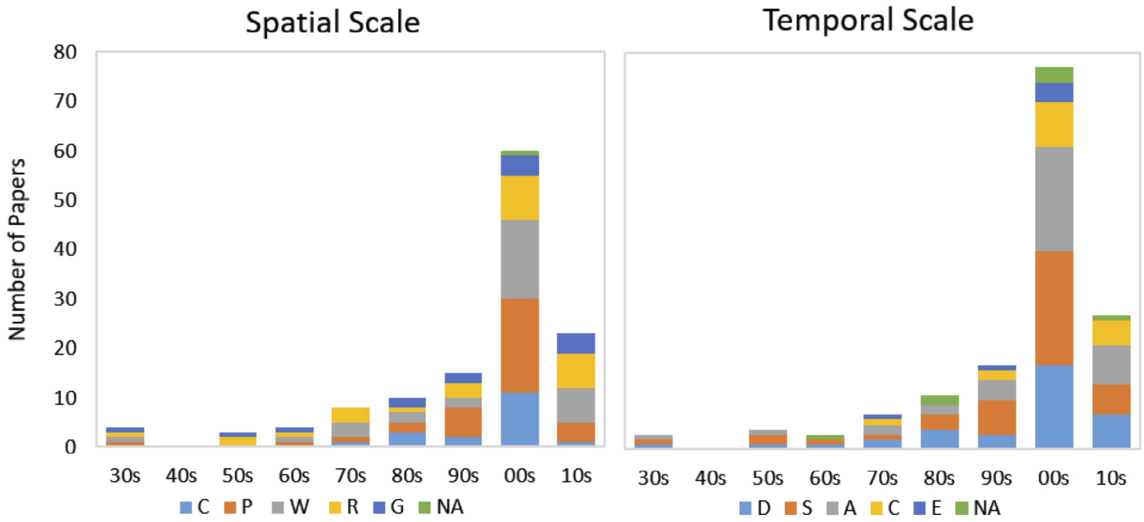


FIGURE 1 Stacked bar charts showing the number of studies at each scale by decade. Bars are stacked from smallest spatial scale on bottom to largest on top (panel a) or shortest time scale on bottom to longest on top (panel b). Studies spanning several scales are considered multiple times. Spatial scale legend corresponds to C=reach, P=plot, W=watershed (1st–4th order), R=regional (larger than watershed), and G=global. Temporal scale legend corresponds to D=diurnal (or less), S=seasonal, A=annual, C=decadal, and E=longer term (evolutionary), NA refers to studies that were independent of scale or scale could not be determined

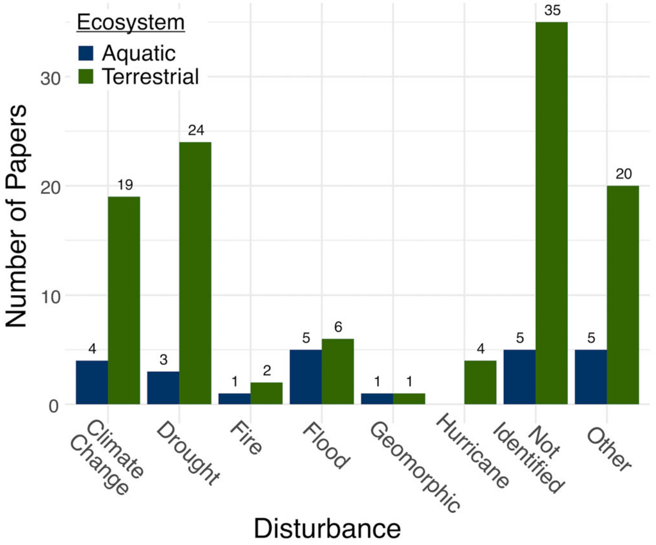


FIGURE 2 Disturbances identified in the influential and highly cited papers

defined disturbances identified in the collection of papers. An equally large number of papers also identified other human impacts, and 35 papers did not include disturbances as part of the study. Over three quarters of the papers focused on terrestrial ecosystems.

With respect to techniques, modelling and field based approaches were both included (more or less evenly). Innovations in remote sensing were included in six papers. Another two used new informatics techniques, and four made use of tracers. None of the papers considered emerging ecophysiological techniques from genetics/genomics.

There are a few papers that appear more than once: Newman et al.(Newman et al., 2006) were included in the highly cited list and two leaf blogs; Dawson and Ehleringer (1991) in two leaf blogs; Huxman et al. (2004), Rodriguez-Iturbe (2000) and Asbjornsen et al. (2011) were all included in the highly cited list and one leaf blog.

The reasons given for why papers were chosen in the leaf blog are notable. The most common reasons given for why papers were valuable or interesting can be grouped into four categories: the paper (a) provides an overview of the field, (b) encourages interdisciplinarity and collaboration, (c) conceptualizes or demonstrates the importance of a particular ecohydrologic process or mechanism or theory, and (d) demonstrates a new technique or a novel application of an existing one. Here, we summarize the specific papers and reasons given for their selection for each of these four categories.

1. Overview of the field.

Ecohydrology researchers valued papers that offer a broad vision about where the field of ecohydrology is (or was). These papers described ecohydrology as a general concept (such as Newman et al., 2006); or review the state of ecohydrology Asbjornsen et al., 2011) or hydrology (e.g., Eagleson, 1982; Jones & Mulholland, 1999; Rodriguez-Iturbe, 2000).

2. Interdisciplinarity and collaboration.

Other MLRs cited papers that encourage interdisciplinarity and working together as a community. Notably, some of these papers are relatively early papers such as Harte and Shaw (1995), Dooge (1986), and Klemeš (1986). MLRs also like more recent papers that bring “socio-” into ecohydrology such as Pataki et al. (2011). Similarly, Zalewski (2002) and Brauman et al. (2007) were selected because they link ecohydrology with ecosystem services and management, and Parolari et al. (2016) which links ecohydrology to the “human experience.”

3. Insight into processes and mechanisms.

Several MLRs selected papers that provide new understanding of interactions among multiple processes (e.g., Sellers et al., 1996; Ivanov, Bras, & Vivoni, 2008) or papers that show how relationships change with scale (Milne, Gupta, & Restrepo, 2002; Noy-Meir, 1973).

Some MLRs identified papers because they recognize place-based processes (e.g., tropical cloud forests, Bruijnzeel & Veneklaas, 1998) or how processes yield patterns (e.g., wetland vegetation distribution in Everglades, Foti, Jesus, Rinaldo, & Rodriguez-Iturbe, 2012 or vegetation distribution in New Mexico, Caylor, Manfreda, & Rodriguez-Iturbe, 2005). Others selected papers because they present processes, mechanisms, and/or theories not considered or previously described well or because the paper provides a particularly salient demonstration of theories or possible mechanisms. Some of these are “classic” papers in that they introduced key theories laying the foundation for much ongoing work, for example, water and carbon in photosynthesis (Cowan & Farquhar, 1977), tile drainage (Hooghoudt, 1952), land surface–atmosphere and albedo (Charney, 1975), how vegetation develops to use available water (Horton, 1933), the River Continuum Concept (Vannote, Minshall, Cummins, Sedell, & Cushing, 1980), the flood-pulse concept (Junk, Bayley, & Sparks, 1989), and stomatal control to explain evapotranspiration response to vapour pressure deficit (Jarvis and McNaughton, 1986). Some noted papers focus on more recent mechanistic theories such as isohydric/anisohydric species differences (McDowell et al., 2008), solar radiation as organizing watershed evolution through ecohydrology (Yetemen, Istanbulluoglu, Flores-Cervantes, Vivoni, & Bras, 2015), the importance of plant traits to explain variation in biogeochemical cycling and climate (Reichstein, Bahn, Mahecha, Kattge, & Baldocchi, 2014), and going beyond variable source areas (McDonnell, 2003).

4. Demonstrates a new technique or an artful application of an existing one.

MLRs also noted papers showing the application of new techniques or the artful application of existing approaches, for example, the use of cellular automata to evaluate vegetation patterns (van Wijk & Rodriguez-Iturbe, 2002), the use of stable isotopes as tracers inside a plant (Zimmermann, Ehhalt, & Muennich, 1967; Dawson & Ehleringer, 1991; Ehleringer & Dawson, 1992); methods that substitute space for time (Huxman et al., 2004; Lauenroth & Sala, 1992) or synthesis techniques that generate global parameters such as plant rooting depth (Fan, Miguez-Macho, Jobbágy, Jackson, & Otero-Casal, 2017; Kleidon & Heimann, 1998). Other examples include Loheide et al. (2005) for their “glorious” modified White method. Bertuzzo, Helton, Hall, and Battin (2017) for nicely demonstrating a scaling method for DOC removal in streams, Garcia et al. (2016) for demonstrating the use of data and models in combination, Kirchner (2009) for demonstrating a method to estimate water balance variables from streamflow, and Brooks, Troch, Durcik, Gallo, and Schlegel (2011) for demonstrating a data fusion approach that uses remote sensing measurements to derive hydrological parameters.

4 | RESEARCH DIRECTIONS

In addition to identifying their favourite ecohydrology paper, we also asked each MLR “What do you see as an important emerging area of ecohydrology?” We summarized answers from 48 MLRs (April 2018–July 2019). The word cloud (Figure 3) shows frequently used terms in the responses. The MLRs varied in professional stage (Figure 4) and the sector in which they were working in at the time their blog was published.

We related the MRLs responses by their connection to the ecohydrology TC's three big questions and found that 24 posts related to the question of connecting impacts of land cover and disturbance on biota and the water fluxes (Q2), 14 were connected to the question of changing climate on ecohydrology (Q1), and 12 were focused on how biota adapt in response to water availability (Q3). Most of the MLRs agreed that scaling across space and time was important concerns, regardless of their specific emerging area of concern.

Research directions were varied: 12 MLRs explicitly mentioned “urban” or “city,” 34 commented on the importance of considering human impacts in the research direction, and six mentioned “management.” Approximately one half of the research directions were related in some way to climate change (20), and 12 explicitly included “climate” in the description. “scale” and “subsurface” were both mentioned six times, and “model” was mentioned in seven posts. Interestingly, no MLRs explicitly mentioned agriculture, but investigations of

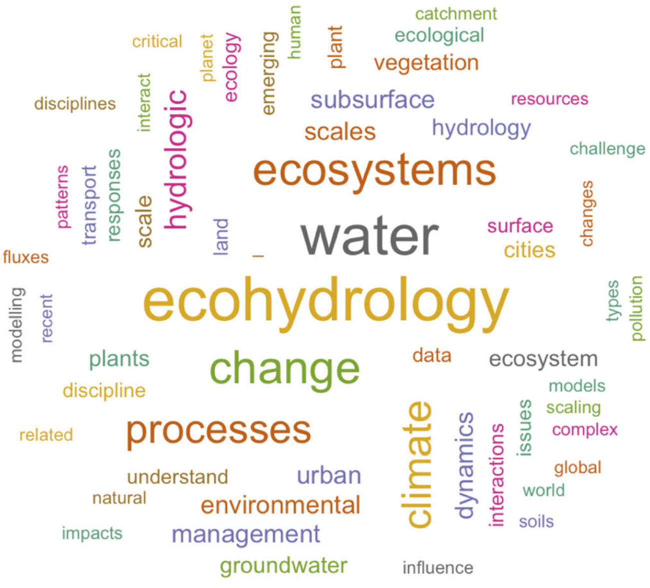
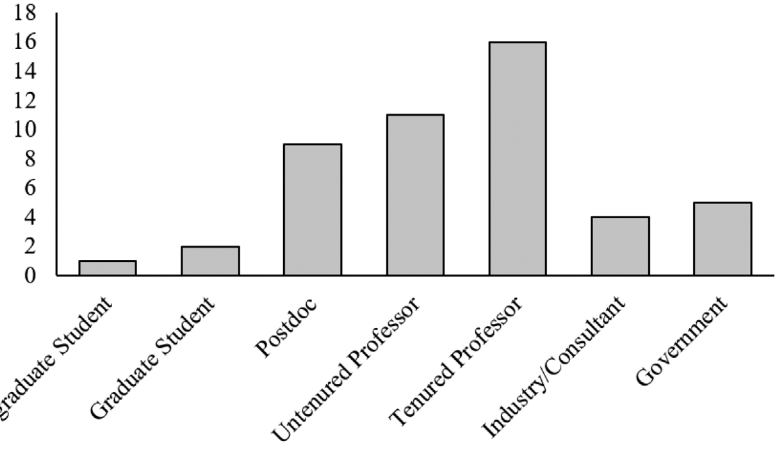


FIGURE 3 Word cloud generated from (April 2018–July 2019) Leaf Blog descriptions of emerging areas of ecohydrology. Common words (such as “the”) removed

FIGURE 4 Number of individual leaf blog posts by career and career stage



interactions between climate change and human impacts would be relevant to agricultural systems.

Generally, the research directions proposed by the MLRs fell into several broad categories:

1. Previously under-represented land cover, land use, or ecosystem types.

Many of the MLRs identified understudied systems as critical future research directions for the ecohydrology field. The importance of understanding urban systems was mentioned by nine MLRs, particularly with how green infrastructure, urban canopies, and synthetic wetlands impact water quantity and quality for a given city or watershed. MLRs also identified the need to move beyond a focus of water-limited (i.e., dry) ecosystems to those limited by energy, coastal or aquatic systems, seasonal wetlands, and snow-dominated or permafrost systems.

2. Incorporating new techniques and methods to address scaling across space and time.

The issue of scaling up from plants to landscapes, across broad spatial scales, and across times was explicitly mentioned in multiple MLRs. Indeed, the issue of scaling in ecohydrology continues to be a persistent conundrum. To resolve our issues of scaling, multiple MLRs identified the use of new models, assimilation of datasets, or using “big data” to find ecohydrological patterns in disparate datasets as potential solutions. Two MLRs mentioned that novel advances to current field or lab methodologies could be used to help address the role of spatio-temporal scaling issues.

3. Improving science communication and stakeholder/public engagement.

Multiple MLRs noted that ecohydrology is a discipline where research outcomes can have immediate societal and environmental impacts if implemented properly. The key will be (a) tailoring our research questions to tackle many of the challenges that humanity faces today (e.g., sustainability of ecosystem services, feeding Earth's population hitting nine billion, and preserving groundwater-dependent ecosystems in the face of increasing drought) and (b) communicating about those results effectively with the public.

4. Integrating social sciences and cross-disciplinary collaboration.

Many MLRs emphasized engaging in interdisciplinary socio-environmental research and several points to the newly emerging field of socio-hydrology as revealing the ways in which coupled natural–human systems evolve on a joint trajectory with society. Collaboration with social scientists was noted repeatedly as vital if ecohydrology is going to have a true impact on real-world problems.

5. Advancing the ecohydrology of climate change.

Not surprisingly, the feedback between ecohydrology and climate change was listed by multiple MLRs as a potential area for future research. Given that much of ecohydrology research has been conducted under nonstationary climatic conditions, even identifying what baseline feedbacks exist between climate, hydrology, and ecology is challenging. As one MLR noted, a core research goal is to understand the “dynamic regulation of transpiration by plants and the way ecosystem processes couple subsurface and atmospheric processes and feedback into weather and climate.”

6. Advancing the field towards a more complete and integrated discipline.

Lastly, many of the MLRs noted the importance of moving the field towards a more complete or integrated “ecohydrology” science, which would improve our understanding of how hydrology and ecology couple together to explain or drive processes in other subdisciplines. The majority of MLRs advocated consideration of both terrestrial and aquatic systems in ecohydrology (Figure 5). MLRs also noted that feedbacks between moisture regimes and microbial

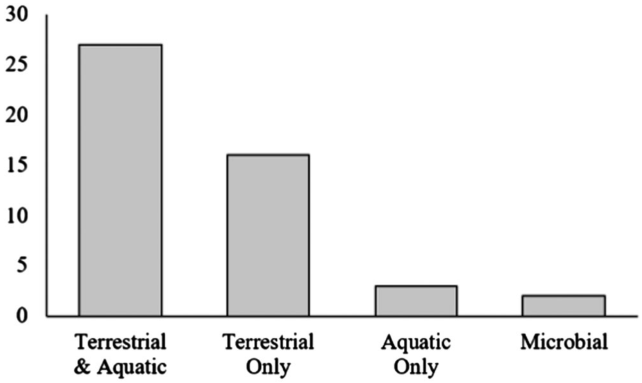


FIGURE 5 Number of blog posts by ecosystem type

communities are currently not well explored and emphasized the need for additional study of feedbacks between ecohydrological processes and biogeochemical cycling across temporal and spatial scales. MLRs further point to water stress or surplus influences on ecosystem biodiversity and competition for resources in ways that have been partially explored by ecosystems ecologists but would benefit from an ecohydrological perspective (see Slette et al., 2019; Zang et al., 2019). The role that ecohydrological processes play in aquatic ecology, responses to disturbance events and multiple stressors, invasive species dynamics, atmospheric composition, and subsurface storage and flow paths were all also identified as potential pathways for future research in the field.

5 | CONCLUSIONS

Our synthesis reveals an ecohydrology community that is increasingly interdisciplinary, engaged in society-relevant problems and that uses new technologies and modelling approaches to accomplish these goals. Both the discussions within the AGU Ecohydrology TC and the analysis of the activities in the larger ecohydrology field (through the invited MLRs perspectives and recently highly cited papers) revealed a growing interest in studies that relate to core societal issues: climate change and increasing pressures from land use and urbanization on water, ecology, and their interaction. Our community, however, often makes progress on these issues by addressing more specific, incremental questions—by using new data, new techniques, new collaborations, and new ways of looking at systems to learn more about how water and ecosystems interact. The AGU Ecohydrology Leaf Blog documents the diversity of how individual ecohydrologists are addressing challenges. Perhaps reflecting the core interdisciplinarity of ecohydrology, many of the ecohydrologists that we interviewed seek to advance the field through cross-disciplinary collaboration and cite influential papers as those that either support interdisciplinarity or provide salient examples. Concurrent with this are influential papers and research directions that focus on specific ecohydrologic processes and mechanisms and on the use of new techniques and approaches to learn about specific processes. Even though review papers often become highly cited, many influential papers (either as noted by our MLRs or by citations) are not necessarily review or "big picture" papers but papers that either provide new insights about ecohydrology or provide a particularly well-researched confirmation of a specific concept or theory. Climate change remains a central driver of ecohydrologic research—and many of the most highly cited or influential papers written in the last decade focus on drought and the sensitivity of semiarid or water-limited systems to climate change. This is not surprising, given the strong interactions between ecosystems and water during dry periods as opposed to flood events. Our survey of research directions, however, also illustrates growing interest in nonwater-limited environments, urban systems, and coastal systems.

Our three big questions and the perspectives that emerge from our blog all emphasize the science needed to understand changing ecosystems and water resources and ultimately to inform societal decisions in response to these changes. Although many AGU disciplines are focusing on "change," ecohydrology posits that to understand environmental change requires thinking about two-way interactions between water as it moves through landscapes and biological organisms and communities that adapt to and respond to water availability and change and use water. To meaningfully address these coupled ecohydrologic systems within a global change context requires expanding both the "hydro" and the "eco" well beyond simple models of evapotranspiration. Ecohydrology must consider multiple scales and a diversity of biogeoclimatic settings and human contexts. Our models, both conceptual and quantitative, must represent not only the state of the environment as it is but where it is going and how human actions can influence those trajectories. This is the challenge for ecohydrology—and it is one that requires multiple expertise on topics ranging from microbes and macropores to species migration and changing rainfall patterns and collaborations that can integrate this knowledge and effectively communicate it to a diverse set of audiences—from young students to experts and from the public to resource managers and policy makers.

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