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Ecohydrology Bearings—Invited Commentary

Ecohydrology in practice: strengths, conveniences, and opportunities

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ABSTRACT

Fifteen years after the term 'ecohydrology' came into use to describe integrative research spanning the two parent disciplines, we discuss methodological traditions of the parent disciplines and assess trends in the methodologies utilized in the young hybrid field of ecohydrology. In particular, we explore whether the marriage between the disciplines is built on a marriage of methodological strengths from the parent fields or a marriage of convenient arenas of methodological overlap. In surveying 267 research articles from January 1996 to June 2010, we found that very few studies integrated the strongest methodological approaches from both parent disciplines. Hydrological strengths in the form of modelling studies are much more prevalent than ecological strengths of manipulative experimentation and hypothesis testing, and the two approaches are almost entirely decoupled in ecohydrological studies. Thus, there remains great opportunity to leverage the strengths of ecological and hydrological traditions to more aggressively build our understanding of coupled ecological and hydrological system functions. Copyright © 2011 John Wiley & Sons, Ltd.

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INTRODUCTION

The way a discipline is practised determines the utility of the endeavour. To a large degree, the promise of an interdisciplinary field such as ecohydrology rests on integrating the strongest aspects of the parent disciplines' methodological approaches in order to leverage the contributions of each. It has been 15 years since a research article containing the word 'ecohydrology' first appeared in a journal indexed by Web of Science®. At the mid-point of ecohydrology's second decade, we believe that it is useful to reflect on the practice of this adolescent interdisciplinary science and assess the opportunities that continue to reside at the intersection of ecological and hydrological research.

Hydrology and ecology both developed out of transformational insights initially formalized in the mid 19th centuries by contemporaries like Henry Darcy, who first used mass balance to explain the flow of water through soil, and Charles Darwin, who first used natural selection to explain the abundance of species. The early to mid 20th century saw the emergence and vigorous growth of both fields into disciplines with strong theoretical scholarship and applied utility. Despite the shared timing of their historical development, hydrological and ecological sciences represent the dichotomy between physical and biological sciences, which form two contrasting frameworks by which modern natural sciences have been organized (Harte, 2002).

As Harte describes them, more physically based sciences such as hydrology have historically focused on idealized systems that can be used to generate broad inference and predictive, universal system attributes across a wide range of natural phenomena. This typological approach is validated by the fact that hydrological dynamics are governed by physics, which can be safely regarded as constant wherever they occur on earth. In contrast, more biologically based sciences like ecology are rooted in the paradigm of evolution and natural selection, which emphasizes the role of variation in shaping system dynamics. Relationships between ecological variables, in contrast to physical variables, are not necessarily constant, either across environments or among individuals in a taxon. As a result, there is far less dependence on simplified, ideal characterizations of systems and an increased use of experimental and statistical methods to control for multiple sources of variation.

The typological/statistical dichotomy at the paradigm level is reflected in the research questions addressed

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by ecological and hydrological sciences and in the ways that research is practiced in each discipline. The basic organizing statement in hydrology is the continuity equation that governs mass balance. As a consequence, research questions in hydrological sciences have centered on developing abstracted, process-based models to make predictive forecasts that typify system dynamics. This focus on modelling and prediction necessitates the development of long-term hydrological datasets that characterize the drivers or outcomes of hydrological processes, with relatively little emphasis on experimental manipulations. Indicatively, the first thing an aspiring hydrologist often learns is how to process time series data or how to implement an equation to estimate infiltration or discharge using empirical coefficients.

In contrast, ecological research questions are mainly organized around organisms' responses to their biotic and abiotic environment. As a result, ecological research tends to focus on comparisons among specific environmental states, while controlling or accounting for other sources of variation. Such comparisons can be based on naturally occurring variability but are usually generated via experimental manipulations designed to reveal functional (but not always process-based) outcomes of specific interactions. For this reason, the first tools in a young ecologist's belt are usually statistical tests that are used to discern and attribute, with a specified degree of certainty, the response of variable Y to condition X.

In both ecology and hydrology, observational studies of patterns in state variables play an important role in building knowledge of system dynamics. But the two disciplines have different characteristic ways of integrating those observed patterns into the development and testing of hypotheses of system functions. In hydrology, process-based modelling utilizes observational studies to provide parameter values for models, validate model predictions, or both. In ecology, on the other hand, observed patterns motivate the design of manipulative experiments that can discriminate between competing hypotheses of underlying processes. In short, hydrology tends to build knowledge of processes using models, while ecology tends to build knowledge of process using controlled experiments, and observational studies contribute to both modes of inquiry.

In both disciplines, the option also exists to empirically measure many processes directly. For instance, technological advances are making tools for measuring water fluxes—such as sap flux probes, pressure transducers, and infrared gas analysers—increasingly readily accessible. As an ecological example, direct measurements of carbon assimilation and respiration with infrared gas analysers have become an indispensable tool in assessing ecosystem responses to climate change. Compared with phenomenological observations of pattern, measurements of processes provide a much more direct and robust link to process-based hypotheses and thus have the potential to greatly accelerate research progress when incorporated into either hydrological modelling studies or manipulative ecological experiments.

Operationally, the most efficient way to marry two disciplines would be to focus on system components and utilize research modalities that both disciplines already have in common. However, this will not necessarily create the most powerful integration in terms of generating novel, robust knowledge. To do that, the marriage should instead utilize each parent discipline's most powerful tools for understanding system dynamics and take on the additional integrative burden of forging intellectual links between those two modes of inquiry. Put another way, the marriage of ecology and hydrology must strive to overlap in the hard areas and not just the easy ones.

We argue that in ecohydrology, the most convenient methodological overlap is in the realm of observational studies of patterns. Such studies are a common component of both disciplines' research approach, and state variables such as soil moisture and stream depth define the critical interface between the ecosphere and hydrosphere. However, these studies are also the most distant from the critical work of refining and testing hypotheses about system processes and functions. Thus, we believe that the greatest methodological potential of ecohydrology lies in merging the experimental, direct hypothesis-testing approach of ecological research with the focus on process-based characterization of system dynamics that is the hallmark of hydrological research. Our advocacy for this strategy is not meant to reflect a general priority for research activities overall. We only wish to posit that adopting such an intentionally aggressive approach to integrating methodological traditions is likely to yield more rapid advances in our understanding of coupled ecological and hydrological dynamics. Moreover, we believe that this type of research is likely to be critical to substantiate ecohydrology as a truly transformative interdisciplinary science.

We have conducted a systematic survey of all ecohydrological research published over the past 15 years during the period of January 1996 to June 2010, in order to assess the extent to which various approaches from the parent disciplines are utilized and how they are being integrated together. We wanted to know whether research to date in the field of ecohydrology represents a marriage of the parent disciplines' strengths, or a marriage of convenience.

METHODS

We compiled all articles published from January 1996 to June 2010 that were indexed in Web of Science® and contained the term 'ecohydrology' in their title, keywords, or abstract. In addition, we included every paper published in the journal Ecohydrology from its initial issue in 2008 through June 2010. Among the compiled publications, we only analysed articles that presented original ecohydrological research findings; we excluded commentaries, reviews, and syntheses.

We made no attempt to define ecohydrology, which is itself the focal subject of 4% of the compiled

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ecohydrological articles. Instead, we have simply analysed every study that self-identifies as ecohydrological research. This sample admittedly reflects only a subset of the complete scope of ecohydrological research. For instance, the compilation did not include articles that self-identified as hydroecology, despite the considerable overlap in research topics conducted under the two banners. Rather, we chose to focus on self-identifying manuscripts because it most directly reflects how ecohydrology is defining itself as an emerging, integrative discipline. For each research article, we classified the used methodologies in two ways, according to approach and hydrological variable type. First, we determined whether the study's methodological approach utilized observational, manipulative experimental, and/or modelling. Observational studies measured ecological and hydrological variables under one or more naturally occurring environmental conditions. Studies were labelled experimental if they utilized planned manipulations to modulate certain variables while controlling for others. The modulated and controlled variables could be ecological, hydrological, or other relevant parameters (such as geomorphology or water chemistry). Studies based on prior or historic manipulations were only included if the report justified that such manipulations provided valid controls for other variables. Otherwise, 'natural experiments' (e.g. rainfall or vegetation density gradients) were categorized as observational. Modelling studies included quantitative explorations of the relationships between ecological and hydrological variables, either by developing new expressions or by exploring novel or comparative contexts. The use of established mathematical/conceptual relationships to calculate one variable from others (such as calculating transpiration by dividing sap flux by leaf area) did not, in itself, qualify as modelling.

Second, we assessed whether the hydrological variables in the study contained state variables, process-oriented variables, or both. We chose to focus on hydrological variables because of their consistent relevance. Water-driven processes are the core of ecohydrological feedbacks, and known physical processes connect all hydrological variables; the same cannot be said of all biotic interactions and ecological variables. Our criterion of a state variable was the common definition: a variable that describes a state of a dynamic system, like root density or temperature. By process-oriented variable, however, we do not mean simply flux. Instead, we mean a flux related to a specified hydrological process. Process-oriented variables quantify the pathways by which state variables change. Variables such as infiltration, evaporation, transpiration, and drainage are fluxes that represent specified hydrological processes, so they met our criterion for process-oriented variables. If changes in soil moisture were used to 'infer' a process by assuming that other unmeasured processes were negligible, that did not qualify as measuring a process variable.

Each article could be marked as containing one or more of the methodology types and one or both of the hydrological variable types. Three articles were excluded because the methods were too ambiguous to allow classification. The results were graphed to visualize the distribution of studies using different methodological approaches and patterns of utilization of state and process-oriented hydrological variables.

RESULTS AND DISCUSSION

Our literature review yielded 383 articles containing ecohydrology or variants in their title, abstract, or keywords. Within those, 70% (267) presented novel research findings and were further analysed. Most of the others were review or synthesis papers or papers providing scientific background for a policy issue, such as estuarine management. Of these 267 research articles, 64% (171) contained observational studies, 39% (104) entailed modelling, and only 13% (34) utilized manipulative experimentation (Figure 1A).

Looking at the variable types used in each approach (Figure 1B), state variables were used most often to asses hydrological characteristics (88% of observational studies), while process-oriented hydrological variables were measured in 43% of observational studies. Experimental studies were uncommon and tended to measure a fairly even proportion of state and process variables for hydrological parameters. Among modelling studies, 96% evaluated process-based hydrological variables. These distributions highlight three main points regarding the nature of the ecology–hydrology marriage over the past 15 years. First, observational studies frequently address ecohydrological function using state variables as proxies

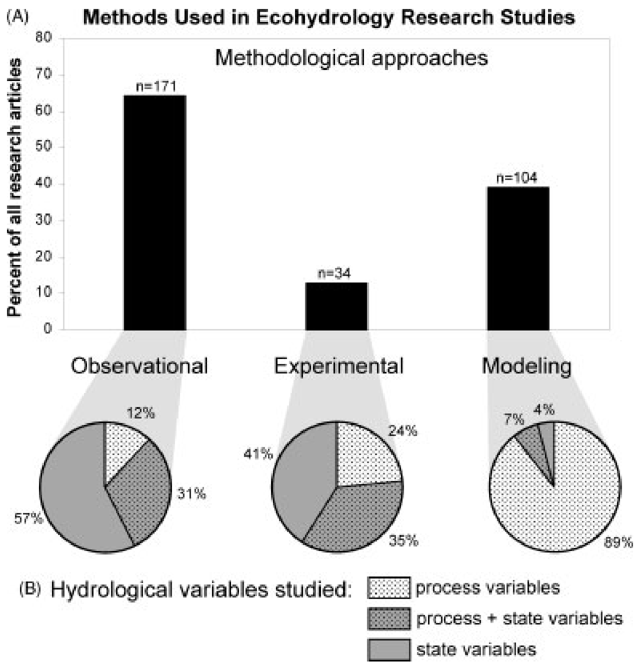

Figure 1. Methodological trends in ecohydrological research. (A) Percentages of ecohydrology research studies, from January 1996 to June 2010, that utilized observational, manipulative experimental, or modelling approaches. (B) Within each methodological approach, percentages of research studies that measured hydrological attributes with process-based variables, state variables, or both.

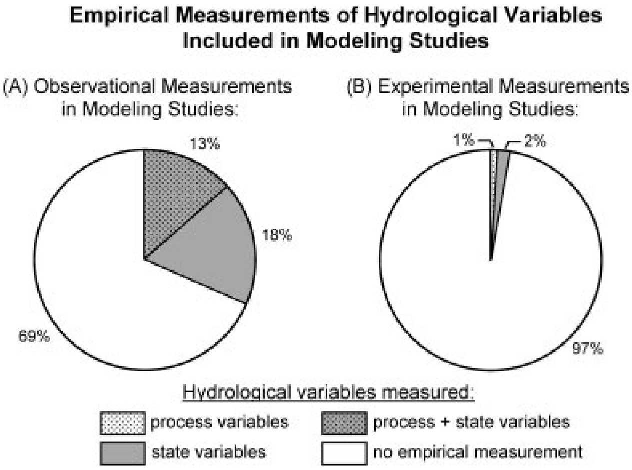

Figure 2. Assessment of the 104 research articles utilizing modelling methodology, according to their coupled use of empirical measurements of hydrological variables. (A) Percentages of modelling studies with different types of observationally measured hydrological variables. (B) Percentages of modelling studies with different types of experimentally measured hydrological variables.

for system processes. Such correlational studies are useful for motivating or corroborating hypotheses, but uncontrolled correlations among state variable proxies cannot test causal hypotheses about underlying processes. Second, precious few manipulative experimental studies are being utilized in ecohydrology, which indicates that the methodological strengths of ecological research are not being utilized in the new hybrid discipline of ecohydrology. Third, process-oriented research on hydrological dynamics is being undertaken largely through modelling research, indicating that the strengths of hydrology as a parent discipline are being utilized but not integrated with ecological strengths of empirical hypothesis testing.

An examination of the coupling of modelling studies with empirical research bears this lattermost point out further. Figure 2 presents the prevalence of reports that coupled modelling research with new empirical measurements, excluding modelling papers that derive parameters from previously published articles or institutional reports. Of the 104 modelling studies, 31% (33) also included observational measurements of hydrological variables. Fourteen of those studies directly measured the processes that were modelled, such as transpiration or runoff, while the other 19 studies measured state variables only, which in each case quantified soil moisture or water depth. Most notably, the analysis revealed that only three ecohydrological modelling studies from the past 15 years were coupled with experimental manipulations. These findings indicate that modelling studies are interfacing with empirical research primarily through observations of state variables and that experimental determination or validation of state or process-related variables is very rare. These two tendencies within the ecohydrological literature reflect a weak marriage of the two parent fields' strengths for understanding system dynamics. Empirical measurement of process-based variables and experimental manipulations, not just validation with observed state variables, are needed to test and refine hypotheses about modelled dynamics.

CONCLUSIONS

Our analysis indicates that during the last 15 years, the field of ecohydrology has made limited progress in terms of integrating the methodological strengths of the respective parent disciplines. Observational, correlational studies in one or more environmental settings are most common in the ecohydrological literature. Although these studies are the least methodologically progressive, the simplicity of their approach does not ensure that they are the most rigorous. To the contrary, such studies provide the weakest mode inference of processes and functions. While nearly 40% of all ecohydrological articles are primarily modelling studies, these same studies are rarely coupled with empirical measurements of process and almost never coupled with experimental studies. Based on these results, we believe that there is great scope and potential for enhancing the practice of ecohydrology, in three specific areas: (1) coupling empirical and modelling approaches, (2) taking process-based empirical measurements, and (3) using manipulative experimental designs.

We recognize that this assessment does not take into account coupled research agendas whose findings may be reported in separate articles. Nevertheless, the dearth of experimental studies that self-identify as ecohydrology would suggest that even broader research programs rarely capitalize on the potential advances that can be garnered by studying processes with manipulative experiments. So-called 'natural experiments' are more common in the ecohydrology literature, but their strength for testing process-based hypotheses depends on the degree to which other variables were constant or controlled across 'treatments.' Planned, controlled, replicated manipulations of hydrological variables can be challenging, but there is great precedence in the ecological and agricultural literature for controlled manipulations, at numerous scales, of a wealth of biotic variables relevant to ecohydrology. Large-scale and long-term manipulative ecological experiments, where such variables have already been subjected to controlled manipulations, offer an underutilized and very powerful context for conducting hydrological research. Likewise, agroecosystems are tremendously powerful arenas for integrating the strengths of both parent disciplines, as Jackson *et al.* (2009) have previously argued.

Recommendations of integrated approaches and process-based research are not new (Bond, 2003; Hannah *et al.*, 2004; Newman *et al.*, 2006; Smetten, 2008), but our review suggests that such opportunities have remained largely undeveloped. Mahatma Gandhi said, 'Be the change you wish to see in the world'. We hope that by reasoning through the links between methodological strengths and advancement of system understanding and by illustrating the sub-optimal methodological trends currently typifying our nascent discipline, we may inspire others to take up the challenge of integrating disciplinary strengths in their research in order to advance the trajectory of the field of ecohydrology.

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