

New Developments in Ecological Hydrology Expand Research Opportunities

Interdisciplinary research efforts to integrate the ecological aspects of water with its physical and societal roles have a long history as well as some interesting new developments. Small, paired, experimental watersheds, with their long-term monitoring systems for data collection and their integrated ecosystem approach to analysis, have been at the center of recent advances.

A study now under way at such watersheds could provide a common analytic framework in ecological hydrology. The study, funded by the National Science Foundation through the Long Term Ecological Research (LTER) network [Swanson and Franklin, 1988], is identifying interactions among vegetation, climate, and streamflow at sites that have been studied individually for decades (Figure 1). Work so far has concentrated on seasonal variations at Andrews, Coweeta, Hubbard Brook, Luquillo, and Casper Creek, which reflect a range of precipitation amounts, types, and timing, as well as a range of forest vegetation types (Figure 2). Initial results are available on the project's Web site at www.fsl.orst.edu/~post/hydro.

The *National Research Council* [1991] has emphasized the ecological importance of the hydrologic cycle, saying it represents a fundamental physical template for biological processes. This template presents some of the best opportunities to search for general principles that may guide the organization of living communities.

In order to adequately manage global water and aquatic resources, forests, agriculture, and human populations, we need a clearer understanding of ecological hydrology—the study of relationships among hydrologic, climatic, and ecologic processes in a hu-

man context. In particular better-articulated general principles about these relationships that can be used predictively across the range of watershed conditions are needed, and this is what LTER hopes to accomplish.

A key concern now in ecological hydrology is how hydrological processes, including the types, rates, timing, and pathways of water throughput at various timescales, influence ecologic processes. Another key concern is what feedbacks and constraints are imposed by ecosystems and landforms on hydrologic processes, including the role of vegetation as a mediator of water input, storage, and usage. Work in ecological hydrology brings the diverse perspectives of ecologists and hydrologists together and galvanizes insights relevant to terrestrial and stream ecology, geomorphology and biogeochemistry of landscapes, and regionalization and modeling of hydrologic processes over wide space scales and timescales.

The decades of work at sites such as Hubbard Brook [Likens *et al.*, 1977; Bormann and Likens, 1979; Likens, 1983] and Coweeta [Swank and Crossley, 1988] have provided fundamental insights into site-level interactions among hydrology, climate, and ecology and their response to human uses. Previous meta-analyses have emphasized the variability in streamflow responses to land use and climate variability among these in-depth, site-level studies [e.g., Hewlett and Hibbert, 1967; Meyer *et al.*, 1993].

Significant advances in ecological hydrology will require collaborative efforts to bring together the original long-term datasets from geographically diverse sites such as those in Figure 1. Original long-term datasets include hydrologic and climatic records, as well as data on vegetation and landforms. A common analytic framework includes putting data in comparable formats and combining them in comparative intersite statistical and

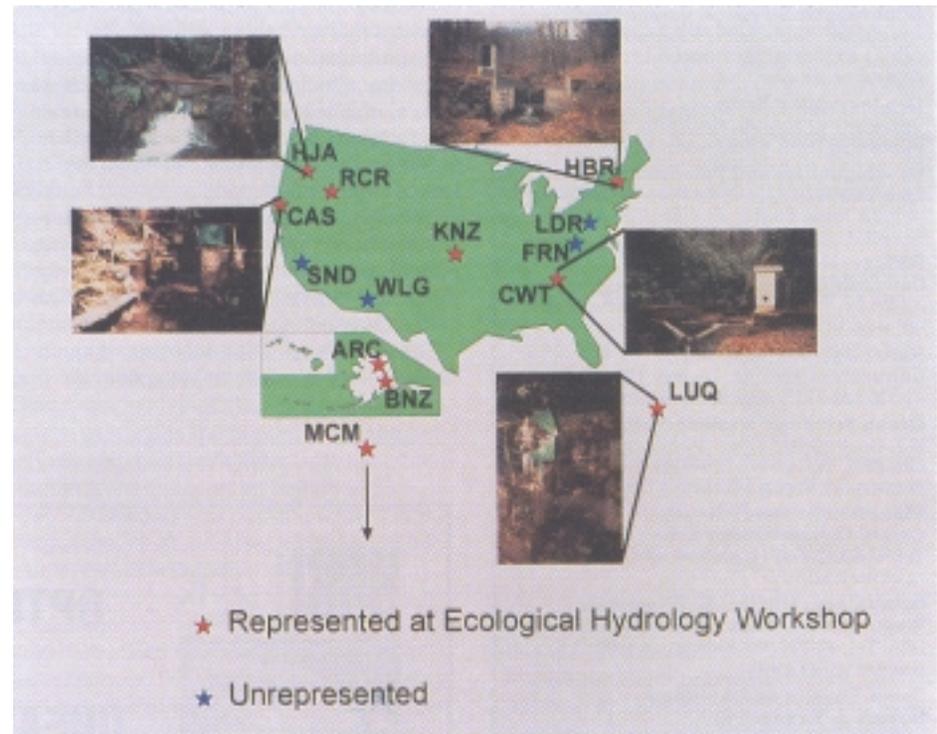


Fig. 1. Sites spanning a range of biome types and hydroclimatological regimes where long-term ecological and hydrologic research has been under way for as long as 6 decades. LTER sites represented at the ecological hydrology workshop (red stars) include the H. J. Andrews (HJA) conifer forest, Coweeta (CWT) deciduous forest, Hubbard Brook (HBR) mixed-conifer forest, Luquillo (LUQ) tropical rainforest, Arctic Tundra (ARC), McMurdo Antarctic Dry Valleys (MCM), Bonanza Creek (BNZ) boreal forest, and Konza Prairie (KNZ). Non-LTER sites represented include the Caspar Creek (CAS) U.S. Forest Service conifer forest and Reynolds Creek (RCR) U.S. Department of Agriculture rangeland site. Other sites with appropriate ongoing work that were not represented at the workshop (blue stars) but are involved in the study are San Dimas (SND), Walnut Gulch (WLG), Femow (FRN), and Leading Ridge (GDR).

modeling analyses to derive general principles.

Sites examined so far display a range of ecologically important patterns of seasonal streamflow variability driven by climate-vegetation-streamflow interactions (Figure 2). Climatically imposed seasonal variation in precipitation is amplified by asynchrony between precipitation and evapotranspiration (ET) at Andrews and Caspar Creek, producing highly variable seasonal streamflow patterns. On the other hand, at Coweeta precipitation is uniformly spread throughout

the year, and seasonal variation in streamflow is produced by summer ET. At Hubbard Brook, seasonal variation in stream flow is the result of snowpack storage and melt during the spring period of leaflessness, as well as summer ET. At Luquillo, ET is almost constant throughout the year because of evergreen vegetation, and streamflow response thus displays little seasonal variation.

This type of cross-site comparison is useful in identifying the relative strength of climate, vegetation, and landscape controls on

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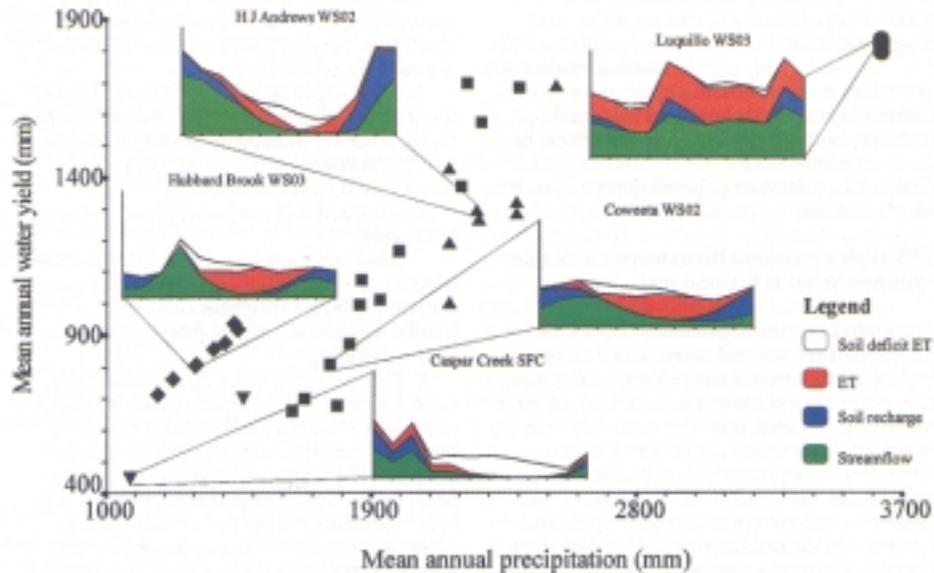


Fig. 2. Mean annual precipitation plotted against mean annual evateryield for small experimental catchments at five sites. The distribution of soil deficit, evapotranspiration (ET), soil recharge, streamflow, and precipitation throughout the year are shown for one representative catchment at each site. For the five small plots, the top of the colored area represents monthly precipitation, except for HBR in April, where the peak is due to snowmelt. The x-axes on the flue plots range from January to December, and the y-axes range from 0 to 450 mm.

streamflow generation by holding some factors constant while examining the variation in other factors. For example, Caspar Creek and Hubbard Brook have approximately the same mean annual precipitation, but mean annual discharge is much higher at Hubbard Brook (Figure 2). This reflects the higher ET at Caspar Creek owing to its relatively warm winter temperatures, whereas subfreezing temperatures and leaflessness at Hubbard Brook conspire to store water in the plant-unavailable form of snow while ET is practically zero. Peak runoff at Hubbard Brook occurs in spring during snowmelt when the deciduous trees have not yet begun transpiring, while peak runoff at the temperate rainforest at Andrews and Caspar Creek occurs during winter when unfrozen soils and dormant conifers let the high amounts of precipitation pass through the system. Vegetation induces soil moisture deficits and reduces streamflow at Andrews, Caspar Creek, Coweeta, and Hubbard Brook for predictable periods defined by the phenology of the vegetation and the available soil water, but soil moisture surpluses and deficits are not regulated by these processes at Luquillo (Figure 2). Many other similar comparisons and contrasts are possible.

An ecological hydrology workshop held at the H. J. Andrews LTER site in November 20-21, 1997, and a special session of the American Geophysical Union's Spring Meeting in Boston, Mass., on May 27, 1998, brought together scientists from the LTER network and from experimental watershed study sites of the U.S. Department of Agriculture's Forest

Service and Agricultural Research Service to discuss a common framework for comparing climate, hydrology, and vegetation interactions across their widely varying sites. Currently, the controls on hydrologic response are examined on an ad hoc basis, focusing on a particular issue for an individual study. These scientists' interest in a collaborative approach to ecological hydrology reflects in part a recognition that their combined long-term datasets have the potential to contribute to issues extending beyond initial treatment effects to ecosystem analyses and the causes and consequences of vegetation succession, climate, and land use change. One commonality emerging from these discussions was the role played by storage at each site. Intersite ecological hydrology comparisons have the potential to reveal the contribution of water storage to daily, seasonal, or interannual variability in streamflow. The influence upon streamflow patterns of various forms of water storage-in snow, soil, and forest canopies-varies among sites. Storages are dominant when and where the inputs to that storage are volumetrically and temporally compatible with the volume and rates of discharge from the store. When the temporal distribution or volumetric inputs overwhelm the store, it becomes unimportant. For example, the canopy store at Luquillo is an important process when the inputs of precipitation are relatively small, short-lived, and well-spaced temporally. However, during flood events, the store is overwhelmed by the volume and timing of the inputs, and thus rendered ineffectual.

Timing of storage turnover—from daily interception and evaporation of canopy water to seasonal snowmelt and soil moisture draw-down—has critical implications for streamflow, availability of water to vegetation, and key feedbacks to stream ecology, by determining the timing of base flow periods when maximum ecological stresses may occur in streams. The degree to which landscapes "remember" the previous climate is also strongly conditioned by the type of storage. Where dominant storages have rapid rates of turnover, little memory may persist, but groundwater-dominated systems transmit a water surplus or deficit over periods of years. For example, at Coweeta, with a large volume of soil storage, the effects of a single drought year can be felt for a number of years afterwards; however, the seasonal nature of the snowpack storage at Hubbard Brook means that the effects of a drought are rarely felt, even in the following year.

Intersite ecological hydrology comparisons also have the potential to clarify how anthropogenic or natural disturbances produce varying hydrologic responses in different landscapes. Different types of climate-vegetation-streamflow interactions imply that the removal of vegetation will have different, but predictable, impacts on hydrologic response. For example, forest cutting produces increases in streamflow peaks at sites, or during seasons, where transpiration by the undisturbed vegetation accounts for large water losses. Thus one expects transpiration-related increases in spring and autumn at Andrews and Caspar Creek, in summer at Coweeta and Hubbard Brook, and all year round at Luquillo. However, forest removal may also produce declines in streamflow at sites, or during seasons, where vegetation modifies precipitation by affecting cloudwater interception or snow accumulation. Examples include interception-related decreases in summer at Caspar Creek, or snow accumulation-related decreases in winter at Hubbard Brook. If consistent relationships between climate, vegetation, landscape attributes, and streamflow can be inferred from intersite ecological hydrology comparisons, predictions of the hydrologic response of ungauged catchments may be facilitated. Ecological hydrology also faces major challenges. Foremost among these is data quality, comparability, and access.

The most difficult challenge for ecological hydrology is the lack of hydrologically relevant data about vegetation, soil, snow, and stream ecology. The importance of such deficiencies depends upon study objectives. For example, critical data are lacking on how vegetation structure affects interception of rain and snow, or how soil water availability and vapor-pressure deficits control transpiration rates for functionally distinct groups of plants. Currently available vegetation and soil maps are rarely compiled using mapping units that relate to hydrologic function. Many sites also do not have data available in computerized format. To conduct a meaningful ecological hydrology analysis may require reinterpretation of available data, additional mapping, or even detailed field measurements.

Inconsistencies among sites or monitoring periods in the type and quality of precipitation and streamflow data, also impose constraints on what we can learn from intersite ecological hydrology analyses. For example, at some sites the rain gauge network is dense and dispersed throughout the catchment be-

ing monitored (HBR), while at other sites there may be one rain gauge per catchment (CWT), or a single rain gauge may be used to determine the inputs for a number of catchments (HJA). Similarly, at some sites, the hydrologic data is of high quality, being measured by v-notch weirs (CWT, HBR), while elsewhere less accurate flumes are used (HJA, CAS) and in some places no weir or flume is used at all (LUQ) (see Figure 1). A major accomplishment of this project will be to collect relevant data from several sites and convert them into consistent formats and units and make them available on the World Wide Web.

Many opportunities remain in ecological hydrology. These initial intersite comparisons were all carried out at an annual or monthly timestep; other ecological hydrology linkages come into focus when data are examined at shorter timescales. A coordinated research program, involving field experiments at plot, small catchment, and landscape scales, historical analyses of long-term data, and modeling and simulation, will be required to capture these subtle patterns. Such a research program may also lead to more consistent monitoring of key environmental variables and promote interactions across sites. The payoff will be an improved understanding of how hydrologic processes provide the template for ecological systems but are themselves modified by the very ecosystems they support.

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