The Ecohydrology of Arid and Semiarid Environments: A Scientific Vision

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Introduction

Improvements in our ability to integrate and utilize scientific information is requisite for enhancing our ability to forecast environmental change and its effects on natural resources, socioeconomic viability, and the preservation/restoration of ecosystem health in sensitive, water-limited environments. The ability of scientists to generate environmental change scenarios will affect the choices societies make and how they adapt and function in a future of great and potentially rapid change (Clark et al., 2001). Solutions to many environmental problems hinge on improving our understanding of processes occurring in what the U.S. National Research Council (2001a) has termed the "Critical Zone": the heterogeneous, near-surface environment in which complex interactions between rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources. In many ecohydrological systems, particularly those in arid and semiarid environments, water dictates the dynamics of weathering, soil formation, biological activity and nutrient pools, and fluxes and transport in the Critical Zone. While the role of water has been widely investigated, we lack the fundamental understanding of its central role that can only come from an integrated, interdisciplinary perspective. In recognition of this constraint, the hybrid discipline of 'ecohydrology' is developing into priority research area. Shared by the ecological and hydrological sciences, ecohydrology seeks to elucidate (a) how hydrological processes influence the distribution, structure, function, and dynamics of ecosystems, and (b) how feedbacks from biotic processes impact the water cycle (Bonell, 2002; Hunt and Wilcox, 2003; Kundzewicz, 2002; Newman et al., 2003; Nuttle, 2002; Porporato and Rodriguez-Iturbe, 2002; Rodriguez-Iturbe, 2000). Our goal in this paper is to illustrate how an ecohydrological approach could be used to advance our ability to predict the effects of natural and anthropogenic perturbations on water-vegetation-nutrient interactions in arid and semiarid environments.

Managing environmental problems in the Critical Zone will require the kind of interdisciplinary collaborations embodied in an ecohydrological perspective. This is especially true for arid and semiarid landscapes where precipitation is low and highly variable and sensitivity to environmental variability and the propensity for catastrophic change is high. Approximately one third of the Earth's land surface is either arid or semiarid, and this fraction is projected to increase (Schlesinger et al., 1990). As a result, these landscapes will increasingly impact human society and land surface-atmosphere interactions (Bonan, 2002; Schlesinger et al., 1990). Arid and semiarid regions contain some of the fastest growing urban and exurban centers in the world (Brown et al., 2005), and will likely play a greater role in global biogeochemical functioning, affecting regions far removed from arid and semiarid environments (Schlesinger et al., 1990).

We begin by presenting two case studies that illustrate why an ecohydrological approach is needed to confront the social and scientific challenges in arid and semiarid landscapes. The first case study features the current problem of widespread drought mortality among trees; the second is the invasion of nonnative vegetation along riparian corridors. We then discuss the scientific challenges illustrated by these problems in the Vision Section. The Strategy Section explores how these challenges can be met using an ecohydrological perspective within the four program elements of the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) initiative. We conclude by outlining the potential benefits of adopting an ecohydrological perspective in the Expected Impacts Section.

Case Study 1: Regional-Scale Drought-Induced Mortality of Trees

Arid and semiarid ecosystems are typically characterized by vegetation that is patchy in distribution, with the proportions and types of woody plants (shrubs or trees) delineating major vegetation types such as shrublands, savannas, woodlands, and forests (House et al., 2004). The proportions and size distributions of woody plants modify the local environment beneath the plant canopy, and near their canopies, and up to scales of the ecosystem or watershed (Martens et al., 2000). The type and pattern of woody plant land cover in water limited landscapes also affects stream flow and ground water recharge (Wilcox, 2002), biophysical land surface-atmosphere interactions (Graetz 1991; Bonan 1997; Hoffman and Jackson 2000), carbon source-sink relationships (Houghton et al. 2003; Pacala et al. 2001) and tropospheric chemistry via emissions of NOx and volatile organic compounds (Guenther et al., 1999; Isebrands et al., 1999, Martin et al., 2003). The nature and extent of woody vegetation cover also has implications for biodiversity, wildlife habitat, livestock, grazing capacity, soil erosion potential, aesthetics, and real estate values. Consequently, changes in woody plant abundance has a wide range of ecological, hydrological, and societal implications. Rapid changes in woody plant abundance may occur in response to regional-scale drought. For example, during the 1950s drought in the southwestern USA, the ecotone between forest and woodland at one location shifted by more than 2 km along an elevational gradient because of extensive tree mortality (Allen and Breshears, 1998), with multiple species affected throughout the region (Allen and Breshears, in press). A current multi-state drought (1999- 2004 [this writing]) encompassing much of the southwestern USA has again effected rapid changes in vegetation cover in piñon-juniper woodlands (Figure 1). For example, piñon mortality has exceeded more than 98% at some locations in New Mexico (Breshears, unpublished data). Solutions to the challenge of developing policy and management plans for lands subject to infrequent but recurring catastrophic change are likely to be found at the interface between ecology and hydrology. What is the critical level of plant available water that triggers tree mortality? Will extensive change in woody plant abundance trigger changes in groundwater recharge or surface runoff and erosion? How will various components of the water budget respond to such vegetation changes? How will climate variability and climate change influence woody cover dynamics; and how will vegetation respond to changes in the frequency and intensity? Research confined to the realm of ecology or to the realm of hydrology cannot address such questions, highlighting the importance of an ecohydrological approach.

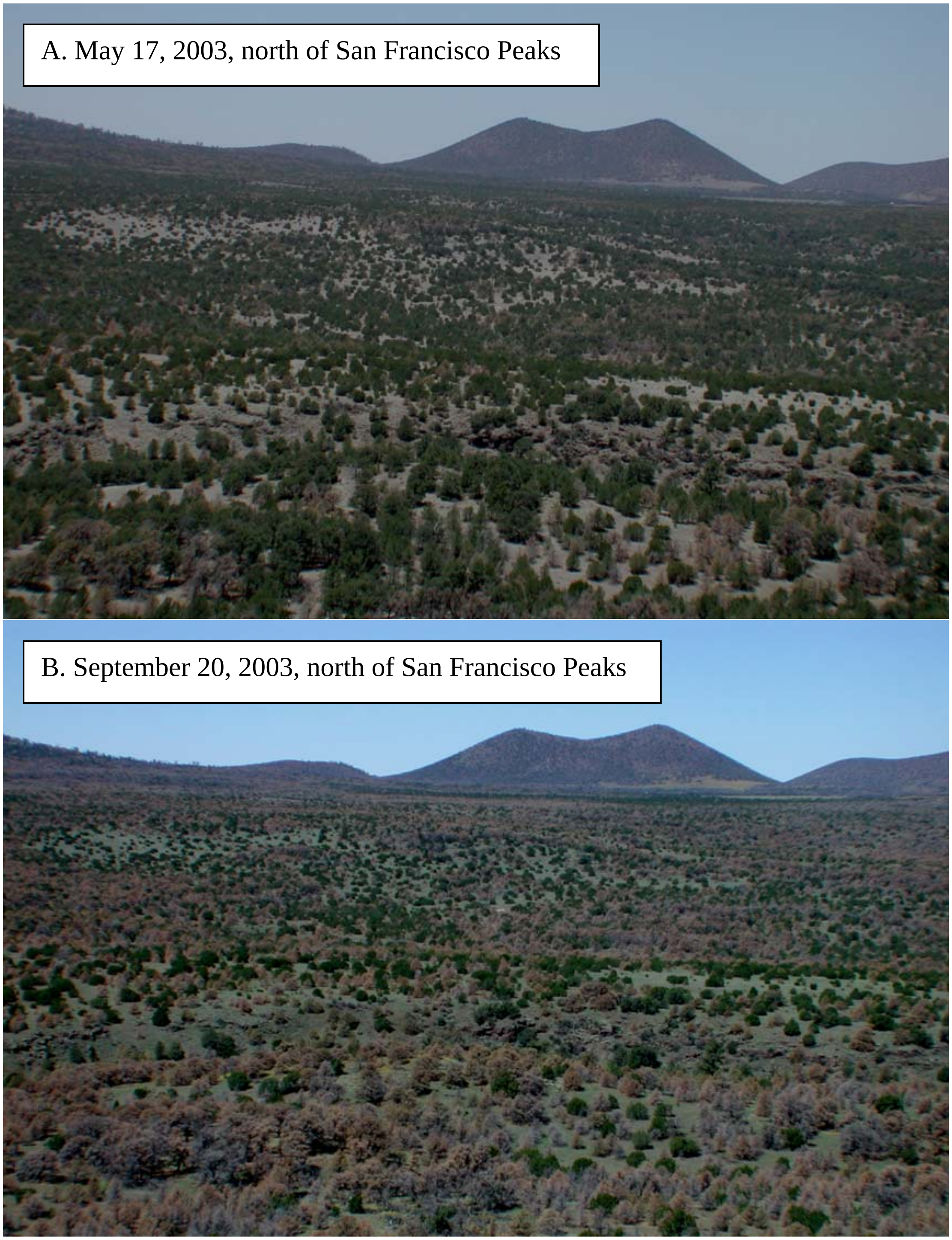

Figure 1. Massive die off of piñon pine over a four-month period in 2003 from drought/bark beetle infestation near San Francisco Peaks, AZ. Green trees in photo B are mostly juniper. Photos: J. Betancourt & N. Cobb.

Case Study 2: Invasion of Nonnative Vegetation Along Riparian Corridors

Riparian corridors in arid lands represent a distinct ecotone between rivers and uplands where novel and key ecological and hydrological processes occur. Water budgets of basins in arid and semi-arid landscapes are strongly influenced by the vegetation which occurs in these transition zones (Dahm et al., 2002), and the character of these ecotones is markedly impacted by human modification of water flow (e.g., Johnson, 1994) and the introduction of non-native plant species. Riparian ecosystems commonly are heavily invaded habitats, serving as dispersal corridors for exotic species of plants and animals (Prieur-Richard and Lavorel, 2000; Tickner et al., 2001). Non-native plants of particular importance in riparian zones of arid and semiarid lands of the western North America are Russian olive (*Elaeagnus angustifolia*) and salt cedar (*Tamarix* spp.) (Figure 2). Salt cedar has colonized about a million hectares of riparian habitat in the western US (Brock, 1994); and Russian olive is widely distributed throughout 17 western states, reaching densities exceeding 1000 trees ha $^{-1}$ (Katz and Shafroth, 2003). The prevalence of riparian plant communities dominated by non-native plants is increasing throughout the western US, yet we know little of their ecological-hydrological interactions and feedbacks. Furthermore, extensive and expensive control and eradication programs are being undertaken (Figure 2) or contemplated based on a limited knowledge and understanding of the causes and consequences of exotic plant invasion. How does water use by non-natives compare to that of the natives they displace? Do exotic plants such as salt cedar and Russian olive significantly alter evapotranspiration and thus influence streamflow and recharge to groundwater? Will removing exotic plants lead to an increase in stream flow and basin groundwater? If so, under what conditions? How might hydrological factors control the pattern and rate of spread of nonnative species, their interactions with native species and their ultimate geographical range? How do riparian communities dominated by exotics respond to drought; and how do they affect fundamental ecosystem processes such as primary production and nutrient cycling? Does the establishment of exotic plants alter disturbance regimes (e.g., pest outbreak and fire) in ways that feed back to impact local hydrology? Coupled studies of the hydrology and ecology of riparian corridors in arid and semi-arid lands are required to answer these questions. A focus on the role of non-native riparian plants would be a formidable, engaging, and socioeconomically relevant area of study for the growing field of ecohydrology.

Figure 2. Riparian salt cedar receiving herbicide application by helicopter. Note the high-density, monoculture habit of this non-native plant. Photo: Charles R. Hart, Texas Cooperative Extension.

Why Should Ecohydrology Be Part of Our Hydrology Vision?

The reasons to begin to formally cultivate an ecohydrological perspective are compelling. Water resource and near-surface environmental issues are extremely diverse and are highly dynamic in space and time, necessitating that problem-solving approaches transcend traditional disciplinary and sociopolitical boundaries. The potential benefits derived from the novel combination of traditional disciplines has been recognized by multiple agencies and the scientific community in general (IBRCS, 2003; National Research Council, 2001; National Research Council, 2001; Newman et al., 2003; Nuttle, 2002; Rodriguez-Iturbe, 2000). Merging of disciplines will help promote development of novel research tools for studying hydrologic and environmental problems as integrated, hierarchical systems of interacting components and processes. Each of the eight grand challenges in environmental sciences identified by the National Research Council (2001) will require a significant and sometimes major role for a hybrid ecological-hydrological approach. Thus, it is important that the hydrological and ecological communities jointly develop new approaches to field experimentation, environmental monitoring, and numerical modeling. We submit that a major part of such an effort should involve the development of approaches aimed at achieving a functional coupling of water, vegetation, and nutrients. In addition to addressing the need for a more interdisciplinary research approach, our proposed focus on ecohydrology also addresses current concerns about the growth of hydrology as a science. Ecohydrology, which does not yet occupy the central role it deserves in hydrological research (Rodriguez-Iturbe, 2000), represents a paradigm shift that will enable the hydrologic discipline to add new dimensions and become more relevant to modern environmental problems (Hunt and Wilcox, 2003; Newman et al., 2003; Nuttle, 2002; Rodriguez-Iturbe, 2000).

The objective of this paper is to articulate a vision of a truly integrated hydrological and ecological research community and in so doing, present the major scientific challenges and needs in arid and semiarid ecohydrology that could be addressed in the context of river-basin scale hydrological observatories. Much of our discussion revolves around closing the water budget, a long-standing challenge in hydrological research. By explicitly linking hydrological and ecological research, new insights on processes controlling the water balance will result, and improve our ability to quantitatively assesses and predict water balance components and fluxes in water-limited systems. A similar argument is made for understanding nutrient balances. Such advances are necessary if we hope to anticipate complex environmental responses to change, and advance the scientific foundation upon which the stewardship of water resources and the management of ecosystem health are based.

Six themes that encompass many of the main scientific challenges in arid and semiarid ecohydrology will be explored:

1. Is it important to partition evaporation and transpiration?
2. What is the value of studying coupled water and nutrient interactions?
3. How does vegetation affect streamflow?
4. How does vegetation affect groundwater recharge?
5. How do climate, water, and landscape components interact?
6. How does vegetation respond to hydrological change?

We also examine three cross cutting themes pertinent to these issues: spatial complexity and scaling, feedbacks, and thresholds. The above list is not intended to be comprehensive, but rather as examples of where cross-disciplinary science can help address difficult societal issues in water-limited environments today and in the future. These issues and themes are addressed in more detail in the Scientific Vision section.

Scientific Vision

Vegetation and water are intimately coupled. Put simply, changes in one affect the other. Our understanding of the interactions between vegetation and water is, however, incomplete as highlighted by the themes and cross cutting issues discussed below.

Understanding Arid & Semiarid Ecohydrology: Six Scientific Themes

Theme 1: Is It Important to Partition Evaporation and Transpiration?

Arid and semiarid ecosystems are by definition water limited, and the amount of biologically available water is arguably the central driver of many ecosystem processes. Biologically available water is determined not only by precipitation, but how precipitation is redistributed through processes such as interception, stemflow, percolation, and runoff. Most hydrological studies have estimated water budgets by lumping canopy interception, soil evaporation (E), and transpiration (T) into a single term (ET) (Huxman et al. 2005; Loik et al. 2004). Although compositing E and T is expedient for some applications, (e.g., runoff assessment), it ‘black boxes’ biological processes that significantly regulate the hydrological cycle directly and indirectly at short (hourly, daily) and long (seasonal or interannual) time scales. Given that lumped ET usually accounts for > 95% of the water budget in arid and semiarid ecosystems (Wilcox et al. 2003), it is critical to partition E from T as these reflect abiotic vs. biologically processed water fractions. There are surprisingly few studies that partitioned E from T, and those studies differ in methodology, ecosystem type, and duration (Huxman et al. 2005; Reynolds et al. 2000). Consequently, we cannot make robust generalizations or predictions about E and T and how their relative importance varies among sites, through time, or in response to land management. Attaining this capability constitutes a major challenge and will require an for ecohydrological approach.

Theme 2: What it the Value of Studying Water and Nutrient Interactions?

Water has typically been regarded as ‘the’ limiting resource and driving force in arid and semiarid community dynamics. However, nutrient availability may also exert a strong and co-dominant influence; and nutrients and water are inextricably linked in many cases. Nutrient availability can limit vegetation responses to precipitation and soil moisture; and soil moisture availability drives N_2-fixation by microbial symbionts of plants and microbial mineralization of soil organic matter. Together, these influence the abundance of nutrients for plant uptake or translocation via leaching and erosion. There are clear evolutionary trade-offs between features enabling plants to tolerate nutrient-poor conditions and features conferring competitive superiority under nutrient-rich conditions (Aerts and van der Peijl, 1993; Berendse and Elberse, 1990; Chapin, 1993; Chapin, 1980). Furthermore, plants can modify soil nutrient status (Hobbie, 1992) in ways that may promote or deter community change (Binkley and Giardina, 1998; Schlesinger and Pilmanis, 1998; Tilman and Wedin, 1991) and hence response to rainfall. Linkages between nutrient availability and plant community dynamics may thus be strong (Rietkerk and van de Koppel, 1997; Wedin, 1999).

The importance of water-nutrient interactions in arid and semiarid environments is not limited to the near-surface or soil zone. The thick vadose zones of the southwestern U.S. can contain large inventories of nitrate at depths below the root zone. Although there are still uncertainties, recognition of this apparently widespread store of nitrate potentially increases estimates of nitrogen inventories by 14 to 71% for warm deserts and shrublands worldwide and 3 to 16% globally (Walvoord et al., 2003). At these locations, the vadose zone has acted as a sink for nitrate for thousands to tens of thousands of years. This begs the question of why these vadose zone inventories have developed in ecosystems with strong nitrogen limitations? Are there hydrological processes that limit more efficient utilization of nitrogen in the soil zone? These large vadose zone nitrate inventories are also a potential water quality issue. If stored nitrate is flushed from the vadose zone into groundwater as a result of climate or land use change, the inventories are large enough in some areas to potentially create a groundwater degradation problem. ***To what extent has our focus on water rather than or in isolation from nutrients constrained our understanding and management of arid and semiarid ecosystems?***

It is generally assumed that at lower levels of annual precipitation, aboveground net primary productivity is limited primarily by water, whereas at higher levels of precipitation, it is limited primarily by nitrogen. Hooper and Johnson (1999) tested this assumption by synthesizing results from fertilization experiments in arid, semiarid and subhumid rangelands. Their survey found no strong evidence of a shift from water- to nutrient-limitation across a wide geographic rainfall gradient. Indeed, responses to nitrogen addition were typically positive, even at dry locations and even in years of below-average rainfall. Such results suggest tight coupling between water and nitrogen and co-limitation (Chapin, 1991; Chapin *et al.*, 1987). Models of the coupled hydrological, carbon and nitrogen cycles support the notion of water-nitrogen co-limitation (Schimel *et al.*, 1997). However, because water, carbon and nitrogen cycles have different response times, inclusion of nitrogen cycling into ecosystem models adds behavior at longer time scales than that observed in purely biophysical models. Tight correlations among nitrogen fluxes with evapotranspiration suggests that either climate change or changes to nitrogen input (e.g., fertilization or N-deposition) will have large and long-lived effects on primary production.

Plant community studies that focus solely on water without accounting for plant available soil nitrogen may be overlooking a critical factor. Contradictory prediction of ecosystem response to moisture might be resolved if nitrogen is factored in. The physiological and evolutionary responses of plants to nutrient limitation and the responses of microbial decomposers to plant tissue chemistry create feedbacks that may reinforce N limitations (Chapin, 1993; Hobbie, 1992; Vitousek, 1982). Disturbances such as grazing and fire may alter or disrupt the feedbacks between vegetation and N availability (Holland *et al*., 1992; Seastedt, 1995; Wedin, 1995; 1999) and propel a community into alternate stable states (Jefferies *et al*., 1994; Pastor and Cohen, 1997; Rietkerk and van de Koppel, 1997; Rietkerk *et al*., 1997). The rates and dynamics of these nutrient-mediated transitions are likely dictated by rainfall amount and variability via effects on plant production and plant population dynamics.

All temperate and tropical biomes receive more N via wet and dry deposition today than during pre-industrial times; Northern Hemisphere temperate ecosystems receive on average more than four times that of pre-industrial levels (Holland *et al*., 1999). Given these increases in N deposition, there is a pressing need to understand how water and N influence ecosystem processes both independently and interactively (Burke *et al*., 1991; Vitousek *et al*., 1997). If, for example, N deposition reduces or alleviates N limitations in arid and semiarid environments (e.g., Schimel et al. 1997), species composition will likely shift and primary production may become more responsive to increases in atmospheric CO_2 and more sensitive to temporal variation in rainfall. How will this affect ecosystem management, restoration and remediation?

Theme 3: How do Plants Affect Streamflow?

In arid and semiarid landscapes, the nature and character of vegetation significantly affects nearly all aspects of water and energy balance over a wide range of spatial and temporal scales. At large spatial scales, the interactions and feedbacks in the land-atmosphere-biosphere system exert important controls on climate and long-term ecosystem response over a region [see discussion below] (e.g., Eltahir and Bras, 1994; Wang and Eltahir, 2000). At the individual plant scale, vegetation response to water stress, disturbances and climate variability occur in relation to local conditions (e.g., Rodríguez-Iturbe et al., 2001; Scott et al., 2000). In arid and semiarid areas, high spatial heterogeneities in topography, soil, and precipitation lead to a juxtaposition of individual plant responses embedded within ecosystem-wide trends. As a result, semiarid regions are frequently sites for biome transition zones or ecotonal boundaries (Buffington and Herbel, 1965; Eagleson, 1982), which often occur on a complex template created by spatially variable landscape and climate conditions.

The role of vegetation in the dynamics of soil moisture, runoff, and streamflow in arid and semiarid regions has been studied through point and hillslope scale observations (e.g., Wilcox et al., 1997; Newman et al., 1998; Neave and Abrahams, 2002; Wilcox et al. 2003), numerical modeling at a point, along a hillslope transect, and over a spatial domain (e.g., Porporato et al., 2002; Ridolfi et al., 2003; Fernandéz-Illescas and Rodríguez-Iturbe, 2004), and through remote sensing data analysis (e.g., Cayrol et al., 2000; Kerkoff et al., 2004). These studies point to the critical function played by vegetation in determining the temporal and spatial variations in the soil moisture and runoff within hillslopes and channel networks. The available runoff in different ecosystems also leads to observable geomorphic patterns. For example, Abrahams (1984) has argued that the high drainage density in water-limited environments is due to large amounts of excess water in the form of runoff created by the interaction of low rainfall rates and sparse vegetation canopies. Excess runoff water is ultimately expressed in the form of erosion and channel network development. In a recent study by Wilcox et al. (2003), a similar concept of resource conservation in a semiarid ecosystem is shown to be directly tied to the spatial pattern of vegetation and topographic characteristics. Both studies suggest that ecohydrological studies in arid and semiarid regions should focus on studying the interaction between runoff processes and vegetation type and pattern as expressed in the long-term catchment geomorphic form.

The tight coupling between vegetation and water lead to the reasonable assumption that water supply in arid and semiarid zones may be augmented through vegetation management. In fact, for semiarid landscapes where woody plants are increasing in density and cover, there may be no more emotional ecohydrological topic than the influence of these plants on streamflow and groundwater supply. In some parts of the United States, it has become an article of faith that if we remove the shrubs, rivers will flow to capacity. There is, in-fact, considerable political and public support for using tax dollars for shrub control with the stated objective of increasing water supply. In Texas, for example, around 40 M dollars has been spent or allocated for cost-sharing shrub control. At the Federal level, the 108th United States Congress is considering a bill that would fund salt cedar control at a level of $20M/year with the goal being of increasing water availability. Unfortunately, this is an example of policy and politics getting ahead of the science. There is still considerable uncertainly as to the magnitude and feasibility of increasing water yield through vegetation management, especially on a large scale. The reality is that for many arid and semiarid landscapes there is little potential for increasing water yield through vegetation management; and in those areas where there may be a linkage, such as salt cedar infested floodplains and riparian zones, it has yet to be conclusively demonstrated. Based on the assumption that woody plants along riparian corridors are directly accessing ground water, the strongest linkages between woody plant cover and water yield are likely to occur in these settings (Huxman et al. 2005). Although this makes sense conceptually, there are remarkably few studies that have demonstrated directly that altering woody plant cover in riparian zones appreciably affects streamflow.

For non-riparian settings, increases in streamflow subsequent to woody plant control have been demonstrated in comparatively few locations experimentally; and all of these have been in regions where streamflow is derived from winter precipitation [e.g., Mediterranean climates (Hibbert, 1983; Williamson et al., 2004) or melting snow (Baker, 1983)]. In parts of Australia, eucalyptus woodlands have been replaced with commercial agriculture on a grand scale. As a result of this conversion ground water tables have risen and contributed to dramatic soil salinity problems (Allison et al., 1990; Walker et al., 1993). Landscapes where springs are common and streams have a perennial baseflow component (e.g., karst rangelands) may have potential for augmenting streamflow and recharge through vegetation manipulation, but again this has not been demonstrated at a landscape scale.

Annual potential evapotranspiration typically exceeds precipitation in arid and semiarid environments; streamflow results primarily from Hortonian overland flow, and there is a reduced connection between surface and subsurface hydrological processes along streams, as compared to more humid climates. As a result, vegetation manipulation in arid and semiarid landscapes may not provide the anticipated societal benefit of increased streamflow as lateral water fluxes are by definition short-lived and limited in spatial extent. Thus, in addition to understanding the ecohydrological processes controlling streamflow, we also need to be aware of which environments have the potential for increased runoff in response to vegetation management.

Theme 4: How do Plants Affect Groundwater Recharge?

Differences in recharge beneath nonvegetated and vegetated lysimeters in the Western US illustrate that plants can substantively influence groundwater recharge (Gee et al., 1994). Another example of the important link between vegetation and recharge is the large-scale conversion of woodlands in Australia noted earlier, where recharge rates increased by two orders of magnitude after vegetation conversion (Allison et al., 1990). Thus, coupling changes in soil water storage to precipitation variability and vegetation dynamics is essential for developing a predictive understanding of recharge. The coupling is two-way: soil water storage varies with rainfall, which also impacts vegetation productivity; and vegetation productivity, in turn, influences recharge. For example, in El Niño years, increases in vegetation biomass and cover serve to dampen the extent of recharge compared to that which would be expected solely based on precipitation (Scanlon et al., 2003; Smith et al., 2000). In contrast, shifts from mesic to xeric vegetation associated with Pleistocene-Holocene climate change (~10,000 – 15,000 years ago) changed interfluvial basin hydrology throughout the southwestern US from recharging (net downward water movement) to discharging (net upward water movement) (Scanlon et al., 2003; Walvoord et al., 2002; Seyfried et al., 2005). An explicit accounting of the role of vegetation is thus critical for forecasting impacts of climate variability and land use/land cover change on recharge.

Correlating vegetation types, cover, biomass, and hydraulic factors to recharge would enable us to use vegetation as a proxy for recharge (Walvoord and Phillips, 2004). Vegetation mapping, which can be readily conducted using ground based, airborne or satellite data could then be used to predict subsurface flow processes and recharge in lieu of subsurface sampling and analyses. Systematic elucidation of relationships between vegetation and recharge developed through coordinated, strategic measurement and monitoring efforts in diverse biomes could generate a database from which to develop more reliable local, regional, and continental estimates of recharge.

Parameters to be measured/monitored include climatic variables (e.g. precipitation, relative humidity, temperature), vegetation parameters (e.g. functional group or species composition, leaf area, net primary production, stomatal conductance, plant water potential, normalized difference vegetation index) and hydrologic parameters (e.g., soil water content and storage, and hydraulic conductivity). From this database, it would be possible to identify critical climate forcing required to produce episodic recharge for a given vegetation state. An example of the need for multi-faceted measurement and characterization strategies is shown by a study of water movement in a ponderosa pine forest and piñon-juniper woodland in New Mexico (Newman et al., 1997). Even though the ponderosa pine forest receives over 40 mm more precipitation per year than the piñon-juniper woodland, downward fluxes were found to be about an order of magnitude less in the ponderosa pine forest. In this case, hydraulic properties (i.e., a low hydraulic conductivity layer in the ponderosa pine soil) exert a control on downward water flux contrary to what would be expected based on the differences in vegetation type and precipitation amount.

Characterizing deep-water dynamics occurring over longer time scales in thick arid and semiarid vadose zones would require vertical profiles of water content and water potential (to ascertain upward versus downward water movement), and chloride (to quantify recharge via chloride mass balance) in the unsaturated zone. Space can be strategically substituted for time to predict changes in recharge related to changes in vegetation that may occur in response to climate variability, land use, fire, and disease. These thick vadose zones take hundreds to many thousands of years to fully equilibrate with current surface conditions. Thus, vertical vadose zone profiles can record the effects of the pre- and post-vegetation change on recharge rates where the deeper depths of a profile preserve the pre-change conditions and the shallower depths preserve the younger post-change conditions. Space-for-time monitoring could also be complimented by strategic local experimental manipulations that are followed through time.

Theme 5: How do Climate, Water, and Landscape Components Interact?

One of the major challenges facing the science of hydrology in the coming decades will be dealing with global-scale environmental change and predicting its effects on hydrological systems. Such change will stimulate feedbacks that will cause the primary characteristics of drainage basins (e.g., vegetation type and distribution, soils, water tables, drainage networks) to evolve. Currently, our ability to simulate such complex feedback responses is unproven. The best way to develop and evaluate such models is to employ them to simulate past events during which major responses have been documented.

Arid/semiarid drainage basins are especially well suited for understanding environmental feedbacks and responses because they contain unusually long and complete records of past environmental change. These records are unusual in part because of the exceptional preservation of organic matter in dry environments. One major and detailed archive of climate variation and vegetation response is the tree ring record. Arid regions of the U.S. have tree-ring records that extend back several thousand years (Grissino-Mayer, 1995; Scuderi, 1993), and in a few cases as much as 8,000 years (Feng and Epstein, 1994). The annual resolution of tree rings over these time scales allows statistically significant analysis of important hydroclimatic phenomena such as ENSO-related variability and climate oscillators on the decadal time scale (e.g., North Atlantic Oscillation, Pacific Decadal Oscillation). The vegetation response to long-term climate forcing is also preserved in a unique arid-region archive: fossil packrat middens (Betancourt et al., 1990). Midden records, which extend as far back as 40,000 years ago, but more commonly cover the past 10,000 to 20,000 years, have enabled detailed reconstructions of vegetation communities and plant migrations in many parts of the southwestern United States. This interval is long enough ago to record events associated with the ending of the last glaciation, which is the most recent major climatic/hydrologic event on the continent (Phillips et al., 2004).

Other independent paleoclimatic and paleohydrological archives can supplement tree-ring and packrat-midden records. One of the most important of these is speleothems (calcium-carbonate precipitates in caves) that can provide time series going back hundreds of thousands of years (Burns et al., 2001); and under favorable circumstances can also yield annual time-resolution records (Polyak and Asmerom, 2001). Aquifers can also serve as paleoenvironmental repositories, going back tens of thousands of years. They can provide temporal information on paleotemperatures, groundwater isotopic composition, and groundwater recharge rates (Fontes et al., 1993). Lacustrine sediments and shoreline deposits from closed-basin lakes in arid regions can provide direct information on fluctuations in the water balance (Street-Perrott and Harrison, 1985).

Ultimately, over significant periods of time, changes in temperature, precipitation, and vegetation produce changes in the physical hydrology of the landscape, manifested as landscape incision, degradation, and alluviation (Bull, 1991; Molnar, 2001; Tucker and Slingerland, 1997). Excellent records of these events are preserved in the arid landscape and have been extensively studied and dated (McFadden and McAuliffe, 1997; Waters and Haynes, 2001). Current topography and its evolution through geomorphic processes is known to impart structural control on the temporal and spatial distribution of runoff, soil moisture, groundwater discharge and radiation exposure in catchments (e.g., Dunne and Black, 1970; Beven and Kirkby, 1979). In arid and semiarid areas, regional and local elevation differences can lead to important shifts in hydrologic behavior, including infiltration, overland flow and erosion (e.g., Neave and Abrahams, 2002; Parsons et al., 2003). These in turn are hypothesized to control water availability and hence the favorability for a species adapted to a particular moisture state. Topographic effects can lead to landscape ‘niches’ that favor particular species as they compete for resources and adapt to disturbances and long-term changes.

Although many paleoenvironmental archives have been individually investigated, and in some cases hydrological models have been constructed based on generalized paleoclimate considerations (Plummer, 2002), there have been few, if any, attempts to link detailed contemporary hydrological investigations and models with the geological record of environmental change. An aggressive approach to meeting the challenge of reliably predicting responses to future changes would start with a thoroughly investigated basin where a detailed and integrated hydrologic/vegetation/geomorphic model was already constructed. All available paleoenvironmental studies should then be synthesized to construct a comprehensive accounting of the hydrological, vegetational, climatic, and geomorphic history of the basin. Additional studies should be done to fill in missing records. Based on these reconstructions, the basin model should be forced using external (mainly climate) records. Modeled responses (runoff, recharge, vegetation dynamics, geomorphic modification) could then be compared with those from the geological record. By an iterative process the model could be improved and refined to better reflect the actual processes and outcomes reflected in the environmental changes. Only by taking a holistic and process-oriented approach to modeling, combined with detailed attention to the geological record, can a solid foundation for the prediction of effects of future environmental changes be laid.

In addition to a paleo perspective, current or modern interactions are important to investigate. A major challenge in evaluating the relationships and interactions among the atmosphere, terrestrial hydrology and vegetation is the role of human effects. Clearly, human activity is a major factor in modifying the landscape with historical changes in agricultural, industrial, transportation and urban/rural development. At the land surface, the fluxes of energy, water and aerosols are regulated by vegetation through partitioning of precipitation and energy into soil moisture, evapotranspiration and infiltration, for example. This partitioning is fundamental to terrestrial hydrology, determining the recharge-runoff relationships that sustain springs, streams and rivers. At the same time vegetation properties (height, patchiness, growth stage, LAI, etc.) modulate albedo and surface roughness, which influence local climate patterns and meso-scale circulation (Copeland, 1996; Pielke and Avissar, 1990; and Pielke et al., 2002). This complex relationship would seem to require a new and collective way of looking at our disciplinary research, which better reflects the likelihood that hidden or presently unmeasured variables and relationships are likely to emerge.

Reductions in rainfall and an increase in temperature during the mid-20th century in southwestern Australia illustrate the relationships between climate, vegetation and land surface hydrology (Pitman et al., 2004). In this example, decreasing precipitation and increasing temperature was associated with reduced streamflow and increased evapotranspiration. The first interpretation by atmospheric scientists was that "..that the changes in temperature were likely caused by the enhanced greenhouse effect, and the changes in rainfall were likely caused by a large scale reorganization of the atmospheric circulation". However, Pitman et al. (2004) argue that major changes in vegetation in the 20th century (reduction of tree cover, and the increase in grassland and agricultural crops) explain the changes in precipitation and temperature through feedback to the atmosphere. So the question remains, is atmospheric change or land cover change or a combination of the two the driver of climate change? It seems clear that a collective "new way of looking" is necessary, whereby the science of change takes a more integrated approach to land surface-atmosphere interactions.

Improving our biophysical representation of terrestrial ecosystems in models of water, energy and mass in ungauged river basins remains an longstanding area of research receiving wide attention (Jakeman and Hornberger, 1996). The models are expected to explain forcings and feedbacks across time scales that encompass seasonal dynamics, episodic (e.g., flash floods), and decadal (e.g., drought) events, and beyond (climate change), while providing spatial detail sufficient for modeling local, basin, and regional responses to land cover and land use. The question becomes: in what way does vegetation and ecology enter this dynamical system?

A model of recharge by Duffy, 2004, illustrates how interactions between climate, water, vegetation, and other landscape components control spatial variation of recharge along a transect across the Rio Grande basin. The model suggests that $P\text{-}ET$ is positive in upland mountain block and front, ~zero over the alluvial piedmont, and negative on the valley floor. From a water balance perspective, these *P-ET* relationships suggest that the upland mountain block and mountain front may be the only significant source of local recharge. Thus, recognition of how climate, hydrology, and vegetation interact across the landscape to control the spatial distribution of recharge is critical to long-term water supply issues in arid and semiarid basins.

Theme 6: How Does Vegetation Respond to Hydrological Change?

The distribution, growth, and mortality of vegetation is more sensitive to the hydrologic cycle than to any other factor (e.g. nutrients, sunlight) on a global average, and this is particularly true in arid climates (Weltzin et al., 2003a). It is well established that the growth and biomass accumulation of vegetation is strongly correlated with total annual precipitation (Knapp and Smith, 2001; Waring and Running, 1998). In the Southwest, seasonality of precipitation input is also critically important because the monsoon precipitation typically arrives in mid-summer; a time of relatively hot weather that can accommodate high growth rates, but can also cause temperature stress and significant cavitation and subsequent mortality if a drought occurs. Such seasonality has dramatic impacts on vegetation life forms (Fernandez-Illescas and Rodriguez-Iturbe, 2004; Schwinning and Ehleringer, 2001), diversity (Chesson et al., 2004), sensitivity to invasion (Weltzin, 2003b) and productivity (Huxman et al., 2004; Smith et al., 1997) of arid and semiarid ecosystems. The current drought is already showing dramatic effects on the vegetation; the current mortality of piñon and ponderosa pine is widespread throughout Utah, Colorado, New Mexico and Arizona (Case Study 1). In contrast, vegetation along riparian corridors is historically accustomed to flooding as a source of nutrients and water. Such flooding has been minimized through engineering efforts to control river flows. Overall, direct anthropogenic manipulations of river flows along with indirect alteration of the climate that shifts the timing, frequency, and magnitude of precipitation are likely to have profound impacts on vegetation survival and productivity in this region where vegetation is already coping with minimal water availability (Weltzin et al., 2003a).

Predicting vegetation response to changes in the hydrologic regime requires models based on first principles of plant carbon-water balance (Landsberg and Waring, 1997; Running and Coughlan, 1988; Williams et al. 1996). Understanding the response of plant carbon gain (photosynthesis) to water availability is necessary because plant productivity and survival are dependent on carbon acquisition. Unfortunately, models are only as good as the data used for parameterization, and in this regard the carbon portions of the models are lagging behind the water components. We have detailed understanding of whole-plant transpiration (Granier, 1987) based on continuous sapflow measurements, on plant thresholds for xylem cavitation (Holbrook and Zwieniecki, 1999; Sperry et al., 2002; Tyree and Sperry, 1988) based on branch-level conductivity measurements, and on stomatal regulation of transpiration (Bond et al., 1999; Cowan, 1977; Jarvis and Morison, 1981; Oren et al., 1999) from leaf-level measurements. This work has identified some fundamental mechanisms by which plants regulate water loss, mechanisms which are commonly incorporated into ecosystem process models. However, technology to measure the response of carbon gain to hydrologic variation has lagged behind water flux measurements. Stable carbon isotope ratios of plant organic matter have demonstrated species adaptation to water availability over the lifespan of plants (Ehleringer et al., 1993). On shorter timescales, eddy covariance measurements of ecosystem carbon exchange are now allowing us to determine the short-term (daily) response to water pulses (Huxman et al., 2004). Ecosystem-scale stable isotope measurements are now showing regional and temporal response of ecosystem water use efficiency to water availability (Bowling et al., 2002;

McDowell et al., 2004). Incorporating this knowledge into an ecohydrological framework is essential for predicting vegetation response to changes in water inputs and for predicting how vegetation will affect water fluxes and water storage. At larger scales, changes in species abundance and composition resulting from climatic fluctuation and disturbance must be taken into account (Neilson and Marks, 1994; Neilson, 1995). Measurements at this scale have truly lagged behind the models. However, new technologies (e.g., advances in satellite remote sensing capabilities) show promise for improving our ability to quantify biogeographic responses to changes in the hydrologic cycle. Understanding the carbon balance response of terrestrial ecosystems to changes in the hydrologic cycle is essential for future prediction of terrestrial carbon sequestration under various climate change scenarios (IPCC, 2001).

Cross-Cutting Issues

Cross-Cutting Issue 1: Spatial Complexity and Scaling of Ecohydrological Processes

Hydrologists have a long history of addressing the topics of spatial complexity, scaling and organization in the context of rainfall processes, runoff dynamics, river network structure and geomorphic evolution (e.g., Bloschl and Sivapalan, 1995; Rodríguez-Iturbe and Rinaldo, 2001; Wood et al., 1990). Recent work suggests vegetation spatial patterns exhibit self-organization and optimality related to climate and to landscape characteristics (Caylor et al., 2004; Fernandez-Illesca and Rodríguez-Iturbe, 2004; and Van Wijk and Rodríguez-Iturbe, 2002). While these perspectives advance our understanding of ecohydrological dynamics, the effects of scale and spatial complexity on water-vegetation interactions have yet to be elucidated (e.g., Kerkoff et al., 2004). For arid and semiarid areas, heterogeneities in meteorological forcing, topographic conditions, geologic settings and plant water use strategies will make the transfer of understanding from the local to the regional scale particularly challenging.

Although some point measurements (e.g., chloride based fluxes and residence times) can be representative of large-scale behavior (see Phillips, 1994), many ecohydrological processes are highly scale dependant. Thus, scaling from the point and plot scale to the watershed and region scale remains a significant challenge in ecohydrology theory, observations, and modeling. Numerous factors contribute to this challenge, including the space-time nature of the precipitation events (e.g., Goodrich et al., 1995; Syed et al., 2003), the scaling behavior of runoff (e.g., Goodrich et al., 1997; Wilcox et al., 2003), and ecosystem response to climate and landscape variability (e.g., Betancourt et al., 1993; Milne et al., 2003; Reynolds et al., 1999; Schlesinger et al., 1990). Our limited understanding and poor quantification of the spatial interactions among traditional hydrologic elements (i.e., topography, soils, rainfall) and the dynamics of communities, ecosystems, and ecotonal boundaries is currently constraining progress. Advances in spatially explicit, process-level mechanistic knowledge of the effects of rainfall, runoff and geomorphic scaling on vegetation pattern and ecosystem function in arid and semiarid regions will require nested levels of field experiments and continuous monitoring at strategically selected sites and spatially-distributed campaigns at multiple scales (e.g., Wilcox et al., 2003). This kind of experimentation and monitoring will also require explicit coordination of data collection with numerical modeling needs from the experimental design phase onward to achieve the maximum benefit of the research approach.

Advances in our understanding and predictive capabilities are likely to come from the pre-meditated enjoining of distinctive perspectives and approaches. Coupling local field observations with remote sensing is a promising approach for developing a regional understanding of climate, landscape, vegetation, and water interactions (e.g., Cayrol et al., 2000a; Rodríguez-Iturbe, 2000; and Roerink et al., 2003); and coupled field- and remote sensing campaigns also offer a means for obtaining distributed information needed to test predictions of spatially-explicit, ecohydrological models. Coupled ecological and hydrological models allow for novel assessments of the impact of climate variability on vegetation and competition for water among plant species and functional groups (e.g., Cayrol et al., 2000b; Peters, 2002; Porporato et al., 2002; Reynolds et al., 2000). Nevertheless, the representation of vegetation dynamics resulting from water stress, competition, and disturbance is generally lacking within models addressing spatial complexity and scaling of hydrological processes. Studies attempting to incorporate dynamic vegetation that responds to moisture variability into a watershed hydrology models are a step in the right direction (Band et al., 1993; Mackay and Band, 1997). However, for dry climates and complex landscapes, spatially explicit models of coupled ecological and hydrologic processes are nascent and have yet to demonstrate diagnostic or prognostic capabilities. By embedding ecosystem processes within spatially distributed hydrological models, the community can begin to explore multi-directional interactions between hydrologic organizational principles (such as self-similarity in river networks) and ecosystem behavior (e.g., Caylor et al., 2004; Milne et al., 2002).

Cross Cutting Issue 2: Thresholds

Threshold-like responses can be viewed as those responses to a driver that are proportionally much larger or of fundamentally different character than previous responses to the same driver. An understanding of threshold-like behavior is critical in the context of resource management as it provides a means of anticipating when adjustments should be made to avert undesirable change or to promote desired change (Brown et al., 1999). Lack of an understanding and ability to manage relative to thresholds leads to “environmental surprises” and missed opportunities.

Threshold behaviors can have both abiotic and biotic components and can be triggered by intrinsic and/or exogenous events, feedbacks within the system, or episodic climatic events. Many environmental thresholds lie within the realm of ecohydrology, wherein either a hydrological trigger can push the system over an ecological threshold or an ecological trigger can push the system over a hydrological threshold. In many cases, it is difficult to reverse system behavior and characteristics after a threshold has been crossed, underscoring the importance of linking effective management to thresholds. One simple example of such an ecohydrological threshold centers on the relationship between runoff and vegetation. If herbaceous vegetation is removed, runoff and associated erosion may increase in a non-linear fashion and produce a positive feedback that further reduces vegetation cover, which further exacerbates soil loss (Davenport et al., 1998; Ludwig et al., in press; Thurow, 1991). Other examples of ecohydrological thresholds include water availability as a trigger for plant germination, establishment, or mortality (Allen and Breshears, 1998; Bowers and Turner, 2001; Villalba and Veblin, 1998; Watson et al., 1996, 1997), closure of woody plant cover (Milne et al., 1996; Martens et al., 2000), land management effects on streamflow (Huxman et al. in press), vegetation effects on groundwater (see Scientific Themes Three and Four), and subsurface flow of water around tree roots (Newman et al., 1998; 2004). Thresholds, then, are an important crosscutting theme along with scaling and feedbacks for addressing the six critical ecohydrology issues detailed earlier. Failure to account for thresholds precludes effective environmental management and can lead to “environmental surprises” with potentially catastrophic consequences (Peters et al., 2004; Shcheffer et al. 2001).

Cross Cutting Issue 3: Feedbacks and Interactions

Ecohydrology inherently embraces the study of feedbacks and interactions between the biotic and hydrologic components of environmental systems. The hydrology of an environment affects ecological processes by constraining photosynthesis and respiration and thus is a direct control on the type, amount, and productivity of vegetation that can exist at a given locale (Waring and Running, 1998). At the global scale, soil water availability is the single most important constraint on photosynthesis, with atmospheric water content a close second (Running et al. 2004). This occurs because during periods of moisture abundance, photosynthesis and hence transpiration are high (open stomates, greater leaf areas), whereas during dry periods, plants limit transpirational water loss (stomatal closure, decreased leaf area) to avoid desiccation, thus constraining photosynthesis. Variation in transpiration feeds directly back on ecosystem hydrology through consumption of soil water that might otherwise have percolated below the root zone and become groundwater recharge. Further, variation in canopy leaf area directly affects precipitation interception, stem flow, throughfall, and soil evaporation. For example, high amounts of leaf area result in greater interception and subsequent evaporation of water, without the water ever reaching the soil surface. Conversely, water intercepted by plant canopies may be funneled to the base of plants via stem flow and concentrated where infiltration rates are high, thus increasing plant available soil moisture. “Carry-over” effects (Ewers et al. 1999) may also allow vegetation to mediate streamflow and groundwater recharge over multi-annum periods via dynamic shifts in vegetation attributes that affect site water balance (e.g., leaf area, root biomass).

Unfortunately, our understanding of these feedbacks relies heavily on ecosystem process models (Landsberg and Waring, 1997; Running and Coughlan, 1988; Williams et al., 1996) developed from and constrained by a limited number of measurements.. This lack of empirical data limits model development and hence our understanding of the complexities of ecologic-hydrologic feedbacks and interactions.

Case Study 1, Regional-scale Drought-induced Mortality of Trees: Relevance to Scientific Themes

The importance of six scientific themes are all exemplified by this case study on regional-scale drought induced mortality.

1. Regional-scale tree mortality represents one of the most dramatic responses of vegetation to hydrological change (Science Theme Six). The dominant vegetation type at a site, which may have required more than a century to reach its current size and structure distribution, can change largely within a year or so in response to drought (Betancourt et al. 1993; Allen and Breshears 1998, 2004). During the 1950s drought in the Southwestern USA, ponderosa pine (*Pinus ponderosa*), piñon (*Pinus edulis*), and juniper (*Juniperus monosperma*) all exhibited dramatic mortality at the lower end of their distributions. Even in locations where the dominant overstory did not change from one species to another, there was still substantial mortality (Allen and Breshears et al. 2004). Herbaceous cover also exhibited extensive mortality in response to the 1950s drought (Herbal et al.). Hence, both woody and herbaceous

plants can exhibit substantial changes in cover in response to drought. Relationships for predicting the associated mortality thresholds, however, are largely lacking.

2. Drought induced changes in overstory structure have the potential to alter several aspects of the water budget, including the partitioning of evaporation from transpiration (Science Theme One). The near-ground energy budget at a site is tightly tied to the structure of the overstory (Breshears et al. 1997, Martens et al. 2000). Reducing in the amount and height of woody plants comprising the overstory produces substantial increases in near-ground solar radiation (Martens et al. 2000). For example, a reduction in tree cover from 42 to 26% tree cover dramatically alters the distribution of locations receiving a high degree of near-ground solar radiation. Changes in near ground solar radiation can translate into changes in soil temperature and then in the consequent soil evaporation rates (Breshears et al. 1998). Hence, we expect that the ratio of evaporation to transpiration could increase dramatically in response to extensive tree mortality, not only due to the reduction in plant biomass that is taking up water for transpiration, but also due to a fundamental change in the near-ground energy distribution. The relative magnitude of such effects on the evaporation-transpiration partitioning, however, has not been evaluated directly and remains highly uncertain.
3. There are several changes that occur in conjunction with extensive tree mortality that are expected to affect water-nutrient coupling (Science Theme Two). As noted above, the soil energy distribution is changed, and this can also alter rates of biogeochemical processes. In addition, biogeochemical cycling rates in semiarid woodlands are particularly sensitive to available water (Klopatek et al. 1998).

Changes in overstory structure are expected to produce large changes in snowfall interception, which has a large effect on soil water content (Breshears et al. 1997). Hence, the effect of increased water input, which could increase biogeochemical rates, needs to be evaluated concurrently with the effect of increased energy input, which could decrease biogeochemical rates and change their seasonal dynamics.

4. The large changes in the surface energy characteristics described above may have the potential to feedback and alter climate/water/landscape relationships (Science Theme Five). Evidence is emerging that local climate patterns can be sensitive to changes in land cover (Peters et al. in press). This relationship needs to be more fully evaluated in the context of the regional-scale mortality event that is occurring, more of which are expected as climate change progresses.
5. The relationship between changing vegetation cover via mortality and streamflow is an open question. As noted above, effects of vegetation on streamflow have often been over-generalized and need to be considered more systematically (Huxman et al. 2004). Because drought can alter woody canopy overstory and herbaceous understory, potentially shifting runoff and erosion rates, duration, and frequency, there is a need for more explicit evaluation via field experiments and modeling if we are to understand the links between wide spread plant mortality and impacts on streamflow.
6. Similarly, the effects of large changes in vegetation on groundwater recharge in arid and semiarid environments remains highly uncertain (Science Issue Four). Woody plant composition may indeed affect groundwater recharge rates (Walvoord and Phillips, 2004). Hence, if mortality in woody plants results in a substantial reduction

of plant biomass, it is possible that groundwater recharge could change. This too remains an important research challenge.

Case Study 2, Invasion of Nonnative Vegetation Along Riparian Corridors: Relevance to Scientific Themes

The extensive invasion of nonnative vegetation into riparian ecosystems (Tickner et al., 2001) is illustrative of how the six issues identified in this paper affect ecohydrology in arid and semiarid environments. Ecohydrology at the interface between land and surface water is at the heart of the changing character of these ecotones in arid and semiarid regions.

1. Highly manipulated river hydrographs commonly result in highly invaded riparian ecosystems. Flow modifications that reduce or eliminates peak flows associated with snowmelt has negatively impacted the establishment of native cottonwoods (*Populus* spp.) that disperse short-lived seeds and that require disturbed, moist, high-light microhabitats for germination and seedling establishment (Molles et al., 1998). Reduced flood magnitudes also lead to channel narrowing, increased woody vegetation, and enhanced seedling survival (Shafroth et al., 2002). Restoration successes for riparian ecosystems depend on re-establishing hydrologic regimes (Stromberg, 2001). Hydrologic changes to shallow alluvial ground waters along riverine corridors also affect interactions between native and nonnative plant species. Declining water tables adversely affect native willows and cottonwoods (Shafroth et al., 2000) that die back when water tables recede to 3 m, but have little effect on drought-tolerant salt cedar (DiTomaso 1998; Horton et al., 2001a,b).

2. Evapotranspiration (ET) and the relative roles of evaporation (E) and transpiration (T) in riparian forests dominated by native vs. nonnative plants is a topic of great interest both for understanding water budgets (Dahm et al., 2002; Cleverly et al., 2002) and for understanding plant competitive interactions (Horton et al., 2001a,b). Dense, monotypic stands of nonnative riparian plants can utilize significant quantities of water and draw down water tables (Sala et al., 1996). Cleverly et al. (2002) used three-dimensional eddy covariance methodology throughout the growing season to measure annual ET from salt cedar stands. Values up to 122 cm/yr were found in dense stands of salt cedar. Based on their potential threat to riparian hydrology, control measures are being widely instituted throughout the western US to remove nonnative riparian plant species. The effects of these control efforts on ET and the relative rates of E and T before and after control is an ecohydrology question of great theoretical and practical concern.
3. Water and nutrient interactions also are thought to be key factors in the invasiveness of nonnative riparian plant species. Many nonnative plant species that have been successful invaders are nitrophylous (nitrogen-loving). Anthropogenic modification of the global nitrogen cycle has more than doubled plant available nitrogen in the biosphere (Vitousek, 1994) and increases in nitrate, ammonium, and phosphate are known to increase salt cedar growth and establishment (Marler et al., 2001). The effects of nitrogen enrichment in rivers and alluvial ground waters on competitive interactions between native and nonnative plant species is a key unanswered question for ecohydrology.
4. The impact of riparian plant communities on stream and river flow is a long-standing question on which there is little consensus. In particular, the role of nonnative riparian plant communities on river flow in arid and semiarid regions has generated much interest

(e.g. Tickner et al., 2001; Brock, 1994; Robinson, 1958). Will the control of nonnative riparian plants increase stream and river flow? Considerable amounts of restoration money are being allocated for the control on nonnative plants along riverine corridors. The answer to the question of whether these manipulations actually enhance surface flow is a crucial ecohydrology question in arid and semiarid environments.

5. Vegetation actively draws down water tables in riparian zones during the growing season. This impact is accentuated during drought periods and in areas with dense nonnative riparian vegetation (Dahm et al., 2003). Groundwater recharge is a function of the hydraulic conductivity of the interface between surface waters and ground waters and the slope of the water table away from the zone of recharge. Riparian ET draws down the water table and increases the gradient in losing reaches of streams and rivers.
6. Riparian zones with extensive regions of nonnative species have been shown to affect water budgets at regional scales (Dahm et al., 2002) but effects on local meteorological conditions are difficult to assess. A link between changes in localized fluxes and regional weather and climate has yet to be demonstrated, but mesoscale climate modeling has the potential to explore this possibility.

The six identified scientific challenges for ecohydrology in arid and semiarid lands all play a significant role in both the invasiveness of riparian corridors and the impacts these large-scale invasions are having on the landscape. Meeting these challenges will require collaborative interactions between ecologists and hydrologists.

Strategy and Technologies

Our high-level strategy for addressing critical scientific challenges in arid and semiarid ecohydrology is to develop a framework wherein ecologists and hydrologists proactively collaborate. This integration will promote synergistic growth and the development of new perspectives that may reveal novel and more powerful approaches to environmental problem solving.

It is likely that all of the CUAHSI Hydrological Observatories will include ecohydrological research in some form. However, we believe at least one of the CUAHSI Hydrological Observatories should have an explicit focus on ecohydrology, and that an observatory situated in an arid or semiarid setting would be an excellent place to do this (because of the acute sensitivity to ecohydrological processes and strong elevational gradient effects). An arid or semiarid observatory would provide a research infrastructure where ecologists and hydrologists could work together from the experimental design phase through interpretation and modeling. Though this is a simplistic strategy, the marrying of the two disciplines has not yet been done on any significant scale, and thus the full benefit of integrated interdisciplinary research is unrealized.

An arid or semiarid CUAHSI observatory with an explicit focus on ecohydrology is ideal because it enables multi-scale research and would contain the ecotonal and hydrological transition zones necessary to understand coupled water, vegetation, and nutrient processes; and effects of management actions/manipulations. The CUASHI Hydrologic Information System will be essential for data management and dispersal in an ecohydrology observatory. The data collected also will be an important “dry” end member for comparative analyses conducted through the Hydrologic Synthesis Center. Such comparisons will be critical for understanding the extent to which arid/semiarid systems act similarly or differently than their more humid counterparts. The Synthesis Center will also benefit from the envisioned approach of field monitoring and experimental designs that incorporate modeling objectives from the outset.

There are many technological constraints that need to be addressed if we are to effectively monitor and characterize arid and semiarid ecohydrological processes, and some examples are given below. The CUASHI Hydrologic Measurement and Technologies Facility will play a vital role overcoming these constraints. In the end, we foresee all four of the CUAHSI components as essential to achieving our ecohydrology vision.

The technology needed to address the scientific challenges and cross cutting issues discussed earlier are extensive. Here we highlight a few of those:

1. Evaporation and Transpiration: Technologies are needed to monitor evaporation and transpiration fluxes independently. Stable isotope and field-based laser technologies are promising avenues. We also need to decrease errors on eddy covariance measurements so that they are smaller relative to other water balance components. In addition, measurement of ET with eddy covariance in complex terrain is not currently feasible. Thus, we need improved eddy technologies or explore alternative approaches to the complex terrain problem.
2. Measurement and Monitoring of Vegetation: continuous monitoring of plant water potential, sap-flow gages in herbaceous vegetation, large-scale quantification of the seasonal progression of leaf area, and measurement of root distributions and turnover are examples of areas where advances need to be made if we are to understand coupled water/nutrient/vegetation behaviors.

3. Quantification of the Spatial Distribution of Precipitation and Intensity: Improved radar, more extensive rain gauge networks, and improvements in automated monitoring of stemflow and throughfall will significantly impact data interpretation and modeling.
4. Snow & Snowmelt: Snow can be an extremely important component of arid and semiarid hydrology. Technologies that provide improved measures of snowpack and water equivalence at low and high elevations are necessary.
5. Runoff and Streamflow: Automated technologies for measuring runoff at multiple scales and improved technologies for measuring streamflow under ephemeral/changing bedform conditions are necessary for understanding scaling relations and surface flow dynamics.
6. Sediment Transport: The relative importance of transport by water and wind is not well understood, and there are difficulties in quantifying sediment dynamics in general. Improved automated measurements of sediment loss and deposition are necessary for addressing issues related to water quality, geomorphic evolution, and interactions with vegetation.
7. Nutrient Measurements: High frequency, *in situ* monitoring of nutrient concentrations, transformations, and fluxes (e.g., nitrate distributions, trace gas fluxes, and soil respiration) at point and larger scales along with atmospheric inputs will provide time series data that are critical for understanding coupled hydrological/nutrient processes. Less intrusive sampling methodologies also are needed, especially for investigating areas adjacent to plant roots.

8. Geophysics and Remote Sensing: measurement at coherent spatial scales with modeling and field investigations can obviate scaling up or scaling down problems. Development of approaches for collection of quantitatively accurate data on subsurface water content (shallow and deep), and other information (e.g., salinity) over large areas (e.g., watersheds or basins) are key to understanding ecohydrological behaviors at scales relevant to management.
9. Numerical Modeling and Data Assimilation: Integration of data collection efforts at multiple scales through in-situ and remote sensing techniques needs to occur within the context of a physically-based model that best captures current theory on ecohydrological processes. Data collection to support modeling efforts should be an explicit objective of observatory plans from the outset. Spatially-explicit models at high resolution will allow a discretization arid and semi-arid domains into relevant ecosystem communities (e.g. riparian corridor) that have significant controls on land surface-subsurface-vegetation interactions.

Expected Impact

This vision paper has described some of the relevant issues and scientific challenges related to the ecohydrology of arid and semiarid environments. Broadly speaking, current resource management issues in these water-limited environments are already serious, and will become increasingly acute as demands from a rapidly growing populations increase. Our ability to forecast impacts of environmental changes resulting from direct and indirect anthropogenic activities will, in turn, determine how well we as a society can adapt and respond to such changes. Robust predictions and progressive and effective solutions to management problems are most likely to arise from an interdisciplinary ecohydrology approach. Thus, a CUAHSI focus on arid and semiarid ecohydrology can potentially provide substantial benefits from scientific, economic, and quality of life standpoints.

An ecohydrology focus at an arid and/or semiarid observatory will also facilitate the training of a new generation of scientists with essential cross-disciplinary experience. Training of this new generation within an ecohydrological observatory context will foster development of science that is robust, adaptable, and flexible; and capable of addressing current as well as new and as yet unforeseen complex environmental problems. Impacts of an ecohydrology vision will extend beyond CUASHI by providing a prototype infrastructure for observing rapid/pulsed behaviors in water-limited environments that can be linked to other U.S. national and international efforts. For example, an improved understanding of arid and semiarid ecohydrology can provide important complementary information to Ameriflux/LTER/NEON/SAHRA efforts. In short, successful implementation of our vision will have broad social and economic impacts, addressing serious issues related to water supply and quality, ecosystem health and diversity, and the goal of becoming better stewards of sensitive arid and semiarid environments.

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