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Long-term data collection at USDA experimental sites for studies of ecohydrology†

M. Susan Moran,[1]* Debra P. C. Peters,[2] Mitchel P. McClaran,[3] Mary H. Nichols[1] and Mary B. Adams[4]

[1] *USDA ARS Southwest Watershed Research Center, Tucson, AZ, USA*
[2] *USDA ARS Jornada Experimental Range and Jornada Basin LTER Program, Las Cruces, NM, USA*
[3] *School of Natural Resources, University of Arizona, Tucson, AZ, USA*
[4] *USDA FS Timber and Watershed Laboratory, Parsons, WV, USA*

ABSTRACT

The science of ecohydrology is characterized by feedbacks, gradual trends and extreme events that are best revealed with long-term experimental studies of hydrological processes and biological communities. In this review, we identified 81 US Department of Agriculture (USDA) experimental watersheds, forests and ranges with data records of more than 20 years measuring important ecosystem dynamics such as variations in vegetation, precipitation, climate, runoff, water quality and soil moisture. Through a series of examples, we showed how USDA long-term data have been used to understand key ecohydrological issues, including (1) time lag between cause and effects, (2) critical thresholds and cyclic trends, (3) context of rare and extreme events and (4) mechanistic feedbacks for simulation modelling. New analyses of network-wide, long-term data from USDA experimental sites were used to illustrate the potential for multi-year, multi-site ecohydrological research. Three areas of investigation were identified to best exploit the unique spatial distribution and long-term data of USDA experimental sites: convergence, cumulative synthesis and autocorrelation. This review underscored the need for continuous, interdisciplinary data records spanning more than 20 years across a wide range of ecosystems within and outside the conterminous USA to address major crosscutting problems facing ecohydrology. Conversely, the heightened interest in ecohydrology has impacted USDA experimental sites by encouraging *new* long-term data collection efforts and adapting *existing* long-term data collection networks to address new science issues. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS ecohydrology; watersheds; forests; ranges; USDA; long-term

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INTRODUCTION

Ecohydrology is an interdisciplinary science focussed on the influence of hydrological processes on biological communities and the feedbacks from biological communities to the water cycle (modified from Newman *et al.*, 2006). Progress in understanding these linkages between hydrology and ecology are often limited by a lack of long-term, empirical ecohydrological data spanning more than a decade and covering a variety of ecosystems. To address the gradual trends and extreme events that characterize ecohydrological feedbacks, adequate timescales for analysis are especially crucial. In fact, the paucity of long-term measurements of hydrological elements and ecosystem dynamics at multiple scales has been identified as the greatest impediment to ecohydrological studies (Breshears, 2005; Newman *et al.*, 2006; Hannah *et al.*, 2007). The interest in long-term datasets has been intensified by the realization that the space-for-time substitution and plot-based studies, commonly used when long-term data are not available, become more relevant when combined with long-term observations (Lauenroth and Sala, 1992; Wainwright *et al.*, 2000).

The US Department of Agriculture (USDA) initiated a network of over 100 experimental watersheds, forests and ranges over the last century to conduct long-term research in response to widespread land and water quality degradation. These 'outdoor laboratories' were established at the basin scale with a data collection protocol designed to detect ecosystem changes and hydrological processes that operate at time frames ranging from multiple decades to centuries. The USDA experimental sites offer the multi-decadal observations and cross-ecosystem studies identified by Jentsch *et al.* (2007) as an urgent need to advance research on extreme events. The place-based research at USDA experimental sites provides the research infrastructure to facilitate the collaboration between ecologists and hydrologists necessary for ecohydrological studies.

The goal of this review is to show the value of long-term, continuous data for studying ecohydrological processes and dynamics. It will be shown here that critical understanding of rare hydrological and ecological events require data records as long as 100 years, and that key questions regarding ecohydrological thresholds, cyclic trends and time lag require measurement repeat

* Correspondence to: M. Susan Moran, USDA ARS Southwest Watershed Research Center, Tucson, AZ, USA.
E-mail: susan.moran@ars.usda.gov

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frequencies as fine as hourly over durations longer than 20 years. These long-term data must be combined with spatial coverage that encompasses a wide range of ecological and hydrological conditions, including extreme conditions that are not widely represented in the conterminous USA. This review introduces the continuity, variety and availability of long-term data collected at experimental sites established by the USDA within the Agricultural Research Service (ARS) and the US Forest Service (USFS). Through a series of examples, we show how USDA long-term data have been used to understand and predict key ecohydrological dynamics. New analyses of network-wide USDA long-term datasets were used as an example of the studies in ecohydrology that can be conducted with the temporal and spatial data currently available. We conclude by identifying research areas that best utilize USDA long-term datasets to address key problems facing the hybrid discipline of ecohydrology, and conversely, the impact of the heightened interest in ecohydrology on long-term data collection efforts and research being conducted at the USDA experimental sites.

VARIETY, CONTINUITY AND AVAILABILITY OF USDA LONG-TERM DATA

Distinctive features that make long-term data collection at the USDA experimental sites valuable for ecohydrological studies are data variety, continuity—both temporally and spatially—and availability (Figures 1 and 2). The information in Figures 1 and 2 was published by Slaughter and Richardson (2000); Marks (2001); Adams *et al.* (2003, 2004); Gburek *et al.* (2003); Harmel *et al.* (2003); McClaran (2003); Rango *et al.* (2003); Seyfried (2003); Steiner *et al.* (2003); Van Liew *et al.* (2003b); Romkens and Richardson (2004); Sadler *et al.* (2006); Keefer *et al.* (2008) and personal communications with site contacts. For these summaries, a given site was determined to have long-term data if it had at least one dataset that met the following five criteria

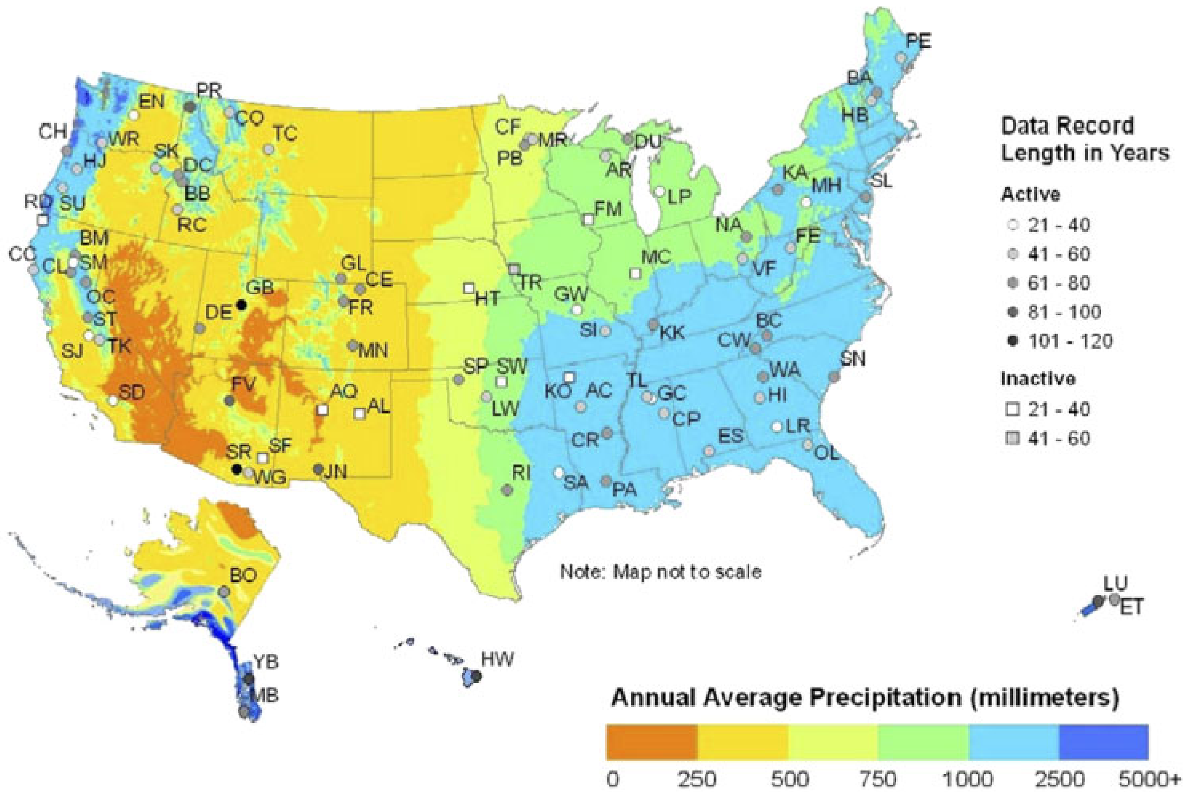
1. Data were collected for 20 years or more at a temporal frequency suitable for monitoring natural processes;
2. The data have sufficient spatial coverage to represent the dynamics of the given watershed, range or forest;
3. The measurement protocol is consistent and documented on the basis of the efforts of a staff dedicated to instrument maintenance, update and calibration;
4. Data are of known quality and available through a permanent, ongoing archive in machine-readable format; and
5. Data collection is associated with a research facility with the mission of conducting studies and publishing results in peer-reviewed literature.

There is inherent value in the sheer length of data collection combined with the spatial coverage of the USA (Figure 1), but even more value is obtained through the broad spectrum of topics addressed by the network of sites (Figure 2). At more than 60 sites, there are decadal records of basin-scale vegetation dynamics. At more than 50 sites, measurements are being made of temporally continuous and spatially extensive meteorological conditions and precipitation events. More than 30 sites support the high-investment, high-maintenance equipment required to make continuous measurements of runoff and sediment yield. Long-term measurements of water quality are being made at dozens of sites. In the past two decades, nearly 20 sites have been instrumented with new sensors to monitor soil moisture at multiple depths and locations to better understand drought, flood, erosion, vegetation and the impacts of climate change. Rodriguez-Iturbe (2000) emphasized the importance of long-term soil moisture measurements and identified the processes where soil moisture is the key link between climate fluctuations and vegetation dynamics. USDA experimental sites offer some of the few records of soil moisture spanning more than a decade. USDA experimental sites also support studies of small and large animals at timescales required to see cyclic dynamics and irreversible changes.

However, this value is diminished when the continuity is interrupted or terminated. Ten of the 81 USDA experimental sites with long-term data are now inactive (Figure 1); sites were defined as inactive if the long-term data collection is not currently ongoing. Data collection at inactive sites was terminated for a variety of reasons, ranging from lack of support to catastrophic natural events. Recent terminations of long-term data collection are often caused by urban development. The Deep Loess Watersheds in Treynor, Iowa, have a 42-year data record that was terminated in 2003 due to plans for a housing development within the monitored watersheds (Hatfield *et al.*, 1999). There are instances when inactive sites were later re-instrumented to initiate research based on analysis of both historic and current measurements. The USDA Entiat Experimental Forest (EEF) in Washington State has a 17-year continuous data record of quality, quantity and timing of streamflow that was terminated in 1977. In 2003, Entiat watersheds were re-instrumented to assess the hydrologic recovery from a severe wildfire that occurred in 1970 (Woodsmith *et al.*, 2004).

Machine-readable, long-term data from USDA experimental sites are generally available on request from the associated research facility. Access ranges from compilation of files on a DVD or ftp site (e.g. data from the Teakettle Experimental Forest) to online data access websites (e.g. Marks, 2001; McClaran *et al.*, 2002; Sadler *et al.*, 2006; Bosch *et al.*, 2007 and Nichols and Anson, 2008). The P^{2}ERLS Project ~~offers a~~ web portal to allow easy access to web pages for research sites within North America and globally. This level of data access is suitable for place-based research that requires a variety of measurements of one or a few locations.

For network-scale research, it is desirable to have thematic subsets of long-term data from many sites available at one online website. The EcoTrends project offers a large collection of long-term ecohydrological data with



Code	Experimental Forest/Range/Watershed	Code	Experimental Forest/Range/Watershed	Code	Experimental Forest/Range/Watershed
AC	Alum Creek EF	GB	Great Basin ER	PE	Penobscot EF
AL	Alamagordo Creek EW	GC	Goodwin Creek EW	PR	Priest River EF
AQ	Albuquerque EW	GL	GLEES	RC	Reynolds Creek EW
AR	Argonne EF	GW	Goodwater Creek EW	RD	Redwood EF
BA	Bartlett EF	HB	Hubbard Brook EF	RI	Riesel EW
BB	Boise Basin EF	HI	Hitchiti EF	SA	Stephen F. Austin
BC	Bent Creek EF	HJ	HJ Andrews EF	SD	San Dimas EF
BM	Blacks Mtn. EF	HT	Hastings	SF	Safford EW
BO	Bonanza Creek EF	HW	Hawaii EF	SI	Sinkin EF
CC	Caspar Creek EF	JN	Jornada ER	SJ	San Joaquin ER
CE	Central Plains ER	KA	Kane EF	SK	Starkey EF&R
CF	CutFoot EF	KK	Kaskaskia EF	SL	Silas Little EF
CH	Cascade Head EF	KO	Koen EF	SM	Swain Mountain
CL	Challenge EF	LP	Lower Peninsula EF	SN	Santee EF
CO	Coram EF	LR	Little River EW	SP	Southern Plains ER
CP	Chipola	LU	Luquillo EF	SR	Santa Rita ER
CR	Crossett EF	LW	Little Washita EW	ST	Stanislaus-Tuolumne EF
CW	Coweeta Hydrologic Lab.	MB	Maybeso EF	SU	South Umpqua EF
DC	Deception Creek EF	MC	Monticello EW	SW	Stillwater Watersheds
DE	Desert ER	MH	Mahantango Creek WE-38 EW	TC	Tenderfoot Creek EF
DU	Dukes EF	MK	McCormick EF	TK	Teakettle EF
EN	Entiat EF	MN	Manitou EF	TL	Tallahatchie EF
ES	Escambia EF	MR	Marcell EF	TR	Deep Loess Research Station EW
ET	Estate Thomas EF	NA	North Appalachian EW	VF	Vinton Furnace EF
FE	Fernow EF	OC	Onion Creek EF	WA	Upper Oconee River Basin EW
FM	Fennimore EW	OL	Olustee EF	WG	Walnut Gulch EW
FR	Fraser EF	PA	Palustris EF	WR	Wind River EF
FV	Fort Valley EF	PB	Pike Bay EF	YB	Young Bay EF

Figure 1. USDA experimental watersheds (EW), forests (EF) and ranges (ER) with long-term data collection (as defined in the text). The data record length was determined for the longest continuous record of measurements available at the site. Active sites have ongoing long-term data collection till date whereas long-term measurements at inactive sites have been discontinued. The precipitation data sources for the background are PRISM Group, Oregon State University http://www.prismclimate.org for conterminous US, USGS 1998 http://agdc.usgs.gov/data/usgs/water for Alaska and the experimental station websites for Hawaii and Puerto Rico.

unique data exploration graphing and synthesis tools (http://www.ecotrends.info), and includes data from 24 of the USDA experimental sites. Rainfall and runoff data for 333 USDA ARS experimental watersheds and sub-watersheds were compiled for downloading as of 1 January, 1991 by the ARS Hydrology and Remote Sensing Laboratory at http://hydrolab.arsusda.gov/wdc/arswater.html. There are plans to make more long-term USDA data available through the ARS STEWARDS (Sustaining the Earth's Watershed, Agricultural Research Data System) website (http://www.ars.usda.gov/is/AR/archive/aug06/data0806.htm) (Steiner *et al*., 2005). Meteorological data from many sites is available through the NOAA Environmental Real-Time Observation Network (http://www.isos.

noaa.gov/) and the NOAA National Climate Data Center (http://www.ncdc.noaa.gov/oa/ncdc.html).

The USDA experimental sites are also part of the growing network-within-a-network concept (Holsinger *et al.*, 2003) that is designed to coordinate long-term data collection across all networks to address more science issues across larger spatial scales (CUAHSI HIS Committee, 2002; Betancourt and Schwartz, 2005; Lugo *et al.*, 2006 and Peters *et al.*, 2008). As part of this concept, the existing federal experimental networks have coordinated with other appropriate observation networks (Band *et al.*, 2003); initiated joint efforts (Ryan, 2003); and developed new multi-agency programs (Weltz and Bucks, 2003). The LTER program (Hobbie *et al.*, 2003) recognized the value of USDA long-term data collections by locating 8 of the 26 LTER sites with existing USDA experimental sites (Figure 3; see Table I for acronym definitions and network information). On the basis of long-term hydrologic, climatic and image data, the USDA ARS Walnut Gulch Experimental Watershed (WGEW) was chosen as 1 of the 15 core sites worldwide by the International Community Earth Observing System (EOS) for satellite product validation and calibration.

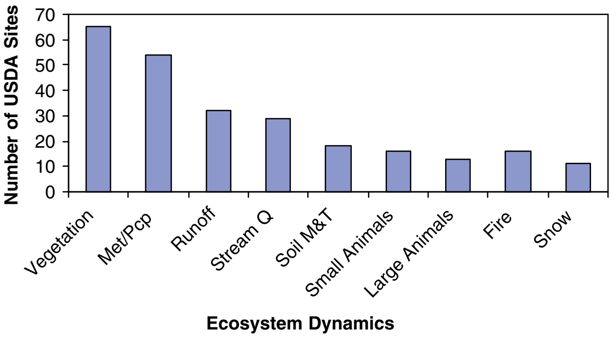


Figure 2. The number of USDA Experimental Watersheds, Forests and Ranges (identified in Figure 1) collecting ongoing data on hydrological and ecological dynamics, where *vegetation* refers to measurements of vegetation characteristics; *met/pcp* refers to meteorological and/or precipitation data; *runoff* is generally measured with weirs and flumes; *stream Q* refers to measurements of stream water quality and quantity, including sediment; *soil M&T* refers to measurements of soil moisture and/or temperature; *small animals* refers to records related to insects, small animals, birds and fish; *large animals* refers to records related to grazing; *fire* refers to a record of fire-related information; *snow* refers to a record of snow-related information.

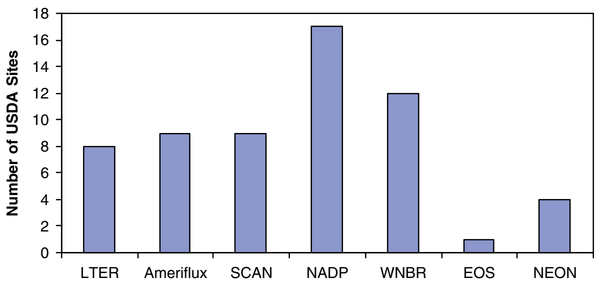


Figure 3. The number of USDA experimental watersheds, forests and ranges (identified in Figure 1) included in the LTER, Ameriflux, SCAN, NADP, WNBR, EOS and proposed NEON networks (see Table I for acronyms and network information).

Four of the proposed 20 core National Ecological Observatory Network (NEON) sites are located with USDA experimental sites that offer long-term data, and several more are being considered. Similarly, USDA experimental sites with long-term data collections are part of the Ameriflux program, the Natural Resources Conservation Service (NRCS) SCAN program, the National Atmospheric Deposition Program (NADP) network, and the UN World Network of Biosphere Reserves. As such, USDA experimental sites that are part of the LTER, Ameriflux, SCAN and NADP networks have made some of their data available through those network websites (Table I).

STUDIES OF ECOHYDROLOGY USING USDA LONG-TERM DATA

Recent reviews of ecohydrology have identified the major scientific issues in ecohydrological research that are best revealed with long-term data (Rodriguez-Iturbe, 2000; Breshears, 2005, 2006; Newman *et al.*, 2006; Hannah *et al.*, 2007; Jentsch *et al.*, 2007; Turnbull *et al.*, 2008). These issues tend to fall into four categories: (1) understanding time lag between cause and effect, (2) identifying critical thresholds and cyclic trends, (3) giving context to rare or extreme events and (4) defining mechanistic feedbacks for simulation modelling. The following sub-sections provide examples of research studies using data collected at USDA experimental sites that have improved understanding and prediction of hydrologic mechanisms that underlie ecologic patterns and processes and ecosystem changes that impact hydrologic function (summarized in Table II).

Time lag between cause and effect

For some process scales, long-term data are necessary to identify the relations between variables with a distinctive time lag. This is particularly true of changes in land use and land cover associated with remediation efforts which, by nature, have an identifiable cause and desired effect. Numerous remediation approaches have been attempted over the past 100 years at USDA experimental sites to limit shrub encroachment and non-native species invasion, minimize soil erosion, protect animal populations and their habitat and generally maintain natural vegetation-soil-animal processes. An example of the time lag associated with remediation was reported for the reclamation dikes constructed to pond runoff water to a depth of several centimetres during rain events at the USDA ARS Jornada Experimental Range (JER) in the Chihuahuan Desert of southern New Mexico. From 1975 to 1978, treatments to establish native and introduced species on the barren areas above the dikes were unsuccessful and the entire experiment was abandoned in 1980 because of the lack of plant establishment and the costs of maintaining the dikes. In 1997, perennial plant establishment associated with the dikes was clearly visible from aerial photographs (Rango *et al.*, 2002) and

Table I. Long-term data collection networks co-located and/or co-operating with USDA experimental watersheds, forests and ranges.

Program	Mission	Sites	Citation and/or website
NSF Long Term Ecological Research (LTER) network, established 1980	To understand long-term patterns and processes of ecological systems at multiple spatial scales	26 programs in a wide variety of habitats	Hobbie *et al*., 2003; http://www.lternet.edu/
Ameriflux network, established 1996	Network objective: To provide continuous observations of ecosystem level exchanges of CO_2, water, energy and momentum spanning diurnal, synoptic, seasonal and interannual time scales	103 sites in North America, Central America and South America; including 87 sites in the USA	Wofsy and Hollinger, 1998; Hargrove *et al*., 2003 http://public.ornl.gov/ameriflux/
USDA Natural Resources Conservation Service (NRCS) Soil Climate Analysis Network (SCAN), established 1991	To (1) integrate information from existing soil–climate data networks and (2) establish new data collection points through partnerships with federal, state, local and tribal entities	The current SCAN network includes 57 remote sites in 33 states and Puerto Rico	Schaefer *et al*., 2007 http://www.wcc.nrcs.usda.gov/scan/
National Atmospheric Deposition Program (NADP), established 1978	To collect data on the chemistry of precipitation for monitoring of geographical and temporal long-term trends	Over 250 sites spanning the continental USA, Alaska, Puerto Rico and the Virgin Islands	http://nadp.sws.uiuc.edu/
United Nations (UN) Man and the Biosphere (MAB) Programme World Network of Biosphere Reserves (WNBR), proposed in 1974	For knowledge-sharing and exchange of experience, research and monitoring, education and training and testing of participatory decision-making, thereby contributing to the emergence of 'quality economies' and to conflict prevention	507 biosphere reserves in 102 countries	http://www.unesco.org/mab/mabProg.shtml
NASA Earth Observing System (EOS) Program, the first mission launched in 1997, the latest launched in 2006 and more planned for this decade	To provide systematic, continuous global observations of the land surface, biosphere, solid Earth, atmosphere and oceans from low Earth orbit for a minimum of 15 years	25 missions and programs (http://eospso.gsfc.nasa.gov/eos_homepage/mission_profiles/index.php) with a series of satellites, a science component and a data system	http://eospso.gsfc.nasa.gov/

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Table I. (*Continued*).

Program	Mission	Sites	Citation and/or website
NSF National Ecological Observatory Network (NEON), proposed in 2002	To establish and sustain the scientific infrastructure and develop the intellectual capital needed to address critical questions about changes in ecological systems and to evaluate the impacts of those changes	20 core observatory sites with satellite sites are proposed for the USA	www.neoninc.org
CUASHI Hydrologic Observatory Network, funded in 2001 for a phased implementation	To encompass a set of regional watersheds, with a research infrastructure to provide spatially and temporally coordinated interdisciplinary datasets resulting from hydrological monitoring, experimentation and characterization	A set of sites around the country are being considered for the implementation phase	CUAHSI HIS Committee, 2002; http://www.cuahsi.org
NSF Collaborative large-scale engineering analysis network for environmental research (CLEANER), proposed in 2005	To formulate and develop engineering and policy options for the restoration and protection of environmental resources	The backbone of CLEANER will be a series of well-instrumented Environmental Field Facilities (EFFs) that represent either distinctive stressed environments or environments that are representative of a common set of conditions and/or stressors	http://www.nsf.gov/pubs/2005/nsf05549/nsf05549.htm
USA National Phenology Network (USA-NPN)	To facilitate collection and dissemination of phenological data to support global change research	Not yet determined, with possible pilot studies at NEON sites and initial observatories established alongside data collection efforts of existing environmental networks	Betancourt and Schwartz, 2005 http://www.usanpn.org/

Table II. Studies cited in this review using multi-decadal, long-term data from USDA experimental watersheds, forests and ranges to address ecohydrological issues.

Research issue	Data	Citation
Time lag between cause and effect		
Response to grassland management	Vegetation measurements 1975 till date; aerial photos 1984 till date	Walton *et al*., 2001; Rango *et al*., 2002, 2006
Effect of stream rehabilitation	18 years of hydrologic measurements	Shields *et al*., 1994, 1995a,b, 1998a,b, 2007
Interactions between land use, climate and management	66 years of rainfall and runoff data	Van Liew *et al*., 2003a; Steiner *et al*., 2008
Critical thresholds and cyclic dynamics		
Non-linear processes of desertification	Field surveys 1915 and 1929; B and W and colour photos 1948 and 1986; satellite imagery 2003	Peters *et al*., 2004
Mesquite shrub encroachment	Aerial photos and satellite images 1936–1996	Goslee *et al*., 2003
Impact of precipitation	Vegetation measurements 1900–1979	Gibbens *et al*., 2005
pattern on perennial	Vegetation measurements 1969–2005	King *et al*., 2008
grass cover	Vegetation measurements 1957–1966	Cable, 1975
Effect of shrub management	Replicate vegetation measurements and aerial photography over 65 years	Rango *et al*., 2005
Burroweed shrub encroachment	100-year record of vegetation measurements	McClaran, 2003
Interactions between land use, rainfall and runoff	45 years of rainfall and runoff measurements	Endale *et al*., 2006
Context of extreme and rare events		
Erosion prediction	Near-30-year records of precipitation and runoff	Edwards and Owens, 1991; Baffaut *et al*., 1996, 1998
Impact of forest clearcutting on hydrology	30–50 years of hydrologic measurements	Hornbeck *et al*., 1993; Swank *et al*., 2001; Adams *et al*., 2003
Hydrologic response to wildfire	18-year record of runoff, vegetation and climate	Woodsmith *et al*., 2004
Land surface simulation modelling		
Rangeland production and utilization modelling	23-year record of vegetation response; 11-year record of soil water content; 15-year record of rainfall, runoff and sediment yield	Springer *et al*., 1984; Wilcox *et al*., 1989; Pierson *et al*., 2001
Soil heat and water modelling	Multi-year frost depths, snow depths and soil temperature data; multi-year, multi-location flood, streamflow and runoff data	Flerchinger and Hanson, 1989; Flerchinger, 1991; Arnold *et al*., 2003
Plant-based gap dynamics modelling	Multi-decadal records of vegetation species and biomass, soil water and nutrients and climate data	Peters, 2002

it was reported that significant rainfall events producing surface runoff were necessary to achieve a positive vegetation response (Walton *et al*., 2001). Rango *et al*. (2006) concluded that remediation efforts were effective but the delayed response to management was on the order of years or decades depending on the precipitation pattern. Similarly, Simanton *et al*. (1978a) reported that the time lag of treatment effectiveness for rangeland renovation was more than 5 years at the WGEW in southeastern Arizona.

Similar time lag have been reported for the effect of stream rehabilitation on biotic systems. A series of studies using short-term ecological experiments (1–11 years) in the context of long-term hydrologic data collection (18 years) were conducted to study the impact of physical habitat rehabilitation (adding stone structures and woody riparian vegetation) on fish community structure and fish habitat at USDA Goodwin Creek Experimental Watershed in Mississippi. Basic findings were that stream rehabilitation increased pool habitat availability but that fish community structure was impacted by both the stream degradation and subsequent rehabilitation (Shields *et al*., 1994, 1995b, 1998a,b, 2007). These studies took advantage of the long-term hydrologic data collection for 8 years before rehabilitation and 10 years after, for a total study period of up to 18 years (Shields *et al*., 1995a, 2007).

The long-term data collection and research infrastructure at USDA experimental sites has been recognized as an ideal venue to assess conservation effects. Steiner *et al*. (2008) utilized an interdisciplinary dataset collected from 1940 to 2005 to study the interactions of variable climate, land use and management at the USDA Little Washita Experimental Watershed in Oklahoma. They reported that flood retarding impounds reduced peak flows by 39% for a 5-year return storm and by 483% for a 10-year storm (Van Liew *et al.*, 2003a).

Critical thresholds and cyclic dynamics

Long-term data are essential for characterizing temporal dynamics of ecohydrological processes and determining when critical ecosystem thresholds are imminent (Rial *et al.*, 2004). An example is the desertification dynamics associated with the transition from black grama grasslands to mesquite shrublands at JER. Peters *et al.* (2004) identified distinct, non-linear processes of desertification, which had been missed at finer timescales. At the most advanced stage of the system, erosion processes dominated the system and livestock management (designed to improve plant competition and seed availability) had little impact on the rate of desertification.

Thresholds often only become apparent when viewed in the context of long-term trends. At JER, Goslee *et al.* (2003) found that when shrub patches reached 2 m diameter they were highly persistent, and this basic threshold was consistent even through the historically severe drought in the 1950s. Such descriptions of ecosystem thresholds (e.g. Gibbens *et al.*, 2005; Rango *et al.*, 2005) would not have been possible without measurements over a long span of time (in this case, over 100 years) of data. This recognition of threshold-based variability and recovery, particularly during drought periods, has helped to distinguish the contributions from soil, management and climate on ecosystem dynamics.

Long-term datasets have been used to correct misconceptions based on shorter windows of data and identify the cyclic nature of some ecohydrological dynamics. For example, the rapid increase of non-palatable burroweed in native grasslands in the southwest USA was met with great anxiety by range managers in the 1930s, and management treatments such as livestock grazing exclusion and fire were initiated at great expense to ranchers. On the basis of a 50-year record of systematic vegetation measured every 3–7 years at Santa Rita Experimental Range in Arizona (SRER), McClaran (2003) identified four separate cycles of increasing and declining burroweed abundance (Figure 4). The cycles of burroweed appeared to be more closely related to winter precipitation patterns and inherent plant longevity than to land management activities. If the same analysis had been made at a coarser temporal frequency (e.g. 10-year repeat measurements), the cyclic nature would have been overlooked and the effects of burroweed management would be less conclusive. Similarly, black grama cover in an area with periodic creosotebush removal and exclusion of cattle and lagomorphs required >50 years before recovery was observed (Havstad *et al.*, 1999).

Thresholds are often found through studies of long-term data that are designed to identify the hydrologic process that dominates the biological response. There are many examples of the use of long-term data from USDA experimental sites in this way. Multi-year studies of nutrient losses from grassland and shrubland habitats at JER determined that loss of soil nutrients does not account for depletion of soil fertility associated with desertification (Schlesinger *et al.*, 2000). More than a decade of measurements (1957–1966) at SRER were used to determine that the influence of previous summer rainfall did not have a direct effect on seasonal grass production, but rather, the rainfall in the month of August was most important (Cable, 1975). These results were supported with a near-40-year record (1969–2005) of precipitation and vegetation cover at WGEW (King *et al.*, 2008). Cable (1977) conducted another study of the seasonal use of soil water by mesquite trees and presented the results in the context of a 51-year record of precipitation measurements. Records of the distribution of the non-native grass Lehmann lovegrass from 1930 till date showed that the precipitation and temperature regimes were the most important variables influencing accurate simulation of the spread of Lehmann lovegrass across the southwest USA (Schussman *et al.*, 2006). Endale *et al.* (2006) used data from 45 years

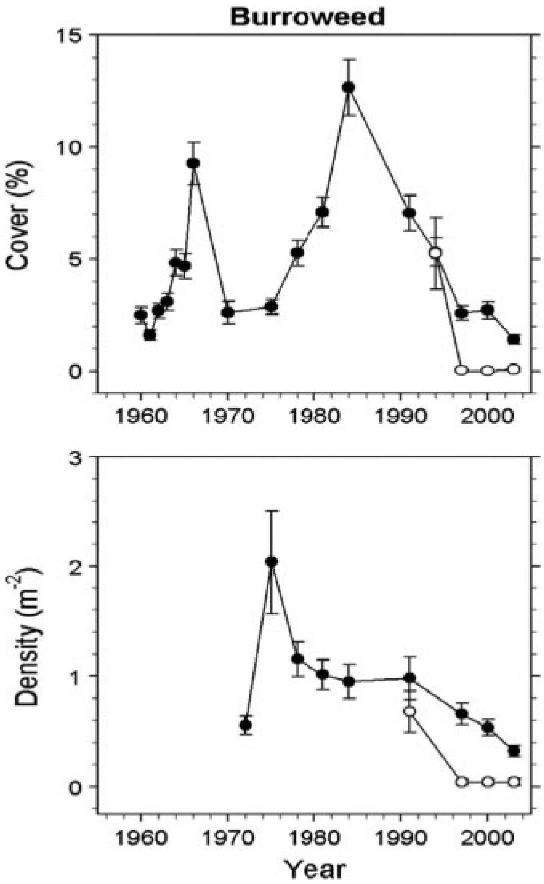

Figure 4. Burroweed (*Isocoma tenuisecta* Greene) cover and density on 71 permanent transects, between 950 and 1250 m elevation, 1960–2003 on the Santa Rita Experimental Range, Arizona. No mesquite or burroweed removal treatments were applied to these transects. Prior to 1991, solid circles represent all 71 transects; after 1991, open circles represent 11 burned in 1994, and solid circles were the 60 unburned transects. Vertical lines represent one ± standard error of the mean. From McClaran, 2003.

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of monthly rainfall and runoff to determine how land use and rainfall variability influenced runoff at the USDA Upper Oconee River Basin in Georgia, finding that row cropping produced the largest runoff amount and Kudzu (*Pueraria lobata*) almost eliminated summer runoff. With a record of brush-to-grass conversion from 1955 to 1976 at WGEW, Simanton *et al.* (1978b) studied the effect of watershed conversion on hydrology and erosion and reported that runoff was a function of the stage of the conversion and the precipitation pattern after the conversion. At JER, Gibbens and Beck (1988) analysed 64 years (from 1915 to 1979) of vegetation quadrat records and reported that the drought years had a tremendous influence on perennial grass basal area. Furthermore, black grama cover was related to different factors prior to the drought (grazing, distance to shrublands) compared to important factors during the drought (soil clay content). The common conclusion of all these studies was that many years of observations are needed to accurately describe the hydrologic effects on vegetation and understand the real and potential thresholds and cyclic patterns determining ecosystem productivity.

Context of rare and extreme events

Extreme events. Studies of long-term, spatially distributed hydrologic measurements have offered a context for the impact of extreme precipitation events in semi-arid regions. The 50-year hydrologic measurements from 11 large flumes, 10 instrumented stock ponds and 88 rain gages at WGEW have been extremely valuable for understanding extreme events in arid-land hydrology. The runoff information from5 small WGEW watersheds over 17 years was combined with gage information for other watersheds in the region to determine the flood frequency and to determine the sizes of 2-, 10- and 100-year floods for ungaged watersheds in the region (Boughton and Renard, 1984). This particular aspect of long-term data is also illustrated by the ironic situation associated with flume construction at WGEW. In 1954, 5 runoff-measuring flumes with capacities ranging from 1500 to 8000 cfs (43–225 cm) were constructed to measure long-term runoff. Within a month, a sequence of large storms occurred at WGEW with runoff rates greater than 8000 cfs such that, by the end of the season, only 1 of the 5 flumes remained operational (Renard *et al.*, 2008). Based on a measured flow of 15 000 cfs in 1957, the flumes were redesigned to measure rates up to 22 000 cfs and have been in continuous operation since 1958.

Analysis of rainfall and runoff measurements over a 30-year period is commonly considered to be statistically representative of the general population; the 30-year time window is the standard unit used in climatology research. However, Baffaut *et al.* (1996) found that 30 years were not enough to obtain stable predictions of the average annual soil loss. For six locations across the USA, the minimum simulation period varied between 50 and 100 years and even longer when significant erosion does not happen every year, such as for dry climates. Based on data from the US National Repository of Soil Loss Data at the USDA ARS National Soil Erosion Research Laboratory in West Lafayette, IN, Baffaut *et al.* (1998) found that (in some cases) 36% of the total soil loss was due to storms that occurred only once every 5 years. Stated differently, it was necessary to include events with a 20-year return period to obtain 90% of the total soil loss; a monitoring period of at least 40 years was therefore necessary to estimate the long-term soil loss at one location. Similarly, based on a 28-year dataset of runoff and erosion at the USDA North Appalachian Experimental Watershed in Coshocton, Ohio, Edwards and Owens (1991) found that one storm caused more than half of the long-term measured erosion. For a 60-year record of tillage effects on erosion in plots at Kingdom City, Missouri, one rainfall event in a 12-year study accounted for 41, 40, 38 and 25% of the total soil loss for conventional corn, conventional soybean, no-till corn and no-till soybean, respectively (Ghidey and Alberts, 1998).

Rare events. Studies of the impact of rare disturbances, such as clearcutting and fire, are only possible because a long-term, historic dataset was collected prior to an abrupt change. An example of such a research opportunity was a study of commercial clearcut logging in 1975 at the USDA USFS Coweeta Hydrologic Laboratory (CHL) in North Carolina. Using long-term hydrologic measurements and logging records from 1935 till date, Swank *et al.* (2001) found that even 15 years after the disturbance, cumulative increases in sediment yield were observed downstream with continuing impact on the invertebrate community structure and productivity (Figure 5). The important impact of logging roads on increases in sediment yield identified by Swank *et al.* was supported by a study of 50 years of stream gage records in the Fernow Experimental Forest (Adams *et al.*, 2003). The impact of clearcutting on water yield was summarized for 11 catchments in USDA experimental sites in the northeastern USA over a period of 30–40 years (Hornbeck *et al.*, 1993). They identified a complex interaction between the water yield response and the configuration and timing of the cutting, the precipitation pattern and post-treatment species composition. They credited this better understanding of the impact of forest treatments on the hydrological cycle to the 'continuing commitment to long-term research' at these USDA experimental forests.

The EEF in Washington State has been the site for numerous studies of hydrologic response to wildfire, owing to a severe wildfire during the summer of 1970, following 10 years of stream gaging as part of a controlled land use experiment. Data collection continued after the fire through 1977. Woodsmith *et al.* (2004) reported that effects of the 1970 fire included greater snow accumulation, earlier initiation of snowmelt runoff at lower mean air temperatures, more rapid melt, increased soil moisture and sharply increased runoff. This was a classic example of the role of USDA experimental

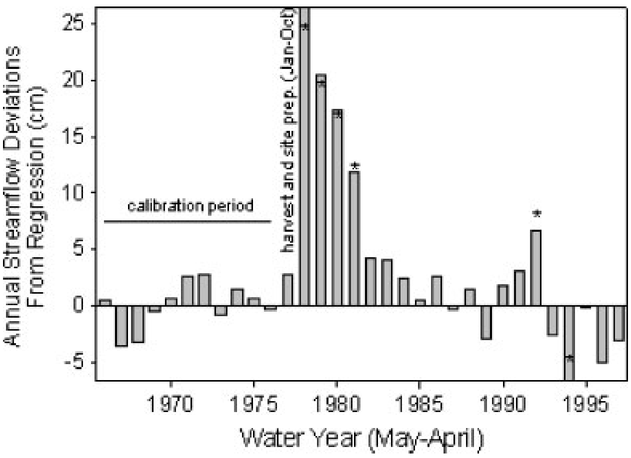

Figure 5. Annual changes in watershed streamflow prior to and following clearcutting and commercial logging, Coweeta Hydrologic Laboratory, Otto, NC, 1967–1995 (* denotes significant change, $P < 0.05$). From Swank *et al.* (2001).

sites to chronicle the biotic and abiotic feedbacks from natural disturbances, such as fires, over extended periods before and after the event.

Common events. Long-term data have the unique role of discriminating a common event from an extreme or rare event. In plot-scale studies utilizing rainfall simulators or rain-out shelters with irrigation systems, it is often necessary to design experiments that capture 'reality' (Wainwright *et al.*, 2000). Long-term measurements of rainfall at JER and SRER have been used to put rainfall simulation and manipulation experiments into context (Neave and Abrahams, 2001; Fravolini *et al.*, 2005). In a discussion of rainfall simulation experiments at WGEW, Wainwright *et al.* (2000) discussed the experimental design of plot-scale studies and concluded rightly that 'plot-scale studies play an important part in improving our understanding of complex, open systems, but need to be integrated with other approaches such as the monitoring of natural events and computer modelling so that mutually consistent understanding of complex ecohydrological systems can be achieved'.

The same can be said of 'short-term' studies, which are conducted under naturally occurring conditions but are sustained for only 1–2 years. Results are often presented by putting the short-term precipitation pattern experienced during the study within the context of multi-decadal rainfall patterns. Partitioning of evapotranspiration (ET) into plant transpiration and soil evaporation at WGEW during 2003 was interpreted in light of a 10-year record of ET and a 30-year record of precipitation (Scott *et al.*, 2006). In a classic ecohydrology study of how mortality of hemlock trees impacts hydrologic processes, results from a 2-year study (2004–2005) were given the perspective of the nearly 100-year record of precipitation and streamflow at CHL (Ford and Vose, 2007). Pezeshki and Shields (2006) interpreted the survival of black willow cuttings planted for riparian zone restoration based on 30 years (1960–1990) of channelization history and a comparison of annual precipitation with the 30-year average to identify the primary factors that controlled survival over periods longer than 2–3 years.

Mechanistic feedbacks for simulation modelling

USDA long-term data from experimental watersheds have played a key role in development and parameterization of models (Renard *et al.* (2008)). Pierson *et al.* (2001) used long-term, small-scale variations in surface runoff and erosion at USDA ARS Reynolds Creek Experimental Watershed (RCEW) to parameterize the Simulation of Production and Utilization on Rangeland (SPUR, 2000) model, then validated model results with larger-scale runoff and erosion yields. Springer *et al.* (1984) used RCEW snow data in the development and initial testing of the SPUR model, and Wilcox *et al.* (1989) used RCEW snow data to verify the ability of the SPUR model to predict snowmelt runoff. Flerchinger and Hanson (1989) and Flerchinger (1991) validated the soil heat and water (SHAW) model with long-term measurements of frost depth, soil temperature, snow depth and soil moisture at RCEW (Seyfried *et al.*, 2001). For the KINEROS model, a period of record with homogeneous runoff conditions (1973–1980) from WGEW was selected to obtain 10 calibration and 30 verification rainfall–runoff events with runoff volumes greater than 0·3 mm (Goodrich, 1990). The Soil and Water Assessment Tool (SWAT) has been refined and validated using (1) flood control structures in the USDA ARS Little Washita Experimental Watershed, Oklahoma; (2) riparian zones in the USDA ARS Little River Watershed, Georgia; and (3) phosphorus runoff and surface cracking of clay soils in the USDA ARS Riesel Experimental Watershed, Texas (Arnold *et al.*, 2003). A mixed lifeform individual plant-based gap dynamics model (ECOTONE) was parameterized and tested using long-term measurements of vegetation species and biomass, soil water and nutrients and climate data from JER and the Sevilleta LTER sites (Peters, 2002). In recent ecohydrology studies, these and other models have been used to better understand the relative importance of biotic versus abiotic factors in vegetation dynamics, and scientists have again turned to the long-term datasets from USDA experimental sites for validation (Gao and Reynolds, 2003; Mueller *et al.*, 2007).

LONG-TERM DATA AND SPATIAL COVERAGE—AN EXAMPLE

Long-term data are key to understanding the influence of spatial complexity and scale on ecohydrological processes (Newman *et al.*, 2006). Yet, it is the rare ecohydrology study that combines both long-term data and broad spatial coverage to understand ecological and hydrological feedbacks. A simple analysis was conducted here based on long-term data available at the USDA websites to demonstrate why both depth and breadth are important for drawing proper conclusions in ecohydrology, and at the same time, to show the ease of accessing

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such data for multi-site analysis. This analysis was not intended to be a complete study, but rather, an example of how USDA long-term data can be compiled and applied to critical ecohydrological questions at the national scale.

Many studies are based on the common assumption that the variability, expressed as the coefficient of variation (CV) of mean annual precipitation, is negatively correlated with the magnitude of mean annual precipitation (Hershfield, 1962; McMahon and Wagner, 1985; Hidy and Klieforth, 1990). A 50-year data record (1950–2000) of precipitation from 13 USDA experimental sites downloaded from the EcoTrends website (http://www.ecotrends.info) supports the hypothesis that drier sites have a higher CV, with a statistically significant negative linear correlation ($r^2 = 0{\cdot}52$, $P < 0{\cdot}01$) between mean annual precipitation and CV (Figure 6(a)). For the same 13 sites, with only a 10-year data record from 1990 to 2000, the correlation was weak ($r^2 = 0{\cdot}13$), apparently linear and not statistically significant (Figure 6(b)). This result was largely due to several years of above-average rainfall, which decreased the CV at the driest sites and increased CV at the wettest sites. When using a 10-year data record from 1950 to 1960, the relation was highly non-linear ($r^2 = 0{\cdot}52$, $P < 0{\cdot}01$), with extremely high CV values for drier sites (Figure 6(c)). This was due to a period of severe drought conditions across the USA in the 1950s, expressing itself in extraordinarily low precipitation and high CV values ($>0{\cdot}4$) for many semi-arid locations.

Only four USDA sites in the EcoTrends dataset had 100-year records of precipitation from 1900 to 2000; and three of these were in semi-arid regions of the western USA. As a result, though a strong linear relation was determined ($r^2 = 0{\cdot}81$, $P < 0{\cdot}01$), it could not be extrapolated to wet sites with precipitation greater than 1500 mm (Figure 7(a)). The 50-year record of precipitation from 1950 to 2000, based on 13 sites in EcoTrends (Figure 6(a)), supported the conclusion that the relation might be linear and could be extended to mesic sites with mean annual precipitation on the order of 2500 mm. When focusing only on the 10-year data record from 1990 to 2000, the number of sites in EcoTrends increased from 13 to 20, adding two sites outside the conterminous USA in Alaska and Puerto Rico. Similar to results presented in Figure 6(b), there was no significant relation between CV and mean annual precipitation for sites in the conterminous USA during that decade (Figure 7(b)). However, extending the analysis to the Bonanza Creek experimental forest in Alaska (with 10-year average annual rainfall = 160 mm) and the Luquillo experimental forest in Puerto Rico (with 10-year average annual rainfall = 3260 mm) provided more information about precipitation dynamics. That is, the CV for Bonanza Creek was nearly four times greater than the CV of semi-arid and mesic locations during this decade. Further, the CV for Luquillo (a site characterized by hurricane activity) was higher than that of any semi-arid or mesic location during this decade. It is clear that if the analysis was done with only the sites of lowest (Bonanza) and highest (Luquillo) precipitation, the result would be a linear relation that did not represent the trend for any of the sites in the conterminous USA.

The next analysis was extended to explore the feedback of inter-annual precipitation variability on runoff

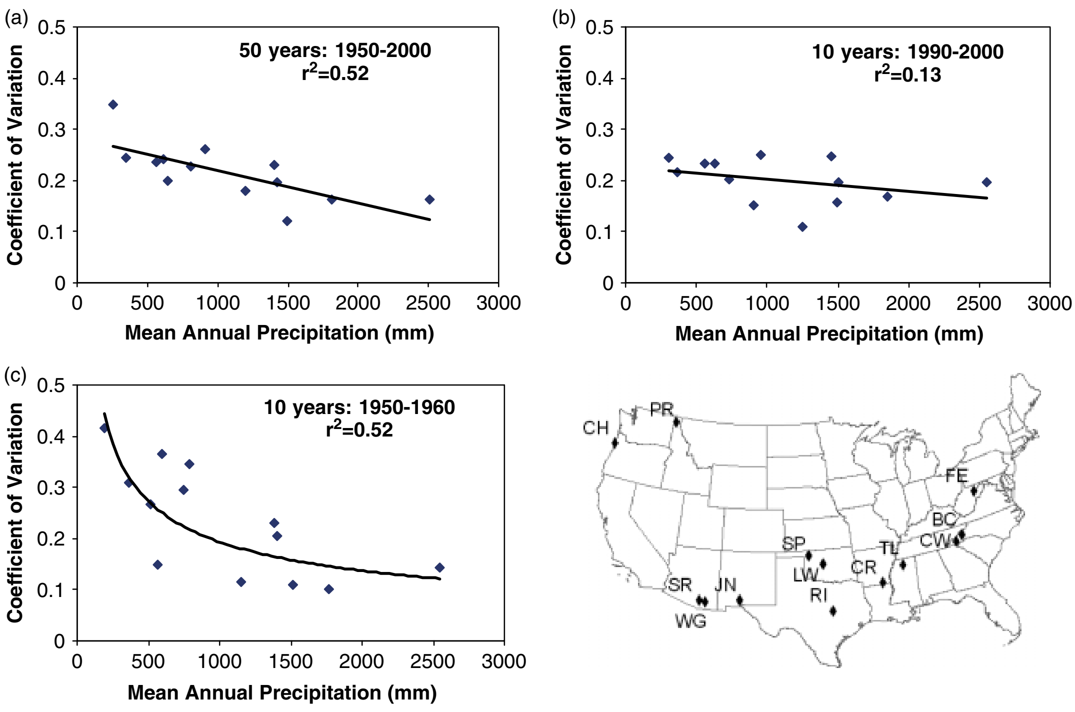

Figure 6. Correlation between the variability (expressed as the coefficient of variation) of mean annual precipitation and the magnitude of mean annual precipitation for 13 USDA experimental sites (locations shown on inset map) with data in the EcoTrends project (http://www.ecotrends.info) for (a) a 50-year data record from 1950 to 2000, (b) a decade (1990–2000) characterized by several years of above-average rainfall and (c) a decade (1950–1960) characterized by severe drought conditions.

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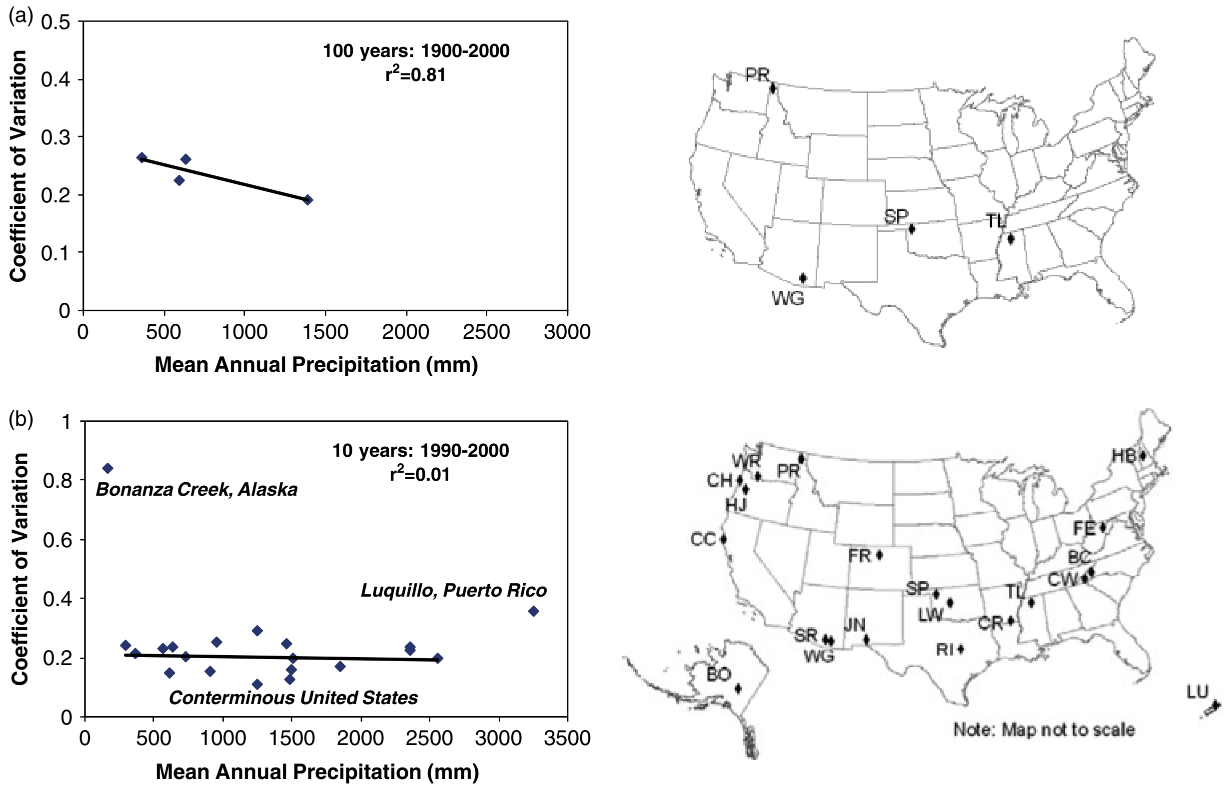

Figure 7. Correlation between the variability (expressed as the coefficient of variation) of mean annual precipitation and the magnitude of mean annual precipitation for (a) 4 USDA sites (locations on map to right) with data in the EcoTrends Project over the 100-year period from 1900 to 2000 and (b) 20 USDA sites (locations on map to right) with data in EcoTrends over the 10-year period from 1990 to 2000, including 2 sites outside the conterminous USA in Alaska and Puerto Rico. The regression line was fit using only the data for the 18 sites within the conterminous USA. Note differences in y-axes scales.

with the 20-year record (1982–2002) of runoff at a semi-arid (WGEW) and mesic site Goodwin Creek EW (GCEW). WGEW is normally dry with occasional runoff in response to high-intensity precipitation events; in contrast, GCEW sustains baseflow that accounts for approximately 17% of the runoff. Both datasets indicate year-to-year variability in annual runoff volume (Figure 8); however, the variability in the WGEW data was substantial with the standard deviation in annual runoff greater than the mean (CV = 1·2). The analysis at these two sites implies that the variation in precipitation (CV ranging from 0·20 to 0·24) results in a considerably higher variation in runoff (CV ranging from 0·5 to 1·2). Further interpretation of these results must take into account the fact that runoff characteristics are a function of rainfall characteristics in combination with watershed physical features such as soil properties, topography and vegetation. Ultimately, the runoff variability will have a feedback on the efficiency of movement of sediment and nutrients through the watershed. The basic data analyses presented here illustrate the importance of both data continuity and spatial coverage for understanding feedbacks and trends in hydrologic patterns. This simple exercise of compiling network-wide, long-term data to investigate commonly held assumptions about the variability and feedback of annual precipitation (Figures 6, 7 and 8) required the following:

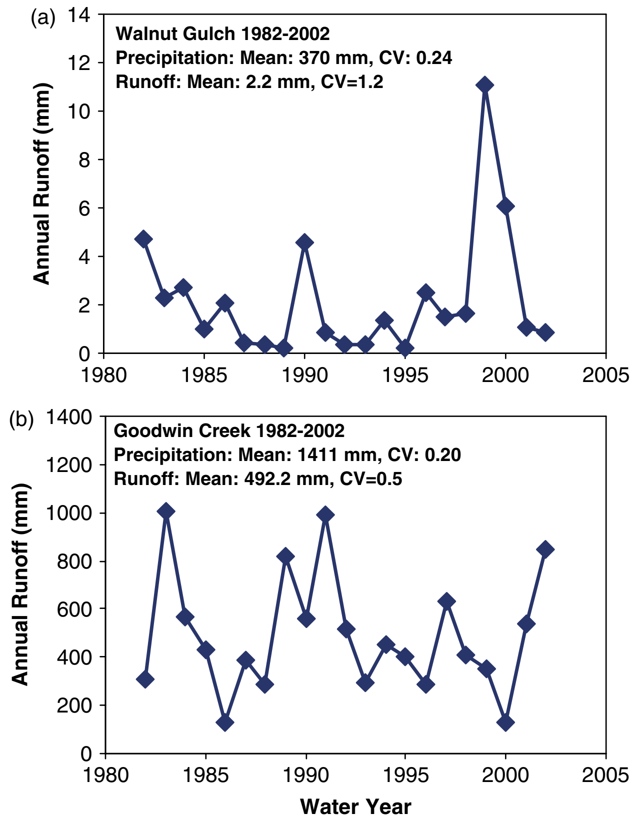

Figure 8. Annual runoff from 1982 to 2002 at WGEW and GCEW. Note differences in y-axes scales.

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1. Continuous measurements at a temporal frequency fine enough, and a duration long enough to capture the hydrological dynamics;
2. Spatial coverage including more than just the extreme hydrological conditions, but rather, a set of sites representing a continuum of conditions from hot to cold and wet to dry; and
3. Coincident ancillary data (i.e. runoff) in addition to the variable of interest (i.e. precipitation) to understand the potential feedbacks and interactions.

LOOKING FORWARD

The call for analysis of long-term data for ecohydrology is clear and strong. Jentsch *et al.* (2007) stated 'we urgently need to advance research on extreme events and their consequences by collecting evidence on their effects from long-term observations and experimental studies in various ecosystems and on various time and magnitude scales'. This urgency was echoed by Newman *et al.* (2006) calling for 'long-term, place-based studies with directed collection of data to test how well feedbacks are represented in models', and Monk *et al.* (2007) demonstrating the 'pressing need for high-quality, long-term paired hydrological and ecological datasets'. Hannah *et al.* (2007) identified a number of future research themes in ecohydrology in which long-term data and place-based research played a 'critical role.' The ongoing place-based research at USDA experimental sites has contributed to the expressed needs of ecohydrology associated with temporal extremes, patterns and thresholds, and sudden and slow environmental change (Table II). Looking forward, there are three areas of research that link the stated needs in ecohydrology to the unique spatial distribution of long-term data at USDA experimental sites: convergence, cumulative synthesis and autocorrelation.

Convergence

The discovery of spatially or temporally convergent processes is an important step towards simplifying the complex interactions of biotic and abiotic systems to make better predictions in ecohydrology. The term convergence is used here to represent a condition in which discrete contributors (that is, biomes, years, geographic regions, etc.) converge to a common feedback pattern that was not apparent in short-term studies or by site-level models alone. Convergence can help explain how feedbacks in ecological systems are affected primarily by one driver and secondarily by another. Because convergence generally occurs with extreme (maximum or minimum) conditions, it identifies the primary limiting resource that will act as a boundary, and thus allows predictions of how a system will respond to extreme events. This is particularly relevant because climate change models predict extreme drought and high temperatures.

A recent example of a study leading to an unexpected convergence will be used here to illustrate the concept. Huxman *et al.* (2004) brought together 14 sites with at least 6 years of concurrent measurements of annual precipitation and annual net primary production (ANPP), including 4 USDA experimental sites, to study rain-use efficiencies (RUE). They discovered a convergence in all biomes to a common maximum RUE during the driest years. They interpreted this to be a distinction between life history and biogeochemical mechanisms, allowing an explanation of how ecological systems are affected by water availability.

Other studies could be directed to meet the challenge of Breshears (2005) to 'develop much more predictive and well-tested relationships for the partitioning among the subcomponents of ET'. A first step is to use long-term, place-based data to understand the convergence to a maximum E/ET for diverse precipitation patterns, or a maximum T/ET for different vegetation types at a single site. Alternatively, like the study by Huxman *et al.* (2004), data from multiple sites could be combined to investigate convergence in all soils to a common minimum E/ET or convergence in all biomes to a common maximum T/ET. Studies such as these will begin to sort out the common responses to extreme events, including floods and droughts, and the feedbacks leading to and resulting from historic transitions.

Cumulative synthesis

Cumulative synthesis has been recognized in other disciplines (chemistry and engineering) as a slow, systematic process leading to deductive conclusions. The hundreds of experiments and years of observations at USDA experimental sites have led to theories about ecohydrological feedbacks and conversely, have identified the phenomena that cannot be explained by preceding theories. In either case, there is potential for huge advances where one more incremental step can lead to a conclusion as a 'last step' in the gradual process of understanding feedbacks (DeBresson and Petersen, 1987).

Basically, cumulative synthesis allows ecohydrological feedbacks to be uncovered by distinguishing the signal from the background noise. For example, Swank *et al.* (2001) showed that long-term records of ecohydrological responses to interactions between precipitation, runoff and vegetation were critical to distinguishing the hydrological response *signal* from temporal vegetation *noise* following a change in land management. Furthermore, the study itself was designed on the basis of the cumulative synthesis of a pre-disturbance knowledge of the system. Brown (2007) identified the knowledge of pre-impact ecological condition as the key element in the design of ecohydrological research. Cumulative synthesis could be applied to both directed disturbances, such as site remediation, urbanization and clearcutting, and to naturally occurring disturbances such as wildfire, desertification, flood, disease and insect infestation.

With the lengthy near-100-year records at many USDA experimental sites, it is possible to discriminate the 'normal' from the 'rare'. Once determined, studies of multiple rare events are possible at a single site with different land use and land cover to discover if the ecosystem response remains the same. Cumulative synthesis utilizes observations over time to sort out the multi-dimensional feedbacks of hydrology and ecology. Though ecohydrology studies are often based on a space-for-time substitution, Newman *et al.* (2006) suggested that these studies be complemented by experimental observations followed through time to provide unique perspectives and to offset weaknesses in each approach.

Autocorrelation

Identifying the conditions that lead to threshold behaviours and the non-linear responses that occur when thresholds are crossed are the key aspects for forecasting environmental change, particularly in drylands (e.g. Mueller *et al.*, 2008). Such conditions are often determined on the basis of short-term studies at one location. It is important to know if these patterns persist over time, and if so, how the ecohydrological patterns determined with long-term data apply over space. This contributes to a determination that the finding is anomalous or that it holds promise for widespread understanding and prediction of ecosystem dynamics. A concept that could be explored with long-term data from USDA experimental sites is the mapping of *ecohydrology regions* based on both the mean and temporal variability of ecohydrological parameters, and further, the continuity in time and space of ecohydrological feedbacks. Measures of spatial autocorrelation can be applied to the full long-term USDA dataset to define the boundaries of the regions defined for specific applications.

For example, the simple compilation and analysis of precipitation and runoff presented in Figures 6 through 8 deserve greater attention (beyond the scope of this review) to examine a broader range of controls on precipitation and runoff variability. The effects of wet or dry years on vegetation condition could be explored as a source of temporal autocorrelation. Spatial autocorrelation analysis would help explain why the linear relation developed for sites in the conterminous USA did not hold for the uniquely dry conditions in Alaska, and the precipitation patterns characterized by hurricane activity in Puerto Rico. Such analyses require assembling and analyzing long-term data on a spatial scale, which has recently been facilitated by web access to data from most USDA experimental sites.

Further, the temporal extremes of interest in ecohydrology are generally related to weather, such as precipitation pulses, El Niño-Southern Oscillation (ENSO) patterns and high temperatures. Long-term data offer field observations of naturally occurring extreme weather events (vs rainfall manipulations) to determine natural event regimes and capture periodic pulses of productivity associated with extreme events. The availability of concurrent hydrological and ecological data with annual resolution covering such long timescales enables statistical analysis of important hydroclimatic phenomena, such as ENSO-related variability and decadal-scale climate oscillations (Swetnam and Betancourt, 1998).

The record of rainfall and runoff at most locations is designed to characterize 'events', which fits the trend in ecohydrology to study long-term precipitation patterns rather than simple mean seasonal or annual total precipitation (Newman *et al.*, 2006) and to account for the resource reserves that are known to modify the performance of biotic systems in short-term or seasonal experiments. A challenge is to study autocorrelation at the appropriate temporal and spatial scale, which is commonly longer and larger than the short-term, site-level studies that make up the bulk of ecohydrological research (Breil *et al.*, 2007; Lake, 2007).

CONCLUDING REMARKS

This review introduces the network of USDA experimental watersheds, forests and ranges as a place-based research framework suitable to address ecohydrological challenges. It is notable that 81 of 112 USDA USFS and ARS experimental sites identified in this review have data records of 20 years or greater and 6 sites have continuous data of over 90 years. More than 40 sites have coincident long-term measurements of basin-scale vegetation dynamics and temporally continuous measurements of meteorological conditions and precipitation events. Of these, 18 sites make continuous long-term measurements of runoff and sediment yield. All 81 sites have long-term data available in machine-readable format, and most sites have data available for download from their websites or from websites supported by other networks.

This review has underscored the need for multi-decadal data for key ecohydrological research as summarized in Table II. That is, the studies detecting cause–effect time lags were based on 18- to 66-year data records with daily to monthly measurement frequencies. The studies focusing on critical thresholds and cyclic dynamics were based on continuous data records over 10–100 years. Results showed that ecosystem dynamics that are generally assumed to have slow progression, such as vegetation die-off, required near-annual measurement frequency to capture threshold events and document decadal cycles (e.g. Figure 4). The studies presenting the context of rare events required data records of 18 years or more to provide sufficient information to identify the rare event and put it in historical context. The effects of extreme weather events on plant diversity are generally based on 100-year recurrence events (Jentsch *et al.*, 2007). The development of land surface simulation models required not only long-term continuous data records of 10–30 years, but also a wide range of measurements covering most or all of the nine themes presented in Figure 2. For example, development of a truly interdisciplinary ecohydrology model for river management will require coupled datasets linking habitat and biota over timescales of decades (Petts, 2007). Though the value of multi-decadal data is widely recognized in ecohydrology (e.g. Brown *et al.*, 2007), there

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are few paired hydrological and ecological datasets with continuity over more than a decade (Hannah *et al*., 2007).

The emphasis in this review on feedbacks and interactions is not a great diversion from the general mission for USDA experimental sites established in the early twentieth century, which was to study the effects of land use and land management on soil, water and vegetation resources. In the early twenty-first century, the mission remains the same but the complexity has increased due to increasing atmospheric carbon, climate variability and unprecedented urbanization. In response, *new* long-term data collection efforts at USDA sites have been designed to coordinate with other networks (Figure 3 and Table I) and *existing* long-term data collection networks have adapted their measurements to address new science issues. The USDA Forest Service is now studying instream flow to better protect and restore habitat for endangered fish and aquatic species (Ryan, 2003). The USDA ARS responded to the latest science questions by funding a long-term, multi-location measurement network called the Rangeland CO_2 Flux Project to understand the role of rangelands in the global carbon cycle (Svejcar *et al*., 1997). USDA watersheds that had originally been instrumented to monitor water quality and the hydrologic cycle, now include measurements of stream chemistry related to cycling of nutrients and pollutants (Hornbeck and Kochenderfer, 2000). Recently, the USDA USFS and USDA ARS formed a collaboration to combine long-term data from their experimental watersheds to better detect and study pathogens in streams. This flexibility and foresight continue to make long-term data collection at USDA experimental sites sustainable, increasing its relevance and value to ecohydrology.

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