AGU PUBLICATIONS

Water Resources Research

COMMENTARY

10.1002/2017WR020838

Special Section:
Earth and Space Science is Essential for Society

Key Points:
- Hydrological data collected over many decades give us the greatest insights into how the water cycle "works" and is changing
- Such data have proven essential in understanding and managing water supplies, floods, and other ecosystem services
- We need to protect long-term studies, promote them, and make data available; their value to society increases over time

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Citation:
Tetzlaff, D., S. K. Carey, J. P. McNamara, H. Laudon, and C. Soulsby (2017), The essential value of long-term experimental data for hydrology and water management, *Water Resour. Res.*, *53*, 2598–2604, doi:10.1002/2017WR020838.

Received 1 APR 2017
Accepted 8 APR 2017
Accepted article online 20 APR 2017
Published online 20 APR 2017

The essential value of long-term experimental data for hydrology and water management

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Abstract Observations and data from long-term experimental watersheds are the foundation of hydrology as a geoscience. They allow us to benchmark process understanding, observe trends and natural cycles, and are prerequisites for testing predictive models. Long-term experimental watersheds also are places where new measurement technologies are developed. These studies offer a crucial evidence base for understanding and managing the provision of clean water supplies, predicting and mitigating the effects of floods, and protecting ecosystem services provided by rivers and wetlands. They also show how to manage land and water in an integrated, sustainable way that reduces environmental and economic costs.

1. Establishing and Evolving Long-Term Watershed Research

The foundations of scientific hydrology and evidence base for sustainable water management are the observational data collected from long-term experimental watersheds distributed around the world [*Hewlett et al*., 1969]. Many were established in response to the First International Hydrological Decade (1965–1974), which called for basic programs of data acquisition and research aimed at expanding quantitative process-based understanding of the hydrological cycle [*Robinson et al*., 2013]. This created a network of experimental sites and an impetus for new studies as knowledge expanded. Some of these well-monitored sites have become part of national or international networks such as Long-Term Ecological Research (LTER) sites [*Knapp et al*., 2012], Critical Zone Observatories [*White et al*., 2015; *Grant and Dietrich*, 2017], or the TERENO network [*Forschungszentrum Jülich et al*., 2016]. Such sites are an invaluable scientific resource: given the multidimensional nature of burgeoning pressures on water supplies [e.g., *Cosgrove and Loucks*, 2015] and the uncertain effects of projected climate change [*Milly et al*., 2015], long-term data are needed more than ever, and these well-monitored sites allow us to see trends and study the effects of different types of environmental change. Current public discourse about the role of science in society and the value of factual information gives us an imperative to reflect on our long-term data collection programs in hydrology, summarize their benefits, and actively promote their critical importance to society.

Watershed studies usually start with a specific question and a group of scientists committing to place-based research and acquiring the resources to initiate empirical observations to understand hydrological processes and other biophysical phenomena [*Burt and McDonnell*, 2015]. A prime example is the seminal catchment studies at the Hubbard Brook Experimental Forest, which pioneered the "watershed ecosystem" approach. Starting in the 1950s, four scientists, with complementary skills linking universities and government agencies, sought to understand the ecological, hydrological, and biogeochemical interactions regulating forest nutrient budgets [*Likens et al*., 1977]. The work showed that while important nutrients like nitrogen and phosphorus were being retained and effectively cycled by the growing forest, weathering-derived nutrients like calcium and magnesium were being lost. This was surprisingly related to increased inputs of acidifying atmospheric pollutants like sulphate which were linked to fossil fuel burning. These acidified soils and stream waters leached base cations and mobilized inorganic aluminum which is toxic to aquatic organisms. The Hubbard Brook study directly contributed to the discovery of the "acid rain" phenomenon in the 1960s and 1970s and informed policy decisions, which led to legislation to cut atmospheric emissions of acidifying pollutants. Over the past two decades, the response of forests and soils, and the recovery of water quality, has been monitored at Hubbard Brook [see *Holmes and Likens*, 2016 for details].

Hydrology proved to be central to many biogeochemical processes and a key control on stream water quality. For example, annual rainfall regulated input fluxes from atmosphere and resulting variation in runoff controlled nutrient outputs. At the time scale of individual storm events, episodic acidification of stream waters was observed; detailed process studies revealed this was due to shallow hydrological pathways that were activated and transferred acidic, aluminum-rich soil waters to streams [*Lawrence et al*., 1986].

Likewise, *Robinson et al*. [2013] report a similar focused start and subsequent unexpected developments at the iconic Plynlimon watershed studies in Wales, UK. Here a long-term paired catchment study was established in the 1960s to answer a simple but important practical question: "Do forests use more water than grasslands in our climate?" This was motivated by practical concerns that extensive commercial afforestation in the UK uplands after the Second World War (to reduce dependence on imported timber) was a threat to public water supply reservoirs, also in the uplands, because trees might transpire more water. At the time, although some early experimental data [*Law*, 1956] were available to suggest that runoff from afforested watersheds was less than neighboring grassland catchments, this was contested, with many believing tree cover increased local rainfall. The facts—revealed by long-term data collected over many decades—showed that trees do indeed use more water than grass, but in complex and unexpected ways. For example, the main reason for greater water use was shown to be high evaporation of high interception storage on coniferous tree canopies which reflects the climate of the often wet, windy UK uplands. This could account for 30–35% of annual rainfall and produce significant reductions in streamflow [*Calder*, 2005]. However, long-term data showed that these impacts were modulated through the forest cycle (a $>$50 harvesting rotation); the effect on reduced flows is highest in the earliest decades of growth but moderates as the forested is thinned and then areas start to be clear-cut. Such insights would have been impossible without monitoring over the entire forest management cycle.

As with Hubbard Brook, the establishment of experimental infrastructure attracted other investigations at Plynlimon. For example, commercial forests also became implicated in the acidification of streams in the UK uplands; as well as causing high interception losses, the large surface area of coniferous forest canopies was very effective at "scavenging" atmospheric pollutants that could increase levels of acidic deposition by up to 50% [*Neal*, 1997]. This was shown by hydrochemical studies at Plynlimon which started in the mid-1980s, which are now also multidecadal and have also revealed the links between hydrology and water quality. For example, storm events were shown to be remarkably acidic, yet low flows could be alkaline [*Neal*, 1997]. This led to process investigations and installation of groundwater wells, which showed that, contrary to initial assumptions that the upland geology had virtually no groundwater storage, groundwater was abundant, actively circulating, hydrochemically heterogeneous, and playing a key role in storm runoff responses [*Haria and Shand*, 2004].

By answering the initial research questions, the Plynlimon study directly influenced UK forestry policy with guidelines for planting and harvesting densities in order to protect the water environment [*Calder*, 2005]. But in addition, the facility and data streams have provided the basis for a wide range of other advances. The high-quality data provided a focus contributing to the development and testing of important conceptual (TOPmodel) and physically based (SHE) hydrological models that have had a major influence on the modeling community [*Kirby et al*., 1991]. Further, some of the more focused process studies provided extremely high-resolution time series that lend themselves to application of advanced novel mathematical analytical methods. For example, *Kirchner et al*. [2000] applied spectral analysis to 3 years of daily chloride time series in precipitation and streamflow. Using chloride as a conservative tracer, this analysis allowed the travel time distributions of water in the Plynlimon watershed to be established and the age of stream water estimated. This revealed that stream water chemistry is "fractal" in nature, integrating both recent precipitation and much older water stored in the subsurface consistent with the groundwater studies of *Haria and Shand* [2004]. In gathering such unique data sets, Plynlimon, like many similar long-term sites, has always been at the forefront of developing and testing field instrumentation that often goes on to be available commercially.

These few examples from Hubbard Brook and Plynlimon show how such "outdoor laboratories" provide us with places to benchmark process understanding. They also show how original questions are invariably more complex than initially assumed, new science questions emerge and, crucially, the research platforms attract others providing a focus for interdisciplinary environmental research, which tends to create a "snowball effect" invariably giving unanticipated insights [*Burt*, 1994]. Of course, such studies require significant long-term investment and commitment, but once established, benefits accrue in nonlinear and unexpected ways giving excellent returns. Monitoring both of these sites continues today giving invaluable factual information on rates of climate change. For example, the average number of frost days at Plynlimon has halved between the early 1970s (~50) and the present (~20) [*Robinson et al*., 2013] and average annual snow depth at Hubbard Brook has decreased from ~80 to ~50 cm over a similar period [*Holmes and Likens*, 2016]. Critically, such trends can be contextualized against ongoing nonstationarity and interannual variability as milder and colder winters still occur. Such context is highly important in understanding extreme and rare events such as large floods and severe droughts which are the hydrological events that usually have the greatest societal impact. At long-term sites, data streams allow us to identify and quantify the linkages among rainfall, soil moisture, groundwater, and runoff, facilitating understanding of flood and drought risk in different types of landscapes [*Huntingford et al*., 2014].

2. Scaling Up: Networks of Experimental Watersheds

Such "gold standard," exhaustively studied sites will always be rare, and the energy devoted to understand such headwater streams needs to be balanced against the need to extrapolate and understand hydrology over larger spatial scales. Indeed, most long-term studies—which form the DNA building blocks of Global watershed science—are more informally managed (often by universities or individual scientists) with short-term funding through a series of grants and graduate students. These start similarly in terms of a curiosity-based set of research questions [e.g., *Soulsby et al*., 1999; *McNamara et al*., 2005; *Laudon et al*., 2013a]. Yet in a more modest way, as time series extend, the value and scientific leverage of these sites become equally invaluable in providing crucial long-term data that gives a context for more focused research driven by hypothesis testing [e.g., *Sier and Monteith*, 2016; *de Wit et al*., 2016; *McCutcheon et al*., 2017]. They also provide ground-truth data of rainfall, soil moisture, streamflow, etc., that helps to constrain remote sensed and modeled data across large spatial scales and various temporal scales to underpin our understanding of Global Hydrology [*Bierkens*, 2015]. This is especially important across huge areas of the world which are subject to rapid environmental change but lie beyond the northern temperate zones where the overwhelming majority of catchment hydrology sites are based [*Burt and McDonnell*, 2015].

In recent years, synthesis studies have sought to integrate data from international networks of sites to leverage more comprehensive understanding through data exchange and collaborations bringing together complementary expertise. For example, a recent synthesis of data from 35 long-term LTER sites in North America highlighted how streamflow trends over decadal time scales reflect the effects of climate teleconnections among sites, but also ecosystem state and the effects of human management [*Jones et al*., 2012]. This provides unparalleled insights into continental-scale hydrological processes and trends that would not have been possible without sustained funding, but perhaps more importantly, offers a nuanced evidence base to inform management and policy development. Other, more informal networks can serve to provide similar leverage; for example, we have been involved in two pan-continental comparative studies of northern basins through the Northwatch [*Tetzlaff et al*., 2013] and VeWa initiatives [*Tetzlaff et al*., 2015] aiming to improve our understanding of implications of climate change. These have helped, among other things, to understand how the variable and changing influence of winter snowpack is affecting the hydrology of northern catchments, with earlier melts and increasing importance of rainfall, and how these are modulated by the watershed resistance to change and resilience for recovery [*Carey et al*., 2010]. The work also predicted how biogeochemistry would be affected with increasing discoloration of stream waters through the mobilization of dissolved organic carbon [*Laudon et al*., 2013b] and the instream ecology shifts to more species better adapted to exploiting increasingly variable flow regimes and warmer temperatures [*Kruitbos et al*., 2013]. Most sites in these two networks are not part of formal national federal study sites, but all have excellent long-terms data sets that have been accumulated as a result of strong levels of commitment by a small number of hydrologists to continue monitoring between funded periods.

Again, the cumulative benefits, interdisciplinarity, and policy relevance of such efforts can be remarkable. For example, the Krycklan catchment study in Sweden has provided fundamental understanding into the hydrology and biogeochemistry of boreal headwater streams and has highlighted the critical importance of the riparian zone in regulating water and solute fluxes [*Tiwari et al*., 2016]. This has directly led to the development of new policies and practical tools for riparian protection in commercial forests in Sweden. Likewise, research in the Girnock catchment in Scotland, a hydrological and fisheries monitoring site (for Atlantic salmon) since 1966, has revealed strong linkages between the fish population dynamics and seasonal and long-term hydrological variability in a northern temperate/boreal environment. These linkages between the landscape and riverscape have been elucidated from isotope studies, which showed the close coupling of catchment water storage (in soil water and groundwater) dynamics, runoff generation, and stream water ages [*Birkel et al*., 2015]. Various life stages of the fish are adapted to average seasonal variations in hydrology: fish spawn and deposit their eggs in river gravels in autumn where they overwinter in the hyporheic zone when streamflow is usually highest and temperatures are lowest [*Malcolm et al*., 2004]; eggs hatch and juvenile fish emerge in late spring as evapotranspiration reduces catchment storage and decreases flows creating much lower in-stream velocities, which young fish need for several months to feed and grow sufficiently to swim in the open current [*Tetzlaff et al*., 2005]. In late summer/early autumn, as evapotranspiration declines and precipitation increases, catchment storage recovers and streamflow increase [*Tetzlaff et al*., 2008]. In response to this, adult fish are able to move into smaller streams and spawn again. Interannual variability in hydrological processes, which can be explicitly linked to storage-discharge dynamics [*Soulsby et al*., 2016], can affect particular year-class of fish; for example, dry autumns may constrain adult fish access and reduce spawning, or wet springs can cause high mortality of newly hatched fish [*Lazzaro et al*., 2017]. The extensive collection of isotope data in the catchment over the past 10 years has identified the dominant runoff processes in the catchment and their controls [*Tetzlaff et al*., 2014]. This provides an unprecedented data set and context for process understanding which is rich resource for model development and testing [*Soulsby et al*., 2015; *van Huijgevoort et al*., 2016; *Benettin et al*., 2017]. This fundamental science has added value in terms of understanding the hydrological context for fish population studies and likely implications for projected climate change to inform policy development for fisheries management [*Millar et al*., 2016].

Other sites provide insights into scarcely monitored biomes and their responses to environmental change. For example, long-term studies in Dry Creek, Idaho, have provided extensive high-quality data that have contributed to basic process understanding of how the ecohydrology of semiarid, snow-influenced environments is strongly dependent on snowmelt inputs in the spring as the main source of water for plant use [*McCutcheon et al*., 2017]. Likewise, long-term studies in Wolf Creek, Yukon, Canada, have for many years focused on understanding the importance of headwaters in arctic permafrost-influenced areas [e.g., *Carey and Quinton*, 2005; *Carey et al*., 2013] and now provide a unique platform for understanding the implications of rapid climate change in such areas. For example, climate warming has led to increased woody vegetation cover, changing the spatial patterns of snowpack accumulation and subsequent melt rate [*Ménard et al*., 2014].

Initiatives to link such catchments studies and data sets are particularly urgently needed in more poorly studied parts of the world where monitoring is much less extensive, yet pressure on land and water resources is rapidly growing, often compounded by rapid climate change. In this context, new network in regions in South America are particularly encouraging [*Boutt and Iroume*, 2017].

3. Linking Watershed Science With Policy and Societal Needs

We need to be more effective showing how long-term monitoring evolving from curiosity-driven research is vital to policy makers and society, providing a fundamental basis for rational decision making [*Lovett et al*., 2007]. Long-term monitoring is usually a challenge for policy makers who often lack mechanisms to commit long-term funding. Policy makers and other stakeholders typically have very specific questions, and the short-time scales of annual financial budgets or electoral cycles might limit long-term studies. Yet the successes of examples like Plynlimon, Hubbard Brook, and the Girnock show that these are not mutually exclusive. The role of scientists should be to understand unexplained phenomena, which may often seem obscure and removed from the needs of policy makers. However, it is clear that scientific knowledge yields long-term dividends, such as the understanding the effects of climate and land use change and the processes governing the vulnerability and resilience to floods and droughts. Similarly, many breakthroughs come from more informally funded research sites, for which input costs are relatively low but the consequent cumulative insights and outputs for society can be very high [*Finn et al*., 2011]. Consequently, despite these challenges, some prove able to withstand even the most difficult funding scrutiny. For example, over 50 years ago in the U.S., the Department of Agriculture proposed a network of research catchments throughout the country specifically designed to inform polices on water cycling in characteristic ecosystems [*U.S. Congress*, 1959].

A corollary of the short-term imperatives of policy makers is that quite often this forces studies to be biased toward modeling applications and virtual experiments as these are cheaper and yield results more rapidly than long-term monitoring [*Silberstein*, 2006]. They are also, of course, more uncertain, and while there is value in modeling and virtual experiments, there is a primacy on the value of real data that provide empirical process understanding and long-term context which is irreplaceable. Fundamentally, such data are also critical for testing models and as we have seen, multiple data streams from long-term, intensively studied sites provide the most exactly means for doing that.

It is clear that there is a need for the hydrological community to be more effective at promoting their work to stakeholders and wider society and to enhance the nonscientific impact and build "hydroliteracy" among the general public. In recent years, more funding agencies are making "impact plans" a prerequisite for grants being awarded; these involve stakeholder engagement, knowledge exchange, outreach activities, and use of social media and the wider media to promote the nonscientific impact of research. Indeed, recent research shows the benefits of encouraging "citizen science" and involving the public in hydrological data collection [e.g., *Lowry and Fienen*, 2013]. International initiatives can also help, for example, the Second International Hydrological Decade, organized by the International Association of Hydrological Sciences (IAHS), focused on Predictions in Ungauged Basins (PUB) to develop tools and approaches to help practitioners using process-based knowledge in hydrological applications in data spare regions, which of course is most of the world [*Bloeschl et al*., 2013]. This has been strengthened in the Third International Hydrological Decade, the "Panta Rhei" initiative [*McMillan et al*., 2016], which is explicitly focusing on human management and viewing water resource systems as integrated natural and social—or sociohydrological—systems.

4. The Future?

We are not the first to highlight the need for sustaining long-term data. Nearly 50 years ago, *Hewlett et al*. [1969] and *Leopold* [1970], two iconic figures in hydrology, answered the call to defend long-term data collection. But it remains the case that long-term data from experimental watersheds have a fundamental value that increases as time goes on. As such they act as sentinels to alert us to trends in basic hydrological metrics, such as the response of rainfall or runoff to environmental change. They also allow us to understand seasonal variations, other natural cycles and extreme evens such as floods and droughts. This is the crucial factual evidence base for managing current and future provision of clean water supplies, predicting and mitigating the effects of floods, and protecting riverine ecosystems.

The highly selective examples given here illustrate just some of this inestimable value to science and society. Yet recent events show that there is a danger that policy makers and the wider public do not fully appreciate this. If society is entering a "posttruth" era, where groundless "alternative facts" are given unwarranted credibility and inconvenient truths of "experts" are routinely dismissed in some quarters, then there is a palpable and serious threat to the scientific enterprise. Thus, we need to tirelessly argue for the importance of maintaining long-term approaches to watershed research sites and data acquisition. As Dr. Jim Kirchner, Professor at ETH Zurich, Switzerland said in the 2016 Langbein Lecture at the AGU Fall Meeting: "Three centuries after the Enlightenment, we should not have to defend the case for rationality in public life, but we do have to . . . because, fundamentally the laws of nature don't care whether we choose to accept them or not, so we'd better know what they are and plan accordingly" (https://www.youtube.com/watch?v=PKjV2sfUN2E&t=82s/). This is an urgent social responsibility for us as scientists. We need to continue to do high-quality science and effectively communicate the findings, but we also need to promote our work and its value to stakeholders and the wider public. It is hoped that this commentary makes a small contribution in this direction.

Acknowledgments
We would like to thank the European Research Council ERC for funding the VeWa project and most of Tetzlaff's time (project GA 335910 VeWa). No data were used in producing this manuscript.

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