



# Watershed studies at the Hubbard Brook Experimental Forest: Building on a long legacy of research with new approaches and sources of data

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## Abstract

The Hubbard Brook Experimental Forest (HBEF) was established in 1955 by the U.S. Department of Agriculture, Forest Service out of concerns about the effects of logging increasing flooding and erosion. To address this issue, within the HBEF hydrological and micrometeorological monitoring was initiated in small watersheds designated for harvesting experiments. The Hubbard Brook Ecosystem Study (HBES) originated in 1963, with the idea of using the small watershed approach to study element fluxes and cycling and the response of forest ecosystems to disturbances, such as forest management practices and air pollution. Early evidence of acid rain was documented at the HBEF and research by scientists at the site helped shape acid rain mitigation policies. New lines of investigation at the HBEF have built on the long legacy of watershed research resulting in a shift from comparing inputs and outputs and quantifying pools and fluxes to a more mechanistic understanding of ecosystem processes within watersheds. For example, hydrogeological studies have shed light on linkages between hydrologic flow paths and soil development that provide valuable perspective for managing forests and understanding stream water quality. New high frequency in situ stream chemistry sensors are providing insights about extreme events and diurnal patterns that were indiscernible with traditional weekly sampling. Additionally, tools are being developed for visual and auditory data exploration and discovery by a broad audience. Given the unprecedented environmental change that is occurring, data from the small watersheds at the HBEF are more relevant now than ever and will continue to serve as a basis for sound environmental decision-making.

## KEYWORDS

acid rain, nitrogen, precipitation, stream water, sulfur, watershed

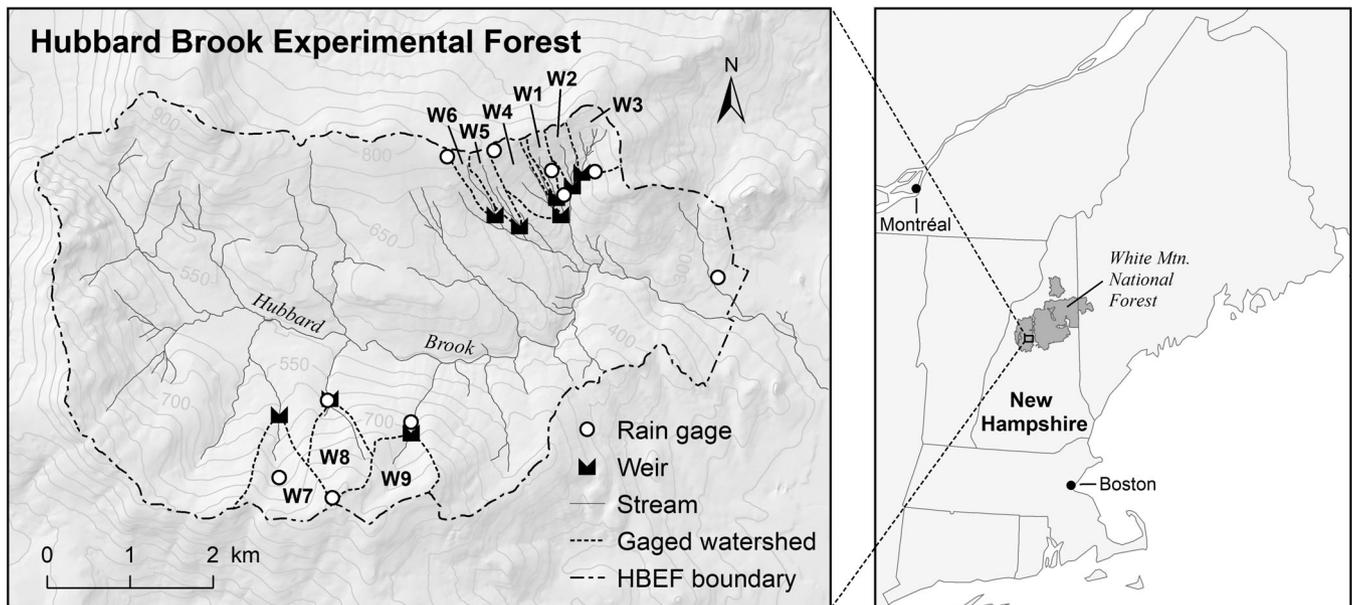
## 1 | SITE DESCRIPTION

The Hubbard Brook Experimental Forest (HBEF) is a 3500-ha field laboratory located in the White Mountain National Forest in central

New Hampshire, U.S. (43°56'N, 71°45'W; Figure 1). It was established in 1955 by the U.S. Department of Agriculture (USDA), Forest Service as a major center for hydrologic research in the Northeast. The climate at the site is humid continental, with average monthly air temperatures ranging from  $-9^{\circ}\text{C}$  in January to  $19^{\circ}\text{C}$  in July. Mean annual precipitation is 1400 mm (64-year annual minimum is 970 mm and maximum is 1940 mm), about a third of which falls as snow. Vegetation is mostly northern hardwood (sugar maple [*Acer saccharum*], American beech [*Fagus grandifolia*], and yellow birch [*Betula alleghaniensis*]) with conifer species (red spruce [*Picea rubens*] and balsam fir [*Abies balsamea*]) at higher elevations (van Doorn et al., 2011). Geology consists of metamorphic rocks of the Silurian Rangeley formation. Soils are derived from glacial drift that varies in thickness, consistency and hydraulic conductivity (S. Bailey, 2019; S. W. Bailey et al., 2014).

The HBEF is named after Hubbard Brook, a tributary to the Pemigewasset River that is within the larger Merrimack River watershed. Hubbard Brook is a fourth to fifth order stream, and its

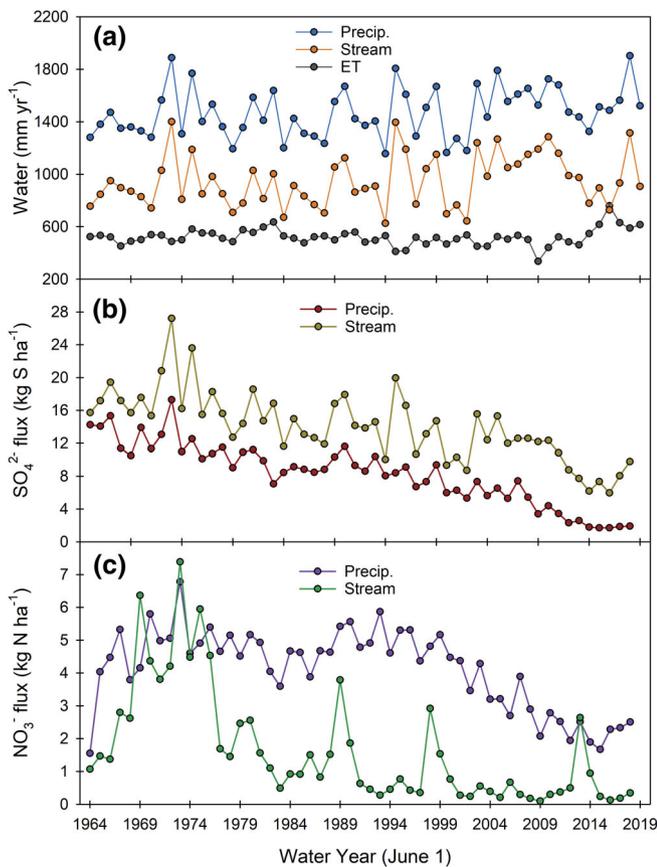
watershed area largely encompasses the boundary of the HBEF (Figure 1). Although there has been a recent effort to gauge streamflow on the main stem of Hubbard Brook, most of the watershed research at the site has focused on nine small, gauged watersheds nested within the larger Hubbard Brook Valley (Figure 1; Table 1). Streamflow at the watershed outlets of these first- and second-order streams has been monitored continuously since as early as the mid-1950s, shortly after the HBEF was established. Streamflow is measured using a v-notch weir (90 or  $120^{\circ}$ ), and four of the watersheds also have a San Dimas flume installed to better capture high flows (A. S. Bailey et al., 2003). Approximately 60% of the precipitation that enters these watersheds leaves as streamflow, and the remainder is attributed to loss via evapotranspiration (Figure 2a). This catchment water balance calculation assumes that interannual change in catchment storage is minor. The fairly strong relationship between annual precipitation and streamflow over the long-term for the June 1 water year used supports this notion (G. E.



**FIGURE 1** Map of the Hubbard Brook Experimental Forest, showing the locations of weirs at the watershed outlets and precipitation gauges within and around the watersheds

**TABLE 1** Description of the small gauged watersheds at the Hubbard Brook Experimental Forest

Watershed	Area (ha)	Slope ( $^{\circ}$ )	Aspect	Elevation (m)	Weir type	Initial year	Treatment year(s)	Treatment
W1	11.8	19.8	S $17^{\circ}$ E	488–747	$90^{\circ}$ V-notch	1956	1999	Calcium addition
W2	15.6	19.8	S $28^{\circ}$ E	503–716	$120^{\circ}$ V-notch	1957	1965–1968	Devegetation
W3	42.4	17.2	S $23^{\circ}$ W	527–732	$120^{\circ}$ V-notch	1957	-	Hydrologic reference
W4	36.1	17.0	S $42^{\circ}$ E	442–747	$120^{\circ}$ V-notch	1960	1970–1974	Progressive strip cut
W5	21.9	17.6	S $28^{\circ}$ E	488–762	$90^{\circ}$ V-notch/Flume	1962	1983–1984	Whole-tree harvest
W6	13.2	16.3	S $37^{\circ}$ E	549–792	$90^{\circ}$ V-notch/Flume	1963	-	Biogeochemical reference
W7	77.4	15.9	N $20^{\circ}$ W	619–899	$120^{\circ}$ V-notch/Flume	1965	-	None
W8	59.4	17.2	N $11^{\circ}$ W	610–905	$120^{\circ}$ V-notch/Flume	1968	-	None
W9	68.4	14.9	N $17^{\circ}$ E	685–910	$120^{\circ}$ V-notch	1995	-	None



**FIGURE 2** Long-term trends in hydrology (a) and fluxes of sulfate (b) and nitrate (c) in precipitation and stream water from the reference watershed (W6) at the Hubbard Brook Experimental Forest

Likens, 2013); however, recent water table data indicate that groundwater levels can be highly variable at this time of year indicating that interannual storage differences may be important in some years. Deep seepage is minimal at the site, which has facilitated use of the small watershed approach to study ecosystem element flux and cycling (Bormann & Likens, 1969; Verry, 2003).

## 2 | HISTORICAL CONTEXT

When the HBEF was established, the effects of forest harvesting on flooding, erosion and sedimentation in streams were not well known. The HBEF became part of a growing network of small watershed studies initiated by the USDA Forest Service at experimental forests across the U.S. to better understand relationships between vegetation and streamflow. To that end, multiple whole-watershed cutting experiments were performed at the HBEF over a period of 20 years, including a vegetation removal experiment, progressive strip cut, and whole-tree harvest (Table 1). These experiments were designed as paired watershed studies in which streamflow in a manipulated watershed is compared to an unmanipulated reference watershed.

In 1963, scientists at the HBEF added a new dimension to this approach by monitoring the chemistry of precipitation and stream

water, which when combined with water volume, enabled calculations of element fluxes in and out of watersheds. The inclusion of solute chemistry in watershed research at the HBEF marked the beginning of the Hubbard Brook Ecosystem Study (HBES). This unique public-private partnership involving the USDA Forest Service, the National Science Foundation's Long Term Ecological Research (LTER) and Long Term Research in Environmental Biology (LTREB) programs, the Hubbard Brook Research Foundation, and a scientific community called the Committee of Scientists (COS) continues today and includes scientists and interested people from diverse institutions around the world. The record of precipitation and stream water chemistry is the longest continuous data set of its kind worldwide (58 years), and the use of the gauged watersheds for studying budgets and cycles of elements (Bormann & Likens, 1967) has become a fundamental approach in ecosystem ecology and biogeochemistry. Early on, the low pH and elevated concentrations of sulfur and nitrogen in precipitation (Figure 2b,c) provided evidence of the importance of acid rain in North America (G. E. Likens & Bormann, 1974). This finding contributed to passage of clean air legislation in the U.S., most notably the Clean Air Act Amendments of 1990, that have improved air and stream water quality. In 1999, a fourth watershed at the HBEF was experimentally manipulated with an aerial application of wollastonite ( $\text{CaSiO}_3$ ). This experiment was designed to evaluate recovery from acid rain by replacing Ca that had been lost from the soil due to decades of acidification (Peters et al., 2004) and examining the ecosystem response to this treatment (Battles et al., 2014; Johnson et al., 2014).

## 3 | DATA AND INSIGHTS

The small watershed approach has been used to show that both human (e.g., harvesting, air pollution) and natural disturbances (e.g., ice storms, soil freezing) can increase nutrient losses in stream water and alter streamflow (Aber et al., 2002). However, the magnitude of responses can be difficult to predict due to interactions among multiple factors such as climate change and climate variability and associated increases in temperature and precipitation (Figure 2a), increases in atmospheric carbon dioxide, and changes in the age and composition of tree species. Although our understanding of how disturbances impact water supply and quality has improved, we are presently unable to explain facets of the record, including a recent marked increase in evapotranspiration during the last few years (Figure 2a), a long-term decline in stream water nitrate that cannot be attributed solely to reductions in nitrogen deposition (Groffman et al., 2018), and a shorter-term unexplained pulse in stream water nitrate during the 2013 water year (Figure 2c).

Multiple plot-scale experiments have been performed at the HBEF to provide a mechanistic understanding of ecosystem response to disturbance. These experiments include a drought study (Asbjornsen et al., 2018), ice storm simulation (Campbell et al., 2020; L. E. Rustad et al., 2020), soil freezing and warming treatments (Groffman et al., 2001; Templer et al., 2017), and nutrient amendments (Goswami et al.,

2018). Biogeochemical models, such as PnET-BGC (Gbondo-Tugbawa et al., 2001) have been useful for synthesis, prediction and cross-site studies that put results from the HBEF in a broader context (e.g., Driscoll et al., 2013). In recent years, there has also been an effort to scale up results from the small watersheds to the full Hubbard Brook Valley, the White Mountain National Forest, and the Northern Forest Region that extends across northern New England and New York (Fahey et al., 2015).

In addition to scaling to larger areas, research at the HBEF seeks to understand how watersheds can be divided into smaller functional units. Variation in soil morphology within a catchment provides insight about how high and how often a transient water table develops in the solum or rooting zone in different portions of the catchments (S. W. Bailey et al., 2019; Gannon et al., 2014; Zimmer et al., 2013). This approach has proven useful for identifying hot spots for biogeochemical processes, and for understanding spatial and temporal variation in stream chemistry.

Related to this work, we have recently enhanced the stream chemistry record by adding sensors that provide high temporal resolution measurements (Sea-Bird Scientific submersible UV analyzer for nitrate and Yellow Springs Instruments EXO2 multi-parameter sonde for measuring fluorescent dissolved organic matter, turbidity, dissolved oxygen, pH, specific conductance and temperature). Stream chemistry is now being recorded at 15-min intervals, which augments the traditional sampling that consists of weekly grab samples and some sporadic event samples. These high frequency-sensor data enable evaluation of hydrologic and environmental conditions that influence concentrations at the storm-event scale (Koenig et al., 2017; Marinos et al., 2018), as well as other phenomena, such as diurnal patterns that were not previously discernable with weekly samples. Although the current suite of measurements obtained with these sensors is more limited than the complete list of laboratory analyses performed, recent research has illustrated how unmeasured solutes can be estimated from these sensor data with machine learning algorithms (Green, Pardo, et al., In press).

Weekly samples of precipitation and stream water, in addition to many other types of samples (e.g., vegetation, soils) are stored permanently in a physical sample archive at the HBEF so they will be available for future research (Veen et al., 1994). The facility was constructed in 1990 and currently contains more than 40 000 samples. Samples are preserved, barcoded, and catalogued with accompanying metadata in a database that can be searched on-line (<https://hubbardbrook.org/d/sample-archive-overview>). Researchers have primarily used subsamples to perform new or improved laboratory analyses (e.g., isotopes, trace metals) and examine historical trends.

## 4 | DATA AVAILABILITY STATEMENT

Hubbard Brook data have been publicly available beginning in 1989 with dial-up access to a PC-based bulletin board system (Veen et al., 1994). Currently, there are more than 200 data sets along with detailed metadata that conform to the Ecological Metadata Language standard accessible through the Hubbard Brook website ([\[hubbardbrook.org/d/hubbard-brook-data-catalog\]\(https://hubbardbrook.org/d/hubbard-brook-data-catalog\)\) and the Environmental Data Initiative repository \(<https://portal.edirepository.org/nis/browseServlet?searchValue=HBR>\). Provisional sensor data are available in near-real time for rapid assessments \(<https://hubbardbrooksensor.shinyapps.io/HBrealtime/>\).](https://</a></p>
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To facilitate data exploration and discovery, visual and auditory tools are being developed for use by students, researchers, land managers, policy makers, and the public. A new platform for data visualization and dissemination was recently released (<https://hbwater.org>) that enables interactive comparisons of solute concentrations and fluxes across watersheds so that users can identify trends, patterns, and anomalies and generate new hypotheses. WaterViz is another new data exploration tool that combines the hydrologic sciences, visual arts, music, and information design (<https://waterviz.org>; L. Rustad et al., 2018). Hydrologic data are transmitted to the internet and used to drive a computer model that calculates all components of the water cycle for the watershed in real time. These data, in turn, drive artistic visualizations and sonifications of the water cycle, reflecting the hydrologic processes occurring at that moment in time. These multimedia tools are making data from the HBEF accessible to a broad audience with the goal of improving understanding how watersheds function to better inform decisions about how they are managed. More information about Hubbard Brook is available in an on-line book (<https://hubbardbrook.org/online-book>) that synthesizes current understanding of ecological, hydrological and biogeochemical processes in the forests and streams.

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