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RESEARCH AND OBSERVATORY CATCHMENTS: THE LEGACY AND THE FUTURE

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The Fernow Experimental Forest, West Virginia, USA: Insights, datasets, and opportunities

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Abstract

Long-term experimental watershed studies have significantly influenced our global understanding of hydrological processes. The discovery and characterization of how stream water quantity and quality respond to a changing environment (e.g. land-use change, acidic deposition) has only been possible due to the establishment of catchments devoted to long-term study. One such catchment is the Fernow Experimental Forest (FEF) located in the headwaters of the Appalachian Mountains in West Virginia, a region that provides essential freshwater ecosystem services to eastern and mid-western United States communities. Established in 1934, the FEF is among the earliest experimental watershed studies in the Eastern United States that continues to address emergent challenges to forest ecosystems, including climate change and other threats to forest health. This data note describes available data and presents some findings from more than 50 years of hydrologic research at the FEF. During the first few decades, research at the FEF focused on the relationship between forest management and hydrological processes—especially those related to the overall water balance. Later, research included the examination of interactions between hydrology and soil erosion, biogeochemistry, N-saturation, and acid deposition. Hydro-climatologic and water quality datasets from long-term measurements and data from short-duration studies are publicly available to provide new insights and foster collaborations that will continue to advance our understanding of hydrology in forested headwater catchments. As a result of its rich history of research and abundance of long-term data, the FEF is positioned to continue to advance understanding of forest ecosystems in a time of unprecedented change.

KEYWORDS

experimental catchments, Fernow Experimental Forest, forest management, hydrological processes, long-term datasets

1 | THE FERNOW EXPERIMENTAL FOREST

Long-term research in small gauged watersheds within the USDA Forest Service Experimental Forest and Range network (USDA-EFR) has contributed substantially to current management of forests (Vose et al., 2012). In 1934, the USDA Forest Service established the Fernow Experimental Forest (FEF) to study mixed hardwood silviculture practices of the Appalachian Mountain region. The Fernow Experimental Forest is located in Tucker County, West Virginia (39°03′N, 79°40′W) with elevations ranging from 706 to 843 m. In this data note, we summarize some of the measurements, data, and findings from 50+ years of hydrological research at the FEF. Hydroclimatologic and water quality datasets are described from long-term monitoring and short-duration studies. We conclude with opportunities for scientific collaboration and data sharing that will advance forest management and hydrologic understanding.

Mean annual air temperature at the FEF is 9.3°C and mean monthly temperatures range from −2.8°C in January to 20.4°C in July (Adams et al., 2012). In the last 60 years mean annual air temperature increased 0.01°C year^{-1}, with minimum temperature increasing 0.02°C year^{-1} and maximum temperature remaining relatively constant (Young et al., 2019). Mean annual precipitation is 1458 mm (Adams et al., 2012) and is distributed evenly throughout the year and has been relatively constant during the last 60 years (Young et al., 2019). Growing season precipitation is associated with convectional thunderstorms and dormant season precipitation is associated with frontal systems (Adams et al., 2012). Stream discharge is dominated by baseflow with flashy storm flow occurring rapidly (<6 hr) after precipitation events. Mean annual runoff (mm) in the reference watershed (WS 4) is 642 mm and evapotranspiration averages 816 mm, indicating that approximately 56% of the rainfall in WS4 returns to the atmosphere as evapotranspiration. Vegetation at the FEF is dominated by mixed mesophytic forest, including over 500 species of vascular plants (Madarish et al., 2002). Overstory species include red oak (*Quercus rubra*), sugar maple (*Acer saccharum*), yellow poplar (*Liriodendron tulipifera*), black cherry (*Prunus serotina*), and other broadleaf species (Madarish et al., 2002). Soils are shallow (<1 m), loamy-skeletal, and well-drained with steep slopes averaging 16% (Adams et al., 2012). The Fernow Experimental Forest has 10 gauged watersheds (Figure 1) including three reference (WS 4, 10, and 13 established in 1951, 1988, and 1993, respectively), one converted from broadleaved forest to a Norway spruce (*Picea abies*) stand in 1973 (WS 6), and one (WS 3) that has been fertilized/acidified from 1989 to 2019. The remaining were treated with various harvesting practices (WS 1, 2, 5, 7). Watershed 14 contains WS 6, 7, and 13 (Figure 1). A detailed watershed management history is described in Adams et al. (2012, table 1).

2 | FERNOW'S EXPERIMENTAL FOREST CONTRIBUTIONS TO SCIENTIFIC UNDERSTANDING OF HYDROLOGICAL PROCESSES

The Fernow has contributed to several cross-catchment studies (Amatya et al., 2016; Ford et al., 2011; Hornbeck et al., 1993; Vadeboncoeur et al., 2018; Vose et al., 2012), and research from the FEF has produced dozens of publications that assess the impacts of forest management on hydrologic processes (e. g. Hornbeck et al., 1993) and water quality. Additionally, ecosystem responses to chronic chemical stressors have been the subject of both long-term acidification experiments (Adams et al., 2006) and observational

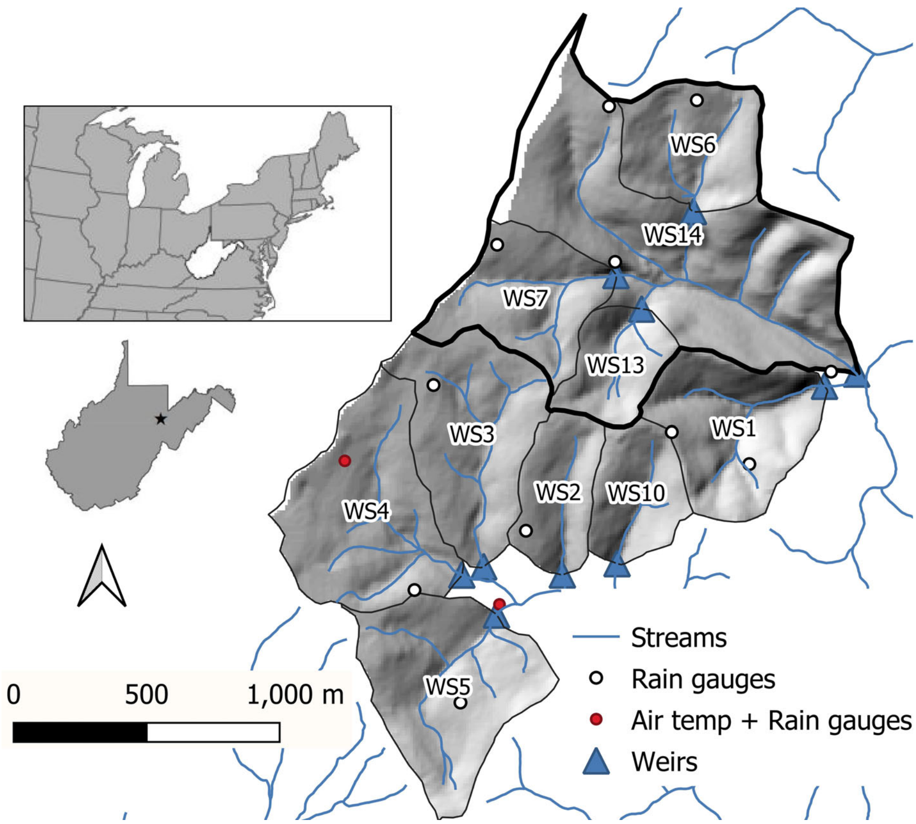

FIGURE 1 Site map of the USDA Forest Service Fernow Experimental Forest (FEF) experimental catchments, West Virginia, USA

studies of ecosystem responses to nitrogen saturation (Peterjohn et al., 1996; Rose et al., 2015; Stoddard, 1994).

2.1 | Land cover, management, and pollution effects on water yield

Extended droughts in the eastern US in the 1960s drove inquiry into water yield from forested watersheds, propelling studies investigating harvest and herbicide applications (Kochenderfer et al., 1990). Clearcutting experiments (WS 3, 6, and 7) were undertaken to understand energy and water budgets (Hornbeck et al., 1993; Tajchman et al., 1997). Research at the Fernow advanced understanding of the influence of species composition on water yield by documenting a significant reduction in streamflow following conversion of broadleaf temperate forest to Norway spruce (Adams et al., 2012; Figure 2). Recent research focused on how climate change influences the water balance [e.g. decreasing evapotranspiration (Vadeboncoeur et al., 2018)] and highlighted that vegetation can mask or amplify climate change effects on water yield (Creed et al., 2014; Jones et al., 2012; Vadeboncoeur et al., 2018; Young et al., 2019). Other recent studies showed increased evapotranspiration due to ecosystem acidification (Lanning et al., 2019), and the attenuation of $C0_2$-enhanced water use efficiency in broadleaf deciduous species by nitrogen pollution (Mathias, 2020).

2.2 | Land cover, management, and pollution effects on water quality

Understanding erosion and sedimentation from land management practices was a major focus for early research (Hornbeck & Reinhart, 1964). Monitoring of stream water chemistry began in 1958 for some analytes but more extensive measurements began in the 1970s (Patric & Smith, 1978) and became standard in the 1980s and onward following improvements in lab facilities and the start of a whole-watershed acidification study in 1989 (reviewed in Adams et al., 2006; Figure 3). Through studies of stream chemistry, the FEF research has advanced understanding of how past land-use practices (legacy effects), the composition of tree species (Peterjohn et al., 2015), and acid deposition have affected ecosystem processes (Edwards et al., 2002). For example, an increase in sugar maple at the Fernow (Schuler & Gillespie, 2000) is associated with higher levels of soil nitrate production and loss through streamflow (Christ et al., 2002; Peterjohn et al., 2015).

2.3 | Legacy of FEF science on governmental policies

Research at the FEF has improved forest management policies in eastern United States deciduous forests, including best management practices (BMPs) such as minimizing road construction impacts on erosion and sedimentation (Kochenderfer, 1970), and protocols to test the efficacy of the BMPs (Ryder & Edwards, 2005). Researchers have also demonstrated the effects of regional air pollution on forests and the effectiveness of Federal policies to reduce its impacts. Continuing monitoring and long-term experiments in the FEF and other forested catchment experiments across vegetative and hydroclimatic gradients are crucial for the ongoing improvement of policies aimed at maintaining resilient ecosystems.

3 | DATA

Core datasets include daily long-term hydro-climatological data for five gauged watersheds (WS 1–5) with measurements starting in 1951, while five watersheds were added later (WS 6–71 956, WS 101984, WS13 1988, WS14 1993). Air temperature and relative humidity were initially measured as daily maximum and minimum and

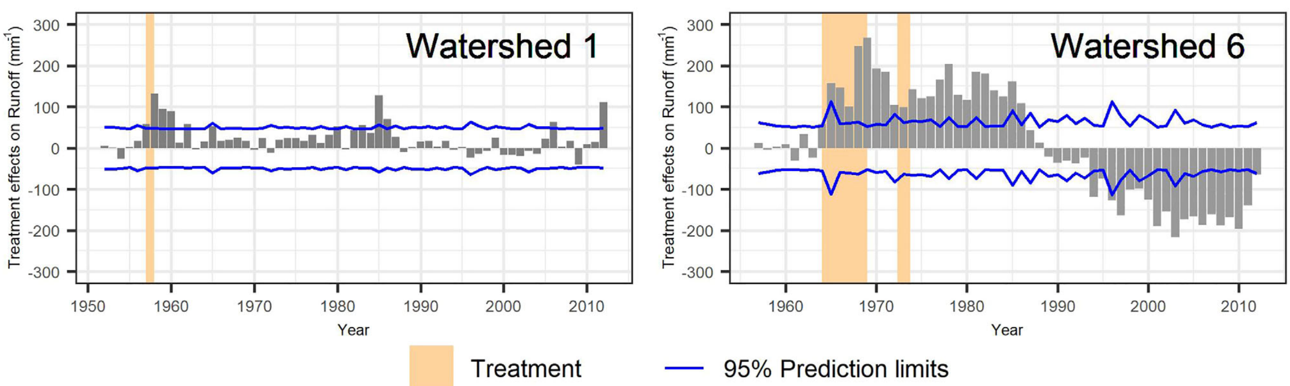

FIGURE 2 Long-term records of treatment effects on runoff for two watersheds. *Left panel*: Watershed 1 was clearcut to 15.2 cm DBH in 1957–1958. Clearcutting initially increased runoff in the first years but returned to pretreatment levels within 4 years. *Right panel*: Watershed 6 had cutting and herbicide treatments between 1963 and 1969 and was planted to Norway spruce in 1973. Initial treatments substantially increased runoff, but conversion to Norway spruce plantation significantly decreased runoff after 20 years. See Adams et al. (2012, table 1) for details

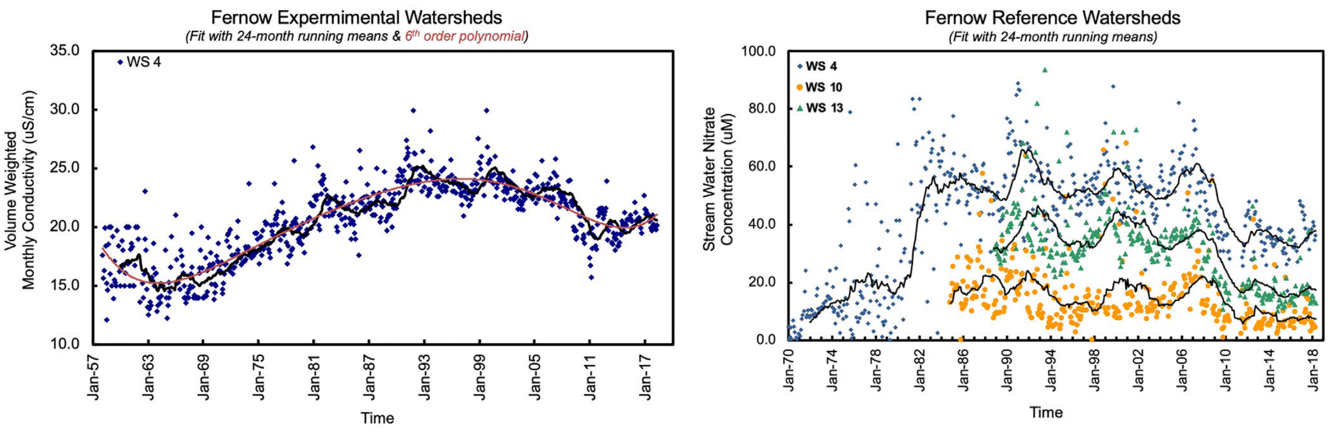

FIGURE 3 *Left panel*: 60-year record of volume weighted monthly conductivity in a reference watershed showing a significant transition from low to high levels of stream solutes. *Right panel*: 48-year record of stream water nitrate concentrations for three reference watersheds showing: (1) a significant increase in stream nitrate levels, (2) substantial differences in nitrate levels between nearby reference watersheds, and (3) synchronous inter-annual variability in nitrate levels among the three reference watersheds

improved to hourly measurements after 1959. Precipitation data have been collected by standard and recording rain gauges since 1951; watershed-weighted rainfall is estimated using Thiessen polygon method. Streamflow estimated from water level has been measured continuously, recorded initially using strip charts and later with dataloggers, WS 1–7 have 120°V-notch weirs and WS 10 and 13 have H-type flumes; biweekly precipitation and stream chemistry started in 1958 with pH, conductivity and alkalinity; while anion and cation analysis began in 1971, data prior to 1981 are less reliable. Growing season (June–October) soil moisture measurements for surface (0–5 cm) mineral soils in WS 3, 4, and 7 are available for 2007–2019 (determined by weighing ~6–10 g of wet soil and drying at 65C for ≥48 hr and 110C for ≥48 hr). Also available are almost three decades (1964–1991) of pan evaporation data sampled daily during the growing season (April to September/October). Finally, data from short-duration studies at the FEF are also available including raw sapflow data in WS4 (growing seasons 2017 and 2018), and a growing database of hyper-spectral and hyper-spatial resolution remote sensing datasets (e.g. Fang et al., 2018; Singh et al., 2015).

4 | FUTURE DIRECTIONS

The Fernow Experimental Forest encourages research and collaboration that propels science-based information to protect stream flow regimes and water quality while maintaining other important ecosystem and economic services including timber production and recreation. Future research avenues may include: (a) Ecohydrological coupling and separation of hydrology and nutrient flux [i.e. testing the 'two-water worlds' hypothesis (Berry et al., 2018) and its implications for water quality]; (b) Water balance dynamics over time, focusing on storage (soil moisture) and evapotranspiration (sapflow and interception); (c) Linking changes in forest composition to present and future susceptibility to drought/climate change; (d) Recovery from ecosystem acidification; and (e) Empirical Dynamic Modelling using long-term records (Sugihara et al., 2012) to explore the causal influence of environmental change and vegetation productivity (using tree-ring records) on hydrology and ecosystem structure (e.g. Watson, 2018). Building on past research that shaped hydrologic management (Vose et al., 2012) and silvicultural practices (Barrett, 1995) of the Appalachian Mountain region, a strategic plan for future research will ensure that the critical knowledge on the interactions between climate, streamflow, and forest management practices will usher in a new era of forest ecosystem management in Appalachia and beyond.

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DATA AVAILABILITY STATEMENT

The extensive amount of publicly available data from the FEF can be accessed at http://www.as.wvu.edu/fernow/data.html. This portal links to specific sources of available data and associated metadata on long-term monitoring of hydroclimatology, water chemistry, rain chemistry, dry deposition, soil productivity experiments, watershed acidification experiments, among others. All USDA FS data are quality-controlled and curated by the FEF data manager. Please contact the FEF (https://www.nrs.fs.fed.us/ef/locations/wv/fernow/) with inquiries about these or other types of data available (e.g. vegetation, litterfall, GIS data).

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