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RESEARCH AND OBSERVATORY CATCHMENTS: THE LEGACY AND THE FUTURE

WILEY

Hydrology and biogeochemistry datasets from Sleepers River Research Watershed, Danville, Vermont, USA

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Abstract

The Sleepers River Research Watershed (SRRW) in Danville, Vermont, USA, was established in 1957 by the U.S Department of Agriculture, Agricultural Research Service (ARS). The 111-km^2 area was selected as a representative mixed-land-use upland landscape in the northeastern USA, with the objective to study fundamental hydrological processes. The U.S. Geological Survey (USGS) currently operates SRRW and is the fourth federal agency to lead it. SRRW has hosted historic research on snowmelt modelling and streamflow generation processes, and USGS has augmented this hydrological foundation with biogeochemical cycling research. This data note describes five freely available data releases in stable repositories, extending to the late 2010s, from the indicated start date: aqueous chemistry and isotopes (1991); precipitation, water temperature, and streamflow (1991); groundwater levels (1991); ground frost depth (1983); and snow depth and water equivalent (1960). USGS research at SRRW is expected to continue, and we plan to update these releases every 1–3 years.

KEYWORDS

biogeochemistry, catchment, frost depth, groundwater level, hydrology, Sleepers River, snow water equivalent, Vermont

1 | DATASET NAME

Sleepers River Research Watershed Long-Term Dataset.

2 | INTRODUCTION

Sleepers River Research Watershed (SRRW), in northeastern Vermont (Figure 1), was established in 1957 by the U.S Department of Agriculture (USDA), Agricultural Research Service (ARS). The site was chosen to represent mixed land-use hydrology in the northeastern USA. The ARS constructed 15 concrete weirs to gage streamflow, and more than 20 meteorological stations to measure precipitation, air temperature, relative humidity, and snow depth and water equivalent. Sleepers River was the site of Tom Dunne's seminal research on the partial area concept for streamflow generation (Dunne & Black, 1970a, 1970b, 1971), and was the site where Eric Anderson of the National Weather Service (NWS) developed the energy balance snowmelt model still in use today for flood forecasting (Anderson, 1968, 1973).

Early U.S. Geological Survey (USGS) research at SRRW in the 1990s extended the hydrologic legacy, applying newer isotopic and chemical approaches, and introducing biogeochemical research. Shanley et al. (1995) used water isotopes and solute chemistry to show that ice layers within snowpacks temporarily impeded meltwater infiltration. The isotopic approach combined with frozen ground measurements demonstrated that deep frost shunts meltwater directly to the stream locally (Shanley et al., 2015), but over larger scales the effect of ground frost is minimal (Shanley & Chalmers, 1999). Kendall et al. (1999) used solute chemistry of hillslope groundwater to show that hillslopes are not always well-connected to the stream, and Hjerdt (2002) extended this work to show that hillslope contributions were focused in convergent hollows. The extensive subsurface chemical database combined with stream event sampling have supported findings that subsurface, chemically evolved 'old' water dominates the high-flow hydrograph (Porter et al., this issue; Kendall et al., 1999; McGlynn et al., 1999; Saiers et al., 2021; Sebestyen et al., 2008; Stewart et al., 2021). Shanley et al. (2002) used water isotopes to show that this old water dominated even in the headwater realm, and did not increase with basin scale as hypothesized.

Pellerin et al. (2012) and Sebestyen et al. (2008) investigated nitrate and dissolved organic carbon (DOC) dynamics during snowmelt (Figure 2). Sebestyen et al. (2009) expanded that work over the annual cycle to project that DOC export would increase and nitrate export would decrease as a result of hydrologic intensification and longer growing seasons by the end of the current century. As in other regions, DOC shows an increasing trend at SRRW (Cincotta et al., 2019), which raises concern for mercury (Hg) export due to the strong Hg-DOC linkage (Dittman et al., 2009; Shanley et al., this issue). Sebestyen et al. (2014) documented high uptake of stream nitrogen associated with autumn leaf fall, and further demonstrated that most of stream nitrate originated from nitrification in the catchment, but that under some conditions unaltered atmospheric nitrate reaches the stream (Sebestyen et al., 2019). The value of long-term monitoring was demonstrated by Mayer et al. (2010), who used the sulfur and oxygen isotope ratios of sulfate to tie an 8-month elevated stream sulfate excursion (Figure 3) to reoxidation and flushing of secondary sulfide minerals in the soil during an historic drought and rewetting cycle. The carbonate bedrock at Sleepers River sets it apart biogeochemically from most other catchments; thus, SRRW is an end member that is often included in cross-catchment comparison studies (e.g., Hornbeck et al., 1997). The research history of Sleepers River over its first 55 years is chronicled in Shanley et al. (2015). The long-term datasets will continue to offer researchers opportunities to evaluate hydrologic and biogeochemical change resulting from climate, land use, and atmospheric deposition changes.

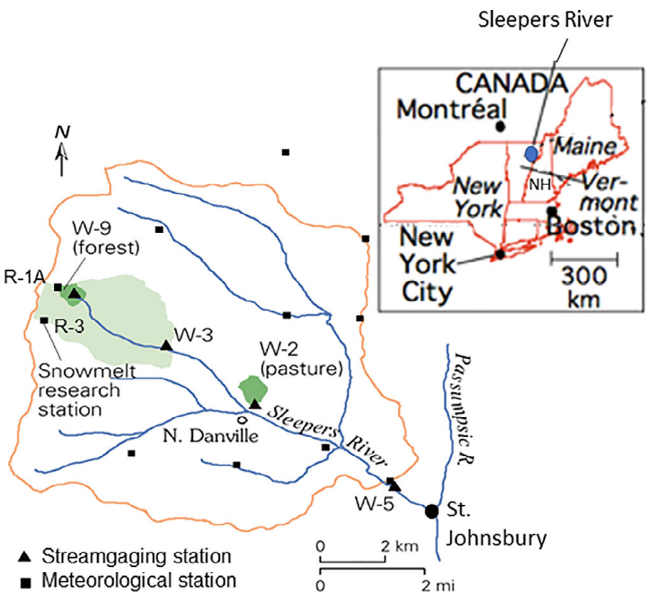

FIGURE 1 Map of Sleepers River research watershed showing study sites and surrounding areas

3 | SITE DESCRIPTION AND METHODS

SRRW is a 111-km^2 watershed in northeastern Vermont (44.49°, −72.16° at outlet of watershed) (Figure 1). The area, in hilly terrain just northwest of St. Johnsbury, is a rural mosaic of dairy farms and forested tracts, linked by mostly unpaved roads, with the tiny village of North Danville the only settlement. Its western divide is formed by

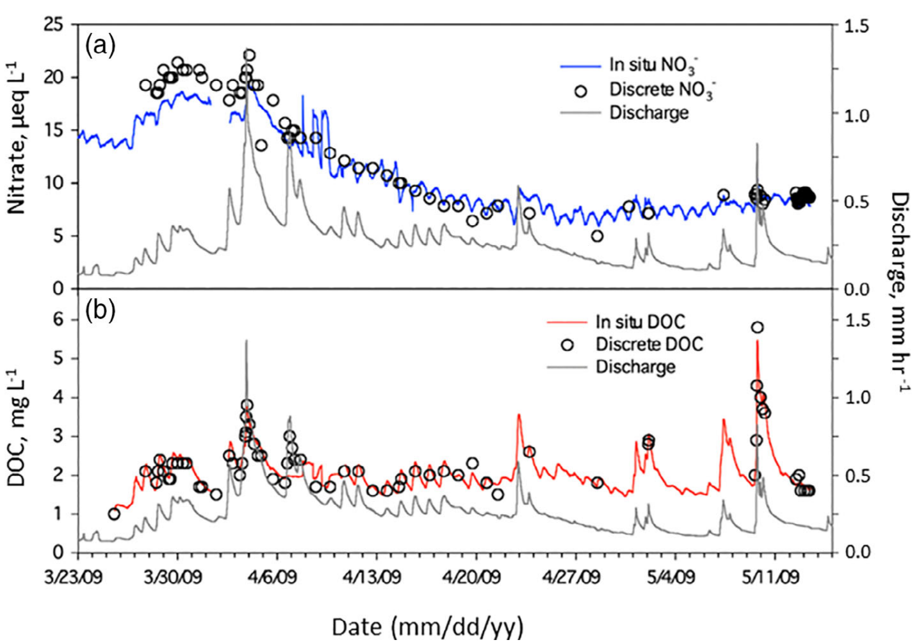

FIGURE 2 W-9 snowmelt hydrograph showing differential response of nitrate (supply limited) and DOC (transport limited) in streamwater [DOC, dissolved organic carbon; NO_3^-, nitrate] modified from and reprinted by permission from Springer Nature Customer Service Centre GmbH, Nature/Springer, Biogeochemistry: Pellerin, B. A., Saraceno, J. F., Shanley, J. B., Sebestyen, S. D., Aiken, G. R., Wollheim, W. M., & Bergamashi, B. A. (2012). Taking the pulse of snowmelt: In situ sensors reveal seasonal, event and diurnal patterns of nitrate and dissolved organic matter variability in an upland forest stream. Biogeochemistry, 108 (1–3), 183–198, DOI: 10.1007/s10533-011-9589-8

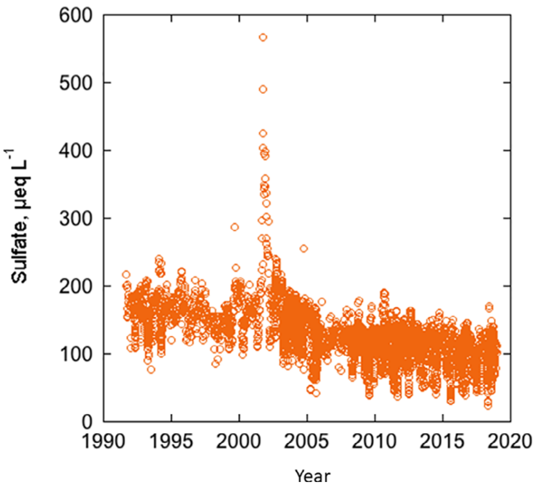

FIGURE 3 This long-term record of stream sulfate concentrations at W-9 reveals (1) an overall trend of decreasing sulfate concentration due to decreasing sulfate input in atmospheric deposition, (2) an 8-month period of elevated concentrations caused by drought in summer 2001, followed by rewetting and flushing of oxidized sulfides. Modified from and reprinted by permission from Elsevier, Applied Geochemistry, Mayer, B., Shanley, J. B., Bailey, S. W. & Mitchell, M. J. (2010). Identifying sources of stream water sulfate after a summer drought in the Sleepers River watershed (Vermont, USA) using hydrological, chemical, and isotopic techniques. Applied Geochemistry, 25(5), 747–754

the ridgeline of the Kittredge Hills, which rise to 801 m. The steep east-facing slopes give way to more rolling terrain as major tributaries join in North Danville to form Sleepers River, which descends to 201 m at W-5, the outlet streamgage. From W-5, Sleepers River flows about 5 km to St. Johnsbury to join the Passumpsic River, which in turn flows about 10 km to the Connecticut River. The Connecticut River flows south to enter Long Island Sound about 150 km east of New York City.

Sleepers River is underlain by the Waits River Formation, a quartz–mica schist with beds of calcareous granulite. The watershed was glaciated, with 0–3 m of dense locally-derived calcareous basal till (more in lower valleys) covering the bedrock. Forest soils developed on the till are Inceptisols and Spodosols, with Histosols common in riparian areas. Localized peat deposits are present in headwater wetlands. Overall, about two-thirds of SRRW is forested in northern hardwoods (sugar maple, yellow birch, and beech). The high-calcium soils favour an elevated percentage of sugar maple and the poor drainage in some areas favours white ash over beech. Balsam fir and red spruce are minor components of the forest, mostly at upper elevations. Open land is primarily pasture, with some corn fields associated with dairy farms. At the forested headwater W-9 watershed, mean annual temperature is 4.6°C and mean annual precipitation is 1332 mm (Shanley et al., 2015). Precipitation is evenly distributed throughout the year with about 25–30% falling as snow. Precipitation stored as snow is released during the brief snowmelt period in March and April, which sustains elevated flow often into the summer months.

The ARS established and operated 16 streamgages, all with concrete weirs, as well as more than 20 meteorological stations at SRRW in the late 1950s to mid-1960s. By the 1980s, ARS and NWS had left the site, and reduced monitoring and topical research projects were sustained by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). Sleepers River was passed by in the 1980s when federal acid rain research funding targeted catchment studies, because carbonates in its bedrock neutralized the acidity. However, key long-term datasets survived, including weekly snow depth and water equivalent (starting 1960), and a ground frost depth network (starting 1983). USGS has maintained these datasets and they are included in the snow and frost data releases.

USGS started its research at SRRW in 1991, when it became one of five sites of the USGS Water, Energy and Biogeochemical Budgets (WEBB) program. USGS resumed or reestablished four of the stream gages and nine of the meteorological stations, the latter with at least air temperature and precipitation measurements. The four streamgages include three nested catchments (W-9, 41 ha; W-3, 837 ha; and W-5, 11 125 ha) and a small agricultural catchment (W-2, 59 ha) (Figure 1). The forested headwater W-9 catchment has been a major focus of USGS research, with weekly and event-based stream and precipitation sampling, subsurface sampling of soil water with zero-tension lysimeters, and a network of 44 10-cm PVC wells augured to bedrock, 1–4 m deep, distributed in varied settings around the catchment.

4 | DATA DESCRIPTION

This Data Note describes five published data releases: hydrometeorology (streamflow, precipitation depth, and air temperature) at the forested headwater, 41-ha W-9 catchment, 1991–2018 (Shanley et al., 2021); all aqueous chemistry and isotope data from the study, 1991–2018 (Matt et al., 2021); groundwater levels across the 44-well network in W-9, 1991–2014 (Shanley et al., 2019); snow depth and water equivalent measurements in open fields and forest clearings, 1960–2019 (Chalmers et al., 2019); and frost-depth measurements at distributed open and forested sites, 1983–2019 (Chalmers et al., 2020).

4.1 | W-9 hydrometeorological data

The streamflow, precipitation depth, and air temperature data in this data release were collected at W-9 at a 5-min timestep. The streamflow is presented at this timestep, while precipitation depth is presented as daily totals and temperature as daily maxima and minima. Annual precipitation and runoff are also tabulated. W-9 has a 120-degree broad-crested concrete weir on bedrock, fitted with a thin steel plate. The empirical equation developed prior to USGS research for this stable control has been repeatedly validated by streamflow measurements, and has been used throughout the study. Gage height is measured in a stilling well adjacent to the weir pool by a float/

counterweight that drives a 10-turn Bourns (Riverside, CA, USA) 3400 Precision Potentiometer wired to a Campbell Scientific (Logan, Utah, USA) CR1000 datalogger. The potentiometer is highly accurate over the small portion of its range used for this small stream. Moreover, the site is visited at least weekly, so there are many more measured control points for adjusting the data than the standard USGS streamgage, which is tracked in real-time but visited less frequently. During ice-free periods the accuracy of the flow is rated excellent, or within 3%. In winter, occasional adjustments were made for ice-affected stage, and measurements are rated fair (95% of values within 10% accuracy). In the rare occurrences of missing data (<5% of the time), we gap filled using relations to the W-3 (Pope Brook) gage, a downstream basin 20 times larger, and these data are also rated fair.

Precipitation for W-9 was computed from measurements by two recording Belfort Instruments Universal weighing bucket gages (Baltimore, MD, USA) in forest openings, one near the weir and one just outside the watershed near its upper elevation. The openings allowed a 45° cone without obstructions over the collector. Accuracy of the Belfort gage is ±1 mm. Precipitation from the two gages was weighted based on land elevation distribution relative to the stations. The buckets are charged with antifreeze in winter to avoid icing and bridging by snow, and with mineral oil the rest of the year to prevent evaporation. Each of the two sites has a non-recording National Weather Service 'Standard Gage' (NWS, 2014), a simple 203-mm diameter cylindrical collector that is measured weekly and is considered the true catch. It is measured to the nearest 0.3 mm. The weighing bucket and standard gage catches usually agreed within a few percent, but the weighing bucket data were prorated to the standard gage each week to account for any differences. Missing records at either gage were filled based on their long-term relation to each other, or in some cases from other nearby meteorological stations at SRRW. Precipitation was computed to daily values, and the chemistry data release also contains the exact weekly amounts to accompany the chemical analysis.

Air temperature was measured by a Campbell Scientific 107 thermistor. Any missing record was filled based on relations to measurements at the weather observatory at the Fairbanks Museum in St. Johnsbury (https://www.fairbanksmuseum.org/eye-on-the-sky). Monthly comparisons with a certified National Institute of Standards and Technology (NIST) thermometer indicated that temperature error was within 0.2° C, which matches the specified manufacturer tolerance.

4.2 | SRRW aqueous chemistry and isotope data

In the last 30 years at SRRW, we have collected nearly 20 000 water samples for chemical and/or isotopic analysis. For much of the study there was no dedicated USGS laboratory. The shifting set of academic and other federal agency collaborators resulted in use of many laboratories, a total of 18 over the study. However, notable continuity has been provided by USDA Forest Service in Durham, NH, which has analysed weekly W-9 stream and precipitation samples for nearly all solutes listed below throughout the project. With these weekly "core" data as a baseline, we focused our additional resources on other laboratories for streamwater samples from events, the other watersheds, and other types of waters, such as groundwater, soil water, overland flow, and throughfall, primarily in W-9.

Samples were most frequently analysed for pH, specific conductance, and major solutes (calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), ammonium (NH_4), nitrate (NO_3), sulfate (SO_4), chloride (Cl), silicon (Si), acid-neutralizing capacity (ANC), and dissolved organic carbon (DOC)), and occasionally for metals (aluminium (Al), iron (Fe), manganese (Mn), strontium (Sr), barium (Ba), and lithium (Li)). A subset of samples was measured for ultraviolet absorbance at 254 nm. Many samples were analysed for water isotopes ($\delta^{18}O$ and a subset of those for $\delta^{2}H$). There were also some analyses for stable carbon isotopes ($\delta^{13}C$) and for the nitrogen and oxygen isotopes of nitrate. Quality of the data was tested by charge balance where possible, but fewer than half of the samples had the requisite complete major ion analysis to check this. Other quality control methods included examining outliers on concentration-discharge relations for stream samples, and on solute pairs that generally had tight linear relations (Ca-ANC; Ca-Mg; Ca-Sr). Most analytes for within-laboratory field duplicates were generally within 10%, while cross-laboratory (comparing to USDA Forest Service Durham Laboratory) field duplicates were generally within 20%.

4.3 | W-9 groundwater level data

A network of 44 PVC groundwater wells was installed in W-9 in 1991 in a variety of landscape positions. Boreholes were power-augered through soil and glacial till to bedrock at 1–4 m. The 51-mm diameter PVC wells were assembled with 1.6 m of screen at the bottom. A permeable fabric sleeve was placed around each screen and filled with native fine sand from the nearest stream channel. A flexible rubber packer was secured around the well above the screen. After the well was placed in the borehole, the annulus above the packer was packed with native glacial till up to land surface. The wells were developed by alternately plunging and purging, using streamwater.

Groundwater levels were measured monthly with an electronic water level sensor (Slope Indicator Co. Model 51 453, Bothell, Washington). Accuracy of the measurement is ±3 mm. Groundwater elevations were referenced both to land surface and sea level. Two 102-mm diameter wells at an upper and lower hillslope position were instrumented for 30-min water level recording, using a Bourns potentiometer similar to that described for stream gage height. These high-frequency measurements are also reported in the data release.

4.4 | Snow and frost data

The longest curated dataset at SRRW, dating to January 1960, is the weekly snow-depth and water-equivalent measurements from R-1A, the highest elevation meteorological station (632 m). The R-3 station at 552 m is missing only a few years since 1960, and we have records since 1985 at 6 other sites along an elevational gradient. Each weekly data point at each site is an average of five replicate measurements. An Adirondack snow tube, which is a 102-mm diameter fibreglass corer with serrated teeth to cut through hard layers, is gently twisted through the snowpack to land surface. Snow depth is read from a rule on the outside of the tube and snow water equivalent (SWE) is determined from the weight of the core in the field with a spring scale. Wooden dowels mark the spot of each core to assure sampling an undisturbed profile the following week. Based on the fairly low relative standard deviation of the five measurements behind each value, error on snow depth and SWE is <5%.

Frost depth has been measured weekly or biweekly since 1983 at five open field locations and a forested transect in and around the W-9 catchment. The frost or frozen ground depth is measured using frost tubes (Brown & Richard, 1968). A solution of methylene blue dye is placed in a sealed Tygon tube suspended within an empty PVC pipe installed to 50-cm soil depth. As the liquid freezes, the ice excludes the blue liquid and freezes clear. The sharp demarcation between blue liquid and clear ice denotes the frost depth, measured from the land surface level mark on the Tygon tube. As frost leaves the ground in spring, it often thaws from above and below, and the depth of surface thawing is also noted. Error on frost depth determination is ±3 mm.

5 | FUNDING AND DATA OWNERSHIP

Data collection was funded by the USGS under the Water, Energy, and Biogeochemical Budgets (WEBB) program, which terminated in 2017. WEBB was administered by the Water Resources Division and then by the Climate and Land Use Change Mission Area. For the last 5 years of WEBB and continuing to present, Sleepers River has been funded by USGS Land Change Science, now known as the USGS Climate R&D Program. All data are property of the U. S. Government and are publicly available. Please cite the full data release references when using in a presentation, publication, or other research product.

6 | DATA SET CONTRIBUTORS

All authors contributed in a substantive way to these data sets. ATC, JCD, SFC, and TES were instrumental in maintaining field data acquisition, entering and checking field data, and collecting water quality samples. SM, JBS, and ATC organized the chemical data from 18 laboratories into a single harmonized database. ATC, SDS, and TES measured and quality-assured the groundwater. SDS collected and analysed hundreds of samples as part of his Ph.D. and continues to oversee Sleepers River sample analysis through the Forestry Science Laboratory in Grand Rapids, Minnesota (chemist John Larson; analysts Nate Aspelin and Keith Oleheiser). Numerous graduate students over the years contributed physical data and laboratory analyses. Other contributors include the staff of the USDA Forest Service at Hubbard Brook and Durham, NH; Jane Hislop, Tammy Wooster, and Jeff Merriam provided laboratory data, while Scott Bailey and John Campbell facilitated. Paul Schuster and Brett Uhle at USGS-Boulder also provided laboratory data.

Data availability

1. Each dataset consists of one or multiple csv files and associated metadata, and all are freely available. All data except the groundwater levels are available as USGS data releases. The groundwater data release is published in the Forest Service Research Data Archive. All data releases are directly accessible via a digital object identifier (DOI).
2. The hydrometeorological dataset is available at: https://doi.org/10.5066/P929KMVK.
3. The chemical / isotopic data set is available at: https://doi.org/10.5066/P9380HQG.
4. The groundwater level dataset is available at: https://doi.org/10.2737/RDS-2018-0064.
5. The snow dataset is available at: https://doi.org/10.5066/P9NMQX70.
6. The frost dataset is available at: https://doi.org/10.5066/P96753GI.
7. In addition, streamflow data from the two larger nested sites, W-3 and W-5, are available from the USGS real-time sites: https://waterdata.usgs.gov/vt/nwis/uv?site_no=01135150 for W-3 (Pope Brook) and https://waterdata.usgs.gov/vt/nwis/uv?site_no=01135300 for W-5 (Sleepers River). Streamflow data for W-2 are not available.
8. The measurements are ongoing and we anticipate updates with the newest data on a 1–3 year basis. DOIs do not change with updates. Inquiries can be directed to James Shanley, jshanley@usgs.gov.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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