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The Forest Soil Moisture Monitoring Network (FSMMN): Multi-depth soil moisture, matric potential, and temperature data from three U.S. experimental forests

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Abstract. The Forest Soil Moisture Monitoring Network (FSMMN) provides a coordinated, multi-depth dataset of soil moisture and temperature measurements from three eastern U.S. Forest Service experimental forests, including Hubbard Brook (New Hampshire), Fernow (West Virginia), and Coweeta (North Carolina). This latitudinal gradient spans distinct soil types, vegetation communities, and precipitation regimes across the Appalachian Mountains, capturing the variability in soil water dynamics. The network currently includes 44 monitoring sites and 262 soil moisture sensors distributed across the three forests, with hourly records beginning in 2022 at Coweeta and Fernow, and in 2023 at Hubbard Brook. At each forest, paired in situ volumetric water content (VWC) and soil matric potential (SMP) sensors were installed at three depth intervals (10-20 cm, 50 cm, and 60-100 cm) within multiple soil profiles across several catchments, enabling the characterization of soil moisture dynamics and hydraulic function at multiple scales. The data undergo automated and manual quality control procedures described in this paper and are updated annually in public data repositories. The dataset enhances the spatiotemporal coverage of soil moisture and temperature observations in forested headwater catchments where long-term, spatially distributed soil moisture records have historically been scarce By capturing both vertical and lateral soil water variability across contrasting forest ecosystems, the FSMMN provides a foundation for cross-site studies linking soil hydraulic properties and catchment water balance at scales relevant to ecological and hydrological modeling.

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1 Introduction

Soil moisture is a fundamental component of the hydrologic cycle, regulating how water moves through landscapes and driving ecosystem processes from plant growth and productivity, carbon cycling, and soil biogeochemical reactions. As climate variability intensifies, shifts in precipitation and extreme events, such as droughts, wildfire, flooding, and landslides, are altering forest productivity, species composition, and hydrologic behavior. Because antecedent soil moisture strongly mediates the severity of these hazards, tracking soil moisture is needed for improving risk prediction and planning (Yu et al., 2023; Krueger et al., 2022; Holden et al., 2025). Long-term, ground-based soil moisture observations capturing temporal and spatial variability are necessary for forecasting forest ecological responses to changing climate and disturbance regimes.

At finer spatial scales, soil moisture content and distribution are governed by antecedent conditions and catchment properties (e.g., soil hydraulic properties, topography, vegetation composition) (Western et al., 2004; Grayson et al., 1997; McMillan and Srinivasan, 2015). Together, these factors determine how water is retained and redistributed, both laterally and vertically, within a watershed. Soil wetness influences the hydrologic connectivity between upslope soils and downslope streamwaters, controlling the timing, magnitude, and sources of runoff (Detty and McGuire, 2010a; Penna et al., 2011; McGlynn et al., 2004), as well as the transport of nutrients and sediments to streams (Pardo et al., 2022; Stieglitz et al., 2003; Seeger et al., 2004). The resulting hydrologic and biogeochemical responses directly regulate streamflow patterns and downstream water quality (Creed and Band, 1998; McGlynn and McDonnell, 2003), which are central to watershed management. These processes depend strongly on the spatiotemporal organization of soil moisture. Yet, soil moisture remains one of the most difficult variables to measure in forested environments, where soils exhibit high spatial heterogeneity across even short distances (Villars et al., 2015).

Collecting soil moisture data in forested environments presents several logistical challenges. Although air- and space-borne remote sensing approaches (e.g., satellites, drones, radiometers) now provide large-scale soil moisture estimates, the precision and scalability of these technologies still require ground-based measurements for calibration and validation (Colliander et al., 2017; Cosh et al., 2004; Kubiak et al., 2024). These products remain limited in their ability to resolve fine-scale spatial moisture variability, short-term fluctuations, and subsurface dynamics, making ground-based measurements essential complementary data. However, establishing and maintaining in situ instrumentation networks can be complicated due to inaccessible or rugged terrain, frequent wildlife disturbances, and the high costs of maintenance and data retrieval. Consequently, existing long-term soil moisture networks are often concentrated in agricultural settings and are unevenly distributed, with far fewer installations in forested landscapes (NOAA NIDIS, 2021). Where forested sites do exist, they are often established in canopy openings on flat terrain to support additional equipment (e.g., flux towers)

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and to overcome issues with power and remote data connectivity. Additionally, most forest monitoring networks rely on single plots or transect measurements (e.g., SCAN, NEON, Mesonets), which fail to capture intra-watershed variability in soil and topographic properties that control water movement within soil profiles and across landscapes.

To address these spatial gaps and expand forest coverage in national monitoring efforts, the Forest Soil Moisture Monitoring Network (FSMMN) was established through a partnership between the U.S. Forest Service and the Natural Resources Conservation Service. The FSMMN aims to provide long-term, high resolution forest soil moisture and temperature datasets that capture both vertical and lateral variability in soil water dynamics across forested catchments. Capturing both dimensions is important for describing the soil water dynamics that are impacted by root-zone processes and the hillslope flowpaths that store and transport water and solutes downslope. The network was designed to complement existing monitoring programs (e.g., Remote Automatic Weather Stations, RAWS) and integrate with long-established hydrometeorological and vegetation datasets at U.S. Forest Service experimental forests. Quality control procedures, including automated flagging and visual inspection, were applied to the datasets following guidance for in situ soil moisture data quality (Quiring et al., 2016; Gaur et al., 2024). The flagging system was designed to enhance transparency and support user interpretation, allowing users to make informed decisions on whether to include or exclude flagged observations based on their specific application.

This paper presents the FSMMN datasets, which currently spans three experimental forests in the eastern United States: Hubbard Brook (New Hampshire), Fernow (West Virginia), and Coweeta (North Carolina). This latitudinal gradient captures a range in precipitation dynamics, soil types, vegetation composition, and forest management histories. Sensors measure volumetric water content (VWC) and soil matric potential (SMP) across multiple depths within spatially distributed soil profiles and catchments. Here, we describe site characteristics, instrumentation, data collection and quality control procedures for the publicly accessible datasets. The FSMMN supports applications in watershed modeling, ecohydrological analyses, and the validation of remotely sensed soil moisture products, while providing a foundation for cross-ecosystem comparisons.

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2 Site Descriptions

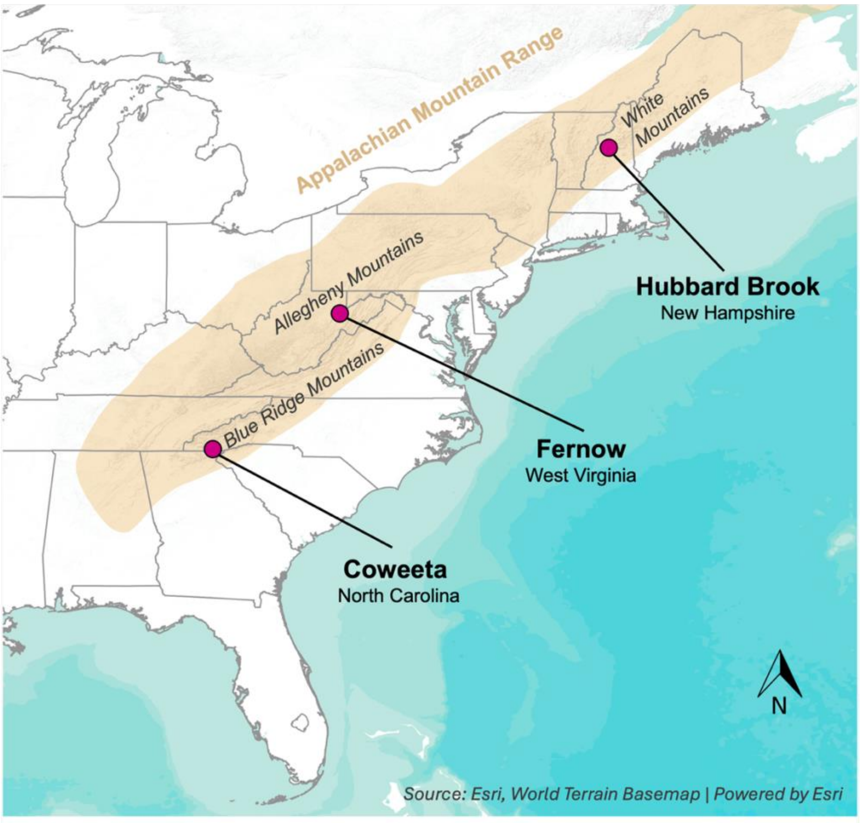

Figure 1. Locations of the experimental forests in the eastern United States, including the Hubbard Brook Experimental Forest, Fernow Experimental Forest, and the Coweeta Hydrologic Laboratory, situated within distinct major subranges of the greater Appalachian Mountains (colored in tan).

Table 1. General soil characteristics of the three FSMMN experimental forests compiled from published literature. Dashes (--) indicate properties for where no published field data were found. Soil texture classes are taken from dominant official soil series descriptions where site-specific field texture data were unavailable.

	Hubbard Brook	**Fernow**	**Coweeta**
Parent Material	Glacial till over schist[a]	Sandstone/shale, Limestone[b, c]	Metamorphic schist and gneiss[b]
Dominant soil order(s)	Spodosols (Haplorthods), Inceptisols (Dytochrepts), lithic Histosols[d]	Inceptisols (Dystrudepts)[b], Alfisols	Inceptisols (Dystrochrepts,

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			Haplumbrepts), Ultisols (Hapludults)[b]
Dominant soil series	Berkshire, Skerry, Becket, Lyman, Tunbridge	Calvin, Dekalb, Belmont	Evard, Cowee, Fannin
Texture	Sandy loam[e, f]	Loam, Silt loam[cl]	Sandy loam, Loam[l]
Drainage	Well-drained	Well-drained, excessively drained	Well-drained
Ksat (m/s)	10^{-4} to 10^{-6} [g]	10^{-4} to 10^{-2} [h]	--
Soil depth	<1 m near bedrock outcrops increasing thickness towards streams[h, i], average is 2m	<1.5[j]	Solum <1-2m, thick saprolite 5-7 meters[k]
Notable features	Thick O horizon, spodic horizon gradient, dense restrictive C layers	High rock fragment content[l]	Porous saprolite

Data Sources
[a] Nezat et al., 2004
[b] Adams et al., 2014
[c] Adams, M.B., 1994
[d] Bailey et al., 2019
[e] Bailey, S.W., 2024
[f] Bower et al., 2023
[g] Benton et al., 2022
[h] Bormann et al., 1970
[i] Fraser, 2020
[j] Bates et al., 2015
[k] Swank and Crossley, 1988
[l] USDA-NCSS, 2026

2.1 Hubbard Brook Experimental Forest

The Hubbard Brook Experimental Forest is in the White Mountain National Forest in New Hampshire, USA (43.9440, -71.7448; Fig. 1). Hubbard Brook is a long-term ecological research site, established in 1955, and is managed by the USDA Forest Service Northern Research Station for hydrologic, biogeochemical, and ecosystem studies. It encompasses approximately 3,180 hectares of mountainous land, ranging from 220 to 1,150 meters in elevation. There is a total of nine gaged watersheds across the valley, which are located at north- and south-facing watersheds.

This region experiences a cool, humid continental climate with cold winters and mild summers. Long-term mean annual air temperature ranges from -3.3 to 6.7 °C and mean monthly air

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temperatures range from a low of -8.6 °C in January to 18.5 °C in July (USDA Forest Service, Northern Research Station, 2025). Annual precipitation averages around 1,400 mm, much of which falls as snow in the winter months, with about 60% leaving as streamflow (~850 mm; Campbell et al., 2021). The growing season for this region is from mid-May to mid-September. Long-term catchment water budgets indicate an increase in the water budget residual (P-runoff) beginning in 2010, primarily driven by an approximate 30% increase in evapotranspiration (ET), although contributions from changes in soil and groundwater storage cannot be ruled out (Green et al., 2021).

Vegetation across the Hubbard Brook valley reflects a transition from northern hardwoods at lower elevations, which are dominated by sugar maple (*Acer saccarum*), American beech (*Fagus grandifolia*), and yellow birch (*Betula alleghaniensis*), to conifer-dominated communities at higher elevations, including red spruce (*Picea rubens*), balsam fir (*Abies balsamea*), and mountain paper birch (*Betula cordifolia*) (Van Doorn et al., 2011).

The soils at Hubbard Brook are largely derived from glacial till overlying schist bedrock (Table 1). The dominant soil type throughout this region is Spodosols (Typic Haplorthods), with localized areas of lithic Histosols and Inceptisols. These soils are generally sandy loam in texture with thick organic horizons, resulting in well-drained soils with high infiltration capacities (solum Ksat 10^{-4} to 10^{-6} m/s; Benton et al., 2022). High-resolution soil mapping at Hubbard Brook has delineated hydropedological units that reflect downslope gradients in moisture dynamics and pedogenic development (Gillan et al., 2015; Fraser et al., 2024). Variations in spodic horizon expression, from ridges to riparian areas, reflect the lateral redistribution of water and solutes (Bailey et al., 2014; Gannon et al., 2017; Bourgault et al., 2015). Together, these patterns illustrate how slope position exerts strong control over soil development, properties, and water table behavior across the hillslope. Water table depth, persistence, and fluctuations are highly heterogeneous across the landscape and strongly correlated with topographic characteristics such as wetness index and landform type (Detty and McGuire, 2010; Pennino et al., 2024).

2.2 Fernow Experimental Forest

The Fernow Experimental Forest is in the Monongahela National Forest in north-central West Virginia, USA (39.0540, -79.6700), within the Allegheny Mountains (Fig. 1). Established in 1934, Fernow is overseen by the USDA Forest Service Northern Research Station and encompasses approximately 1,900 hectares of rugged, forested terrain. The site includes a network of 10 gauged watersheds, many of which are used in long-term studies on forest management, hydrology and biogeochemical cycling. Elevations at Fernow range from 533 to 1,112 meters, with steep slopes (20-60%) and deeply incised valleys.

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The climate at Fernow is classified as humid continental, with cool winters and warm summers. The forest has a mean annual precipitation of 1,500 mm and a mean annual air temperature of 9.3 °C, which has historically ranged from 7.3 to 10.9 °C (Adams et al., 2012). Mean annual streamflow is approximately 710 mm/year. Precipitation is evenly distributed throughout the year, and snowfall is common during the winter months. The growing season typically spans from early May through mid-October. Long-term water balance estimates indicate mean annual ET of approximately 820 mm/year, accounting for roughly 56% of mean annual precipitation (Tajchman et al., 1997), with recent analyses suggesting ET may be declining at this site (Vadeboncoeur et al., 2018).

The Fernow is considered a mixed deciduous hardwood forest with dominant canopy species including red oak (*Quercus rubra*), tulip poplar (*Liriodendron tulipifera*), sugar maple (*Acer saccharum*), and American beech (*Fagus grandifolia*), as well as a conifer component of Eastern Hemlock (*Tsuga canadensis*) and red spruce (*Picea rubens*) (Madarish et al., 2002). Prior to the onset of chestnut blight in the early 1900s, American chestnut (*Castanea dentata*) was considered a large component of the forest (Anagnostakis, 2012).

The dominant soil types at Fernow are classified as Inceptisols and Alfisols and are closely related to the elevation and geologic formations from which they formed (Table 1). For example, the Calvin and Dekalb series (Typic Dystrudepts) are derived from the sandstone and acid shale Hampshire formations, whereas the Belmont series (Typic Hapludalf) is associated with the Greenbriar limestone formation. Contrasts in the supply of base cations from weathering of the parent material types contribute towards differences in the natural fertility and productivity of these soils (Adams et al., 2012). Soil series found here do not typically have fragipans or hydraulically restrictive layers and are generally well drained (Ksat 10^{-4} to 10^{-2} m/s; Bates et al., 2015). Angular cobbles and channers increase with depth and comprise 50-90% of lower horizons, with average depth to lithic contact at 1 meter with deeper areas typically less than 1.5 meters (Soil Survey Staff, 1967). Shallow, perched water tables occur during and after precipitation events with high spatial variability at the hillslope scale (Bates et al., 2015).

2.3 Coweeta Hydrologic Laboratory

The Coweeta Hydrologic Laboratory, established in 1934, is in the southern Appalachian Mountains of western North Carolina, USA (35.0583, -83.4300), within the Nantahala National Forest (Fig. 1) and is overseen by the USDA Forest Service Southern Research Station. The laboratory encompasses approximately 1,600 hectares of steep, forested terrain, with elevations ranging from 675 to 1,595 m. There are 16 gauged experimental watersheds, which vary in land use history, treatment, and aspect (Miniat et al., 2021).

The region has a humid, temperate climate, receiving year-round precipitation averaging 1,500 to 2,400 mm annually (Miniat et al., 2017). Orographic effects influence the distribution of rainfall

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across Coweeta, with the highest amounts on the southwestern ridge of the basin (Daly et al., 2017). Rainfall is distributed evenly across the seasons, and snowfall is rare and short-lived. Long-term streamflow records for reference Watershed 18 indicate that approximately 56% of mean annual precipitation is exported as streamflow (~1,000 mm; Kloeppel et al., 2003). The average annual temperature is approximately 13°C (USDA Forest Service Southern Research Station, 2023). The growing season typically spans from early April through late October, though this window is lengthening with increasing annual air temperatures (Hwang et al., 2018, Oishi et al., 2018). Annual ET at Coweeta has been estimated at approximately 800-1,000 mm/year and is notably consistent despite warming temperatures and high interannual variability in precipitation (Oishi, 2018).

The vegetation at Coweeta is a mixed deciduous forest, with a canopy dominated by various oak species (*Quercus spp.*), hickories (*Carya spp.*), tulip poplar (*Liriodendron tulipifera*), and red maple (*Acer rubrum*), and an understory of rhododendron (*Rhododendron maximum*) (Elliot and Swank, 2008). Like most of the eastern North American forests, chestnut blight eliminated American chestnuts in this region (*Castanea dentata*; Anagnostakis, 2012; Elliot and Swank, 2008).

Soils at Coweeta are mainly Inceptisols and Ultisols, formed from colluvial material and residuum derived from metamorphic and metasedimentary bedrock (Thomas, 1996; Velbel et al., 1988; Table 1). These soils are generally sandy loams and sandy clay loams, with broadly similar chemical and mineral properties. The solum averages about 1 meter in depth and is underlain by a thick, weathered saprolite layer measuring 5–6 meters at lower elevations, which becomes progressively thinner toward ridge crests and higher slopes (Swank and Crossley, 1988; Adams et al., 2014). Hillslope soil moisture gradients are prominent during drier periods in the upper horizons of the soils, particularly on steeper slopes, with drier ridge positions leading to progressively wetter midslope and toeslope zones, shaping vegetation patterns across the gradient (Yeakley et al., 1998).

3. Methods and Data

3.1 Instrumentation

In total, 263 soil moisture sensors were installed at 44 sites across the three forests, with 12 sites located in Hubbard Brook (Fig. 2a), 12 in Coweeta (Fig. 2b) and 20 in Fernow (Fig. 2c). For consistency across the network, sites were chosen to represent a range of soil types across the forest (e.g., major soil map units). Additional criteria included site placement at least 10 meters away from a perennial stream, at least 10 meters away from another site, and ease of access to the site (e.g., near a hiking trail or road). At each forest, local research goals and objectives were also considered when determining exact site placement. For example, at Fernow, sites were also targeted to represent various hillslope positions (ridge, midslope, toeslope, valley bottom) and

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aspects, with additional emphasis placed on wide spatial distribution of each site within each catchment (Fig. 2c). At Hubbard Brook, many site locations were selected to directly support ongoing ecosystem studies by collocating sensors with existing long-term biogeochemical and ecological measurements. Sites west of Watershed 6 (WS6; Fig. 2a) were targeted to link spatiotemporal variability in soil moisture and temperature with measurements of soil pore-chemistry, foliar nutrient chemistry, soil microbial community monitoring, and trace gas flux observations. The placement of monitoring equipment outside of the watershed boundary reflects the status of WS6 as a control watershed where destructive sampling, such as soil pit excavation, is not permitted.

Installed sensors included TEROS 11, TEROS 12, and TEROS 21 (METER Group, Inc., Pullman, WA, USA). The TEROS 12 was used as the primary instrument for measuring VWC, soil electrical conductivity (EC), and temperature. The TEROS 11, which measures VWC and temperature only, were used where TEROS 12 sensors were not available (five sites at Fernow). Both sensors use time domain reflectometry to measure apparent dielectric permittivity, which is internally converted to VWC using factory calibration equations. While the TEROS 12 incorporates bulk EC into its calibration, soil EC values at Fernow were very low (max values ranged from 0.012 - 0.145 mS/cm), resulting in minimal influence of EC on reported VWC. Values from the TEROS 11 calibration were therefore considered comparable. The TEROS 21 (Gen 2) measures SMP by quantifying water content of a porous ceramic disk and converting it to water potential through its characteristic curve. All sensors were connected to a ZL6 data logger (METER Group, Inc.). Product ranges, resolution, and accuracy are provided in the appendix (Table A1), following manufacturer specifications.

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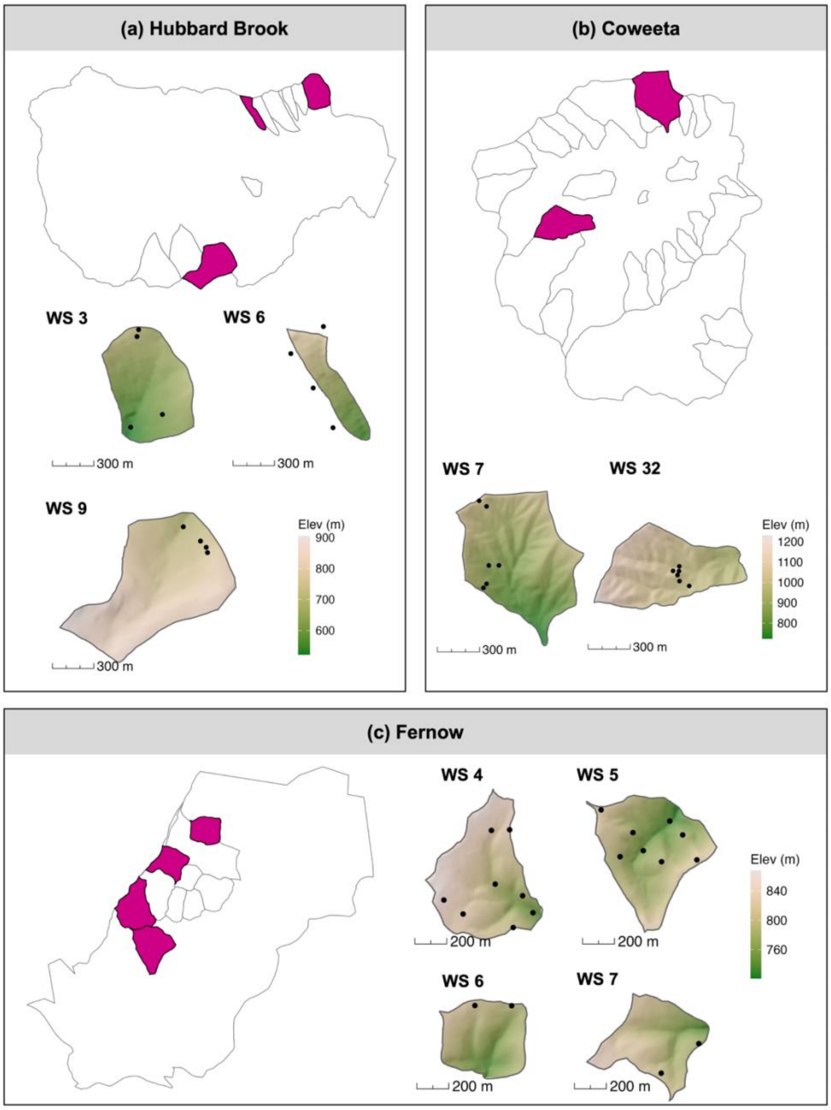

Figure 2. Locations of the instrumented watersheds at the Hubbard Brook Experimental Forest, Coweeta Hydrologic Laboratory, and Fernow Experimental Forest. The maps of each forest (a, b, and c) outline forest boundaries with highlighted catchments indicating the watersheds within the soil moisture network. Each instrumented catchment shows black dots that denote the individual site locations within each watershed.

3.2 Installation

Soil pits were excavated to 100 cm depth or until lithic contact was met (Fig 3a, b). At Hubbard Brook, total pit depth was limited to the base of the lowest spodic horizon (lower Bhs horizon, or

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at the top of the C horizon) to ensure that sensors were installed above where the perennial water table has been shown to exist in this forest (Fig. 3c). Each soil pit was fully described (Fig. A1-3) and pedon descriptions are included in the data repository.), and pedon descriptions are included in the data repository.

Depth ranges targeted for VWC and SMP sensor installation were 10-20 cm (shallow), 50 cm (mid), and 60-100 cm (deep) (Fig. 3; Fig A1-3). Exact sensor depths within each range were adjusted to avoid rock fragments, large roots, or nonrepresentative thin horizons. For shallow sensor placement, installation into the organic horizon (O) was avoided. Sensors measuring VWC were installed within the shallow, mid, and deep targeted depth ranges, with sensors measuring SMP paired at two of those depth ranges. At Coweeta and Fernow, the shallow and deep ranges were selected to have both sensor types. To account for a transient water table and shallow depth to lithic contact at higher elevations within Hubbard Brook, the SMP sensors were installed at the shallow and middle depths. A replicate sensor measuring VWC was installed at all mid-range depths (Fig. 3).

TEROS 11 and 12 prongs were gently pushed horizontally into the pit wall, while TEROS 21 sensors were installed into small, chiseled cavities packed with soil slurry to ensure full contact between the wafer and the surrounding soil. After installation, pits were carefully backfilled to avoid disturbing installed sensors and sensor cables were secured within split-loom tubing that connected to the data logger. Data loggers were mounted on metal posts and protected with clear tackle boxes to minimize wildlife and excess water interference (Fig. 4). Silicone gel was applied to all openings to prevent moisture entry into the box.

Soil physical analyses (e.g., soil texture, bulk density, hydraulic conductivity) were not conducted at individual sensor locations as a part of this study. Published soil datasets for these forests do exist, particularly at Hubbard Brook (e.g., Bailey, S.W., 2024; Bower et al., 2023), but given the high spatial heterogeneity of soil properties along hillslopes in steep, forested catchments, these measurements should not be assumed to be representative of specific FSMMN monitoring sites. Detailed soil profile descriptions collected during sensor installation are provided in each EDI data repository alongside the timeseries datafiles and sensor placement within each profile is summarized in Appendix Figures 1-3.

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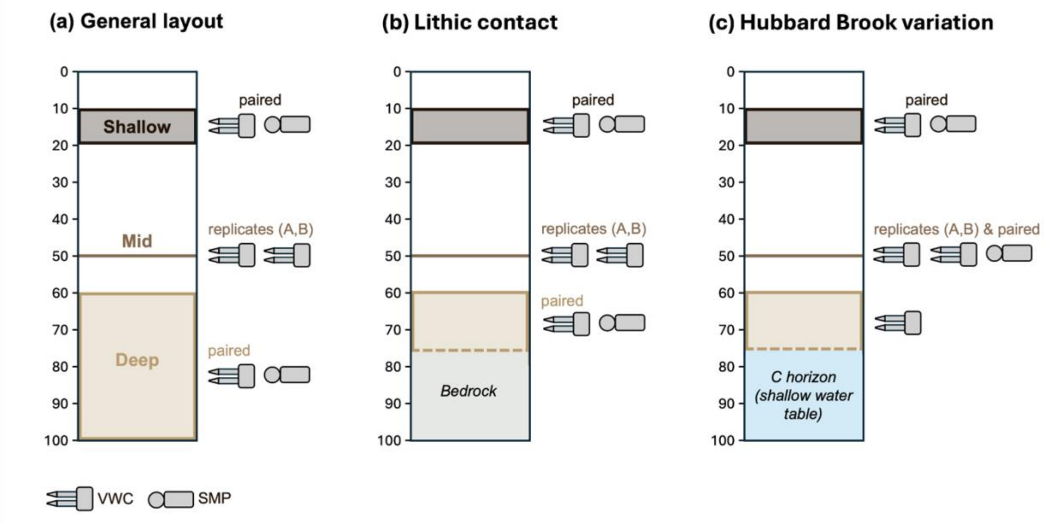

Figure 3. Soil pit excavation and volumetric water content (VWC) and soil matric potential (SMP) sensor installation procedures. (a) Typical pit excavation extends to 100 cm depth. Sensors were installed horizontally into pit walls at three target depth intervals (shallow: 10-20 cm, mid: 50 cm, and deep: 60-100 cm). (b) Total pit depth was shallower if lithic contact was reached. (c) At Hubbard Brook, installation variations were made to account for the shallow, fluctuating water tables. All deep sensors were installed above the C-horizon and paired VWC/SMP pairs were placed at shallow and mid ranges.

Figure 4. Photographs of a ZL6 data logger installed at the Fernow Experimental Forest. The data logger was encased in a clear tackle box and zip tied to a metal T-post which was driven into the ground. Sensor wires were encased in black split loom tubing and passed through a hole

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drilled in the bottom of the tacklebox. Any gaps due to modification of the tacklebox were sealed with silicone gel. Photos by A. Tan (USDA NRCS).

3.3. Data Collection

Data loggers recorded soil conditions at hourly intervals. Data was manually downloaded during maintenance visits by connecting a laptop via micro-USB. Maintenance frequency varied between 1 and 8 months, depending on site accessibility and seasonal conditions. During each visit, field staff downloaded data, replaced rechargeable batteries, and inspected sensor connections to the data logger. Downloaded files were compiled so that each data logger was represented by a single .csv file containing its full record.

Early deployments at Coweeta and Fernow required troubleshooting in response to poor solar charging of batteries under dense canopy cover, resulting in data gaps in the earlier records. Maintenance protocols were subsequently standardized across all sites to improve data continuity. Various strategies were implemented to preserve data logger battery life, including disabling cellular telemetry due to poor cellular reception and testing the performance of alkaline versus rechargeable lithium batteries at each forest.

3.4 Quality Control Procedures

Quality Control (QC) included both automated steps and manual visual inspection (Fig. 5). Automated QC was implemented using a suite of custom R functions (R Core Team, 2025) that applied a consistent flagging scheme across all forests. The flagging functions were designed following guidance for in situ soil moisture data quality control outlined in Quiring et al. (2016) and Gauer et al. (2024). A conservative approach was taken to value removal throughout the QC process. Rather than removing all suspect observations, the QC functions result in flags that are retained in the dataset alongside raw and QC-processed values, which allows users to make informed decisions on whether the flagged data meets the quality requirements for their specific application. Table 2 outlines each QC function, its associated flag marker, and whether the function acted to remove the flagged value from the QC adjusted dataset. A companion flag codes summary file is also included in each data repository, which describes each flag, its decision criteria, and threshold values applied, to support user interpretation and reproducibility.

All data downloads were compiled into one .csv file per data logger, and each row in the dataset represents an hourly measurement. Where gaps in the timeseries were identified (timestamps absent from the raw data logger record), new rows were inserted with the correct timestamp, and all sensor values were filled as “NA”. These inserted rows were flagged with ‘t’ to distinguish logger-level missing records from sensor-level missing values (‘n’), which occur when the data logger recorded a timestamp but logged “NA” for a given sensor.

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QC-processed values were removed and recorded as "NA" for the first seven days immediately after SMP sensor installation to allow the moisture in the ceramic disk time to equilibrate with the surrounding soil. Values were also removed during soil freeze events (Fig. 7) and when numerically impossible. Soil freeze events were classified as periods when the soil temperature reached or fell below 0 °C and until the temperature rose to 0.25 °C. This threshold was selected to capture artificially low soil moisture values when the temperature oscillated around 0 °C while minimizing removed data. Increasing the threshold to 0.5 °C and 1 °C increased the number of flagged points across all sensors by 41% and 176%, respectively, without improving identification of artificially low soil moisture values.

Additional functions were used to flag data without removing values. These included flagging values outside of the sensor's reported range of accuracy (Fig. 6), periods of low data density (Fig. 8), areas that showed sensor 'skipping' (Fig. 8), and abrupt increases in soil moisture with no local precipitation recorded in the prior 12 hours. High increases in VWC were defined as values with a step increase (hour-to-hour value increase) more than 3 standard deviations from the mean step increase at that sensor. This threshold was selected to capture erratic sensor behavior without over-flagging real soil moisture increases over 12 hours from a precipitation event (e.g., water table dynamics, slow infiltration, snowmelt). Precipitation data were obtained from the Environmental Data Initiative archive for Hubbard Brook (USDA Forest Service, Northern Research Station, 2025). The precipitation data used for Coweeta and Fernow were unpublished records provided by site personnel (USFS personnel, unpublished data, 2025a & 2025b).

Flagged datasets were then manually reviewed with a focus on identifying noise from poor soil contact, wildlife disturbance, or sensor malfunction (see Fig. 8) so that problematic time series intervals could be removed. Both raw and QC-processed data are included in the final product, with the raw data, QC-processed data, and data flag columns contained in adjacent columns for ease of use (Fig. 5).

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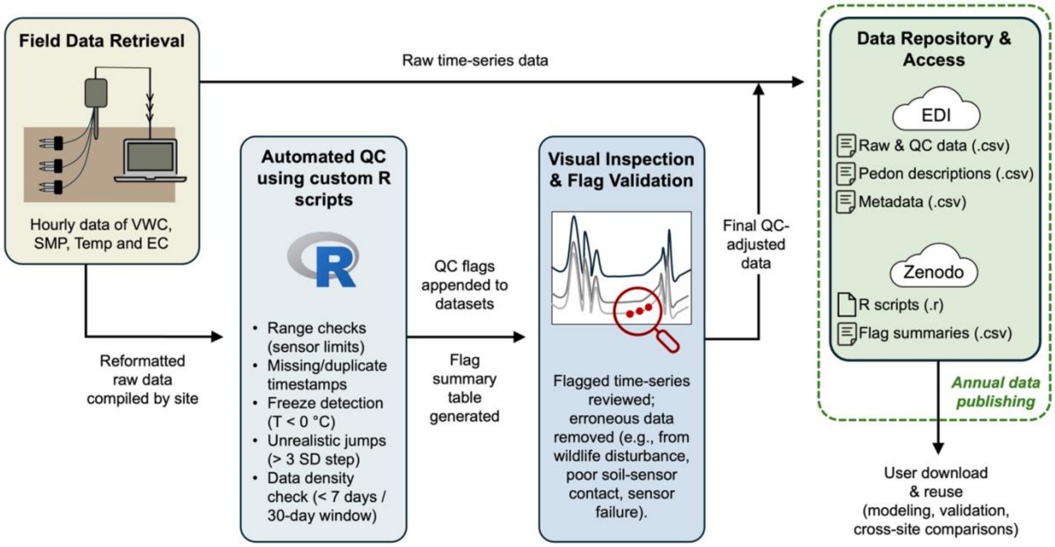

Figure 5. Data collection and quality control workflow for the Forest Soil Moisture Monitoring Network (FSMMN), illustrating the progression from field data collection to a public quality-controlled dataset, which are archived on the Environmental Data Initiative (EDI).

Table 2. Quality-control flag definitions, associated criteria used to identify suspect or erroneous soil moisture observations, and whether flagged values were removed from the dataset.

Flag	Flag Criteria	Removed
t	Missing timeseries entries in the data record	no
n	Missing values with a timeseries entry	no
r	Values outside the manufacturer’s range of reported sensor accuracy	no
f	Values that were recorded during freezing temperatures (flagged when $T \leq 0$°C until $T \geq 0.25$)	yes
z	Values that were numerically impossible (e.g., EC = 0)	yes
c	First seven days of SMP measurements immediately following an installation	yes
l	Low data density periods (< 7 days of recorded data in a 30-day window)	no

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s	Values logged in between two recordings of NA	no
p	Abrupt increases in VWC exceeded three standard deviations above the mean step step change, when no precipitation occurred in the preceding 12 hrs (Fig. 5)	no

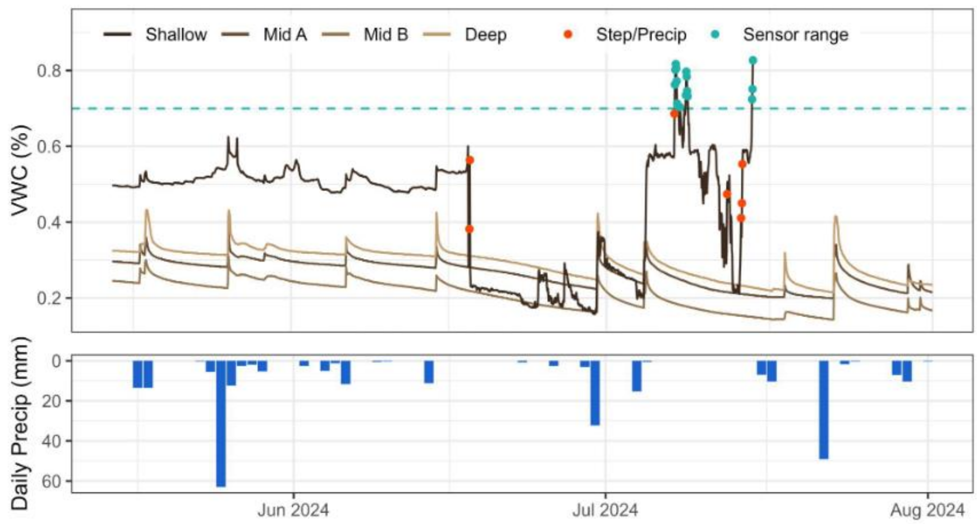

Figure 6. Time series plot of volumetric water content (VWC) at multiple depths (shallow, mid, deep) at Fernow (site Fw5F). The 10 cm sensor values at this location were manually removed from the dataset after a visual inspection of flagged data. Poor sensor behavior was indicated by erratic increases in soil moisture values with no corresponding recorded precipitation (orange flags). Values were also flagged when recorded as higher than the upper limit of the sensor's range (teal flags).

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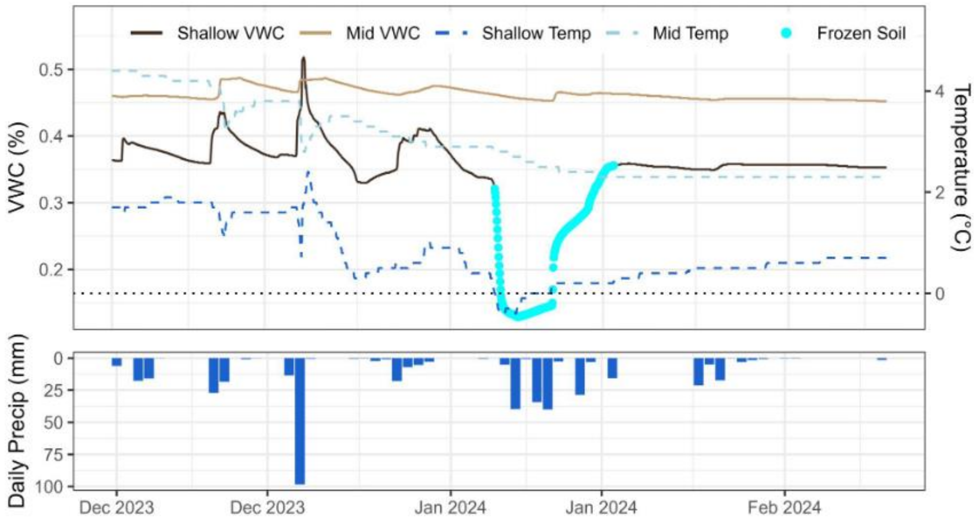

Figure 7. Time series plot of volumetric water content (VWC) and temperature at multiple depths (shallow, mid) and daily precipitation at Hubbard Brook (site HBw9C). Light blue flags indicate where data was removed by QC functions due to frozen soil. Removal of values after a freeze continues until the sensor records above 0.25 °C.

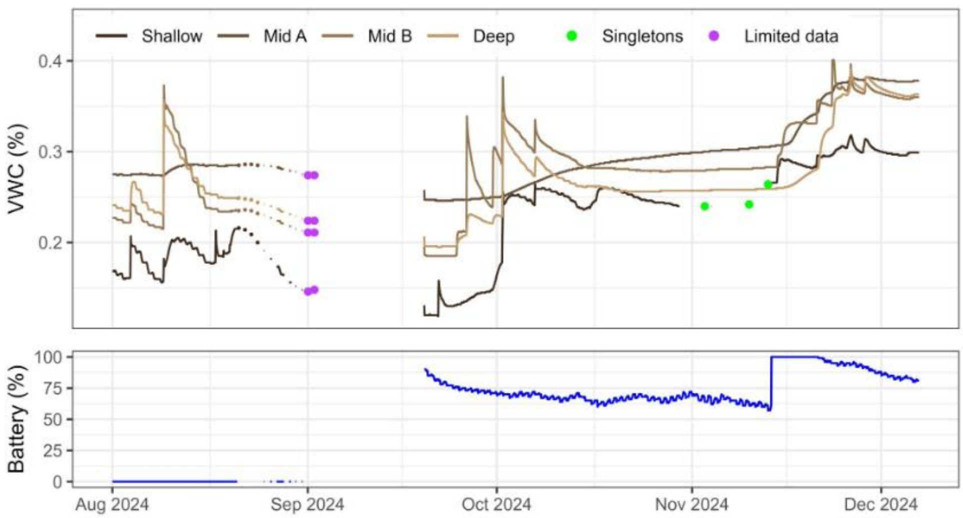

Figure 8. Time series plot of volumetric water content (VWC) at multiple depths (shallow, mid, deep) and data logger battery percentage at Fernow (site Fw5C). Automated flagging helps bring attention to areas of limited data due to loss of power (purple flags), and sensor behavior indicating poor connection to the data logger (green flags) during the data QC process.

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3.5 Data Records

Soil moisture records start in March 2022 at Coweeta, September 2022 at Fernow, and July 2023 at Hubbard Brook, extending through mid-2025. Data collection is ongoing. Overall data completeness varies across forests and between sensor types (TEROS 12 vs. TEROS 21).

VWC, SMP, and temperature data completeness is generally high at Hubbard Brook (mean 96-97%), and somewhat lower at Fernow (87-89%) and Coweeta (60-64%). The lower completeness at Fernow and Coweeta is partly attributable to battery and solar charging issues encountered during the early deployment period. Solar panels were not consistently able to maintain battery charge under dense forest canopy cover, resulting in time gaps (flag t) in some early records while battery replacement and download schedules were adjusted. Soil EC measurements had the lowest data completeness out of any measurement type, with mean completeness of 55% at Fernow, 58% at Coweeta, and 87% at Hubbard Brook. The primary drivers of EC data loss differ by site: at Fernow and Coweeta, missing values (flag n) and timestamp gaps (flag t) account for the majority of missing data, while at Hubbard Brook, data loss was primarily driven by the removal of impossible EC values (flag z). Only two sensors experienced freezing events during the entire record, both at Hubbard Brook (HBw3C at 10cm and HBw9C at 15cm). For guidance on logger-sensor-depth combinations that warrant caution prior to use, refer to Table 3. Additional information regarding date ranges of missing data gaps and flag summaries for each sensor can be found at https://doi.org/10.5281/zenodo.18202618 (Piche, 2026).

Two sources of measurement uncertainty and variability are relevant for users of the FSMMN dataset. First, the METER standard mineral soil calibration was applied rather than conducting individual site-specific calibrations, which was not feasible across the entire network. The standard calibration has a stated accuracy of ±0.03 m^3/m^3 for the TEROS 12 (METER Group, n.d.) and was deemed appropriate for these sites. Second, high spatial heterogeneity in soil properties can lead to variation in soil moisture measurements at fine scales. Because a single sensor represents moisture conditions over a small sensing volume, point measurements may not fully capture the variability present even at short distances across space or within the soil profile, especially in soils with heterogenous structure, texture, or rock fragment content. It is worth noting that the porous saprolite at Coweeta, increased levels of rock fragment content at Fernow, and dense glacial till at Hubbard Brook are all expected to contribute to fine-scale moisture heterogeneity with increasing depth where these features become more prominent.

Paired VWC sensors installed at similar mid-depths within every soil profile provide an in situ estimate of measurement variability. Mean absolute deviation of VWC between paired sensors averaged across sites was 0.043 m^3/m^3 at Coweeta, 0.037 m^3/m^3 at Fernow, and 0.034 m^3/m^3 at Hubbard Brook (SD: 0.030, 0.026, 0.024 m^3/m^3, respectively). No systematic relationship was

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observed between the direction or magnitude of paired sensor deviations and soil moisture content or soil properties across forests. A small number of sites showed notably higher mean deviation (Fw5H: 0.085, Cw32A: 0.081, and Cw7B: 0.080 m^3/m^3) and data from these sites should be interpreted with additional caution given the higher disagreement between sensors values.

Table 3. Logger-sensor combinations that have significant amounts of missing data, which may warrant caution prior to use if assuming a full dataset. Site identifiers follow the naming convention used throughout the dataset (HB: Hubbard Brook, F: Fernow, C: Coweeta).

Site	Description of missing data
HBw6B	Data completeness is 65-67% for all sensors and depths, including a gap in recorded data from June-November 2024, accounting for 24% of the record.
Fw4C	Multiple data gaps spanning the entire record. Both sensors at 10 cm are less than 33% complete. All other depths at this data logger are 55-77% complete.
Fw4E	A data gap for all sensors and depths occurred between April and late August 2024 (22% of the current record).
Fw5E	Logger-wide data gaps result in completeness below 54% across all sensors and depths. The record at this data logger does not begin until July 2024, reflecting a late sensor deployment.
Fw5F	Multiple sensor failures. For example, the VWC sensor at 10cm is 0% complete (flag X).
Cw7A	Data completeness is below 46% for all sensors and depths.
Cw7F	Severe logger-wide sensor failure with data completeness <35% for all sensors and depths.
Cw32F	The SMP sensor at 15cm is 0% complete (flag X). All other sensor depths for this data logger are approximately 58% complete.

3.6 Precipitation Characteristics of Monitoring Period

Precipitation records during the sensor deployment period captured a range of hydroclimatic conditions across the three experimental forests. At Coweeta, full-year annual totals ranged from 1,510–1,866 mm (Appendix Table A2). The longest dry spell (continuous days where precipitation was <1 mm/day) was 32 days long during September-October 2022. The largest multi-day storm event occurred during Hurricane Helene (September 25-27, 2024), producing a 3-day total of 228 mm at Coweeta (106 mm on September 26 alone), followed by a 15-day continuous dry period (Figure 9). At Fernow, the complete 2024 annual precipitation total (1,196 mm) was approximately 20% below the long-term mean of 1,500 mm (Adams et al., 2012). The longest dry spell lasted 13 days during May-June 2023, and the largest single-day event was 85 mm on June 7, 2025. At Hubbard Brook, the 2024 annual total was near-normal relative to the

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long-term mean (1,453 mm at Watershed 6). The longest dry spell was 17 days in September 2024, directly preceding the arrival of Hurricane Helene remnants (66 mm on September 26, 2024). Across all three forests in 2024, precipitation was distributed relatively evenly across seasons (16–34% of annual total per season). Summaries of the annual precipitation totals for each forest during the sensor deployment period can be found in Appendix Table A2.

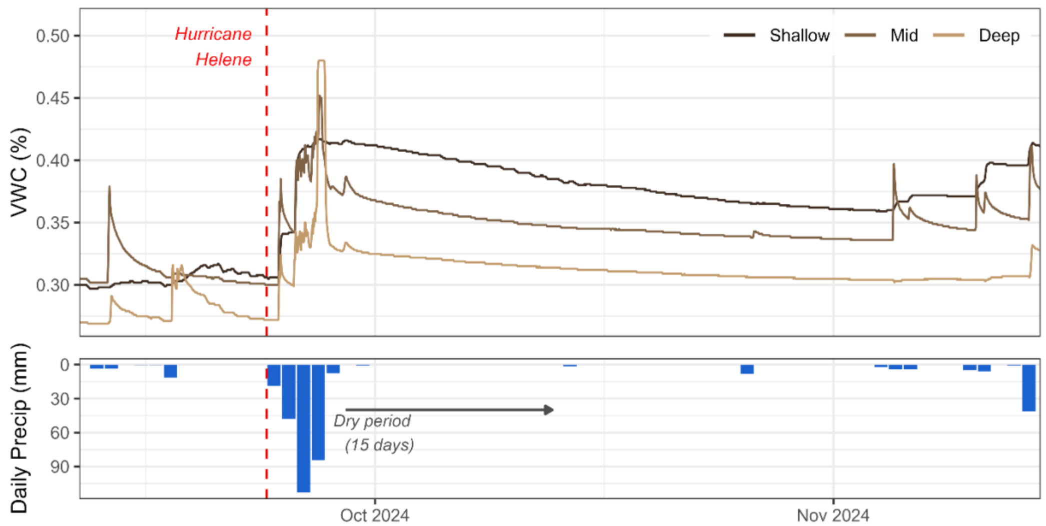

Figure 9. Daily precipitation and volumetric water content at three depths (shallow: 15cm, mid: 50cm, and deep: 80cm) at site Cw32F at Coweeta Hydrologic Laboratory, demonstrating the soil moisture wet up response to Hurricane Helene (total storm 228 mm) and the following recession of moisture during a continuous, multi-week dry period.

4 Data and Code Availability

All FSMMN datasets are publicly accessible through the Environmental Data Initiative (EDI) repository.

- Hubbard Brook Experimental Forest: https://doi.org/10.6073/pasta/2eb8ea3a25e81ead1188af94ccfede72 (NRCS-USFS Forest Soil Moisture Monitoring Network, 2025a)
- Fernow Experimental Forest: https://doi.org/10.6073/pasta/3394903db59772e9aef31c7b9628fb42 (NRCS-USFS Forest Soil Moisture Monitoring Network, 2025b)
- Coweeta Hydrologic Laboratory: https://doi.org/10.6073/pasta/3e11ea6cf7bcfe8791a3abd29c9b7638 (NRCS-USFS Forest Soil Moisture Monitoring Network, 2025c)

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Each repository contains the raw and quality-controlled datafiles (.csv) for the entire dataset record for every data logger. The flagging codes (.txt), pedon descriptions (.csv), and sensor metadata files (.csv) are also provided in separate files. Appendix Figure A4 illustrates the relational structure of each repository dataset, linking all soil moisture timeseries datafiles to their associated sensor metadata table, pedon descriptions, and the flag code reference. The repository description and README file (.txt) contains additional metadata such as variable definitions, temporal and geographic coverage, and additional parent project information. All custom R scripts used for data compilation, flagging, and quality control are available through the FSMMN Zenodo repository: https://doi.org/10.5281/zenodo.18202618 (Piche, 2026). Annual data and code updates will continue as new data downloads and site expansions are completed.

5 Summary and Conclusions

The Forest Soil Moisture Monitoring Network (FSMMN) provides coordinated, multi-depth soil moisture and temperature observations across forested headwater catchments spanning the eastern United States. By capturing the lateral and vertical variability of soil water dynamics across climatic and physiographic settings, the network fills an observational gap in intra-watershed soil moisture measurements that represent diverse soil types, landscape positions, and hydrologic regimes across multiple forests. The FSMMN also represents one of the few co-deployments of VWC and SMP sensors in forested systems intended for long-term measurement, allowing for the assessment of the quantity and energy state of soil water, a capability largely lacking across research networks. The utility of these deployments is illustrated by the dataset's capacity to capture soil moisture responses to extreme precipitation events, such as calculating antecedent dry conditions and characterizing soil profile saturation and recession behavior (e.g., Figure 9).

The integration of soil moisture and temperature measurements with decades of meteorological, streamflow, and vegetation records strengthens the long-term research programs at each experimental forest. FSMMN observations support watershed modeling, ecohydrological process studies, and the validation of remotely sensed soil moisture products across comparative scales (e.g., cross-site, cross-watershed, cross-forest). Long-term research at Hubbard Brook, Coweeta, and Fernow has consistently emphasized the need for sustained, spatially distributed soil moisture monitoring for understanding how hydroclimatic change influences vegetation dynamics, ecosystem productivity, and forest resilience (Green et al., 2021; Elliot and Vose, 2011; Moran et al., 2008). At Hubbard Brook, declining winter snowpack and more frequent freeze-thaw cycles (Wilson et al., 2024; Campbell et al., 2010) directly influence soil moisture recharge, making continuous moisture measurements necessary for evaluating subsequent growing-season water availability. Quantifying changes in soil moisture regimes are particularly relevant for interpreting ongoing species-composition shifts, including mesophication in southern Appalachian Mountains (e.g., Coweeta), which can alter forest dynamics (Hawthorne and

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Miniat, 2018; McQuillan et al., 2025). Findings from Fernow have shown that antecedent wetness and soil water deficits strongly mediate stormflow sensitivity in Appalachian headwaters, demonstrating how soil water status drives landscape-scale hydrologic responses (Kochenderfer et al., 2007). Contrasting evapotranspiration trajectories across these forests, including increasing at Hubbard Brook (Green et al., 2021), declining at Fernow (Vadeboncoeur et al., 2018) and relatively stable at Coweeta (Oishi et al., 2018), present an opportunity to investigate how root-zone water storage and availability mediate the different forest water balance responses.

Beyond direct observations of VWC and SMP, the FSMMN dataset supports the derivation of several ecologically and hydrologically relevant soil moisture metrics. For example, using VWC, seasonal storage change and threshold exceedance statistics relevant to drought monitoring, runoff generation, and long-term change detection can be calculated. From paired VWC-SMP records, site-specific soil moisture release characteristics can be parameterized (e.g., fitting van Genuchten model parameters), enabling the estimation of plant available water or hydraulic conductivity as inputs for hydrologic and land surface models (Van Looy et al., 2017; Koster et al., 2009; Brocca et al., 2017; Novick et al., 2022). Co-located measurements of water content and matric potential at similar depths also provide the basis for estimating root-zone water stress (Novak et al., 2005) and hydraulic redistribution (Warren et al., 2006; Neumann and Cardon, 2012) and for the identifying key hydrologic thresholds, such as the onset of lateral flow (Gannon et al., 2017), which governs runoff generation and subsurface connectivity in steep forested terrain (McGuire & McDonnell, 2010).

The paired VWC-SMP measurements also provide the means to constrain the soil and groundwater storage component of catchment water balance estimations. When combined with long-term hydrometeorological records at each forest, the FSMMN datasets can provide the subsurface constraints needed to partition water balance residuals into storage and flux components, which directly addresses open questions about ET dynamics at these forests (Green et al., 2021; Vadeboncoeur et al., 2018; Oishi et al., 2018). Detailed soil maps can complement these observations by improving the representation of subsurface storage and release processes by capturing how spatial heterogeneity in soil properties, landscape structure, and antecedent wetness shape catchment hydrologic behavior (Detty and McGuire, 2010; Singh et al., 2018).

The FSMMN network is designed for expansion, with planned installations at the Marcell (Minnesota) and Sierra Ancha (Arizona) Experimental Forests. This will extend the network into boreal and semi-arid forested ecosystems, broadening the network's environmental gradient and enabling cross-biome comparisons of soil water dynamics. The FSMMN datasets are also potentially suitable for contribution to other soil moisture dataset networks, such as the International Soil Moisture Network (ISMN; Dorigo et al., 2011) or the National Coordinated Soil Moisture Monitoring Network (NCSMMN; NOAA NIDIS, 2021). Integration with these

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networks would further increase the visibility and accessibility of these data beyond the reach of the current EDI repository. Continued coordination with complementary monitoring programs will further strengthen the capacity to observe and predict forest hydrologic response to climate and land use change.

Appendix A

Table A1. Product specifications (range, resolution, and accuracy) for each sensor type used across the network. Detailed information on the principles of measurement and sensor specifications can be found in the manufacturer's documentation (METER Group, n.d.)

	Sensor					
	TEROS 11		TEROS 12			TEROS 21
Metric	VWC	T	VWC	T	EC	SMP
Range	0.00-0.70 m^3m^{-3}	-40 to +60 °C	0.00-0.70 m^3m^{-3}	-40 to +60 °C	0-20,000 uS/cm	0 to -100,000 kPa
Resolution	0.0010 m^3m^{-3}	0.1 °C	0.0010 m^3m^{-3}	0.10 °C	1 uS/cm	0.1 kPa
Accuracy	+/- 0.03 m^3m^{-3}	+/- 1°C from -40 to 0°C and +/- 0.5°C from 0 to +60°C	+/- 0.03 m^3m^{-3}	+/- 1°C from -40 to 0°C and +/- 0.5°C from 0 to +60°C	+/- (5% + 10 uS/cm) from 0-10,000 uS/cm and +/- (8% + 10 uS/cm) from 10,000-20,000 uS/cm	+/- (10% of reading + 2 kPa) from -100 to -5kPa

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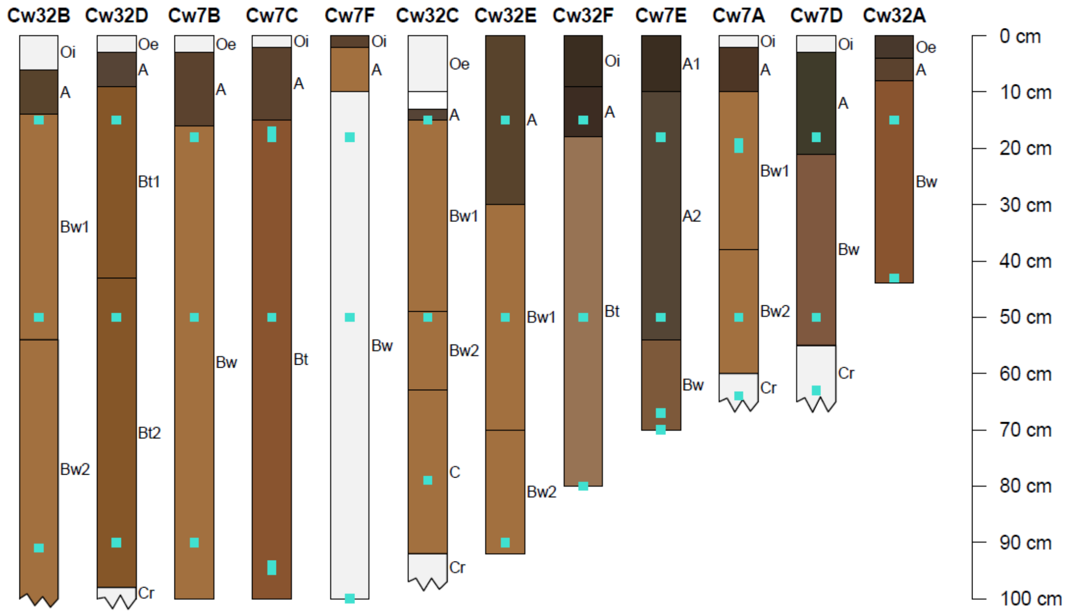

Figure A1. Diagram of the 12 soil profiles described during soil moisture sensor installation in watersheds 7 and 32 at the Coweeta Hydrologic Laboratory in North Carolina. Each soil horizon color depicts the Munsell soil color chip as identified in the field, unless shown in white, which indicates no color was recorded for that horizon. A ragged boundary indicates the continuation of a horizon beyond the depth of excavation, whereas a solid line indicates the absolute bottom depth of the horizon. Sensor placement depths are shown as light green squares.

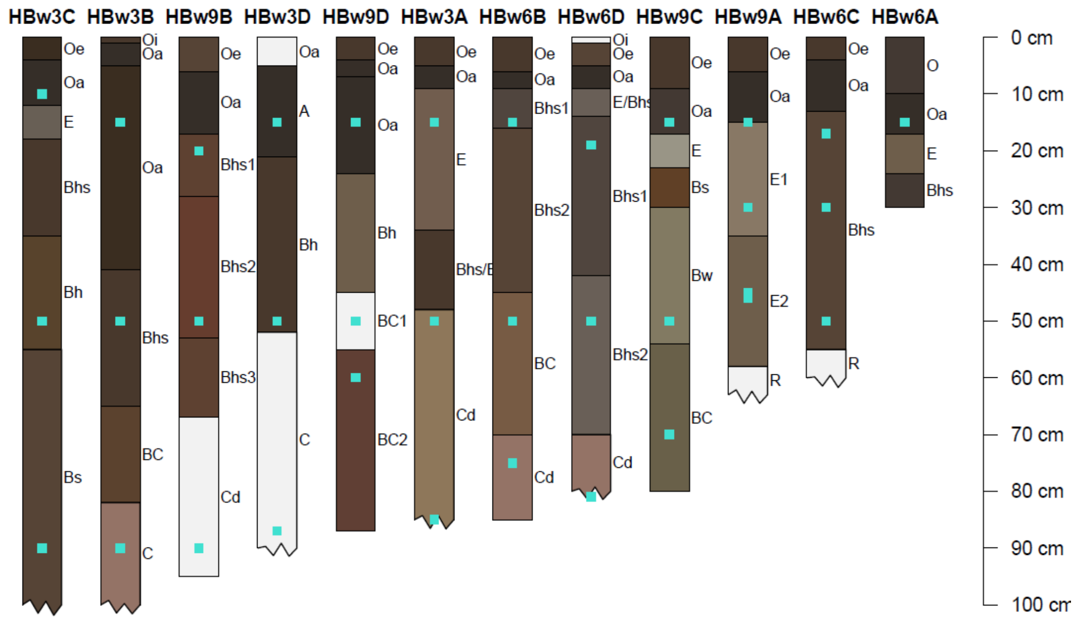

Figure A2. Diagram of the 12 soil profiles described during soil moisture sensor installation in watersheds 3, 6, and 9 at the Hubbard Brook Experimental Forest in New Hampshire. Each soil horizon color depicts the Munsell soil color chip as identified in the field, unless shown in white, which indicates no color was recorded for that horizon. A ragged boundary indicates the continuation of a horizon beyond the depth of excavation, whereas a solid line indicates the absolute bottom depth of the horizon. Sensor placement depths are shown as light green squares.

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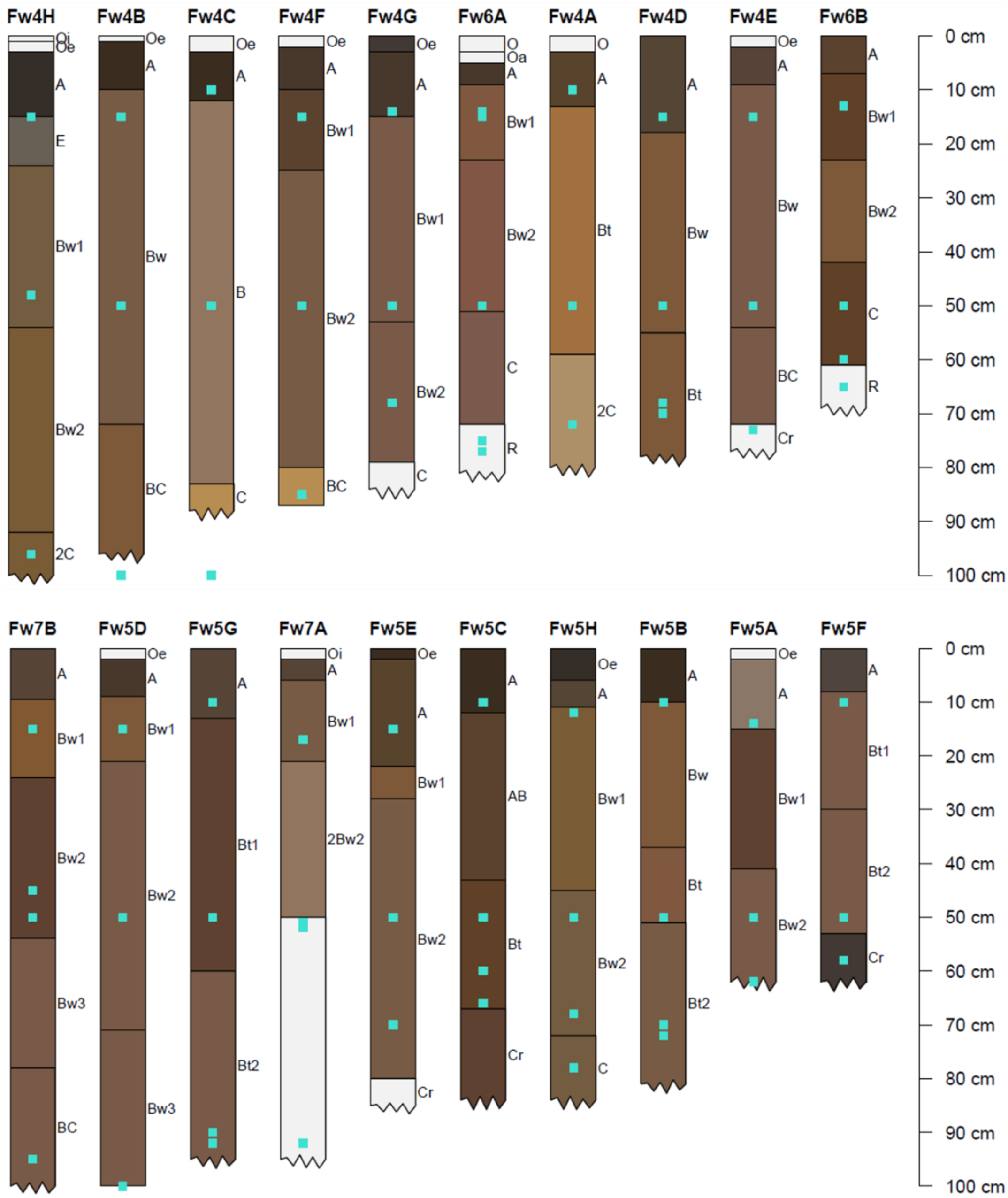

Figure A3. Diagram of the 20 soil profiles described during soil moisture sensor installation in watersheds 4, 5, 6 and 7 at the Fernow Experimental Forest, West Virginia. Each soil horizon color depicts the Munsell soil color chip as identified in the field, unless shown in white, which indicates no color was recorded for that horizon. A ragged boundary indicates the continuation of

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a horizon beyond the depth of excavation, whereas a solid line indicates the absolute bottom depth of the horizon. Sensor placement depths are shown as light green squares.

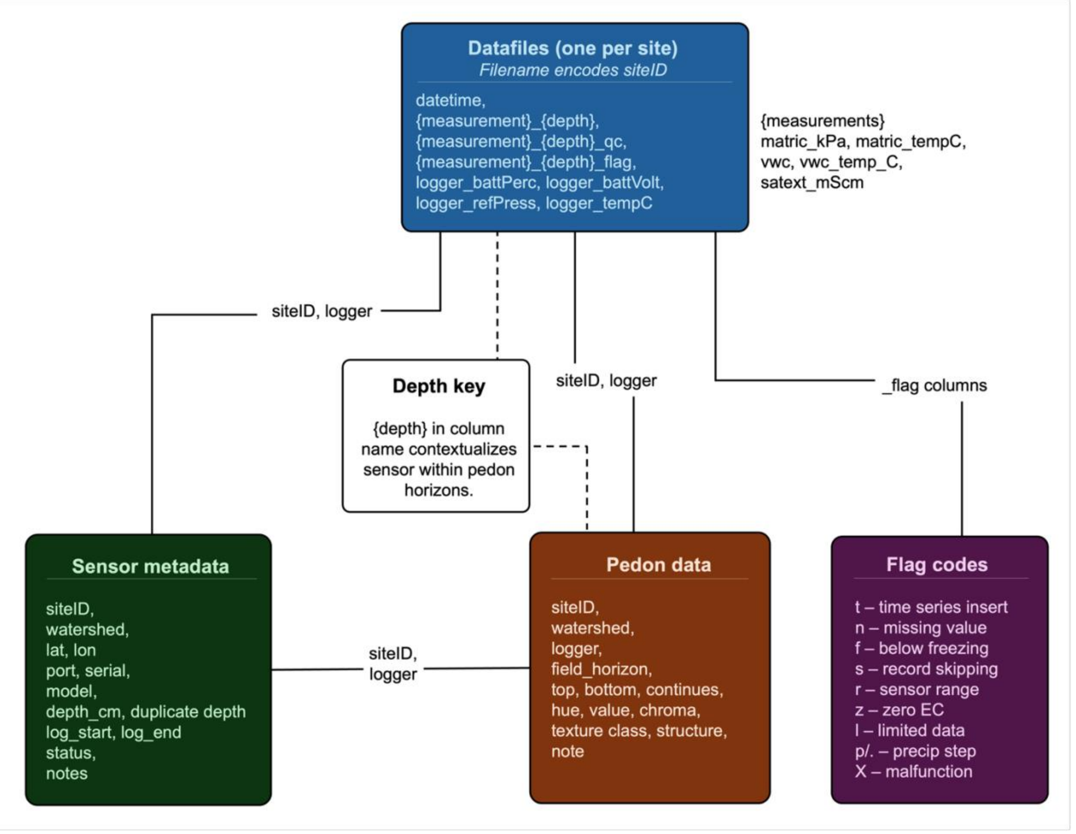

Figure A4. Schematic of the file structure of Forest Soil Moisture Monitoring Network (FSMMN) data repositories, illustrating the relationships between the site datafiles and three companion files (sensor_metadata.csv; pedons.csv, flag_codes.csv). Each datafile is named by a unique site identifier (siteID) and contains hourly timeseries of volumetric water content, soil matric potential, temperature, and electrical conductivity, with associated quality control and flag columns.

Table A2. Summary of annual precipitation totals for each forest across the sensor deployment period. Long-term means are provided for context: Fernow and Hubbard Brook means are drawn from published literature (Adams et al., 2012; Campbell et al., 2021); Coweeta's mean is based on the complete 2023-2024 record annual average.

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Site	2022	2023	2024 (full record)	2025	Long-term mean	Precipitation data source
Coweeta	1,352 (Mar-Dec)	1,510	1,866	818 (Jan-Jun)	1,688	USFS personnel, unpublished data, 2025a
Fernow (RG C)		892 (Apr-Dec)	1,196	891 (Jan-Jun)	1,500	USFS personnel, unpublished data, 2025b
Hubbard Brook (RG 6)		977 (Jul-Dec)	1453	438 (Jan-Apr)	1,400	USDA Forest Service, Northern Research Station, 2025

7 Author Contributions

A.P.: Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing (original draft), Writing (review and editing)

E.P.: Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing (original draft), Writing (review and editing)

B.R.: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing (review and editing)

E.R.: Investigation, Project administration, Supervision, Writing (review and editing)

A.C.O.: Investigation, Project administration, Resources, Supervision, Writing (review and editing)

M.G.: Investigation, Methodology, Supervision, Validation, Writing (review and editing)

S.W.: Funding acquisition, Project administration, Resources, Supervision, Writing (review and editing)

S.C.: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing (review and editing)

8 Competing Interests

The authors declare that they have no conflict of interest.

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