Watershed Dynamics and Evolution (WaDE)

ORNL Science Focus Area 2026 Annual Report

Understanding the role of heterogeneous land cover and hydrologic regime on watershed function

Contents

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ESS Environmental System Science

The freshwater resources supplied by streams and their surrounding watersheds are vital to energy capture and security, human and environmental health, and economic prosperity. Abundant water of suitable quality is needed to support hydropower, cooling operations, human consumption, recreation, irrigated agriculture, and industry. Water availability for these purposes depends on how precipitation that falls on a watershed is transported along diverse flow paths and on the chemical and biological reactions that occur during transport. Hydrologic disturbances (e.g., severe storms or drought events) and changes in land use and land cover (LULC) alter these watershed processes with varied, cascading implications for water resources. Extreme hydrologic events also directly threaten energy infrastructure and disrupt power production (e.g., diverting hydropower operations from electricity generation to flood mitigation) often beyond the spatial footprint of the actual event.

Understanding the processes that control fluxes of water and matter through watersheds is vital to the nation's ability to ensure and predict availability of clean and abundant water for energy and societal needs and to anticipate how extreme events impact the security of the country's energy systems. Long-term research on fundamental watershed processes and concurrent development of modeling capabilities to simulate these processes can provide new scientific understanding and tools for assessing water availability under diverse hydrologic and land use scenarios.

The U.S. Southeast contains significant energy systems and water resources that are uniquely vulnerable to effects of compound disturbances. The Southeast's major river systems have their headwaters in the Appalachian Mountains, including the Tennessee River Basin (TRB), the most intensively used freshwater resource region in the contiguous United States that provides approximately 8% of the country's total power via thermoelectric and hydropower plants and drinking water to 5.2 million people. Regional urbanization is projected to increase by up to 192% over the next 50 years. This land use change, in combination with shifting hydrologic regimes, alters watershed processes and poses new risks to energy and economic prosperity in the region.

Predicting the interactive effects of hydrologic disturbance and LULC change on water resources first requires an improved understanding of interconnected

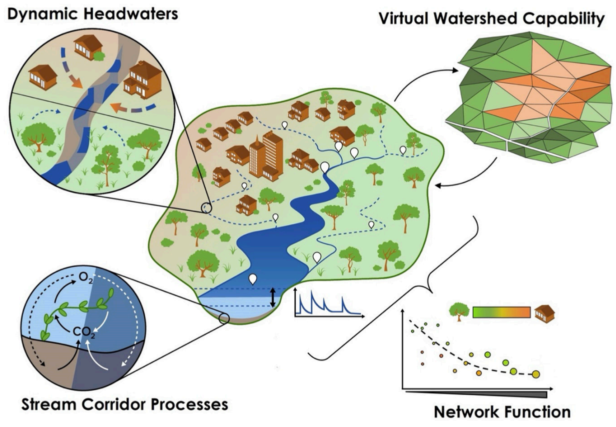


Fig. 1. Research Foci. Conceptualization of 9-year research foci needed to support transferable understanding of watershed hydrobiogeochemical function within and across stream networks that drain heterogeneous land covers: upland-stream interactions, controls on coupled in-stream metabolic processes, emergent network-scale behaviors, and development of configurable virtual watershed capabilities.

hydro-biogeochemical processes within watersheds and how they aggregate to affect watershed function. To address these needs, the Watershed Dynamics and Evolution (WaDE) Science Focus Area (SFA) is working to advance predictive understanding of how the dominant processes controlling watershed hydro-biogeochemical function operate under a range of hydrologic regimes and vary along stream networks that drain heterogeneous land covers.

SFA Knowledge Gaps

Land Cover Effects on Watershed Function. Researchers lack sufficient understanding of if, how, and at what scale land cover influences the generation and export of water and solutes from the landscape to the stream network and how this affects local and emergent hydro-biogeochemical function within the stream network.

Hillslope–Catchment Interactions. Researchers have limited understanding of the mechanistic controls on upland–stream interactions and how these interactions vary under different hydrologic regimes and land cover.

Integrated Measures of Watershed Function. Researchers have an incomplete understanding of how measures of stream function, such as stream metabolism, integrate complex watershed properties that vary in space and time.

Mid-Order, Heterogeneous Watersheds. Existing observational networks are skewed to higher-order streams and end-member systems dominated by forested, agricultural, or highly urbanized land cover, leading to a hampered mechanistic understanding at the scale of low- to mid-order watersheds.

Integrated Modeling. Model predictions of watershed function at basin to continental U.S. scales are uncertain due to an incomplete mechanistic understanding of how key processes depend on land cover and hydrologic regimes.

Research Themes

The WaDE SFA is organized around three integrated research themes and a crosscutting modeling activity (see Fig. 1, p. 1). This multiscale, model-observation-experiment framework supports advancement of a deeper predictive understanding of:

- Hydro-biogeochemical processes and feedbacks that control flow generation and solute mobilization and export from headwater catchments with heterogeneous land cover (Theme 1)
- Resultant feedbacks among flow, solute concentrations, and stream function in stream corridors (Theme 2)
- Emergent patterns in stream metabolism at network scales (Theme 3)

Concurrent development of a configurable virtual watershed capability is helping to synthesize process understanding, support numerical experiments, and aid empirical experimental approaches (Modeling Crosscut).

WaDE research activities focus on mid-order watersheds within the upper half of the TRB (see Fig. 2, p. 3). Study sites are representative of three broad groupings of regional watershed types and include an extensive network of watersheds for low-intensity observations (see Fig. 2A, p. 3) and a series of intensive, focus watersheds (see Fig. 2B and 2C, p. 3). Observations from these study systems coupled with the virtual watershed capabilities support and test the transferability of process understanding gained in one system to increasingly disparate ones. We also utilize Lookout Creek Watershed within the Oregon Cascades as a more contrasting testbed (high-gradient, low-nutrient relative to the dominantly low-gradient, high-nutrient TRB watersheds) to compare our understanding of the drivers of dissolved oxygen and organic carbon degradation processes and test the transferability of our multiscale stream corridor modeling capabilities.

This annual report summarizes WaDE accomplishments from July 2025 to June 2026, a period representing the third full year following the SFA's Phase 1 triennial peer review in November 2022 and acceptance in January 2023 by the Environmental System Science program within the U.S. Department of Energy's (DOE) Biological and Environmental Research (BER) program.

Since July 2025, WaDE team members continue to be recognized leaders in their fields, as evidenced by (1) the submission or publication of 19 impactful

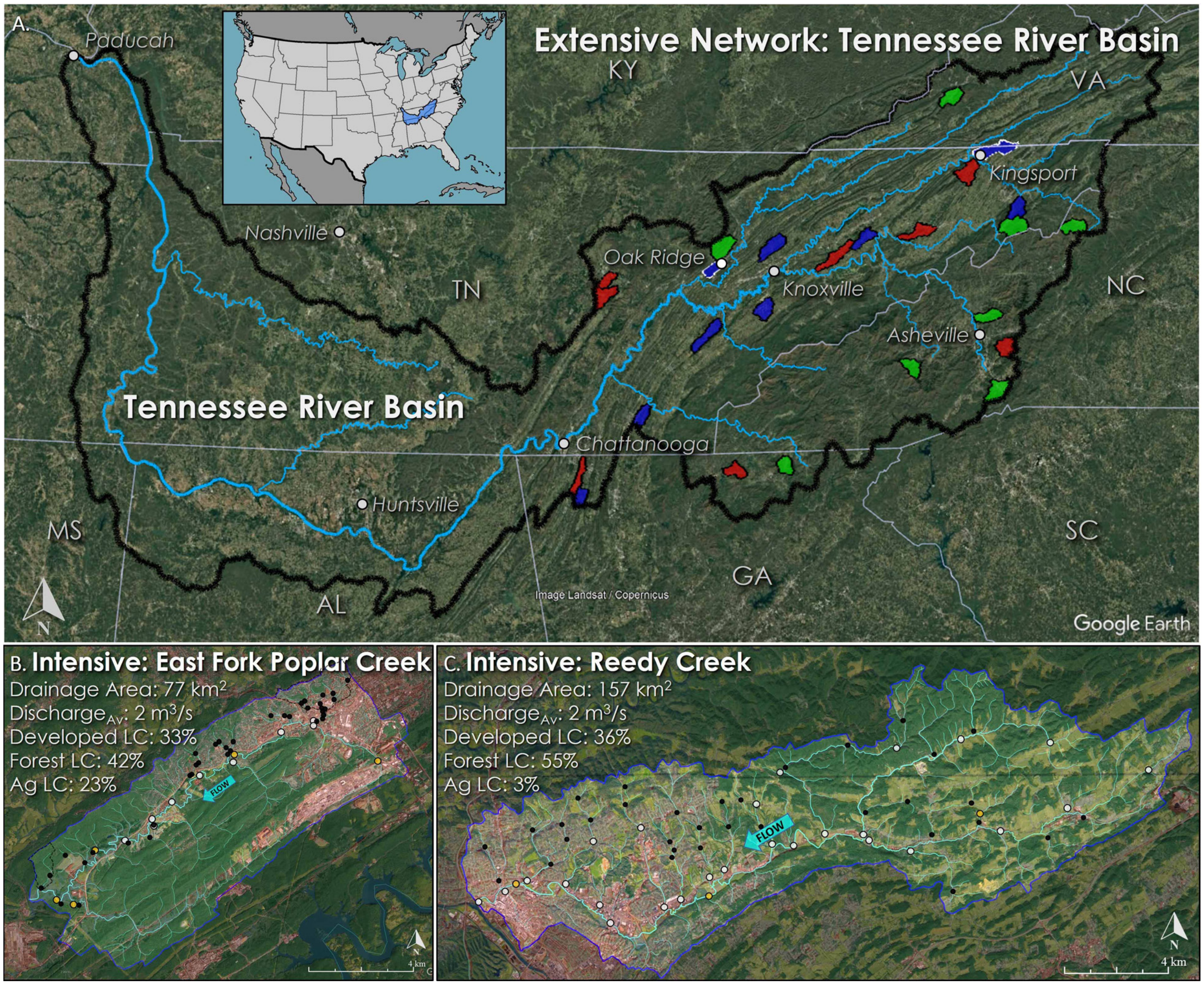


Fig. 2. Mid-Order Study Watersheds Across the Tennessee River Basin. **(A)** Extensive network of study watersheds; colors denote representative clusters based on watershed characteristics known to influence water quality. Details of intensive study watersheds: **(B)** East Fork Poplar Creek near Oak Ridge, Tenn., and **(C)** Reedy Creek near Kingsport, Tenn. Colors highlight the predominant, opposing land cover gradients; dots are the established observation locations.

manuscripts; (2) invited contributions to conferences and workshops such as the Powell Center Working Group on trace metal bioavailability; (3) hosting 10 student interns and visiting faculty; and (4) collaborative ties to multiple DOE-funded and externally funded projects. The team has made significant progress towards our research objectives, with notable cross-theme synergy in the areas of understanding and representing flow and function in intermittent streams; response and recovery of stream biogeochemical functions to storm disturbance; carbon and (micro)nutrient speciation, availability, and uptake; and diversity and function of the microbial communities that underpin key biogeochemical processes.

Research highlights from the past year include configuring our multiscale stream corridor modeling capability to model stream oxygen dynamics and metabolism; employing artificial intelligence techniques to improve our ability to resolve subsurface structure; and concluding a 2-year comprehensive survey at 54 sites across the East Fork Poplar Creek (EFPC) watershed (see Fig. 2B, this page) that is being used to evaluate how stream chemistry, microbial communities, and microbial function vary with flow regime (i.e., perennial versus non-perennial) and land cover. These highlights and others are discussed in greater detail in the following sections.

Theme 1 *Dynamic Headwaters*

Theme 1 integrates hydrogeology, (eco)hydrology, geochemistry, and microbiology to examine how local and downstream biogeochemical processes respond to expansion and contraction of the stream network. Geophysical measurements reveal structural controls on subsurface flow paths that exchange water with the stream network. Water exchange between vegetation, soil, and the atmosphere is traced to evaluate impacts of plant water use on streamflow generation. The chemical and microbial composition of stream water and sediments provides insight into the mobility and bioavailability of macro- and micronutrients. We investigate how interactions across these components shape shifting connectivity between the heterogeneous landscape and stream network and in-stream processes. The guiding research questions for Theme 1 are:

- **Question 1.1:** What are the landscape characteristics that control the frequency and duration of flow in non-perennial streams?
- **Question 1.2:** How do carbon and (micro)nutrient mobilization and chemistry vary in response to changes in sediment saturation across different flow regimes?
- **Question 1.3:** How does variable saturation affect microbiological activity and associated nutrient acquisition and transformation?

FY25–FY26 Accomplishments

In the past year, Theme 1 made significant progress toward evaluating surface and subsurface controls on streamflow, water use by riparian vegetation, spatial and temporal patterns of stream chemistry, and fundamental processes driving biogeochemical transformations. Field work targeted (1) analysis of headwater tributaries across flow regimes and land cover gradients and (2) process-based investigations at a tributary in a highly developed catchment (urban intensive site) and a tributary in a forested catchment (forested intensive site) in the EFPC watershed. Laboratory experiments provided insight into geochemical reactions driving field observations.

Numerical Modeling of Intermittent Flow. We developed a coupled fluid flow and electrical model using the Advanced Terrestrial Simulator (ATS) and COMSOL Multiphysics to integrate field-based self-potential and hydraulic head measurements and to quantify stream–groundwater exchange patterns at the urban and forested intensive sites in the EFPC watershed. A ground-penetrating radar survey was conducted at the forested site to evaluate how subsurface heterogeneity influences stream intermittency patterns. Subsurface heterogeneity in lithology and structure was found to modulate meteorological controls on streamflow persistence, with fractures playing a vital role in sustaining streamflow. Additional self-potential surveys helped to distinguish between connected and disconnected losing conditions and their relative influence on water loss to vertical percolation and resulting flow persistence. At the urban site, analysis of seasonal hydro-chemical signals revealed anthropogenic imprints on streamflow patterns, with urban sources sustaining surface water during periods when a channel would naturally have been dry, delaying flow cessation, and artificially shortening the duration of stream intermittency.

Water Use by Riparian Vegetation and the Ecohydrologic Drivers of Streamflow. We used continuous sensor measurements and water isotopes as conservative tracers to evaluate water exchange between the atmosphere, riparian vegetation, groundwater, and stream network at the urban and forested intensive sites. Riparian sap flow appears strongly correlated with vapor pressure deficit but generally disconnected from soil volumetric water content, precipitation, and both in-stream and groundwater levels. New soil moisture sensors have been installed within the existing sap flow cluster to better understand the relationship between soil moisture and riparian vegetation water usage. Stable isotope data indicates trees at both sites are likely using near-surface soil water instead of groundwater or stream water. Tight clustering in the isotopic ratios of soil, ground, stream, and xylem waters in the

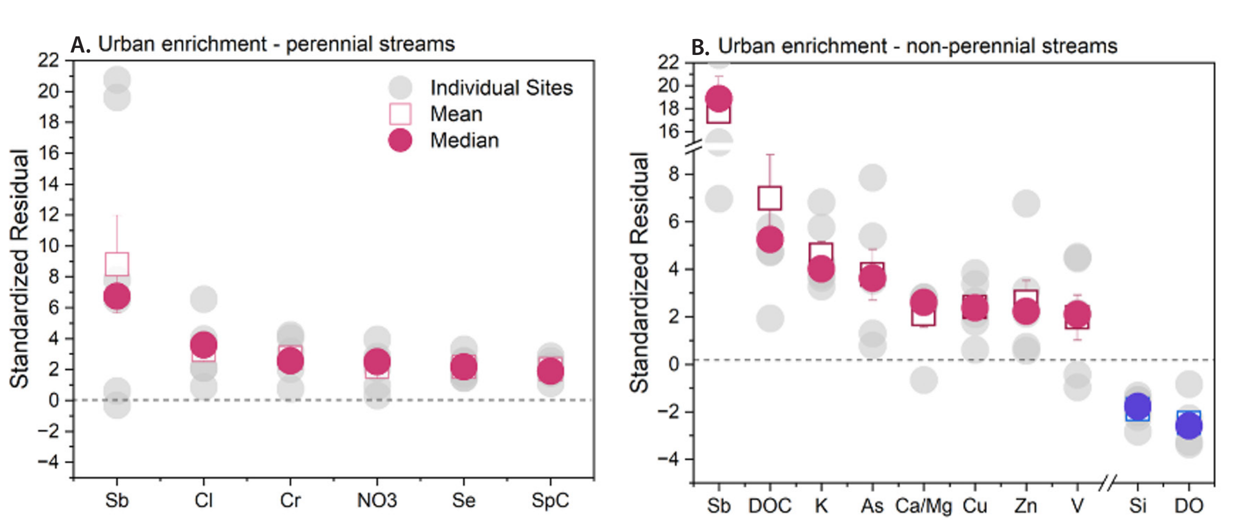


Fig. 3. Solute Enrichment from Urban Development. Significant enrichment (magenta) or depletion (blue) of parameters in **(A)** perennial and **(B)** non-perennial streams draining highly developed catchments (>70% developed), as determined by the mean (open squares) and median (closed circles) standardized residuals of actual concentrations relative to predicted concentrations derived from observations of low to medium development streams. Gray symbols indicate the standardized residual for each highly developed site.

forested site suggests all water sources are more homogeneous compared to the urban site. Further investigations comparing individual tree distances and intra-storm event samples are needed to fully understand how urban versus forested land cover impact streamflow generation.

Urban Impacts on Stream Chemistry Across Flow Regimes. We completed a 2-year comprehensive survey of stream chemistry at 54 sites across the EFPC watershed to evaluate how stream chemistry varies with flow regime (i.e., perennial versus non-perennial) across an urban-to-forested gradient. Results show carbonate weathering signatures increased with decreasing elevation, likely due to increasing inputs from deeper flow paths with longer residence times. Streams draining highly developed catchments contained enriched major ion and trace element signatures consistent with weathering of carbonate infrastructure, road salt, and excess nutrients, but these anthropogenic impacts could only be identified within the context of hydrologic flow paths (see Fig. 3, this page). Perennial and non-perennial streams exhibited different enrichment patterns that may reflect distinct sources or processes (see Fig. 3, this page) and unique geochemical conditions that develop as streams dry and rewet. This study presents a framework for evaluating anthropogenic impacts within the context of natural variability by decoupling urbanization from effects of increasing groundwater contribution. These patterns and their underlying processes have important implications for the suitability of water resources for different usages (e.g., freshwater salinization impacts on infrastructure corrosion and contaminant mobilization).

Water–Rock Interactions and Weathering Dynamics. We applied an integrated hydrological-geochemical framework to understand controls on calcium and sulfate dynamics in the EFPC and fully forested Walker Branch watersheds. Our approach combined (1) long-term discharge records with baseflow separation; (2) machine learning to isolate core concentration–discharge behavior independent of seasonal and long-term trends; (3) river load estimation modeling to estimate solute export; and (4) sulfate isotope ($\delta^{34}S$ and $\delta^{18}O–SO_4$) measurements to identify sulfur sources. EFPC baseflow chemistry is strongly influenced by gypsum dissolution, with contributions increasing systematically downstream (see Fig. 4, p. 6), consistent with deeper groundwater flow paths intersecting a gypsum reaction front at depth. In contrast, Walker Branch displays much lower sulfate concentrations, and high-flow enrichment is

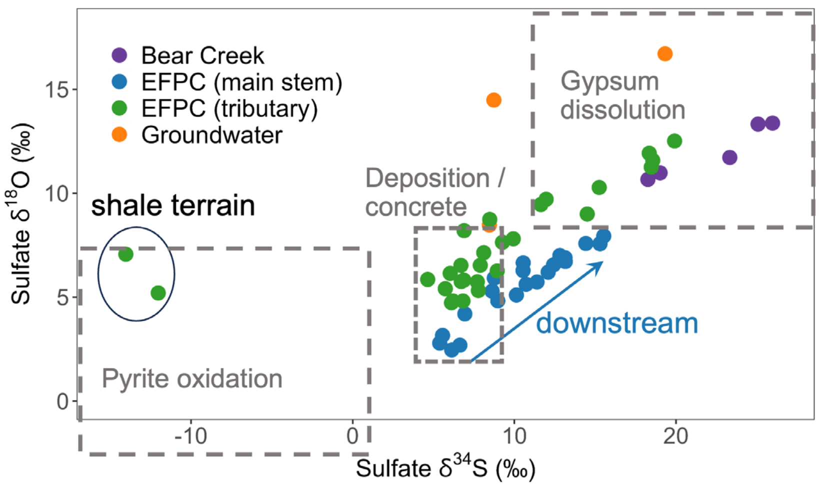


Fig. 4. Sulfate Dynamics. Dual-isotope composition of dissolved sulfate ($\delta^{34}S$–SO_4 versus $\delta^{18}O$–SO_4) across East Fork Poplar Creek and its tributaries.

best explained by flushing of shallow legacy sulfate derived from historical atmospheric deposition rather than mineral sulfide oxidation. These contrast highlights a transition from deep, gypsum-controlled groundwater sources in EFPC to surface- and deposition-dominated sulfur cycling in forested catchments like Walker Branch Watershed.

Speciation of Redox-Active Metals in Headwater Stream Sediments. We investigated the distribution and solid-phase speciation of redox-active metals in a forested versus urban tributary in the EFPC watershed to better understand the impacts of land cover and stream intermittency. We employed a dual-scale spectroscopic approach, coupling bulk X-ray absorption near-edge structure (XANES) spectroscopy with spatially resolved micro-focused XANES (μXANES) on intact, unground sediment grains. Unsupervised machine learning revealed distinct geochemical signatures separating urban and forested tributaries. Results show that mineral weathering processes produce secondary minerals and organic-metal phases in both highly developed and forested streams within the watershed. Forested sites reflected geogenic, biotic, and environmental weathering processes, while developed sites reflected anthropogenic inputs and altered redox dynamics. The surface-sensitive μXANES analyses were essential for accurately identifying chemically active phases relevant for element cycling that were obscured in the bulk XANES analyses.

Trace Element Bioavailability Across Flow Persistence and Land Cover Gradients. To assess how stream properties shape micronutrient bioavailability, we evaluated potential zinc (Zn) and copper (Cu) bioavailability across the EFPC watershed using the Biotic Ligand Model (BLM), a geochemical speciation model developed to assess aquatic toxicity. Unsupervised machine learning analysis of stream chemistry identified five distinct stream typologies within EFPC (see Fig. 5, p. 7). Dissolved Zn and Cu concentrations were highest in the main stem, but their bioavailability was suppressed by high concentrations of ions that compete for uptake (e.g., calcium) and formation of Zn-carbonate and organic Cu complexes. Perennial and non-perennial tributaries had lower dissolved concentrations but higher relative proportions of bioavailable Zn and Cu due to low concentrations of inhibiting factors. In highly developed tributaries, anthropogenic calcium enrichment suppressed Zn bioavailability while Cu bioavailability increased. This study demonstrates the effects of developed land cover and varying flow regime on trace element bioavailability and serves as a test case for applying the BLM at a watershed scale to assess subsidy-stress gradients to organisms.

Headwater Stream Microbiological Composition and Function. We completed a 2-year survey of microbial community composition and enzyme activities controlling the decomposition of organic matter in four stream habitats (water column, epilithic biofilms, leaf litter, and streambed sediments) at 54 tributary sites across the EFPC watershed to test the hypothesis that urbanization and lack of permanent surface water

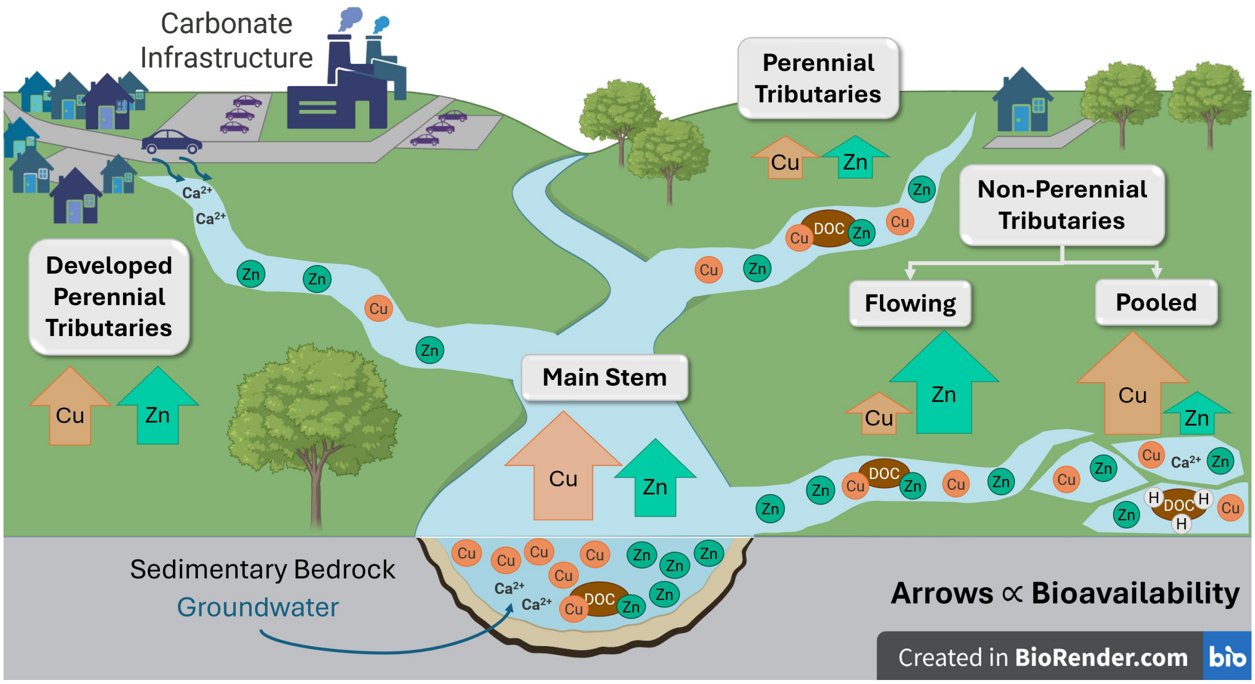


Fig. 5. Bioavailability of Copper (Cu) and Zinc (Zn) Across Five Distinct Stream Typologies in the East Fork Poplar Creek Watershed. Bioavailability was modified by complexation with dissolved organic matter and biological competition for uptake with ions such as calcium (Ca). Effects of increased metal concentrations on bioavailability in developed catchments were mitigated by decreases in dissolved organic matter and increases in dissolved ions from weathering of carbonate infrastructure.

flow (i.e., non-perennial flow) would both impair microbial structure and function, with additive effects. Initial results show that microbiological patterns associated with non-perennial flow regimes and urbanization differed among stream microhabitats. Flow regime only affected stream microbial populations under relatively intense urbanization (see Fig. 6, p. 8). In contrast, microbial activity appears to be more sensitive to non-perennial flow conditions, with a consistent signal of greater heterotrophy [net carbon (C) release to atmosphere] than autotrophy (C sink from atmosphere) in non-perennial streams. Continuing investigations aim to understand how combinations and proportions of these microhabitats help explain the microbial role in nutrient and C processes in urban non-perennial streams.

Storm Flow Dynamics. Brief, high-intensity flow events disproportionately drive the flushing, transformation, and transport of solutes from terrestrial headwaters to downstream river networks. Since summer 2025, we have been measuring groundwater–stream connections during baseflow and storm events at the EFPC urban and forested intensive sites, with a focus on inorganic solutes (e.g., nutrients, base cations, and metals) and organic matter composition. Initial results show that dissolved organic carbon (DOC) concentrations were comparable between groundwater and stream water at each intensive site but overall higher at the urban site during baseflow. Shifts in DOC concentrations and aromaticity of the urban groundwater and stream water during the first storm event measured to date indicate increasing contributions of DOC that most likely originate from surface soils rather than groundwater during storm events.

FY27 Planned Activities

We will develop manuscripts targeting the research detailed above. We will also continue experiments that (1) investigate surface water–groundwater interactions in dynamic headwaters, including calibrating the coupled hydrological-geophysical model at both intensive study sites in EFPC; (2) explore

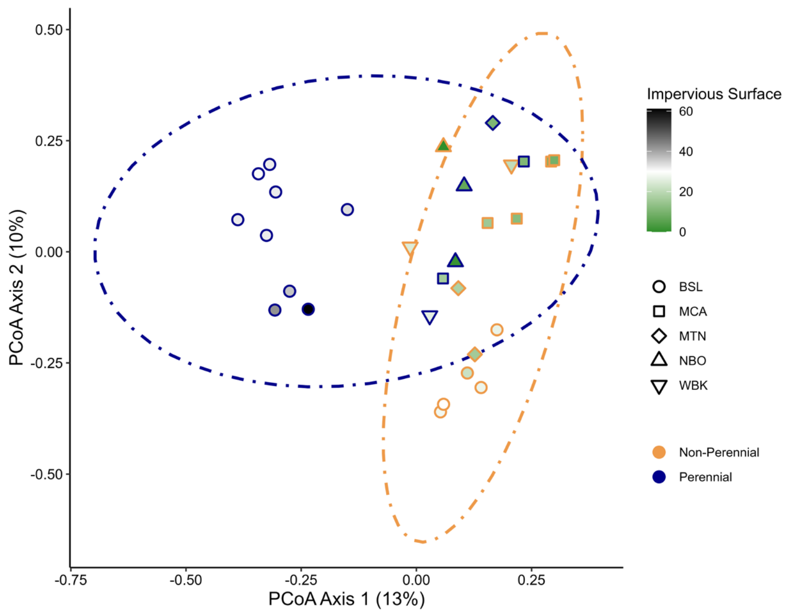


Fig. 6. Water Column Microbiome Composition. Principal coordinates analysis (PCoA) of water column protist community composition in the perennial (blue) and non-perennial (orange) headwater tributaries of East Fork Poplar Creek (EFPC) with a dash line of the 95% confidence interval. Shapes represent different tributary catchments of EFPC. The fill color (gray to green) shows the percentage of urban land cover within the site's drainage area.

the observed spatiotemporal patterns in stream chemistry, including quantifying the relative roles of atmospheric deposition, sulfide oxidation, and carbonate/evaporite weathering in shaping sulfate and calcium export at Reedy Creek; (3) evaluate how organic matter and metals are stored in stream sediments and mobilized into surface water using nano- to micron-scale analytical techniques; and (4) investigate how chemical composition of the headwaters shifts both during storm events and as streams dry out and how these headwater fluxes contribute to local and downstream biogeochemical processing of C and nutrients.

Theme 2
Stream Corridor Processes

Theme 2 aims to quantify reach-scale processes over seasons and land cover gradients in mid-order streams using a combination of field experiments, laboratory mesocosm studies, long-term observations, and modeling. This work's foundation lies in quantifying stream metabolism at the stream-reach scale as an integrated metric of watershed function to evaluate ecosystem health and stream response to different land cover and flood disturbance. The guiding research questions for Theme 2 are:

- **Question 2.1:** What are the relative contributions of water column and sediment processes to gross primary production (GPP) and ecosystem respiration (ER)?
- **Question 2.2:** How do organic matter burial and anaerobic processes affect stream metabolism?
- **Question 2.3:** How does disturbance by floods impact the resistance and resilience of reach-scale GPP and ER?

FY25–FY26 Accomplishments

Evaluating Stream Ecosystem Resistance and Resilience to Storm Disturbance. To examine storm disturbance effects on stream metabolism and ecosystem stability, we developed and refined a long-term, event-based framework to quantify storm impacts on GPP and ER (see Fig. 7, p. 9) at the two long-term monitoring EFPC sites. We improved methods for identifying storm disturbance and recovery periods, developed phase-specific metrics that separate resistance and resilience response intervals, and advanced site- and storm-type comparisons of metabolic severity and intensity. The work is being extended to evaluate hydrologic controls on metabolic response and explore complementary machine learning approaches for interpreting storm-day oxygen dynamics, where standard metabolism estimates may be less reliable under highly unsteady flow conditions.

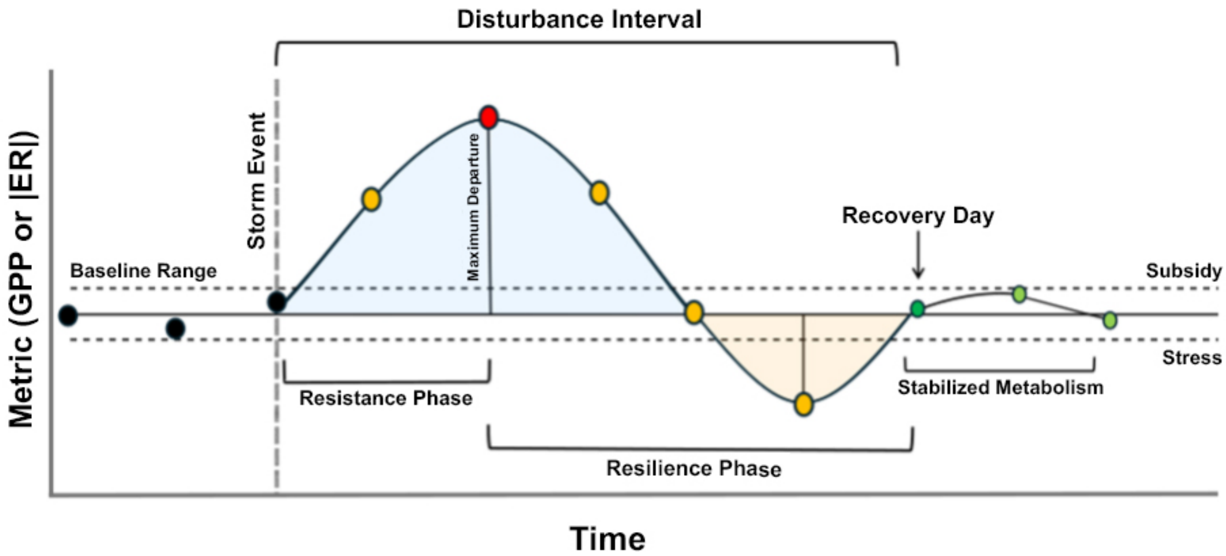


Fig. 7. Conceptual Diagram Illustrating Ecosystem Metabolic Disturbance and the Components of Stability. The disturbance interval spans the storm event to recovery day and is split into two phases, resistance and resilience, by the time of maximum departure. Severity is measured as the area under the curve relative to baseline and can be partitioned into a subsidy (positive; blue shading) and stress (negative; orange shading) response. Stability is defined by the combined magnitude and duration of the response within the disturbance interval.

Linking Stream Water Nitrogen to Argon and Methane to Argon Saturation Ratios to Estimates of Ecosystem Metabolism. The inclusion of anaerobic processes (e.g., denitrification and methanogenesis) alongside traditional oxygen-based estimates of GPP and ER can improve predictions and understanding of watershed biogeochemical dynamics, but simultaneous daily estimates of reach-scale anaerobic processes remain challenging to conduct across multiple sites in a stream network. We are exploring linkages between GPP, ER, net denitrification, and net methane flux across the EFPC mainstem and major tributaries. Nitrogen (N_2) and methane (CH_4) saturation in stream waters relative to equilibrium concentrations was measured monthly for a year (see Fig. 8, p. 10). Random forest, a type of machine learning analysis, showed water column signals of anaerobic processes are loosely coupled with estimates of aerobic stream metabolism. Neither N_2 nor CH_4 saturation was related to ER, but CH_4 saturation was negatively related to GPP, suggesting oxygen production from GPP may limit CH_4 saturation by facilitating CH_4 oxidation in the stream. CH_4 saturation was positively related to water temperature, unlike N_2, suggesting N_2 and CH_4 saturation ratios respond to different aspects of stream biogeochemistry.

Microbial Dynamics and Processes Over Time and Space. This year, we completed microbial community analyses of (1) 2 years of surface water samples collected from more than 54 sites across EFPC; (2) complementary groundwater samples collected from wells adjacent to EFPC and the Bissel tributary, and (3) select stream and spring samples from the Reedy Creek watershed. We are characterizing spatial-temporal microbial dynamics and identifying biotic patterns that correlate with, and potentially respond causally to, abiotic factors, with the ultimate goal of improving predictive understanding of ecosystem function. Temporally, microbial communities in the EFPC network varied in patterns consistent with seasonal forcing but did not resolve into reproducible, cyclical "seasonal states" (see Fig. 9, p. 10). Spatially, stream communities were compositionally similar to those in groundwater and springs but distinct from those in sediments, soils, and periphyton. Distinct compositional patterns between EFPC and the various tributaries may provide microbial "fingerprints" that can be correlated with geochemical signatures and used to better resolve source contributions,

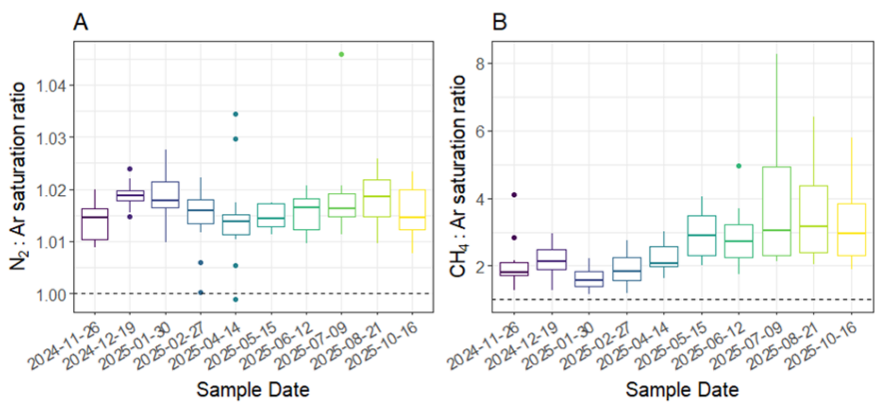


Fig. 8. Nitrogen (A) and Methane (B) Saturation Ratios in East Fork Poplar Creek Surface Water Samples. The horizontal line at value = 1 indicates equilibrium with atmospheric concentrations. Values above 1 indicate net production of each gas relative to other sampling dates. Boxplots show median, first, and third quartiles across sites on each sampling date. Outliers are indicated by points outside boxes.

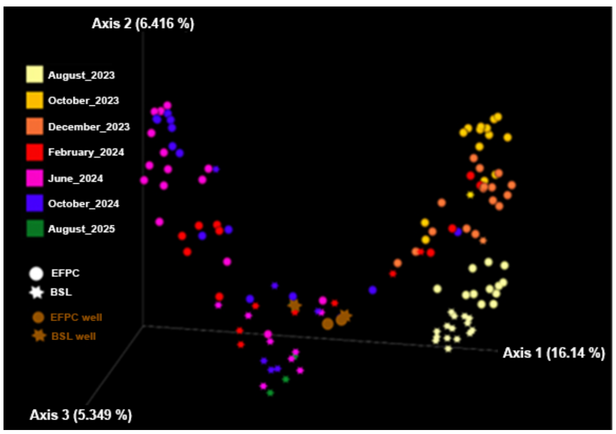


Fig. 9. Beta Diversity Analysis (Bray Curtis Distances) of Seasonal Variation Across East Fork Poplar Creek and Bissel Tributary (BSL) Stream Water Microbial Communities. Each dot corresponds to a sampled location.

flow-path influences, and watershed-scale biogeochemical processes. The Reedy Creek network had distinct compositional patterns relative to EFPC, but one taxa, Patescibacteria, is predominantly associated with subsurface sources in both watersheds and may serve as a useful tracer lineage.

Time as an Organizing Principle: Transient Windows Govern Solute Dynamics in Aquatic Systems. Disentangling the complex drivers of time-varying solute concentrations in streams is challenging, in part because observational time series frequently have gaps and inconsistent sampling frequencies and conventional analysis approaches often assume synchronous, time-averaged environmental controls. We applied an interrupted time series model to a 6-year time series of methylmercury (MeHg) concentration in EFPC and found that solute dynamics are governed by transient windows (TW)—short-lived, asynchronous physicochemical shifts that make time an active organizing principle, capturing the inherent endogeneity of processes controlling solute transformations. We identified 23 distinct Hg-to-MeHg transformation functions organized into four dominant TW, representing episodic production driven by dissolved Hg and DOC, temperature, and interactions between total and dissolved Hg. Unlike conventional models, our results reveal that MeHg production is governed by reorganization across TWs, reframing aquatic biogeochemistry as episodic, event driven, and state dependent. The TW framework is widely transferable and resolves a fundamental paradox in environmental science: why time-averaged models persistently fail despite mechanistic understanding.

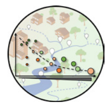
Geophysical Characterization of Floodplain–Surface Water Exchange Flows in Shallow Epikarst-Karst Systems. Self-potential (SP) signals are the result of natural electrical fields generated as water flows through the ground, such as in floodplains where stream water interacts with underground rock layers. To better understand preferential groundwater–surface water flow patterns within the karstic floodplain aquifer around EFPC, we developed an interpretative SP data-processing and tomography (SPT) framework based on a hypothetical dataset and then applied the framework to data from prior SP mapping on the EFPC floodplain. The combined results of concurrent 2D electrical resistivity tomography (ERT) mapping and the new SPT framework yielded quasi-3D models that depict zones of preferential groundwater flow both laterally through epikarst and vertically along faults and fractures in the karst zone of the limestone aquifer. The results refine the hydrogeologic conceptual model of groundwater flow through the complex fracture networks and hydraulically connected dissolution cavities within the aquifer. These fracture–cavity connections function as conduits capable of transporting and storing nutrients and have important implications for element cycling, nutrient processing, and aquifer and surface water management.

Localization of Spatiotemporally Heterogeneous Subsurface Flows Using Artificial Intelligence. Understanding how water moves underground is crucial for managing water resources and predicting environmental change. SP mapping helps monitor subsurface water flows, but interpreting SP data can be difficult because of the complex subsurface environment and the presence of noisy, short-term signals. We developed a deep learning method to help analyze SP data collected from the EFPC floodplain, the results of which are detailed in the Research Highlight on p. 19.

Subsurface Sloping-Layer Interface Mapping with Otsu Technique and Singular Value Decomposition (SVD) Reduced-Dimensionality Neural Network (NN) ERT Inversion. To improve our ability to characterize subsurface structure (e.g., soil versus bedrock or aquifer versus confining unit) and heterogeneity, we compared the performance of reduced-dimensionality approaches for a multilayer perceptron (MLP) neural network for interpreting 2D ERT inversion. We used SVD to reduce input parameters, thereby reducing model complexity and improving accuracy, and used Otsu segmentation on inverted field ERT measurements to locate sloping interfaces between two layers of contrasting resistivity, specifically buried bedrock. The SVD-MLP-NN and MLP-NN models have similar performance with low average relative error, but the SVD-MLP-NN method has higher computational efficiency.

FY27 Planned Activities

Manuscripts detailing the work characterizing subsurface structure are either published or in review, and the manuscript about TW influence on stream mercury concentrations is also in review. A manuscript detailing developments quantifying stream metabolic stability to storm disturbance is in progress. Ongoing work on anaerobic metabolic processes will explore relationships identified through random forest and develop a manuscript that sets out hypotheses to be tested regarding links between aerobic and anaerobic aspects of C and nitrogen cycles. We are continuing an investigation started by a student intern last summer into nitrate spiraling patterns in the mainstem of EFPC upstream and downstream of the wastewater treatment plant, with completion of the interpretation and manuscript draft awaiting final sample analyses.



Theme 3 *Network Function*

Theme 3 aims to resolve the large-scale organizational drivers of emergent patterns and regimes in stream function within and across mid-order stream networks with heterogeneous land cover. Our work integrates measurements from high-frequency sensor networks, synoptic sampling campaigns, network-distributed experiments, and forward and inverse modeling tools to evaluate network-scale patterns and synchrony in coupled metabolic processes (e.g., stream metabolism, C spiraling, and particulate C degradation) to key watershed structures (especially land cover) and dynamic forcings (e.g., expansion and contraction of the stream network and storm disturbances). The guiding research questions of Theme 3 are:

- **Question 3.1:** When and where do metabolic regimes synchronize along a stream network, or why do they diverge?
- **Question 3.2:** How do variable inputs of flow and solutes from non-perennial tributaries influence rates of stream metabolism in the downstream mainstem, and how does this effect scale with the length of the flowing network?

FY25–FY26 Accomplishments

This past year, we concluded 2 years of bimonthly synoptic chemistry sampling across our EFPC site network (see Fig. 2B, p. 3) and completed modeling of nearly 3 years of colocated stream metabolism. These two valuable datasets support multiple

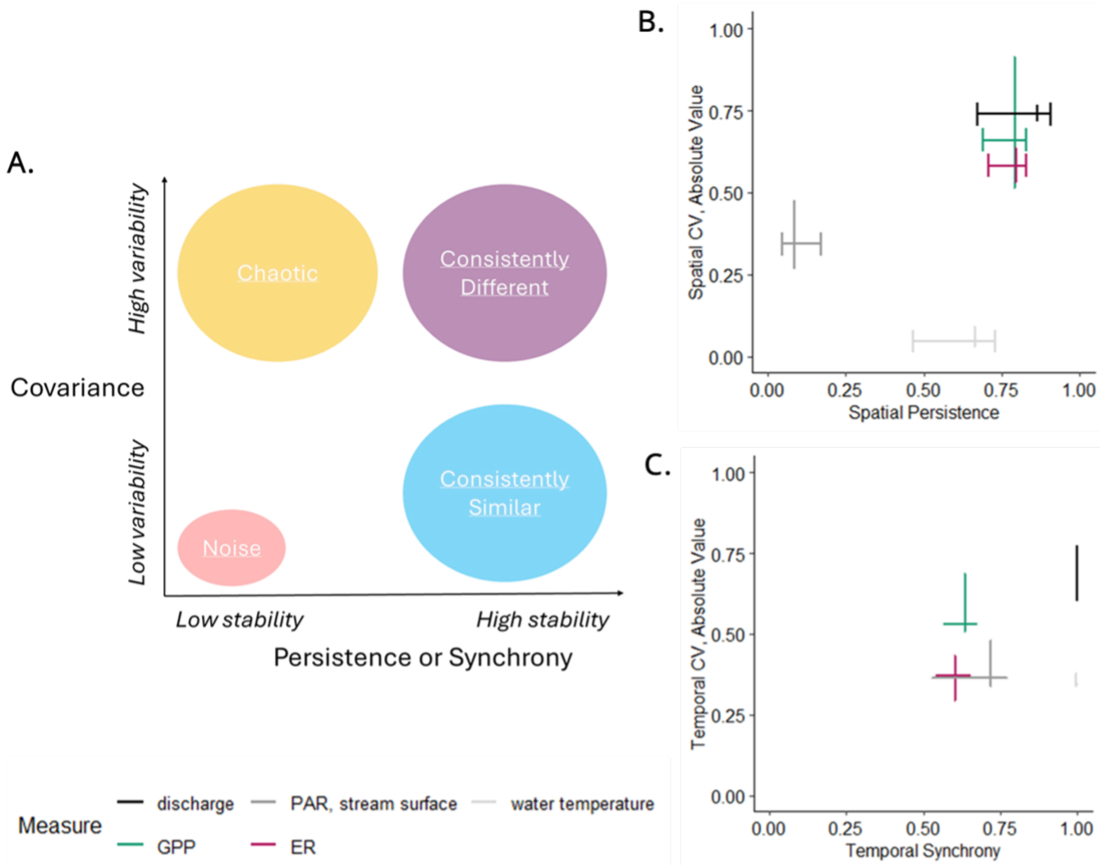


Fig. 10. Variability and Stability in Measures of Metabolism and Key Drivers in East Fork Poplar Creek. **(A)** A conceptual model to distinguish measures based on their combined variability in magnitude (covariance) and stability of order (persistence or synchrony). **(B)** Spatial covariance and persistence of daily metabolic rates and their drivers for each day in the time series. **(C)** Temporal covariance and synchrony across each site in the watershed. The median and 25th and 75th percentile is shown across all days (B) and sites (C). Spatial persistence and temporal synchrony calculated per Gu et al. 2021.

Theme 3 research efforts, detailed below, in addition to Theme 2 investigations of nutrient spiraling and anaerobic metabolism and validation of the whole watershed metabolism modeling capabilities developed within the Modeling Crosscut. Beyond EFPC, we supported a second synoptic campaign at Reedy Creek (see Fig. 2C, p. 3) in fall 2025 to evaluate the stability of spatial biogeochemical patterns relative to a prior wet-season campaign. We also conducted two additional synoptic campaigns across our regional sites (see Fig. 2A, p. 3), which, combined with data from our regional sensor network, inform an evaluation of the predictive power of watershed attributes and investigations into both the short- and long-term impacts of Hurricane Helene's historic disturbance. These regional activities, complementary experiments at the H.J. Andrews Experimental Forest, and several national-scale synthesis efforts also collectively provide insights to support transferability across different watershed systems and network scales.

Synchrony in Metabolic Regimes Relative to Key Drivers. The spatial and temporal synchrony of GPP, ER, and their key drivers (light, temperature, and discharge) are being assessed over a nearly 3-year period across the EFPC network of mainstem and tributary sites (see Fig. 10, this page). Light availability to the stream differs spatially between sites due to differences in local riparian land cover and temporally as canopy opens and closes between seasons. Stream temperatures are consistently similar throughout the year across the watershed, except in the winter

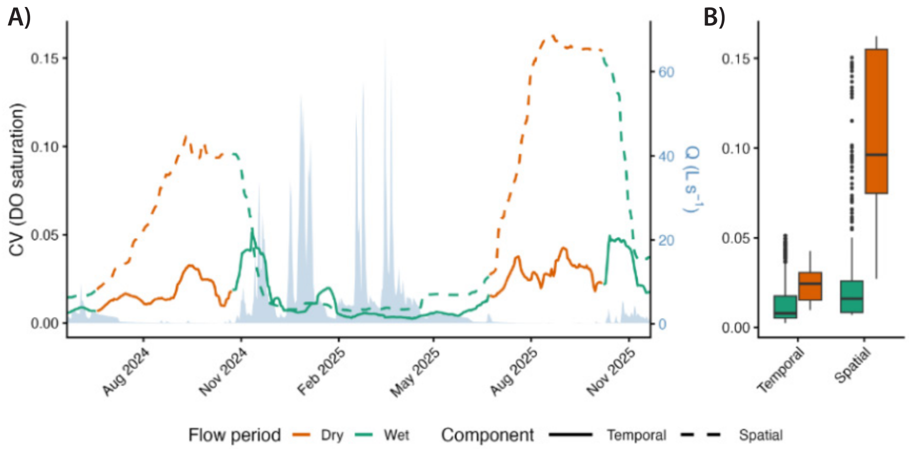


Fig. 11. Temporal and Spatial Components of the Variability in Dissolved Oxygen (DO) Saturation Across Dry and Wet Flow Periods. **(A)** Solid lines show temporal coefficient of variation (CV); dashed lines show spatial CV. Shaded area indicates discharge (Q, right axis). Spatial variability is consistently greater than temporal variability but is elevated during dry periods relative to wet. **(B)** Boxplots summarize the full distributions by component and flow period.

when urban-industrial point sources differentially warm the stream water. Metabolic rates (GPP and ER) are more similar in magnitude between sites, despite greater variability in metabolism drivers (temperature and light) across the same sites.

Drivers of Dissolved Oxygen (DO) Dynamics Across a Spatially Intermittent Mountain Headwater Stream Network. We conducted light-dark DO flux incubations, continuous sensor deployments, and a synoptic water chemistry sampling campaign to support empirical analysis of network-scale DO patterns and drivers across drying and rewetting cycles within a montane headwater watershed. Preliminary results indicate that spatial variability in DO saturation consistently exceeds temporal variability, but this variability is amplified during dry periods (see Fig. 11, this page), suggesting hydrologic fragmentation decouples reach-scale controls and elevates local drivers' influence on network-scale DO dynamics.

Resistance and Resilience of Stream Metabolism to Storm Disturbance. Two projects have focused on evaluating different aspects of how stream metabolism responds to storm disturbance. The first utilized both Theme 3 and U.S. Geological Survey sensor data to evaluate the response of stream metabolism to Hurricane Helene (>1-in-1,000-year event producing record streamflow) relative to other storm events at four nested sites in the Upper French Broad River near Asheville, N.C. At all sites, the time for post-storm recovery of GPP was significantly related to stormflow volume, with recovery following Helene scaling consistently with the magnitude of the hydrologic disturbance. Conversely, there was no pattern between the recovery of ER and storm size.

The second project applied machine learning techniques (e.g., random forest models) to investigate the metabolic recovery time and magnitude to storm flow perturbations across a nationally distributed set of 50+ sites. Spatially variable measures, including land cover and other watershed attributes, are stronger predictors of post-storm metabolic recovery than traditional temporally variable measures including light, temperature, and storm severity. This project and associated manuscript are led by a DOE Summer Undergraduate Laboratory Internship (SULI) intern.

Systematic Review of the Methods and Magnitudes of DO Exchanges in Streams and Rivers. We synthesized DO fluxes from 230 empirical studies dating from 1964 to 2024 to assess where, how, and under which hydrologic conditions individual oxygen exchanges have been quantified in streams and rivers and the magnitudes of these exchanges. Substantial geographic and hydrologic biases were revealed, including limited quantification of hyporheic and other subsurface processes and a lack of measurements in non-perennial streams. Notably, in-channel and out-of-channel processes exhibited the highest variability in flux magnitudes yet were measured far less frequently than whole-stream metabolism and gas exchange, underscoring the need for concurrent, multi-compartment empirical observations.

Network-Scale Microbiological Composition and Function. To better understand the biological drivers of stream C processing at the network scale and ultimately inform the modeling of microbial contributions to stream metabolism and decomposition, we surveyed microbial community composition and decomposition enzyme activities from four microbial habitats (water column, epilithic biofilms, leaf litter, and streambed sediment) across Theme 3's EFPC site network (see Fig. 2B, p. 3). Preliminary results reveal that impervious surface within the watershed directly relates to the autotrophic relative abundance within the water column. We found a seasonal shift from a high relative abundance of autotrophs in the summer to a predominantly heterotrophic community in autumn, driven by leaf fall. Habitat-specific analysis further illustrates the extent to which C processing could vary within the stream site. We compared an index of relative C versus nitrogen or phosphorus demand by the microbial community across the four habitats. The microbiomes on cotton strips and leaf litter showed highest relative C demand, while epilithic biofilms were lowest, likely because photoautotrophs in those biofilms produced more available sugars. Further research is investigating how the taxonomic makeup and proportion of stream habitat relate to C processes within the stream network.

Synchrony and Key Drivers of Organic C Spiraling Dynamics. We published the first of a series of planned papers on C spiraling dynamics in TRB streams, focusing on daily frequency trends in Walker Branch Watershed over 7 years (Pilla et al. 2026). We used advanced time series analyses to quantify subannual patterns in C spiraling dynamics and linked these responses with seasonal biogeochemistry and canopy phenology, suggesting potential for transferability to other stream networks with little to no monitoring data. This work is informing analysis of C spiraling synchrony across the EFPC network, wherein spatial persistence and temporal synchrony metrics have been analyzed from eight sites over 2 years. Initial results suggest C spiraling is very spatially persistent and longitudinally predictable, but temporal synchrony varies seasonally, likely due to differences across sites, including variation in canopy cover and phenology. Together, this body of work provides insight into complex C dynamics across stream networks that are vital components of the global C budget to predict changes in water and C availability, usage, and transport at broader scales in unmonitored watersheds.

Variability of Organic C Decomposition in a Mountain Headwater Stream and Hyporheic Zone. We have been analyzing the spatiotemporal variability of particulate organic C (POC) decomposition rates in an intermittent headwater stream in the Western Cascades of Oregon to compare against rates and drivers in the TRB and understand the utility of these measurements in the context of local-to-global C budgets. Repeat cotton strip deployments from July through November were used to estimate decomposition rates in the stream and hyporheic zone as the stream disconnected and reconnected. Variability in decomposition rates increased as the stream became more disconnected. Drivers of POC decomposition vary locally and included nutrient availability, DO concentrations, and discharge in this system, while temperature and macroinvertebrates were the main contributors in Walker Branch (Griffiths and Tiegs 2016). WaDE-supported Oregon State University student Cassie Knudson successfully defended her Master of Science thesis based on this work in May 2026.

Using Watershed Characteristics to Predict Stream Chemistry and Aid Cross-System Transferability. Stream water quality is strongly related to interactions between watershed characteristics (e.g., land cover and geology) and hydrometeorological forcings, which is the basis for WaDE's determination of representative watershed clusters for the TRB (partially shown in Fig. 2A, p. 3). However, the relative importance of individual watershed characteristics for driving spatial and temporal patterns in stream chemistry remains difficult to generalize. In two paired studies, we are first evaluating how well a deductive model based on the WaDE clusters, network position, and time of year predicts extant heterogeneity in stream chemistry across the full TRB (see Fig. 12, p. 15). For the second study, we conducted two synoptic

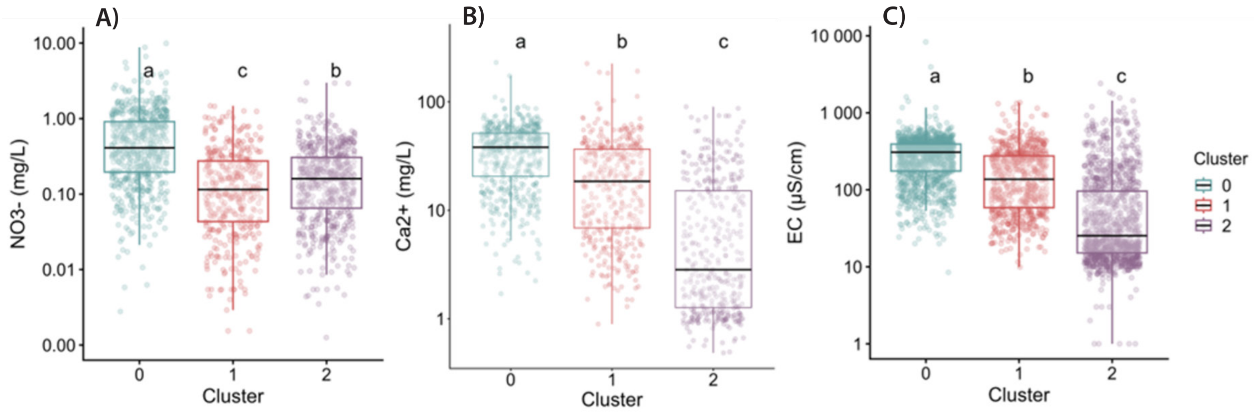


Fig. 12. Preliminary Results of Water Quality Parameters Across WaDE Tennessee River Basin Clusters. **(A)** Nitrate (NO_3^-), **(B)** calcium (Ca^{2+}), and **(C)** electrical conductivity (EC). The center line represents the median, and the lower and upper hinges correspond to the 25th and 75th percentiles. Water quality data is sourced from ChemLotUS (Fernandez et al. 2025).

chemistry sampling campaigns across the regional TRB sites to apply the understanding of landscape drivers and flow conditions gained in the first, TRB-wide study to explain the magnitude and relative importance of different species of C export (POC, DOC, and dissolved inorganic C).

FY27 Planned Activities

We will continue with data interpretation and submission of multiple journal manuscripts and datasets related to the efforts detailed above. To leverage the capabilities provided by the maturing model for stream oxygen dynamics and metabolism, we are designing a cross-theme experiment to test how inverse modeling of the DO two-station method to estimate ER and GPP can improve information gain and understanding of stream metabolism relative to one-station estimates. We will also test the application of emerging deep learning and other artificial intelligence tools to aid transferability of watershed understanding to novel watershed systems and conditions. This work includes an inductive analysis of our growing multimodal EFPC dataset of coupled metabolic processes (e.g., stream metabolism, C and nutrient cycling, extracellular enzymatic activity, POC degradation, and microbial community composition) and explanatory variables to evaluate which variables and relationships have the highest predictive power and compare this to the predictive power of variables we can most easily quantify.

Modeling Crosscut

The Modeling Crosscut continues to develop a virtual watershed modeling capability to support hypothesis-driven modeling subtasks within each theme. We use the DOE-developed watershed modeling simulator ATS (Coon et al. 2019) for integrated surface/subsurface hydrology and reactive transport. The Watershed Workflow toolset (Coon and Shuai 2022) facilitates preparation of the data-intensive model inputs from community data product. Biogeochemical reactions are represented by coupling the Alquimia interface (Molins et al. 2022) to PFLOTRAN's (Hammond et al. 2014) reaction models. We use ATS's multiscale capability (Jan et al. 2021; Le et al. 2023) to represent the effects of small-scale hyporheic zone biogeochemical reactions at the appropriate scale using hyporheic age-based subgrid models. This unique multiscale stream corridor modeling capability avoids ad hoc upscaling and explicitly accounts for rate-limiting mass transfer between the flowing channel and biogeochemically active transient storage zones. Without site-specific calibration, our ATS flow model for EFPC agrees well with available data. We use this model in a variety of numerical experiments focused on stream network expansion and contraction dynamics and stream metabolism.

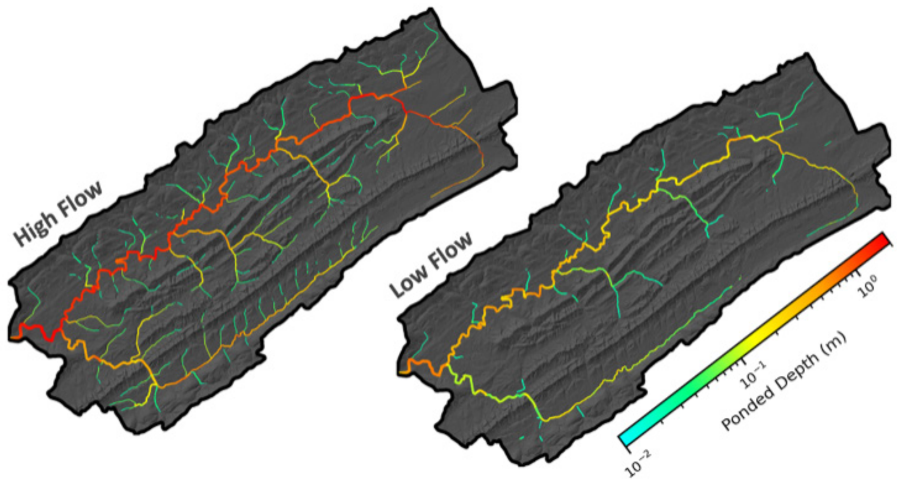


Fig. 13. Snapshots of the Simulated Stream-Network Inundation Fields During High- and Low-Flow Conditions. Color scale representing ponded depth is transparent at zero depth, revealing shaded topography. Discharge and active network lengths are derived from these simulations.

FY25–FY26 Accomplishments

Flow Model for Lookout Creek Watershed. We used ATS and the Watershed Workflow with unstructured stream-aligned meshes to model flow in the Lookout Creek Watershed in the H.J. Andrews Experimental Forest in Oregon to build additional confidence in our variable resolution watershed hydrology simulation capacity. Without watershed-specific calibration, simulated hydrographs are in good agreement with data from gauging stations. For the entire Lookout Creek Watershed, the modified Kling-Gupta efficiency is 0.81, indicating excellent model performance. The ability to match gauge hydrographs without calibration confirms previous results for EFPC and other watersheds.

Stream Network Expansion Contraction. We continue to use our spatially resolved EFPC flow model in numerical experiments to better understand stream network expansion and contraction. The extent of the flowing network within a watershed is highly dynamic and an important control on water/solute residence times and connectivity between terrestrial and aquatic ecosystems. Stream network expansion and contraction dynamics thus have important implications for stream biogeochemistry and freshwater ecology. The relationship between stream discharge (Q) and active network length (L) is central to understanding those dynamics and has been studied for decades. However, that relationship is still highly uncertain because direct observation is labor intensive and thus limited to small catchments and coarse temporal resolution.

Our high-resolution EFPC model made it possible to explore expansion and contraction dynamics with a much higher degree of detail than had been previously possible (see Fig. 13, this page). We found a clear pattern of hysteresis in the Q–L relationship in EFPC and its subcatchments (see Fig. 14, p. 17). The strength of hysteresis as quantified by the hysteresis index H (Zuecco et al. 2016)—the area between the rising and falling limbs of the normalized Q–L trajectory—varies among events but is always positive, indicating clockwise loops (L peaking before Q). Moreover, a clear trend of increasing hysteresis with increasing catchment size was found (see Fig. 14A, p. 17). Hysteresis creates scatter in the Q–L relationship and reduces the predictive capability of Q–L relationships identified from small catchments. However, a robust relationship free of hysteresis emerges when asynchronous event-scale peaks of Q and L are considered instead. The event-scale asynchronous relationship remains consistent across nested catchments of varying size, independent of antecedent wetness, season, and storm details.

Metabolism Modeling Capabilities. We configured our multiscale stream corridor modeling capability implemented in the ATS-PFLOTRAN system to model stream oxygen dynamics and metabolism while considering the effects of hyporheic exchange (Gomez-Velez et al. 2026). Using that new capability, we explored hyporheic

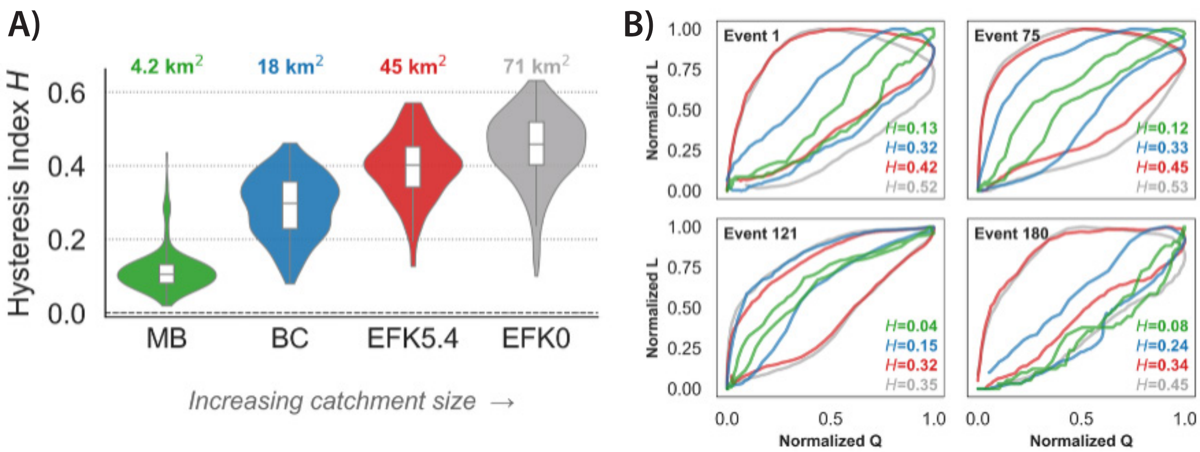


Fig. 14. Relationships Between Network Length and Discharge in East Fork Poplar Creek. **(A)** Distribution of the hysteresis index H for 215 storm events across four nested domains showing increasingly pronounced hysteresis with increasing catchment size (left to right). **(B)** Representative hysteresis loops.

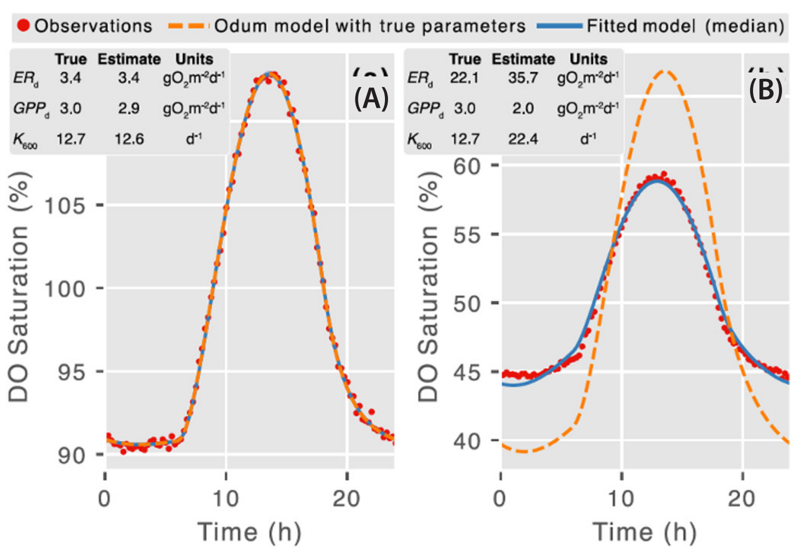


Fig. 15. Results from Synthetic Parameter Estimation Studies Using the Single-Station (Odum) Model to Fit Results from Our More Realistic Multiscale Forward Model. Red dots are results from the forward simulation, which are used as synthetic observations and analyzed with the single-station model. **(A)** Parameters for the forward models are recovered with low bias. **(B)** The single-station model fits the observation but with high bias. These results show the single-station model works well in some conditions but can produce good results for the wrong reasons (good fit with high bias in estimated parameters).

exchange's role in channel oxygen dynamics at reach scales and how the exchange process impacts estimated values of the metabolism metrics ER and GPP. We found hyporheic exchange significantly affects diel oxygen dynamics, even for nonreactive streambed sediments. We also found that the single-station metabolism model (Odum 1956; Appling et al. 2018), the conventional approach to estimating ER and GPP that ignores hyporheic exchange, performs well in many situations but results in significant biases in some situations, even when oxygen data are well fitted (see Fig. 15, this page). These situations pose a major challenge in the interpretation of metabolism assessment estimates.

We combined our high-resolution EFPC flow model with our multiscale model for stream metabolism to produce first-of-a-kind simulations of DO at the watershed scale. These simulations explicitly represent a diversity of hyporheic flow paths, mass transfer limitations between flowing stream channel and metabolically active hyporheic zones, and nonlinear (dual Monod) ER reaction kinetics in the hyporheic zone in a network-scale model. Preliminary simulations reproduce the general seasonal patterns of observed DO concentrations at East

Fork kilometer (EFK) 5.4. Match to observations at EFK16.2 is also good, although the simulation does produce slightly higher DO concentrations in winter. Work is underway to refine these preliminary simulations, but they already demonstrate that our modeling tools are capable of high-resolution simulations of DO and stream metabolism at the watershed scale without sacrificing fidelity in the representation of small-scale hyporheic zone processes.

FY27 Planned Activities

We will submit a journal article on our modeling of DO dynamics and stream metabolism at full network scales. We will also use our multiscale model for stream metabolism to analyze high-resolution DO measurements. Specifically, we use inverse modeling in a two-station configuration to estimate ER and GPP and compare those estimates with the single-station model.

Selected Research Highlights

In FY26, 19 manuscripts were submitted by the WaDE team, of which nine are published or in press. Nine datasets were also published or submitted to permanent archives. This section highlights three of these papers.

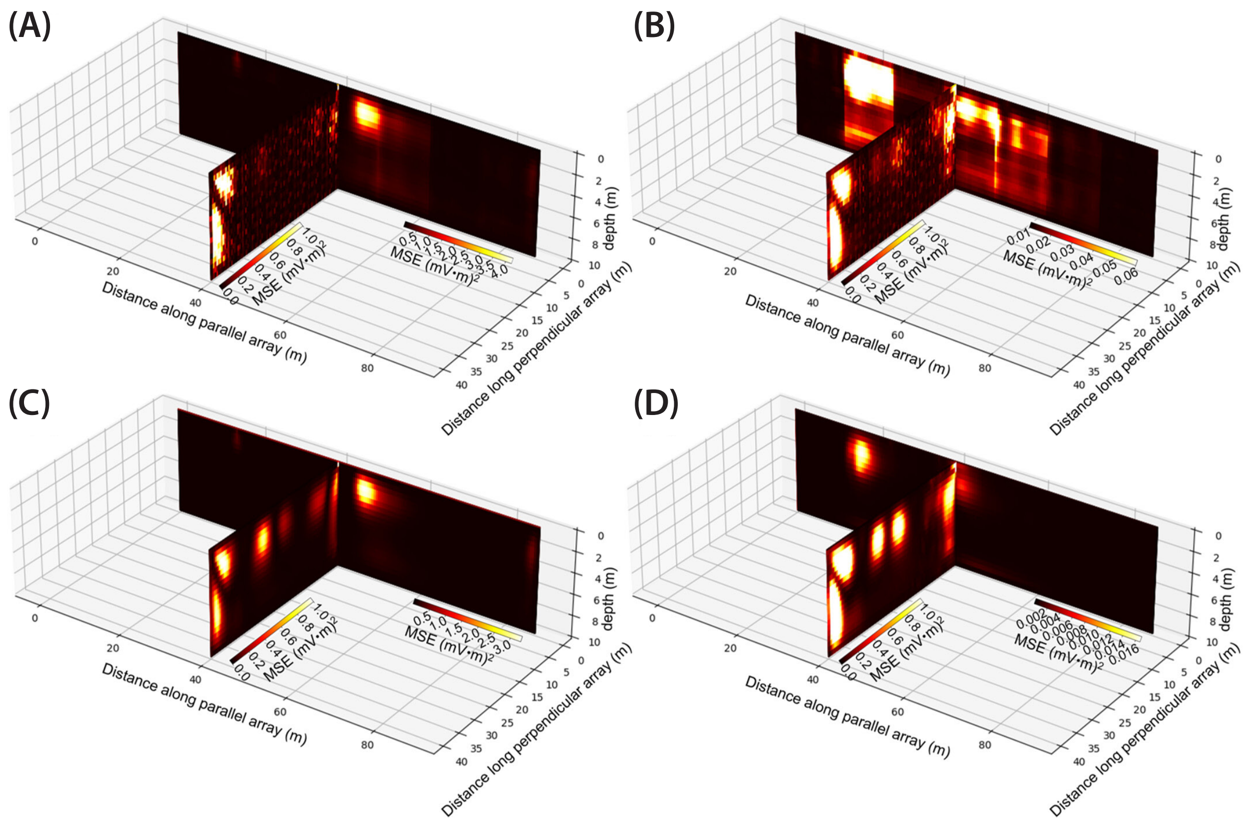
Research Highlight

Using Machine Learning Models to Find Underground Moving Water

Subsurface water movement can be located with deep learning and natural electrical fields.

The Science

In a new study, a team of researchers measured natural electric fields created as water moves through the ground. The resulting dataset, collected over 6 months, included more than 10 million measurements. Researchers then developed a machine learning method to help interpret the data and identify places in the underground where water was moving. Using these methods, moving water was consistently detected near an underground break or crack in the rock.



Anomalies (yellow-to-white color) in machine learning reconstructions of self-potential tomographies are indicative of locations with moving water. **(A and C)** Single-date images. **(B and D)** Average anomalies for data collected over 6 months. [Reprinted under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0) from Yin, H., et al. 2026. “Localization of Spatiotemporally Heterogeneous Subsurface Flows Using Autoencoder-Based Deep Learning Framework for Time-Lapse Self-Potential Tomography,” *Journal of Geophysical Research: Machine Learning and Computation* **3**(3), e2025JH001208. DOI:10.1029/2025JH001208.]

The Impact

Understanding how water moves underground is crucial for managing water resources and predicting environmental change. However, collecting and interpreting the needed data is difficult due to complex properties of soils and rock and changes over time and location. This work demonstrates consistent locations of water movement can be identified using machine learning methods to help interpret data.

Summary

Self-potential (SP) signals, natural electrical fields generated as water flows through the ground, are a valuable method for understanding subsurface water movement. However, interpreting SP data is challenging due to the complex underground environment and the presence of short-term noise.

A team of researchers developed a deep learning method to help analyze SP data collected from a floodplain in Oak Ridge, Tenn., where stream water interacts with underground rock layers. Researchers first converted raw SP measurements into a series of SP tomography frames showing the estimated flow patterns over time. The team then trained deep learning models called autoencoders to learn what normal SP patterns look like, so the models could detect times of unusual changes based on reconstruction errors. Spatial patterns of these errors were analyzed to locate potential zones of subsurface fluid flow. Among the models tested, those based on vision transformer and convolutional long short-term memory autoencoders performed best. Identified zones of active water movement were consistently located near a fault or karst feature and were observed across multiple monitoring lines, confirming the method's reliability for mapping underground water flows.

Publication

Yin, H., S. J. Ikard, D. F. Rucker, S. C. Brooks, Z. Dai, M. R. Soltanian, and K. C. Carroll. 2026. "Localization of Spatiotemporally Heterogeneous Subsurface Flows Using Autoencoder-Based Deep Learning Framework for Time-Lapse Self-Potential Tomography," *Journal of Geophysical Research: Machine Learning and Computation* **3**(3), e2025JH001208. DOI:10.1029/2025JH001208.

Research Highlight

Accounting for the Hyporheic Zone in Stream Metabolism Models

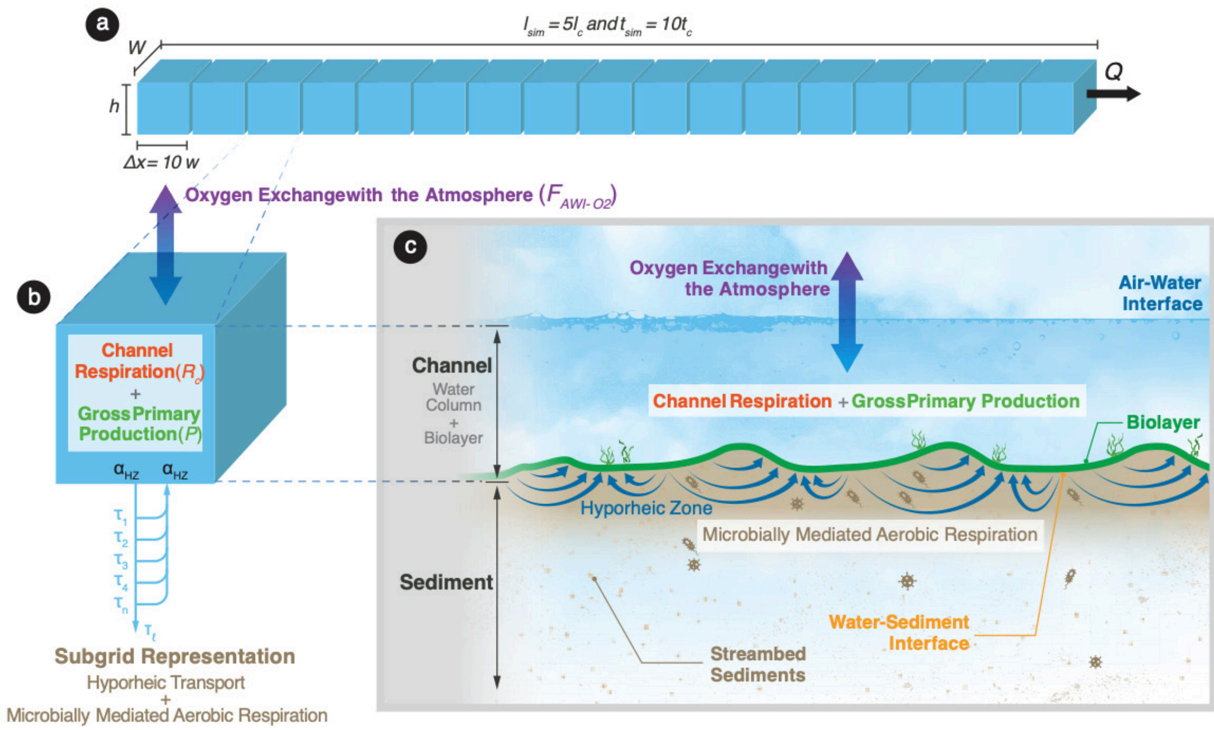
A multiscale reactive transport model provides new insights into stream oxygen dynamics.

The Science

Stream metabolism, the set of processes that transform carbon and produce and consume oxygen in streams, is an important indicator of stream health. Researchers developed a new model to represent stream oxygen dynamics that explicitly accounts for in-channel processes and oxygen consumption by microbial respiration in the hyporheic zone, the water-saturated sediments near the channel. Researchers found mass exchange and hyporheic zone transport significantly alter oxygen dynamics, even for sediments that do not support respiration. Existing models that combine the hyporheic zone with the stream channel can result in significant biases in estimated metabolism rates.

The Impact

Rates of oxygen production by photosynthesis and consumption by respiration in streams are often estimated from changes in oxygen concentrations using the single-station metabolism (SSM) model. The



Multiscale model for oxygen dynamics in stream corridors. Transport in the stream channel **(a)** is coupled to subgrid models for hyporheic exchange and reactive transport in the adjacent sediments **(b)** to mimic the natural stream metabolism processes **(c)**. [Reprinted under a Creative Commons License (CC BY 4.0) from Gomez-Velez, J. D., et al. 2026. "Hyporheic-Zone Processes and Stream Oxygen Dynamics: Insights from a Multiscale Reactive Transport Model," *Water Resources Research* **62**(1), e2025WR040208. DOI:10.1029/2025WR040208.]

SSM model makes a critical assumption that all processes that consume oxygen can be lumped into a single ecosystem respiration rate. Researchers found the SSM model can produce biased metabolism assessments even when oxygen dynamics are well represented. They propose a new model that better accounts for the metabolically active hyporheic zone and provides a more robust method for assessing stream metabolism from dissolved oxygen dynamics.

Summary

Aquatic ecosystem metabolism encapsulates the daily fixation (gross primary production) and mineralization (ecosystem respiration) of organic carbon, producing and consuming oxygen in the process. In streams and rivers, those metabolic fluxes are commonly estimated from observed oxygen concentrations by inverse modeling using a model that describes how oxygen concentrations in the water column vary throughout a day. The most common model for those assessments, the SSM model, implicitly assumes that all processes consuming oxygen can be lumped into a bulk estimate of respiration. Researchers configured a recently developed multiscale model for transport and reactions in stream corridors to represent stream metabolism and used it to explore consequences of simplifying assumptions in the SSM model.

This multiscale model explicitly represents mass exchange limitations between the stream channel and the hyporheic zone as well as transport and respiration along multiple pathways in the hyporheic zone. Numerical experiments with the multiscale model provide insights into the effects of hyporheic processes on oxygen dynamics. While the SSM model performed well in many situations, researchers identified conditions where significant bias is produced by neglecting hyporheic exchange, even when oxygen data are well fitted. These situations pose a major challenge in the interpretation of metabolism assessment using the SSM model.

Publication

Gomez-Velez, J. D., S. S. Rathore, M. J. Cohen, and S. L. Painter. 2026. "Hyporheic-Zone Processes and Stream Oxygen Dynamics: Insights from a Multiscale Reactive Transport Model," *Water Resources Research* **62**(1), e2025WR040208. DOI:10.1029/2025WR040208.

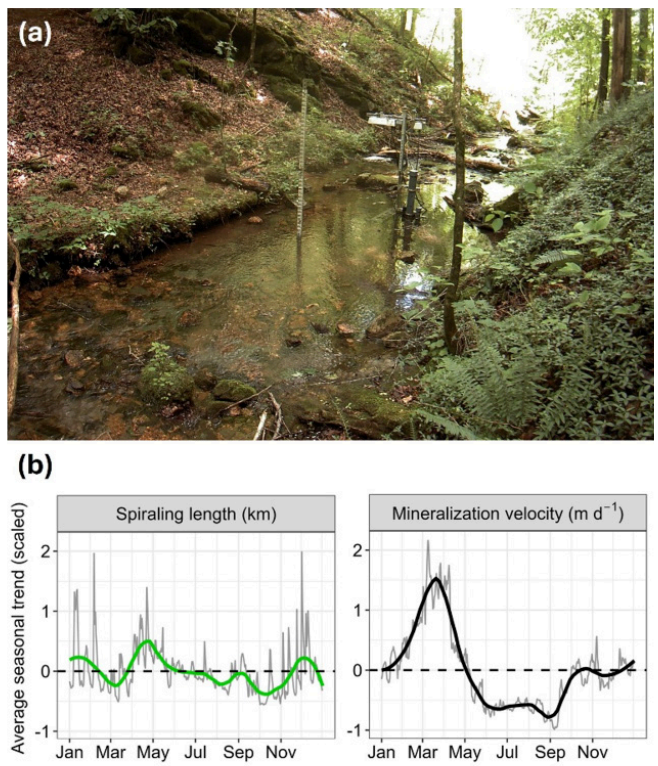
Research Highlight

Rapid Organic Carbon Spiraling in a Headwater Stream Linked with Seasonal Streamflow, Biogeochemistry, and Canopy Phenology

Seven years of daily organic carbon spiraling in a well-studied headwater stream linked with riparian tree phenology and in-stream primary productivity.

The Science

Headwater streams are abundant worldwide and important processors and transporters of organic carbon. Organic carbon spiraling can be used to understand and compare the retention and mineralization of organic carbon in streams to understand carbon use efficiency versus downstream transport. In a small headwater stream (Walker Branch in Tennessee), organic carbon spiraling length was one order of magnitude shorter compared to other small streams. Organic carbon spiraling was faster during the more biologically active periods of spring and autumn and slower in summer and winter when carbon retention was lower but downstream transport higher. Light, primary production, and nitrate were the strongest drivers of patterns in organic carbon spiraling in Walker Branch, where short- or long-term changes in these variables could influence carbon processing and downstream transport.



(a) Walker Branch during spring canopy cover, with **(b)** the average seasonal patterns in carbon spiraling metrics over 7 years. [(a) Courtesy PhenoCam Network. (b) Adapted from Pilla, R. M., et al. 2026. "Rapid Organic Carbon Spiraling in a Headwater Stream Linked with Streamflow, Biogeochemistry, and Canopy Phenology," *Freshwater Science*. DOI:10.1086/740164.]

The Impact

This study highlights the rapid organic carbon processing in Walker Branch relative to other headwater streams. Further, long-term trends toward earlier and longer canopy cover resulting in reduced light and primary production may slow organic carbon spiraling, reducing localized in-stream processing and potentially shunting more downstream. However, effects of long-term reductions of nitrate at Walker Branch suggest opposing effects, which would result in faster organic carbon spiraling and greater in-stream retention. This detailed time series analysis enhances understanding of current and future responses of carbon processing in headwater streams as well as implications for downstream carbon dynamics.

Summary

Researchers used 7 years of daily data in a small headwater stream to assess seasonal and interannual patterns in organic carbon spiraling and then linked these data with potential driver variables. Organic carbon spiraling is a useful way to assess carbon retention, processing, and transport in streams, though it has received notably less attention compared to nutrient spiraling. Further, analyses of seasonal and interannual variability in organic carbon spiraling are currently limited, leaving knowledge gaps in the driving mechanisms of and potential changes to within-stream carbon spiraling and downstream carbon transport. Walker Branch had very rapid organic carbon spiraling rates compared to other small headwater streams and was most rapid in spring and autumn during biologically active periods in the ecosystem. Carbon spiraling was primarily driven by seasonal variability in light, primary production, and nitrate, but trends in these drivers suggest opposing effects on organic carbon spiraling at Walker Branch. While these analyses and mechanisms give important insights into organic carbon spiraling at highly temporally resolved scales, future studies on seasonal variability in organic carbon spiraling should build on this work across a variety of stream types to understand their roles in global organic carbon processing.

Publication

Pilla, R. M., N. A. Griffiths, and B. J. Roberts. 2026. “Rapid Organic Carbon Spiraling in a Headwater Stream Linked with Streamflow, Biogeochemistry, and Canopy Phenology,” *Freshwater Science*. DOI:10.1086/740164.

Postgraduate Spotlight

Developing and training the next generation of scientists and engineers is a key goal of the WaDE SFA and Oak Ridge National Laboratory (ORNL). As part of this year's report, we highlight two of our outstanding postdoctoral researchers—Robert Brown and Erin VanderJeugdt—who are contributing to WaDE's overall goals and objectives. See WaDE's website for a complete list of the project's postgraduate alumni (wade.ornl.gov/history).

Robert Brown

Robert Brown earned his bachelor's degree in sustainable development and biology from Appalachian State University, where he developed

his interest in freshwater ecology. He completed a summer internship at Ball State University and an AmeriCorps term with the Western Pennsylvania Conservancy's Watershed Conservation Initiative. Brown studied interactions between burrowing bivalves and methane cycling in urban streams for his master's thesis at University of North Carolina–Greensboro with Anne Hershey. While writing his thesis, he completed a second AmeriCorps term with RiverLink, working in environmental education with K–12 students in the French Broad River Basin. Brown also worked as an environmental educator with Muddy Sneakers Inc. before starting his PhD at Tennessee Technological University with Justin Murdock. Brown's dissertation research focused on applying field and laboratory methods to assess nutrient retention capacity of restored floodplain wetlands. As a postdoctoral researcher with the U.S. Environmental Protection Agency, Brown moved to Oregon to study impacts of wildfire on stream habitat in the Pacific Northwest using long-term monitoring data from the U.S. Forest Service. Brown's current work in Theme 2 of WaDE focuses on biogeochemical linkages between aerobic and anaerobic metabolic processes in streams. In his spare time, Brown enjoys trail running, hiking, and snowboarding, with a recent foray into mountain biking.

Erin VanderJeugdt

Erin VanderJeugdt received her bachelor's degree in environmental science from the University of North Carolina–Chapel Hill. During her time

there, she completed two independent research projects at the University of North Carolina's satellite campuses: measuring the bioremediation effects of retention ponds at the Institute of Marine Sciences in Morehead City, N.C., and quantifying freshwater resources on San Cristobal Island in the Galapagos Islands. After graduating in 2016, she spent several years as a research technician at the Duke River Center working with Emily Bernhardt and at the Marine Biological Laboratory working with Anne Giblin at the Plum Island Long Term Ecological Research site. These positions were her first exposure to biogeochemistry and helped her find her research specialty and passion. As a graduate student at Kent State University, she worked with Lauren Kinsman-Costello and specialized in phosphorus–iron interactions in Arctic soils. Her research focused on how redox regimes impact iron's crystallinity and associations with organic matter and the implications for phosphorus availability in the Arctic. She completed her PhD in 2025 and began her postdoctoral position at ORNL last July. Her current work in WaDE's Theme 1 focuses on changes in the C lability of non-perennial streams in response to storms and sediment respiration as stream beds dry-down and rewet. In her spare time, VanderJeugdt enjoys reading, climbing, camping, embroidery, and playing video games.

National and International Impact

ORNL WaDE SFA team members attend strategic conferences, workshops, and working groups in the United States and abroad to gain insights into the state of the science, identify collaborative opportunities, and share project findings and strategies with the broader watershed and freshwater science research community. From July 2025 to June 2026, SFA scientists delivered or published 21 presentations, posters, or abstracts (see Appendix C, p. 30 for details). This section highlights team members' contributions to key international conferences and community working groups.

Powell Center Working Group on Defining Subsidy–Stress Gradients for Metals and Relevance for U.S. Surface Waters. Elizabeth Herndon is co-principal investigator (PI) on this working group and leads a task synthesizing trace element concentrations across continental U.S. streams to evaluate potential limitation or toxicity to aquatic organisms. A curated dataset has been developed and will be released in conjunction with a manuscript describing the unique challenges of handling highly censored data. The working group has also developed a perspective paper detailing a "limiting-optimal-toxic continuum" conceptual model for trace element use by aquatic organisms that will be developed into a quantitative framework and paired with stream concentrations.

Research Coordination Network for Investigating Nitrogen Fixation Across Aquascapes. Robert Brown contributes to a working group investigating the ecological significance and scaling relationships of nitrogen fixation from genes to ecosystems. Brown is coauthoring a perspective manuscript on the ecology of nitrogen fixation across a mosaic of inland and coastal waters that will provide a framework to strengthen integration of aquatic community and ecosystem consequences resulting from biologically fixed nitrogen. Additional manuscripts focused on identifying environmental drivers of nitrogen fixation and scaling nitrogen fixation rates globally are also being prepared.

Sensor-Based Time-Series Repository for Environmental Assessment and Modeling (STREAM) Workshop. Marie Kurz was selected to join a small group of researchers at a workshop in Fayetteville, Ark., from February 23 to 27, 2026, to evaluate, launch, and utilize a collaborative database harmonizing high-frequency water quality sensor data across the continental United States. A perspective and multiple research manuscripts are in development.

American Geophysical Union (AGU) Fall Meeting. Multiple SFA team members attended the AGU Fall Meeting in New Orleans, La., from December 15 to 19, 2025. Notable contributions included invited talks by Marie Kurz and Saubhagya Rathore and a Town Hall, "Leveraging Regional Disturbances for Novel Scientific Inquiry," co-organized by Kurz and Elizabeth Herndon with colleagues from Pacific Northwest National Laboratory.

River Corridor Critical Zone Workshop. Jonathan Behrens, Robert Brown, and Marie Kurz were invited to join an immersive field workshop at the H.J. Andrews Experimental Forest in Oregon from July 26 to August 1, 2025, hosted by WaDE collaborator Adam Ward. Workshop participants shared and received training across a wide range of field methods; discussed critical zone science, study design, and career mentorship; and laid the groundwork for the review, novel interpretation, and synthesis of synoptic watershed datasets.

Working Group on Stream Metabolism in Developed Watersheds Nationally. Jonathan Behrens and WaDE collaborator Erin Hotchkiss are co-PIs on a working group formed after a workshop held last year by Behrens and Hotchkiss at the 7th Symposium on Urbanization and Stream Ecology. Behrens is leading the team developing a manuscript that reviews the state of the science and relevant conceptual models and identifies research gaps to better conceptualize and predict metabolism in streams draining urbanized watersheds across the nation.

Organizational Leadership and Collaborative Research Activities

Marie Kurz and Elizabeth Herndon are the SFA program co-leads and are responsible for planning and coordinating the project's overall scientific direction and ensuring integration and success. They are the points of contact with BER Environmental System Science program managers and speak to Paul Bayer biweekly on SFA progress and potential issues. The theme leaders and modeling activity lead—Elizabeth Herndon and Alex Johs for Theme 1, Scott Brooks for Theme 2, Marie Kurz and Natalie Griffiths for Theme 3, and Scott Painter for Modeling Crosscut—are responsible for integrating activities within and across themes. Theme 1 collaborates with Kamini Singha (Colorado School of Mines) and Holly Barnard (University

Fig. 16. 2026 WaDE All-Hands Meeting.

of Colorado–Boulder). Singha provides expertise in subsurface geophysics, and Barnard provides expertise in how vegetation impacts stream dynamics. Erin Hotchkiss (Virginia Polytechnic Institute and State University) is an aquatic ecologist and biogeochemist with expertise in understanding how environmental change impacts biogeochemical processes in freshwater ecosystems. Hotchkiss primarily supports Theme 2 but also engages in Theme 3 research activities. Adam Ward (Oregon State University) and Matt Cohen (University of Florida) collaborate with Theme 3 and provide expertise in network-scale hydrology and ecosystem metabolism, respectively. Lydia Zeglin (Kansas State University) is a microbial ecologist with expertise in stream microbial diversity; her expertise spans across all three themes in collaboration with ORNL microbial expertise from Mircea Podar. The theme leaders, along with the broader team, meet biweekly to provide updates on current research directions, future plans, and staffing changes.

ORNL WaDE SFA Partners

Colorado School of Mines
University of Colorado Boulder
Virginia Tech
University of Florida
Oregon State University
Kansas State University

Annual All-Hands Meeting

WaDE hosted an all-hands meeting at Dancing Bear Lodge in Townsend, Tenn., on March 12 and 13, 2025. The meeting included members of the SFA Science Advisory committee and faculty and students from all collaborating institutions (see Fig. 16, this page).

National Laboratory Investments

ORNL is committed institutionally to the success of the WaDE SFA program. In FY26, ORNL supported a Laboratory-Directed Research and Development project, “Cross-Scale Ecosystem Stability Following Hurricane Disturbance,” that supports synergistic research developments and invested in further equipment upgrades in support of the WaDE SFA.

Appendix A. References Cited

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Appendix B. SFA Publications

Manuscripts Published or In Press

Gleasman, G., X. Mo, J. W. Atkins, D. Hagan, B. J. Campbell, D. L. J. Patabandige, A. Bourbonnais, M. Baalousha, S. C. Brooks, P. Ku, F. Santos, S. D. Richardson, P. Du, and A. Tat-Shing Chow. 2025. “Post-fire Biogeochemical Processes: Implications to Source Water Quality in Fire-Influenced Watersheds,” *Environmental Science & Technology* **59**(29), 1476714779. DOI:10.1021/acs.est.4c11860.

Gomez-Velez, J. D., S. S. Rathore, M. J. Cohen, and S. L. Painter. 2026. “Hyporheic-Zone Processes and Stream Oxygen Dynamics: Insights from a Multiscale Reactive Transport Model,” *Water Resources Research* **62**(1), e2025WR040208. DOI:10.1029/2025WR040208.

Neupane, A., E. M. Herndon, J. M. DeBruyn, A. Chhetri, and S. Jagadamma. 2025. “Manganese Concentration Influences Nitrogen Cycling in Agricultural Soil,” *Applied Soil Ecology* **215**, 106460. DOI:10.1016/j.apsoil.2025.106460.

Painter, S. L., and G. Destouni. 2026. “Hydrology in the Age of Artificial Intelligence: From Fragmentation to Coherent Terrestrial Hydrosphere Science,” *Water Resources Research* **62**(2), e2026WR043509.

Pearl, S., M. J. Rand, P. A. Gantzer, E. M. Herndon, M. Amani, T. R. Kjeldsen, and L. D. Bryant. 2025. “Manganese in Drinking-Water Reservoirs: A Multi-Disciplinary Review of Current Issues, Biogeochemical Controls, and Oxygenation-Based Management,” *Journal of Environmental Management* **395**, 127573. DOI:10.1016/j.jenvman.2025.127573.

Pilla, R. M., N. A. Griffiths, and B. J. Roberts. 2026. “Rapid Organic Carbon Spiraling in a Headwater Stream Linked with Streamflow, Biogeochemistry, and Canopy Phenology,” *Freshwater Science*. DOI:10.1086/740164.

Wang, L., S. Loew, X. Gu, and Q. Lei. 2026. “Emergence of Diverse Failure Patterns in Weathering-Induced Landslides: Insights from Particle Finite Element Simulations,” *Journal of Geophysical Research: Earth Surface* **131**(1), e2025JF008771. DOI:10.1029/2025JF008771.

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Manuscripts Submitted or In Review

Ahmed, T., D. VanLeeuwen, R. A. M. Mohamed, S. C. Brooks, M. R. Soltanian, J. D. Gomez-Velez, and K. C. Carroll. In review. “Spatiotemporal Sediment Transport Impacts to Streambed Hydraulic and Transport Properties Revealed by Fixed-Year Mixed Effects Models,” *Hydrological Processes*.

Bidas, K., H. Li, F. Santos, E. Rooney, B. Reinhart, L. He, C. Do, Q. Zhao, R. Tappero, and E. Herndon. In revision. “Manganese Oxides Incubated in Acidic Forest Soil Retain More Organic Carbon than Iron Oxides,” *Environmental Science & Technology.*

Costello, D., E. Herndon, et al. Submitted. “From Limitation to Toxicity: An Integrated Framework for Evaluating Effects of Critical Elements on Freshwater Organisms and Ecosystems,” *Environmental Science & Technology Letters.*

Danczak, R. E., A. E. Goldman, M. Borton, R. K. Chu, J. G. Toyoda, V. A. Garayburu-Caruso, E. B. Graham, J. W. Morad, L. Renteria, J. R. Wells, S. Arnon, S. Brooks, E. Bar-Zeev, M. Jones, N. Jones, J. Lewandowski, C. Meile, B. M. Muller, J. Schalles, H. Schulz, A. Ward, and J. C. Stegen. In revision. “Meta-Metabolome Ecology Reveals that Geochemical Conditions and Microbial Functional Potential Are Linked to DOM Development Across Seven Rivers,” *Science of the Total Environment*.

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Rathore, S. S., J. D. Gomez-Velez, E. M. Herndon, and S. L. Painter. In revision. "Hysteretic Dynamics of Stream Network Expansion and Contraction Revealed Through High-Resolution Integrated Hydrological Modeling," *Water Resources Research*.

Stewart, W., W. Marechal, R. S. Rathore, V. L. D. Badisa, B. Mwashote, G. Chen, S. Brooks, and V. Ibeanusi. In review. "Mercury Resistant Bacterial Strains from Oak Ridge Reservation Site: Potential Candidates for Mercury Bioremediation," *Journal of Basic Microbiology.*

Data Product Releases

Brooks, S. C., and K. A. Lowe. Available. [Data Set] Bear Creek Sonde Data at Kilometer 0.9 Water Year 2025. ORNL Mercury Science Focus Area (SFA) Data Collection, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, USA.

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Appendix C. Presentations and Conferences

Adams, J., and M. J. Kurz. 2025. "Response of Stream Metabolism to Hurricane Helene and Other Stormflow Disturbances," *American Geophysical Union Annual Meeting*. New Orleans, La., December 15–19, 2025.

Albert-Black, C. 2025. "Spatial Assessment of Trace Metal Bioavailability Across Different Headwater Streams," *American Geophysical Union Annual Meeting*. New Orleans, La., December 15–19, 2025.

Beall, M. C., S. C. Brooks, J. D. Velez-Gomez, and E. R. Hotchkiss. 2026. "Evaluating Stream Resistance and Resilience to Storm Disturbance," *Virginia Tech Research Day*. Blacksburg, Va., February 8, 2026. *Second Place Poster Award.

Beall, M. C., S. C. Brooks, J. D. Gomez-Velez, and E. R. Hotchkiss. 2026. "Quantifying Stream Metabolic Stability to Storm Disturbance Using Integrated Resistance and Resilience Metrics," *Society for Freshwater Sciences Annual Meeting*. Spokane, Wash., May 17–21, 2026.

Behrens, J., R. Brown, N. A. Griffiths, S. Brooks, E. R. Hotchkiss, S. Rathore, and M. Kurz. 2026. "Pinpointing Drivers of Covariance, Persistence, and Synchrony in Stream Metabolism Across a Heterogeneous Watershed," *Society for Freshwater Sciences Annual Meeting*. Spokane, Wash., May 17–21, 2026.

Brown, R. S., J. R. Behrens, S. C. Brooks, N. A. Griffiths, E. R. Hotchkiss, and M. J. Kurz. 2026. "How Are Changes in Stream Water N_2:Ar and CH_4:Ar Saturation Ratios Linked to Estimates of Ecosystem Metabolism?" *Society for Freshwater Sciences Annual Meeting*. Spokane, Wash., May 17–21, 2026.

Gomez-Velez, J., S. S. Rathore, M. Cohen, and S. L. Painter. 2025. "Investigating the Impact of Hyporheic Exchange on Stream Oxygen Dynamics and Its Implication for Metabolism Assessments," *American Geophysical Union Annual Meeting*. New Orleans, La., December 15–19, 2025.

Gu, X. 2026. "How Micro-Scale Observations Can Reveal Landscape-Scale Processes," *American Chemical Society Spring Meeting*. Atlanta, Ga., March 22–26, 2026.

Johnson, E., R. Brown, S. Brooks, N. Griffiths, et al. 2026. "Nutrient Removal in a Stream Receiving Treated Wastewater and Industrial Effluent," *Tennessee Water Resources Symposium*, American Water Resources Association. Burns, Tenn., April 15–17, 2026.

Knutson, C. 2025. "Variability of POC Decomposition in a Mountain Headwater Stream," *American Geophysical Union Annual Meeting*. New Orleans, La., December 15–19, 2025.

Krause, J. 2025. "Subsurface Flowpath Heterogeneity Drives Dissolved Oxygen Dynamics in a Spatially Intermittent Headwater Stream," *American Geophysical Union Annual Meeting*. New Orleans, La., December 15–19, 2025.

Krause, J. 2026a. "From Synthesis to Sensors: Understanding Oxygen Regimes in Headwater Streams," *Boase Hydrologic Sciences and Water Resources Engineering Seminar Series*. University of Colorado Boulder, Colo.

Krause, J. 2026b. "Rethinking Catchment-Scale Oxygen Frameworks in a Non-Perennial Headwater Stream," *BIOGEOMON*. Umeå, Sweden, June 8–12, 2026.

Kurz, M. J., E. Herndon, F. Santos, A. Myers-Pigg, and N. McDowell. 2025. "Town Hall: Leveraging Regional Disturbances for Novel Scientific Inquiry," *American Geophysical Union Annual Meeting*. New Orleans, La., December 15–19, 2025.

Kurz, M. J., S. C. Brooks, R. Brown, J. Gomez-Velez, N. A. Griffiths, E. Herndon, A. Johs, P. V. V. Le, S. L. Painter, and S. S. Rathore. 2025. "Integrating Groundwater-Surface Water Interactions into a Systems Perspective of Watershed Hydro-Biogeochemical Function and Ecosystem Health" (Invited), *American Geophysical Union Annual Meeting*. New Orleans, La., December 15–19, 2025.

Le, P. V. V., S. S. Rathore, J. Gomez-Velez, J. Behrens, M. J. Kurz, S. C. Brooks, and S. L Painter. 2025. "Multiscale Modeling of Stream Oxygen Dynamics in River Networks," *American Geophysical Union Annual Meeting*. New Orleans, La., December 15–19, 2025.

McNabb, C. 2025. "Riparian Ecohydrologic Drivers of Streamflow Across LULC Types," *American Geophysical Union Annual Meeting*. New Orleans, La., December 15–19, 2025.

Painter, S. L. 2025. "Building Confidence in Integrated Hydrologic Models: Experience with the ATS Code," *American Geophysical Union Annual Meeting*. New Orleans, La., December 15–19, 2025.

Pilla, R. M. 2025. “Applying Analytical Techniques to Sensor Network Data Informs Predictability of Stream Carbon Dynamics” (Invited Early Career Feature), *Environmental System Science Principal Investigator (PI) Meeting*. Washington, D.C., April 15–17, 2025.

Rathore, S. S., J. Gomez-Velez, E. Herndon, and S. L. Painter. 2025. “Temporal and Spatial Scaling of Stream Network Expansion and Contraction Dynamics” (Invited), *American Geophysical Union Annual Meeting*. New Orleans, La., December 15–19, 2025.

VanderJeugdt, E., K. Lowe, X. Yin, X. Gu, and E. Herndon. 2026. “Storm Hydrologic Connectivity in Non-Perennial Streams and Its Influence on Dissolved Organic Carbon,” *Society for Freshwater Sciences Annual Meeting*. Spokane, Wash., May 17–21, 2026.

Appendix D. Acronyms and Abbreviations

AGU	American Geophysical Union
ATS	Advanced Terrestrial Simulator
BER	Biological and Environmental Research program
BLM	Biotic Ligand Model
BSL	Bissel tributary
C	carbon
Ca	calcium
CH_4	methane
Cu	copper
CV	coefficient of variation
DO	dissolved oxygen
DOC	dissolved organic carbon
DOE	U.S. Department of Energy
EC	electrical conductivity
EFK	East Fork kilometer
EFPC	East Fork Poplar Creek
ER	ecosystem respiration
ERT	electrical resistivity tomography
ESS	Environmental System Science program
FY	fiscal year
GPP	gross primary production
H	hysteresis index
Hg	mercury
L	active stream network length
LULC	land use and land cover
MeHg	methylmercury
MLP	multilayer perceptron
N_2	nitrogen
NN	neural network
NO_3^-	nitrate
ORNL	Oak Ridge National Laboratory
PCoA	principal coordinates analysis
PI	principal investigator
POC	particulate organic carbon
Q	stream discharge
SFA	science focus area
SP	self potential
SPT	self-potential tomography
SSM	single-station metabolism
STREAM	Sensor-Based Time-Series Repository for Environmental Assessment and Modeling
SULI	DOE Summer Undergraduate Laboratory Internship
SVD	singular value decomposition
TRB	Tennessee River Basin
TW	transient window
WaDE	Watershed Dynamics and Evolution
XANES	X-ray absorption near-edge structure
µXANES	micro-focused XANES
Zn	zinc