

Watershed Continuum Monitoring Approach: combining multiple water quality patterns along stream and river flowpaths to track sources, pathways, and processing of pollutants[☆]

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ABSTRACT

There is a growing need to improve and expand water quality monitoring approaches to more accurately track the sources, fate, and transport of multiple chemicals and pollutants holistically and quantify the effects of best management practices (BMPs) at the watershed scale. An overarching question raised by scientists, environmental managers, and the general public is: how far can water quality impacts from disturbances or benefits from watershed management and restoration propagate along stream and river flowpaths? Many studies using the classic watershed approach focus on analyzing changes in water quality over time at one or a few sampling stations, whereas theories such as the River Continuum Concept focus on predicting shifts in energy sources and biological communities along rivers but have not been directly applied to water quality. We propose to merge these concepts to create a Watershed Continuum Monitoring Approach (WCMA) that combines both spatial and temporal monitoring in order to better detect and quantify trends and transitions in multiple water quality indicators along flowpaths. Specifically, an array of multiple water quality indicators are analyzed at multiple downstream points along a watershed flowpath over time. These multiple water quality indicators are analyzed together for making comparisons to infer hydrological, biological, and geochemical processes controlling sources, transport, and attenuation of pollutants (e.g., analogous to stream tracer studies at the watershed scale). The WCMA leverages the natural expansion of watershed areas along a flowpath, which reflect transitions in land use, land cover, and environmental management across spatial and temporal dimensions for making direct comparisons across different stream reaches and spatial trend analysis. WCMA facilitates monitoring of multiple water quality indicators together, and identification of hot spots in sources and attenuation of pollutants or

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mixtures of pollutants. We illustrate practical applications of the WCMA to analyze water quality trends, transitions, and tradeoffs (*i.e.*, a tradeoff occurs when one pollutant is reduced but another is directly or indirectly increased downstream). We explore case studies that quantify: (1) downstream reductions in concentrations of multiple pollutants along a stream flowing to a major drinking water source due to engineered and nature-based solutions, (2) downstream reductions in multiple pollutants and water quality tradeoffs along streams experiencing stormwater BMPs and stream restoration, (3) comparisons in downstream reductions of multiple pollutants and nutrient uptake along streams draining into major drinking water sources based on types of stream restoration, (4) comparisons of downstream pollutant reductions along streams experiencing riparian forest conservation vs. stream restoration, and (5) mapping and visualizing hot spots of increasing water quality problems such as hypoxia, contaminant mobilization, and freshwater salinization that extend downstream to tidal rivers of the Chesapeake Bay. We explore future applications of WCMA for tracking decreasing trends in salinity, *E. coli*, and other pollutants of emerging concern. WCMA can holistically inform progress towards achieving multiple water quality goals and also be used as a screening tool for selecting monitoring sites and targeting management in strategic locations. Overall, WCMA enables the simultaneous quantification and comparison of sources and transport and attenuation rates for different chemicals and pollutants across a broader range of watershed sizes and flowpath lengths, which is critical for understanding ecological, hydrological, geochemical, and biogeochemical processes along human-impacted streams and rivers.

1. Introduction

Freshwaters around the world are being impacted by multiple suites of physical, chemical, and biological stressors, which are driving the need for managing and restoring water quality globally (Meybeck, 2003; Chittoor Viswanathan and Schirmer, 2015; Kaushal et al., 2018a; Kaushal et al., 2018b; Van Vliet et al., 2023). There has been a rise in multiple stressors due to the increasing interactive effects of land use, changing environmental conditions, and novel pollutant mixtures and chemical cocktails of nutrients, metals, salt ions, and organic contaminants (*e.g.*, Kaushal et al., 2018a, 2018b; Kaushal et al., 2020; Galella et al., 2021; Brauns et al., 2022; Shelton et al., 2024; Mayer et al., 2024; Marin et al., 2025). Monitoring and achieving multiple water quality goals, particularly when there are multiple types of impairments, has become a looming challenge across space and time (Syberg et al., 2016). While there have been some successes in reducing point and nonpoint sources of pollutants in the U.S. and elsewhere (Boynton et al., 2008; Kaushal et al., 2008; Chittoor Viswanathan and Schirmer, 2015; Fleming et al., 2022), it has been difficult to demonstrate the effectiveness of many water quality best management practices (BMPs) at the watershed scale. There is a growing need to improve and expand our water quality monitoring approaches to more accurately track the sources, fate, and transport of multiple pollutants and quantify the effects of BMPs. Here, we address an overarching question: how far can water quality impacts, benefits, or tradeoffs from disturbances and management within watersheds propagate along stream and river flowpaths? We propose a monitoring approach that merges both spatial and temporal monitoring from the classic watershed approach with the River Continuum Concept in order to better quantify trends, transitions, and tradeoffs in multiple water quality indicators along stream and river flowpaths.

Despite considerable financial investments, our knowledge remains unclear regarding the potential for current watershed management and stream restoration strategies to successfully achieve multiple water quality goals together or whether there can be water quality trade-offs due to a variety of factors (*e.g.*, Corsair et al., 2009; Kaushal et al., 2022; Wood et al., 2022; Galella et al., 2023a). Knowledge gaps exist because of: (1) the traditional focus on analyzing only one or a few pollutants, which doesn't comprehensively inform us about potential co-benefits and/or tradeoffs across water quality parameters, (2) the relatively small spatial scales in which we typically monitor or study stream-floodplain restoration projects, and (3) the lack of available, extensive high-resolution spatial or temporal data to provide adequate context to appropriately interpret effects of watershed restoration activities. A recent assessment of chemical monitoring in aquatic surface water habitats in the US demonstrated that available data were inadequate to assess exposure risk for nearly all chemicals of potential environmental concern (Bub et al., 2025). Other work reveals considerable spatial

heterogeneity in water quality along many human-impacted landscapes and multiple pollutants to consider when assessing watershed BMPs and restoration for pollutant reductions (Kaushal et al., 2018a, 2018b). Most water quality monitoring approaches were developed from studies in forest watersheds and minimally disturbed landscapes, which may not adequately represent water quality changes in human-impacted landscapes.

1.1. Classic watershed concepts lack spatial awareness dealing with distributed human activities

Water quality monitoring based on the classic watershed approach provides critical information on sources, trends, and fluxes in pollutants over time, which is often necessary for making management decisions and tracking recovery from disturbances (Likens et al., 1996). Yet, it raises the question of whether similar temporal trends and results would be observed at other locations within the watershed (Likens and Buso, 2006). From a spatial perspective, the River Continuum Concept (RCC) predicts shifts in energy flows and biological communities with distance downstream due to riparian zones and in-stream processing of organic matter (Vannote et al., 1980), but this concept has not been applied to water quality monitoring. The RCC did not explicitly consider common water quality metrics relevant to environmental management and make connections with the surrounding broader watershed. Nutrient spiraling is another popular theory that has been used to advance understanding of stream ecosystem functions (Newbold et al., 1981; Webster, 2007). Although nutrient spiraling studies are conducted over limited spatial scales, there are important implications for scaling results to predict nitrogen uptake in streams across biomes due to biogeochemical and physical factors (Mulholland et al., 2008; Grant et al., 2018). Traditional concepts and theories have been developed and used for minimally disturbed watersheds but do not always capture the spatial, temporal, and chemical heterogeneity present in many human-impacted landscapes (Kaushal and Belt, 2012; Kaushal et al., 2023a) or even larger forest watersheds with heterogeneous soils and geology (Driscoll et al., 1987; Likens and Buso, 2006). Thus, expanding and merging traditional watershed monitoring approaches along the river continuum could help more accurately connect changes in geology, soils, and human activities with downstream changes in water quality across space and time.

1.2. Monitoring designs using before after control interventions can fall short in assessments

For more practical applications, monitoring designs implementing Before After Control Interventions (BACI) have also been developed related to assessing the effects of watershed management on water quality (Underwood, 1994). These BACI approaches often use a single

station to analyze changes over time before and after a management intervention compared with a reference site, which can present challenges for interpretation and reproducibility (Underwood, 1994). Innovations of traditional BACI designs, such as Before-After-Control-Reference-Impact (BACRI) approaches, incorporate comparisons among degraded, control and reference streams to better distinguish management effects from broader climatic or environmental variability, but such studies remain rare (Walsh et al., 2015). Further, interpretations of management and restoration successes and failures can be complicated by observations across different hydrologic conditions during years of the study. Thus, an improved monitoring and assessment approach is needed to better understand how water quality changes are occurring across multiple stream reaches, which can serve as reference conditions for making multiple comparisons (Kaushal et al., 2023b). Specifically, we need to better understand where the water quality changes are occurring along watershed flowpaths (e.g., are concentrations and loads decreasing everywhere in the watershed or just in certain places?). Despite costly investments in time, effort, and financial resources to restore water quality (Bernhardt et al., 2005), there can be a general lack of confidence in watershed management outcomes because we have not been able to answer questions related to water quality improvements definitively or have had trouble communicating those results to agencies based on temporal and spatial scales of monitoring (Grant et al., 2022; Kaushal et al., 2023b).

1.3. Chemical cocktails: analyzing mixtures to track pollutant sources, fate, and transport

Most of our approaches for studying water quality are also focused

on monitoring individual chemicals or pollutants. While classic work in water quality has focused on analyzing trends in one pollutant at a time, there can also be coupled biogeochemical cycles that are important to monitor (Schlesinger et al., 2011; Aufdenkampe et al., 2011; Pataki et al., 2011). Going even a step further, multiple pollutants can be tracked and compared together as chemical cocktails to gain even more information about sources, transport, and transformation of different chemical elements along stream and rivers flowpaths (i.e., chemical cocktails made up of salt ions, nutrients, organic contaminants, etc.) (Kaushal et al., 2018a, 2020; Shelton et al., 2024; Mayer et al., 2024; Marin et al., 2025). Along human-impacted watersheds, tracking downstream changes in chemical cocktails together can provide more holistic, comprehensive, and spatially explicit assessments of water quality and which can be an extension of nutrient spiraling approaches comparing reactive and conservative tracers along stream reaches (Marti et al., 2004; Hoellein et al., 2017). For example, a more holistic analysis of chemical cocktails offers unique opportunities for: (1) tracking sources of pollution using chemical mixtures, and (2) co-management of pollutants based on similarities in fate and transport. Thus, new and improved watershed monitoring approaches and statistical methods can be constructed by simultaneously analyzing downstream changes in multiple chemical cocktails to better understand interactions among coupled chemical cycles and to characterize the full scope and magnitude of water quality problems and then target management solutions along more strategic intervention points (Kaushal et al., 2020; Kaushal et al., 2023a, 2023b, 2023c; Maas et al., 2023; Malin et al., 2024; Shelton et al., 2024).

The Watershed Continuum Approach

Connecting the Dots with Space-Time Monitoring

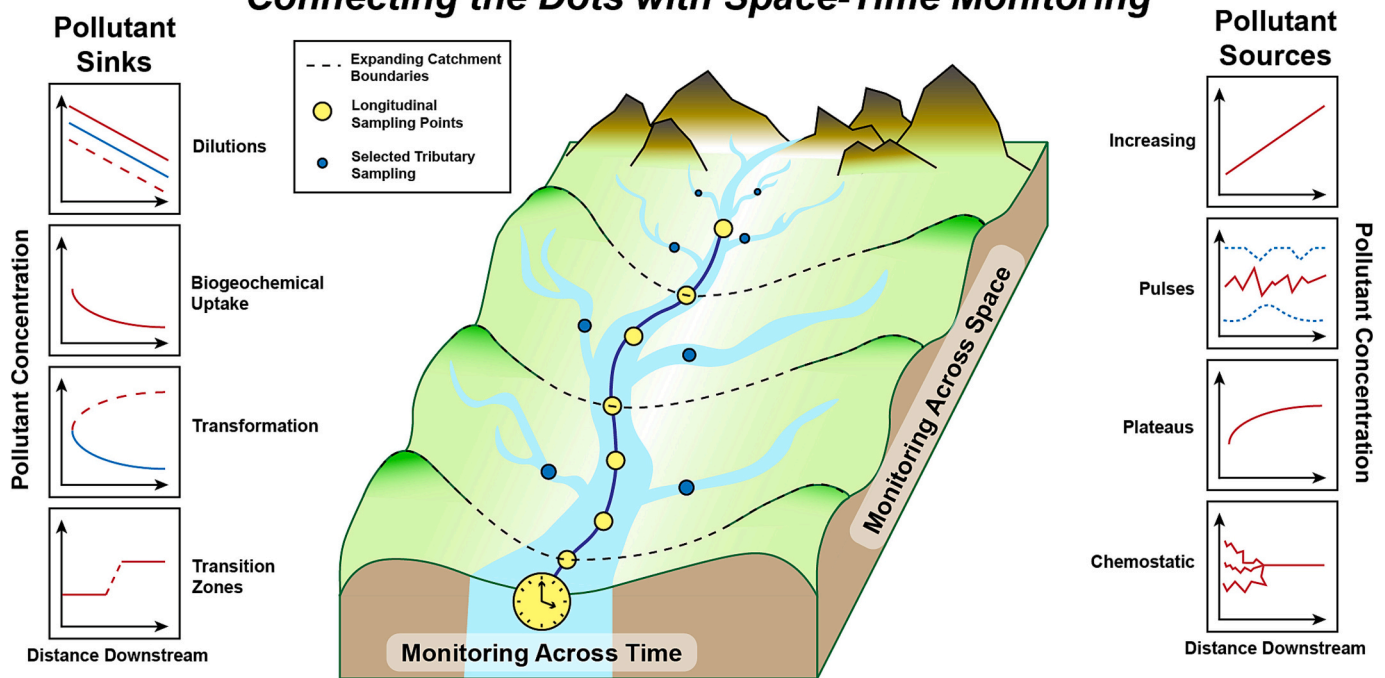


Fig. 1. Conceptual model of the Watershed Continuum Monitoring Approach (WCMA), which integrates spatial and temporal dimensions to track water quality trends, transitions, and tradeoffs across watersheds. WCMA combines both spatial and temporal monitoring along flowpaths in order to better detect and quantify trends, transitions, and tradeoffs in multiple water quality parameters. An array of pollutants or stressors is analyzed at multiple locations along a watershed flowpath over time. The WCMA leverages the natural expansion of catchment areas along a flowpath, which reflect transitions in land use, land cover, and environmental management across spatial and temporal dimensions. WCMA connects longitudinal and lateral trends in pollutant concentrations and loads along streams and rivers with monitoring over time. WCMA can inform progress towards addressing multiple water quality goals and management tradeoffs in impaired waters. Types of downstream pollutant trends and transitions along watersheds are further described in Kaushal et al. (2023a).

1.4. Watershed continuum monitoring approach tracks chemical cocktails along stream flowpaths

In this paper, we propose a Watershed Continuum Monitoring Approach (WCMA) that combines both spatial and temporal monitoring in order to better detect and quantify trends, transitions, and tradeoffs in multiple water quality indicators along flowpaths (Fig. 1). WCMA merges the classic watershed approach with the river continuum concept and nutrient spiraling theory by focusing explicitly on stream and river flowpaths as basic units of study within surrounding watersheds (Fig. 1). WCMA can be used for studies of pollutant uptake rates along streams and rivers by comparing downstream changes in multiple water quality indicators together to understand conservative and reactive transport. WCMA connects and traces longitudinal patterns in pollutant concentrations, mixtures, and loads along mainstem stream and river flowpaths over time while also considering lateral inputs from tributaries. In practice, an array of multiple water quality indicators are analyzed together across multiple locations along watershed flowpaths with repeated longitudinal monitoring over time. The WCMA leverages the natural expansion of watershed areas along a flowpath, which reflect transitions in land use, land cover, and environmental management across spatial and temporal dimensions for making comparisons across multiple stream reaches and spatial trend analysis (Fig. 1).

WCMA results in a vastly improved ability to monitor multiple water quality indicators, and identify hot spots in sources and attenuation of pollutants (McClain et al., 2003; Inamdar et al., 2022) (Fig. 2). WCMA can also be useful in revealing control points influencing transport and attenuation of water quality signals throughout watersheds along streams and rivers (Bernhardt et al., 2017) (Fig. 2). WCMA can reveal rates and locations of biogeochemical transformations from one chemical form to another or empirical relationships between chemical reactants and products along stream and river flowpaths (Kaushal and Belt, 2012; Kaushal et al., 2014, 2023a). Currently, there are mismatches between the small spatial scales we monitor local changes in water quality and our goals to assess broader watershed management and changes in chemical sources, transport, and transformation at larger regional scales (Fig. 3). For example, we rely on watershed models to

provide information on sources, transport, and transformation of chemicals and pollutants at spatial scales of > 10 km along stream and river flowpaths (Fig. 3). Using WCMA allows us to adjust and bridge spatial scales relevant to specific monitoring, management, and modeling questions (Figs. 2 and 3), and can be valuable in screening and targeting future sites for conservation or restoration or selecting sites for establishing routine monitoring stations before expensive financial investments are made over time (Kaushal et al., 2023a, 2023b).

We illustrate practical applications of the WCMA in various case studies from the Chesapeake Bay watershed. We show how the WCMA can be applied by researchers and environmental managers using practical methods of analyzing concentrations, loads, and watershed exports across space and time. We demonstrate how WCMA can be particularly useful for tracking pollution to sensitive receiving waters such as major drinking water sources and supplies, lakes and reservoirs, and tidal rivers and estuaries (Kaushal et al., 2023a; Shelton et al., 2024) (Fig. 2). WCMA has potential to evaluate the effects of changes in different social, ecological, and technological solutions to water management along watershed flowpaths to protect receiving waters such as drinking water sources (Grant et al., 2026). There is a tendency to focus on one environmental problem at a time, but there can be interactions and interconnections among different water quality problems such as: nutrient pollution (Carpenter et al., 1998; Kaushal et al., 2011; Hobbie et al., 2017), freshwater salinization (Kaushal et al., 2005; Kaushal et al., 2018b), metals and organic contaminants (Beasley and Kneale, 2002), organic matter overloading (Duan et al., 2014; Epstein et al., 2016), and hypoxia along rivers (Boynton et al., 2008; Blaszcak et al., 2019a). These interconnections and interactions among problems and opportunities for co-management would be missed without considering pollutant sources, transport, and transformation together along flowpaths. WCMA can provide a comprehensive snapshot of environmental problems and management outcomes along flowpaths and indicate whether some water quality tradeoffs may be difficult to avoid. Thus, a monitoring approach such as WCMA is needed to identify, track, and inform management of multiple water quality problems holistically from sources to receiving waters (Fig. 2).

What Questions Can Longitudinal Monitoring Answer Across Expanding Spatial Scales?

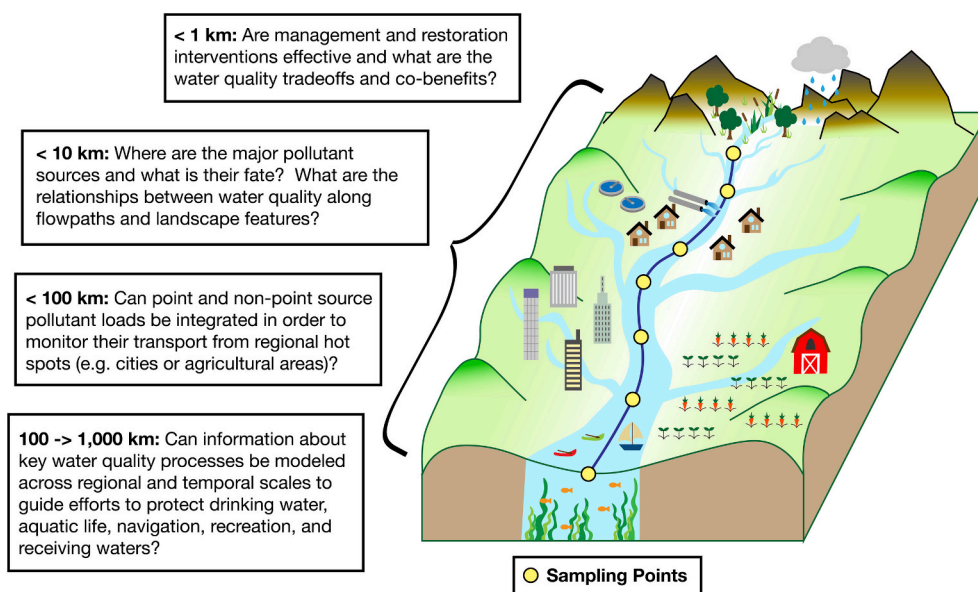


Fig. 2. The Watershed Continuum Monitoring Approach (WCMA) can be applied by scientific researchers and environmental managers to answer important questions regarding changes in concentrations, loads, and watershed exports along stream and river flowpaths. WCMA can be particularly useful for tracking sources, transport, and transformation of multiple pollutants to sensitive receiving waters such as major drinking water sources and supplies, lakes and reservoirs, and tidal rivers and estuaries.

Mismatches Across Monitoring Scales to Inform Regional Watershed Management

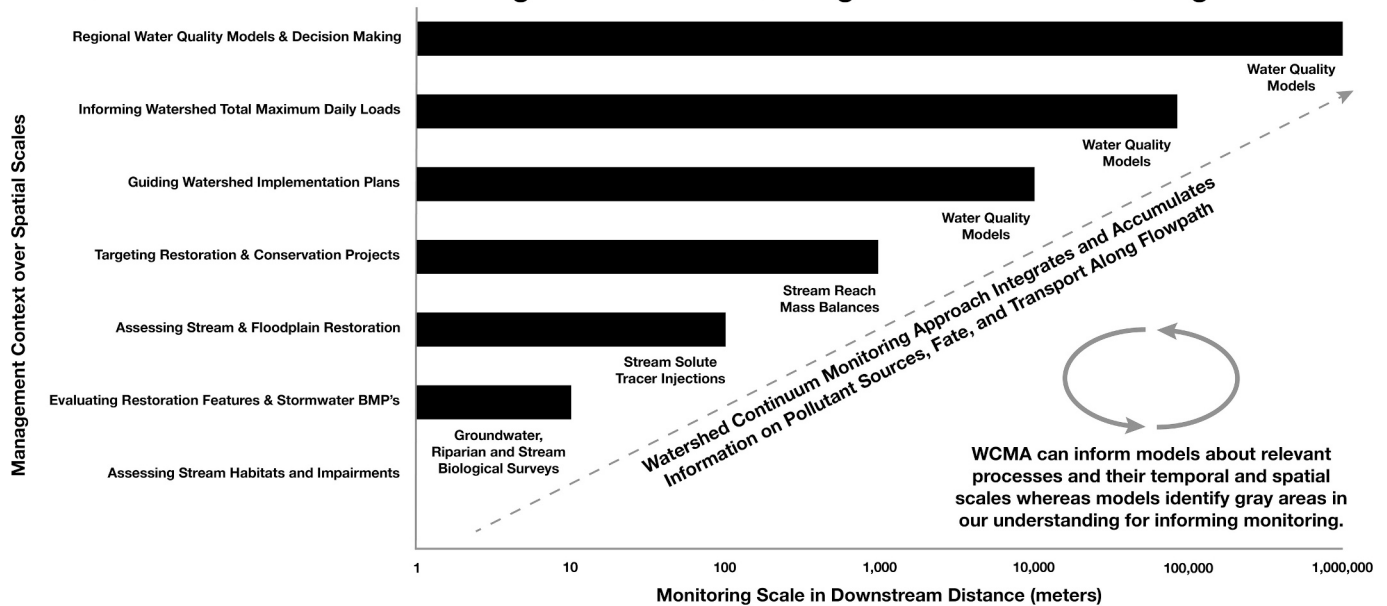


Fig. 3. There are often mismatches between the small spatial scales we monitor for changes in water quality and our goals to assess best management practices at watershed and regional scales. Traditional monitoring approaches do not facilitate analysis of changes in chemical sources, transport, and transformation along stream and river flowpaths, particularly across broader spatial scales and stream and river lengths. Typically, we rely on watershed models to provide information on sources, transport, and transformation of chemicals and pollutants at spatial scales of >10 km along stream and river flowpaths, and these models represent gray areas in our knowledge of water quality processes. Using the Watershed Continuum Monitoring Approach (WCMA) allows us to adjust and bridge spatial scales relevant to specific monitoring, management, and modeling questions and goals. WCMA can also be valuable in screening and targeting future sites for conservation or restoration or selecting sites for establishing routine monitoring stations before expensive financial investments are made over time. Information from WCMA can be used to inform models regarding key water quality processes and their importance at varying spatial and temporal scales. As a positive feedback, models can also inform future sampling and monitoring locations to better understand and predict water quality processes along specific stream and river reaches that are hot spots for sources, transport, or transformation of chemicals and pollutants.

1.5. What monitoring might miss without WCMA: tracking water quality co-benefits and tradeoffs

Given that many watershed restoration plans focus on addressing one or only a few pollutants individually, holistic assessments of co-management, co-benefits and tradeoffs associated with chemical cocktails are not always considered (Kaushal et al., 2018a; Blaszczyk et al., 2019b; Kaushal et al., 2020; Marin et al., 2025; Bub et al., 2025). In optimal cases, one management strategy may increase the efficiency of reducing multiple pollutants that have shared sources, transport, and transformation pathways thereby yielding co-benefits (Malin et al., 2024). In other cases, there may be water quality tradeoffs among management and restoration strategies (Duan et al., 2019; Wood et al., 2022; Inamdar et al., 2023) (Table 1). For example, some stream restoration and stormwater management strategies can increase the ponding and pooling of water (e.g., retention/detention ponds, wetlands), which can successfully lead to significant nitrogen removal through denitrification in pools, retention of phosphorus, and attenuation of stormwater pulses (e.g., Duan et al., 2016, Pennino et al., 2016a, Williams et al., 2017, Duan et al., 2019, Williams and Filoso, 2023) (Table 1). However, ponded and pooled stormwater features also lead to increased water temperatures, decreased dissolved oxygen concentrations, fluctuations in pH, phosphorus desorption and release from sediments (Duan and Kaushal, 2013; Duan et al., 2016), and release of iron and other redox sensitive metals due to low oxygen conditions (Williams et al., 2016; Kaushal et al., 2023a). In addition, production of greenhouse gases due to increased organic matter and decreased dissolved oxygen can represent another tradeoff in ponded and pooled and wetland features (Smith et al., 2017). Another example is the potential trade-off between salinization of drinking water supplies and water supply conservation practices, such as indirect potable water reuse; indirect potable water reuse refers to a water conservation practice where

Table 1

Examples of water quality tradeoffs associated with certain forms of stream, river, and floodplain restoration and stormwater best management practices.

Potential Water Quality Benefits	Potential Water Quality Costs
Decreased nutrients and sediments due to greater retention in hydrologically connected floodplains and pools which allows more time for biological uptake, denitrification, and for suspended sediments to settle out	Increased hypoxic and anoxic periods of low dissolved O ₂ (DO)
Decreased N and P along restored stream flowpaths due to greater biological uptake (particularly young restorations with smaller trees for shading light)	Increased production of algae and bacteria, labile organic matter, and biochemical oxygen demand (BOD).
Decreased concentrations of Na ⁺ and Cl ⁻ from road salts via soil ion exchange in hydrologically connected floodplains and pools	Increased mobilization of N, P, and metals from soil ion exchange sites and Na dispersion of soils
Decreased sediment due to settling and retention of particulates in engineered pools and floodplains	Increased mobilization and internal loading of dissolved P from sediments due to desorption at low DO and high pH
Decreased stream velocity due to pools and ponding	Increased streamwater temperatures, particularly during warmer summer months
Increased microbial denitrification and sulfate reduction due to favorable redox conditions	Changes in alkalinity generation and pH and production of greenhouse gases such as CH ₄ , N ₂ O, and CO ₂
Increased stream metabolic activity influencing nutrient uptake due to primary production and decomposition	Greater fluctuation in DO and pH during day and night cycles
Increased organic matter from microbial and plant activity provides a substrate and energy source for denitrification and other microbial processes	Increased organic carbon and changes in organic matter quality are related to positive or negative effects on retention and release of metals and organic contaminants

highly treated wastewater is added to a drinking water supply to provide enough water to meet consumptive demands for uses by people, industries, etc. (Bhide et al., 2021). Thus, there is a growing need to identify water quality tradeoffs associated with stormwater management, wastewater management, drinking water management, and watershed, stream, and river restoration strategies along multiple points reflecting water management strategies along watershed flowpaths (Table 1).

Accounting for downstream water quality tradeoffs raises fundamental questions regarding how we monitor and manage streams and rivers. For example, how far can water quality tradeoffs or co-benefits from management and restoration strategies be propagated throughout watersheds (Fig. 2)? As a more specific example, how far do nitrogen concentrations decrease downstream as water flows through step pools, stream-wetland complexes, in-stream ponds, and regenerative stormwater conveyance features, while dissolved oxygen and pH decrease, and phosphorus (P), iron (Fe), and metals are released into solution (e.g., Duan et al., 2016; Duan et al., 2019; Kaushal et al., 2023a)? Similarly, does production of organic matter from algal and bacterial growth increase in pools, further contributing to biochemical oxygen demand and change in redox conditions? Do road salts retained in stormwater management BMPs and floodplain reconnection projects mobilize nitrogen, phosphorous, and metals through ion exchange (e.g., Kaushal et al., 2022, Maas et al., 2023, Galella et al., 2023a, 2023b, Kaushal et al., 2025)? When watersheds become progressively urbanized along flowpaths from its headwaters, are the water quality benefits of proactive investments in wastewater infrastructure and reductions in point sources of pollution (e.g., reductions in downstream N and P concentrations) balanced or exceeded by increased inputs of chemical cocktails from more distributed nonpoint stormwater runoff to streams along the broader watershed continuum (e.g., Grant et al., 2026)? Answers to these looming questions and others are critical for accurately monitoring and managing multiple water quality costs and benefits associated with different management decisions.

How long and how far downstream do water quality tradeoffs persist in response to different restoration and management strategies across time (e.g., Wood et al., 2022; Mayer et al., 2022; Kaushal et al., 2023b; Inamdar et al., 2023; Galella et al., 2025)? Some tradeoffs may be temporary and others may be more permanent. An example of a temporary tradeoff is mobilization of nutrients, metals, and salt ions in response to tree removal and soil disturbances in response to construction activities during restoration (Wood et al., 2022; Kaushal et al., 2022; Inamdar et al., 2023; Galella et al., 2025). In addition, there may be situations where positive water quality responses (nutrient and sediment reductions) from restoration and management are transient if underlying drivers and causes of impairments in watersheds are not addressed and fixed. In the long-term, some water quality benefits and co-benefits of restoration and management activities can outweigh any negative tradeoffs (e.g., McMillan and Noe, 2017; Wood et al., 2022; Mayer et al., 2022; Napora et al., 2023; Galella et al., 2025), and it is useful to consider the timescales of water quality benefits when developing a unified monitoring approach across space and time. We show that water quality tradeoffs and co-benefits can be tracked together across time and space using WCMA. In some cases, WCMA can be more cost effective than targeted storm event sampling or purchasing and maintaining sensors or extrapolating from monitoring information from only a few locations. WCMA can be a comprehensive method that analyzes concentrations, loads, and mixtures of multiple pollutants together along flowpaths providing holistic information on pollutant sources, retention, and transformation along flowpaths (Kaushal and Belt, 2012; Kaushal et al., 2014; Kaushal et al., 2023a, 2023b). Overall, the WCMA can provide a practical framework for monitoring multiple water quality goals and tradeoffs together.

2. Water quality assessments using the Watershed Continuum Monitoring Approach

2.1. WCMA assesses progress towards addressing multiple water quality goals and tradeoffs

Longitudinal monitoring along stream and river mainstems with consideration of tributary inputs has been successfully used to track the fate and transport of point sources of pollution along streams and rivers (Marti et al., 2004; Haggard et al., 2005; Pennino et al., 2016a; Hoellein et al., 2017; Runkel et al., 2023), but it can also be applied to track nonpoint source pollution and water quality transition zones along streams and rivers (e.g., Dent and Grimm, 1999; Cooper et al., 2014; Kaushal et al., 2023a; Newcomer Johnson et al., 2014; Shelton et al., 2024; Murphy et al., 2024; Welty et al., 2023; Wheeler and Ledford, 2023; Duan et al., 2019; Duan et al., 2021; Duan et al., 2025). WCMA explicitly integrates repeated longitudinal monitoring surveys along a stream or river flowpath over time while also comparing multiple water quality indicators together to infer sources, fate, and transport of pollutants along streams and rivers (Fig. 1, Table 2). Some of the key principles of WCMA are described further below and in previous studies (e.g., Kaushal et al., 2023a; Maas et al., 2023; Malin et al., 2024; Shelton et al., 2024).

2.2. First principle of WCMA: Monitoring a stream or river flowpath across both space and time

WCMA typically involves monitoring at least 10-20 points (depending on stream order, size, and flowpath length) along a longitudinal stream flowpath repeatedly over time and analyzing multiple water quality indicators together. Depending on watershed size, samples along the mainstem should occur along a flowpath and at least 100

Table 2

Examples of components of the Watershed Continuum Monitoring Approach.

The Watershed Continuum Monitoring Approach (WCMA)	
First Principle of WCMA: Monitoring a Stream or River Flowpath across Space and Time	
1.	Analyze longitudinal trends across flowpaths using longitudinal stream synoptic monitoring across time (2-D WCMA monitoring)
2.	Analyze longitudinal trends along flowpaths and lateral tributaries and/or stormwater outfalls across time (3-D WCMA monitoring)
3.	Analyze longitudinal and lateral inputs to stream and vertical groundwater inputs across time (4-D WCMA monitoring)
4.	Examine potential hot moments and hot spots across space-time. Monitor before and after events chronologically over time. Identify significant events in the timeline of the study, e.g. restoration activities, BMP construction, road salting events, storm events, etc. Monitor upstream and downstream of natural and managed features of interest. Identify significant points along flowpaths representing differences in restoration, conservation, and stormwater BMPs.
Second Principle of WCMA: Comparing, Combining, and Grouping Multiple Water Quality Indicators Together to Track Pollutant Sources, Fate and Transport along Flowpaths	
5.	Monitor multiple water quality goals and chemicals simultaneously, i.e. chemical cocktails.
6.	Measure and estimate chemical concentrations, loads, mixtures, exports, and chemical cocktails across space and time
7.	Link patterns in chemical concentrations, loads, exports, and chemical mixtures with landscape variables including watershed areas, impervious surface cover, forest and wetland cover, presence of stormwater BMPs, riparian forest buffer width, etc.
8.	Where possible, collect ancillary supporting field data linking water quality patterns to biogeochemical processes affecting multiple chemicals (e.g., pH, dissolved oxygen), sensor data (e.g., specific conductance, turbidity), and laboratory data (e.g., metals, ions, fluorescence, nutrients).
9.	Examine the data from multiple water quality indicators visually by plotting over space and time to reveal and illustrate trends, hotspots, hot moments, etc.
10.	Analyze and compare data from multiple water quality indicators using appropriate statistics to detect patterns across space and time (e.g., regression, ANOVA, time-series, spatial kriging, breakpoint analysis, etc.)

meters from tributary inputs to ensure mixing; major tributaries should be sampled to capture lateral inputs (Kaushal et al., 2014; Newcomer Johnson et al., 2014; Cooper et al., 2014; Kaushal et al., 2023a, 2023b; Shelton et al., 2024). Throughout all steps of WCMA, it is implicit that monitoring over time should occur to understand temporal trends and effects of hydrologic events at a minimum of 2-dimensions (longitudinal and temporal, although there can also be value in quantifying lateral tributary inputs and even groundwater if/when possible) (Table 2). Longitudinal sampling during baseflow and steady-state conditions can show remarkably stable, persistent, and repeatable longitudinal patterns in the chemistry along stream flowpaths due to the importance groundwater contributions and/or consistent locations with biogeochemical transformations or changes in the surrounding watershed (Welty et al., 2023; Wheeler and Ledford, 2023; Kaushal et al., 2023a). Thus, longitudinal stream synoptic monitoring during baseflow is recommended for improving comparability over time, particularly when estimating downstream pollutant retention, transformation, and uptake metrics. However, longitudinal monitoring during hydrologic events such as rain storms or snow events can also reveal the downstream transport of pulses of pollutants along the watershed during unsteady flow (Maas et al., 2023; Kaushal et al., 2023a).

Water quality benefits can be identified by analyzing longitudinal trends in concentrations and loads of pollutants per unit stream length, riparian buffer width, forest cover, and drainage area along streams (Gove et al., 2001; Kaushal et al., 2023a; Maas et al., 2023; Shelton et al., 2024; Malin et al., 2024). Ranges in chemical concentrations and loads across various different stream reaches can be compared to assess changes in their spatial variability along stream and river flowpaths. Empirical relationships can also be derived for longitudinal changes in concentrations and loads of chemical reactants and products along flowpaths. Water quality tradeoffs can be quantified by analyzing and comparing trends in pollutants (biochemical oxygen demand, P, and metals) or dissolved oxygen status (Kaushal et al., 2023a) along flowpaths. Neutral effects and steady-state conditions can be identified by the absence of longitudinal trends over time and stable chemical concentrations (e.g., Hale and Godsey, 2019; Kaushal et al., 2023a).

Drivers of longitudinal transitions in water quality benefits and tradeoffs along streams can be determined using: (1) knowledge of project designs and the detailed locations of stormwater management and restoration projects (Newcomer Johnson et al., 2014; Malin et al., 2024), (2) local changes in watershed land use/land cover, stream features, soils and underlying geology and/or (3) formal analysis of statistical breakpoints along stream flowpaths (Shelton et al., 2024) (Table 2). Locations of longitudinal breakpoints can inform us whether trends in multiple pollutants or water quality tradeoffs shift in response to stream restoration features or riparian conservation efforts (Newcomer Johnson et al., 2014; Shelton et al., 2024) (Table 2). The significance of identifying statistical breakpoints and transitions can be valuable for identifying changes in sources of pollutants along flowpaths and detecting abrupt changes in the effects of surrounding land use, underlying geology, or management interventions for particular stream and river reaches along watersheds. Identification of the importance of lateral inputs from tributaries can inform us whether there are hot spots of pollution originating from subwatersheds to assess water quality in 3-dimensions (longitudinal, lateral, and temporal) (Newcomer Johnson et al., 2014). Thus, analysis of trends and transition zones can allow us to determine how far restoration effects and tradeoffs can be transported further downstream and/or whether there are discontinuities due to lateral tributary inputs or new pollution sources and inputs (Table 2).

2.3. Second principle of WCMA: Comparing and grouping multiple water quality indicators together to track pollutant sources, fate and transport along flowpaths

As a second principle, relationships between individual water quality indicators can be analyzed together for making comparisons or for

identifying and tracking sources, fate, and transport of groups of pollutants or chemical cocktails (Table 2). Relationships among water quality indicators and changes in chemical cocktails can also be tracked within the context of restoration features, riparian buffer width, forest cover, drainage area, and pollution events (Kaushal et al., 2023a; Maas et al., 2023; Shelton et al., 2024; Marin et al., 2025) (Table 2). This component of WCMA allows us to compare longitudinal patterns in conservative and reactive pollutants and understand processes such as ion exchange, redox-sensitive reactions, reactions and interactions with organic matter, biological uptake of limiting nutrients, and hydrologic dilution and storage (Kaushal et al., 2023a) (Table 2). Specifically, groups and mixtures of pollutants can be classified, delineated, and visualized using combined principal component analysis (PCA) and multiple linear regression to determine relationships among multiple elements that form chemical cocktails plotted against restoration and riparian conservation metrics (Maas et al., 2023; Shelton et al., 2024) or individually (Kaushal et al., 2023a) (Table 2). A combination of correlations (Shelton et al., 2024) and hierarchical clustering can also reveal common ion covariance patterns which reflect sources and flowpaths through the watershed (Marin et al., 2025). Our previous work has shown common and reproducible longitudinal trends in water quality among multiple pollutants, which were significantly related to riparian buffer width and cumulative forest cover in watersheds (Kaushal et al., 2023a; Maas et al., 2023), zoning and land planning (Shelton et al., 2024), and restoration and stormwater management (Malin et al., 2024; Shelton et al., 2024; Kaushal et al., 2023a). These longitudinal trends, typologies, and transitions in water quality associated with urbanization, restoration, and management can be commonly detected along streams and rivers across local, regional, and national scales (e.g., Gove et al., 2001; Pennino et al., 2016b; Duan et al., 2017; Duan et al., 2021; Kaushal et al., 2023a; Welty et al., 2023; Shelton et al., 2024; Murphy et al., 2024).

3. Applying WCMA as a water quality assessment tool: case studies from the Chesapeake Bay Region

3.1. Assessing downstream water quality changes due to diverse watershed management

In this section, we show explicit applications of WCMA to track sources, fate, and transport of pollutants along streams and rivers. WCMA can be used to compare downstream distances, rates, and ranges that pollutants are reduced, increased, or stabilized across a much broader range of watershed sizes and flowpath lengths than many traditional monitoring approaches. The ability of WCMA to be applied across a range of spatial and temporal scales is relevant to many ecological, hydrological, geochemical, and biogeochemical studies of human-impacted streams and rivers. Specifically, we highlight the unique ability of WCMA to reveal water quality co-benefits and tradeoffs along stream and river flowpaths. Our four case studies from the Chesapeake Bay region offer novel insights into effects of restoration and tradeoffs on water quality. WCMA can assess diverse goals, mandates, and strategies for achieving total maximum daily load (TMDL) reductions of pollutants at the watershed scale (*sensu* Elshorbagy et al., 2005; Shenk and Linker, 2013; Passeport et al., 2013). Diverse strategies for achieving TMDLs include watershed best management practices (BMPs) aimed at reducing nonpoint source pollution, engineering approaches for stream restoration and stormwater management, and setting riparian and forest conservation goals (e.g., Strecker et al., 2001; Shenk and Linker, 2013; Passeport et al., 2013; Noe et al., 2020; Fox et al., 2021; Rossi et al., 2022). Engineering solutions such as stormwater BMPs and stream restoration can reduce nutrients, salts, metals, and pathogens (e.g., McPhillips et al., 2016; Lintern et al., 2020; Kaushal et al., 2022; Galella et al., 2023a; Long et al., 2025), but they may only be effective over limited spatial scales. Nature-based solutions typically involve conservation of forested lands and wetlands, and tree planting

and enhancing riparian buffer width and length (Howarth et al., 2025). There are challenges for monitoring both engineered and nature-based solutions along flowpaths (Grant et al., 2022; Rippy et al., 2024; Noe et al., 2024; Long et al., 2025). Case studies below illustrate how WCMA can assess effectiveness of diverse engineered and nature-based solutions at the watershed scale.

3.2. Case study 1 goal: tracking sources, fate, and transport of salt and nutrient pollution to a major drinking water source

There is a need to evaluate engineering and nature-based solutions to growing water quality issues in the watershed of the Occoquan Reservoir, a major drinking water supply in Northern Virginia (Bhide et al., 2021; Grant et al., 2022). The reservoir's watershed, the Occoquan Watershed, drains 1480 km² of mixed rural, suburban, and urban land uses in Northern Virginia, and is underlain primarily by silicate and carbonate bedrock and sediments (Lindholm, 1979). The downstream Occoquan Reservoir is one of the two primary sources of water supply for nearly 2 million people in Fairfax County, Virginia, USA and surrounding communities, and the location of the nation's first experiment

in “deliberate indirect potable reuse”—the practice of deliberately adding highly treated wastewater to reservoirs and groundwater basins used for potable supply (National Research Council, 2012). The success of this experiment in water recycling, which has been operating continuously for over 40 years, inspired the construction of similar facilities around the country and world (Lazarova et al., 2013).

However, starting around 1995, sodium (Na) concentrations in the Occoquan reservoir began to rise. Sodium can affect the taste of water; e. g., the World Health Organization has set a taste threshold for Na at >200 (NaCl mg)/L (World Health Organization, 1996), while the U.S. the Environmental Protection Agency (EPA) has set a health advisory for individuals on a severely restricted Na diet and a lower taste threshold for Na in drinking water at 20 and 30 mg/L of Na, respectively (Dietrich and Burlingame, 2015). Concerned that this trend of elevated sodium might continue, the local water purveyor (Fairfax Water) has explored possible responses, including a reverse osmosis treatment upgrade that would cost approximately \$ 1 billion USD, not including operating and maintenance costs, lost production water, brine disposal, and a vastly higher carbon footprint (Grant et al., 2022). This case study highlights how freshwater salinization is creating new challenges for regionally

Detecting Watershed Pollutant Reductions from Engineered and Nature-Based Solutions Across Space-Time

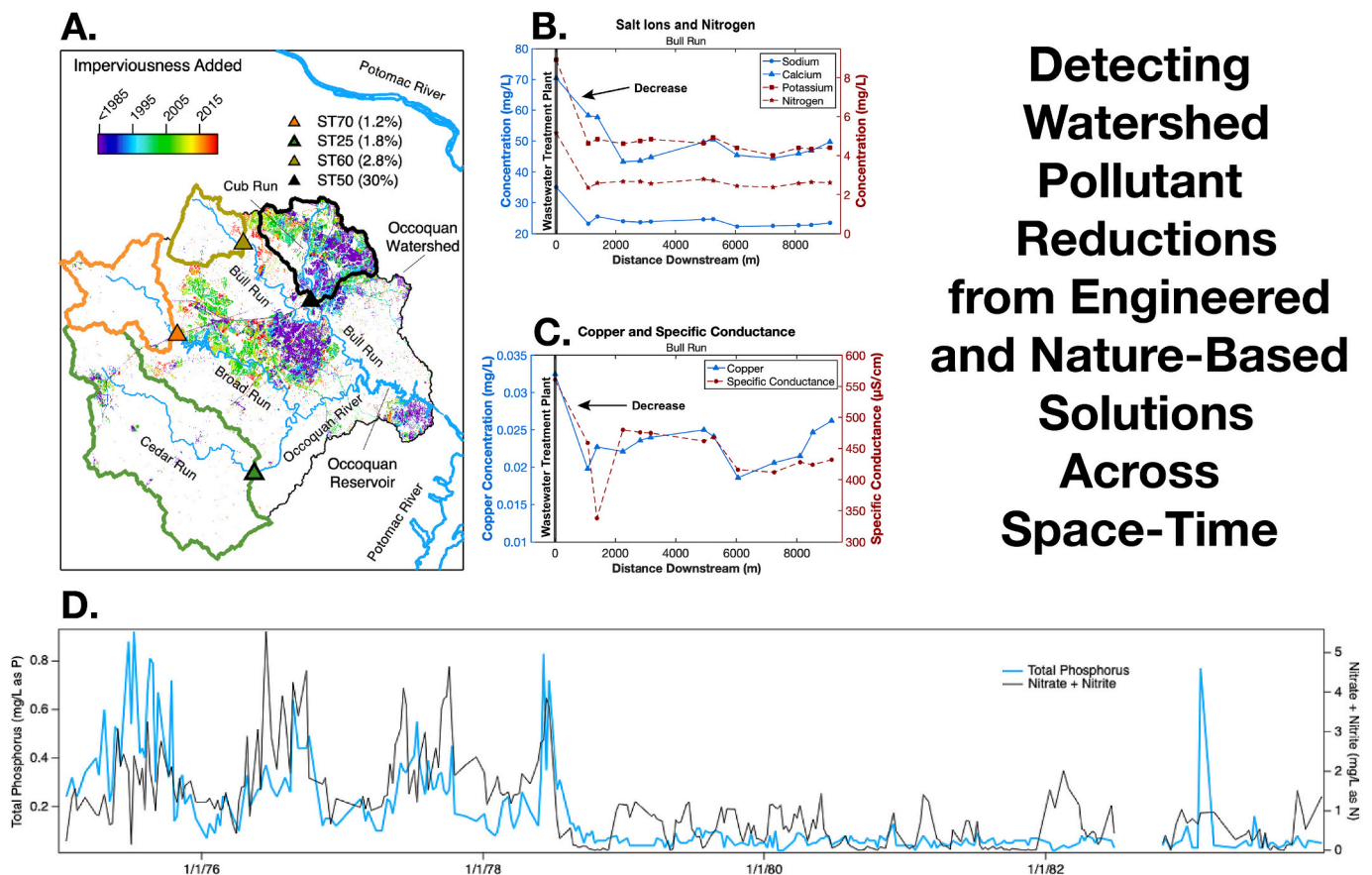


Fig. 4. A detailed analysis of water quality by decade within the Occoquan Watershed across an urban to rural gradient experiencing progressive residential development. In the decade 1994-2003, there was rapid urban expansion in the watershed (indicated in A, the map of impervious cover added over time), which corresponded with increased inputs of nitrate and total phosphorus. There are major questions regarding how much urban pollutants are retained and transformed along Bull Run before reaching the Occoquan drinking water reservoir (B, C). At monitoring station ST50, there has been a dramatic decline in nitrate and total phosphorus concentrations over time. Interestingly, both nitrate and total phosphorus at ST50 were elevated during the first decade of monitoring; this was probably due to the discharge of partially treated sewage from wastewater treatment plants that discharged to Cub Run upstream of ST50 (D). These wastewater treatment plants stopped discharging partially treated effluent in the late 1970s as a larger more advanced wastewater treatment plant Upper Occoquan Service Authority (UOSA) came online and all of the sewage in the region was directed to UOSA. In the decade from 1984 to 1993, after the partially treated sewage discharges to Cub Run were curtailed, there was a marked reduction in both nitrate and TP concentrations (D). Ion concentrations, nitrogen, dissolved organic matter fractions, and specific conductance levels were impacted by the upstream wastewater treatment plant at Bull Run during longitudinal stream synoptic monitoring in January 2021 (Kaushal et al., 2023a). Sodium, calcium, potassium, and nitrogen concentrations decreased immediately following the treatment plant and plateaued at around 2000 meters downstream (B). Copper levels and specific conductance decreased sharply until around 2,000 meters, then fluctuated until the end of the Bull Run stream flowpath. At around 6,000 meters, concentrations began to gradually increase (C).

important drinking water supplies. The extensive history of water quality monitoring in the Occoquan watershed also allows us to investigate the effects of management regimes over time on changes in water quality across both time and space (e.g., Bhide et al., 2021; Grant et al., 2022; Rippey et al., 2024; Kaushal et al., 2023a; Maas et al., 2023; Shelton et al., 2024; Bhide et al., 2025; Roston et al., 2025; Grant et al., 2026).

A key question is how much salt and nutrient pollution from these watersheds can be attenuated and retained along flowpaths in response to management decisions and are there any water quality tradeoffs? We explored this question using the WCMA along Bull Run, which flows for approximately 53 km until it enters the Occoquan Reservoir in northern Virginia. Briefly, Bull Run drains a watershed area of over 300 km² of suburban and urban land use and receives highly treated wastewater effluent from the Upper Occoquan Service Authority (UOSA) treatment plant (Bhide et al., 2021; Grant et al., 2022; Bhide et al., 2025; Grant et al., 2026). After receiving treated wastewater effluent from UOSA, Bull Run flows through an approximately 1,500 acre regional park with extensive conservation areas including forests and wetlands that help attenuate pollutants in streamwater before entering the Occoquan Reservoir (Kaushal et al., 2023a; Maas et al., 2023; Shelton et al., 2024). Using the WCMA, we found decreases in concentrations of nitrogen, different fractions of dissolved organic matter, and major salt ions along the flowpath. Thus, WCMA revealed downstream reductions in multiple pollutants along the stream flowpath, which represented water quality co-benefits from the forest conservation area (a nature-based solution) (Fig. 4). Interestingly, there was also an increase in concentrations of some trace metals downstream of UOSA occurring along the flowpath, which likely represents secondary mobilization of metals via enhanced ion exchange from salt retention in sediments (e.g., Kaushal et al., 2022; Galella et al., 2023a; Marks et al., 2024). Thus, the WCMA can reveal the potential for significant water quality co-benefits and tradeoffs along direct watershed flowpaths to the reservoir, which are critical to protecting water quality in a major drinking water supply in northern Virginia. Ironically, the downstream attenuation and retention of salt ions we observed along the Bull Run flowpath using WCMA is likely contributing to long-term increasing trends in sodium concentrations due to salt accumulation in the watershed (Bhide et al., 2021; Grant et al., 2022; Bhide et al., 2025; Grant et al., 2026).

3.3. Case study 2 goal: comparing benefits of stream restoration versus riparian forest conservation on pollutant reductions to major drinking water sources

This WCMA case study further explores and compares the downstream water quality benefits of nature-based solutions such as forest conservation with different forms of stream-floodplain restoration. Stream-floodplain reconnection approaches are expensive, and there are questions regarding the most effective forms of stream restoration from a cost-benefit perspective. Stream restoration activities involving stream-floodplain reconnection can improve water quality downstream by enhancing retention of nutrients and road salt under certain conditions (Kaushal et al., 2008; Newcomer Johnson et al., 2014; Duan et al., 2019; Kaushal et al., 2023a; Maas et al., 2023). Specifically, engineered stream and floodplain restoration can: (1) increase denitrification rates and reduce nitrogen concentrations in streams, stream-wetland complexes, and hyporheic zones (Kaushal et al., 2008; Harrison et al., 2012; Harrison et al., 2014; Newcomer Johnson et al., 2014; Forshay et al., 2022), (2) increase nitrogen uptake rates along restored streams (Bukaveckas, 2007; Klockner et al., 2009; Newcomer Johnson et al., 2014); (3) reduce nitrogen loads in some restored streams, particularly in headwater stream reaches (Filoso and Palmer, 2011; Mayer et al., 2022; Williams and Filoso, 2023), and (4) reduce concentrations and mixtures of multiple pollutants or chemical cocktails along longitudinal flowpaths through restored stream and wetland features (Kaushal et al., 2023a; Maas et al., 2023; Malin et al., 2024; Shelton et al., 2024).

While stream restoration approaches are widely used, forest conservation can also improve water quality. However, less work has comprehensively and directly compared how stream restoration activities and riparian forest conservation have enhanced the retention and release of a suite of different pollutants of concern along stream flowpaths. Previous work has shown that riparian forest conservation can enhance pollutant uptake along streams (Mayer et al., 2007; Sweeney and Newbold, 2014). For example, longitudinal pollutant reductions along watershed flowpaths can be statistically related to cumulative forest and wetland cover above sampling points (Kaushal et al., 2023a) or riparian buffer width (Gove et al., 2001; Maas et al., 2023). We illustrate applications for WCMA for quantifying and comparing longitudinal pollutant reductions along stream reaches experiencing different forms of stream restoration and conservation. Specifically, we consider the effect of cumulative forest cover on the relationships between longitudinal pollutant concentrations and loads along stream flowpaths in our case studies. We explore two case studies from the Baltimore-Washington D.C. metropolitan region and explicitly apply WCMA to quantify water quality benefits and co-benefits. We show that there can be quantifiable reductions and decreasing trends in nutrients, salt ions, and metals with increasing distance downstream, as the two streams flow through stream restoration features or forest conservation areas, but rates of downstream pollutant attenuation differ with differing management (Fig. 5).

As a first example, we quantified the effects of riparian forest conservation on water quality co-benefits that contribute to drinking water source protection in the Washington D.C. metropolitan region. Watts Branch is a 16 km long stream in Montgomery County, MD that joins the Potomac River <300 meters before a drinking water intake to a major drinking water treatment plant operated by Washington Suburban Sanitary Commission that provides drinking water to the Washington D. C. metropolitan region. The Watts Branch watershed has experienced dramatically increasing urban development over decades in headwaters originating in Rockville, Maryland, USA. However, riparian zones and forest cover along the lower part of the watershed show potential to reduce stream contamination through natural filtration, soil stabilization, and nutrient sequestration (Figs. 5 and 6). We found that downstream riparian forest conservation along Watts Branch showed the potential to decrease nitrogen, major salt ions (Ca²⁺, Mg²⁺, Na⁺, K⁺), and trace metals (e.g., Fe, Mn, Sr, Cu) *en route* to the Potomac River. There were relationships between percent forest cover in the watershed and reductions in N, Ca²⁺, Mg²⁺, K⁺, Fe, Mn, Sr, Cu) as the stream flowed through reaches with increasingly wide riparian forest buffers (Fig. 6). These pollutant reductions with forest cover cannot be explained by simple dilution further downstream because there are distinct transitions showing different statistical relationships with distance downstream and watershed exports of pollutants (nitrogen, sodium, copper) along the flowpath (Fig. 6). Forested areas show potential to be an effective, nature-based remediation strategy to reduce nutrient, salt, and metals pollution along streams (Kaushal et al., 2023a, Maas et al., 2023, Shelton et al., 2024). In addition to reducing overall stream pollution, urban forest restoration and protection can be an effective solution to protect drinking water supplies. These results suggest that a future research frontier is to compare nature-based and engineering solutions.

As a second example, multiple pollutants were reduced along Spring Branch, a stream-floodplain restoration site, draining 407 ha and flowing into a major drinking water reservoir for Baltimore; Spring Branch is described in detail elsewhere (Klockner et al., 2009; Svirichchi et al., 2011; Newcomer Johnson et al., 2014) (Fig. 5). The Spring Branch restoration was conducted in different phases along its approximately 6 km of flowpath length (Newcomer Johnson et al., 2014). The headwaters of Spring Branch originate in a storm drain in a residential neighborhood, and then enters a series of stormwater BMPs consisting of engineered stream-wetland complexes and stormwater ponds before flowing through suburban land use and emptying into Loch Raven reservoir.

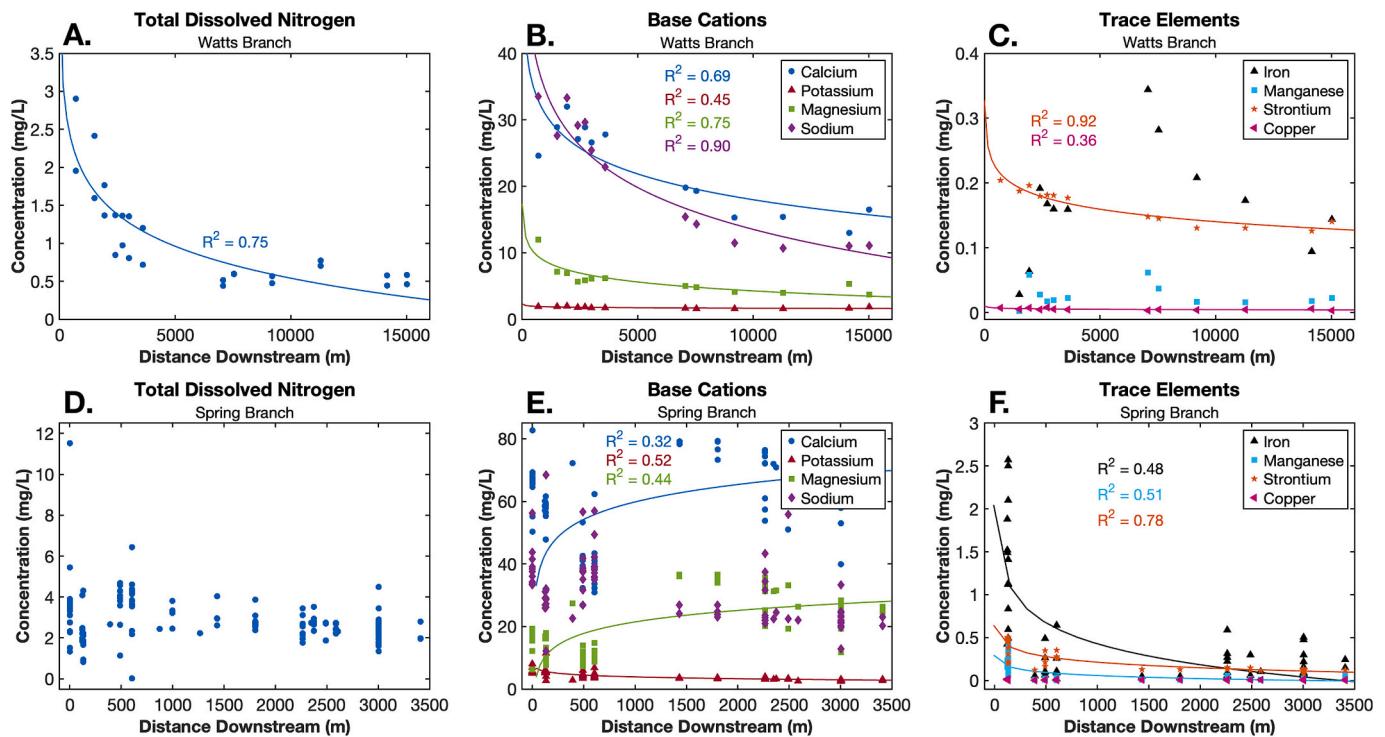


Fig. 5. Total dissolved nitrogen, base cation, and trace element concentrations reveal interesting trends along the flowpaths of Watts Branch in Montgomery County, MD, and Spring Branch in Baltimore County, MD. The longitudinal synoptic surveys at Watts Branch were completed about a year apart on August 2, 2023 and July 25, 2024. The longitudinal surveys at Spring Branch were completed roughly every month from the summer of 2008 to the spring of 2009, on June 23, 2008, September 15, 2008, October 8, 2008, November 3, 2008, December 3, 2008, January 9, 2009, February 11, 2009, March 11, 2009, April 9, 2009, and May 6, 2009. At Watts Branch, total dissolved nitrogen ($-0.61\ln(x) + 6.13$, $R^2 = 0.75$) decreases logarithmically with distance downstream and generally decreases along the flowpath at Spring Branch (A, D). Base cation concentrations also decrease logarithmically at Watts Branch, with calcium ($-5.60\ln(x) + 69.53$, $R^2 = 0.69$) and sodium ($-9.09\ln(x) + 97.20$, $R^2 = 0.90$) having the highest average concentrations, followed by magnesium ($-1.93\ln(x) + 22.08$, $R^2 = 0.75$), and potassium ($-0.09\ln(x) + 2.53$, $R^2 = 0.45$) (B, E). Spring Branch displayed differing trends, with calcium ($8.03\ln(x) + 4.32$, $R^2 = 0.32$) and magnesium ($5.29\ln(x) - 15.10$, $R^2 = 0.44$) increasing logarithmically and potassium ($-0.84\ln(x) + 9.67$, $R^2 = 0.52$) decreasing logarithmically. Trace element concentrations decreased logarithmically at both sites, with iron being the highest at Watts Branch, followed by strontium ($-0.03\ln(x) + 0.40$, $R^2 = 0.92$), manganese, and copper ($-8.85e-4\ln(x) + 0.01$, $R^2 = 0.36$). At Spring Branch, iron ($-0.35\ln(x) + 2.86$, $R^2 = 0.48$) is also the highest, followed by strontium ($-0.09\ln(x) + 0.86$, $R^2 = 0.78$), manganese ($-0.05\ln(x) + 0.41$, $R^2 = 0.51$), and copper (C, F). Logarithmic fits for elements that produced an R^2 value of less than 0.30 were omitted.

There were also sanitary sewer repairs to reduce sewer leaks to the stream, riparian tree planting, removal of a concrete-lined channel to reconnect the stream with its floodplain, and installation of in-stream structures to foster geomorphic stability (see Klocker et al., 2009, Svirichi et al., 2011, Newcomer Johnson et al., 2014 for further details). There were sharp increases in loads of total dissolved nitrogen, dissolved organic carbon, Cu, and Mn along Spring Branch that were influenced by abrupt increases in streamflow (Fig. 7). Load accumulation curves along the stream flowpath revealed hot spots of pollutant loading along the stream (Fig. 7). The WCMA also allowed us to quantify longitudinal patterns in nitrogen export and retention along stream reaches (watershed export at upstream sampling point subtracted from watershed export at sampling point directly downstream) (Fig. 8). We found that different stream reaches showed different N retention with the stormwater management BMPs in the headwaters showing the highest N retention, and the percentage of N retained along stream reaches was influenced by the incoming N load and N uptake capacity could become saturated (Fig. 8). Previous work at Spring Branch showed that there was substantial nitrogen uptake and denitrification using a combination of stable isotope tracer studies (Newcomer Johnson et al., 2014) and N mass balances (Svirichi et al., 2011).

Longitudinal patterns of downstream pollutant attenuation can be compared for restoration along Spring Branch and conservation along Watts Branch using WCMA. Similar to the effects of riparian forest conservation at Watts Branch, there were longitudinal reductions in concentrations of metals (Fe, Mn, Sr, Cu) along the flowpath of the

Spring Branch restoration (Fig. 5); there was also rapid attenuation of metals and nitrogen concentrations along the pond/wetland stormwater BMPs in the headwaters in Spring Branch, which were consistent with high rates of denitrification and nitrogen uptake measured in the same locations by Newcomer Johnson et al. (2014). However, similar downstream pollutant attenuation trends occurred along Watts Branch over much longer distances downstream due to forest conservation compared with restoration (Fig. 5). Engineered restoration solutions (particularly involving pools and wetlands) have the potential to reduce multiple pollutants over shorter distances downstream compared with riparian forest conservation but they can lead to water quality tradeoffs (please see case study 3 below). Unlike the primarily forested stream reaches of Watts Branch, concentrations of salt ions such as Ca^{2+} and Mg^{2+} increased along the flowpath of restored Spring Branch likely due to ion exchange with Na^+ from road salt inputs (Fig. 5). Both conservation and restoration show the potential for attenuation and reduction of pollutants along flowpaths contributing to drinking source water protection, but there can be water quality tradeoffs regarding pollutant uptake lengths and unintended consequences from biogeochemical processes as discussed in the case study below.

3.4. Case study 3 goal: analyzing water quality benefits and tradeoffs in response to stream restoration and tracking how far they propagate along flowpaths

Stream restoration has the potential to minimize nonpoint source

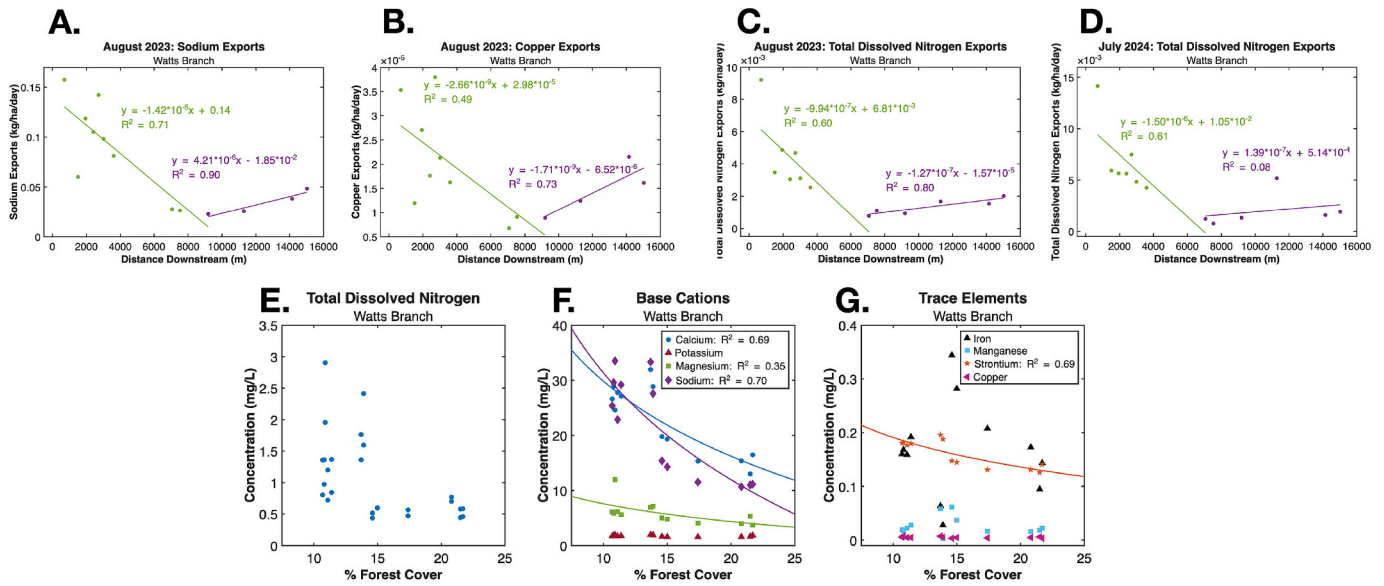


Fig. 6. Total dissolved nitrogen and ion concentrations typically decrease with percent forest cover in the Watts Branch watershed in Montgomery County, MD. The longitudinal synoptic surveys at Watts Branch were completed about a year apart on August 2, 2023 and July 25, 2024. On August 2, 2023, sodium exports decrease linearly until around 9,000 m downstream ($-1.42 \cdot 10^{-5}x + 0.14$, $R^2 = 0.71$) and increase linearly until the end of the flowpath ($4.21 \cdot 10^{-5}x - 1.85 \cdot 10^{-2}$, $R^2 = 0.90$) (A). Copper exports display a very similar pattern, again decreasing linearly until around 9000m ($-2.66 \cdot 10^{-5}x + 2.98 \cdot 10^{-5}$, $R^2 = 0.49$) and increasing until the end of the flowpath ($-1.71 \cdot 10^{-5}x - 6.52 \cdot 10^{-6}$, $R^2 = 0.73$) (B). Total dissolved nitrogen exports showed a slightly different trend, decreasing linearly until around 7000m downstream ($-9.94 \cdot 10^{-7}x + 6.81 \cdot 10^{-3}$, $R^2 = 0.60$) and increasing slowly until the end of the flowpath ($1.27 \cdot 10^{-7}x + 1.57 \cdot 10^{-5}$, $R^2 = 0.80$) (C). On the July 25, 2024 survey, total dissolved nitrogen exports mirrored the trends on August 2, 2023, again decreasing until 7,000 m downstream ($-1.50 \cdot 10^{-6}x + 1.05 \cdot 10^{-2}$, $R^2 = 0.61$) and slowly increasing until the end of the flowpath ($1.39 \cdot 10^{-7}x + 5.14 \cdot 10^{-4}$, $R^2 = 0.08$) (D). As percent forest cover increases, total dissolved nitrogen decreases and plateaus at around 14.6% forest cover (E). Base cation concentrations decrease logarithmically, with calcium ($-19.63 \ln(x) + 75.04$, $R^2 = 0.69$) and sodium ($-27.98 \ln(x) + 95.78$, $R^2 = 0.70$) having the highest average concentrations, followed by magnesium ($-4.67 \ln(x) + 18.34$, $R^2 = 0.35$), and potassium (F). Trace elements also decrease logarithmically, with iron having the highest average concentration, followed by strontium ($-0.08 \ln(x) + 0.37$, $R^2 = 0.69$), manganese, and copper (G). Logarithmic fits for elements that produced an R^2 value of less than 0.30 were omitted.

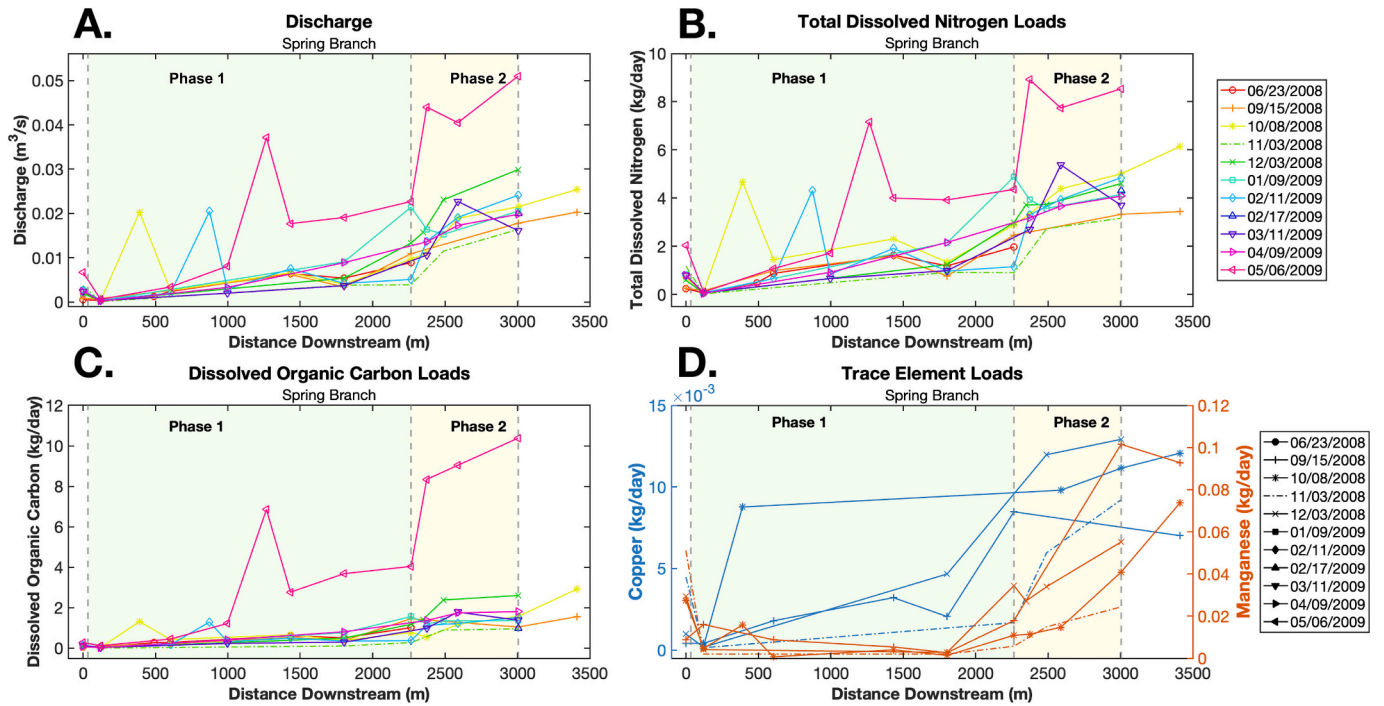


Fig. 7. Discharge, total dissolved nitrogen loads, dissolved organic carbon loads, and trace element loads increase across the flowpath of Spring Branch in Baltimore County, MD. Spring Branch underwent two phases of restoration, beginning at a pond inlet, separated by a site upstream of a storm drain, and ending at Dulany Valley Road, a roadway that experiences heavy traffic. Longitudinal stream discharge peaks following the second phase of the restoration (A), influencing the loads of total dissolved nitrogen (B), dissolved organic carbon (C), and trace elements (D). All parameters steadily increase longitudinally along the first phase, then finally peaks at the end of the second phase.

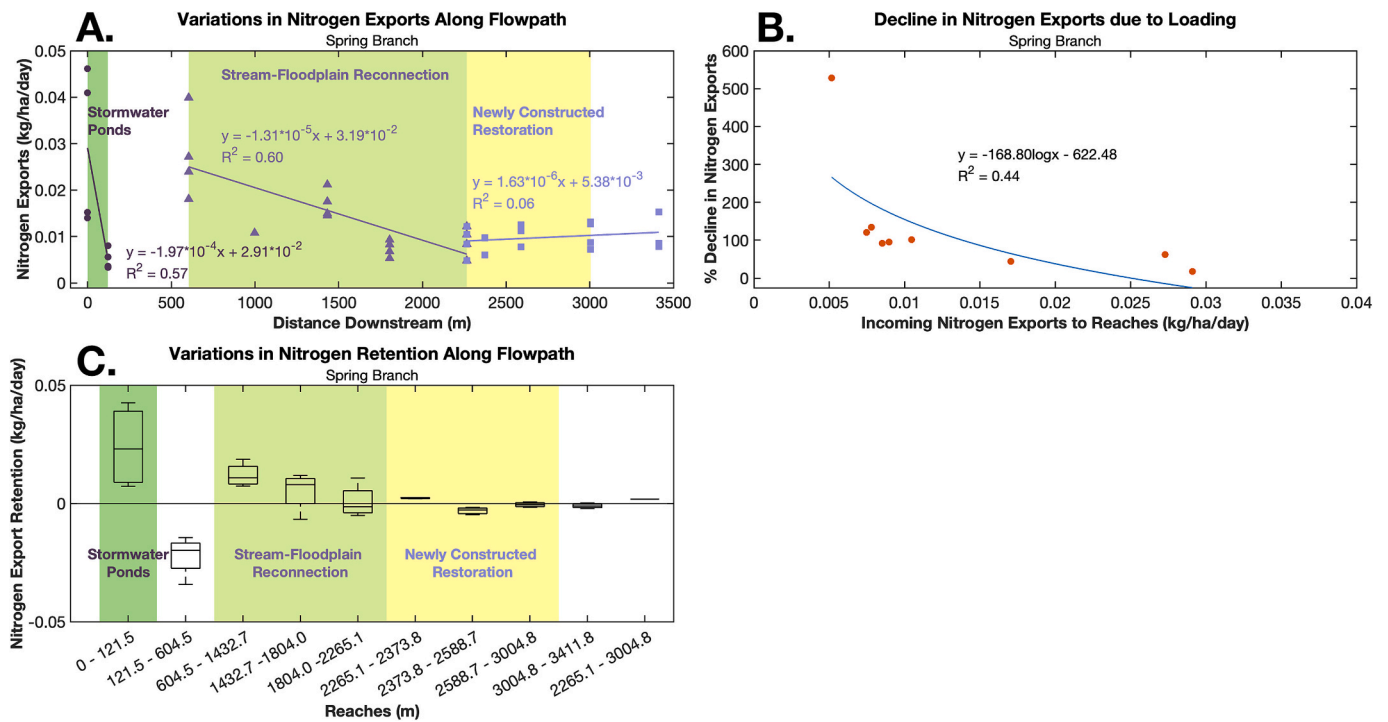


Fig. 8. Nitrogen exports and retention decrease along the flowpath of Spring Branch in Baltimore County, MD. Following two phases of restoration, Spring Branch has three major sections. The first section contains stormwater ponds, which is where the nitrogen exports and retention values are the highest, then suddenly decrease ($-1.97 \times 10^{-4}x + 2.91 \times 10^{-2}$, $R^2 = 0.57$). Values then increase longitudinally approaching the stream-floodplain reconnection, followed by a steady decrease to the newly constructed restoration ($-1.31 \times 10^{-5}x + 3.19 \times 10^{-2}$, $R^2 = 0.60$). Until the end of the flowpath, values seem to increase slightly or plateau ($1.63 \times 10^{-6}x + 5.38 \times 10^{-3}$, $R^2 = 0.06$) (A). Additionally, the percent decline in nitrogen exports decreases logarithmically with the incoming exports to each stream reach ($-168.80 \ln(x) - 622.48$, $R^2 = 0.44$) (B, C).

pollution but it can also contribute to water quality tradeoffs that can be evaluated by WCMA. A key question is how far do the benefits or tradeoffs propagate in response to stream restoration along watershed flowpaths. Stream and river ecosystems have some capacity to retain and transform multiple pollutants through biological uptake and transient storage (Bukaveckas, 2007; Kaushal et al., 2008; McMillan and Noe, 2017), sediment trapping and deposition on floodplains (Noe et al., 2019; Noe et al., 2020), ion exchange on soils and sediments (Kaushal et al., 2022; Galella et al., 2023a; Maas et al., 2023), complexation and

sorption reactions (Kaushal et al., 2018a; Napora et al., 2023), and other biogeochemical processes. However, pollutant retention functions along streams, floodplains, and hyporheic zones can be overwhelmed by excess nitrogen (Mayer et al., 2022; Grant et al., 2018; Mulholland et al., 2008) and excess salt pollution (Maas et al., 2023). Furthermore, there can be tradeoffs where other pollutants are released in response to decreases in dissolved oxygen, increases in ion exchange, changes in pH, sodium dispersion of sediments, and desorption of pollutants (e.g., Wood et al., 2022; Mayer et al., 2022; Kaushal et al., 2022; Kaushal et al.,

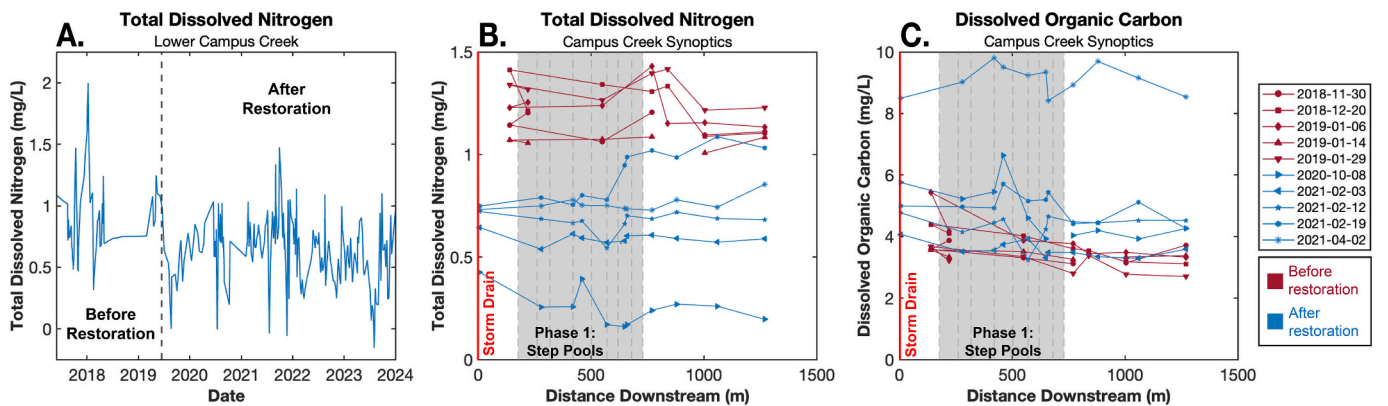


Fig. 9. Longitudinal and temporal trends in total dissolved nitrogen and dissolved organic carbon levels at Campus Creek in College Park, MD. Beginning in 2017, weekly samples were collected at a site located at the end of the stream, denoted as “Lower Campus Creek” (A). Regenerative stormwater conveyance step pools were added during mid-2019, which denoted Phase 1 of the restoration effort at Campus Creek. The average total dissolved nitrogen levels decreased from about 0.87 mg/L to 0.63 mg/L after the restoration. Additionally, longitudinal synoptic surveys were completed before and after the restoration, beginning at a storm drain and ending at Lower Campus Creek. There is a clear distinction between the pre- and post-restoration surveys, as the average total dissolved nitrogen levels decreased from about 1.27 mg/L to 0.64 mg/L (B). Post-restoration, dissolved organic carbon levels increased from about 3.61 mg/L to 5.73 mg/L (C). The restoration did not trigger an immediate response in nitrogen or dissolved organic carbon levels. Rather, levels seemed to be consistent longitudinally, but displayed stark temporal differences.

2023a, 2023b). In this case study, we explicitly apply WCMA (monitoring multiple water quality indicators along a flowpath across space-time) to further analyze water quality tradeoffs in addition to characterizing spatial and temporal variability in water quality along restored streams.

Water quality tradeoffs can be tracked as consequences of engineering and restoring an urban stream into a regenerative step pool conveyance system (RSC which involves the pooling and ponding of water) (Fig. 9). Campus Creek in the Anacostia River watershed is located near the University of Maryland campus in College Park,

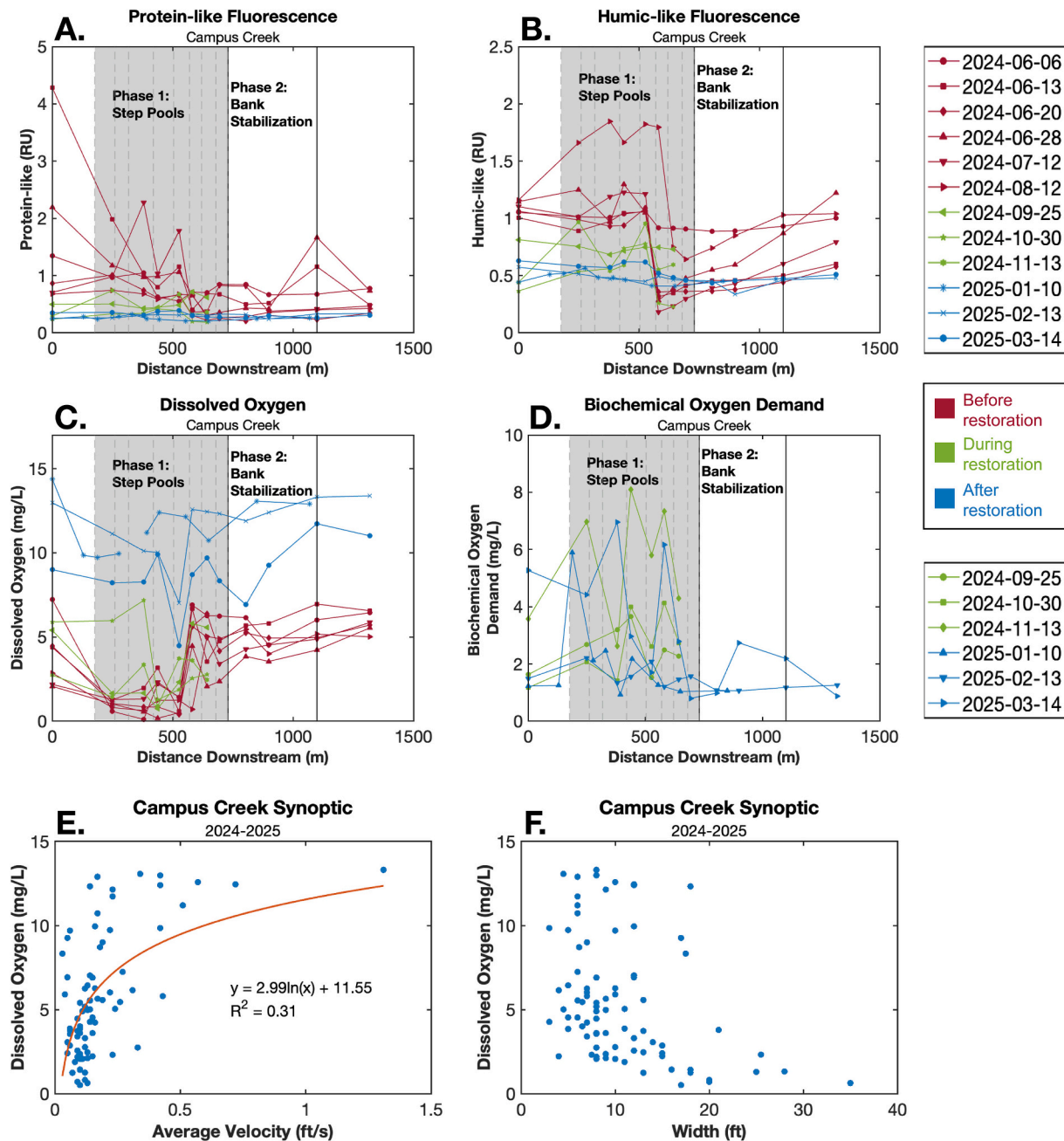


Fig. 10. Organic matter composition and dissolved oxygen concentrations were impacted by restoration efforts at Campus Creek in College Park, MD. During Phase 1 of the restoration, regenerative stormwater conveyance step pools were added during mid-2019 (Phase 1). In fall of 2024, Campus Creek underwent a second restoration (Phase 2) for bank stabilization. Dissolved organic matter fractions, dissolved oxygen, and biochemical oxygen demand incubations revealed the extent to which the dissolved organic matter is microbially derived. Samples were taken from longitudinal synoptic surveys completed before, during, and after the Phase 2 restoration. Both humic-like and protein-like fluorescence were the highest pre-restoration, subsequently decreasing during and after (A, B). The opposite trends were observed for dissolved oxygen levels and biochemical oxygen demand (B, D). In the step pools before and during the Phase 2 restoration, humic-like fluorescence and biochemical oxygen demand peak (B, D). Following Phase 2 restoration, the values decrease and begin to plateau. These trends suggest that the restoration reduced microbially-derived dissolved organic matter and increased dissolved oxygen levels in the step pools. These longitudinal surveys validate the effectiveness of Phase 1, as the step pools did not trigger a response until the ecosystem restoration had matured over time. Following Phase 2, both spatial and temporal trends were observed following the different stages of the restoration. The longitudinal trends in dissolved oxygen may also be explained by the physical characteristics of the stream. The step pools are consistently wider and have a lower average velocity than the unrestored portions of the stream. Dissolved oxygen seemed to increase logarithmically with velocity ($2.99\ln(x) + 11.55$, $R^2 = 0.31$) and generally also decreased with stream width (the logarithmic fit for DO and width that produced an R^2 value of less than 0.30 was omitted) (E, F).

Maryland, USA, ~8 km northeast of Washington, DC (Kaushal et al., 2022). Campus Creek has a drainage area of 1.76 km² and has 26.5% impervious cover in its watershed (Kaushal et al., 2022). During Phase 1 of restoration, Campus Creek was restored in 2019 using a step-pool regenerative stormwater conveyance system designed to slow the flow of water and increase nutrient retention during Phase 1 (Duan et al., 2019). A more recent Phase 2 restoration of Campus Creek was completed downstream of Phase 1 during fall of 2024, and it involved downstream bank stabilization. Further details on the site description of Campus Creek can be found elsewhere (Haq et al., 2018, Kaushal et al., 2022, Wood et al., 2022, Kaushal et al., 2023a, 2023b). Following Phase 1 of the restoration of Campus Creek in 2019, there was a rapid pulse in metals, nutrients, and salt ions in the stream and shallow groundwater due to disturbance of soils and vegetation during the construction process, which represented a water quality tradeoff lasting a few weeks and months (Kaushal et al., 2022; Wood et al., 2022). Another water quality tradeoff documented along Campus Creek was the retention of road salt pollution and mobilization of other metals into solution due to ion exchange (Kaushal et al., 2022; Malin et al., 2024). Although short-term tradeoffs in water quality were documented in Campus Creek, there has not been a long-term analysis of water quality tradeoffs across space and time.

Following the original restoration in 2019 (Phase 1), there was a declining trend in total dissolved nitrogen concentrations in Campus Creek over several years (Fig. 9). WCMA revealed that there was a 27.6% reduction in total dissolved nitrogen concentrations longitudinally along the entire stream flowpath after the stream restoration (Fig. 9). However, there was also a 58.7% increase in dissolved organic carbon concentrations in response to construction of the step pool conveyance system (Fig. 9). Stream width increased along this reach of Campus Creek with the construction of step pools, and average stream velocity decreased with stream width along the pools (Fig. 10), which has likely resulted in an increase in hydrologic residence time through the reach. The efforts during Phase 1 have led to distinct longitudinal trends in concentrations of total dissolved nitrogen and dissolved organic carbon along the step pools over time (Supporting Information Fig. 1). However, maturation of the Phase 1 restoration project and ecological succession and ecosystem development over time was required to observe these distinct longitudinal trends in nitrogen and carbon (Figs. 9 and 10, Supporting Information Fig. 1). Overall, using the WCMA over space and time showed that water quality improvements and tradeoffs can take time to occur as restored stream and floodplain ecosystems evolve.

The ponding and pooling of water in the engineered step pools during the Phase 1 restoration likely enhanced production of organic matter by algae and microbial communities and increased biochemical oxygen demand (Fig. 10). Similar longitudinal patterns were observed before, during, and after the Phase 2 restoration (Fig. 10). Analysis of fluorescence indices showed that the increased organic matter in engineered step pools was produced from both in-stream algal and microbial sources and accumulation of humic-like organic matter from leaves and soils (Fig. 10). A finer-scale analysis showed a longitudinal decline in protein-like and biological reactive organic matter along step pools (Supporting Information Fig. 1). There was a longitudinal increase in biochemical oxygen demand along the engineered step pools and dissolved oxygen concentrations declined to almost zero during warmer summer months (Fig. 10). Thus, the transformation of the urban stream to a step pool stormwater conveyance system was effective at reducing nitrogen pollution across space and time at the whole watershed scale, but there were localized water quality tradeoffs associated with production of organic matter and decreased dissolved oxygen that occurred along the engineered step pools (Fig. 10). Overall, increased biological activity in some restoration features may enhance production of organic matter from microbes and algae contributing to increases in biochemical oxygen demand and hypoxia.

3.5. Case study 4 goal: mapping changes in water quality hot spots along rivers to tidal waters

Mapping and modeling how watershed restoration strategies contribute to downstream water quality is critical for anticipating water quality impacts in receiving waters and shaping policy and management. The WCMA demonstrates that there can be successful pollutant reductions and tradeoffs that can be quantified along and among streams. Linking WCMA with mapping and modeling of chemical cocktails can help us visualize when, where, and how pollutant sources are a problem. Mapping chemical cocktails can also help pinpoint water quality hot spots and environmental risks along streams and rivers across seasons.

Maps of water quality risks can address: (1) visualizing spatial extent of hot spots of water quality impairments from headwaters to rivers, (2) guiding and evaluating placement of expensive stormwater management in urban areas and analyzing the cumulative impacts of smaller scale stormwater management features like swales, bioretention, and rain gardens further downstream, (3) guiding placement of engineered stream-wetland complexes and conveyance pools in locations along stream and river reaches, where it is most likely to see a water quality benefit, (4) mapping the spatial extent to which stream restoration, floodplain reconnection, and bank stabilization appear to improve water quality, while also mapping tradeoffs, and (5) illustrating the spatial effects of surrounding forest and wetland conservation areas in improving water quality along streams and rivers and maps for prioritizing future conservation. Thus, mapping and modeling multiple water quality trends, transitions, and tradeoffs along the watershed continuum can help us visualize the role of management, restoration, and surrounding land use on water quality spatially and temporally.

We illustrate the value of water quality mapping and visualization of multiple water quality parameters using WCMA along the Anacostia River. Historically, the Anacostia River and its tributaries have received substantial loads of pollutants from combined sewer overflows, urban runoff from impervious surfaces, sanitary sewer leaks, and other sources (Kaushal et al., 2023a). Water quality issues have necessitated TMDLs on nutrients, metals, oxygen demand, and fecal coliforms along the Anacostia River network (Maryland Department of the Environment and Washington D.C. Department of Energy and Environment). These TMDLs are being addressed by a variety of actions ranging from reducing combined sanitary sewer overflows, sanitary sewer upgrades, stream-floodplain restoration strategies, and other approaches (Kaushal et al., 2023a). Although not traditionally considered a best management practice (BMP), in this context, we consider parks to be effective BMP's. The Anacostia River flows through a series of parks (the Anacostia National Park system) managed by the U.S. National Park Service including: Colmar Manor Community Park and Anacostia River Park in Maryland, and the National Arboretum, Kenilworth Aquatic Gardens, Kingman Island, and Anacostia Park in Washington, D.C., where there are fringing tidal freshwater wetlands, riparian forests, and tidal backwaters (Kaushal et al., 2023a). These hydrologically connected forests and wetlands provide opportunities for pollutant retention (Kaushal et al., 2023a), but less work has analyzed and mapped water quality tradeoffs along the flowpath.

Longitudinal water quality maps after a winter road salt event revealed the spatial and temporal importance of freshwater salinization as a water quality issue. Longitudinal water quality maps show elevated specific conductance and concentrations of different salt ions along the entire flowpath of the Anacostia River and a lack of dilution during winter, even as discharge increases further downstream. Longitudinal monitoring also revealed that concentrations of salt ions such as Na⁺, Ca²⁺, and Mg²⁺, and trace metals such as Cu were elevated along the flowpath with hot spots in urban areas near impervious surfaces (Fig. 11); this co-mobilization was likely due to enhanced ion exchange in soils and sediments triggered by increased Na (Marks et al., 2024). During summer, longitudinal monitoring showed that Na decreased

Freshwater Salinization Syndrome Along the Watershed Continuum

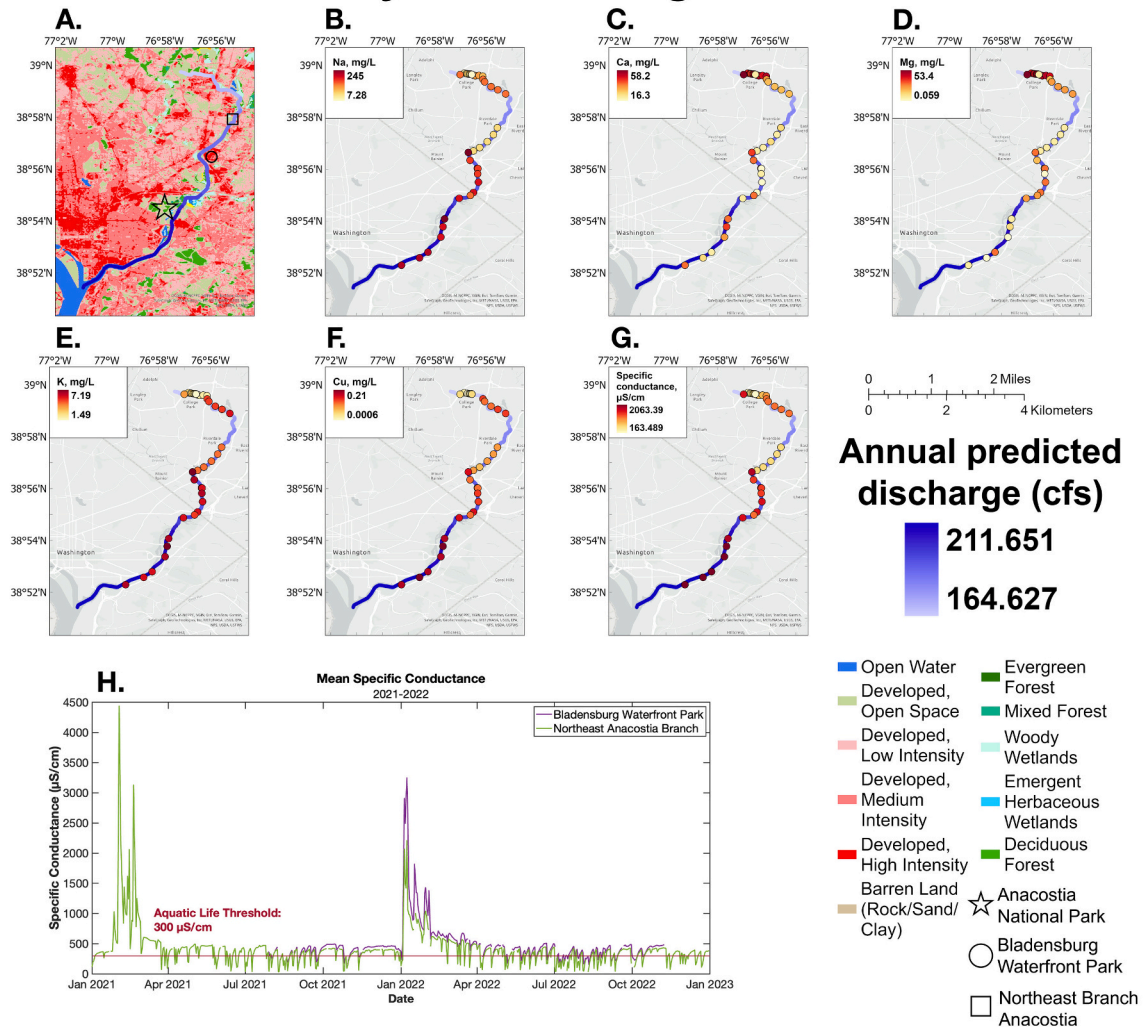


Fig. 11. During the winter, the Anacostia River in Washington, D.C. experienced freshwater salinization syndrome (FSS) along its flowpath. A series of longitudinal synoptic surveys were completed on January 6, 2022, January 17, 2022, and January 19, 2022. Calcium and magnesium concentrations peaked at the headwaters and decreased past the urban influence of the Northeast Branch Anacostia River. Levels peaked again due to tidal inputs at Bladensburg Waterfront Park, followed by a general decline into the city (C, D). Sodium, potassium, and copper concentrations increased until the Northeast Branch Anacostia River, indicating that urbanization imposed a greater impact onto those elements. Concentrations rose again at Bladensburg Waterfront Park and into the city (B, E, F). Specific conductance experienced hotspots at both the Northeast Branch Anacostia River and Bladensburg Waterfront Park (G). Concentrations increased longitudinally into the city, illustrating how FSS is influenced by urban pollution and tidal inputs. From 2021 to 2022, the daily mean specific conductance levels at Northeast Branch Anacostia River and Bladensburg Waterfront Park regularly exceeded the aquatic life threshold of 300 $\mu\text{S}/\text{cm}$. Two large peaks in specific conductance levels occurred following road salt incidents after snow storm events each year (H).

along the flowpath through the tidal freshwater wetlands and parks. Despite the benefits of the tidal freshwater wetlands and parks for achieving pollutant reductions, longitudinal water quality maps also revealed hypoxia in these river reaches during summer (Fig. 12). Dissolved oxygen concentrations were below 4 mg/L during summer months extending along fringing tidal freshwater wetlands in the various parks along the Anacostia (Fig. 12). This hot spot of river hypoxia also had elevated concentrations of redox-sensitive dissolved metals such as Fe and Mn, in addition to Cd and Cu (Fig. 12). Longitudinal water quality maps using the watershed continuum approach can reveal the spatial and temporal extent of water quality issues such as freshwater salinization and hypoxia, and also hot spots of pollution and chemical cocktails.

4. Knowledge gaps and frontiers

In this paper, we explored the WCMA for analyzing water quality

tradeoffs such as which pollutants of concern are retained (nutrients and salts), which pollutants are released, when and under which environmental conditions, and at which spatial and temporal scales retention and release might occur. There are emerging questions regarding how WCMA can: (1) inform progress towards achieving multiple water quality goals, (2) compare water quality tradeoffs associated with stormwater management, stream restoration, and forest conservation, and (3) provide information to land planning and zoning departments on the role of forest cover as an underappreciated driver of water quality trends along streams and rivers (Kaushal et al., 2023a; Maas et al., 2023; Malin et al., 2024; Shelton et al., 2024). Case studies from this paper suggest that there are many future questions involving contaminants of emerging concern, integrating the role of sensors into WCMA, and investigating other problems and applications below.

River Hypoxia and Metal Mobilization Along the Watershed Continuum

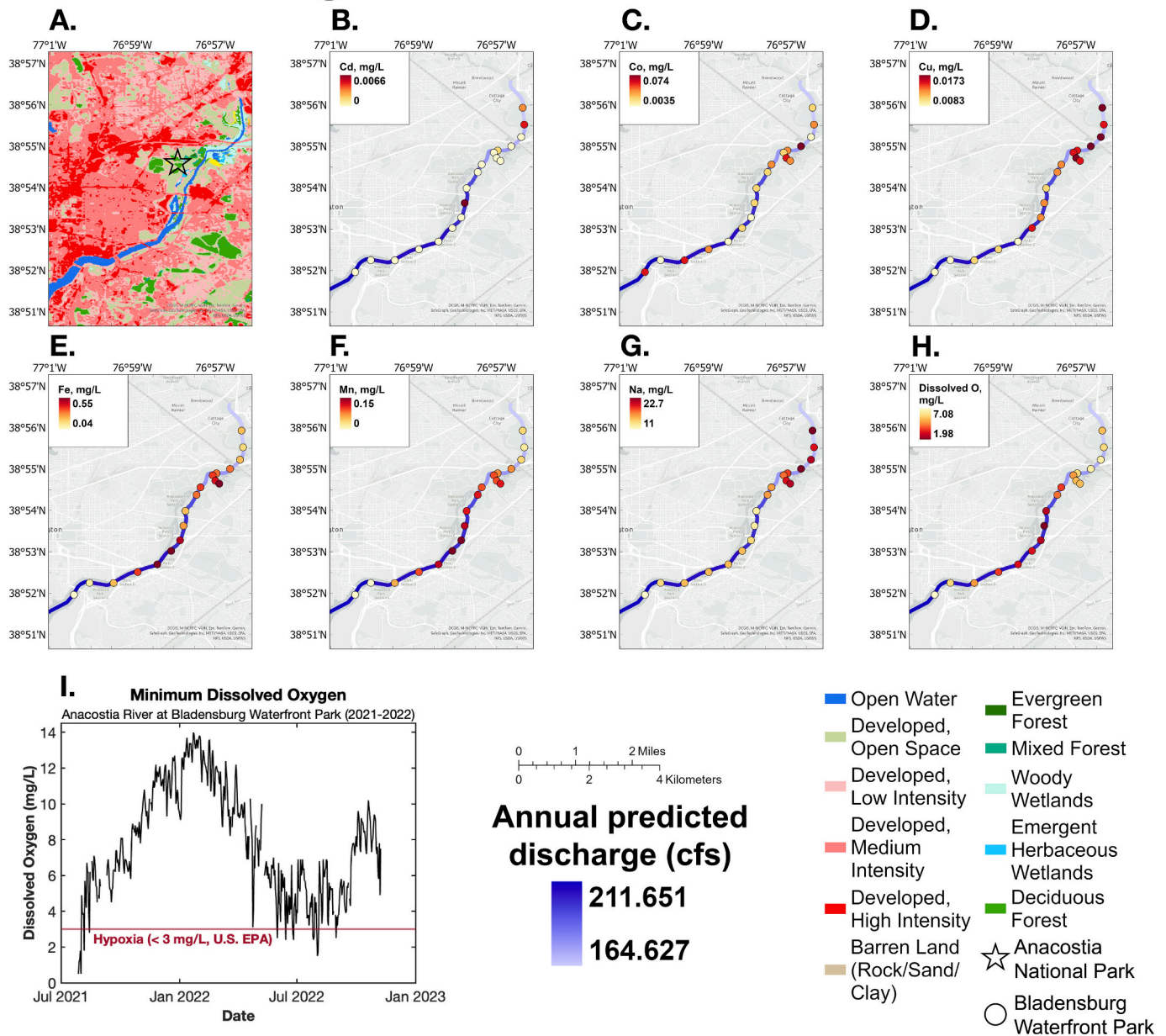


Fig. 12. During the summer, the Anacostia River in Washington, D.C. experienced hypoxia along its flowpath. A longitudinal synoptic survey was completed on July 19, 2022. Cadmium, cobalt, copper, and sodium peaked at the tidal inputs of Bladensburg Waterfront Park and decreased along the flowpath (B, C, D, G). Iron and manganese were less affected by the tidal inputs and instead gradually increased, then peaked along the fringing wetlands of the Anacostia National Park system, a series of national parks along the Anacostia River (E, F). Dissolved oxygen levels followed similar trends along the flowpath (H). During the summers of 2021 and 2022 at Bladensburg Waterfront Park, minimum dissolved oxygen levels steeped below the EPA hypoxia level of 3 mg/L (I).

4.1. Assessing freshwater salinization risks and management along watershed flowpaths

The WCMA can be used to better map the impacts and risks of Freshwater Salinization Syndrome (Kaushal et al., 2018b) and to understand if localized management activities are reducing salinity across finer spatial scales through retention or source reductions (Kaushal et al., 2023a, 2023b, 2023c; Maas et al., 2023; Malin et al., 2024; Shelton et al., 2024). For example, the effects of salinity BMPs may show considerable spatial variability across watersheds based on placement. From a spatial perspective, there may be hot spots and hot moments

(sensu Vidon et al., 2010) of salt inputs along watersheds after winter months due to uneven applications, storage, and accumulation of road salts within watersheds (Marks et al., 2024). Challenges associated with assessing effectiveness of salinity BMPs can include spatial variability in: covering salt storage facilities to minimize runoff, salt application rates on certain roads within watersheds, chloride outreach and education to public and private applicators in local parking lots, local access to training opportunities for better salt management, use of liquid brines and applications before snow events in some areas, permit requirements, and participation in salt smart certification programs for local parking lots and sidewalks. The WCMA could allow an assessment of salinity

risks at finer spatial scales to isolate effects of differences in management spanning parking lots, neighborhoods, roadways, parks and forest conservation, and restoration projects along flowpaths (Maas et al., 2023; Shelton et al., 2024).

A future application of WCMA is to address how the propagation and dissipation of road salt pulses along watersheds have responded to improved road salt management strategies and stormwater management BMPs. As an example, Long Branch, an urban watershed in Virginia, USA, shows a decreasing trend in specific conductance since 2014, while most nearby watersheds continue increasing (Fig. 13). Specific conductance can be a proxy for chloride and other salt ions (Kaushal et al., 2019; Moore et al., 2019). A chloride total maximum daily load (TMDL) was implemented in this watershed in 2020. Fairfax County has primarily instituted non-structural BMPs by implementing the Virginia Salt Management Strategy (SaMS), which is a plan to improve how salt is used on roads in Northern Virginia. This plan is designed to adjust salt application practices to ensure only the minimum amount of salt necessary is being applied while still maintaining public safety. High-frequency sensor data show that there has been a consistent decline in mean daily specific conductance in Long Branch since 2014 (Fig. 13B) (U.S. Geological Survey, 2025), and this unique decreasing trend in the region began before the implementation of the salinity BMPs. A more detailed seasonal analysis shows that the overall decreasing trend in Long Branch is being driven by values of specific conductance decreasing during the spring and summer months (Fig. 13C).

Interestingly, there are still large pulses of salinity in Long Branch during winter months and sometimes during the fall months when older groundwater from the lowest intraannual base flow and longest hydrologic residence times is discharged into the streams. Surprisingly, the salts that get applied during the winter and then wash off during spring seem to be decreasing. Thus, despite the fact that there are still salt pulses, the overall amount of salinity washing off roads in the spring is decreasing, which is potentially related to stormwater BMPs. Based on our seasonal analysis, we hypothesize that increasing stormwater BMPs in this watershed have been retaining salt. Recent work in the Long Branch watershed has shown that dry weather concentrations of chloride during autumn were higher after years with more snow/salt application indicating that salts were being stored in the watershed and released via groundwater discharge (Chanat and Custer, 2025). Non-structural salinity BMPs such as the Virginia Salt Management Strategy, education, and outreach may have also led to reduction in road salt application rates during more recent years, but would not explain the trends observed over longer time scales. The mean residence time for chloride in groundwater is only 1.27 years in the Long Branch watershed (Chanat and Custer, 2025). This suggests that urban land cover may create limited residence time for solutes and thus fast responses to management actions. Given the long-term nature of this salinity decline, climate factors such as warmer winters and changes in precipitation patterns may also be important drivers of change. Future work can use the WCMA to directly investigate and quantify salt attenuation and retention along watershed flowpaths (*sensu* Kaushal et al., 2022, Maas et al., 2023, Galella et al., 2023a, Brown et al., 2024, Chanat and Custer, 2025).

4.2. Comparing engineering and restoration approaches vs. nature-based solutions

Our case studies suggest that co-managing water quality needs to be considered from the added perspective of forest conservation and riparian buffer width (Wayland et al., 2003; Sweeney et al., 2004; Mayer et al., 2007; Noe et al., 2024). Specifically, WCMA can detect reductions in multiple pollutants along streams draining forest conservation areas and parks. The concept of parks as water quality BMPs has been less considered, but may show promise in reducing nutrients, salts, and metals similar or better than engineering solutions on a watershed scale (Li et al., 2009; Wahlroos et al., 2015; Kaushal et al., 2023a; Shelton

et al., 2024). Overall, there is a need to compare co-management, co-benefits, and tradeoffs using different restoration, conservation, and policy approaches to achieve pollutant load reductions in rivers.

Identifying tradeoffs and co-benefits using WCMA can help guide decisions related to when and where to implement nature-based solutions vs. engineered restoration approaches along watershed flowpaths. Several recent studies have shown that forested parks coincide with detectable improvements in downstream water quality pertaining to salts, nutrients, and some metals (Kaushal et al., 2023a, Maas et al., 2023, Malin et al., 2024, Shelton et al., 2024). However, the exact mechanisms for water quality improvement in these forest and wetland conservation areas is unknown. The obvious explanation would be a decrease in nonpoint and point pollution sources in adjacent forests and wetlands. Although less considered, less polluted soils may have more available ion exchange sites that are less saturated and readily able to bind contaminants. There may also be differences in organic matter quantities and quality in forested conservation areas and wetlands that subsidize biogeochemical processes and water quality improvements (Gift et al., 2010). There may be differences in natural microbial communities in forested and wetlands sites that affect pollutant retention (Inamdar et al., 2023). There may also be similarities in hydrologic connectivity between streams and floodplains in both forest conservation and restoration areas (*sensu* Newcomer Johnson et al., 2016, McMillan and Noe, 2017). Although it may take time to achieve progress towards forest reference conditions related to hydrology, organic matter availability, microbial communities and soil health metrics (Wood et al., 2022; Inamdar et al., 2023; Galella et al., 2025), more work needs to compare nature-based solutions to engineering solutions (Noe et al., 2024) on changes in downstream water quality using WCMA.

4.3. Can organic matter be a tracer of downstream water quality degradation or restoration?

Our case studies revealed that organic matter composition may be important for restoring water quality but may also contribute to hypoxia as a water quality tradeoff (Figs. 6 and 12). Restoration approaches involving forests, wetlands, and ponds can increase organic matter, which is a critical substrate for denitrification, sorption of phosphorus, metals, and organic contaminants (Kaushal et al., 2018a, 2020). More research using WCMA needs to unravel the role of different fractions of dissolved organic matter on regulating downstream water quality functions and as tracers of nonpoint source pollution. Protein-like DOM consists of aromatic amino acids released by biotic particles, producing fluorescent signals in the ultraviolet portion of the electromagnetic spectrum. Humic-like dissolved organic matter (DOM) consists of highly aromatic products formed from decomposing plant and animal matter, producing fluorescent signals in the visible spectrum. Given that dissolved organic matter composition can now be more easily characterized using fluorescence spectroscopy, DOM composition could be a useful tracer of wastewater inputs or natural sources of DOM from forests and wetlands in response to stream-floodplain reconnection, stream-wetland complexes, evidence of microbial and algal transformations influencing natural organic matter inputs, and developing proxies for certain organic contaminants. Future research could focus on elucidating the role of different types of organic matter in stream and river restoration and accounting for potential water quality benefits and tradeoffs *en route* to coastal waters (e.g., Davies and Smyth, 2025).

4.4. Chemical cocktails are tracers of pollutants and hydrological processes along watersheds

Pollution inputs in heterogeneous landscapes can represent multiple tracer studies throughout watersheds influenced by different human activities (Runkel et al., 2023). While nitrogen, phosphorus, and sediment drive current management, pollutants of emerging concern represent both a challenge and an opportunity for restoring water

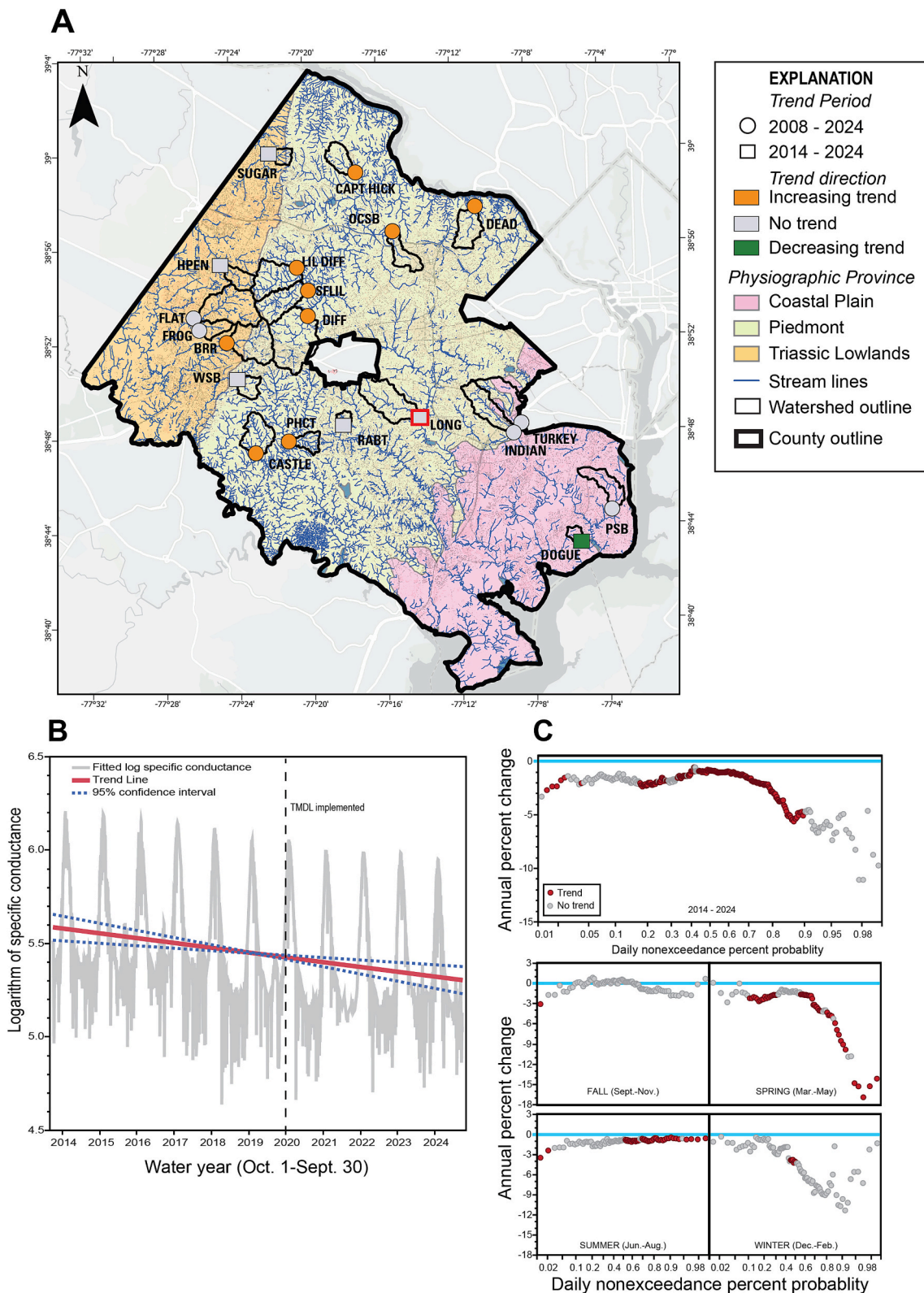


Fig. 13. (A) Map of U.S. Geological Survey (USGS)-Fairfax County monitoring network indicating the direction of trends in specific conductance for measurements collected each month from 2008 through 2024 or 2014 - 2024 depending on length of record. (B) Trend in high-frequency (15-minute interval) specific conductance measurements at Long Branch (outlined in red in panel A), USGS station 01654500 (U.S. Geological Survey, 2025) from water year 2014 through 2024 using a general additive model approach. Dashed line notes the onset of the chloride TMDL and implementation of the salt management strategy (SaMS). There is not an exact date for implementation of the stormwater BMPs. Trends were computed using a seasonal Mann-Kendall test. (C) Trends in mean daily specific conductance at Long Branch (outlined in red in panel A), from 2014 through 2024 with nonexceedance probabilities of mean daily values. A water year begins October 1 and ends September 30th and is named for the year in which it ends.

quality in the future. On one hand, emerging pollutants (salts, *E. coli*, metals, organic pollutants) present additional stressors to aquatic life, habitat degradation, and drinking water sources (Kaushal et al., 2005, 2020, 2022; Mayer et al., 2024). On the other hand, they serve as valuable tracers identifying shared pollution sources in watersheds. The full power of pollutants of emerging concern as tracers of water quality is seldom harnessed because they are either not analyzed at all or considered individually without connecting them to commonly regulated pollutants.

For example, human inputs of nitrogen, carbon, and redox-sensitive metals can be viewed as reactive tracers and human inputs of some salt ions can be viewed as more conservative tracers (e.g., Marti et al., 2004; Runkel et al., 2013; Kaushal et al., 2023a). Our case studies showed that longitudinal studies can quantify pollutant uptake and transformation rates along watersheds. For example, we were able to estimate load accumulation curves with distance downstream to understand how rates of pollutant loading change along flowpaths. Load accumulation rates can be critical for pinpointing sources of pollution along watersheds and apportioning load contributions from upstream vs. proximal sources. In our case studies, we documented how pollutant exports per watershed area decrease along distance downstream and showed that this is a quantitative method for assessing the effectiveness of different watershed management strategies across varying spatial and temporal scales. Overall, our case studies show how pollutant sources change along watersheds and how the biogeochemical response or uptake capacity of the stream or river also changes.

Furthermore, different levels of hydrologic connectivity and the influence of wetlands can be identified and confirmed by analyzing longitudinal concentrations of redox sensitive elements such as Fe and Mn along flowpaths (Kaushal et al., 2023a; Malin et al., 2024). Fe and Mn are chemical indicators of hydric soils in wetlands, and dissolved Fe and

Mn concentrations along flowpaths have the potential to be indicators of hydrologic connectivity (Kaushal et al., 2023a, Malin et al., 2024), although this has been less explored. Thus, different chemical cocktails can be used to trace watershed hydrological processes and flowpaths relevant to tracking nonpoint pollution sources (Shelton et al., 2024).

4.5. Sensor arrays can be incorporated into the watershed continuum monitoring approach

Future work could integrate high-frequency sensor measurements of pH, dissolved oxygen, specific conductance, and other water quality metrics to better understand acute water quality fluctuations over daily timescales to elucidate specific contaminant sources, movement, and transformation along flowpaths (Galella et al., 2021). Furthermore, such sensor data can support inferences about how the range of pH and reduction-oxidation conditions in a stream may affect the speciation of dissolved elements and compounds, affecting bioavailability and toxicity. In addition, sensors can also be used to better quantify water quality exceedances and understand diurnal cycles along flowpaths. The opportunity for a wide range of chemical proxy development with sensors (Kaushal et al., 2018a; Morel et al., 2020) may lead the path to high-frequency mass balances or attenuation estimates across night and day along flowpaths. Sensors have been used to document changes in water quality over time in response to improved stormwater and sewer management. For example, there have been reductions in peak turbidity and relationships between streamflow and turbidity due to stormwater management upgrades in an urban watershed over time in Maryland, USA (Fig. 14). In addition, there have been corresponding reductions in concentrations of ammonium and *E. coli* due to stormwater and sewer management (Fig. 14). However, it is unclear whether those water quality improvements reflect only localized and incremental changes

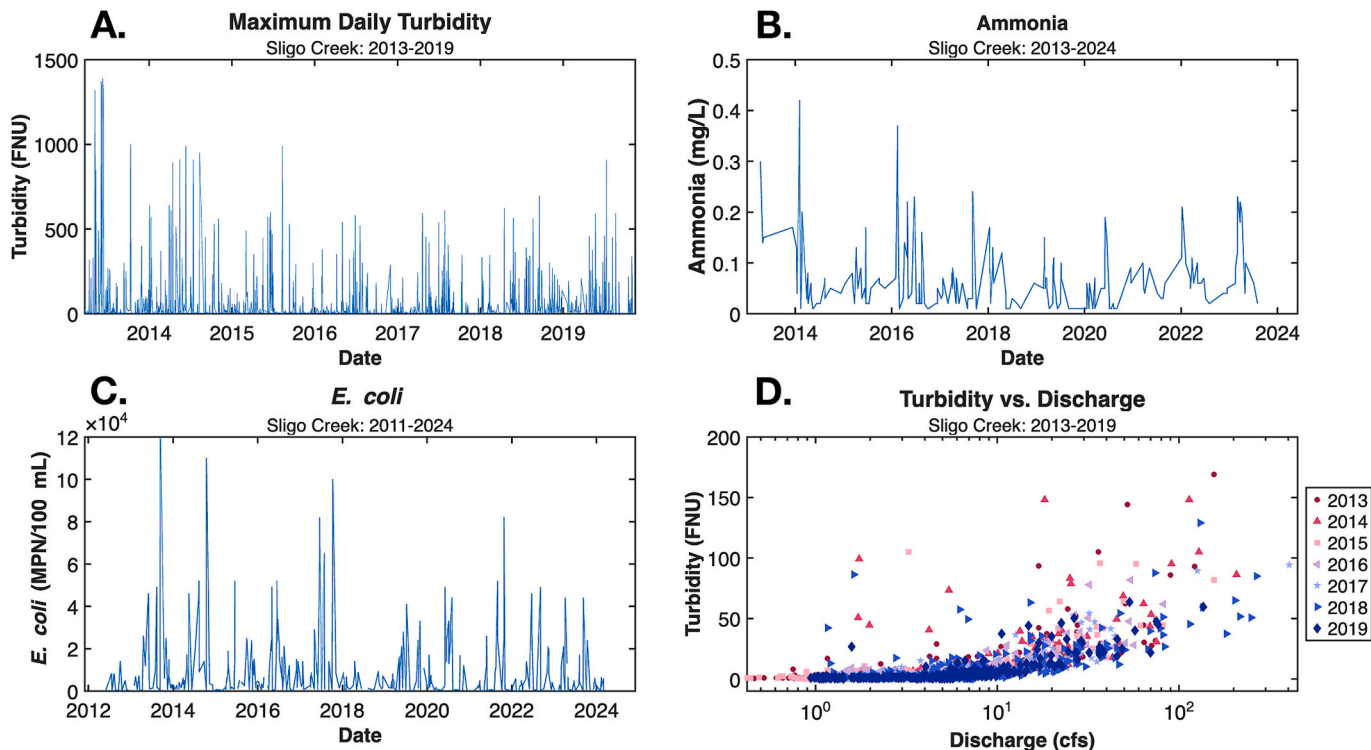


Fig. 14. Trends in maximum daily turbidity, ammonia, *E. coli*, and discharge at Sligo Creek near Takoma Park, MD. Data were downloaded from the U.S. Geological Survey station USGS-01650800 (U.S. Geological Survey, 2025), located 0.5 miles northwest of Takoma Park, MD and 2.0 miles upstream from the mouth. The altitude of the gage is 161.37 feet above North American Vertical Datum of 1988 and has a drainage area of 6.45 square miles. There was an overall decline in turbidity, ammonia, and *E. coli* levels from 2011 to 2024 (A, B, C). A positive relationship was observed between turbidity and discharge, with the relationship gradually decreasing and attenuating over time from 2013 to 2019 due increasing stormwater management and stream restoration practices in the watershed (D). These trends are most likely attributed to stormwater management and stream restoration efforts.

occurring over tens or hundreds of meters or can actually persist further downstream over longer distances. Watershed assessments using WCMA can investigate how the sources, fate, and transport of pollutants of emerging concern such as *E. coli* and enterococci bacteria change along flowpaths (Surbeck et al., 2010; Grant et al., 2011). Integrating sensors into WCMA along flowpaths can also provide an opportunity to form public and private alliances with the commercial vendors, government agencies, and citizen scientists from rivers to estuaries (Slaughter et al., 2024).

5. Conclusions

WCMA provides longitudinal assessments of water quality and clearly defines hot spots and hot moments of pollutant attenuation along watersheds. WCMA can provide estimates of how much pollutants (salts, metals, nutrients, organics, pathogens) are removed per unit length of stream and watershed area. WCMA can also inform the most optimal locations for future restoration projects based on potential for retention of pollutants and address the likelihood that problems can be fixed. WCMA can also provide information on whether pollutant reductions may be sustained downstream and over what spatial scale along stream reaches those reductions will occur. WCMA can also help elucidate which design elements of restoration features and conservation areas can improve water quality, reduce negative tradeoffs, and maximize co-benefits. Analysis of multiple pollutants together along flowpaths can help us accurately identify shifts in pollution sources, comprehensively evaluate management and restoration outcomes, and inform the next generation of restoration to achieve multiple pollutant reductions and co-benefits (e.g., future locations where interventions are likely to work and how to enhance hot spots of pollutant retention through designs).

Landscape-scale assessment of water quality requires integration of spatial and temporal dimensions across the suite of chemicals of concern in waterways (Bub et al., 2025). The watershed continuum monitoring approach provides holistic information improving co-management of stream stressors and detecting the tradeoffs of restoration activities along the entire flowpaths of streams and rivers across space and time. Monitoring along the entire watershed is needed in heterogeneous urban and agricultural landscapes to better inform riparian buffer goals, land zoning and planning and forest conservation, stream restoration protocols in the Chesapeake Bay region regarding water quality tradeoffs associated with different types of stream-floodplain reconnection (Chesapeake Stormwater Network (CSN), 2020), and restoration goals for larger rivers. Higher spatial and temporal resolution monitoring is needed to accurately detect tradeoffs in restoration activities and riparian buffer conservation to inform future stream restoration protocols (e.g., Chesapeake Stormwater Network (CSN), 2020). Specifically, a space-time framework for accounting for tradeoffs can allow managers to better prescribe restoration approaches under various scenarios and predict expected benefits while reducing costs and negative trade-offs. WCMA can provide further information on where to implement restoration interventions along watersheds and map hot spots of pollutant sources and sinks at the river network scale. WCMA can be applied to both headwater streams and larger rivers. Water quality assessments using WCMA can allow agencies to better account for the multiple effects of restoration and conservation across varying spatial and temporal scales. WCMA can also expand our scientific knowledge by linking patterns in propagation of water quality effects from different human activities and management with relevant ecosystem processes from headwaters to downstream receiving waters.

Credit authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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