ABSTRACT

Thesis Title: LONGITUDINAL STREAM SYNOPTIC (LSS) MONITORING TO EVALUATE WATER QUALITY IN RESTORED STREAMS

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Many kilometers of streams are being restored in the Chesapeake Bay watershed and elsewhere in efforts to stabilize streambanks, protect infrastructure, and improve water quality. Urban development and impervious surface cover increase peak flows, which degrade streams. Restoration strategies often employ engineering approaches to enhance stream-floodplain reconnection, dissipate erosive forces from urban runoff, and enhance contaminant retention. In this study, longitudinal stream synoptic (LSS) monitoring (sampling multiple points along flowpaths across both space and time) was conducted to assess the effectiveness of different forms of stream restoration in attenuating pollutants downstream. Spatial and temporal monitoring of carbon, nutrients, salt ions, and metals were conducted across five watersheds experiencing varying levels of stream-floodplain reconnection and stormwater management within the Chesapeake Bay region. Study sites included Sligo Creek (minimal floodplain reconnection), Paint Branch (streambank stabilization without significant reconnection), Scotts Level Branch (engineered stream-floodplain reconnection), Little Paint Branch (natural

floodplain reconnection from sedimentation), and Campus Creek (regenerative stormwater conveyance with engineered floodplain reconnection). We investigated: (1) whether changes in water chemistry can be detected along longitudinal flowpaths in response to stream-floodplain reconnection, and (2) which monitoring scales across space and time can provide useful information regarding the effectiveness of restoration. Results from this work suggest that longitudinal synoptic monitoring can track the fate and transport of multiple contaminants and evaluate restoration strategies across high spatial-resolution scales. Along all five watersheds, stream water chemistry varied substantially across finer spatial scales (sometimes within hundreds of meters) in response to changes in landscapes, restoration features, or local hydrology. There were significant declining concentrations ($p<0.05$) or stable concentrations of nutrients, salts, and metals as streams flowed through restoration features. There were significant increasing trends in chemical concentrations (*e.g.* Na^+, Ca^{2+}, K^+) in unrestored stream reaches with increasing impervious surface cover. Principal component analysis (PCA) also indicated that there were changes in the chemical compositions of mixtures of salts, metals, and nutrients in response to restoration projects, storm events, and seasons. Interestingly, dissolved Fe and Mn concentrations showed significant increasing trends along some stream reaches with hydrologically connected floodplains. Fe and Mn also showed significant decreasing trends along some unrestored stream reaches surrounded by increasing impervious surfaces. Increased concentrations of dissolved Fe and Mn may have been an indicator of increased hydrologic connectivity between groundwater and surface water and decreased redox potentials. Overall, longitudinal water quality changes over meters and kilometers can be useful in detecting effects of stream restoration on water quality at the watershed scale. Results suggest that water quality in urban streams can change locally in response to restoration projects for multiple chemicals, but

the incremental changes associated with different forms of stream restoration and riparian conservation can also be overwhelmed across broader watershed spatial scales and during storm events.

LONGITUDINAL STREAM SYNOPTIC (LSS) MONITORING TO EVALUATE WATER QUALITY IN RESTORED STREAMS

by

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Tables

Table 1. Stream characteristics. Stream length and stream elevation drop were calculated using Google Earth measuring tools. Basin area, impervious surface cover (ISC), and forest cover data retrieved from USGS StreamStats.

Watershed	**Basin Area, km^2**	**Stream Length, km**	**Stream Sinuosity**	**Stream Elevation Drop, m**	**ISC %**	**Forest Cover %**	**Restoration Approach**
Sligo Creek	29.0 km^2	14.2 km	1.33	111 m	41%	12%	Scattered stormwater ponds, bioretention zones, and minimal in-stream projects
Scotts Level Branch	10.4 km^2	8.7 km	1.22	57 m	41%	14%	Floodplain Reconnection with riprap, J-hooks
Paint Branch	80.5 km^2	5.35 km (22.5 km)	1.24	18 m	33%	24%	Floodplain Reconnection with riprap, J-hooks
Campus Creek	1.8 km^2	1.4 km	1.13	17 m	24%	23%	Regenerative Stormwater Conveyance system

Table 2. Table defining all longitudinal synoptic and diurnal sampling dates. Synoptic date column defines the date of longitudinal sampling and either the start or end date of diurnal sampling. The two synoptic dates marked with "N/a" did not include longitudinal sampling, but automated samplers were placed starting on the dates listed in parentheses. "Road Salting" events are characterized by sampling dates within a week after road salting in the watershed.

Watershed	**Synoptic Date**	**Diurnal Sampling Site(s)**	**Event**	**Avg Daily Discharge, cfs**	**Avg Daily Specific Conductance**
Sligo Creek	06/08/2022	SC2, SC7, SC12	Stormflow	4.38	612
Sligo Creek	08/17/2022	SC2, SC7, SC12	Stormflow	2.23	N/a
Sligo Creek	11/04/2022	SC7	Baseflow	2.08	670
Sligo Creek	03/01/2023	N/a	Baseflow	3.93	600
Scotts Level Branch	03/27/2021	N/a	Baseflow	2.54	520
Scotts Level Branch	08/12/2021	N/a	Stormflow	0.41	359
Scotts Level Branch	09/02/2021	N/a	Stormflow	2.13	202
Scotts Level Branch	11/02/2021	SLB10	Baseflow	1.63	394
Scotts Level Branch	01/05/2022	N/a	Road Salting	1.01	1820
Scotts Level Branch	01/12/2022	N/a	Road Salting	0.98	2120
Scotts Level Branch	02/22/2022	SLB1, SLB7, SLB10	Baseflow	1.8	731
Scotts Level Branch	05/25/2022	SLB1, SLB7, SLB10	Stormflow	1.31	378

Scotts Level Branch	08/09/2022	SLB1, SLB7, SLB10	Stormflow	1.09	329
Scotts Level Branch	11/09/2022	N/a	Baseflow	0.59	420
Paint Branch	09/16/2021	PB8	Stormflow		
Paint Branch	N/a	PB8 (10/20/2021)	Baseflow		
Paint Branch	02/16/2022	PB1, PB6, PB9	Baseflow		
Paint Branch	05/17/2022	PB1, PB6, PB9	Stormflow		
Paint Branch	08/02/2022	PB1, PB6, PB9	Stormflow		
Paint Branch	11/16/2022	N/a	Stormflow		
Campus Creek	09/02/2021	CC0	Stormflow		
Campus Creek	10/06/2021	N/a	Baseflow		
Campus Creek	N/a	CC0 (10/20/2021)	Baseflow		
Campus Creek	02/09/2022	CC6, CC4, CC0	Stormflow		
Campus Creek	05/10/2022	CC6, CC4, CC0	Stormflow		
Campus Creek	07/15/2022	N/a	Baseflow		
Campus Creek	07/26/2022	CC6, CC4, CC1	Baseflow		
Campus Creek	10/28/2022	N/a	Baseflow		

Figure Captions

Fig 1. Site Map. Scotts Level Branch, Sligo Creek and Paint Branch watersheds are outlined. Circle markers depict longitudinal sampling sites at Scotts Level Branch, Sligo Creek, Campus Creek, Paint Branch, and Little Paint Branch. Stars represent USGS Stream Gauge locations. Map colors depict land cover characteristics described by the NLCD Land Cover Classification Legend.

Fig 2. Longitudinal land use and cumulative drainage area of all five streams. Percent impervious surface cover (ISC) and forest cover are plotted. Green bars represent restored areas along the flowpaths.

Fig 3. Conductivity measurements are provided by USGS gauges at each stream. Campus Creek does not have a USGS gauge along its flowpath, but synoptics on that stream are shown on the Paint Branch Mean Daily Specific Conductivity plot (Figure 3c) because it is a major tributary of Paint Branch.

Fig 4. Biweekly temporal concentrations of Na+ (a) and dissolved Mn (b) at Sligo Creek, Scotts Level Branch, and Paint Branch. Relationships between cumulative biweekly Temperature and DO (c) and DOC and TDN (d). Solubility of oxygen in water at various temperatures at 1 atmospheric pressure, based on published equations by Rounds et al. (2006), is represented in orange (c).

Fig 5. Principal component analysis (PCA) of LSS monitoring data categorized by monitoring campaign at Paint Branch (a), baseflow, stormflow, and road salt events at Scotts Level Branch (b), and level of hydrologic connectivity at Sligo Creek to show differences in chemical cocktails based on those factors.

Fig 6. Longitudinal variations in Ca^{2+}, K^{+}, Mg^{2+}, Na^{+}, and dissolved Mn and Fe at Sligo Creek.

Fig 7. Variations in longitudinal dissolved organic carbon (a) and total dissolved nitrogen (b) at Scotts Level Branch. Relationship between DOC and TDN at Scotts Level Branch (c).

Fig 8. Longitudinal variations in Ca^{2+}, Mg^{2+}, and dissolved Fe and S at Scotts Level Branch.

Fig 9. Longitudinal discharge measurements (a), base cation concentrations (b), daily load of base cations (c), and daily load of base cations normalized to basin area (d) plotted against distance downstream at Scotts Level Branch.

Fig 10. Longitudinal variations in Ca^{2+}, K^{+}, Mg^{2+}, Na^{+}, and dissolved Mn and Fe at Campus Creek.

Fig 11. Base cation concentrations of hourly samples taken after a storm events at Sligo Creek (a) and during a storm event at Paint Branch (b). Carbon and nitrogen concentrations collected from the same storm event at Paint Branch (c).

Fig 12. Longitudinal variations in Na^{+} and dissolved Fe at Paint Branch (a). Na^{+} and dissolved Fe concentrations at Paint Branch at the full watershed scale (b). Vertical solid black lines represent similar sampling sites between the repeated LSS monitoring sites and the watershed-scale sampling sites. Arrows indicate parks and restorations along the flowpath.

Figures

Figure 1

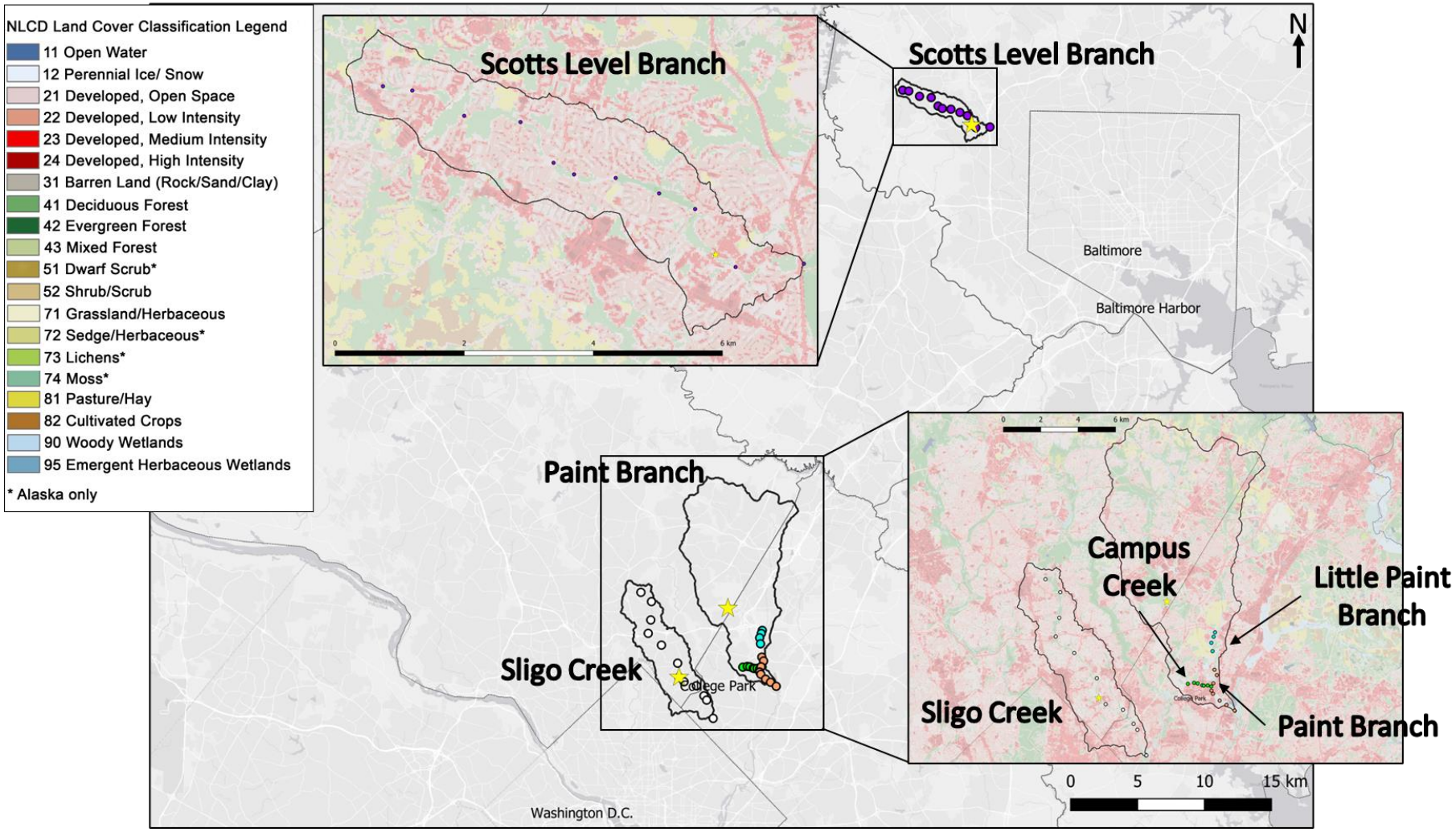


Figure 2

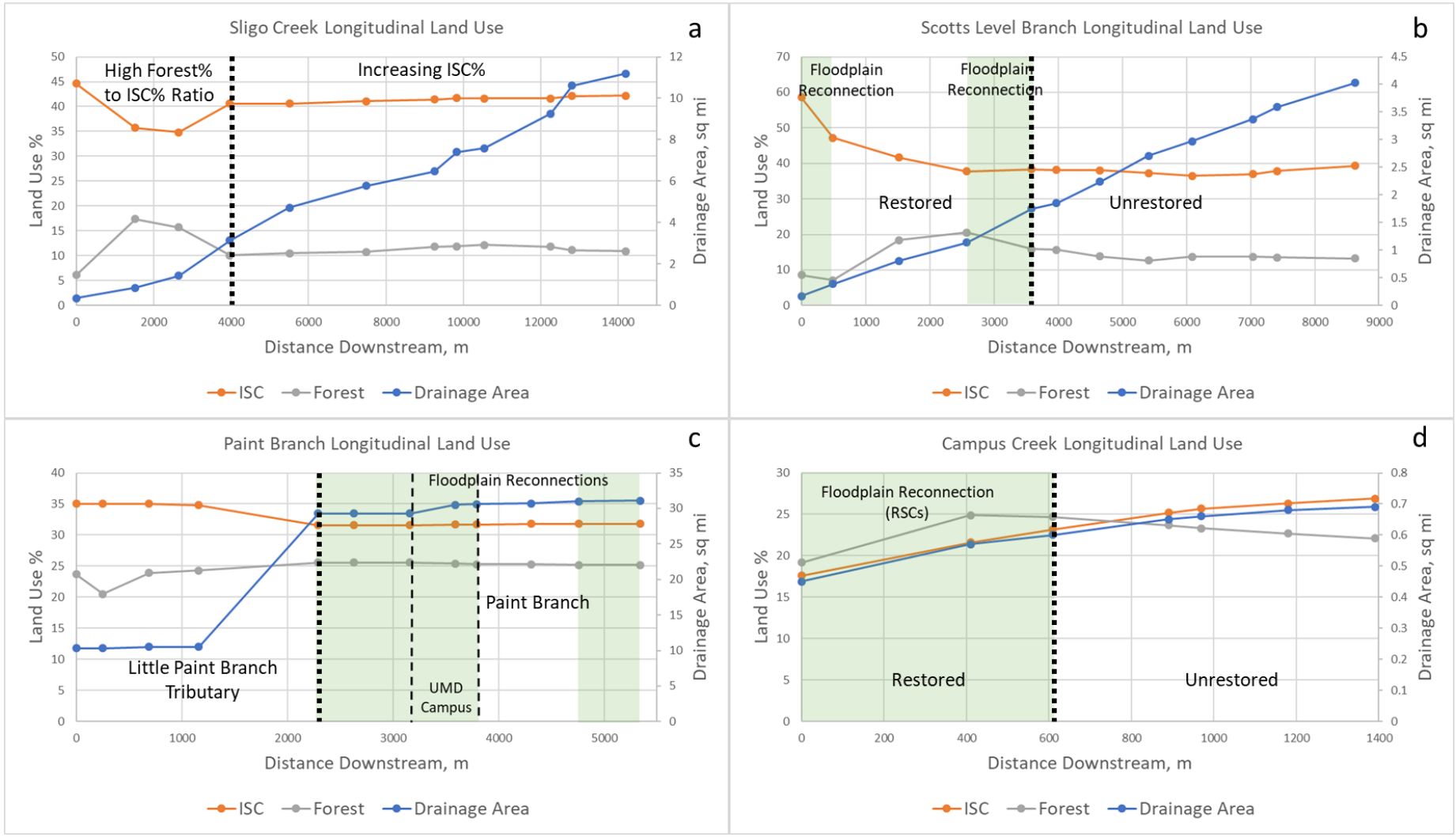


Figure 3

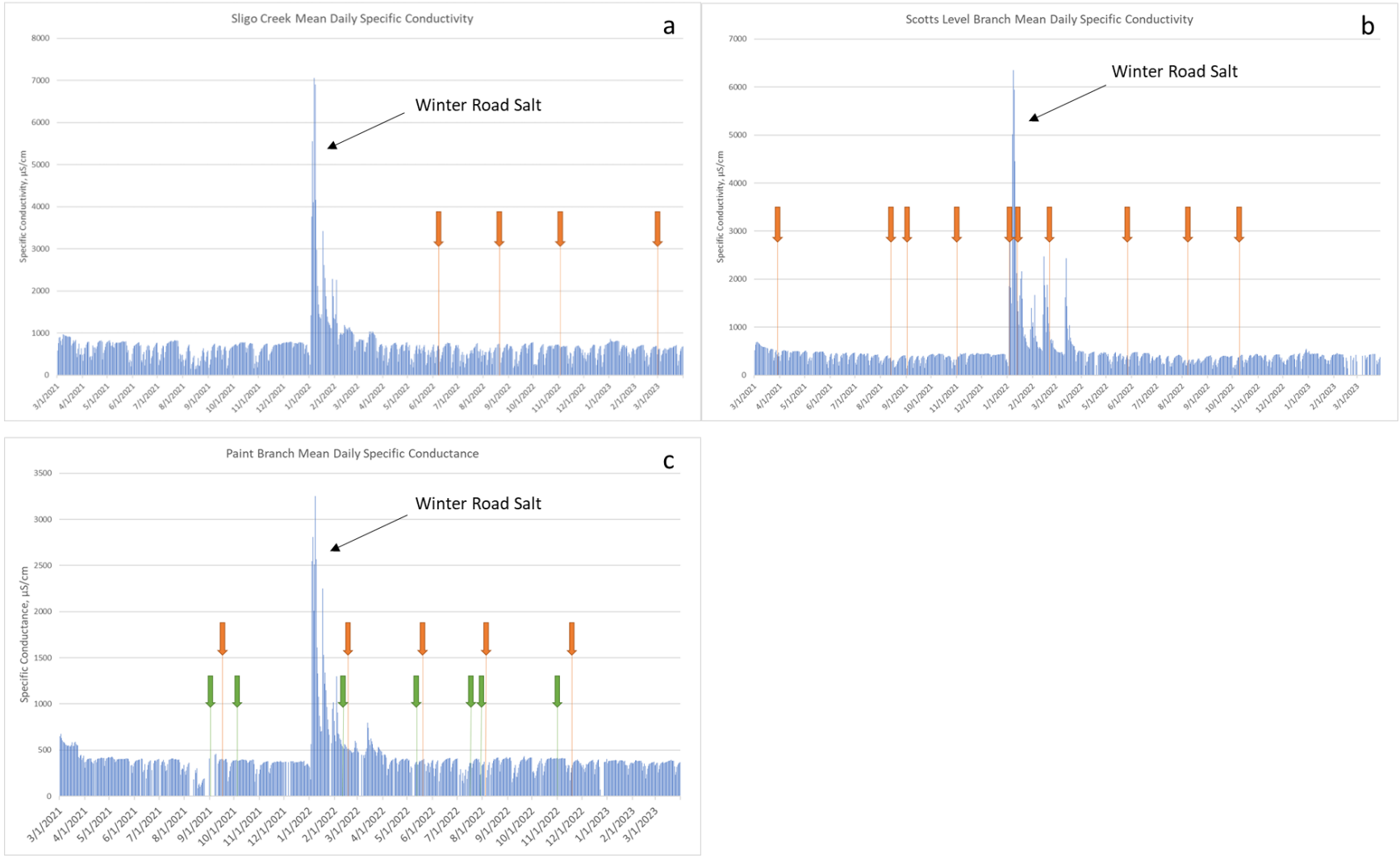

Sligo Creek Mean Daily Specific Conductivity
a
Winter Road Salt
Specific Conductivity, µS/cm
Scotts Level Branch Mean Daily Specific Conductivity
b
Winter Road Salt
Specific Conductivity, µS/cm
Paint Branch Mean Daily Specific Conductance
c
Winter Road Salt
Specific Conductance, µS/cm

Figure 4

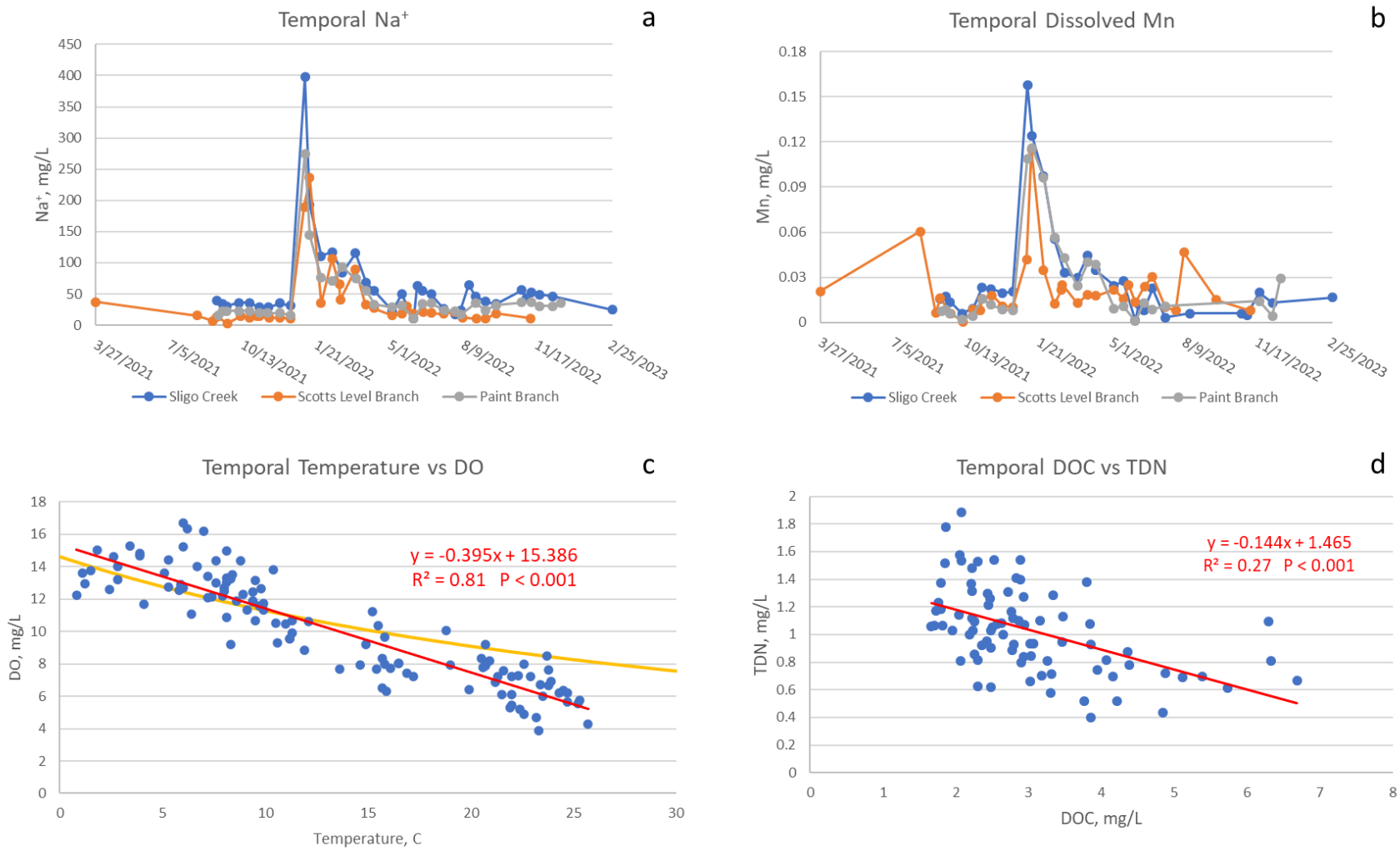

Temporal Na⁺
a
Na⁺, mg/L
450
400
350
300
250
200
150
100
50
0
3/27/2021
7/5/2021
10/13/2021
1/21/2022
5/1/2022
8/9/2022
11/17/2022
2/25/2023
Sligo Creek
Scotts Level Branch
Paint Branch
Temporal Dissolved Mn
b
Mn, mg/L
0.18
0.15
0.12
0.09
0.06
0.03
0
3/27/2021
7/5/2021
10/13/2021
1/21/2022
5/1/2022
8/9/2022
11/17/2022
2/25/2023
Sligo Creek
Scotts Level Branch
Paint Branch
Temporal Temperature vs DO
c
y = -0.395x + 15.386
R² = 0.81 P < 0.001
DO, mg/L
18
16
14
12
10
8
6
4
2
0
0
5
10
15
20
25
30
Temperature, C
Temporal DOC vs TDN
d
y = -0.144x + 1.465
R² = 0.27 P < 0.001
TDN, mg/L
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
DOC, mg/L

Figure 5

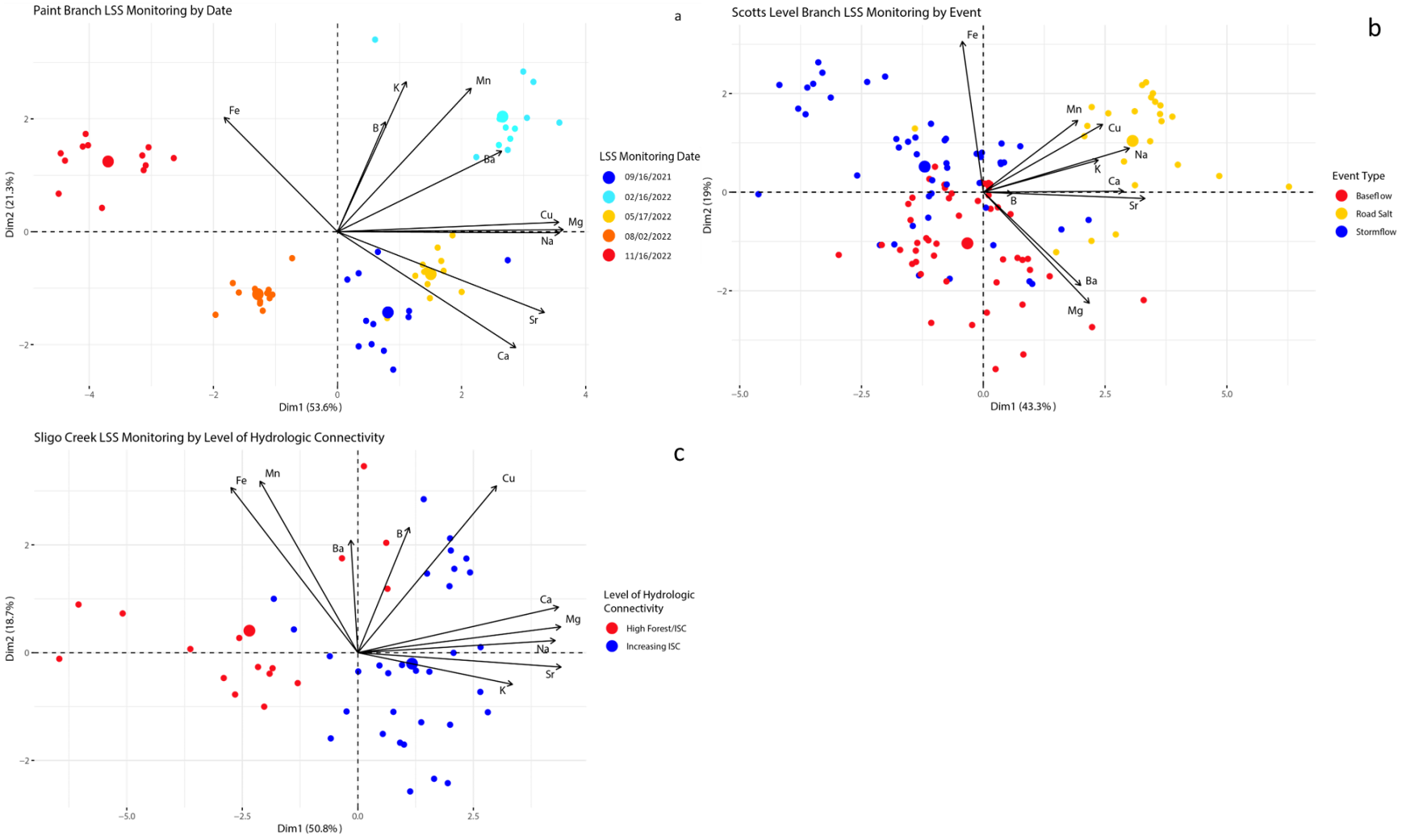

Paint Branch LSS Monitoring by Date
a
Fe
K
B
Mn
Ba
Cu
Mg
Na
Sr
Ca
Dim2 (21.3%)
Dim1 (53.6%)
LSS Monitoring Date
09/16/2021
02/16/2022
05/17/2022
08/02/2022
11/16/2022
Scotts Level Branch LSS Monitoring by Event
b
Fe
Mn
Cu
Na
K
Ca
B
Sr
Ba
Mg
Dim2 (19%)
Dim1 (43.3%)
Event Type
Baseflow
Road Salt
Stormflow
Sligo Creek LSS Monitoring by Level of Hydrologic Connectivity
c
Fe
Mn
Cu
Ba
B
Ca
Mg
Na
Sr
K
Dim2 (18.7%)
Dim1 (50.8%)
Level of Hydrologic Connectivity
High Forest/ISC
Increasing ISC

Figure 6

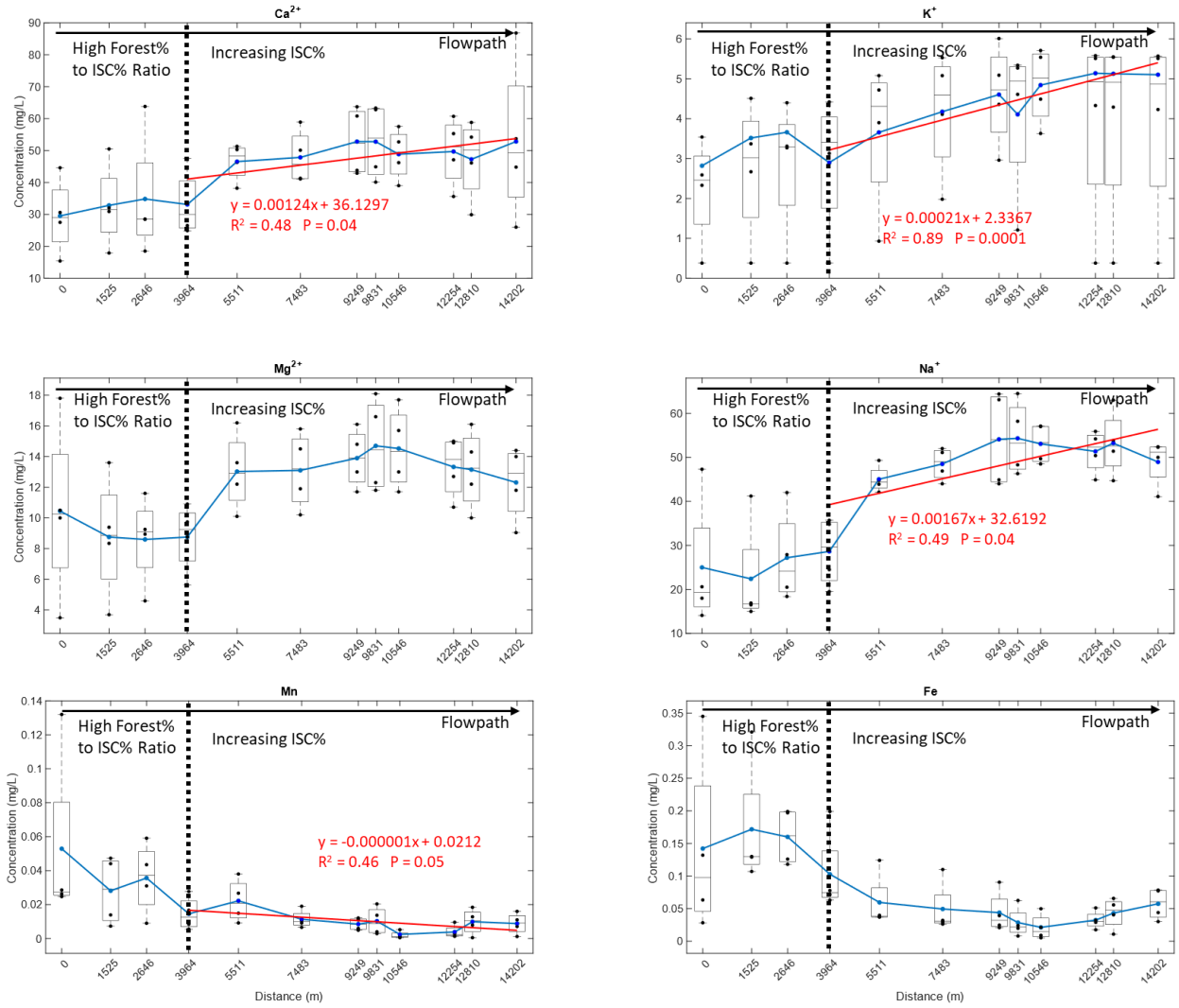

Ca2+
High Forest% to ISC% Ratio
Increasing ISC%
Flowpath
Concentration (mg/L)
y = 0.00124x + 36.1297
R² = 0.48 P = 0.04
K+
y = 0.00021x + 2.3367
R² = 0.89 P = 0.0001
Mg2+
y = 0.00167x + 32.6192
R² = 0.49 P = 0.04
Na+
Mn
y = -0.000001x + 0.0212
R² = 0.46 P = 0.05
Fe
0 1525 2646 3964 5511 7483 9249 9831 10546 12254 12810 14202
Distance (m)

Figure 7

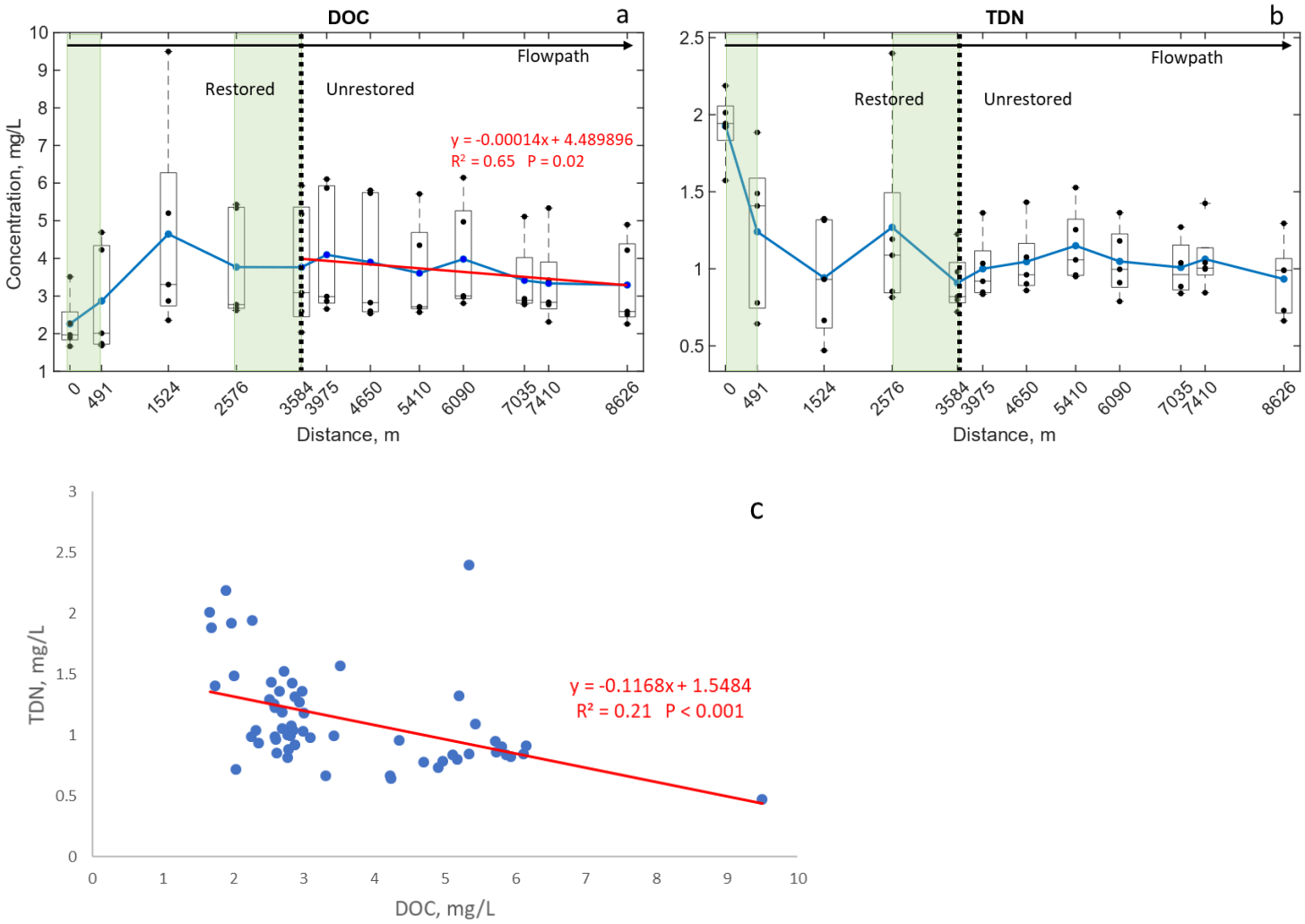

DOC
a
Flowpath
Restored
Unrestored
y = -0.00014x + 4.489896
R² = 0.65 P = 0.02
Concentration, mg/L
Distance, m
TDN
b
Flowpath
Restored
Unrestored
Distance, m
C
y = -0.1168x + 1.5484
R² = 0.21 P < 0.001
TDN, mg/L
DOC, mg/L

Figure 8

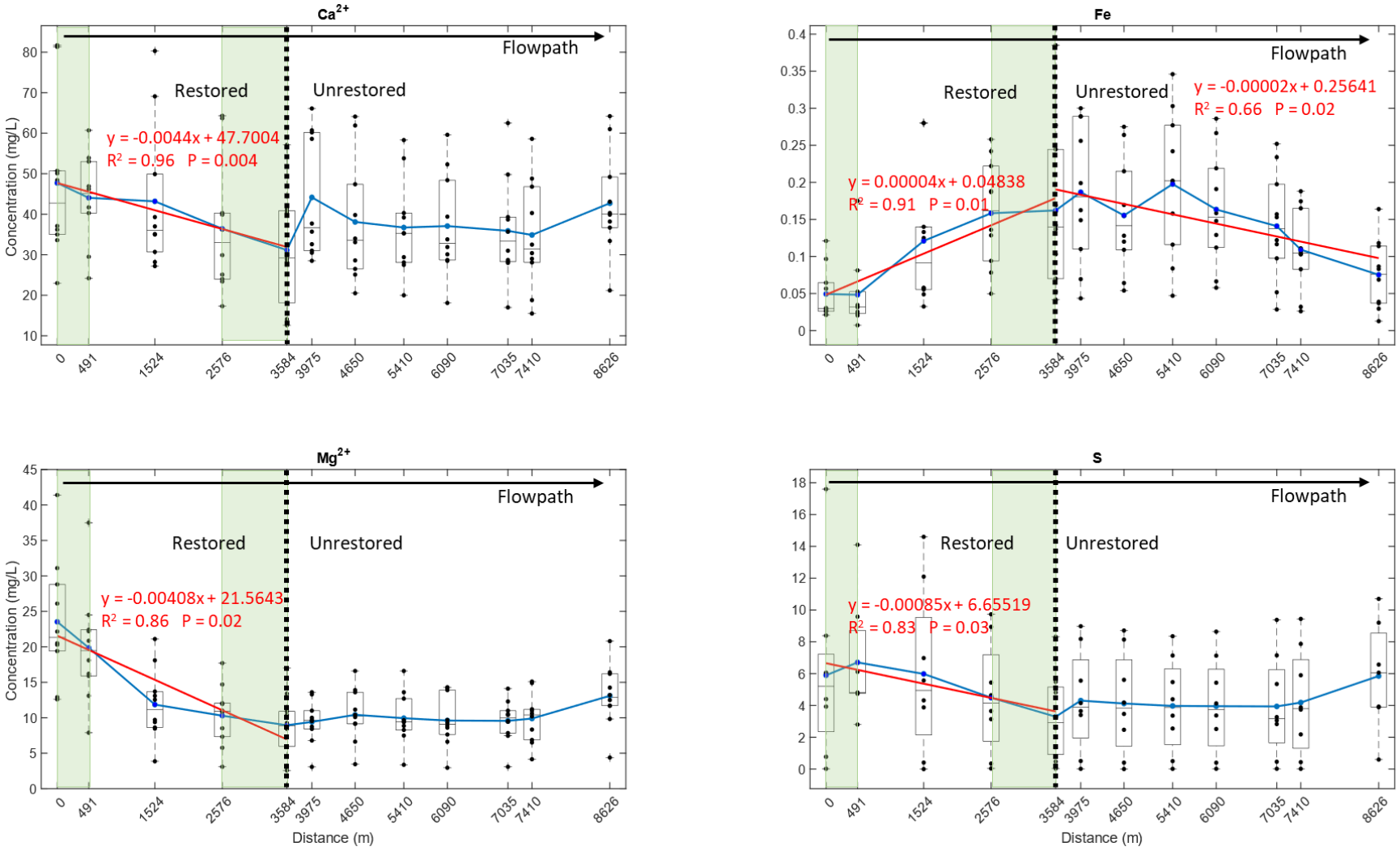

Ca2+
Flowpath
Restored
Unrestored
y = -0.0044x + 47.7004
R² = 0.96 P = 0.004
Concentration (mg/L)
Fe
y = -0.00002x + 0.25641
R² = 0.66 P = 0.02
y = 0.00004x + 0.04838
R² = 0.91 P = 0.01
Mg2+
y = -0.00408x + 21.5643
R² = 0.86 P = 0.02
S
y = -0.00085x + 6.65519
R² = 0.83 P = 0.03
Distance (m)

Figure 9

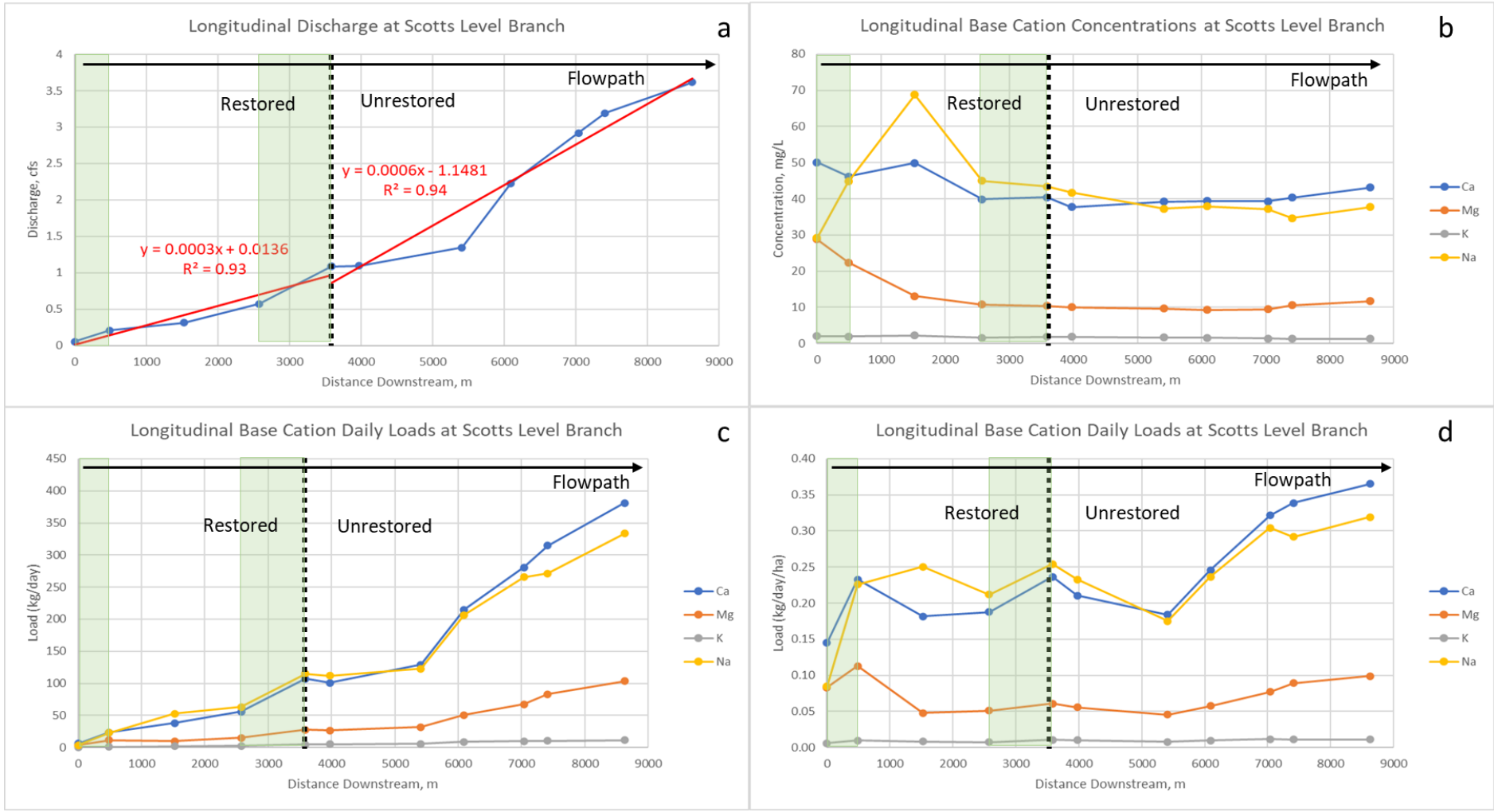

Longitudinal Discharge at Scotts Level Branch
a
Flowpath
Restored
Unrestored
y = 0.0006x - 1.1481
R² = 0.94
y = 0.0003x + 0.0136
R² = 0.93
Discharge, cfs
Distance Downstream, m
Longitudinal Base Cation Concentrations at Scotts Level Branch
b
Flowpath
Restored
Unrestored
Concentration, mg/L
Distance Downstream, m
Ca
Mg
K
Na
Longitudinal Base Cation Daily Loads at Scotts Level Branch
c
Flowpath
Restored
Unrestored
Load (kg/day)
Distance Downstream, m
Ca
Mg
K
Na
Longitudinal Base Cation Daily Loads at Scotts Level Branch
d
Flowpath
Restored
Unrestored
Load (kg/day/ha)
Distance Downstream, m
Ca
Mg
K
Na

Figure 10

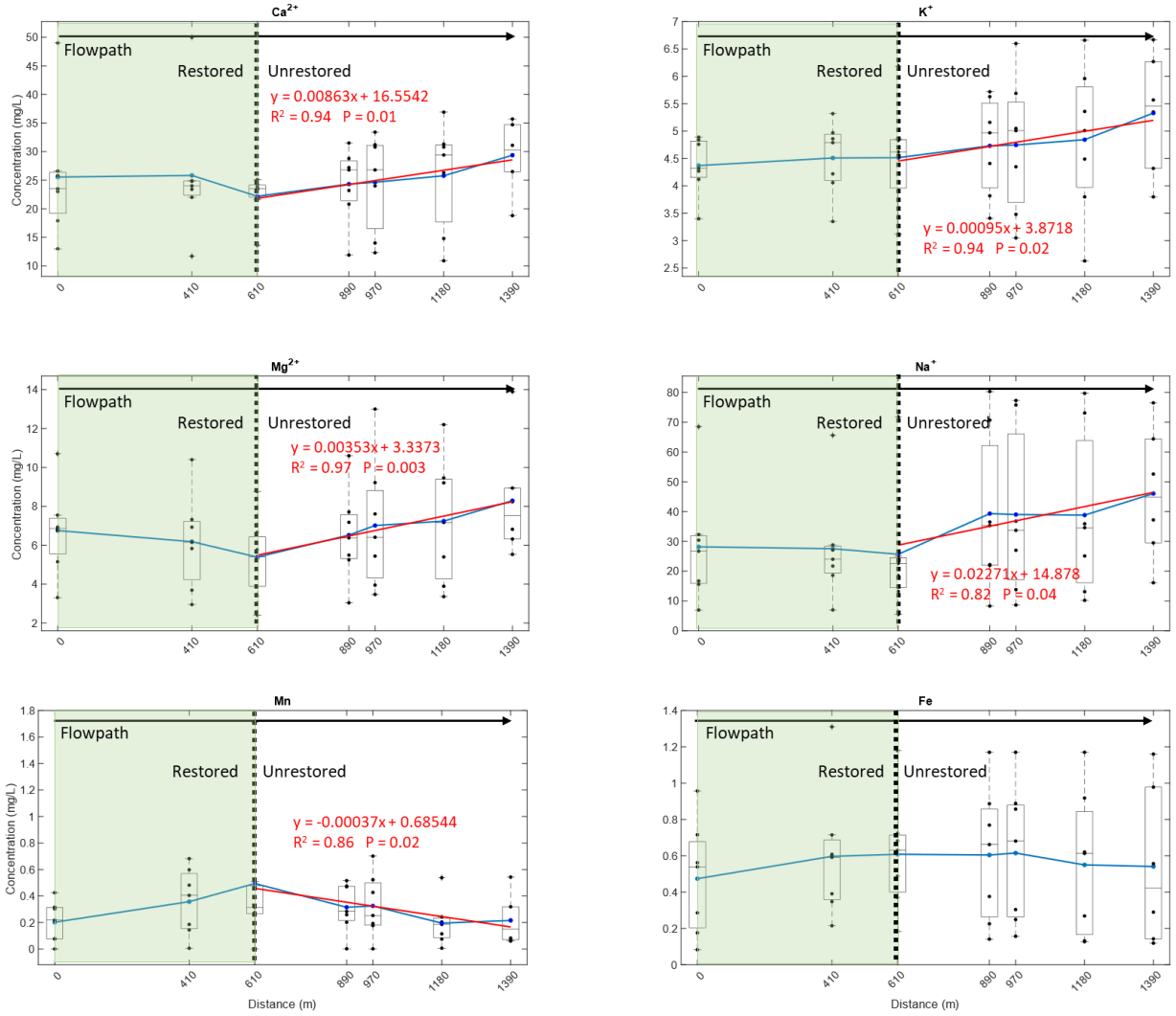

Ca2+
Flowpath
Restored
Unrestored
y = 0.00863x + 16.5542
R² = 0.94 P = 0.01
K+
y = 0.00095x + 3.8718
R² = 0.94 P = 0.02
Mg2+
y = 0.00353x + 3.3373
R² = 0.97 P = 0.003
Na+
y = 0.02271x + 14.878
R² = 0.82 P = 0.04
Mn
y = -0.00037x + 0.68544
R² = 0.86 P = 0.02
Fe
Concentration (mg/L)
Distance (m)

Figure 11

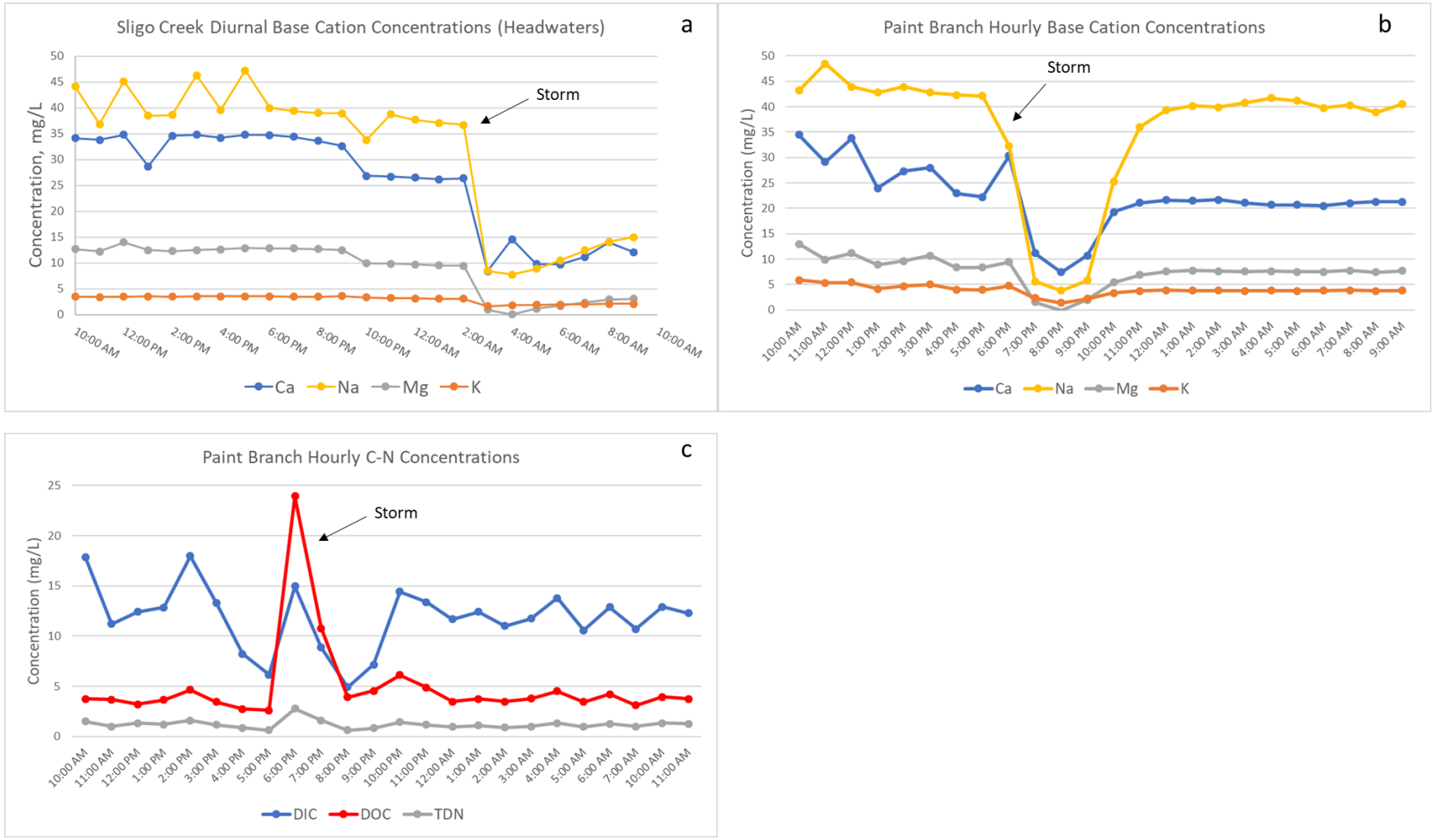
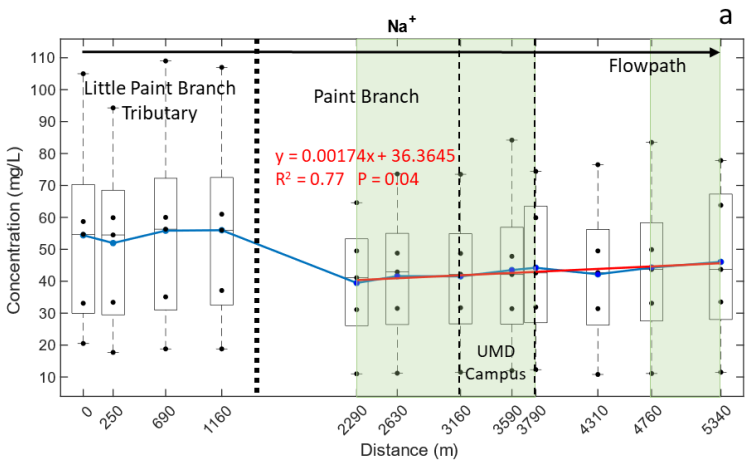
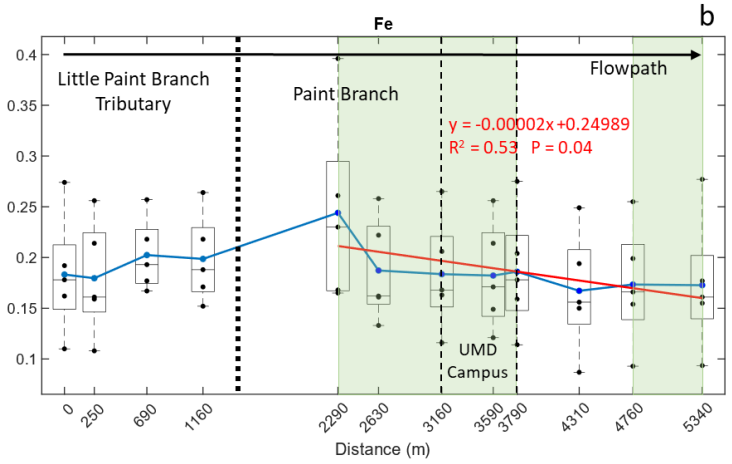
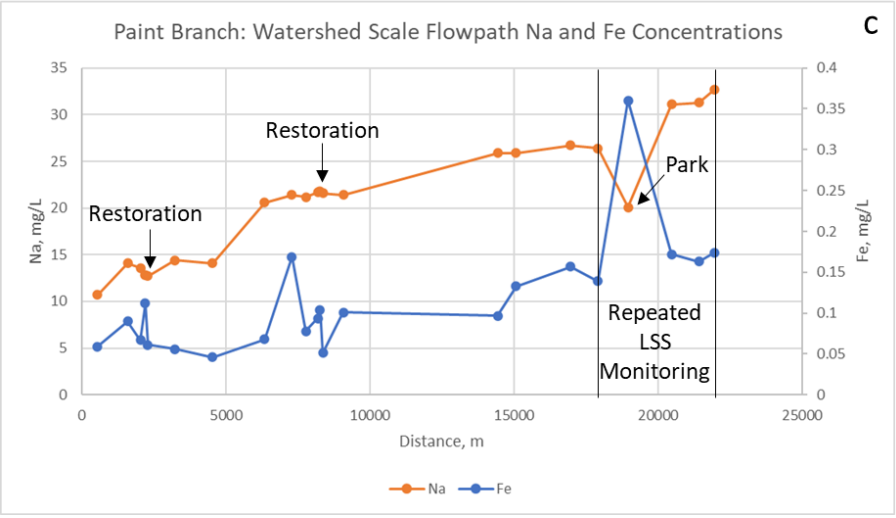

Sligo Creek Diurnal Base Cation Concentrations (Headwaters)
a
Concentration, mg/L
Storm
Ca
Na
Mg
K
Paint Branch Hourly Base Cation Concentrations
b
Concentration (mg/L)
Storm
Ca
Na
Mg
K
Paint Branch Hourly C-N Concentrations
c
Concentration (mg/L)
Storm
DIC
DOC
TDN

Figure 12


a
Na+
Flowpath
Little Paint Branch Tributary
Paint Branch
y = 0.00174x + 36.3645
R² = 0.77 P = 0.04
UMD Campus
Concentration (mg/L)
Distance (m)
0
250
690
1160
2290
2630
3160
3590
3790
4310
4760
5340


b
Fe
Flowpath
Little Paint Branch Tributary
Paint Branch
y = -0.00002x +0.24989
R² = 0.53 P = 0.04
UMD Campus
Distance (m)
0
250
690
1160
2290
2630
3160
3590
3790
4310
4760
5340


c
Paint Branch: Watershed Scale Flowpath Na and Fe Concentrations
Restoration
Restoration
Park
Repeated LSS Monitoring
Na, mg/L
Fe, mg/L
Distance, m
Na
Fe

Introduction

Many kilometers of streams in the Chesapeake Bay watershed and across the U.S. are being degraded by urbanization and its impacts on water quality. Urbanization can impact a watershed's physical, chemical, and biological characteristics (FISRWG, 1998; Paul & Meyer, 2001; Walsh et al., 2005) and reduce water quality. Pollution from nutrients, metals, and salts impact sensitive downstream receiving waters such as drinking water supplies or coastal waters. Billions of dollars have been spent on rehabilitating water quality through stream restoration and engineering stream channels and floodplains in the U.S. and elsewhere (Bernhardt et al., 2005; Newcomer-Johnson et al., 2016). Despite the growing prevalence of stream restoration, questions remain about whether stream restoration using engineering approaches can actually improve urban water quality and how to effectively restore and monitor streams. Although stream restoration strategies are diverse (Newcomer-Johnson et al., 2016), the goal of many stream restoration projects is to reconnect streams with floodplains and riparian wetlands that are sinks for carbon and nutrients. Stream-floodplain reconnection has been shown to increase nutrient retention along stream flowpaths (Bukaveckas, 2007; Kaushal et al., 2008; Mayer et al., 2022; McMillan & Noe, 2017), but there can be spatial and temporal variability across stream reaches and projects (Booth et al., 2004; Filoso & Palmer, 2011; Kaushal et al., 2023a,b; Sivirichi et al., 2011).

Most work evaluating the effects of stream restoration on water quality has focused on nutrient retention in restored streams while ignoring the fate and transport of salts, metals, and organics together (Kaushal et al., 2023a,b; Maas et al., 2023). It is difficult to assess stream restoration effectiveness using conventional monitoring approaches that rely only on monitoring

one or a few contaminants over time at just one or a few fixed locations. Urban watersheds have spatial and temporal dimensions, which influence water quality along a continuum of flowpaths (Kaushal & Belt, 2012; Kaushal et al., 2023a,b, 2014b; Maas et al., 2023). Here, we explore a longitudinal stream synoptic (LSS) monitoring approach for analyzing multiple chemicals to assess the effectiveness of stream restoration across both space and time. We used repeated LSS monitoring to identify whether restoration features can attenuate multiple contaminants, such as nutrients, salts, and metals, along flowpaths. Repeated LSS monitoring can help identify which restoration approaches may be effective over spatial and temporal scales (Kaushal et al., 2023a,b; Maas et al., 2023).

Runoff and contaminants are more efficiently transported to urban streams due to flashy runoff from impervious surfaces and storm drains (Walsh et al., 2005). Increased runoff increases hydrologic disconnectivity between the stream and its floodplain, which causes polluted water to bypass the upper soil horizons of floodplains (with ample organic matter and plant roots for retention of contaminants) (Groffman et al., 2002; Kaushal et al., 2008; Walsh et al., 2005). Increasing impervious surface cover due to urbanization leads to less infiltration of precipitation and more overland flow during storm events (Booth & Jackson, 1997; Fanelli et al., 2017; Paul & Meyer, 2001). Runoff from impervious surfaces is delivered to urban streams from storm drains with minimal opportunity for biogeochemical retention of nonpoint pollution sources such as leaky sewer pipes underneath streams, road salts, fertilizers, vehicles, and other sources (Cooper et al., 2014; Galella et al., 2021; Kaushal et al., 2020; Maas et al., 2023; Mayer et al., 2010; Morel et al., 2020). There are increased peak stormflows and pulses of contaminants during storms, and there is hydrologic disconnectivity between streams and floodplains and riparian zones (Groffman et al., 2002; Walsh et al., 2005). An urban stream can become

hydrologically disconnected from its floodplain due to increased runoff and erosion of stream banks contributing to channel incision (Groffman et al., 2002) and other geomorphic changes (Leopold et al., 2005). Shallow groundwater flowing through the riparian zone cannot adequately interact with vegetation and organic matter in upper soil horizons (Fanelli et al., 2017; Groffman et al., 2002; Kaushal et al., 2008), and can result in decreased retention of pollutants such as nitrogen (Forshay et al., 2022; Hanrahan et al., 2018; Kaushal et al., 2008) and phosphate (Davis et al., 2015; McMillan et al., 2014).

Stream restoration has been used in efforts to reduce impacts from urbanization; approaches are diverse and may include channel or in-stream hydromorphic methods, restoring riparian zones, or entire watershed actions, with the possible goals of enhancing water quality, channel stability, riparian or in-stream habitats, biodiversity, or any combination of these (Newcomer-Johnson et al., 2016; Palmer et al., 2014). Diverse approaches for stream restoration have been described in detail in Newcomer-Johnson et al. (2016), but the most common approaches that have shown the potential to improve water quality are (1) stream-floodplain reconnection, which can enhance N uptake in streams and hyporheic zones and foster denitrification (Kaushal et al., 2008; Mayer et al., 2022; Newcomer-Johnson et al., 2016); (2) enhancing hydrologic connectivity between streams and oxbow wetlands, which can enhance denitrification and N removal (Harrison et al., 2011, 2012a); (3) creating stream-wetland complexes (Filoso & Palmer, 2011; Forshay et al., 2022; Newcomer et al., 2014); and (4) regenerative stormwater conveyance (Duan et al., 2019; Williams & Filoso, 2023). There are also other engineered restoration approaches such as natural channel design (Rosgen, 1996, 2011) in which stream channels are widened, point bars or cutbanks are added, or the sinuosity of the channel is increased.

Typically, stream restoration approaches are used for habitat rehabilitation, flow velocity control, and streambank and substrate stability (Palmer et al., 2014; Smith and Prestegaard, 2005). Floodplain reconnection has been shown to enhance N and P retention (Bukaveckas, 2007; Duan et al., 2019; Forshay et al., 2022; Newcomer-Johnson et al., 2016; Williams & Filoso, 2023). However, it is unclear whether stream-floodplain reconnection approaches have the potential to retain multiple contaminants (Kaushal et al., 2022; Wood et al., 2022). For example, recent work has suggested that there may be water quality tradeoffs, such as (1) increases in multiple contaminants mobilized due to removal of trees and disturbance of soils during the construction process (Kaushal et al., 2022; Wood et al., 2022); (2) retention and release of chemical cocktails in restored streams due to road salt (Kaushal et al., 2022); (3) weathering of chemical cocktails from geological substrates used during the restoration process (Williams et al., 2016); and (4) low dissolved oxygen (DO) impacts on aquatic organisms induced by reconnecting streams to wetland and ponded features (Fanelli et al., 2019).

Although there is much interest in evaluating restoration efforts, many studies have monitored water quality at one or a few sites in restored streams. Typical monitoring approaches are: sampling streams on a weekly or bi-weekly basis over a decade (Mayer et al., 2022); collecting groundwater along water well transects on a monthly basis (Wood et al., 2022); and/or using combinations of bi-weekly sampling and longitudinal synoptic sampling (Newcomer-Johnson et al., 2014; Pennino et al., 2016b; Sivirichi et al., 2011). Assessing stream restoration effectiveness depends greatly on when and where monitoring is conducted along a stream network (Kaushal et al., 2023a,b; Newcomer-Johnson et al., 2014; Sivirichi et al., 2011) and whether multiple contaminants are monitored (Kaushal et al., 2022; Maas et al., 2023). Here, we ask whether we are missing important changes in water quality associated with different forms of

stream restoration by not incorporating high resolution LSS monitoring where streams are sampled frequently along the entire flowpath.

Our research objective was to explore the effects that stream restoration can have on stream chemistry by sampling across various spatial and temporal scales. We explored: (1) whether changes in water chemistry can be detected along flowpaths in response to stream-floodplain reconnection, and (2) which monitoring scales across space and time can provide useful information regarding water quality changes in response to restoration? Overall, there are many challenges when it comes to evaluating restorations, depending on available time, resources, and money. It is important to understand both the advantages and disadvantages of sampling across different spatial and temporal scales when designing monitoring programs. Consideration of multiple spatial and temporal scales allows for improved comparisons of seasonality, hydrologic conditions, pollution events, and land use management practices within and among watersheds (Kaushal et al., 2023a; Maas et al., 2023). Here, we explore applications of a longitudinal stream synoptic (LSS) monitoring repeated over time to evaluate water quality along restored stream flowpaths. The LSS monitoring approach used here evolved from methods described in Kaushal et al. (2023a, 2014b), Maas et al. (2023), Newcomer-Johnson et al. (2014), Pennino et al. (2016b), and Smith et al. (2017). In this study, we repeated LSS monitoring over time and across seasons and hydrologic events in order to better understand potential water quality tradeoffs in response to restoration and the potential for co-management of pollutants.

Methods

LSS Study Design: Monitoring the Impacts of Restorations Along Watershed Flowpaths Across Space and Time

Four watersheds with stream restoration efforts were monitored across various spatial and temporal scales along their flowpaths to explore the impacts of watershed restoration projects on stream chemistry. Typically, the streams were sampled longitudinally along their flowpaths at least once per season to capture changes in water chemistry along the flowpath. All stream sampling sites were located along the main stream channels and the same sampling sites were chosen for each longitudinal synoptic. Automated stream samplers were placed at each stream during longitudinal sampling to capture diurnal stream chemistry data. Temporally, each of the four streams was monitored (1) bi-weekly over an annual cycle to capture the influence of seasonality on water quality changes; (2) seasonally during baseflow and stormflow conditions to capture varying water quality responses; and (3) hourly over diurnal cycles to capture the short-term influence of brief storm events.

Three of the four watersheds (Sligo Creek, Scotts Level Branch and Paint Branch) have USGS gauges and high-frequency sensors for monitoring continuous water quality; two of the USGS monitoring stations (Sligo Creek and Scotts Level Branch) were located along the flowpaths in this study. Throughout this study, longitudinal and temporal relationships were measured for total dissolved nitrogen (TDN), dissolved organic carbon (DOC), dissolved and particulate elements (B, Ba^{2+}, Ca^{2+}, Cu, Fe, K^{+}, Mg^{2+}, Mn, Na^{+}, S, and Sr^{2+}), and field measurements (temperature, DO, conductivity, total dissolved solids, salinity, pH, and oxygen reduction potential). Stream discharge measurements were taken from USGS monitoring stations

for Scotts Level Branch, Sligo Creek, and a nearby reach of Paint Branch throughout this study. Discharge measurements were also performed at Scotts Level Branch during one longitudinal synoptic sampling event (in March of 2021) to explore the role of hydrological factors on changes in chemical concentrations and loads along the longitudinal flowpath.

While there were variations in management and surrounding land use, Sligo Creek and Scotts Level Branch offered a unique opportunity to compare the effectiveness of different stream restoration approaches because these streams had comparable land use/land cover along their flowpaths and similar hydrology including similar seasonal precipitation (Appendix, Figure A). Annually, precipitation, evapotranspiration, and runoff peaked at similar times at Sligo Creek and Scotts Level Branch. Sligo Creek normally has higher annual precipitation, and Scotts Level Branch has had more outlier flooding events due to heavy rainstorms. Otherwise, precipitation levels and hydrology between the two watersheds are quite similar (Appendix, Figure A). Both watersheds have an average impervious surface cover of 41% and similar average forest covers at 12-14% (Table 1), and they both feature a decrease in impervious surface cover relative to forest cover at the top of the watershed followed by similar steady patterns (Figure 2). Similarly, Little Paint Branch and Campus Creek were both small nested watersheds within the larger Paint Branch watershed, which provided opportunities for comparison. Campus Creek was restored using regenerative stormwater conveyance (RSC), a technique in which a series of step pools was added to reduce the velocity of the water moving along the flowpath, whereas Little Paint Branch experienced "natural floodplain reconnection" due to sedimentation following the construction of a major highway upstream (Blanchet, 2009). Variations in longitudinal patterns in chemistry along these comparable sites can reveal the influence of management *versus* natural geomorphic recovery in response to disturbance.

Site Descriptions

All five watersheds are located within Maryland, USA and are tributaries of the Chesapeake Bay (Figure 1). Four of the watersheds are within the Anacostia Watershed. Brief descriptions of the five studied watersheds and their restoration strategies are summarized below and in Table 1. The watersheds differ in percent impervious surface cover, percent forest cover, and drainage area (Figure 2). The stream restoration strategies and management among streams were dependent upon local hydrology, watershed size, accessibility of the stream channel's surrounding floodplain, and the extent of urban infrastructure in and around the stream.

Sligo Creek Watershed (Minimal Floodplain Reconnection but Changes in Impervious Surface Cover)

Sligo Creek is a 14.2 km stream within a 29.0 km^2 watershed that flows through Montgomery and Prince George's Counties in Maryland. Sligo Creek is a tributary of the Northwest Branch of the Anacostia River, which flows into the Potomac River and the Chesapeake Bay. This urbanized watershed has an average impervious surface cover of 41% and a forest cover of 12%. Restoration on Sligo Creek focused primarily on stream channel stabilization, as well as stormwater management projects scattered throughout the basin. Sligo Creek was a reference site in a hydrologically disconnected stream (it did not undergo floodplain reconnection due to a narrow stream corridor and residential development in close proximity to the stream channel). The Sligo Creek watershed restoration project has undergone six phases since 1989 when Montgomery County decided to restore water quality and habitat conditions in the stream (George, 2012). Phases I-IV (conducted in 1989, 1992-1994, 1996, and 1999) created stormwater retention ponds and wetlands into the watershed. Phase V (conducted in 2005-2007) introduced low-impact development (LID) stormwater management bioretention systems, and

Phase VI (conducted in 2010-present) implemented additional stormwater management techniques across 48% of the upper Sligo Creek subwatershed. Restoration projects at Sligo Creek have resulted in a 41% reduction in peak flow discharge and overall improvements in water quality (George, 2012). Samples were collected from twelve sites spanning from headwaters to its confluence and sampling was conducted at the same location during each LSS sampling campaign.

Scotts Level Branch Watershed (Floodplain Reconnection Along Headwater Reaches)

Scotts Level Branch is an 8.7 km stream within a 10.4 km^2 watershed in Baltimore County, Maryland. Scotts Level Branch is a tributary of Gwynn's Falls, which is a tributary of the Middle Branch of the Patapsco River. This watershed drains residential development and has an average impervious surface cover of 41% and a forest cover of 14%. Two restoration projects involving floodplain reconnection have been implemented along the flowpath at Scotts Level Branch (Scotts Level Branch Stream Restoration Project, 2019). The most upstream restoration project, constructed in 2019, is from sample site SLB1 (0 m) to SLB2 (491 m), while the second stream restoration project, completed in 2014, extends from sample site SLB4 (2576 m) to SLB5 (3584 m). A third floodplain reconnection project focused on a first-order tributary (which flows into the channel upstream of site SLB5) was under construction in the Fall of 2022. Two additional projects are still in design. The goal of these projects was to regrade the landscape around deeply incised reaches of the flowpath to reconnect the stream to its floodplain and reduce sediment and nutrient runoff into the stream (Ryan, 2022). Additionally, plants native to Maryland watersheds were reintroduced to the floodplain, and stream sinuosity was increased where possible to slow stream water flow and reduce the probability of further incision. Samples

were collected from twelve sites from headwaters to its confluence and sampling was conducted at the same location during each longitudinal synoptic survey.

Paint Branch Watershed (Streambank Stabilization and Minimal Floodplain Reconnection) and Its Subwatersheds

Paint Branch is a 22.5 km stream that flows through Montgomery and Prince George's Counties in Maryland. Having the largest drainage area of this study, its 80.5 km^2 watershed is a fourth-order tributary of the Northeast Branch of the Anacostia River, that feeds into the Potomac River and the Chesapeake Bay. The watershed has an average impervious surface cover of 33% and a forest cover of 24%. The Paint Branch watershed has undergone multiple restorations including one performed by the U.S. Army Corps of Engineers in 2015 and another sanctioned by the MDOT Maryland Transit Administration and finished in 2021 as part of the Purple Line mass transit project. The 2015 project, was designed to restore fish passage and connectivity of in-stream habitats along the stream corridor (Roach, 2018), and ultimately included floodplain reconnection strategies, when the USFWS identified that floodplain connectivity was a main contributor to impairment in the stream (USFWS, 2015). This project also focused on restabilizing eroding stream banks through the University of Maryland campus. The project spans sampling sites PB5 (2290 m) through PB9 (3790 m). The more recent 2021 restoration project, sampled at sites PB11 (4760 m) and PB12 (5340 m), also included floodplain reconnection strategies as well as ways of improving habitat and overall stream stability (Paint Branch Stream Restoration, n.d.). Two subwatersheds of Paint Branch were also monitored; Little Paint Branch and Campus Creek. These two subwatersheds represent the opportunity to compare contrasting approaches to stream restoration and management that are nested within the larger Paint Branch watershed, which was also sampled in this study.

Little Paint Branch (Natural Floodplain Reconnection from Sedimentation)

This study explored 5.35 km of the Paint Branch flowpath, starting in the Little Paint Branch tributary, which flows into the downstream reach of the main Paint Branch flowpath. In addition, there was one longitudinal synoptic survey of the entire Paint Branch watershed from headwaters to outflow extending 22 km. Little Paint Branch was sampled at sites PB1 (0 m) through PB4 (1160 m), and the main channel of Paint Branch was sampled at sites PB5 (2290 m) through PB12 (5340 m). The Little Paint Branch tributary has undergone a natural floodplain reconnection (Blanchet, 2009) following the construction of an interstate connector highway just upstream of the study's first sampling site. These two reaches of the flowpath were studied to compare natural and constructed stream restorations, as well as to focus more directly on restored areas around the urbanized landscape surrounding the University of Maryland at College Park campus. Samples were collected at twelve sites from Interstate-495 to the confluence and sampling was conducted at the same location during each synoptic (Figure 1). The first four sampling sites were along the Little Paint Branch tributary, and the other eight sampling sites were along the main Paint Branch flowpath for direct comparison during the exact same sampling dates (Figure 1). The larger synoptic survey of the entire Paint Branch watershed (from headwaters to outflow along 22 km) occurred just once and points along the flowpath drained different restoration projects and parks surrounded by urban land use.

Campus Creek Watershed (Floodplain Reconnection with Regenerative Stormwater Conveyance along Headwater Reach)

Campus Creek is another tributary of Paint Branch. Unlike Little Paint Branch, it experienced extensive engineering of its channel and the construction of RSCs (Kaushal et al., 2022; Wood et al., 2022). Campus Creek is a 1.4 km stream located in College Park, Maryland.

Its 1.8 km^2 watershed is the smallest of this study, flowing from the College Park Golf Course at its headwaters and through the University of Maryland campus. The watershed has an average impervious surface cover of 24% and a forest cover of 23%. Campus Creek is a tributary of the Paint Branch watershed, located just upstream of sample site PB8 (3590 m). The restoration project at Campus Creek, completed in November 2019, was designed to address stormwater runoff and erosion of the stream channel (Carmichael, 2020). The project was sampled from sample site CC6 (0 m) through CC4 (610 m). The strategies used in this watershed were the addition of small wetland-like overflow areas, where runoff from heavy rainfall events could be temporarily stored, as well as the addition of regenerative stormwater conveyance (RSCs). This project spanned about 900 linear meters, over half of the watershed's flowpath, starting just downstream of its headwaters. Samples were collected from seven sites from headwaters to its confluence and sampling was conducted at the same locations during each LSS monitoring campaign until July 2022 when a heavy storm made the site farthest downstream inaccessible and sampling was moved twenty meters further downstream.

Longitudinal Stream Synoptic Monitoring

A survey of each stream and its floodplain *via* satellite maps was used to determine monitoring site locations along the flowpaths. Similar to other studies, many monitoring sites along the flowpaths were located upstream of road crossings or pedestrian bridges over the channels for easier access to the stream (Wayland et al., 2003). All water samples were collected from the stream channel at each site while monitoring longitudinally downstream. Grab samples were collected in 125 mL bottles after rinsing in stream water three times. A Yellow Springs Instrument (YSI) ProQuatro multiparameter meter was used in conjunction with the grab sample to collect *in-situ* data for temperature, DO, conductivity, total dissolved solids (TDS), salinity,

pH, and oxidation-reduction potential (ORP). When applicable, grab samples and field probe measurements (Appendix, Figures B-F) were collected at the same time as an automated sample collection. All longitudinal synoptic sampling events are listed in Table 2, while Figure 3 shows each synoptic event on a relative time scale plotted against specific conductance at that location.

Diurnal Sampling Along Stream Flowpaths During Baseflow and Storms

ISCO (Teledyne) portable automated samplers were deployed at select monitoring sites along the flowpath to collect samples on a diurnal cycle to characterize both baseflow conditions and capture brief storm events (Table 2). Automated samplers were programmed to collect one sample every hour for a full twenty-four-hour diurnal cycle. The measured diurnal cycle usually started before the longitudinal sampling but occasionally began the day before. If more than one automated sampler was deployed in nearby streams, they were all programmed to collect samples simultaneously. At the end of the diurnal cycle, samples collected by the automated samplers were transferred to 125 mL bottles and filtered in the lab.

Land Use Characterization and Precipitation Data

Aside from field data collection, multiple resources were used to collect additional watershed information. The USGS database provided stream conditions over time *via* stream gauge data collection, as well as geologic maps of Maryland and spatial analytical tools through StreamStats (U.S. Geological Survey, 2019). The Maryland Topography Viewer, provided through the Maryland Mapping & GIS Data Portal, was used to determine site elevations. Precipitation data were obtained through Parameter-elevation Regressions on Independent Slopes Model (PRISM) which is based on the National Weather Service (NWS) data (Appendix, Figure A).

Discharge Measurements and Calculations

Discharge measurements were either available from the United States Geological Survey or through in-field discharge data collection. USGS stream gauges collect data every five minutes (U.S. Geological Survey, 2016). The gauges at Sligo Creek (USGS Gauge 01650800 near Takoma Park, MD) and Paint Branch (USGS Gauge 01649190 near College Park, MD) measure gauge height (ft), discharge (cfs), DO (mg/L), pH, specific conductance (µS/cm at 25 °C), temperature (°C), and turbidity (FNU). The stream gauge at Scotts Level Branch (USGS Gauge 01589290 at Rockdale, MD) measures the same parameters, minus DO. Discharge measurements used in this report are average daily discharge, maximum peak discharge, and average annual discharge.

Longitudinal discharge measurements were performed once at Scotts Level Branch during March 2021. At each synoptic site along the longitudinal flowpath, stream velocity measurements were collected to calculate discharge values, and channel width and depth measurements were collected to build cross-sectional plots. Relationships between stream chemistry and discharge with respect to longitudinal distance from headwaters were assessed. Cross-sectional velocity measurement locations were chosen at each site by considering accessibility of the stream in that area of the flowpath. For each discharge measurement, total stream width was measured, followed by incremental depth and velocity measurements to determine discharge and cross-sectional topography (similar to Kaushal et al., 2014, Kaushal et al., 2023, Newcomer-Johnson et al., 2014, and Sivrichi et al., 2011). A velocity measurement taken at two-thirds depth was used to calculate stream discharge (Holmes et al., 2001).

Sample Processing and Water Chemistry Analyses

Laboratory methods for sample processing and elemental analyses followed those described previously (Galella et al., 2021; Haq et al., 2018; Kaushal et al., 2019; Maas et al., 2023). All samples were filtered, acidified, and processed after collection. Each sample was pumped through pre-ashed 0.7 µm glass fiber filters using a vacuum. Sample bottles were triple rinsed in deionized water and filters were replaced between each sample to prevent cross contamination. A portion of each filtered sample was acidified to 0.5% using ultra-pure nitric acid to prevent biological activity and flocculation between particles during long-term storage.

Non-acidified samples were frozen until analyzed on a Total Organic Carbon Analyzer (TOC-L; Shimadzu, Columbia, Maryland) to measure total dissolved nitrogen (TDN) and dissolved organic carbon (DOC). Samples were injected in the TOC-L with an acid to transform inorganic carbon into carbon dioxide. The organic carbon content was calculated by subtracting the inorganic carbon from the total carbon in the sample. Total dissolved nitrogen concentrations were calculated by combusting each sample and passing it through a non-dispersive infrared detector (Galella et al., 2023; Haq et al., 2018; Maas et al., 2023; Wood et al., 2022).

Acidified samples were analyzed via inductively coupled plasma optical emissions spectrometer (ICP-OES) using a Shimadzu Elemental Spectrometer (ICPE-9800, Shimadzu, Columbia, Maryland, USA) to measure base cation (Ca^{2+}, K^{+}, Mg^{2+}, Na^{+}) and other element (B, Ba^{2+}, Cu, Fe, Mn, S, and Sr^{2+}) concentrations. Comparisons to external commercial check standards were used to assess instrument accuracy. The TOC-L has a detection limit of 4 µg/L for carbon measurements and 5 µg/L for nitrogen measurements, and a maximum reproducibility coefficient of variation of 1.5% (Shimadzu, 2011). The ICP-OES has uncertainties of 0.6, 10, 0.6, and 0.6 µg/mL for Ca^{2+}, K^{+}, Mg^{2+}, and Na^{+}, respectively (Sellers, 2014). All analytical

methods followed those described in US Environmental Protection Agency Quality Assurance Plans and followed in previous studies (Galella et al., 2021; Galella et al., 2023).

Statistical Analyses

Linear regression was used to explore relationships between chemical concentrations and distance downstream. Separate models were developed for flowpaths through restoration or forest features and flowpaths through degraded conditions or increasing impervious surface cover. Linear regression calculations were performed using MATLAB version R2022b. Principal component analysis (PCA) was used to investigate dominant chemistry patterns across temporal and spatial scales. All data collected from LSS monitoring were pooled and PCA was performed on the cumulative data for each individual stream. PCA results were displayed three ways; by LSS sampling campaign date, by baseflow/stormflow responses, and by differences in surrounding land use/land cover. PCA calculations were performed using R-studio 2023.06.1+524 using FactoMineR and factoextra (Lê et al., 2008).

Results

Routine Monitoring Over Time

There were distinct seasonal patterns in chemical concentrations in the watersheds reflecting the effects of dominant processes such as road salting during winter months, biogeochemical transformations, and changes in hydrology. For example, there were peaks in concentrations of Na^+ and Mn in all streams during winter months coinciding with winter road salting events (Figure 4a,b). There were significant inverse relationships between DOC and TDN in all streams over time (Figure 4d), reflecting the importance of biogeochemical reactions such as denitrification, uptake of nitrogen, and primary production of organic carbon (Kaushal et al.,

2014b). Similarly, there were significant inverse relationships between water temperature and DO in all streams over time (Figure 4c). Na^+ and Mn were excellent indicators of road salts entering the stream in all three watersheds, as they all spiked in all three watersheds after salting events; Mn and other metals can be mobilized by road salt events due to ion exchange, sodium dispersion of organic matter and release of sorbed and complexed metals, and other biogeochemical processes (Galella et al., 2021; Kaushal et al., 2019). Overall, seasonal cycles appeared to be consistent across sites, although the peaks and persistence of chemical concentrations varied.

Specific conductance can be an indicator of surface water contributions during storms *versus* groundwater contributions during baseflow (Occhi, 2011; Pellerin et al., 2008). LSS monitoring was done across a wide range of discharges, storm events, and specific conductance fluctuations driven by salting events in these streams. The presence of any emergent or consistent longitudinal patterns in water chemistry along the flowpaths can provide valuable information regarding the spatial heterogeneity of water quality along the streams and the functioning of the stream restoration. Correspondingly, there were large seasonal variations in specific conductance during the sampling period with seasonal pulses in specific conductance during winter months when road salts were applied (Figure 3). LSS monitoring occurred primarily during baseline levels of specific conductance, although there was some LSS monitoring during winter road salt events, particularly at Scotts Level Branch (Figure 3). Mean daily specific conductance also fluctuated during non-winter months, usually due to changes in streamflow and storm events.

Differences in Chemical Cocktails Across Seasons and Sampling Locations

Principal Component Analysis (PCA) plots visually represent the changes in the compositions of chemical mixtures of salt, metals, and nutrients in response to restoration activities, storm events, and seasons in urban streams (Figure 5). Data from LSS monitoring were standardized by subtracting the mean and dividing by the standard deviation of each parameter (Gelman, 2008). Any missing data values due to sample handling or instrument detection limits were estimated using the minimum value of that parameter. The five LSS monitoring events along the Paint Branch flowpath appear as clusters of data in the PCA plot (Figure 5a), showing that the chemical makeup of the watershed changes depending on the time of year. These data clusters are more isolated than those observed in PCAs representing data at Scotts Level Branch (Figure 5b) and Sligo Creek (Figure 5c). At Scotts Level Branch, monitoring occurred at least twice during each of baseflow, stormflow, and road salting events in the watershed. A PCA plot shows the importance of monitoring a stream during these various weather events, as a distinct variation in chemical cocktails can be seen depending on the flow intensity and introduction of road salts to the watershed (Figure 5b). Finally, there was a difference in stream chemistry at Sligo Creek based on surrounding land use/land cover along the flowpath, emphasizing the importance of sampling at multiple locations along the flowpath (Figure 5c). Along Sligo Creek, sampling sites with a higher ratio of forest cover to impervious surface cover had a stream water chemical composition different than sites draining a lower ratio of forest cover to impervious surface cover.

Longitudinal Patterns in Streamwater Chemistry Along Watershed Flowpaths

Patterns of salt ion concentrations and redox-sensitive reactions were explored as biogeochemical indicators of hydrologic connectivity. We expected that hydrologic connectivity would be linked to longitudinally decreasing salt ion (Ca^{2+}, K^{+}, Mg^{2+}, Na^{+}) trends due to dilution and retention on ion exchange sites in soils and sediments (Galella et al., 2023; Kaushal et al., 2022). We also expected Fe, Mn, and sulfate (SO_4^{2-}) reduction, suggesting increased redox reactions, and increases in dissolved Fe and Mn concentrations with decreases in elemental S in response to decreased redox potentials. In addition, we expected an inverse relationship between DOC and TDN in some stream reaches, which could suggest denitrification where hydrologic connectivity was greater.

Sligo Creek Watershed (Minimal Floodplain Reconnection and High Impervious Surface Cover)

There were distinct patterns in longitudinal water quality along different stream flowpaths that appeared to be influenced by stream restoration features and surrounding land use. For example, there were increasing trends in base cation concentrations from headwaters to confluence at Sligo Creek, likely influenced by surrounding land use (Figure 6). In the reaches of Sligo Creek draining land use with less impervious surface cover, base cations of Ca^{2+}, Na^{+}, and K^{+} increased significantly at rates of 1.00, 1.14, and 0.04 mg/L per km downstream, respectively. Mg^{2+} decreased at a rate of 0.42 mg/L per km at this reach of the flowpath. In the reaches of Sligo Creek draining land use with increasing impervious surface, all base cations increased significantly at 1.24, 1.67, 0.21, and 0.25 mg/L per km downstream for Ca^{2+}, Na^{+}, K^{+}, and Mg^{2+}, respectively. Overall, the rates of base cation increase in the two segments of Sligo Creek and were faster where there was more impervious surface cover suggesting low retention in groundwater and therefore poor hydrologic connectivity along the flowpath. Fe and Mn

concentrations decreased along Sligo Creek's entire flowpath (Figure 6), suggesting decreasing DO levels along the flowpath and further indicating changes in surrounding land use and decreased hydrologic connectivity.

Scotts Level Branch Watershed (Floodplain Reconnection Along Headwater Reaches)

Total dissolved nitrogen (TDN) decreased between both restored reaches at Scotts Level Branch, while dissolved organic carbon increased, but there were few statistically significant trends (Figure 7). Linear regression of dissolved organic carbon (DOC) of the trend along the flow path revealed a significant decrease below the restored reach of the flowpath ($R^2 = 0.645$, $F(1,6) = 10.9$, $p<0.05$). We observed an inverse relationship between DOC and TDN at Scotts Level Branch (Figure 7c), suggesting increased denitrification in restored reaches and indicating increased hydrologic connectivity. There were significant ($p<0.05$) decreasing linear trends of 4.40 and 4.41 mg/L per km downstream in base cations Ca^{2+} and Mg^{2+}, respectively, in the restored reach (Figure 8). Decreasing linear trends in base cations in restored reaches suggest that Scotts Level Branch is either diluting or retaining pollutants as water moves longitudinally along the flowpath in the restored reach. Conversely, there were no significant linear relationships in base cation concentrations along the unrestored reaches of Scotts Level Branch; there appeared to be a plateau and stabilization in chemical concentrations through these unrestored stream reaches (Figure 8). Stable forest and impervious surface cover percentages after sampling site SLB6 (3975 m), as well as the introduction of Scotts Level Park at site SLB7 (4650 m), appeared to influence steady state concentrations of some chemicals along the unrestored segment of the flowpath. S and Fe are redox-sensitive elements that can reflect the amount of DO in the stream. A significant ($p<0.05$) decreasing trend in S and a significant ($p<0.05$) increasing trend in Fe in the restored reach (Figure 8) reflects a lower DO in the stream

water from slower flows due to stream restoration. Elemental S concentrations increase below restored reaches while Fe significantly decreases, which potentially reflects less floodplain reconnection along the unrestored flowpath.

Discharge measurements at Scotts Level Branch were taken once during baseflow conditions within a few days of a storm event. Linear regressions reveal that discharge and stream velocity showed increasing trends between the restored reaches ($R^2 = 0.93$, $F(1,3) = 39.2$, $p < 0.001$) and also along the unrestored reaches ($R^2 = 0.944$, $F(1,5) = 79.6$, $p < 0.01$) (Figure 9a). All four base cations (Ca^{2+}, K^+, Mg^{2+}, Na^+) generally decreased in concentration from headwaters to confluence (Figure 9b). Na^+ peaked at the third sampling site, but then continued to decrease along the flowpath. Using the longitudinal discharge and longitudinal base cation concentrations, the longitudinal base cation mean daily loads were calculated and plotted against the distance downstream (Figure 9c). Mean daily loads increased along the flowpath, with Ca^{2+} and Na^+ reaching around 380 and 340 kg/day, respectively. K^+ had a comparatively much smaller mean daily load, likely because it is a biologically available nutrient to plants (Tripler et al., 2006). When normalized to basin area and discharge, we observed that export of salt ions did not follow the same pattern as stream discharge (Figure 9d). Stable export between restoration features suggests that there is retention of salt ions and that the longitudinal patterns in loads are not just hydrologically driven.

<u>Paint Branch Watershed: Campus Creek Watershed (Floodplain Reconnection with Regenerative Stormwater Conveyance along Headwater Reach)</u>

Along Campus Creek, concentrations of all four base cations plateaued in the stream reach draining the restoration project with RSCs, but increased ($p<0.05$) in the degraded, unrestored reach downstream of the restoration area (Figure 10). Ca^{2+}, K^+, Mg^{2+}, and Na^+

increased by 8.63, 0.95, 3.53, and 22.7 mg/L per km downstream in the degraded, unrestored reach of Campus Creek, respectively. There was also less variability in chemical concentrations along the restored reach than the unrestored reach. Concentrations of base cations were stable within the RSCs of the restored reach, while there was a significant increase in base cations further downstream in the unrestored reach. Fe and Mn concentrations increased throughout the restored reach, followed by a modest decrease in Fe and a significant ($p<0.05$) decrease in Mn through the degraded, unrestored reach (Figure 10). Consistent with longitudinal patterns observed at Sligo Creek and Scotts Level Branch, the increasing trends in dissolved Fe and Mn concentrations suggest increased hydrologic connectivity through Campus Creek's RSCs. Previous work at this same site has shown that concentrations of DO declined through the RSCs at Campus Creek, sometimes to undetectable levels, which enhance conditions for Fe and Mn reduction and increased concentrations of Fe and Mn in these restoration features (Kaushal et al., 2023).

Flashy Variations in Chemistry due to Stormflow Conditions at Sligo Creek and Paint Branch

In order to investigate flashiness of streamwater chemistry due to stormflow, Sligo Creek and Paint Branch were sampled hourly over 24 hours (Figure 11). Baseflow conditions were sampled either before or after storm events. There was relatively little variation in chemical concentrations during baseflow conditions compared to stormflow conditions. However, stormflow showed large fluctuations or flashiness in chemical concentrations. For example, the storm event captured in the headwaters of Sligo Creek showed a dilution in base cations, in response to a heavy influx of runoff (Figure 11a). Baseflow concentrations, captured between sampling times 10:00 AM and 2:00 AM, are generally stable until the storm event enters after

2:00 AM. The quick salt ion dilution is followed shortly after by the beginning of a recovery period (Reisinger et al., 2017), where concentrations can be observed rising back to their normal baseflow conditions. Hourly concentrations of base cations at Paint Branch showed a brief dilution during a heavy rainstorm during the same evening when the automated stream sampler was deployed but rebounded quickly after the storm (Figure 11b). Diurnal samples collected at Paint Branch were also measured for dissolved inorganic carbon (DIC), DOC, and TDN (Figure 11c). In contrast to the dilution observed in salt ion concentrations due to the storm event, carbon and nitrogen experienced a pulse in concentrations likely due to hydrologic flushing of nonpoint pollution sources within the watershed.

Little Paint Branch (Natural Floodplain Reconnection) and Paint Branch (Streambank Stabilization and Minimal Floodplain Reconnection)

Paint Branch and the Little Paint Branch tributary offer a comparison between a tributary and mainstem chemistry. The mainstem Paint branch shows significantly ($p<0.05$) increasing Na^+ and decreasing Fe. These patterns are not found along the Little Paint Branch tributary (Figure 12a,b). If consistent with other watersheds in this study, the increasing Na^+ and decreasing Fe found along Paint Branch may suggest that it has poor hydrologic connectivity with its floodplain, even though it is a restoration project. The reach along the Paint Branch mainstem sampled with repeated LSS monitoring was relatively small compared to the watershed-scale length of the Paint Branch flowpath (22 km in length). When considering changes across the entire Paint Branch watershed, there were sharp increases in Na^+ and dissolved Fe in stream reaches experiencing restoration or surrounding parks (Figure 12a,b). These rapid increases near restoration sites and conservation areas in parks further support the idea that dissolved Fe can be an indicator of local redox conditions. However, the significant

decrease in Fe measured with repeated LSS monitoring at the reach scale did not significantly impact longitudinal patterns at the watershed scale. This suggests that reach-scale engineered stream restoration projects, such as the one on the mainstem of Paint Branch, will show localized but not necessarily watershed scale impacts (Figure 12c).

Discussion

This study investigates longitudinal patterns in the transport of nutrients, salt ions, organic matter, and metals along restored flowpaths to provide further insights into whether restoration can influence different chemical cocktails. We found that repeated LSS monitoring can be used to detect changes in stream chemistry at varying spatial and temporal scales in response to stream-floodplain connection. Hydrologic connectivity can be linked to longitudinally decreasing salt ion trends, increased concentrations of redox sensitive elements (dissolved Fe and Mn), and relationships between carbon and nitrogen indicating denitrification. We also found that in general, stream reaches with restored flowpaths by means of stream-floodplain reconnection show more geochemical indicators of hydrologic connectivity (changes in Fe, Mn, S, C, N) than stream reaches with minimal to no restoration strategies. Periods of baseflow and stormflow, as well as seasonal road salting events, can result in different chemical cocktails longitudinally along flowpaths and over time.

There are many considerations and challenges when monitoring and evaluating the effectiveness of stream restoration projects. Each stream restoration project may be unique, and there can be variability in stream restoration responses not only among sites but also variability along stream reaches within the same restoration project (Kaushal et al., 2008, 2023b; Sivirichi et al., 2011). Varying spatial and temporal scales of monitoring can impact perceptions of

positive and negative outcomes for both biological and water quality responses (Griffith & McManus, 2020; Kaushal et al., 2023b). Although most work has focused on analyzing changes in urban water quality over time, there is growing work investigating how water quality changes along urban stream flowpaths (*e.g.*, Deemy & Rasmussen, 2017; Duan et al., 2019; Fernald et al., 2006; Kaushal & Belt, 2012; Kaushal et al., 2014b; Lintern et al., 2018; Newcomer Johnson et al., 2014; Pennino et al., 2016b; Smith et al., 2017; Welty et al., 2023). Analysis of spatial patterns in water quality represents a research frontier in hydrological sciences (Lintern et al., 2018).

Similarly, many studies evaluating the effects of stream restoration on water quality have focused on N because of its impacts associated with eutrophication, but more work also needs to holistically consider the fate and transport of salt ions, organic matter, and metals (Galella et al., 2023; Kaushal et al., 2018b, 2022, 2020; Morel et al., 2020). For example, freshwater salinization is increasingly recognized as an urban water quality issue, and major ions in urban streams can be significantly greater than in agricultural and forest streams, with road salt and chemical weathering of impervious surfaces suggested as potential sources (Kaushal et al., 2017). Less work has focused on understanding mechanisms of salt retention along flowpaths (Oswald et al., 2019), but stream restoration involving floodplain reconnection may have the potential to retain salt ions within limits (Cooper et al., 2014; Kaushal et al., 2022; Maas et al., 2021, 2023). Changes in concentrations of redox sensitive elements like Fe, Mn, S, and N may be valuable indicators of localized inputs of subsurface groundwater to streams or the effects of associated wetlands with lower levels of DO (*e.g.*, Kaushal et al., 2023c, 2014b; Lautz & Fanelli, 2008; Sharma et al., 2022).

Biogeochemical and Hydrological Processes that Influence Chemical Cocktails

Interestingly, our results showed that the base cations (Ca^{2+}, K^{+}, Mg^{2+}, and Na^{+}) tend to decrease along restored reaches. Recent work shows that stream restoration and stormwater management have the potential to retain different salt ions (Galella et al., 2023; Kaushal et al., 2023c, 2022) Ion exchange and dilution are the two main mechanisms for decreasing salt ions in restored stream reaches which have enhanced hydrologic connectivity with floodplains (Galella et al., 2023; Kaushal et al., 2022; Maas et al., 2023). Engineering floodplains to increase meanders, riffles, and pools can increase hydrologic exchange (Bukaveckas, 2007; Kasahara & Hill, 2006; Kaushal et al., 2008; Klocker et al., 2009). These engineered features can increase the sinuosity and length of the stream channel, leading to enhanced hyporheic exchange and a longer residence time for water within the stream (Bukaveckas, 2007; Kasahara & Hill, 2006). As water moves slowly through the restored stream reach, it has more contact time with the streambed, enhancing opportunities for ion exchange processes to occur between the water and the sediments or biofilms present (Bukaveckas, 2007; Klocker et al., 2009). Although less considered, stream sediments can also act as a reservoir for salt ions through ion exchange and influence water quality (Kaushal et al., 2023b,c, 2022; Maas et al., 2023). Stream restoration efforts may focus on managing sediment inputs and transport and introduce geologic substrates and expose soils with the capacity for ion exchange. Sediment management strategies, such as stabilizing eroding stream banks or installing sediment traps, may promote ion exchange in streams. Hyporheic exchange may also increase opportunities for ion exchange and retention along flowpaths (Kaushal et al., 2022). Slowing water flow can also increase the opportunity for dilution by allowing additional water to mix with the saline stream water, thereby reducing salt ion concentrations (Kaushal et al., 2022; Maas et al., 2021, 2023).

Stream restoration projects that incorporate floodplain reconnection, wetland creation, or the addition of woody debris can enhance nutrient cycling and biogeochemical processes (Harrison et al., 2012b; Kaushal et al., 2008; Newcomer Johnson et al., 2014, 2016; Passeport et al., 2013). Stream restoration often involves the re-establishment of riparian vegetation, which plays a critical role in ion exchange processes as well as the movement of water throughout the floodplain. Restoration can also involve construction activities that disrupt riparian soils and vegetation leading to pulses of nutrients, major ions, and metals in ground water and streams (Kaushal et al., 2022; Wood et al., 2022). The roots of riparian vegetation can release organic acids and other compounds that alter the chemistry of the surrounding soil and stream water, influencing ion exchange reactions (Dosskey et al., 2010; Gift et al., 2010; Miller et al., 2016). Additionally, organic matter inputs from vegetation and leaf litter contribute to the development of biofilms and microbial communities on streambed surfaces (Romaní et al., 2013). These biofilms can promote denitrification and ion exchange by providing organic surfaces for ion adsorption and facilitating microbial-mediated transformations (Groffman et al., 2005; Kapoor & Viraraghavan, 1997; Xu et al., 2022). A discussion of whether the cumulative effects of stream restoration on longitudinal biogeochemical patterns and processes can be detected is explored further in our case studies and comparisons below.

Restoration Strategies May Influence Longitudinal Patterns of Stream Water Chemistry

Scotts Level Branch and Sligo Creek are two watersheds within 40 miles of each other on Maryland's Piedmont plateau and are comparable in watershed size, land use, and hydrologic characteristics. Thus, differences in longitudinal patterns in chemical concentrations between Sligo Creek and Scotts Level Branch may be strongly influenced by differences in management

along the stream valley (a combination of surrounding riparian management, land use, or stream-floodplain restoration activities).

The Sligo Creek and Scotts Level Branch watersheds showed contrasting longitudinal patterns of base salt cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}). Base cation concentrations at Sligo Creek generally increase downstream along the flowpath. Conversely, Scotts Level Branch showed attenuation of base cation concentrations downstream, along with a general decrease in concentrations through the restored areas along the flowpath. There was a significant ($p<0.05$) inverse relationship between longitudinal concentrations of DOC and TDN along both streams (Appendix, Figure G) that could be due to denitrification (Mayer et al., 2010; Taylor & Townsend 2010) and/or biological uptake and transformation of N to organic matter (Kaushal et al., 2014a). There were strong, significant ($p<0.05$) longitudinal increases in dissolved Fe and decreases in S concentrations along restoration features at Scotts Level Branch likely due to floodplain reconnection, decreased DO in groundwater, and Fe and SO_4^{2-} reduction. In contrast, Sligo Creek showed no patterns in Fe and Mn, suggesting lower degrees of stream-floodplain connection. These differences in stream water quality may be due to stream-floodplain reconnection at Scotts Level Branch and the lack of a comparable restoration approach at Sligo Creek. The decreased hydrologic connectivity between the floodplain and Sligo Creek due to a narrow and highly urbanized stream corridor and a focus on bank stabilization approaches and armoring could be one factor explaining multiple differences in longitudinal patterns of chemical concentrations along the flowpath.

Detecting Impacts of Engineered Floodplain Reconnection on Longitudinal Water Quality

Of the two subwatersheds of Paint Branch in this study, Campus Creek has the highest degree of engineered stream-floodplain connection via the RSC construction. There were significant increases in Na^+, Ca^{2+}, Mg^{2+}, and K^+ in the degraded reach, but not in the upstream restored reach. Previous work has shown that there can be substantial retention of salt ions in the restored reach of Campus Creek likely due to base cation exchange (Kaushal et al., 2022). There is also likely dilution of salt ions in the RSC systems (Kaushal et al., 2022). The combination of retention and dilution processes may be enhanced by stream-floodplain reconnection in smaller upstream reaches, but there may be a limited capacity for contaminant retention processes in downstream reaches with higher peak flows. Base cation concentrations measured at Campus Creek during longitudinal monitoring were comparable to previous studies (Kaushal et al., 2022; Wood et al., 2022). Previous work at Campus Creek has also shown that there can be a longitudinal increase in dissolved Fe and Mn in the RSCs, as well as a significant relationship between dissolved Fe and Mn concentrations and riparian buffer width along the flowpath (Kaushal et al., 2023a).

Effects of Hydrologic Variability and Seasonality on Urban Chemical Cocktails

Fluctuations in streamflow and seasonal pollution events can result in varied chemical cocktails. A PCA shows the differences in chemical cocktails during periods of baseflow, stormflow, and in response to road salting events in the Scotts Level Branch watershed (Figure 5). Sudden changes in streamflow due to storm events can dramatically upset the natural baseflow concentrations of base cations, DOC, and TDN (Figure 11). Under certain conditions,

both natural and engineered systems can be overwhelmed by storm and road salting events, potentially resulting in either dilution of ions or pulses of contaminants. Annual wet and dry periods will also impact chemical cocktail concentrations in stream water, as observed at Paint Branch (Figure 5a). In general, less is known about diurnal cycles of water chemistry and the impacts of storms on elemental chemistry along small urban streams; there may be substantial fluctuations in some chemical concentrations throughout the day and night (Kaushal et al., 2020). For example, one study monitored a river in southwest Germany every 15 minutes for 355 days to explore diurnal patterns in nitrate and concluded that diurnal variability was caused by in-stream processes (Greiwe et al., 2021). Another study found significant changes in concentrations of nitrate, base cations, and other major anions at the Montousse catchment at Aurade in southwest France over sampling periods of hours to decades (Ponnou-Delaffon et al., 2020). In this study, there were large diurnal fluctions in stream chemistry during storm events compared to baseflow, which suggests that pollution events may also have an important impact on longitudinal transport and transformation of chemicals.

Influence of Natural Floodplain Reconnection on Longitudinal Patterns in Streamwater Chemistry and Redox Sensitive Elements as Indicators of Hydrologic Connectivity.

Redox-sensitive elements have been used as indicators of hyporheic exchange in wetlands (Briggs et al., 2013; Hoagland et al., 2020; Soils, 2002). In saturated soils, Fe, Mn, S, and N are reduced under low DO conditions and switch to forms available for anaerobic microbial respiration (Mayer et al., 2010), whereas redox-sensitive metals form particulates in unsaturated soils (D'Amore et al., 2004; Ou et al., 2019). In restored streams, redox reactions influence the oxidation and reduction of redox-sensitive metals. For example, under aerobic conditions, Fe and Mn tend to be present in their oxidized forms (Fe^{3+} and Mn^{4+}), which are less

soluble and tend to precipitate as solid particles. In hydrologically connected systems, as oxic surface water flows into hypoxic and anoxic groundwater, redox-sensitive elements, like Fe and Mn, become electron acceptors and reduce to more soluble forms. This in turn increases the concentrations of redox-sensitive Fe and Mn in the surface water, which may indicate hydrologic connectivity between streams and groundwater. Conversely, under hypoxic and anoxic conditions, these metals are reduced to more soluble forms (Fe^{2+} and Mn^{2+}), which can stay dissolved in the water column and increase dissolved Fe and Mn concentrations. Therefore, a stream that is hydrologically connected with its floodplain allows for greater surface water-groundwater interactions and potentially higher subsurface DO. Restoring a hydrologic connection is a goal of many stream restoration efforts (Feng et al., 2022), but evaluating whether hydrologic connectivity is actually achieved may be complex and challenging. Results from this study suggest measurements of redox-sensitive elements may serve as geochemical indicators of hydrologic connectivity that improve our ability to understand groundwater-surface water interactions along restored streams.

Effects of Watershed Spatial Scales on Detecting Longitudinal Patterns in Chemical Concentrations

Unlike the other stream reaches, longitudinal patterns in chemical concentrations were difficult to detect along Paint Branch when conducting repeated LSS monitoring over relatively smaller spatial scales. Interestingly, the smaller scale restoration project along Paint Branch near the University of Maryland campus actually showed that there was minimal hydrologic connectivity when analyzing geochemical indicators. For example, there was a longitudinal increase in Na^{+} and decrease in dissolved Fe concentrations. These longitudinal trends in geochemical indicators underscores the notion that not all stream restoration projects will show

positive signs of hydrologic connectivity. However, there were clear increases in Na^+ and dissolved Fe concentrations in restoration projects and conservation areas along the entire Paint Branch at the watershed scale over 22 km (Figure 12c). This discrepancy between smaller reach- and whole watershed-scales points to the need to conduct LSS monitoring at spatial scales sufficiently long enough to detect potential "hot spots" of hydrologic connectivity.

Potential Benefits of Incorporating LSS Monitoring Approaches in Assessing Restoration

The LSS monitoring approach described in this study can be used to monitor other streams and rivers with their own unique forms of restoration, whether natural or engineered. By considering both temporal and spatial scales, we can gain a more well-rounded assessment of management activities within a watershed context. In addition, there can be value in incorporating a watershed chemical cocktail approach considering multiple chemicals holistically (Galella et al., 2023; Kaushal et al., 2018a, 2020; Maas et al., 2023; Morel et al., 2020). Stream monitoring can focus purely on physical changes, chemical changes, biological changes, or any combination of these. Evaluating these parameters together will provide the most information regarding cumulative changes along flowpaths or over time (Kaushal et al. 2023b). Diurnal sampling of baseflow, storms, and road salting events can reveal important information regarding limitations and context for our interpretations of successes and failures in restoration (Kaushal et al., 2023b). Spatial and temporal resolution of sampling should be planned according to individual watersheds. Physical, chemical, and biological characteristics of a stream can change along a flowpath, and disentangling the drivers can be difficult. Changes in erosion and depositional patterns can change the physical flow of a stream; point and nonpoint sources of pollution into the channel can alter the chemistry; the amount of canopy cover and direct sunlight can affect biota processes (Yoshimura & Kubota, 2022). Therefore, sampling at only one

location or the top and bottom of a stream reach may not be adequate. Exploring stream sampling locations around tributaries, roadways, new construction, and natural and engineered stream restorations can sometimes help to explain where and how the physical, chemical, and biological characteristics of a watershed are behaving along its flowpath (Cooper et al., 2014; Kaushal et al., 2014, 2023a; Maas et al., 2023; Newcomer-Johnson et al., 2014; Pennino et al. 2016a; Sivirichi et al., 2011).

Longitudinal Stream Synoptic Monitoring Can Help Evaluate Trade Offs Associated with Restoration

Stream restoration projects involve efforts to improve the ecological health and functionality of streams and their surrounding environments. While these projects aim to restore natural processes and enhance ecosystem services, they often involve trade-offs due to various factors (Wood et al., 2022). Large-scale stream restoration projects can offer the greatest potential for watershed rehabilitation (Shields et al. 2003), but they can be expensive, requiring significant financial resources (Kenney et al., 2012). Restoration projects can also take a long time to implement and achieve desired outcomes and delays can occur due to permitting requirements, stakeholder consultations, and the natural time needed for ecosystems to recover (Mayer et al., 2022). Balancing the urgency of restoration goals with the time required for project completion is a trade-off.

Streams are complex ecosystems with interconnected components, including physical, chemical, and biological factors. Disturbing an ecosystem to restore its flowpath can disrupt existing ecological relationships, leading to unintended consequences and increases in contaminant concentrations (Kaushal et al., 2022; Mayer et al., 2022; Wood et al., 2022). There

may be trade-offs between the desired scope of restoration activities and negative impacts (Kaushal et al., 2023b, Wood et al., 2022). We observed that prioritization of restoration goals and careful planning is necessary to balance cost considerations with ecological benefits. LSS monitoring approaches can reveal tradeoffs. For example, we observed decreases in DO in RSCs at Campus Creek (Appendix, Figure E), and this has been documented elsewhere (Kaushal et al., 2023a). LSS monitoring also revealed local changes in pH associated with restoration features (Appendix, Figure E). Changes in DO and pH associated with restoration may influence habitat for aquatic organisms, although not a focus of this study. Future work incorporating more metrics in LSS monitoring could help identify whether modifying stream channels may alter the habitat for certain species or change sediment transport patterns. Balancing the restoration objectives with potential ecological impacts and tradeoffs is crucial. Implementing adaptive management approaches that allow for learning and adjustment based on LSS monitoring results can help mitigate these trade-offs.

Management Implications and Conclusions

This study shows that there can be longitudinal patterns in water chemistry with distance downstream, and these relationships can be different among different stream reaches experiencing variations in land use, restoration, and management. Results from this study show that, depending on where we sample along an urban stream, we can get completely different answers and insights regarding investigating patterns and processes of water quality. Results from longitudinal monitoring in this study also suggest that there may be differences in the impacts of restoration in headwater systems *versus* further downstream. For example, in Scotts Level Branch and Campus Creek, it was possible to detect longitudinal patterns influenced by stream restoration. However, these patterns were not as evident along the shorter stream reaches

of Paint Branch, which were much further downstream and larger. Restoration projects along headwater reaches may have more of an impact than restorations on downstream reaches or with minimal floodplain reconnection (Filoso and Palmer, 2011; Newcomer-Johnson et al., 2014). For smaller watersheds, headwater restoration projects may be more useful for improving overall water quality along a shorter flowpath. For larger watersheds, headwater restoration projects may be impractical, if there are many first-order streams at the top of the flowpath. In this case, fewer but larger restoration projects downstream may be less expensive to complete. If the upstream sources of pollution are not controlled, the constant flow of lesser-quality water may overwhelm ecosystem contaminant retention functions in a restoration project.

LSS monitoring has the potential to detect hydrologic connectivity, localized disturbances along stream flowpaths, and help prioritize reaches for stream restoration impacted by wastewater leaks and other disturbances. One potentially promising indicator of hydrologic connectivity may be dissolved Fe and Mn concentrations along flowpaths. Our results at the reach scale and entire watershed scale of Paint Branch suggested that increases in dissolved Fe and Mn can occur in restoration and conservation areas with increased potential for groundwater-surface water interactions. LSS monitoring can also identify areas along streams receiving pollution. Sewage leaks represent a major nonpoint source of pollution in urban streams of our study region (Kaushal et al., 2011). Many public sewage drain pipes are commonly buried near streams in urban developments (Kaushal & Belt, 2012) as the pipes need to run downhill for gravitational flow. As baseflow stream velocity throughout the stream network slows and discharge from urban areas increases, stream channels are subject to erosion. If sewage drain pipes are placed too close to the stream, they can become exposed through weathering and erosion, which contributes to rusting and cracking of the pipes and eventually leads to sewage

leaks. This would heavily pollute the stream network and may require expensive rehabilitation efforts (Bonneau et al., 2017; Kaushal & Belt, 2012). This can have a great impact on the quality of its water and surrounding environment (Roy & Bickerton, 2012). Most stream restoration projects in and around Maryland strive to improve water quality (Newcomer-Johnson et al., 2016), as many streams ultimately empty into the Chesapeake Bay (Chang et al., 2021). A stream-floodplain reconnection approach would need to work to protect and maintain, if not relocate, nearby sewage drain pipes in surrounding stream watersheds to prevent groundwater from the incursion of excess pollutants. This approach reverses hydrologic degradation and brings polluted water to hot spots of contaminant retention in floodplains.

Overall, the longitudinal data collected from each of the four watersheds in this study show the importance of monitoring streams at various spatial and temporal scales. Changes in stream chemistry can occur along a flowpath, so sampling one location along a flowpath over time will not provide an accurate overview of the watershed as a whole. Local natural and anthropogenic inputs such as tributaries or new construction can change the chemistry of a stream and the rest of the downstream flowpath. Future stream restoration projects should be monitored over both spatial and temporal scales. Multidimensional monitoring approaches including lateral, longitudinal, or surface-groundwater sampling should be considered when assessing the effectiveness of a stream restoration. In addition, more longitudinal sampling locations throughout a watershed allows for more accurate conclusions about local changes in water chemistry along flowpaths.

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