Hyporheic exchange in an urban beaver pond mediates high nutrient groundwater inflow and pond productivity

Sarah H. Ledford[a]*, Shellby Miller[a,b], Luke Pangle[a], and Elizabeth B. Sudduth[c]

[a] Georgia State University, Department of Geosciences, PO Box 3965, Atlanta, GA 30302, USA

[b] Present address: Metro North Georgia Water Planning District, 229 Peachtree St, Suite 100, Atlanta, GA 30303, USA

[c] Georgia Gwinnett College, Department of Biological Sciences, Building H, Suite 3209, 1000 University Center Lane, Lawrenceville, GA 30043, USA

* Corresponding Author: sledford@gsu.edu

Abstract

The rebound of beaver populations across North America has resulted in new understanding of how their alteration of stream channels affects hydrology and biogeochemical cycling, but their increased impact on urban areas has not been well investigated. Urban beaver ponds have the potential to slow and retain runoff, reconnect surrounding floodplains, and reduce nutrients. Where management allows, beaver ponds may partially ameliorate water quality problems in urban streams and enhance the ecological function of the broader riparian zone. In this study we measured water chemistry in surface (over ten months) and hyporheic (over three months) waters, including nitrate, ammonium, and dissolved organic carbon (DOC), to assess the impact of urban beaver dams on water quality. Pond water is sourced from groundwater, with anoxic conditions in the surface water at the top of the pond that become increasingly oxic moving longitudinally through the pond. Large diel dissolved oxygen swings in the pond indicate high sestonic productivity. There are distinct hyporheic geochemical signatures above and below the dam as well as across the dam indicating the dam is driving downwelling above the dam and upwelling below. Hyporheic ammonium concentrations and surface nitrate concentrations are high above the dam and decrease below the dam, showing that shifting oxic conditions drive nitrogen speciation. The δ^{15}N and δ^{18}O values of nitrate point to diffuse sewage leaks as the main source of nutrients to the pond instead of overland runoff. In addition, surface waters have lower δ^{15}N and δ^{18}O of nitrate and DOC concentrations than groundwaters, indicating denitrification may drive the decrease in nitrate concentration. With increasing presence of beaver in urban streams, surface water-groundwater interactions through urban beaver dams have the potential to remediate urban sources of nutrients from ponds.

Keywords: Urban, beaver pond, nitrate, dissolved organic carbon, surface water-groundwater interactions

1. Introduction

Land cover change to impervious surfaces in urbanized environments changes the timing, quantity, and quality of water reaching streams and rivers (Kaushal and Belt, 2012; Leopold, 1968; Walsh et al., 2005). Urban streams have flashier hydrographs (Smith and Smith, 2015), are deeply incised (Booth et al., 2016; Walsh et al., 2005), and have higher nutrient concentrations compared to forested streams (Stets et al., 2020). In addition, urbanization has decreased the density of ponded surface water in humid climates (Steele et al., 2014), and those ponds that remain have decreased flow path complexity (as approximated by smaller perimeter to area ratios) and are less likely to be directly connected via surface flow paths with rivers and streams (Steele and Heffernan, 2014). Because of these changes, urban stream managers are faced with addressing both flooding and water quality issues.

One current management approach to address these issues are attempts to retain and/or infiltrate stormwater within the landscape. While stormwater detention and retention basins, along with low impact development, are typically built off of the stream channel, some retention ponds (e.g., regional ponds, U.S. Environmental Protection Agency, 2005) may be built in-line with the prevailing channel (i.e., directly connected along the surface flowpath), thus dramatically expanding the wetted perimeter of the channel. Billions of dollars have been invested in green stormwater infrastructure implementation (Bernhardt et al., 2005; Prudencio and Null, 2018) with limited measured improvement in reducing stormflow and conflicting results in changes in water quality (Hopkins et al., 2022). Watershed-scale improvements should not be expected when only small percentages of impervious cover in a watershed are being captured (Bell et al., 2020). In contrast, the resurgence of beaver and beaver dams on the landscape, including in urban environments, has potential to create ponds and wetlands that function like engineered approaches to addressing urbanization, as they may retain water on the landscape, induce surface water-groundwater (SW-GW) interactions, and impact water quality (Bailey et al., 2018).

Many extensive summaries of the impacts beaver have on hydrology and biogeochemistry exist (Brazier et al., 2020; Larsen et al., 2021), but there has been minimal work to understand the role of beaver in urban environments (Bailey et al., 2018). Beaver engineer their landscape by building dams to ease access to food and as protection from predators (Larsen et al., 2021). In non-urban locations where beaver have reestablished, there is clear flow attenuation due to damming compared to pre-beaver conditions (Puttock et al., 2021, 2017). This flow attenuation extends beyond surface water discharge, with measured increases in groundwater recharge via surface water infiltration during flood events above and below beaver dams (Westbrook et al., 2006). Locations with higher beaver population densities have more surface water storage (Johnson-Bice et al., 2022). This retention of water by beaver on the landscape helps protect parts of the landscape from increasing drought- and climate change-driven wildfires (Fairfax and Whittle, 2020). The hydraulic jumps created by in-stream beaver dams create more heterogeneous SW-GW interactions including inducing downwelling into the hyporheic zone (Briggs et al., 2013; Lautz et al., 2010). Reduced water velocities allow for sediment aggradation above beaver dams (Pollock et al., 2007) and decreased downstream export of sediment (Puttock et al., 2017).

The role of beaver in restoring montane river systems to their more natural "river beads" morphologies (Wohl et al., 2018) is well established (Burchsted et al., 2010; Gorczyca et al., 2018; Pollock et al., 2014), but understanding the role of beaver in urban environments is only just starting. Many of the ecosystem services of beaver ponds and wetlands in montane systems would be beneficial in urban areas. Sediment aggradation results in deposition of organic matter above the dam, increasing nutrient cycling within the pond (Brazier et al., 2020). Some studies find that nitrogen and phosphorus are retained through beaver dam complexes (Puttock et al., 2017) while others have shifts in nutrient retention related to flow regime (Wegener et al., 2017). Dissolved organic carbon (DOC) is typically exported from beaver ponds because of increased productivity in the pond and increased hydrologic connectivity (Brazier et al., 2020; Puttock et al., 2017). Beaver dams have also been shown to be hypoxic, with downstream impacts on temperature and dissolved oxygen that may not be beneficial for the stream ecosystem (Stevenson et al., 2022). The potential role of beaver dams in modifying discharge regime and water quality is additionally complicated in areas where human-beaver conflicts arise (Auster et al., 2022; Bailey et al., 2018).

With increased reports of beaver in urban environments (Figure 1) and the known benefits beaver provide in landscapes less impacted by anthropogenic activities, expanded understanding of their role in urban systems is needed. With that in mind, we had three objectives to this work: (1) to evaluate spatial variation in hyporheic geochemistry above and below an urban beaver dam to assess how SW-GW interactions are driving geochemical change, (2) to evaluate longitudinal variation in surface-water geochemistry within the beaver pond and in the outflow below across antecedent moisture conditions, and (3) to use multiple tracers to identify sources and cycling of nitrogen in the system. We hypothesized that (1) hyporheic exchange through the beaver pond results in distinct geochemical signatures above and below the dam, (2) reactive ion concentrations will change systematically along longitudinal pond profiles due to enhanced in-pond processing, whereas conservative ion concentrations will exhibit no regular spatial pattern, since they are primarily controlled by spatially heterogeneous groundwater discharges to the pond, (3) nitrogen enters urban beaver ponds through diffuse waste sources, most likely groundwater sourced, and (4) warm temperatures, high hydrologic retention, and direct light lead to high productivity ponds with high rates of nitrogen cycling and limited permanent removal of nitrogen.

113

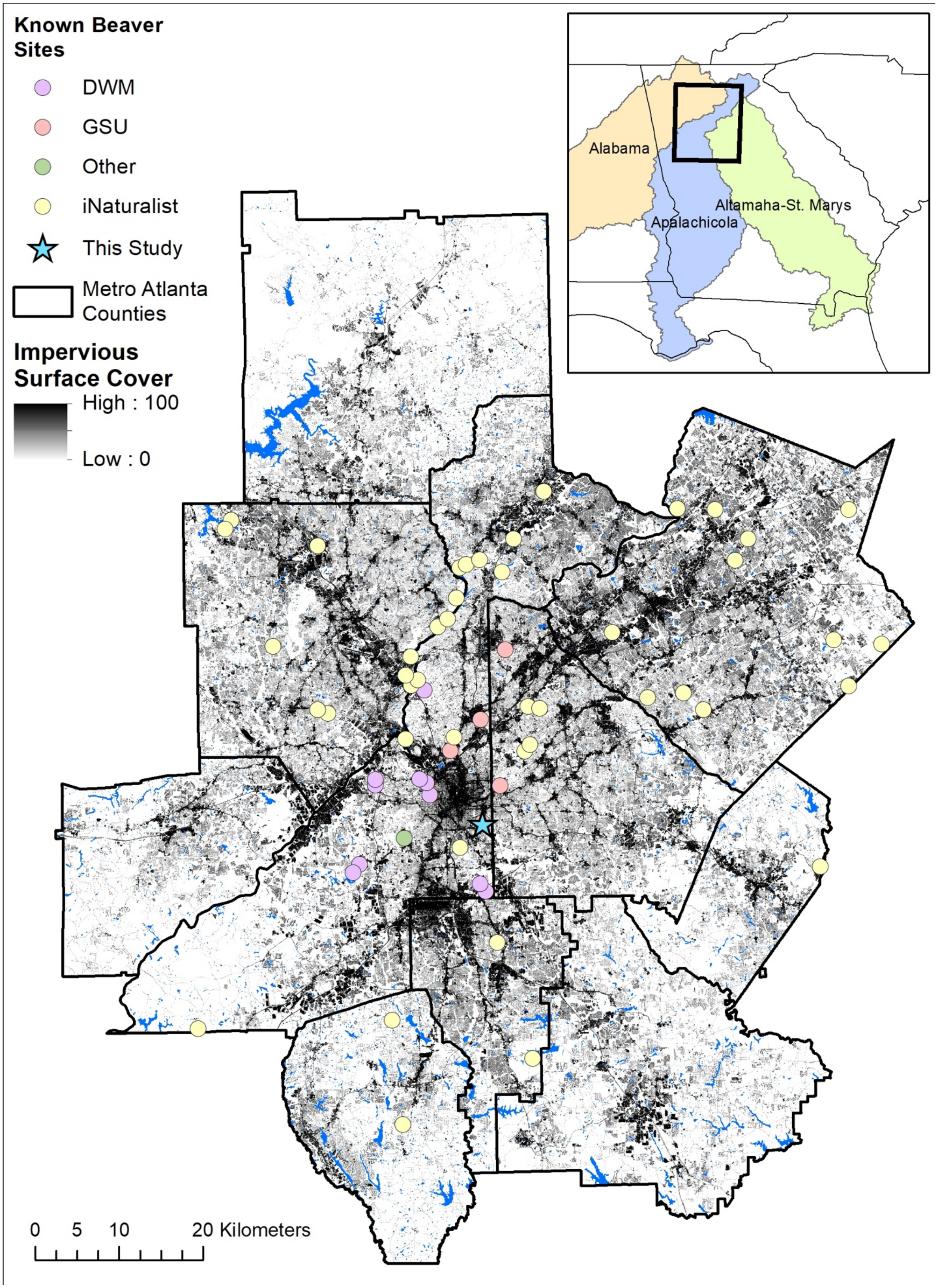
Known Beaver Sites
DWM
GSU
Other
iNaturalist
This Study
Metro Atlanta Counties
Impervious Surface Cover
High : 100
Low : 0
Alabama
Apalachicola
Altamaha-St. Marys
0 5 10 20 Kilometers

Figure 1. Summary of some known beaver locations in metropolitan Atlanta. Data are sourced from the Atlanta Department of Watershed management ("DWM", 2016-2021, pers. comm.), iNaturalist (2018-present), and authors' knowledge ("GSU" and "Other"). iNaturalist results include both research-grade observations, which are reported in the GBIF (GBIF.org, 2023), and regular reports from users to represent the range of beaver occupancy in the metropolitan Atlanta region.

2. Methods

2.1. Site Description

The former location of the beaver dam and pond at the Tapestry community garden is in the southeastern quadrant of the City of Atlanta, GA, USA (Figure 2c) in the upper-most headwaters of the Altamaha-Oconee-Ocmulgee watershed, approximately 3 km away from the subcontinental divide. Aerial imagery analysis through Google Earth Pro indicates the pond was established between May 2014 and August 2015 and was abandoned in early 2021, soon after which the dam washed out. Atlanta receives an average of 130 cm of precipitation per year, almost all of which falls as rain (Konrad and Fuhrmann, 2013). The area is in the Piedmont physiographic region, with highly fractured and heterogeneous igneous and metamorphic bedrock that is primarily felsic overlain by weathered regolith with a base of saprolite (Harned and Daniel, 1989; Higgins et al., 2003). Piedmont soils have high clay content (Markewich et al., 1990), and urbanization has resulted in soils with simpler profiles, however, often with high disturbance and the addition of fill during construction (Herrmann et al., 2018).

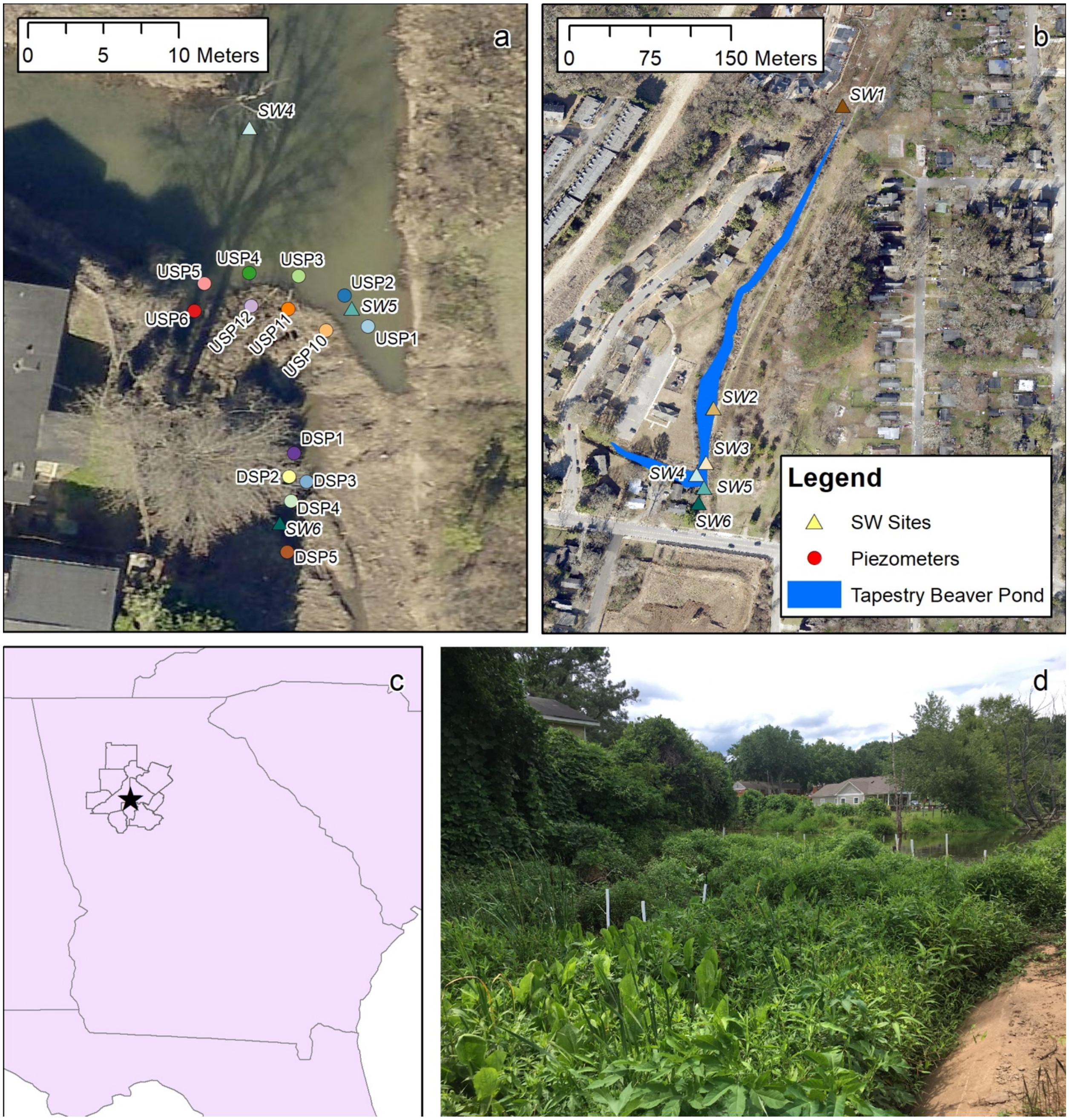

Figure 2 (a) Locations of the beaver dam with 14 piezometers and three surface water sampling sites indicated. (b) Larger view shows all six surface water sampling sites and the approximate location of the whole pond. Pond flows from top to bottom of image. (c) Location of the site within the state of Georgia, with the 10 counties of metropolitan Atlanta identified. (d) Photo taken from below the beaver dam (covered in vegetation), looking upstream with the downstream piezometers on the left and the upstream piezometers on the right. The large-diameter pipe that followed the eastern edge of the pond is visible in the foreground. Aerial imagery in panels a and b is from 2019 (Fulton County GIS, 2023).

The pond had a beaver dam of approximately 16 m length and 1.5 m height (Fig 2a), creating an approximately 2,500-m^2 upstream ponded reach by flooding a main stem and a tributary (Fig 2b), with the pond size varying depending on antecedent moisture conditions. At baseflow, we estimated average depth of the pond within about 20 m distance of the dam to be 0.56 m. The pond was fed by groundwater discharge and stormwater runoff from a 0.34 km^2 water and sewershed (City of Atlanta, pers. comm.), with no perennial surface inflow. The upstream section of the existing channel is piped from approximately 0.5 km above the former beaver pond to below the next culvert, where the two discharges (pond outflow and piped stream) combined to form Intrenchment Creek. The dam mostly consisted of some wood on the downstream side held together with soil and mud on the upstream side, creating a low porosity barrier that would become completely covered in vegetation during the summer (Fig. 2d). During baseflow, some water would flow over the dam on the eastern side when the pond level was high, but it was not uncommon for the only flow to be diffuse flow through the dam instead of over the dam. Approximately 35 m below the former pond is a road culvert outfitted with a bottom drain that frequently clogged. During storms, this road crossing kept water velocity from getting high enough to blow out the dam and the whole lower section below the dam would be ponded because of the faulty drain (Fig. S1). The contributing area is urbanized, mostly consisting of single-family homes on lots typically under 0.4 acres, estimated to be 48% impervious and 98% developed in 2011. An 8-foot diameter concrete pipe is the eastern boundary for the pond (Fig 2d), although it is unclear if the pipe carries a buried stream, stormwater, and/or separated sewage.

2.2. Sampling

Samples of surface and hyporheic waters were collected approximately weekly from June 16, 2019 to August 13, 2019 (Table 1). Additional surface water samples were collected weekly from September 5, 2019 to March 12, 2020, stopping at the start of the COVID-19 pandemic (Figure 3 and Table 1). Surface water samples were collected longitudinally from six sites, although SW1 dried up periodically (Figure 2b). Hyporheic samples were collected from six piezometers above the dam, three piezometers in the dam, and five piezometers below the dam (Figure 2a). Piezometers were made of either 3.8 or 5.1 cm inner diameter PVC and had 10 cm screened lengths, installed so the bottom of the screen was located 15 to 25 cm below the sediment-water interface. Before sampling, piezometers were purged using a drill-powered pump until empty and samples were collected after they re-filled. All samples were measured *in situ* using a YSI ProDSS sonde that was calibrated in the lab before each use and measured temperature, pH, specific conductance, and dissolved oxygen (DO). 60 mL samples were collected in HDPE bottles and transported to the lab where they were filtered with 0.45 μm MCE filters and stored frozen.

Sampling Type	**Dates**	**Analyses**	**Locations relative to dam**
Hyporheic grab samples	June 16-August 13, 2019 (9 sample dates)	*In situ* (temperature, pH, specific conductance, DO);	6 piezometers above the dam (USP1-6), 3 piezometers in the

		major anions and cations; DOC; a subset with high NO_3^- were analyzed for $\delta^{15}N$ and $\delta^{18}O$	top of the dam (USP10-12) and 5 piezometers below the dam (DSP1-5)
Surface water grab samples	June 16, 2019-March 12, 2020 (34 sample dates)	*In situ* (temperature, pH, specific conductance, DO); major anions and cations; DOC; a subset with high NO_3^- were analyzed for $\delta^{15}N$ and $\delta^{18}O$	5 longitudinal sites in pond above dam (SW1-5, from top of pond to bottom), 1 site in stream below dam (SW6)
Surface water loggers	June 15- August 23, 2019 at 10-minute interval	Dissolved oxygen and specific conductance	One site in pond above dam (attached to USP2)

Table 1. Summary of sampling types, time frames, analyses, and locations relative to the beaver dam.

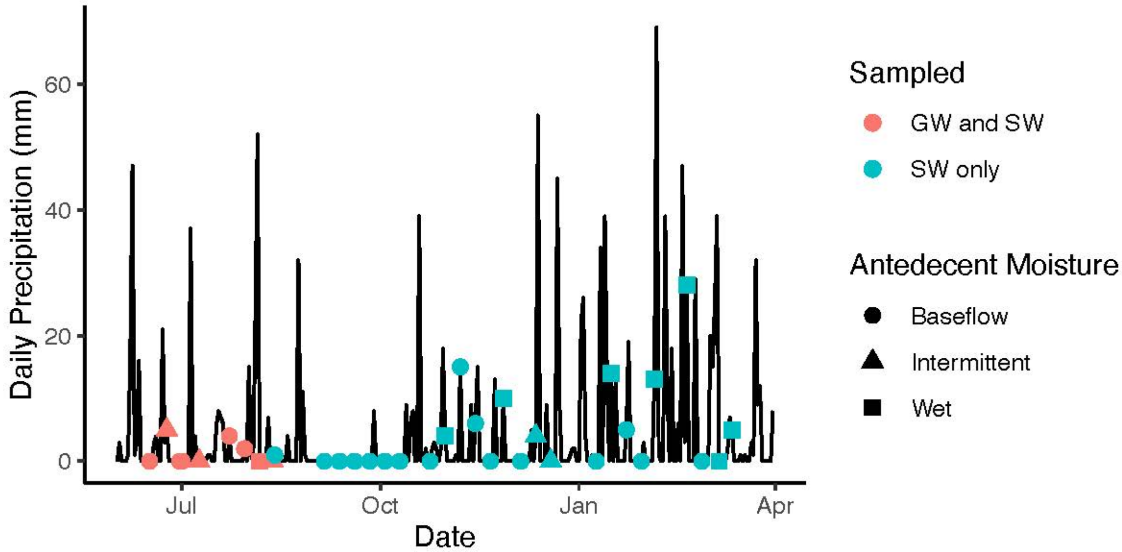

Figure 3. Daily hyetograph in mm, averaged from daily precipitation totals two nearest USGS stations (02203700 and 02203655) for the monitoring period. Dates of sample collection, types of samples collected, and attributed antecedent moisture conditions are indicated. Note that 15-minute precipitation data were used to classify antecedent moisture, so a date that is indicated as 'baseflow' but has precipitation on this figure had rain fall during the day after sampling.

A PME dissolved oxygen logger and Onset Hobo conductivity logger were installed to measure dissolved oxygen and specific conductance in the pond at 10-minute intervals alongside USP2 (Figure 2a). Loggers were installed from June 15, 2019 to August 23, 2019. The DO logger probe was cleaned weekly during hyporheic water sampling.

Antecedent moisture conditions for each sampling event were determined by averaging conditions between the two closest USGS gaging stations that also record precipitation. Gage 02203700 is 5.2 km southeast from the site, and gage 02203655 is 5.4 km south. Antecedent precipitation over 48 hours prior to sampling ranged from 0 to 6.5 cm. 15-minute precipitation data were used to group samples into three categories: (1) dry or baseflow, with no rain at either gage within 48 hours of initiation of sampling; (2) intermediate, with rain 24 to 48 hours before initiation of sampling but no rain within 24 hours; and (3) wet, where it rained within 24 hours of initiation of sampling. The only outlier was February 5, 2020, where neither gage recorded rain but the field notes indicated it had been raining at the site.

2.3. Laboratory Analyses

All samples were analyzed by ion chromatography for major anions (Cl^-, NO_2^-, Br^-, NO_3^-, and SO_4^{2-}) and cations (Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}) on ThermoScientific Aquions. Each run was calibrated with 5 in-house independently created standards for both cations and anions, along with running external U.S. Geological Survey standards for calibration verification. Samples that were outside of calibration range were diluted and re-run. Phosphate in samples was measured but was routinely below the detection limit and is not used in analysis. Nitrite, bromide, and ammonium had some measures that were below the detection limit. They were replaced with a minimum detection limit estimated as the standard deviation of the same standard which was rerun at least three times during each analysis. DOC was measured as non-purgeable organic carbon on a Shimadzu Total Organic Carbon analyzer calibrated using in-house standards.

A subset of forty-four of the summer 2019 samples were analyzed for $\delta^{15}N$ and $\delta^{18}O$ of nitrate at the University of Pittsburgh Regional Stable Isotope Laboratory on an Isoprime Continuous Flow Mass Spectrometer following the denitrifier method (Sigman et al., 2001). This subset was determined by first selecting any groundwater samples with enough nitrate mass to analyze (eight samples), with the remaining consisting of surface water samples from the summer. Only downstream hyporheic waters had enough nitrate to analyze, from four of the nine sample dates. Surface water samples from the eight of the nine dates were analyzed, focusing on sites from the main pond to below the dam (SW3-6) although SW2 was also analyzed from five dates. These samples were filtered with 0.2 μm MCE filters and frozen until subsequent analysis. Samples with more than 2% nitrite of the total oxidized nitrogen (NO_2 + NO_3) had the nitrite removed through sulfamic acid reduction (Granger and Sigman, 2009) prior to isotopic analysis. A denitrifying bacteria strain (*Pseudomonas aurofaciens*) converted NO_3^- into N_2O gas that was then introduced into the isotope ratio mass spectrometer. Samples were corrected using international reference standards USGS-32, USGS-34, USGS-35, and IAEA-N3; these standards were also used to correct for linearity and instrument drift. All samples were run in duplicate, and precision is ± 0.25 ‰ for $\delta^{15}N$ and ± 0.5 ‰ for $\delta^{18}O$.

2.4.Statistical Analyses

All statistical analyses were completed in R version 4.0.2 (R Core Team, 2022). Datasets frequently had a non-normal distribution as tested both with a probability plot correlation coefficient and Shapiro-Wilk normality test, so non-parametric statistical approaches were used. Comparison of upstream to downstream groundwater geochemistry was done with the one-sided Wilcoxon rank-sum test using wilcox.test(). Because of ties, an exact p-value was not calculated and estimated p-values under 0.05 were interpreted as a change in concentration through the beaver dam. The sample estimate of difference in location was used to calculate a percent difference between up- and downstream-sites. A principle component analysis (PCA) of the ion chemistry of groundwater samples was completed using prcomp(). Unit variables were all scaled to have the same variance before analysis. Lastly, a Kruskal Wallis test was used to compare surface water sites at each antecedent moisture condition using kruskal.test(). A p-value below 0.05 indicates that the median of at least one site differs from the others. A pairwise Wilcoxon rank-sum test with a Bonferroni adjustment was done to identify which sites differed using pairwise.wilcox.test(). This could only be done on the baseflow samples (n = 21 dates) as the intermediate (n = 5) and wet (n = 8) samples had too few samples to test. All tests are in the stats package in base R.

3. Results

3.1. Groundwater Geochemistry

Groundwater geochemistry is highly variable across the small spatial area monitored (Figure 4, S2, and Table S1), and sites vary in temporal stability, consistent with H1. Specific conductance, ammonium, calcium, magnesium, and potassium all follow similar spatial patterns with the highest concentrations in the 5 eastern-side upstream piezometers (USP1, USP2, UPS3, USP4 and USP10). DOC has minimal spatial variability across the thirteen piezometers. Sulfate, nitrate, and nitrite have higher concentrations in the two most western upstream piezometers (USP6 and USP12). After aggregating and comparing data from piezometers located upstream of the dam versus those located downstream, we found statistically significant ($p < 0.05$) reductions in concentrations of ammonium, magnesium, and potassium (Figure 5), which is generally consistent with observed spatial trends. Although spatial trends in chloride, sodium, and bromide are not visually apparent (Figure 4 and S2), this aggregated comparison does reveal lower concentrations of these ions below the dam compared to above (Figure 5). pH, DO, sulfate, and nitrate all increase below the dam (Figure 5), and there is no statistical difference in DOC or nitrite across the dam (Table S2). Nitrate doubles in concentration in groundwater below the dam, with the highest percent change, while ammonium decreases by 80%.

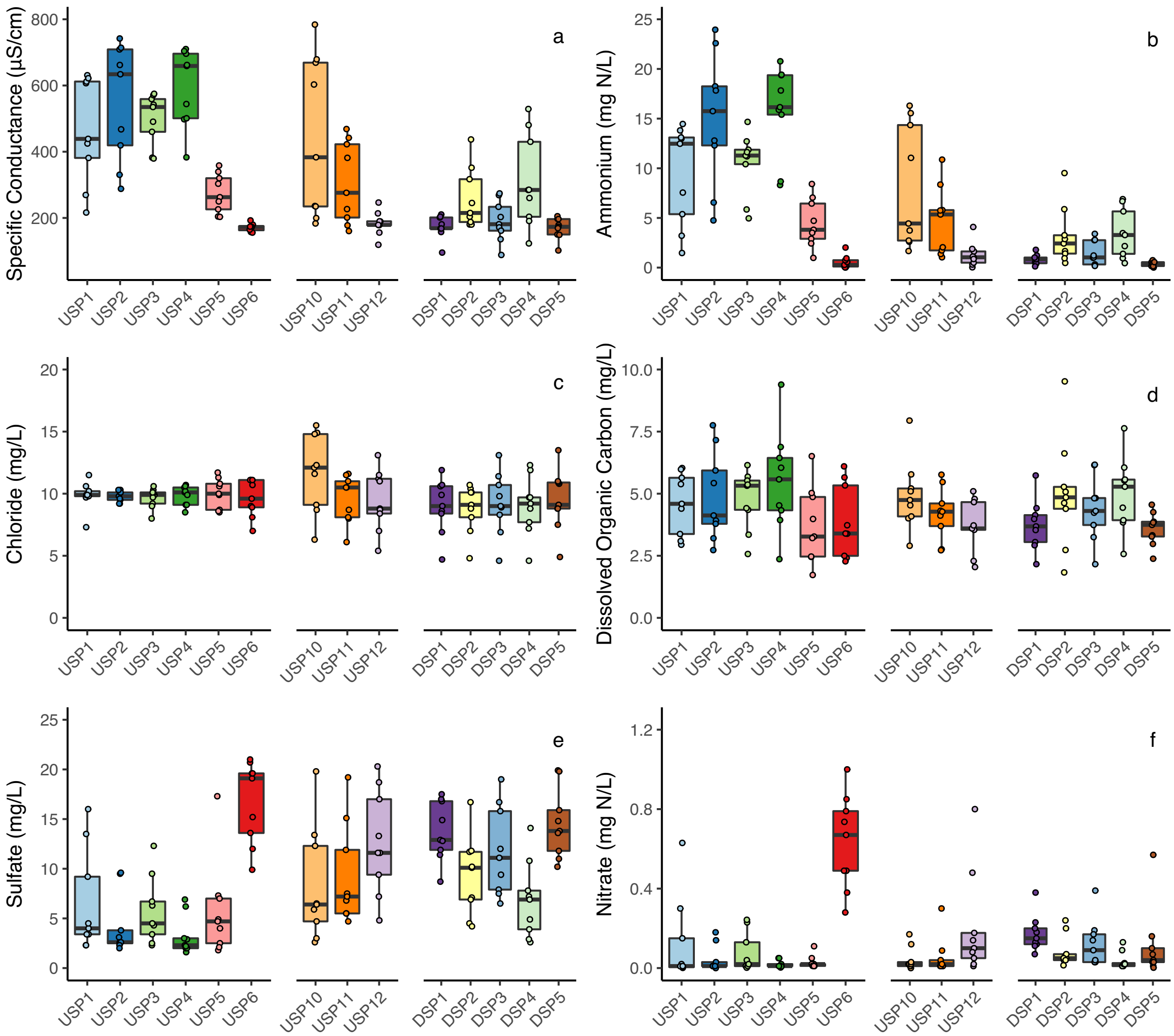

Figure 4. Boxplot of geochemistry of groundwater for (a) specific conductance, (b) ammonium, (c) chloride, (d) DOC, (e) sulfate, and (f) nitrate. Each solute is grouped as piezometers upstream of the dam (USP1-6), piezometers in the top of the dam (USP10-12), and piezometers below the dam (DSP1-5). Figure S2 shows the remaining ions.

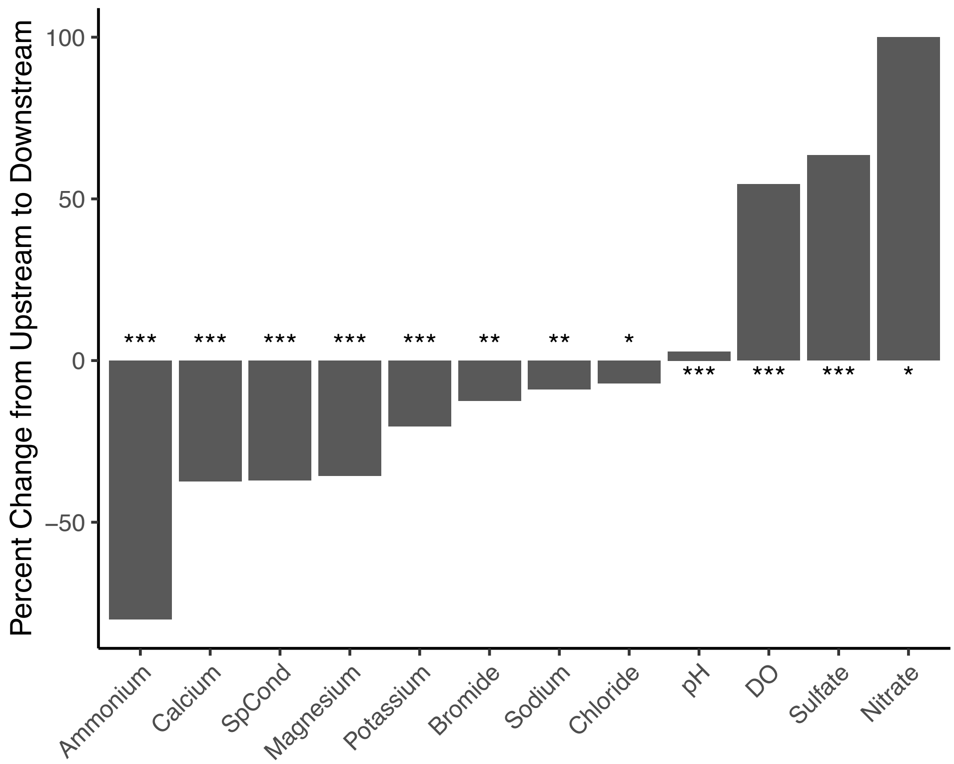

Figure 5. Wilcoxon rank-sum comparison of upstream piezometer geochemistry to downstream. The percent change is the sample estimate from the Wilcoxon rank-sum test divided by the median upstream concentration, where positive changes indicate concentration was higher in groundwater below the dam, while negative changes indicate concentration was lower below the dam. * indicates $0.05 > p > 0.01$; ** indicates $0.01 > p > 0.001$, *** indicates $p < 0.001$. Exact values reported in Table S2.

PCA indicates that 84.6% of the variability in the groundwater geochemistry can be explained by the first three components (Table 2). PC1 explains 53% of the variation and has strong negative loadings for ammonium, potassium, magnesium, and calcium. PC2 explains 22% of the variation, with strong negative loadings for sodium, chloride, and sulfate, while PC3 explains 9% with a strong positive loading for DOC and bromide.

	PC1	*PC2*	*PC3*
Cl^-	-0.21	**-0.54**	-0.02
Br^-	-0.24	-0.24	**0.56**
NO_3^-	0.21	**-0.34**	0.19
SO_4^{2-}	0.30	**-0.41**	0.14
Na^+	-0.27	**-0.50**	-0.04
NH_4^+	**-0.39**	0.13	-0.04
K^+	**-0.41**	0.05	-0.10
Mg^{2+}	**-0.42**	-0.04	-0.14
Ca^{2+}	**-0.42**	0.03	-0.10
DOC	-0.16	0.31	**0.77**
Percent variability explained	***53%***	***22%***	***9%***

Table 2. Loadings for the first three components of the PCA, with the largest loadings in bold.

PCA results have similar spatial groupings to the boxplots. The eastern-side upstream piezometers, which have high specific conductance, ammonium, calcium, magnesium and potassium and low sulfate and nitrate, all plot with low PC1 scores while the western-side upstream and all downstream piezometers plot with higher PC1 scores (Figure 6). Individual samples have more variability in PC2 through time, with the downstream piezometers and USP12 showing ranges in PC2 from 3 to -4 across all samples. However, mean PC2 values for all sites except USP6 are similar to each other, clustering between -1 and 1. PC3 also has individual samples with high variability across time, but mean values at each piezometer show little variability from other sites.

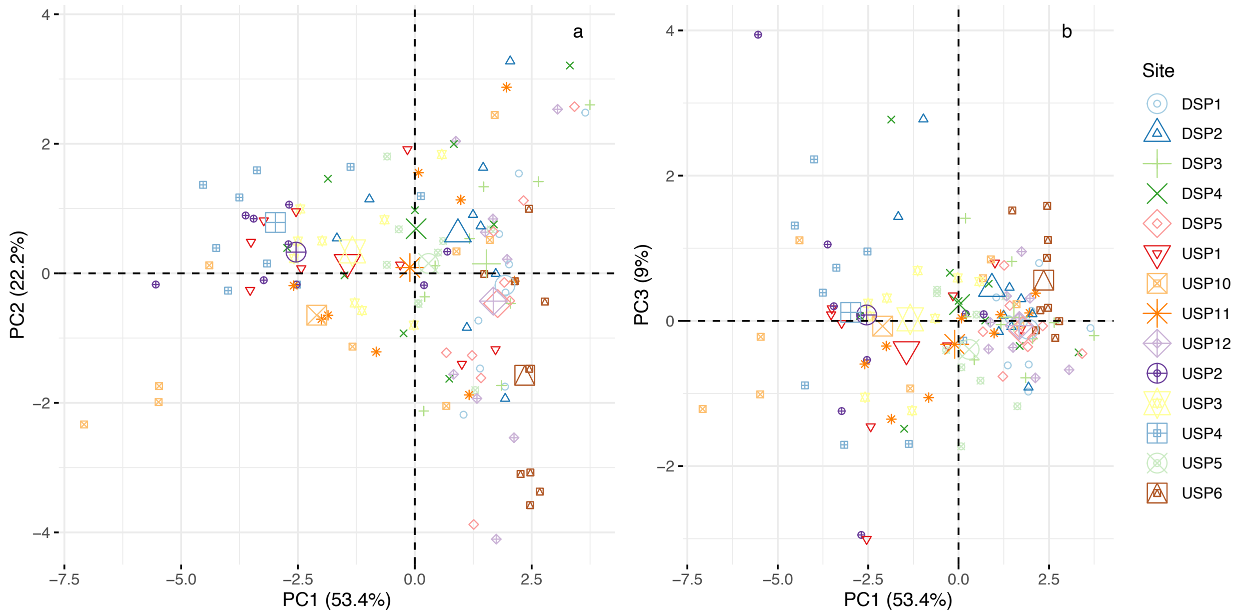

Figure 6. Individual samples (smaller symbols) and site means (larger symbols), in principal component space for (a) PC1 vs. PC2 and (b) PC1 vs. PC3.

We define PC1 as representing an overall urban groundwater signature, dominated by calcium, magnesium, potassium, and ammonium concentrations (Table 2), where low values of PC1 indicate a piezometer location where groundwater dominates (horizontal flow) or groundwater may be upwelling to the surface. Higher values of PC1 are interpreted as piezometer locations where surface water is downwelling, as all four of those ions have lower concentrations in surface water (Table S3). All four ions have lower concentrations in groundwater below the dam and higher PC1 scores (Figure 5 and 6), indicating higher surface water contributions to these sites.

3.2. Surface Water Geochemistry

At baseflow conditions, nine of the measured constituents (Table S3) have a difference in concentration along the pond, with the sites the furthest upstream in the pond (SW1) and below the beaver dam (SW6) showing the most differences from other sites. Ammonium increases in concentration below the dam (Figure 7, Table S4), as SW6 has higher concentrations than SW2-5, in agreement with H2. Nitrate, nitrite, and DO concentrations all increase longitudinally along the pond up to the dam before decreasing below the dam (Tables S5-7), also consistent with H2. Sulfate, magnesium, and sodium all have lower concentrations at SW1 than most other sites (Figure 7 and S3; Tables S8-10), which is contrary to H2. In contrast, potassium and DOC have higher concentrations at SW1 (potassium only) or SW 1 and 2 (DOC) that then plateau below that point (Tables S11-12). There is no statistically significant difference in concentration for specific conductance and bromide at baseflow.

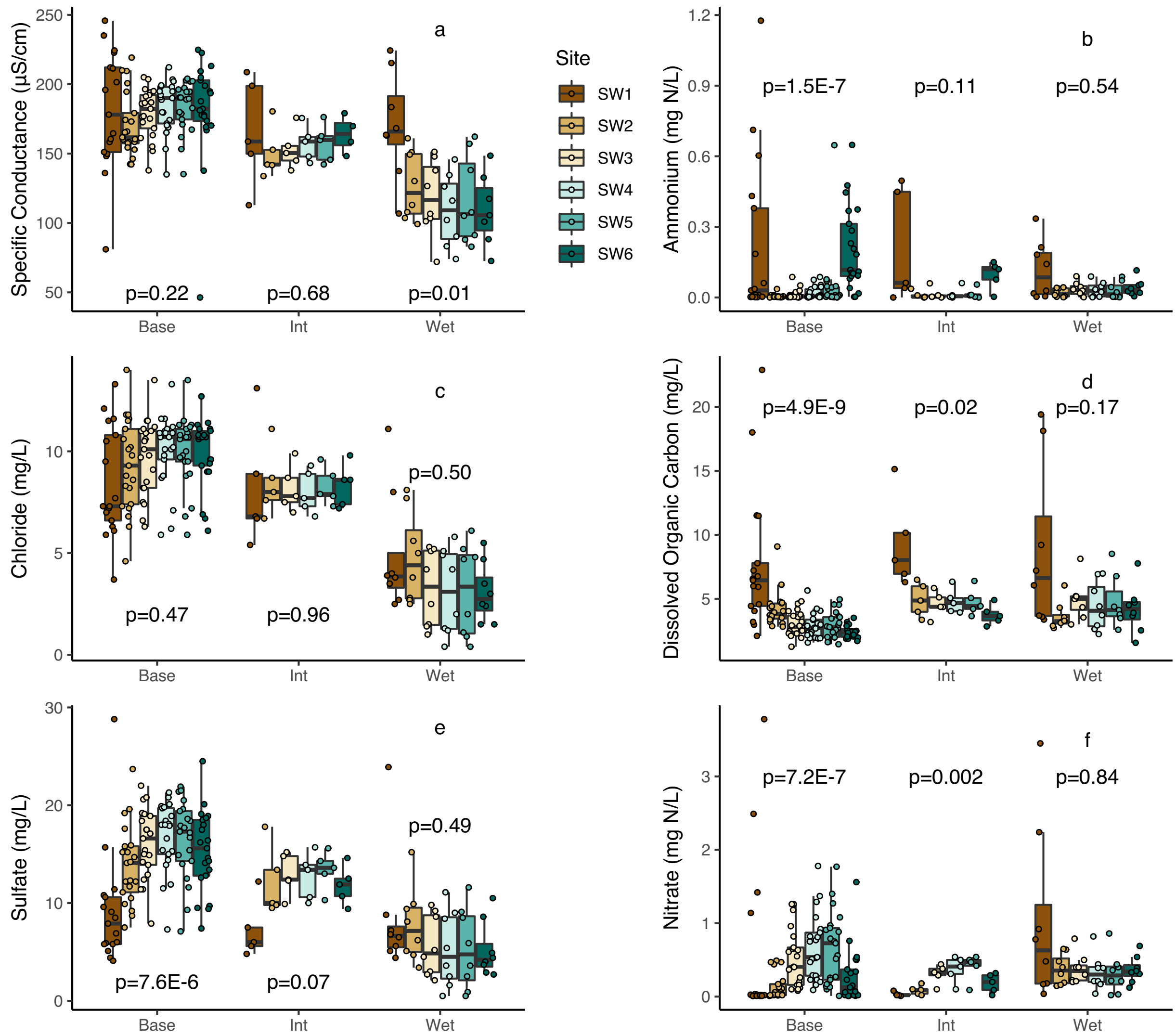

Figure 7. Boxplots of surface water geochemistry samples across sampling sites for (a) specific conductance, (b) ammonium, (c) chloride, (d) DOC, (e) sulfate, and (f) nitrate. Sites flow from the top of the pond to the dam (SW1-5) while SW6 is below the dam. Results are separated by antecedent moisture conditions where Base=baseflow and Int=intermediate. Large-scale approximation to the Kruskal Wallis test p-values are reported, comparing sites across that moisture condition. Figure S3 shows the remaining ions and pairwise Wilcoxen rank sum results are reported in Tables S4-12.

At intermediate and wet antecedent moisture conditions, the sites are more similar in concentration to each other than at baseflow (Figure 7 and S3). Nitrate, nitrite, and sulfate have similar patterns of lower concentrations at SW1 and 2 that then increase longitudinally along the pond. Nitrate and nitrite have the same pattern of decreasing below the dam during intermediate wetness as was seen during baseflow. DOC and potassium also have similar patterns, although with less, but still statistically significant, difference between sites. During wet conditions only specific conductance and magnesium change along the pond, although bromide and potassium are close to the statistical cut-off (p-values of 0.052 and 0.07 respectively). Nitrate has a distinct shift during wet conditions, as SW1 goes from having the smallest range in nitrate during baseflow to the largest, while other sites decrease in variability. During wet conditions, average conservative ion concentrations across all sites are lower than during dry conditions, and the shift towards homogeneous concentration across sites hints that overland runoff reaching this pond is not bringing large fluxes of ions. Shifts in the longitudinal pattern of conservative ion concentrations during wet conditions also indicate spatial variability in the volume of runoff reaching the pond, driven by tributaries and different drainage patterns reaching the stream, and/or variability in chemical composition of runoff. In contrast, more reactive ions either do not decrease in average concentration during wet conditions (potassium, nitrite, and ammonium) or show an increase in concentration at SW1 (nitrate and DOC).

3.3. Surface and groundwater isotopes

Analysis of $\delta^{15}N\text{-}NO_3$ and $\delta^{18}O\text{-}NO_3$ isotopes was limited by low concentrations to mostly surface water sites (Figure 8). Low nitrite concentrations in samples (Figure S3) mean these values reflect the isotopic signature of nitrate. $\delta^{18}O$ isotopes of nitrate range from 6.8 to

16.3‰ while $\delta^{15}N$ isotopes range from 5.1 to 14.2‰. These isotopes indicate that the most likely sources of nitrate in this system are soil or sewage waste (Kendall, 1998), as we had predicted with H3. Only one date (8/6/19) falls within the soil N category, and it was the only day during summer 2019 that was classified as wet (5.2 cm of rain within 24 hours of sample collection). SW and GW sites had similar ranges in $\delta^{18}O$, although GW samples had a slightly smaller range, but within a single sampling date, GW samples tended to have heavier $\delta^{15}N$ values, indicating a potential denitrification signal in the groundwater.

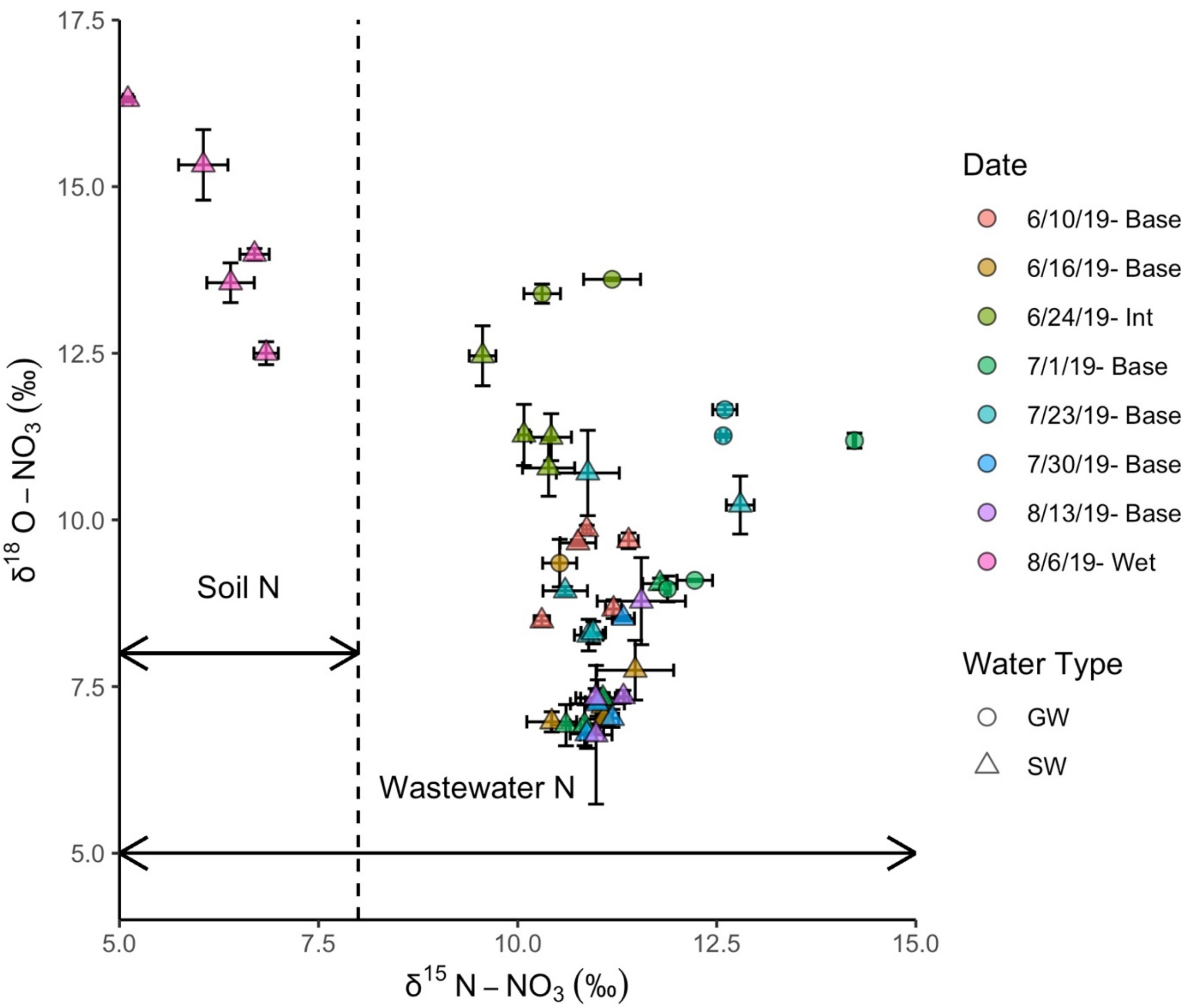

Figure 8. Isotopic ratios of $\delta^{15}N$ and $\delta^{18}O$ of nitrate in surface and groundwater samples. Colors indicate sampling date while shape indicates the source of the water (surface or groundwater). Ranges of $\delta^{15}N$ sources from Kendall (1998).

3.4. Logger data

Loggers in the pond above the beaver dam measured specific conductance and dissolved oxygen for three months during summer 2019 (Figure 9). Dissolved oxygen has large diel swings, routinely switching between complete or near anoxia to super-saturation (up to 200% saturation on one day) in a single day, supporting H4. Specific conductance in the pond was around 200 μS/cm at baseflow and showed smaller diel cycles of around 10 μS/cm. Large dilution events during storms decreased specific conductance to 50-100 μS/cm typically. Along with decreasing specific conductance, rain events frequently lower both diel minimum and maximum DO saturations.

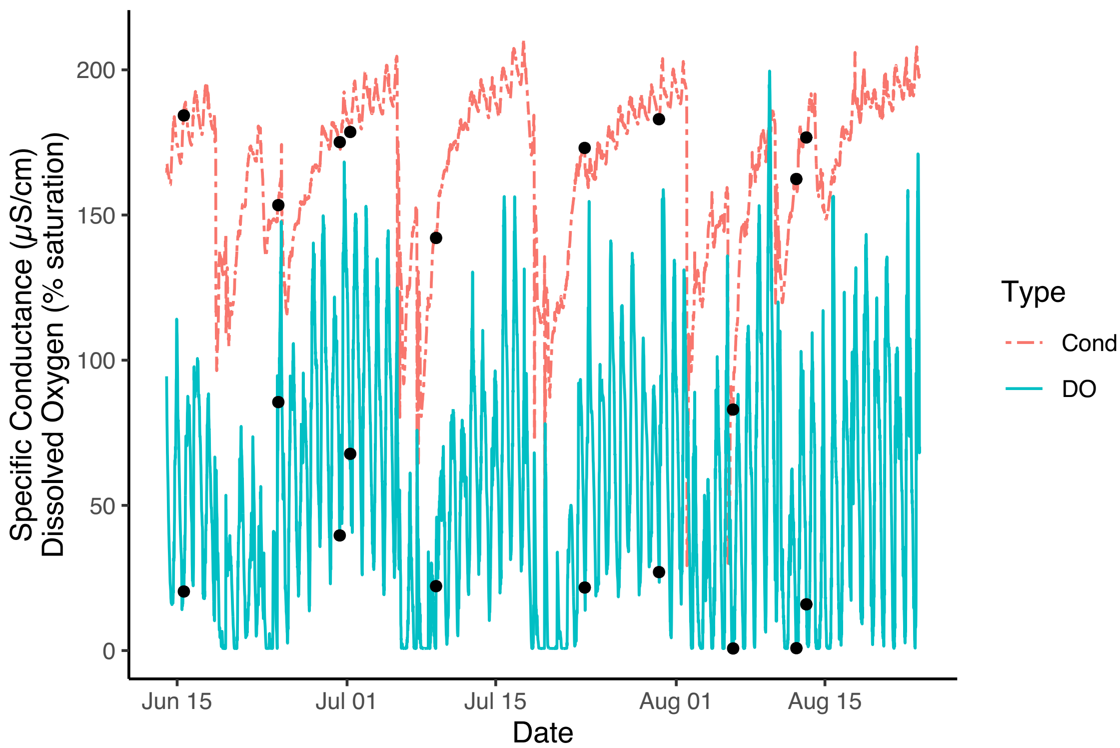

Figure 9. 10-minute measurements of dissolved oxygen (in percent saturation) and specific conductance from summer 2019 in the surface water above the dam. Points indicate times when grab samples were collected. Loggers were located outside USP2.

4. Discussion

4.1. Variability in groundwater ion patterns indicates spatial patterns in hyporheic up- and downwelling

The first objective was to evaluate spatial patterns in hyporheic geochemistry around an urban beaver dam. We hypothesized that there would be distinct geochemical signatures above and below the dam driven by biogeochemical reactions through the dam. Two spatial patterns of ion geochemistry emerged: (1) conservative ions indicate mixing of surface and groundwater and (2) temporary variation in other ions that do not reflect longer-term trends.

The PCA results reflected the spatial patterns in major ion trends across the beaver dam. Calcium, magnesium, and potassium concentrations in groundwater are typically attributed to geologic weathering (Peters, 2009) as calcium and potassium are sourced from the weathering of feldspars, and magnesium and potassium can be sourced from the weathering of biotite (Kaushal et al., 2020), both common in the Piedmont (Rose, 2007). High cation concentrations are also seen throughout urban environments, sourced from increased weathering of anthropogenic building materials (Bird et al., 2018; Kaushal et al., 2020). Natural and urban weathering products are predicted to be higher in groundwater (Kaushal et al. 2020), thus, piezometer locations with high ion concentrations and low PC1 scores are pond bottom locations with limited vertical hyporheic flux or areas of groundwater discharge to the channel (Figure 10). The addition of high ammonium concentrations to these more conservative ions could be sourced from long-term accumulation of organic matter on the bottom of the pond or a potential leaking sewage source (discussed in further detail below).

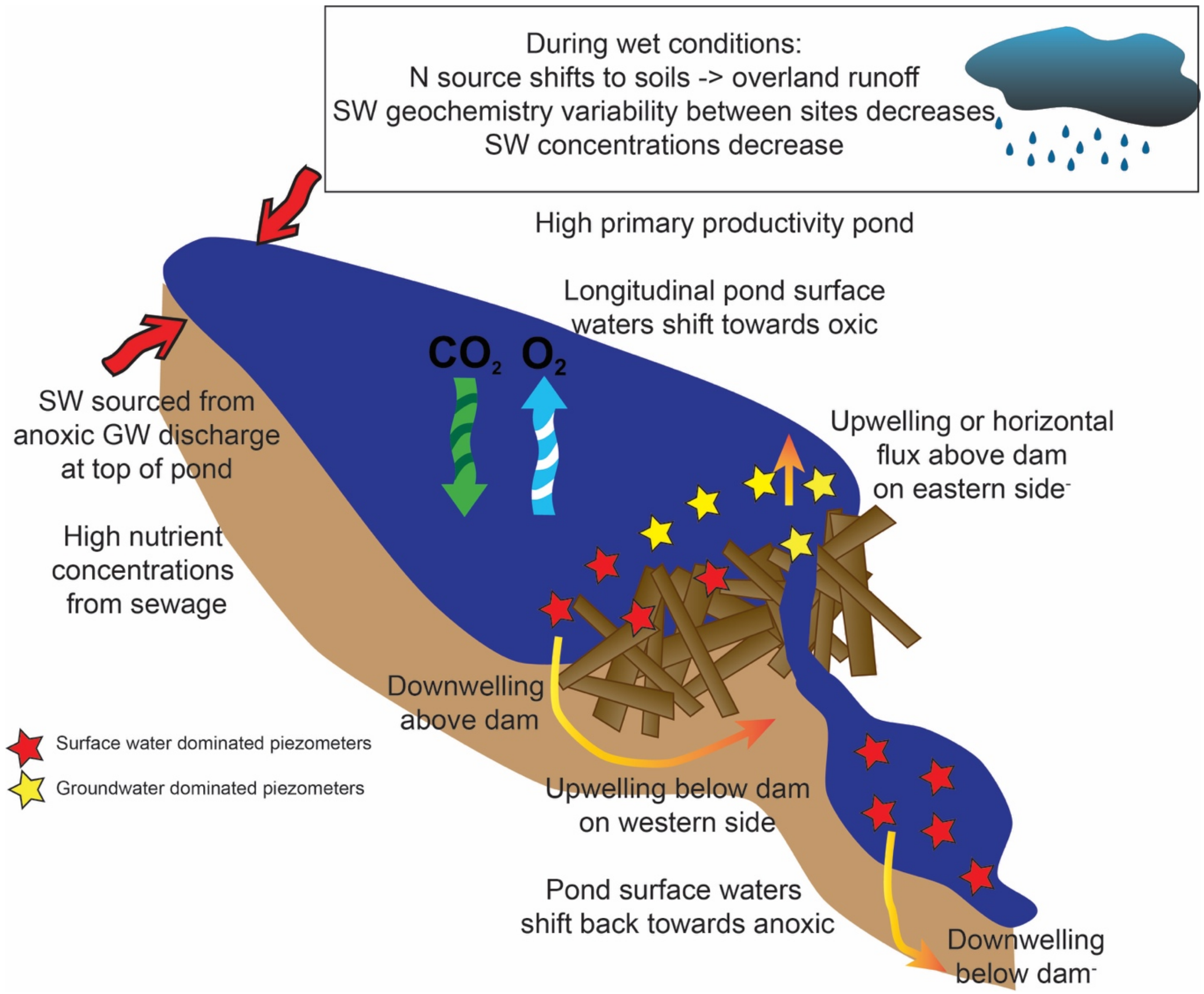

Figure 10. Conceptual model of dominant processes driving groundwater and surface water ion chemistry in an urban beaver pond.

The spatial patterns in chemistry point to hyporheic downwelling of surface waters on the western side of the dam, but potentially not on the eastern side, where piezometers remain dominated by groundwater (Figure 10). It is well established that beaver dams induce flow both around and through dams (Briggs et al., 2013; Wang et al., 2018; Westbrook et al., 2006). Our site had uniform morphological units above (pool) and below (pool/glide) the dam, and previous work has shown that distinct morphological units are similar in their hyporheic flux direction

(Briggs et al., 2013). However, we see that there is variability in downwelling along the length of the dam, with the western side dominated by surface waters. Downstream piezometers indicate localized downwelling of surface water below the dam, with high PC1 scores. Higher sulfate, nitrate, and DO concentrations in groundwater below the dam clearly indicate the shift in redox condition to more oxic (Figure 5). The impacts these patterns of hyporheic flow paths have on nitrogen speciation match those seen in peatland beaver environments, where ammonium tends to be the most concentrated nitrogen-based molecule in the groundwater whereas nitrate is more prevalent in surface waters. However, we found no difference in DOC concentrations above and below the dam unlike peatland beaver ponds (Wang et al., 2018). It is also clear that ponds located in highly-urbanized areas will be limited in the spatial extent over which they can flood or expand, which will limit their overall impacts on surface water-groundwater exchange (Wegener et al., 2017; Westbrook et al., 2006).

PC2 and 3 are driven by individual samples varying in scores, but mean PC values at most piezometers all cluster together. These components are driven by sodium, chloride, DOC, and bromide. Previous work in Atlanta linked sodium, chloride, and potassium in baseflow concentrations to leaking sewage as a single, over-arching non-point source of contamination (Rose, 2007), but this pattern is not seen in our site, as potassium does not follow the same pattern as sodium and chloride. Differences in mean concentrations between sites, as is seen in PC2 and 3, are instead driven by individual site outliers, and thus represent short-term temporal variability. Nitrate and nitrite are not included in the first three PCs as major drivers, indicating they play a minimal role in explaining the spatial patterns in groundwater geochemistry.

4.2. Variability in surface water geochemistry is driven by groundwater sources, surface water-groundwater interactions, and shifting oxic conditions

The second objective was to use spatiotemporal variability in surface geochemistry to assess sources and drivers of pond chemistry. We hypothesized reactive ions would follow patterns based on predicted productivity in the pond, while conservative ions would not have spatial patterns. This is because the increased residence time created by ponding urban runoff would distinctly shift processing and fluxes of biogeochemical molecules (Covino, 2017; Murray et al., 2021; Wegener et al., 2017), but conservative ions would be driven by spatially heterogeneous groundwater discharge. Qualitative analysis of deuterium injections in the pond and in an un-dammed upstream reach suggest at least 10 times greater residence times in the pond (Figure S4), illustrating a clear increase in hydrologic retention and water residence time as in other beaver ponds (Majerova et al., 2020, 2015).

Biogeochemically active constituents followed our hypothesized patterns (Figure 10). Nitrate, nitrite, and DO concentrations increase from the top of the pond to the middle (Figure 7 and S3) while ammonium and DOC concentrations decrease, all driven by a shifting dynamic from anoxic headwaters towards oxic waters near the dam. These patterns reverse below the dam as oxygen decreases, in part due to upwelling anoxic groundwater, with lower nitrate and nitrite and higher ammonium in surface water below the dam, but no change in DOC concentration. There is wide variability in observed nutrient changes below beaver ponds, with studies that determine they are sinks for nutrients such as nitrate, ammonium, and DOC (Klotz, 2010; Law et al., 2016) or have variable responses based on season (Devito et al., 1989), flow condition (Wegener et al., 2017), or pond age (Murray et al., 2021). Shifts from organic to inorganic nitrogen and shifts in oxidation state, as we see here, are clearly common below beaver dams

(Devito et al., 1989; Larsen et al., 2021). Unlike many other sites (Cirmo and Driscoll, 1993; Puttock et al., 2017), we do not see an increased export of DOC below our pond. While biogeochemical solutes behaved as we expected, conservative ions did not match our hypothesis, as they did follow a longitudinal spatial pattern. Sodium, sulfate, and magnesium all increase in concentration in the pond below SW1, while potassium decreased (Figure 7 and S3). The spatial patterns in both conservative and biogeochemically active solutes identify two key drivers of surface water geochemistry: the potential for distinct groundwater inputs that increase conservative ion concentrations along a portion of the pond, as has been seen in boreal systems (Naiman et al., 1994), and the importance of redox changes along and below the pond (Figure 10).

Recent rainfall dilutes surface water concentrations of all ions, with more recent rainfall (wet) resulting in lower concentrations than rainfall the day before (intermediate; Figure 10). Nitrate is one outlier in this pattern at SW1, with concentrations increasing during wet conditions, while the rest of the pond is diluted (Figure 7). This could be due to a potential point-source contribution of nutrients to this site, although there are no visible pipes discharging at this location, or flushing/oxidation of anoxic waters causing ammonium, which is high at baseflow, to nitrify. DOC and potassium are less impacted by dilution than the other ions, so precipitation events appear to be mobilizing both ions, as was seen in Puttock et al. (2017). For DOC, this could be driven by re-suspension of organic matter from the bottom of the pond, as qualitative observations point to high turbidity during rain events (Figure S1). When it has been raining, the pond chemistry between sites homogenizes as residence time decreases.

4.3. High productivity leads to nitrogen transformation in ponds, with lower concentrations below the dam

The third objective of this work was to use variations in nutrient chemistry in surface and groundwaters, along with other tracers, to identify sources and cycling of nutrients. We hypothesized that diffuse, groundwater-driven sources and long residence times in the pond would lead to high productivity in surface waters. The most likely sources of nitrogen to the pond include sewage leaks, direct fixation of N_2 gas, overland runoff collecting fertilizer and dry deposition, and soil organic matter. The isotopic results (Figure 8) suggest that wastewater is the most likely source of nitrate to this system, supporting our hypothesis of a groundwater-based source. Sewage is a common source of nutrients to urban streams, both through point-source routes such as sanitary sewer overflows (Davis et al., 2022) and through non-point source leaks (Divers et al., 2014). The high potassium concentrations in groundwater also point to wastewater (Peters, 2009), but high ammonium concentrations in groundwater could also be sourced from decomposition of organic matter (Arango and Tank, 2008). High ammonium, DOC, and potassium and low DO at SW1, the most upstream site, indicate that waste, soil organic matter, or immediately high productivity are important in driving chemistry along this pond (Figure 10).

The pond has very high primary productivity in summer, with diel DO swinging from near anoxic conditions to 150% saturation and above (Figure 9 and 10). DOC concentrations, however, are somewhat low for urban systems (3-7 mg/L, Figure 7; McDonough et al., 2020). Groundwater discharge to the pond during baseflow and overland flow during storms may be diluted in DOC in this system compared to other urban systems, although with comparable nitrogen (Fork et al., 2018; Kalev and Toor, 2020). DOC at the groundwater dominated SW1 site is highest and similar in concentration to hyporheic samples, but concentrations quickly drop to below 5 mg/L in the rest of the pond. This is despite the high canopy cover in the watershed (estimated at 40% in the neighborhood planning unit that the watershed falls within and up to 80% near the stream, Trees Atlanta, 2015) and may be driven by the fact that the upstream section of this stream is piped next to the pond with no active inflow to the pond. Increased decomposition, supported by the decrease in DOC in pond water, and/or nitrification along the pond gradient result in nitrate and nitrite concentrations increasing in the surface water, with maximum concentrations just above the beaver dam (Figure 10).

$\delta^{15}N$ of nitrate increases along the pond, although $\delta^{18}O$ decreases, and groundwater below the pond has higher values of both $\delta^{15}N$ and $\delta^{18}O$ (Figure 8 and S5), likely indicating that some of the nitrate decrease along and below the pond is driven by denitrification (Kendall, 1998). There is no change in DOC concentrations in surface or groundwater immediately above or below the dam, although groundwater has higher DOC than surface waters and the biomass of the dam could provide an additional source of DOC (Puttock et al., 2017) to offset what could be consumed with denitrification. Nitrate and DO concentrations, which increase in surface water at the top of the pond, are lower in surface waters below the dam, while ammonium concentrations are higher below the dam and decoupled from surface water DOC patterns (Figure 7). These lines of evidence all point to high cycling of nutrients through, around, and over the dam, with a combination of nitrification of ammonium and denitrification driving changes in concentration.

4.4 Management Implications

It is clear from the widespread nature of urban beaver (Figure 1) that understanding their functioning in light of surrounding land uses is needed (Bailey et al., 2018). This study found that urban beaver ponds increase hydrologic retention, induce hyporheic exchange, and shift biogeochemical cycling as has been seen in non-urban ponds (e.g., Majerova et al., 2020; Wang et al., 2018; Wegener et al., 2017). The geomorphic impacts of beaver on stream incision and widening are greatly needed in urban environments (Pollock et al., 2014). However, there are unique characteristics to urban ponds that limit the local and downstream impacts of beaver due to the interaction between urban flow paths and pond morphology. Specifically, we identify two key differences that require further exploration and have management implications: (1) the limited spatial extent of beaver ponds in urban areas and inability to build multiple-dam complexes, and (2) impacts to the number of beaver and lifespan because of hazards of the urban environment and less permanence to their structures due to the flashy nature of urban streams.

Urban beaver ponds are more likely to be constricted in space, with expanding pond-wetland systems also the most likely to drive human-beaver conflict. In watersheds where significant urban land cover has existed for multiple decades, there is pervasive incision, widening, and straightening of stream channels (Chin, 2006). Dams constructed by beaver, and the upstream ponded areas they create, may not overtop the channel banks, and in many cases may not lead to dramatic expansion of the wetted channel area outside of its pre-existing eroded banks, unlike has been hypothesized for beaver-based restoration efforts (Pollock et al., 2014). This is in strong contrast to the multi-dam and flooded meadow complexes reported for non-urban watersheds (e.g., Wegener et al., 2017), which yield a complex and time-variable array of water flow pathways. Urban impacts on channel slope are more variable among watersheds (Chin, 2006), although the installation of culverts may act as artificial nick points, thus enhancing local channel slopes. Collectively, greater slope and capacity along with reduced channel sinuosity and floodplain connectivity are likely to reduce water residence in urban beaver ponds compared to their non-urban counterparts. Mountain beaver ponds remove more nutrients during higher flow (Wegener et al. 2017), and that is attributed to retention in the wider beaver meadow complex, including wetlands. Urban beaver ponds that are located in-channel will most likely not be able to establish such wetland complexes due to the flashy nature of the urban hydrograph and the extreme channel incision cutting off floodplain reconnection, even with a dam. This limits their ability to establish lateral connectivity during storms, and they will thus be residence-time limited with less biogeochemical processing (Wegener et al 2017; Covino 2017) than rural ponds. In more suburban areas, where beaver meadow complexes have more space to develop off-channel, these systems may act more like mountain ponds with higher residence times during high flow. However, even if urban beaver ponds cannot be managed to the size and scope of non-urban, our results still point to an increase in hydrologic residence time, an increase in SW-GW interactions that would not otherwise exist, and a potential increase in denitrification. A key research gap is understanding the habitat availability for beaver in urban environments, how it differs from forested catchments (Touihri et al., 2018), and what impact habitat limitations might have on their functioning compared to forested catchments.

A second key difference in beaver pond functioning is the longevity of pond existence. Our observations indicate these ponds are less permanent structures on the landscape than in areas with less human land use. For example, we estimate beaver typically stay in one urban location for about 5 to 10 years before they move on, compared to an average of 44 years in glaciated landscapes (Butler, 2012). In addition, the extremely high flows seen in urban streams during storms (e.g., Forgrave et al., 2022) cause dams to blow out routinely and ponds to drain. The shifts between anoxic and oxic conditions from this periodic draining drive increased decomposition of organic matter, distinctly shifting carbon and nutrient dynamics (Sheppy, 2022). This time-scale issue could be exacerbated by more frequent human-beaver interactions in urban areas. For example, one beaver pond in the City of Atlanta was noted and routinely drained by residents in order to conduct stream trash clean-ups and has since been removed to repair a bridge. In addition, in areas where people perceive beavers as a problem and support lethal beaver control measures, beaver dam longevity is shortened even more compared to less impacted systems (Siemer et al., 2013).

5. Conclusions

The potential impact of urban beaver ponds on water chemistry remains understudied, despite the growing importance of these ecosystem engineers to cities (Bailey et al., 2018) and their widespread nature (Figure 1). Groundwater geochemical patterns reflect surface and groundwater interactions, with downwelling above and below the dam, but with spatial heterogeneity in these interactions. Shifts in surface water presence in groundwater also reflect changing oxidation conditions, with high ammonium in anoxic surface and groundwaters and high nitrate and nitrite in oxic areas. The surface water pond is highly productive, and nutrient sources to surface and groundwater are likely a combination of mineralization of biomass and long-term wastewater leaks. Changes in nitrate isotopes and concentrations of DOC, ammonium, and nitrate point to potential increase in denitrification along the pond and through the dam. During storm events, retention time in the pond decreases, and the system becomes geochemically homogeneous as overland runoff flushes the pond. Low retention during storms may point to these ponded features not helping with stormwater retention in cities, as they do in agricultural and forested areas (Burchsted et al., 2010; Puttock et al., 2021, 2017). However, the ecosystem benefits of beaver in urban areas reach beyond flow dynamics, including shifting nutrient cycling, increasing connectivity, and helping restore incision (Pollock et al., 2014, 2007), pointing to an important role for beaver in urban systems in the future. It is clear that beaver can fill a key role in the management of hydrology and water quality in urban environments when human-beaver conflicts can be averted (Bailey et al., 2018; Westbrook and England, 2022) as we still grapple with the legacy of previous management strategies that did not attempt to allow for co-existence (Wohl, 2021).

Acknowledgments

S.H. Ledford, L. Pangle, and E. Sudduth were supported by the National Science Foundation under grant EAR-2135216. S. H. Ledford, L. Pangle, and S. Miller were additionally supported by a USGS 104b grant from the Georgia Water Resources Institute. S. Miller was supported by a Georgia State University Research Initiation Grant to S. H. Ledford and funding for isotopic analysis was supported by a Geological Society of America Research Grant to S. Miller. We thank Emily Elliott and her lab for isotopic analysis. DOC analysis was supported by a National Science Foundation MRI-1826920 to E. Sudduth. Many thanks to Christopher Wheeler and Scout Morgan for field assistance.

Data Availability

Ion and isotope geochemistry and logger data are available in HydroShare: Ledford, S. H. (2022). Tapestry Beaver Pond Geochemistry, HydroShare, http://www.hydroshare.org/resource/8bb8e869e2b9442989163fbaa1d616ea

Author Contributions:

SH Ledford: Conceptualization, Methodology, Formal Analysis, Investigation, Resources, Data Curation, Writing- Original Draft; Writing- Review & Editing, Visualization, Supervision, Project Administration, Funding Acquisition; **S Miller**: Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation, Writing- Review & Editing; **L Pangle**: Resources, Writing- Review & Editing, Funding Acquisition; **E Sudduth**: Resources, Writing- Review & Editing, Funding Acquisition

References

Arango, C.P., Tank, J.L., 2008. Land use influences the spatiotemporal controls on nitrification and denitrification in headwater streams. Journal of the North American Benthological Society 27, 90–107. https://doi.org/10.1899/07-024.1

Auster, R.E., Barr, S.W., Brazier, R.E., 2022. Beavers and flood alleviation: Human perspectives from downstream communities. Journal of Flood Risk Management e12789. https://doi.org/10.1111/jfr3.12789

Bailey, D.R., Dittbrenner, B.J., Yocom, K.P., 2018. Reintegrating the North American beaver (Castor canadensis) in the urban landscape. WIREs Water. https://doi.org/10.1002/wat2.1323

Bell, C.D., Wolfand, J.M., Panos, C.L., Bhaskar, A.S., Gilliom, R.L., Hogue, T.S., Hopkins, K.G., Jefferson, A.J., 2020. Stormwater control impacts on runoff volume and peak flow: A meta-analysis of watershed modelling studies. Hydrological Processes 34, 3134–3152. https://doi.org/10.1002/hyp.13784

Bernhardt, E.S., Palmer, M.A., Allan, J.D., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton, S., Dahm, C., Follstad-Shah, J., Galat, D., Gloss, S., Goodwin, P., Hart, D., Hassett, B., Jenkinson, R., Katz, S., Kondolf, G.M., Lake, P.S., Lave, R., Meyer, J.L., O'Donnell, T.K., Pagano, L., Powell, B., Sudduth, E., 2005. Synthesizing U.S. river restoration efforts. Science 308, 636–637.

Bird, D.L., Groffman, P.M., Salice, C.J., Moore, J., 2018. Steady-state land cover but non-steady-state major ion chemistry in urban streams. Environmental Science & Technology 52, 13015–13026. https://doi.org/10.1021/acs.est.8b03587

Booth, D.B., Roy, A.H., Smith, B., Capps, K.A., 2016. Global perspectives on the urban stream syndrome. Freshwater Science 35, 412–420. https://doi.org/10.1086/684940

Brazier, R.E., Puttock, A., Graham, H.A., Auster, R.E., Davies, K.H., Brown, C.M.L., 2020. Beaver: Nature's ecosystem engineers. WIREs Water e1494. https://doi.org/10.1002/wat2.1494

Briggs, M.A., Lautz, L.K., Hare, D.K., González-Pinzón, R., 2013. Relating hyporheic fluxes, residence times, and redox-sensitive biogeochemical processes upstream of beaver dams. Freshwater Science 32, 622–641. https://doi.org/10.1899/12-110.1

Burchsted, D., Daniels, M., Thorson, R., Vokoun, J., 2010. The River Discontinuum: Applying Beaver Modifications to Baseline Conditions for Restoration of Forested Headwaters. BioScience 60, 908–922. https://doi.org/10.1525/bio.2010.60.11.7

Butler, D.R., 2012. Characteristics of beaver ponds on deltas in a mountain environment. Earth Surface Processes and Landforms 37, 876–882. https://doi.org/10.1002/esp.3218

Chin, A., 2006. Urban transformation of river landscapes in a global context. Geomorphology, 37th Binghamton Geomorphology Symposium 79, 460–487. https://doi.org/10.1016/j.geomorph.2006.06.033

Cirmo, C.P., Driscoll, C.T., 1993. Beaver pond biogeochemistry: Acid neutralizing capacity generation in a headwater wetland. Wetlands 13, 277–292. https://doi.org/10.1007/BF03161294

Covino, T., 2017. Hydrologic connectivity as a framework for understanding biogeochemical flux through watersheds and along fluvial networks. Geomorphology, Connectivity in Geomorphology from Binghamton 2016 277, 133–144. https://doi.org/10.1016/j.geomorph.2016.09.030

Davis, L.J., Milligan, R., Stauber, C., Jelks, N.O., Casanova, L., Ledford, S.H., 2022. Environmental injustice and Escherichia coli in urban streams: Potential for community-led response. Wiley Interdisciplinary Reviews: Water e1583. https://doi.org/10.1002/wat2.1583

Devito, K.J., Dillon, P.J., Lazerte, B.D., 1989. Phosphorus and nitrogen retention in five Precambrian shield wetlands. Biogeochemistry 8, 185–204. https://doi.org/10.1007/BF00002888

Divers, M.T., Elliott, E.M., Bain, D.J., 2014. Quantification of nitrate sources to an urban stream using dual nitrate isotopes. Environmental Science & Technology 48, 10580–10587. https://doi.org/10.1021/es404880j

Fairfax, E., Whittle, A., 2020. Smokey the Beaver: beaver-dammed riparian corridors stay green during wildfire throughout the western United States. Ecological Applications 30, e02225. https://doi.org/10.1002/eap.2225

Forgrave, R., Elliott, E.M., Bain, D.J., 2022. Event scale hydrograph responses highlight impacts of widespread stream burial and urban infrastructure failures. Hydrological Processes 36, e14584. https://doi.org/10.1002/hyp.14584

Fork, M.L., Blaszczak, J.R., Delesantro, J.M., Heffernan, J.B., 2018. Engineered headwaters can act as sources of dissolved organic matter and nitrogen to urban stream networks. Limnology and Oceanography Letters 3, 215–224. https://doi.org/10.1002/lol2.10066

Fulton County GIS, 2023. Fulton County 2019 Aerial Imagery. https://gis.fultoncountyga.gov/apps/AerialDownloadMapViewer/

GBIF.org, 2023. GBIF Occurrence Data 01 January 2023. https://doi.org/10.15468/dl.a2xwxv

Gorczyca, E., Krzemień, K., Sobucki, M., Jarzyna, K., 2018. Can beaver impact promote river renaturalization? The example of the Raba River, southern Poland. Science of The Total Environment 615, 1048–1060. https://doi.org/10.1016/j.scitotenv.2017.09.245

Granger, J., Sigman, D.M., 2009. Removal of nitrite with sulfanic acid for nitrate N and O isotope analysis with the denitrifier method. Rapid Communications in Mass Spectrometry 23, 3753–3762. https://doi.org/10.1002/rcm.4307

Harned, D.A., Daniel, C.C., 1989. The transition zone between bedrock and regolith: conduit for contamination?, in: Groundwater in the Piedmont: Proceedings of a Conference on

Groundwater in the Piedmont of the Eastern United States. Editors C.C. Daniel, R.K. White, and P.A. Stone.

Herrmann, D.L., Schifman, L.A., Shuster, W.D., 2018. Widespread loss of intermediate soil horizons in urban landscapes. Proceedings of the National Academy of Sciences 115, 6751–6755. https://doi.org/10.1073/pnas.1800305115

Higgins, M.W., Crawford, T.J., Atkins, R.L., Crawford, R.F., 2003. Geologic Map of the Atlanta 30' x 60' quadrangle, Georgia.

Hopkins, K.G., Woznicki, S.A., Williams, B.M., Stillwell, C.C., Naibert, E., Metes, M.J., Jones, D.K., Hogan, D.M., Hall, N.C., Fanelli, R.M., Bhaskar, A.S., 2022. Lessons learned from 20 y of monitoring suburban development with distributed stormwater management in Clarksburg, Maryland, USA. Freshwater Science 000–000. https://doi.org/10.1086/719360

Johnson-Bice, S.M., Gable, T.D., Windels, S.K., Host, G.E., 2022. Relics of beavers past: time and population density drive scale-dependent patterns of ecosystem engineering. Ecography 2022. https://doi.org/10.1111/ecog.05814

Kalev, S., Toor, G.S., 2020. Concentrations and Loads of Dissolved and Particulate Organic Carbon in Urban Stormwater Runoff. Water 12, 1031. https://doi.org/10.3390/w12041031

Kaushal, S.S., Belt, K.T., 2012. The urban watershed continuum: evolving spatial and temporal dimensions. Urban Ecosystems 15, 409–435. https://doi.org/10.1007/s11252-012-0226-7

Kaushal, S.S., Wood, K.L., Galella, J.G., Gion, A.M., Haq, S., Goodling, P.J., Haviland, K.A., Reimer, J.E., Morel, C.J., Wessel, B., Nguyen, W., Hollingsworth, J.W., Mei, K., Leal, J., Widmer, J., Sharif, R., Mayer, P.M., Newcomer Johnson, T.A., Delaney Newcomb, K., Smith, E., Belt, K.T., 2020. Making 'chemical cocktails'- Evolution of urban geochemical processes across the periodic table of elements. Applied Geochemistry 119, 104632. https://doi.org/10.1016/j.apgeochem.2020.104632

Kendall, C., 1998. Tracing nitrogen sources and cycling in catchments, in: Isotope Tracers in Catchment Hydrology. Elsevier, Amsterdam, pp. 519–576.

Klotz, R.L., 2010. Reduction of High Nitrate Concentrations in a Central New York State Stream Impounded by Beaver. Northeastern Naturalist 17, 349–356.

Konrad, C.E., Fuhrmann, C.M., 2013. Climate of the Southeast USA: Past, Present, and Future, in: Ingram, K.T., Dow, K., Carter, L., Anderson, J. (Eds.), Climate of the Southeast United States: Variability, Change, Impacts, and Vulnerability, NCA Regional Input Reports. Island Press/Center for Resource Economics, Washington, DC, pp. 8–42. https://doi.org/10.5822/978-1-61091-509-0_2

Larsen, A., Larsen, J.R., Lane, S.N., 2021. Dam builders and their works: Beaver influences on the structure and function of river corridor hydrology, geomorphology, biogeochemistry and ecosystems. Earth-Science Reviews 218, 103623. https://doi.org/10.1016/j.earscirev.2021.103623

Lautz, L.K., Kranes, N.T., Siegel, D.I., 2010. Heat tracing of heterogeneous hyporheic exchange adjacent to in-stream geomorphic features. Hydrological Processes 24, 3074–3086. https://doi.org/10.1002/hyp.7723

Law, A., McLean, F., Willby, N.J., 2016. Habitat engineering by beaver benefits aquatic biodiversity and ecosystem processes in agricultural streams. Freshwater Biology 61, 486–499. https://doi.org/10.1111/fwb.12721

Leopold, L.B., 1968. Hydrology for Urban Land Planning- A Guidebook on the Hydrologic Effects of Urban Land Use (No. Geological Survey Circular 554). U.S. Geological Survey, Washington, D.C.

Majerova, M., Neilson, B.T., Roper, B.B., 2020. Beaver dam influences on streamflow hydraulic properties and thermal regimes. Science of The Total Environment 718, 134853. https://doi.org/10.1016/j.scitotenv.2019.134853

Majerova, M., Neilson, B.T., Schmadel, N.M., Wheaton, J.M., Snow, C.J., 2015. Impacts of beaver dams on hydrologic and temperature regimes in a mountain stream. Hydrology and Earth System Sciences 19, 3541–3556. https://doi.org/10.5194/hess-19-3541-2015

Markewich, H.W., Pavich, M.J., Buell, G.R., 1990. Contrasting soils and landscapes of the Piedmont and Coastal Plain, eastern United States. Geomorphology, Proceedings of the 21st Annual Binghamton Symposium in Geomorphology 3, 417–447. https://doi.org/10.1016/0169-555X(90)90015-I

McDonough, L.K., Santos, I.R., Andersen, M.S., O'Carroll, D.M., Rutlidge, H., Meredith, K., Oudone, P., Bridgeman, J., Gooddy, D.C., Sorensen, J.P.R., Lapworth, D.J., MacDonald, A.M., Ward, J., Baker, A., 2020. Changes in global groundwater organic carbon driven by climate change and urbanization. Nat Commun 11, 1279. https://doi.org/10.1038/s41467-020-14946-1

Murray, D., Neilson, B.T., Brahney, J., 2021. Source or sink? Quantifying beaver pond influence on non-point source pollutant transport in the Intermountain West. Journal of Environmental Management 285, 112127. https://doi.org/10.1016/j.jenvman.2021.112127

Naiman, R.J., Pinay, G., Johnston, C.A., Pastor, J., 1994. Beaver Influences on the Long-Term Biogeochemical Characteristics of Boreal Forest Drainage Networks. Ecology 75, 905–921. https://doi.org/10.2307/1939415

Peters, N.E., 2009. Effects of urbanization on stream water quality in the city of Atlanta, Georgia, USA. Hydrological Processes 23, 2860–2878. https://doi.org/10.1002/hyp.7373

Pollock, M.M., Beechie, T.J., Jordan, C.E., 2007. Geomorphic changes upstream of beaver dams in Bridge Creek, an incised stream channel in the interior Columbia River basin, eastern Oregon. Earth Surface Processes and Landforms 32, 1174–1185. https://doi.org/10.1002/esp.1553

Pollock, M.M., Beechie, T.J., Wheaton, J.M., Jordan, C.E., Bouwes, N., Weber, N., Volk, C., 2014. Using Beaver Dams to Restore Incised Stream Ecosystems. BioScience 64, 279–290. https://doi.org/10.1093/biosci/biu036

Prudencio, L., Null, S.E., 2018. Stormwater management and ecosystem services: a review. Environ. Res. Lett. 13, 033002. https://doi.org/10.1088/1748-9326/aaa81a

Puttock, A., Graham, H.A., Ashe, J., Luscombe, D.J., Brazier, R.E., 2021. Beaver dams attenuate flow: A multi-site study. Hydrological Processes 35, e14017. https://doi.org/10.1002/hyp.14017

Puttock, A., Graham, H.A., Cunliffe, A.M., Elliott, M., Brazier, R.E., 2017. Eurasian beaver activity increases water storage, attenuates flow and mitigates diffuse pollution from intensively-managed grasslands. Science of The Total Environment 576, 430–443. https://doi.org/10.1016/j.scitotenv.2016.10.122

R Core Team, 2022. R: A language and environment for statistical computing.

Rose, S., 2007. The effects of urbanization on the hydrochemistry of base flow within the Chattahoochee River Basin (Georgia, USA). Journal of Hydrology 341, 42–54. https://doi.org/10.1016/j.jhydrol.2007.04.019

Sheppy, J., 2022. Comparing the quantity, source, and biodegradability of dissolved organic matter in urban stormwater ponds to beaver ponds in the greater Atlanta area (Thesis). Georgia State University, Atlanta, GA.

Siemer, W., Jonker, S., Decker, D., Organ, J., 2013. Toward an Understanding of Beaver Management as Human and Beaver Densities Increase. Human–Wildlife Interactions 7. https://doi.org/10.26077/gvs7-b614

Sigman, D.M., Casciotti, K.L., Andreani, M., Barford, C., Galanter, M., Böhlke, J.K., 2001. A Bacterial Method for the Nitrogen Isotopic Analysis of Nitrate in Seawater and Freshwater. Anal. Chem. 73, 4145–4153. https://doi.org/10.1021/ac010088e

Smith, B.K., Smith, J.A., 2015. The Flashiest Watersheds in the Contiguous United States. Journal of Hydrometeorology 16, 2365–2381. https://doi.org/10.1175/JHM-D-14-0217.1

Steele, M.K., Heffernan, J.B., 2014. Morphological characteristics of urban water bodies: mechanisms of change and implications for ecosystem function. Ecological Applications 24, 1070–1084.

Steele, M.K., Heffernan, J.B., Bettez, N., Cavender-Bares, J., Groffman, P.M., Grove, J.M., Hall, S., Hobbie, S.E., Larson, K., Morse, J.L., Neill, C., Nelson, K.C., O'Neil-Dunne, J., Ogden, L., Pataki, D.E., Polsky, C., Roy Chowdhury, R., 2014. Convergent surface water distributions in U.S. cities. Ecosystems 17, 685–697.

Stets, E.G., Sprague, L.A., Oelsner, G.P., Johnson, H.M., Murphy, J.C., Ryberg, K., Vecchia, A.V., Zuellig, R.E., Falcone, J.A., Riskin, M.L., 2020. Landscape Drivers of Dynamic Change in Water Quality of U.S. Rivers. Environ. Sci. Technol. 54, 4336–4343. https://doi.org/10.1021/acs.est.9b05344

Stevenson, J.R., Dunham, J.B., Wondzell, S.M., Taylor, J., 2022. Dammed water quality—Longitudinal stream responses below beaver ponds in the Umpqua River Basin, Oregon. Ecohydrology 15, e2430. https://doi.org/10.1002/eco.2430

Touihri, M., Labbé, J., Imbeau, L., Darveau, M., 2018. North American Beaver (Castor canadensis Kuhl) key habitat characteristics: review of the relative effects of geomorphology, food availability and anthropogenic infrastructure. Écoscience 25, 9–23. https://doi.org/10.1080/11956860.2017.1395314

Trees Atlanta, 2015. Tree Canopy Atlanta. https://geospatial.gatech.edu/TreesAtlanta/

U.S. Environmental Protection Agency, 2005. National Management Measures to Control Nonpoint Source Pollution from Urban Areas (No. EPA-841-B-05-044). USEPA Office of Water.

Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., Morgan II, R.P., 2005. The urban stream syndrome: current knowledge and the search for a cure. Journal of the North American Benthological Society 24, 706–723. http://dx.doi.org/10.1899/04-028.1

Wang, X., Shaw, E.L., Westbrook, C.J., Bedard-Haughn, A., 2018. Beaver Dams Induce Hyporheic and Biogeochemical Changes in Riparian Areas in a Mountain Peatland. Wetlands 38, 1017–1032. https://doi.org/10.1007/s13157-018-1059-9

Wegener, P., Covino, T., Wohl, E., 2017. Beaver-mediated lateral hydrologic connectivity, fluvial carbon and nutrient flux, and aquatic ecosystem metabolism. Water Resources Research 53. https://doi.org/10.1002/2016WR019790

Westbrook, C.J., Cooper, D.J., Baker, B.W., 2006. Beaver dams and overbank floods influence groundwater–surface water interactions of a Rocky Mountain riparian area. Water Resources Research 42. https://doi.org/10.1029/2005WR004560

Westbrook, C.J., England, K., 2022. Relative Effectiveness of Four Different Guards In Preventing Beaver Cutting of Urban Trees. Environ Manage 70, 97–104. https://doi.org/10.1007/s00267-022-01658-z

Wohl, E., 2021. Legacy effects of loss of beavers in the continental United States. Environ. Res. Lett. 16, 025010. https://doi.org/10.1088/1748-9326/abd34e

Wohl, E., Lininger, K.B., Scott, D.N., 2018. River beads as a conceptual framework for building carbon storage and resilience to extreme climate events into river management. Biogeochemistry 141, 365–383. https://doi.org/10.1007/s10533-017-0397-7