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Does a State Park with a Recreational Reservoir Result in Water Quality Improvements within an Agriculturally Dominated Watershed in SW Ohio?

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1. Abstract

Water quality in the agricultural Midwest is notoriously degraded, primarily due to elevated sediment and nutrient levels. Forested natural areas may be able to improve freshwater environments by reducing pollutant inputs, while also filtering out pollutants from upstream areas. Processes including but not limited to sediment deposition, denitrification, and nutrient uptake may be particularly effective at improving water quality. In this study, we examined the effects of Hueston Woods State Park on water quality in SW Ohio. The park contains 4 mid-order streams and a hyper-eutrophic lake. Surface water, groundwater, and tile drain water samples were collected at 2-week intervals from December 2019 through December 2021 across twenty one sites. Parameters analyzed included total nitrogen, nitrate, total phosphorus, soluble reactive phosphorus, total suspended sediment, dissolved organic carbon, pH, and conductivity. Changes in water quality varied across measured parameters. Overall, at the park level, nitrate concentrations and conductivity significantly decreased, while total phosphorus and dissolved organic carbon significantly increased. Interestingly, changes at the park level were primarily driven by changes in the lake rather than the streams. Smaller streams also generally exhibited more frequent significant changes in water quality relative to larger streams within the study area. Tile drains outside of the park exhibited the highest dissolved nutrient concentrations in the study area and groundwater exhibited lower nutrient levels within the park, but not across all sites. The results of this study show that public lands that primarily consist of forest cover can be effectively utilized to improve some water quality parameters, however, natural areas may also result in unexpected water quality trends that can be undesirable in some areas (e.g. an increase in total phosphorus). Additional studies are needed to examine how natural areas with unique physical characteristics (e.g. stream and lake size, topographic position, geomorphology, among many others) impact water quality.

2. Introduction

Despite the implementation of a wide variety of agricultural best management practices (e.g. no-till agriculture, planting of winter cover corps, utilization of riparian buffers, targeted nutrient applications), aquatic environments throughout the agricultural Midwest continue to be largely plagued by excessive nutrient concentrations and eutrophication (Culbertson et al. 2016; Gildow et al. 2016; Miltner, 2010, 2018; Renwick et al. 2018). The lack of significant water quality improvements with current land management practices, highlights the need for new or additional land management practices. Although extensive research (e.g. Singh, 2021; Witing et al. 2022) has examined how field based best management practices impact water quality (e.g. riparian buffers adjacent to fields), less is known about how larger protected tracts of land, such as state parks, impact water quality in the agricultural Midwest. State parks which are protected from agricultural land use practices, such as fertilizer application and soil tillage, may produce significant water quality benefits, although their impact has yet to be tested in the region.

In southwest Ohio, extensive nutrient pollution has resulted in the eutrophication of local aquatic ecosystems (Vanni et al. 2011; Kelly et al. 2018; Slone et al. 2018) and largely contributed to toxic algal blooms (OEPA, 2014; USGS, 2015). In the Great Miami River watershed, which produces some of the highest nutrient yields in the Midwest, ~70% of the total nitrogen and total phosphorus loads originate from non-point source pollutants (MCD, 2016). As a result, during summer months, the Great Miami River regularly experiences high chlorophyll concentrations and large diurnal swings in dissolved oxygen (OEPA, 2012; MCD, 2017). Acton Lake, which is located about 10 km north of Oxford, Ohio also experiences intense hyper-eutrophic conditions in summer months due to excessive nutrient loading from the watershed (Williamson et al. 2021). Currently it is unknown if water quality significantly varies above and below the lake (a constructed reservoir) or if the reservoir is beneficial or harmful to downstream water quality.

Generally, aquatic scientists focus on lentic or lotic systems separately from each other. Rarely are water quality in streams and lakes examined together. However, throughout the Midwest, lentic environments are commonly located within larger lotic drainage networks (Dattamudi et al. 2020). The largest lentic water bodies within these drainage networks are artificial reservoirs (https://nid.usace.army.mil/#/). The development of reservoirs significantly alters local hydrology which can also have subsequent effects on other physical (e.g. evaporation; Tian et al. 2021), chemical (e.g. dentification; Sun et al. 2022), and biologic (e.g. species habitat suitability; Pelicice et al. 2015) characteristics within a watershed. Thus, it can be largely beneficial to examine lentic and lotic systems holistically, as reservoirs will be impacted by upstream stream characteristics, and streams below reservoir outlets will be impacted by the reservoir itself. In this study we examine the impact of a stream-reservoir system together.

Hydrologic conditions in the Midwest are largely driven by seasonality and storms (O'Connor and Costa, 2004; Nangia et al. 2010). Specifically, stream flow in the region is generally highest during spring and winter and lowest during fall and summer months. This pattern is due to relative demands for evapotranspiration relative to supplied precipitation. Storms which produce large amounts of precipitation can occur in any month and recently, large storms in particular, appear to be more frequent and of increasing magnitude (unpublished data from author from Hueston Woods State Park, Ohio). Highly predictable changes in discharge (seasonal) and less predictable hydrologic changes (shorter lived individual storms) may have significant impacts on water chemistry. For example, nutrient and sediment concentrations can either increase if rain events introduce nutrients from adjacent lands or can decrease if rain events result in dilution (Carpenter et al. 1998; Liu et al. 2022). Furthermore, rain events can alter rates of in stream process such as sediment deposition (Guerit et al. 2019), denitrification (Smith et al. 2006), and interactions between water and the stream bed, such as hyporheic exchange (Sawyer et al. 2009).

Previous studies have shown that vegetation dynamics including NDVI (the normalized difference vegetation index) can also significantly impact stream chemistry (Griffith et al. 2002). Vegetation, particularly if it has a high degree of connectivity with the stream channel, can not only alter stream morphology, but also directly impact water chemistry by consuming dissolved nutrients (Levi et al. 2015), trapping particulate nutrients and sediment by reducing runoff (Lyons et al. 2000), and altering rates of carbon sequestration (Aishan et al. 2018). However, vegetation can also be a source of these water quality parameters, particularly during the fall season when deciduous plants lose their leaves, which can subsequently decompose within the stream channel (e.g. Mulholland et al. 2000). These can then further increase levels of total suspended solids within the stream channel (Nagao et al. 2020).

Channel morphology can have significant impacts on hydrology and thus biogeochemical processes that occur within a stream channel. For example, pools and riffles have both been repeatedly shown to meaningfully impact denitrification and nutrient uptake, sediment deposition, and decomposition rates of carbon (Sable and Wohl, 2006; Naranjo et al. 2015; Tsuchiya et al. 2021). Stream processes can also vary based on stream position within a watershed. This has been emphasized in the widely cited River Continuum Concept (Vannote et al. 1980), however, others note that local stream characteristics can mask many of the generalizations within the River Continuum Concept (Burchsted et al. 2010). Local differences may be particularly important when examining processes within relatively small stream segments.

The primary goal of this study was to determine if water quality significantly changes as surface water and groundwater flow from farmland, through a relatively small state park (~4.5 mi^2), and then out of a recreational reservoir within the state park. Specifically, we quantify changes in nutrient [total nitrogen (TN), total phosphorus (TP), nitrate (NO3-), soluble reactive phosphorus (SRP)], suspended sediment (total suspended sediment; TSS), and dissolved organic carbon (DOC) concentrations, along with conductivity and pH. A secondary goal is to determine the impact of vegetation cover (NDVI), stream discharge, channel geomorphology, and a stream's landscape position on the observed changes of the water quality parameters. We hypothesized that: 1) nutrient and suspended sediment concentrations will significantly decrease, while DOC concentrations will increase, as water flows from farmland and through the state park, however, changes in water quality will vary between sub-parameters (e.g. TP and SRP), and 2) that the greatest water quality improvements will occur during low flow and high NDVI periods.

3. Study Area

Four Mile Creek is a tributary of Seven Mile Creek, which drains into the Great Miami River. Acton Lake is a small recreational reservoir that divides the Four Mile Creek watershed roughly in half. For this study we focus on the upper half of the watershed (i.e. drainages upstream of Acton Lake). Most of the watershed's area is contained within Preble County in Ohio, however, the watershed also contains small portions of Wayne and Union Counties in Indiana. The Four Mile Creek watershed upstream of Acton Lake is agriculturally dominated (>80% of land cover is agriculture). Agricultural land cover within the watershed primarily consists of soybeans and corn (>70%) and grasses/pastures are also common (~20%). Developed areas mostly consist of small farmsteads and other low intensity development. Over the last several decades (1990s to 2020s) the watershed has undergone a substantial shift from conventional to conservation tillage. Conservation tillage has recently plateaued and is currently at about 60%. Tile drains are extensively utilized in the watershed to moderate soil moisture, however, it is not well known how many tile drains are in the watershed, nor how many of the existing tile drains are functioning. Agricultural land cover and management practices in the Four Mile Creek watershed are common within many rural watersheds throughout the agricultural Midwest and SW Ohio, thus the watershed can be used as an analog for surrounding watersheds in the region.

The climate is SW Ohio is characterized as temperate. The highest temperatures generally occur in July and August, with the lowest average temperatures generally occurring in January. Precipitation in the region generally peaks in May and is lowest in February (Farthing et al. in revision). Over recent decades, flood magnitude in the study area appears to have increased (Grudzinski, unpublished data), likely impacted by climate change. Geology consists of Ordovician bedrock (limestone and shale) and Wisconsin glacial till. Detailed geologic and land use history for the Four Mile Creek watershed can be found in Rech et al. (2018).

Hueston Woods State Park contains four main tributaries that flow from North to South prior to their confluence with Acton Lake. From largest to smallest by discharge, these are Four Mile Creek, Little Four Mile Creek, Marshall's Branch, and Deer's Ear (Deer's Ear is an unofficial name). These four streams generate over 95% of the surface water discharge that flows into Acton Lake. Channel morphology generally consists of pool-riffle sequences with occasional bedrock exposure. Watershed area, stream width, depth, channel area, substrate particle size, relative water residence time, and other stream characteristics are summarized in Table 1 (from Farthing et al. in revision). Acton Lake is a human-made reservoir that's main purpose is recreation. Depth increases from north to south from about 1 m to 8 m near the outflow. Due to high nutrient levels, the reservoir is considered to be hyper-eutrophic. Extensive algal blooms in the reservoir occur annually with the greatest intensities occurring during dry summer months.

Table 1

Watershed Characteristics and Stream Morphology

Parameter	Four Mile Creek	Little Four Mile Creek	Marshall's Branch	Deer's Ear
Total Drainage Basin Area (km^2)	134.36	83.60	14.33	10.88
Total Pool Volume in Study Area (m^3)	1198.4	1033.5	908.27	347.12
Discharge (m^3/s)	0.51	0.277	0.047	0.051
Baseflow Residence Time (min)	39.54	64.09	323.41	113.19
Average Width (m)	18.36	17.48	12.25	9.09
Average Depth (m)	0.62	0.63	0.48	0.42
Average Channel Area (m^2)	11.43	11.06	6.08	4.20
Average Width: Depth	29.5	27.63	27.03	23.36
Median Creek Bed Particle Size				
D-16 (mm)	4.85	45	22.5	16
D-50 (mm)	22.5	128	60	60
D-84 (mm)	128	Bedrock	128	90

The total drainage basin area (km^2) was measured in ArcGIS Pro 2.7.2 following watershed delineation. The discharge (m^3/s) and pool volume (m^3) were measured in the field during baseflow conditions on 10/04/20. Residence time (RT) is a function of discharge (Q) and pool volume (V) and is calculated as RT=V/Q. The average channel width and depth were also measured in the field during base flow conditions on 12/07/2020. The average channel area (m^2) was calculated by multiplying each cross section width by average depth. The creek bed sediment was also surveyed on 10/04/20 utilizing a Wolman pebble count. (Source: Farthing et al. in revision)

4. Methods

Water quality was sampled every 2 weeks for 2 hydrologic years (December, 8 2019 through December 13, 2021) from 6 agricultural tile drains upstream of Hueston Woods State Park, 9 stream locations, and 6 shallow groundwater wells (3 agricultural wells adjacent to study streams and 3 wells within Hueston Woods State Park above the confluence of the study streams and Acton Lake). The study design is shown in Figure 1.

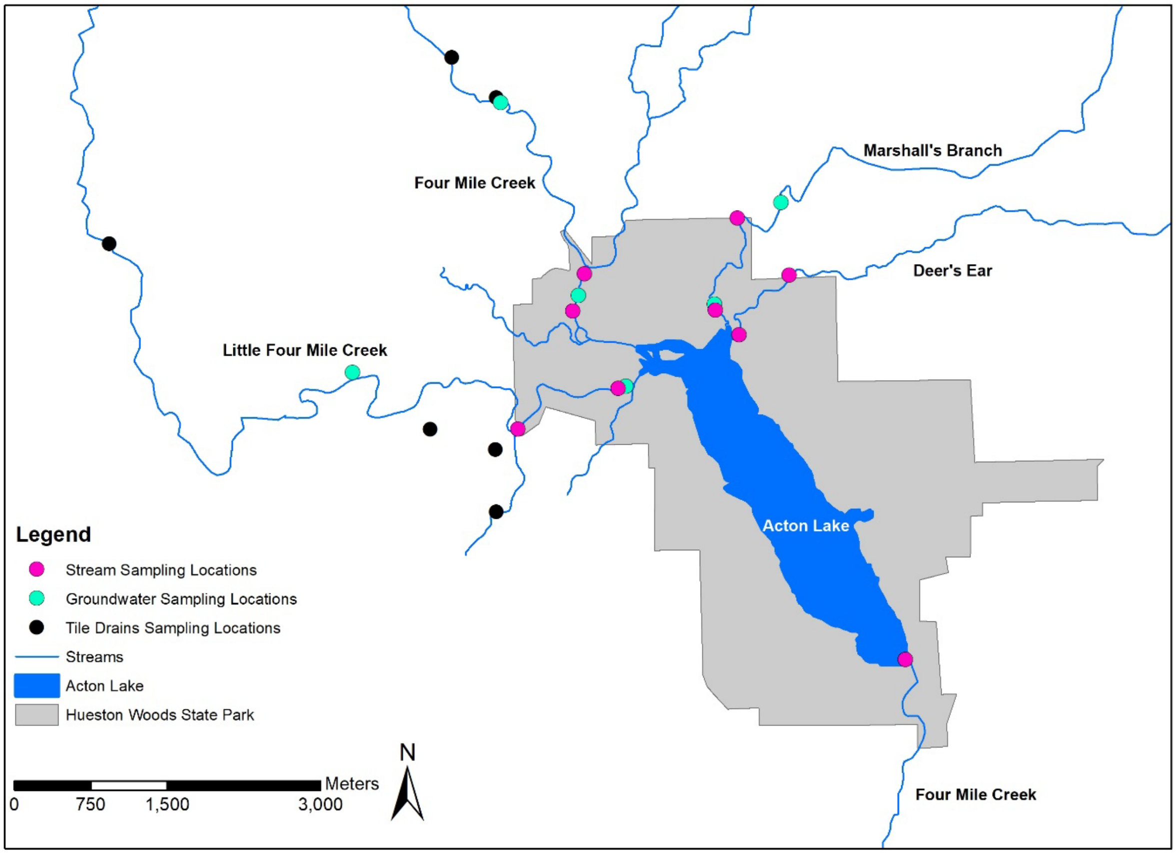

Figure 1. Study area and water sampling locations by type (figure produced by Agnieszka Marchlewska). Note: Although the downstream site on Four Mile Creek may appear to be located a significant distance above Acton Lake, directly below the site there is consistently stagnant backwater from the lake due to flat topography.

Nutrient-Sediment Sampling and Analysis: During each sampling day, two pre-washed bottles (125 ml and 4 L) were filled with water from; the thalweg of each stream sampling site, from each well site following a purge, and from outlets of selected tile drains (when flowing). Once obtained, water samples were transported on ice in a cooler and subsequently refrigerated at 4° C until processing (within 48 hours). TSS concentration (mg/L) for each sampling location was determined by filtering 2-3 L of water through pre-weighted type a/e glass fiber filters. Then sediment laden samples were filtered for 48 hours at 105°C, and weighed on a microbalance (Mettler Toledo model XP6). Dried weight was then divided by the volume of water filtered (Rice et al. 2017). During sediment filtration, a 125 mL subsample of filtered water was collected and preserved with sulfuric acid for NO_3-, NH_4+, and PO_4- analyses. A 40 ml vial was also filled with filtered water for DOC analyses. At this time, the unfiltered 125 mL samples were also be preserved with sulfuric acid for TN and TP analyses. Nutrient concentrations were measured with a Lachat Quickchem 8500 (series 2) auto-analyzer following method 10-107-04-1-A (for TN, NO_3-, and NH_4+) and 10-115-01-1-Q (for TP and PO_4-) within the Center of Aquatic and Watershed Sciences at Miami University (Wendt, 2000). DOC samples were analyzed on a Shimadzu TOC-V (CPH) total organic carbon analyzer. Details on DOC sample processing and concentration quantification can be found within Rose et al. (2009).

Conductivity and pH: Conductivity and pH were measured with a YSI handheld probe on an unfiltered water sample that was collected during each sampling day.

Stream Discharge and Stage: Discharge was measured during various flow conditions to create a stage-discharge rating curve for each stream. Stream discharge measurements were completed with a Flowtracker 2 velocity meter within each of the study streams. Since measuring discharge during high flow is not safe nor practical within these streams, moderate flows were quantified with an acoustic doppler current profiler, and the highest potential flows were modeled with USFS software WinXSPro following Hardy et al. (2005), as timing direct measurements of the highest flows is not practical within these flashy streams. To model high flows WinXSPro software requires channel morphology data, thus at each stream's gaging station, the channel cross section was manually surveyed with a surveyor's level and stadia rod following Harrelson et al. (1994). Cross section surveys were completed at ~30 cm (1 ft) increments with additional survey locations in areas of high topographic variability (e.g. Lazar et al. 2019). Stream stage was continuously recorded at 5-minute intervals with Onset HOBO U20 water level loggers at 3 of the 4 streams. Since Deer's Ear did not have direct discharge measurements, these values were scaled by watershed area relative to Marshall's Branch which has a similar watershed area and is directly adjacent to the watershed. Thus, hydrologic behavior between the watersheds is similar at both seasonal and individual storm time scales. Stage data was downloaded from the HOBO loggers approximately every 3 months and subsequently converted to discharge. Baseflow stream discharge was calculated during a period of typical baseflow in order to calculate relative residence time between streams. Although residence time will vary under different flow conditions, the relative residence time will follow similar trends between sites as channel morphology does not significantly change with single storm events.

NDVI: We determined the extent of vegetative growth or "greenness" with the Normalized Difference Vegetation Index (NDVI). NDVI values were obtained from Sentinel-2 satellite data and were then processed within Google Earth Engine (Gorelick et al. 2017). The data was calculated based on 10-day composites around stream sampling dates with 5 days consisting of pre-collection data and 5 days consisting of post collection data. The data was averaged based on a 100 m buffer adjacent to each creek.

Channel Morphology: Channel morphology data were surveyed during the study period (see Harrelson et al. 1994 for detailed surveying methods). Variables included channel width, depth, area, w:d, total pool volume, and substrate size (D_{16}, D_{50}, D_{84}). These variables were quantified for ~10 cross sections within each stream between upstream and downstream sampling points. Fewer cross sections were used for the calculations within Four Mile Creek as the segment between upstream and downstream sampling points is relatively homogeneous and consists of a single large pool and a small riffle.

Event Mean Concentration: In order to compare water quality parameters between the numerous upstream sampling sites and the single outflow point from Acton Lake we weighted upstream flows by discharge for each of the 4 study streams (e.g. USGS 2004;

https://pubs.usgs.gov/sir/2004/5200/pdf/sir20045200.pdf). The flow weighted averages are referred to EMCs (Event Mean Concentrations) in the results section below (e.g. Lazar et al. 2019).

Statistical Analyses:

Statistical analyses were completed in R Studio v.3.6.2. Statistical analyses utilized a combination of ANCOVA (analysis of covariance), regression coefficient t-tests, paired t-tests, Akaike Information Criterion, Bayesian Information Criterion, and confidence intervals. Bonferroni corrections were completed to account for the number of statistical tests completed in order to increase conservativeness of the statistical results. Channel morphology data were not included in the statistical models as they would limit the robustness of the analyses. Details on the statistical analyses can be found within Farthing et al (in revision) and Larson et al (in preparation).

The results section below focuses on comparing changes in water quality within the state park. Results include both findings from statistical analyses and descriptive evaluations (e.g. seasonal trends in nutrient concentrations) of changes in water quality between the park-farmland boundary, stream confluences with Acton Lake, and the outflow of Acton Lake. Statistical tests are utilized to identify significant changes in water quality between the longitudinal sampling locations (e.g. park border vs. lake confluence vs. outflow). While data are summarized below, all raw data are also included within Appendix 1. If EMC confidence intervals between longitudinal samples included 0, statistically significant differences did not exist between the sampling locations. If the lower and upper limits were both positive, the results indicate a downstream decrease in a water quality parameter, while if the lower and upper limits were both negative, then a significant increase in the downstream direction was detected. If confidence intervals included 0 for discharge and/or NDVI then a statistically significant relationship between these independent variables and changes in water quality parameters were not detected. If both confidence interval values were negative then a significantly negative relationship was detected. If both confidence interval values were positive then a significant positive relationship was detected.

5. Results

5.1 Total Nitrogen

Total N concentrations exhibited seasonal patterns across sites with the lowest concentrations occurring during summer and fall months and the highest concentrations occurring during spring and winter (Figure 2). Total N EMCs were not significantly different (CI: -0.15 to 1.40) between the lake outflow and the park entrance. Significant decreases in TN occurred within the streams (CI: 0.0071 to 0.17), but not within the lake (CI: -0.25 to 1.32). The lack of significant change in TN EMCs at the park level was mainly driven by the lack of change within the lake (change in park vs. change in lake R^2=.99) rather than the changes that occurred within the streams (change in park vs. change in streams R^2=.016). Within the streams, Marshall's Branch exhibited significant decreases in TN concentrations (CI: 0.76 to 0.90), while the remaining three streams did not (Figure 3). Within Marshall's Branch, changes in TN concentrations were positively correlated with stream discharge (CI: 0.32 to 2.48) (greater decreases occurred at lower flows) and negatively correlated with NDVI (CI: -2.37 to -1.21) (greater decreases occurred at higher NDVI values). Within the remaining streams no statistically significant relationships were detected between changes in TN concentration and stream discharge or NDVI (Table 2).

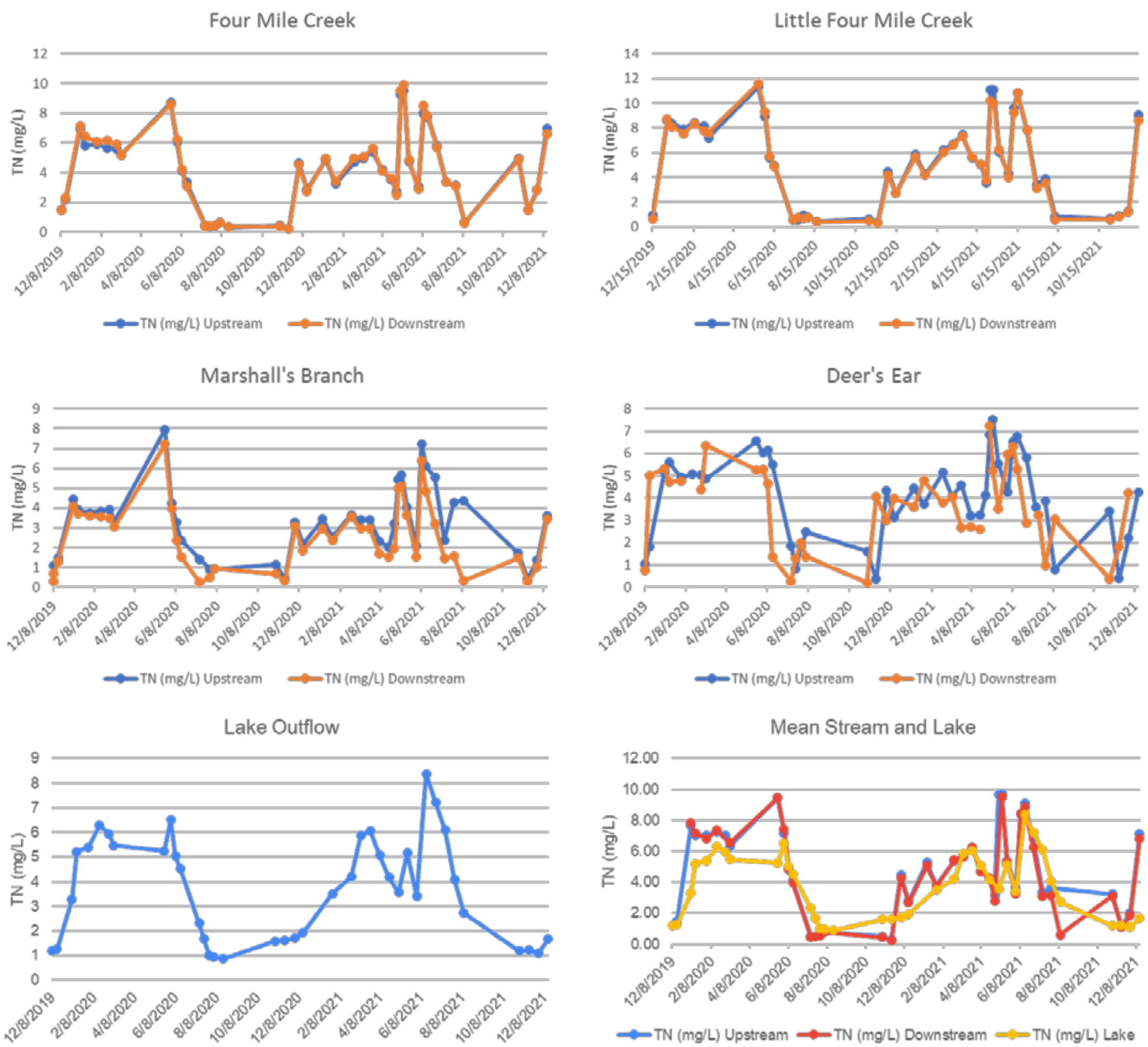

Figure 2. Stream and lake total nitrogen concentrations.

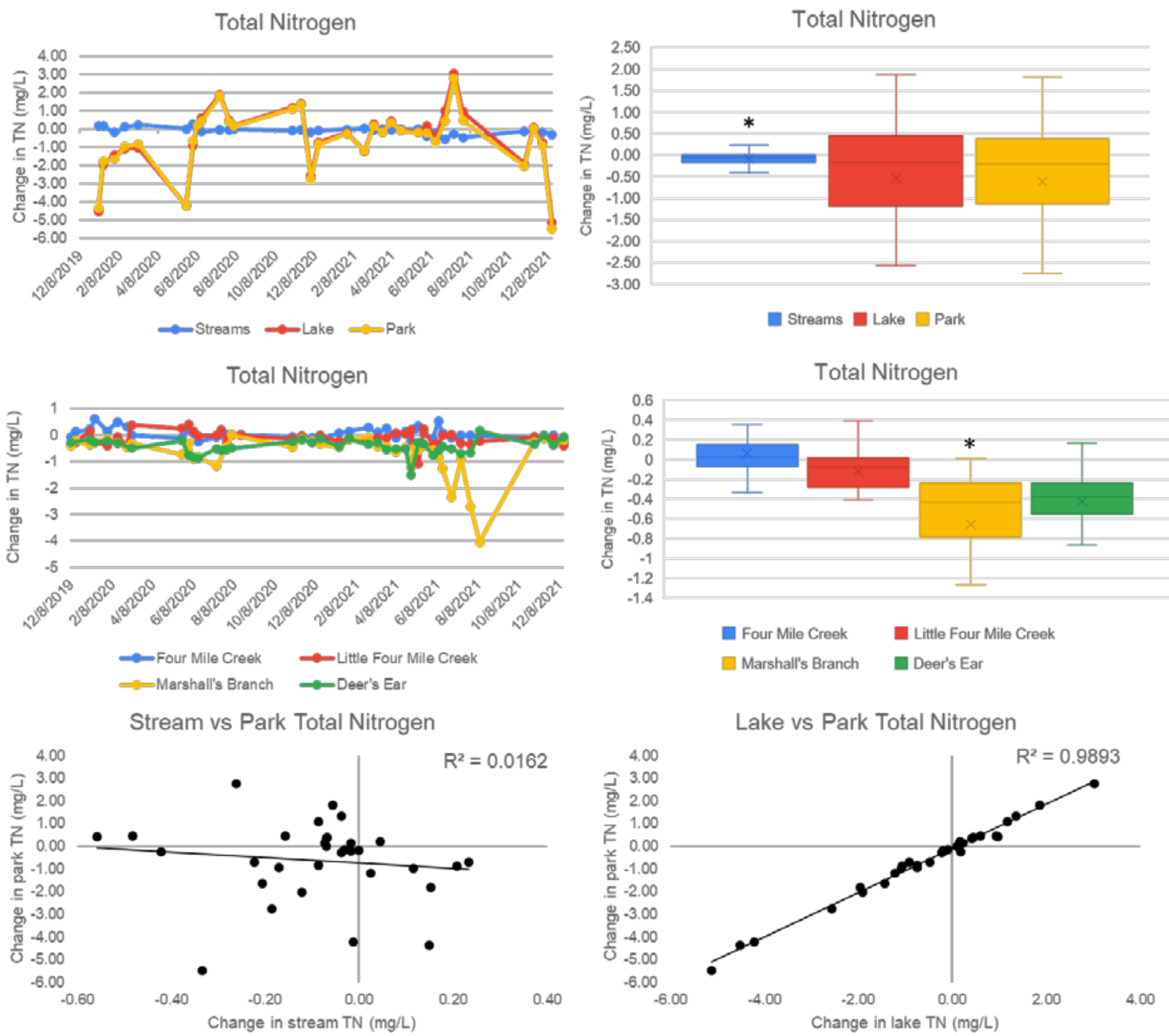

Figure 3. Changes in TN concentrations between sites (top and middle). Relationship between the change in TN concentrations at the park level compared to changes in TN concentrations within the streams (bottom left) and Acton Lake (bottom right). An * indicates statistically significant changes.

EMC changes	TN	TP	NO3-	SRP	TSS	DOC	pH	Conductivity
Park	--	↑	↓	--	--	↑	--	↓
Lake	--	↑	↓	--	--	↑	--	↓
Streams	↓	--	↓	--	--	--	--	--
Impact by Creek								
Four Mile Creek	--	--	--	--	↑	--	--	--
Little Four Mile Creek	--	↓	--	--	↓	--	--	--
Marshall's Branch	↓	↓	↓	↓	↓	↓	↓	--
Deer's Ear	--	--	↓	↓	--	↓	--	--
Relationship with Q								
Four Mile Creek	--	--	↑	--	--	--	--	--
Little Four Mile Creek	--	↑	--	--	↑	--	--	--
Marshall's Branch	↑	↑	↑	↑	↑	↑	--	--
Deer's Ear	--	--	--	↑	↓	↓	--	--
Relationship with NDVI								
Four Mile Creek	--	--	--	--	--	--	--	--
Little Four Mile Creek	--	--	--	--	--	--	--	--
Marshall's Branch	↓	↓	↓	↓	--	↓	--	--
Deer's Ear	--	--	--	--	--	--	↓	--

Table 2. Significant changes in water quality parameters (top 2 sections) and relationships between changes in water quality parameters with discharge and NDVI (bottom two sections).

5.2 Total Phosphorus

Total P concentrations did not exhibit strong seasonal patterns although several spikes were observed primarily during winter and spring periods (Figure 4). Total P EMCs were significantly higher at the lake outflow relative to the park entrance (CI: -0.074 to -0.011). Significant increases in TP concentrations occurred within the lake (CI: -0.075 to -0.017), but not within the streams (CI: -0.0021 to 0.0093). The significant increases in total P EMCs within the park were mainly driven by the changes observed within the lake (R^2=.97) rather than the streams (R^2=.25). Although stream TP EMCs did not significantly vary between upstream and downstream sampling sites, significant decreases in TP concentrations were detected within Little Four Mile Creek (CI: 0.69 to 0.87) and Marshall's Branch (CI: 0.41 to 0.60). Significant differences in TP concentrations were not detected between upstream and downstream sampling sites within Four Mile Creek or Deer's Ear (Figure 5). Within Little Four Mile Creek and Marshall's Branch changes in TP concentrations were positively correlated with stream discharge (CI: 0.0021 to 0.014 and 0.14 to 0.26 respectively). Within the remaining streams no significant relationships were detected between changes in TP concentration and stream discharge. NDVI was negatively correlated with changes in TP concentration within Marshall's Branch (CI: -0.080 to -0.027). There was no significant relationship between NDVI and change in TP concentration within the other three streams (Table 2).

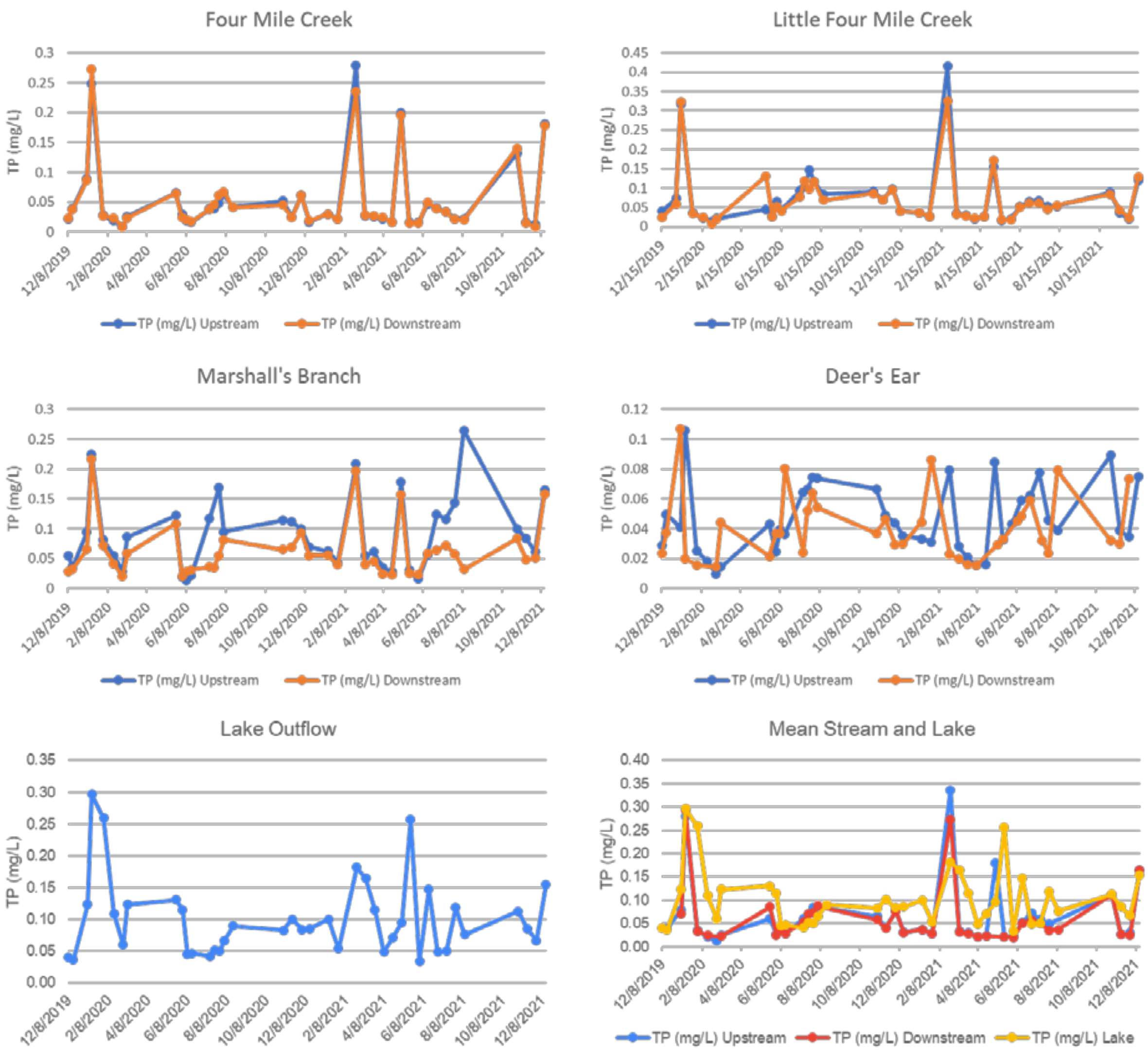

Figure 4. Stream and lake total phosphorus concentrations.

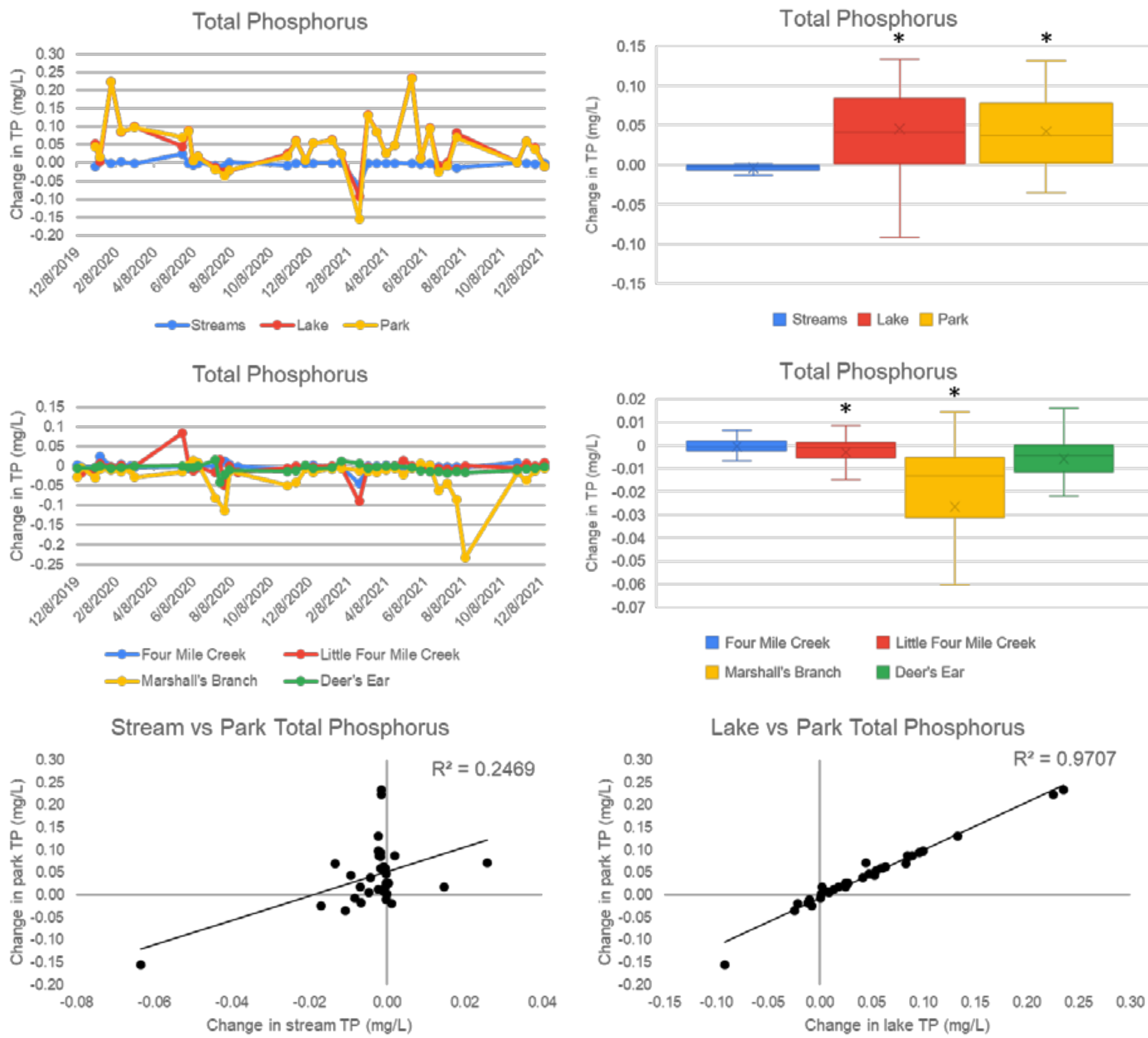

Figure 5. Changes in TP concentrations between sites (top and middle). Relationship between the change in TP concentrations at the park level compared to changes in TP concentrations within the streams (bottom left) and Acton Lake (bottom right). An * indicates statistically significant changes.

5.3 Nitrate

Nitrate concentrations exhibited seasonal patterns across sites with the lowest concentrations occurring during summer and fall and the highest concentrations occurring during spring and winter (Figure 6). Nitrate EMCs were significantly lower at the lake outflow relative to the park entrance (CI: 0.5607 to 2.212). Significant decreases in nitrate EMCs occurred within the streams (CI: 0.00023 to 0.12) and within the lake (CI: 0.49 to 2.16). The significant decreases within the park were largely driven by decreases within the lake (R^2>.99) rather than the streams (R^2=.018). Within the streams, Marshall's Branch and Deer's Ear exhibited significant decreases in nitrate concentrations (CI: 0.84 to 0.95 and 0.89 to .99) while Four Mile Creek and Little Four Mile Creek did not (Figure 7). Within Four Mile Creek and Marshall's Branch changes in nitrate concentrations were positively correlated with stream discharge (CI: 0.026 to 0.068 and 0.15 to 0.64 respectively). Within Little Four Mile Creek and Deer's Ear no significant relationship was detected between changes in nitrate concentration and stream discharge. NDVI was negatively correlated with changes in nitrate concentration within Marshall's Branch (CI: -1.78 to -0.97). There was no significant relationship between NDVI and change in nitrate concentration within the other three streams (Table 2).

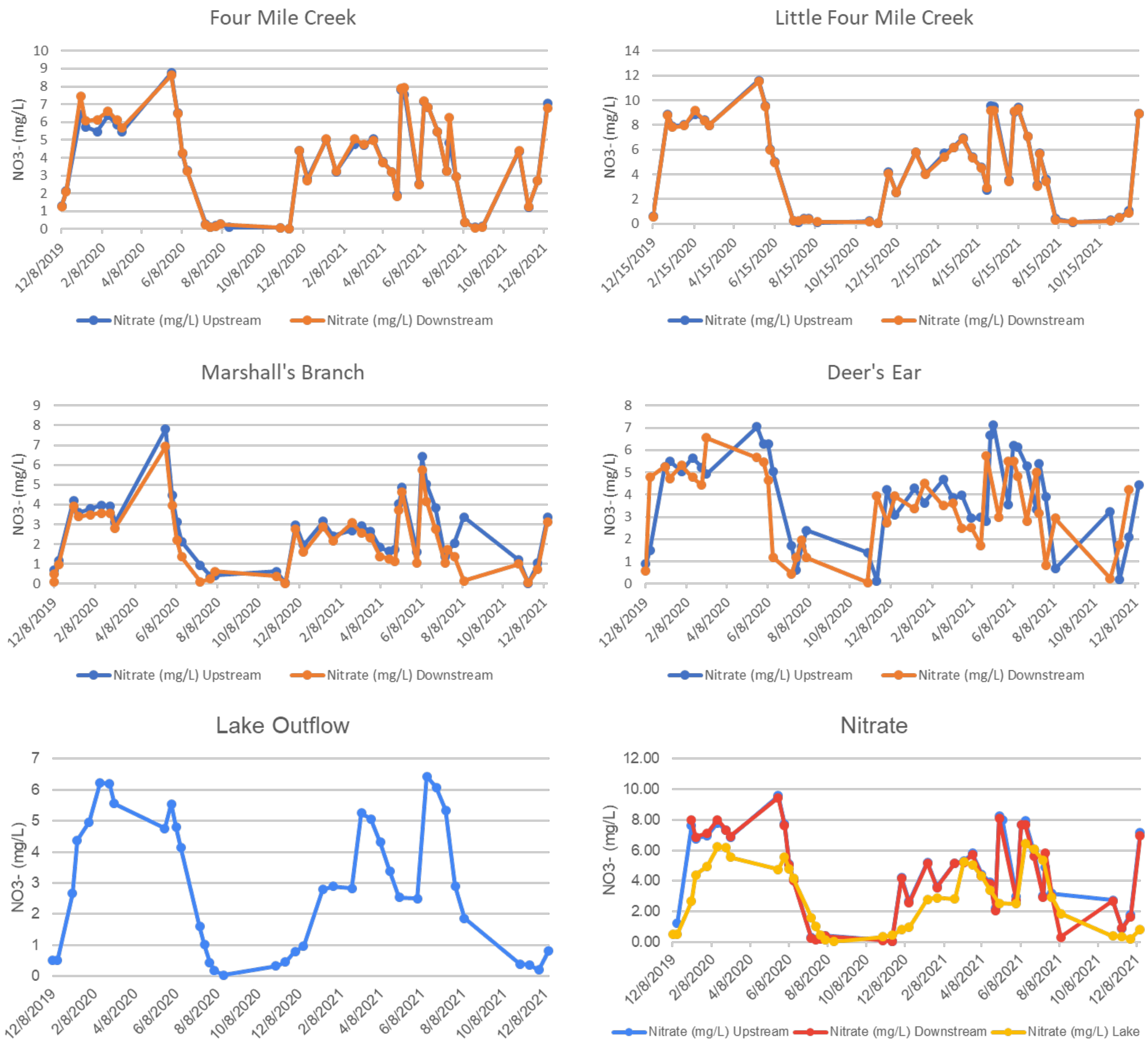

Figure 6. Stream and lake nitrate concentrations.

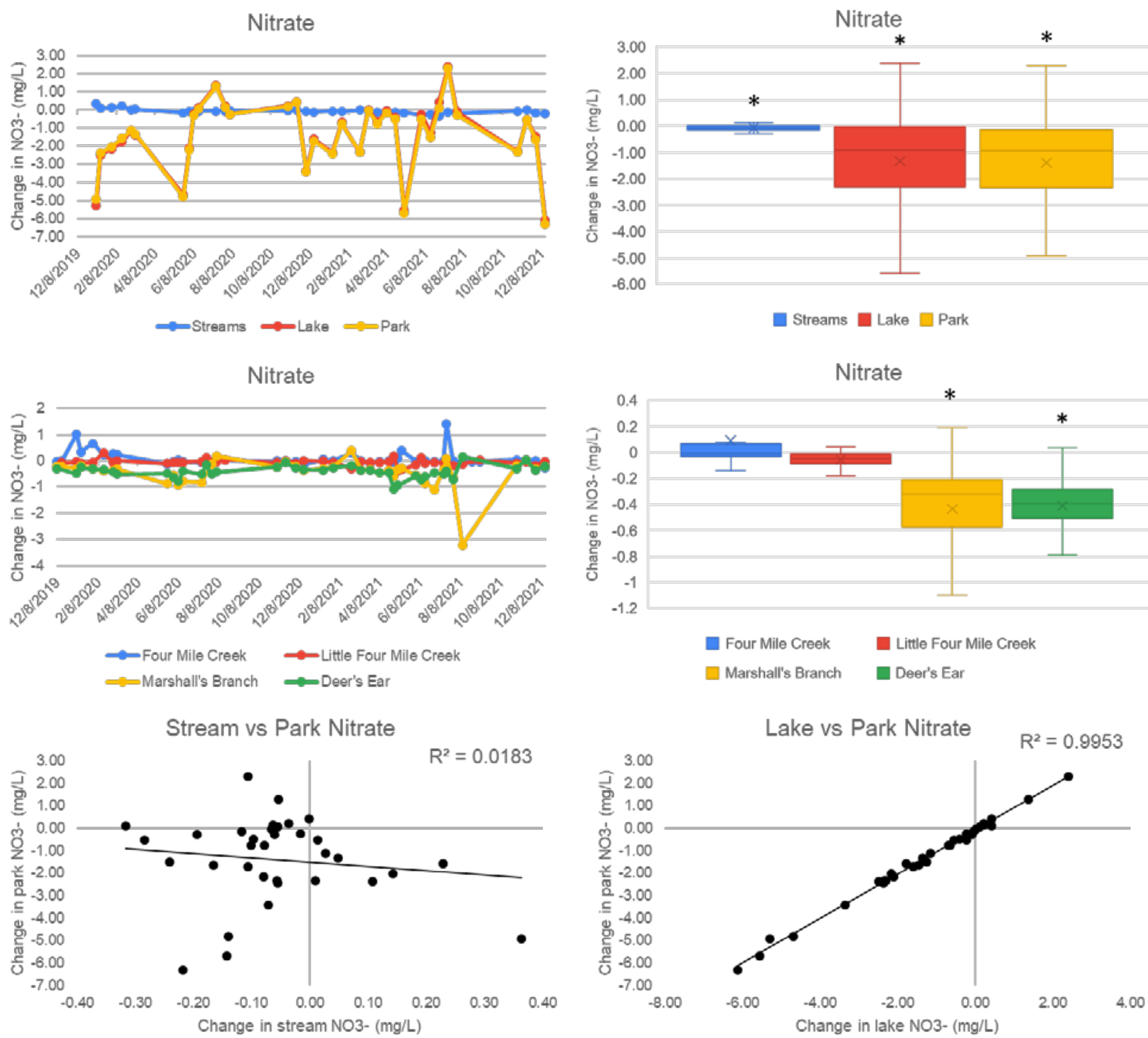

Figure 7. Changes in nitrate concentrations between sites (top and middle). Relationship between the change in nitrate concentrations at the park level compared to changes in nitrate concentrations within the streams (bottom left) and Acton Lake (bottom right). An * indicates statistically significant changes.

5.4 Soluble Reactive Phosphorus

Soluble reactive phosphorus concentrations varied throughout the year, but were generally highest during late winter months within the lake. Soluble reactive phosphorus concentrations did not exhibit strong seasonal trends within the streams. Additionally, several spikes in SRP occurred throughout the study streams, although these do not appear to be linked to a particular season (Figure 8). No significant differences in SRP EMCs were detected within the streams, lake, or park overall. The lack of significant change in SRP EMC concentrations at the park level was mainly driven by the lack of change within the lake (R^2=>.99) rather than the streams (R^2=<.01). Within the streams, Marshall's Branch and Deer's Ear exhibited significant decreases in SRP concentrations (CI: 0.32 to 0.53 and -0.096 to 0.091) between upstream and downstream sampling sites. No significant differences in SRP concentrations were detected within Four Mile

Creek or Little Four Mile Creek between upstream and downstream sampling sites (Figure 9). Within Marshall's Branch and Deer's Ear changes in SRP concentrations were positively correlated with stream discharge (CI: 38.79 to 69.59 and 80.55 to 125.06 respectively). Within the remaining streams no significant relationships were detected between changes in SRP concentration and stream discharge. NDVI was negatively correlated with changes in SRP concentration within Marshall's Branch (CI: -71.26 to -23.91). There was no significant relationship between NDVI and change in SRP concentration within the other three stream (Table 2).

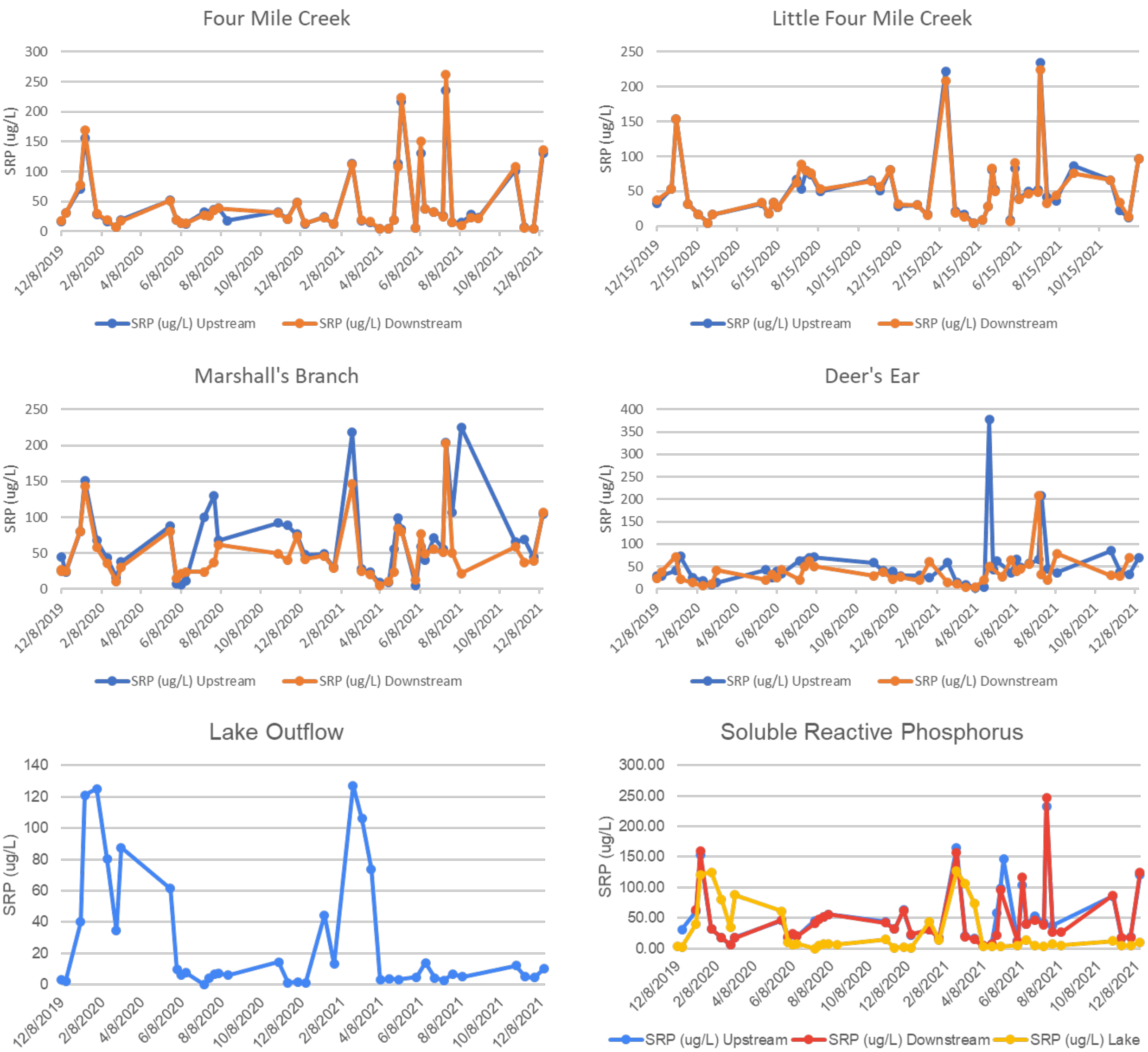

Figure 8. Stream and lake SRP concentrations.

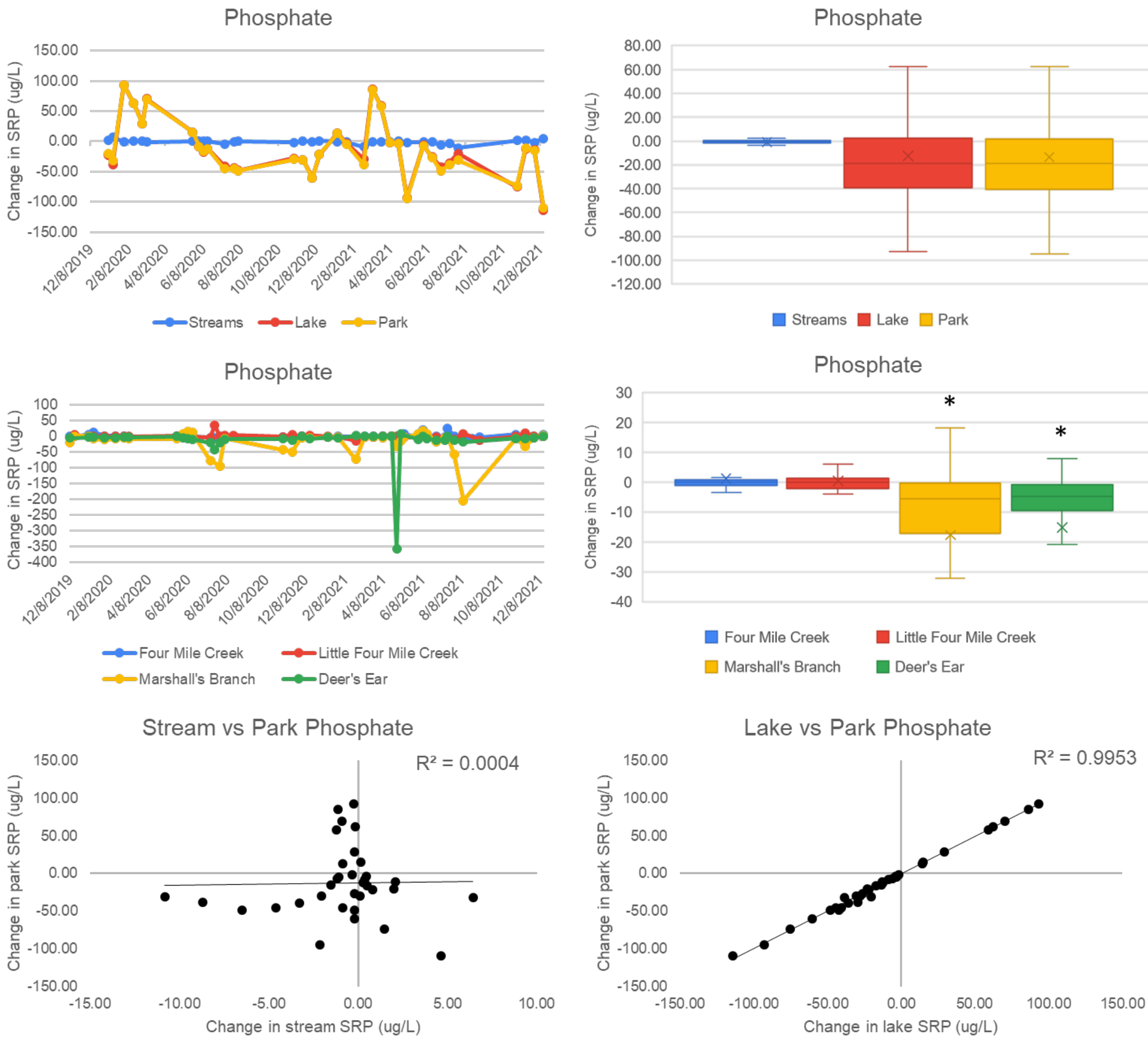

Figure 9. Changes in SRP concentrations between sites (top and middle). Relationship between the change in SRP concentrations at the park level compared to changes in SRP concentrations within the streams (bottom left) and Acton Lake (bottom right). An * indicates statistically significant changes.

5.5 Total Suspended Sediment

Total suspended sediment concentrations did not exhibit strong seasonal patterns, and several spikes occurred across seasons (Figure 10). No significant differences in TSS EMCs were detected within the streams, lake, or park overall. The lack of significant change in TSS EMC concentrations at the park level was mainly driven by the lack of change within the lake (R^2=.96) rather than the streams (R^2=.74). Within the streams, Little Four Mile Creek and Marshall's Branch exhibited significant decreases in TSS (CI: 0.23 to 0.41 and 0.066 to 0.40 respectively), while Four Mile Creek exhibited a significant increase (CI: 1.02 to 1.51) (Figure 11). Within

Little Four Mile Creek and Marshall's Branch changes in TSS concentrations were positively correlated with stream discharge (CI: 3.41 to 7.56 and 2.21 to 47.96 respectively), while in Deer's Ear changes in TSS concentrations were negatively correlated with stream discharge (CI: -97.57 to -3.73). NDVI was not a significant predictor of changes in TSS in any of the streams (Table 2).

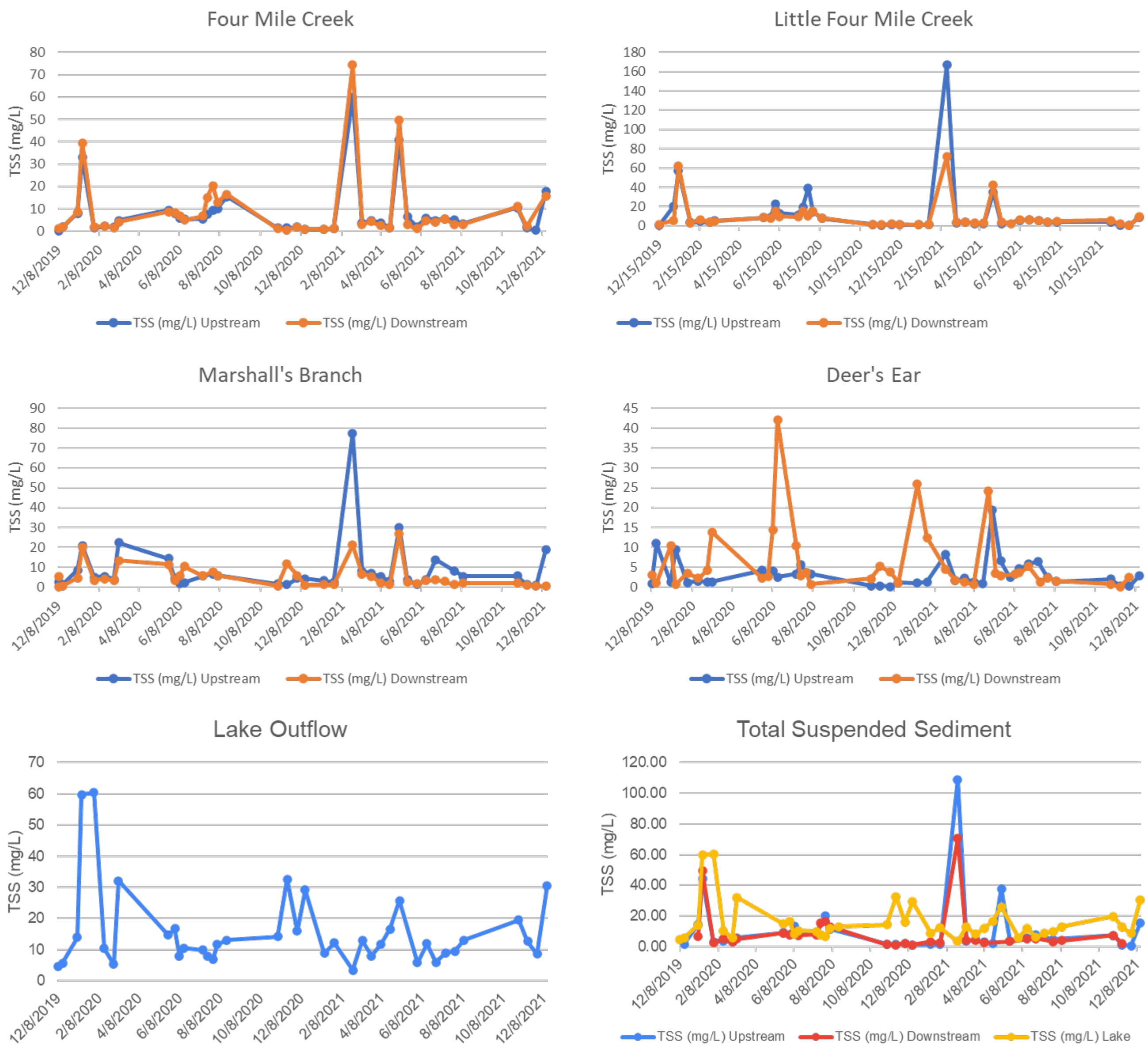

Figure 10. Stream and lake TSS concentrations.

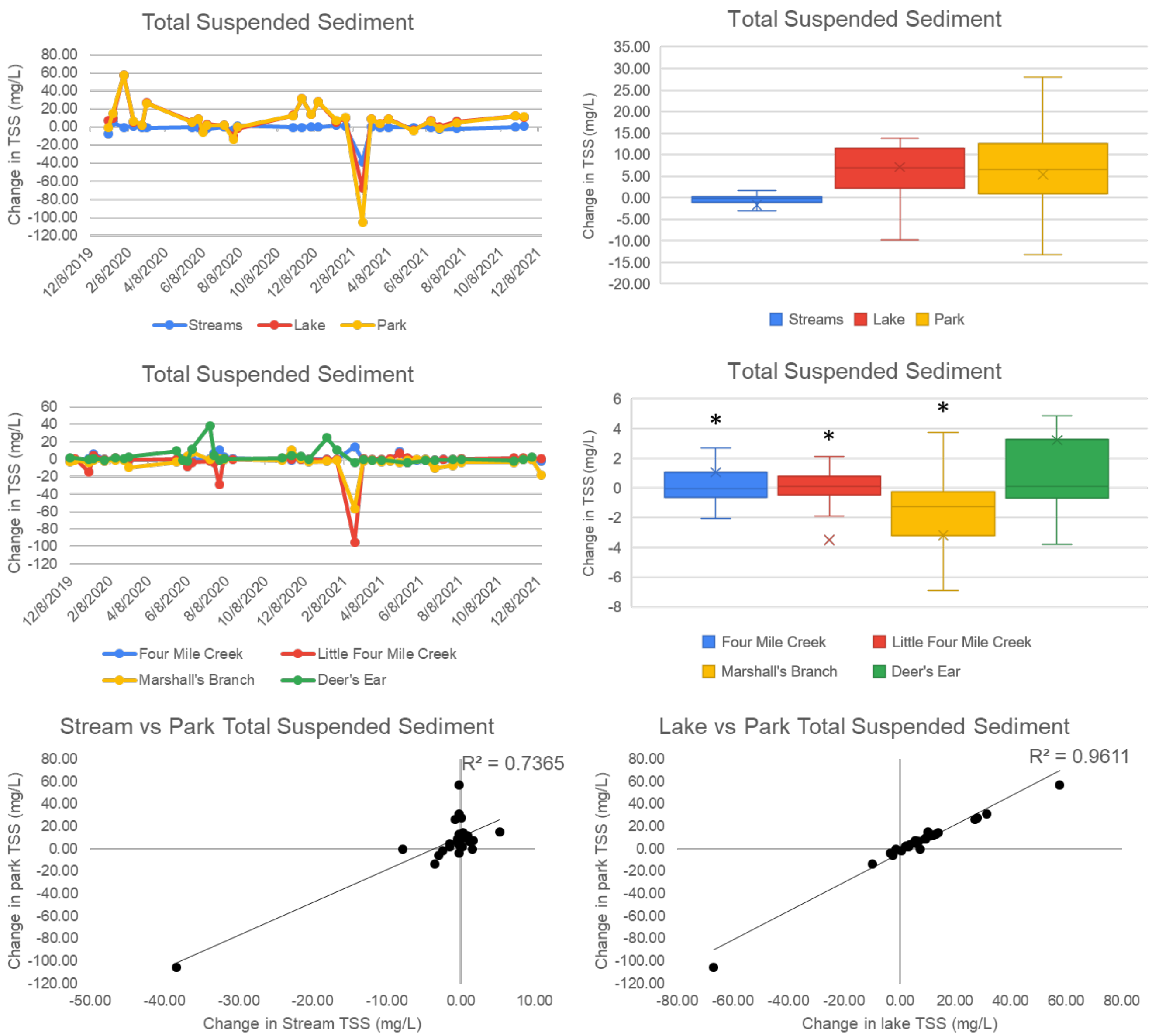

Figure 11. Changes in TSS concentrations between sites (top and middle). Relationship between the change in TSS concentrations at the park level compared to changes in TSS concentrations within the streams (bottom left) and Acton Lake (bottom right). An * indicates statistically significant changes.

5.6 Dissolved Organic Carbon

Dissolved organic carbon concentrations did not exhibit notable seasonal patterns throughout the study period (Figure 12). DOC EMCs were significantly higher at the lake outflow relative to the park entrance (CI: -1.62 to -0.89). Significant increases in DOC EMCs occurred within the lake (CI: -1.68 to -0.94) but not within the streams (CI: -0.0021 to 0.11). The significant DOC increases within the park were largely driven by DOC increases within the lake (R^2=.98) rather than changes within the streams (R^2=<.01). Within the streams, DOC concentrations significantly decreased within Marshall’s Branch and Deer’s Ear (CI: 0.39 to 0.71 and 0.12 to 0.70 respectively). Significant changes in DOC concentrations were not detected within Four Mile Creek or Little Four Mile Creek (Figure 13). Within Marshall’s Branch changes in DOC concentrations were positively correlated with stream discharge (CI: 0.72 to 1.68) and within Deer’s Ear changes in DOC concentration were negatively correlated with stream discharge (CI: -2.04 to -0.38). NDVI was negatively correlated with changes in DOC concentration within Marshall’s Branch (CI: -1.79 to -0.33). There was no significant relationship between NDVI and change in DOC concentration within the other three streams (Table 2).

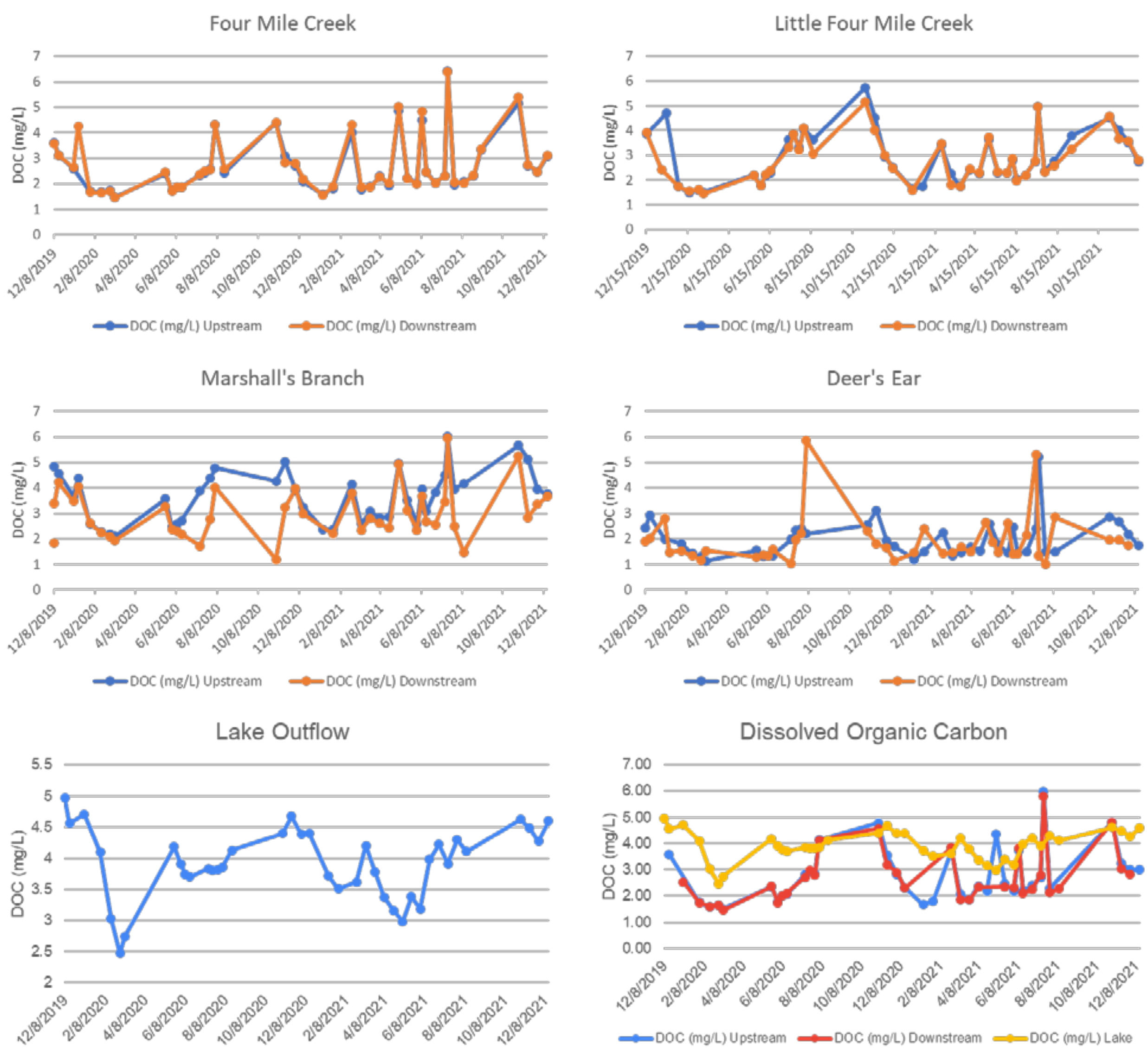

Figure 12. Stream and lake DOC concentrations.

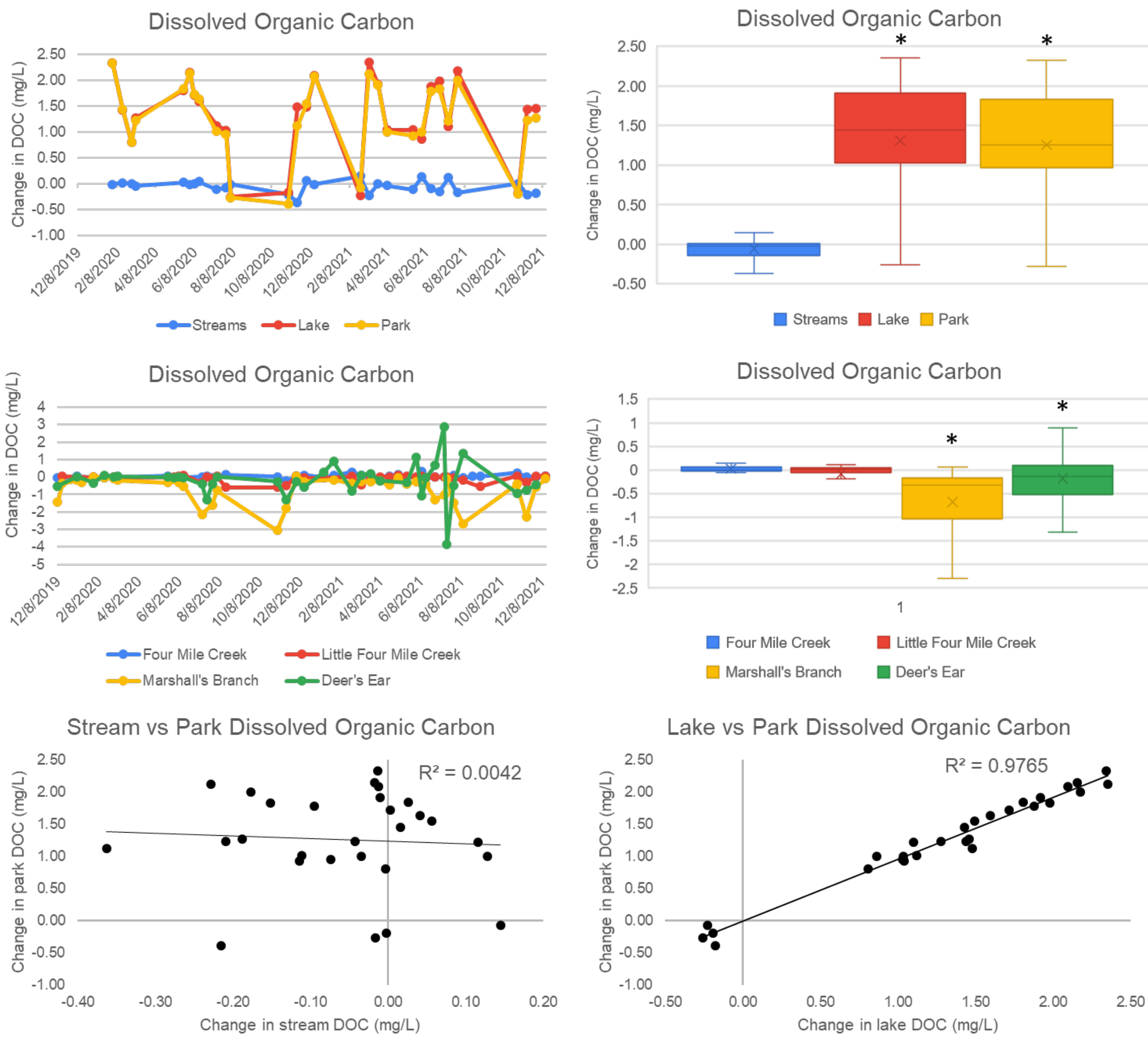

Figure 13. Changes in DOC concentrations between sites (top and middle). Relationship between the change in DOC concentrations at the park level compared to changes in DOC concentrations within the streams (bottom left) and Acton Lake (bottom right). An * indicates statistically significant changes.

5.7 pH

Seasonal patterns in pH concentrations were not observed during the study period (Figure 14). No significant differences in pH were detected within the streams, lake, or park overall. The lack of significant change in pH at the park level was mainly driven by the lack of change within the lake (R^2=.83) rather than the streams (R^2=<.01). Within the streams, Marshall's Branch exhibited significant decreases in pH (CI: 1.49 to 1.82) while the remaining three streams did not experience significant changes (Figure 15). Changes in pH were not significantly related to discharge within any of the streams. NDVI was negatively correlated with changes in pH within

Deer’s Ear (CI: -1.29 to -0.030). There was no significant relationship between NDVI and change in pH concentration within the other three streams (Table 2).

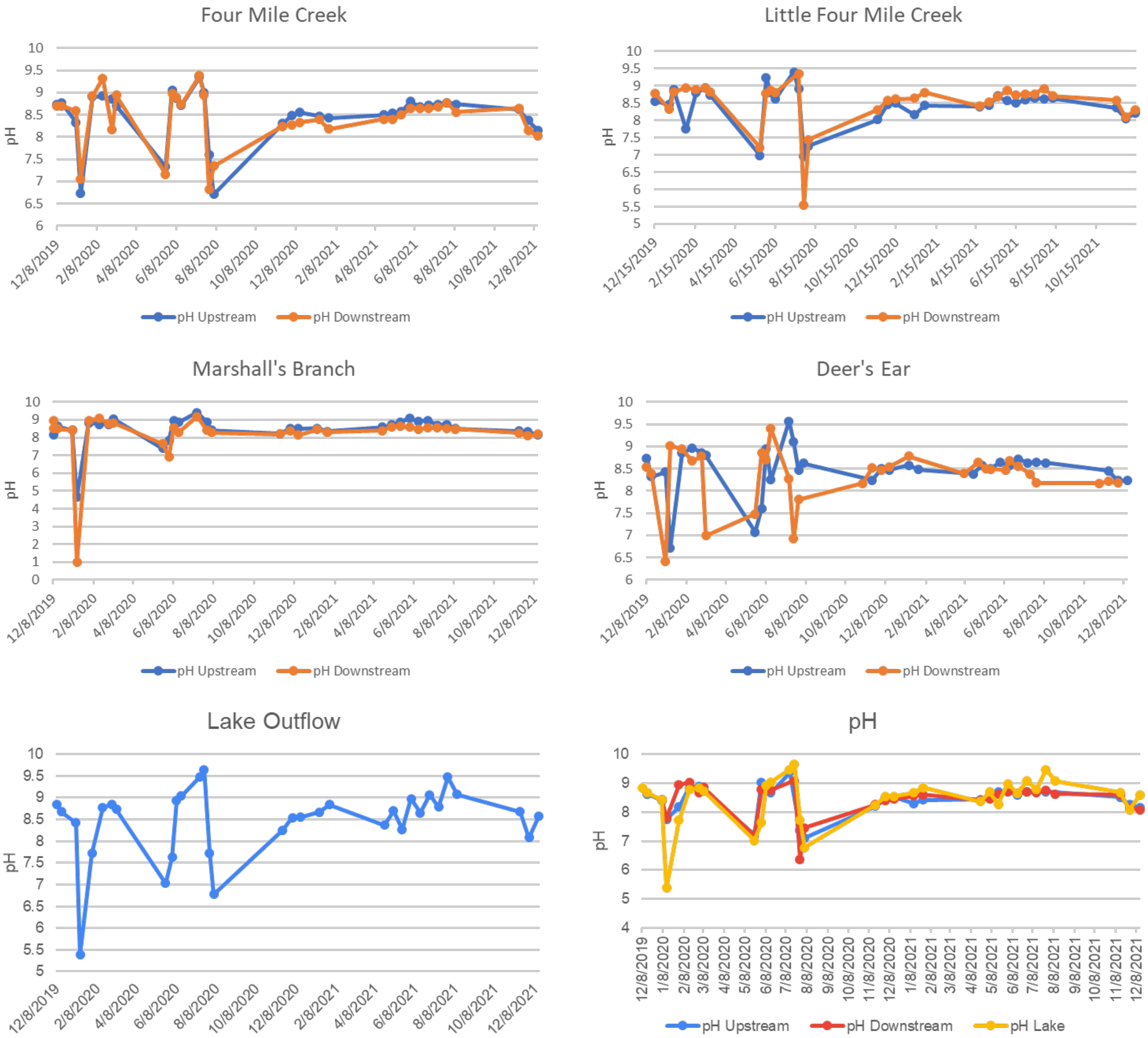

Figure 14. Stream and lake pH levels.

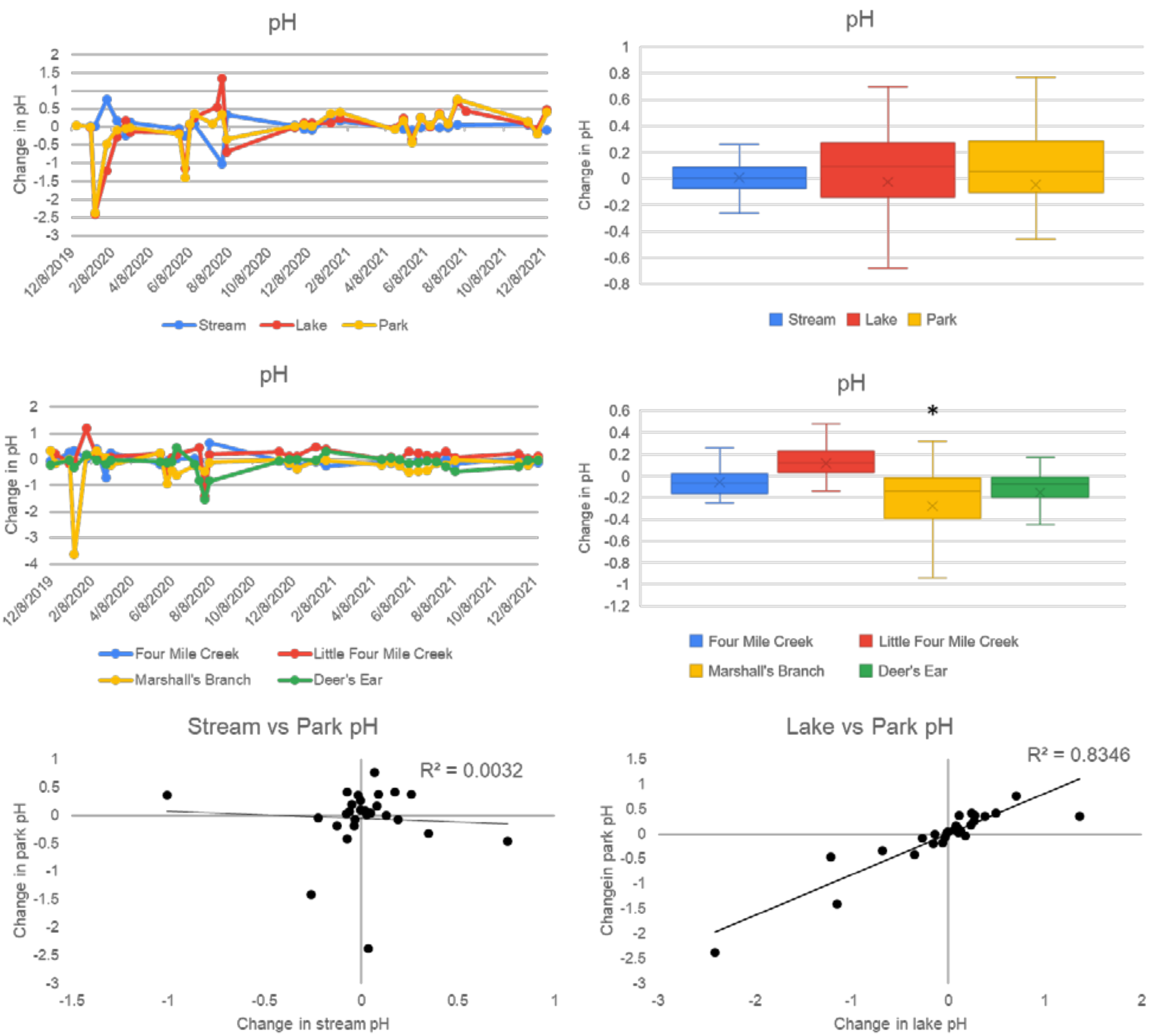

Figure 15. Changes in pH between sites (top and middle). Relationship between the change in pH at the park level compared to changes in pH within the streams (bottom left) and Acton Lake (bottom right). An * indicates statistically significant changes.

5.8 Conductivity

Stream conductivity exhibited the highest levels during winter months with no notable trends in remaining seasons (Figure 16). Conductivity levels were significantly lower at the lake outflow relative to the park entrance (CI: 61.39 to 131.13). Significant decreases in conductivity occurred within the lake (CI: 67.60 to 134.69) but not the streams (CI: -24.24 to 14.47). The significant decreases within the park were largely driven by decreases within the lake (R^2=.71) rather than the streams (R^2=.12) (Figure 17). Conductivity did not significantly change within any of the streams between upstream and downstream sampling sites, nor were changes in conductivity related to discharge or NDVI within any of the streams (Table 2).

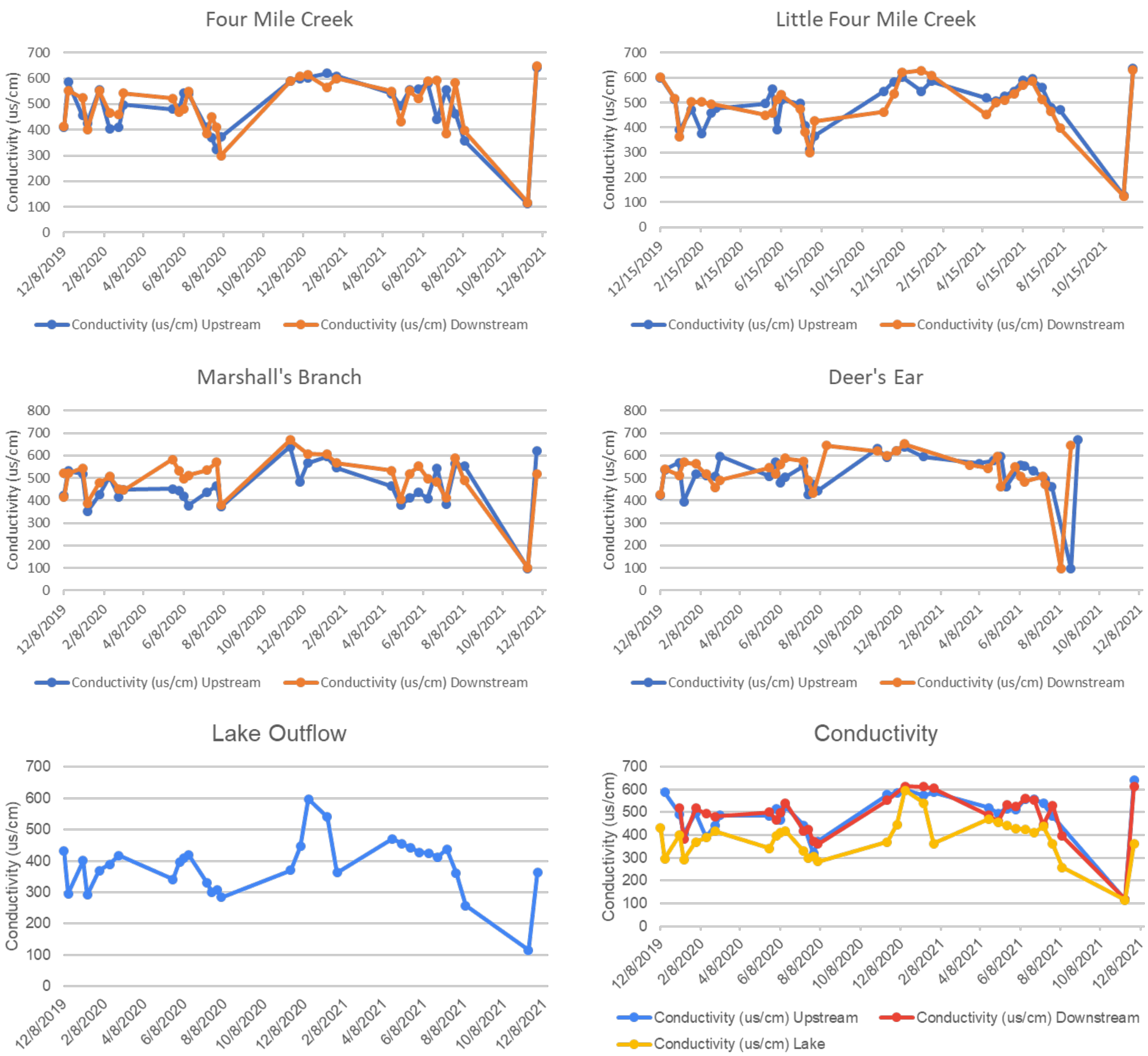

Figure 16. Stream and lake conductivity levels.

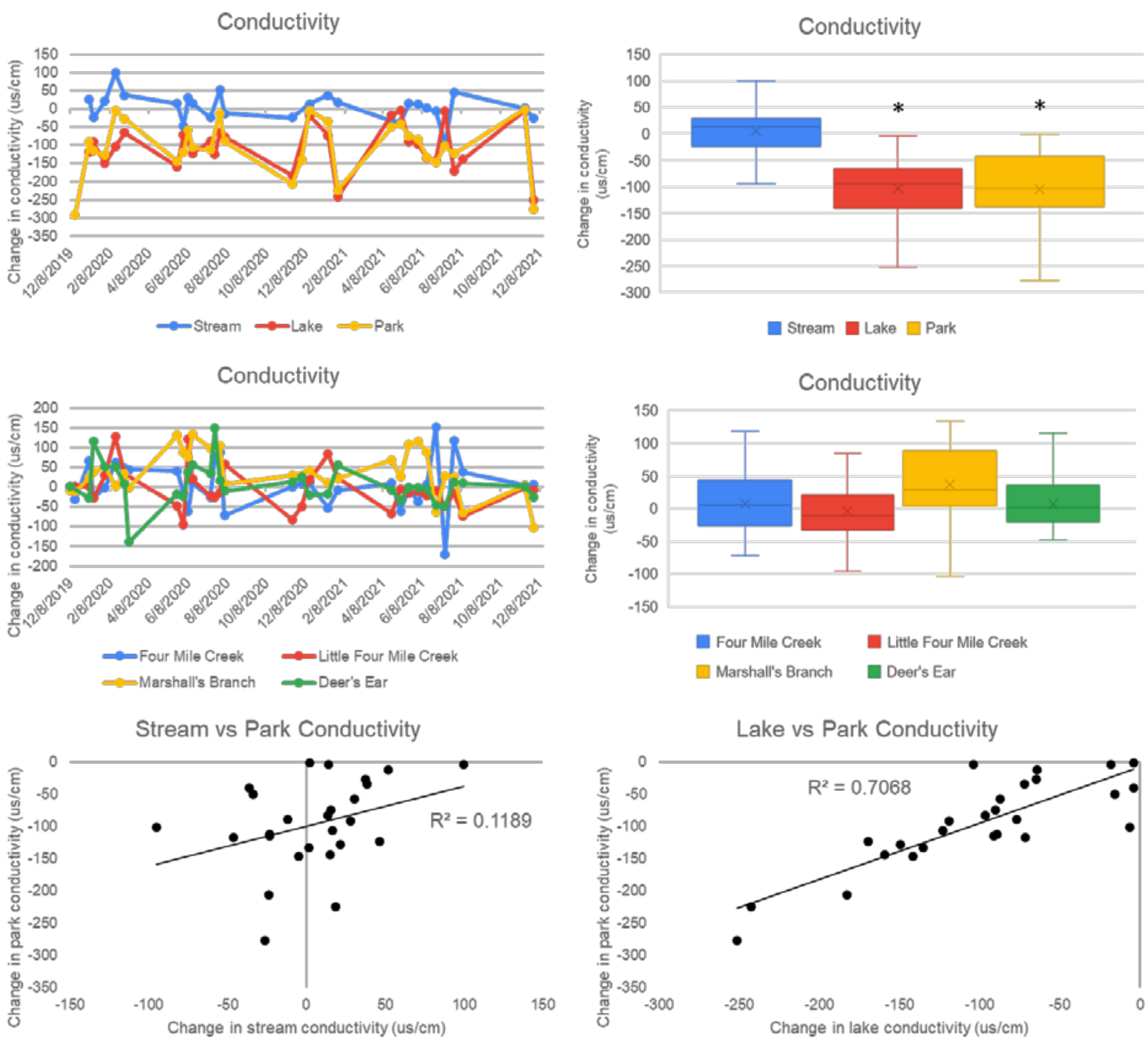

Figure 17. Changes in conductivity between sites (top and middle). Relationship between the change in conductivity at the park level compared to changes in conductivity within the streams (bottom left) and Acton Lake (bottom right). An * indicates statistically significant changes.

5.9 Groundwater

Trends in groundwater inside and outside of the park varied by watershed. We summarize these trends below, but also caution overinterpretation as the dataset is largely seasonal (dry periods during fall and summer produced no groundwater samples) and also not as robust is sample size as the surface water data. Nitrate concentrations marginally decreased ($p=0.088$) within Marshall Branch and showed insignificant changes within the Four Mile Creek and Little Four Mile Creek watersheds. SRP concentrations marginally decreased ($p=0.069$) within Four Mile Creek and showed insignificant changes within Little Four Mile Creek and Marshall's Branch. DOC concentrations significantly decreased within Four Mile Creek ($p<0.01$), marginally decreased within Marshall's Branch ($P=0.055$) and significantly increased within Little Four Mile Creek (p=0.011). pH significantly increased within Four Mile Creek (p=0.034) and Little Four Mile Creek (p=0.027) and significantly decreased within Marshall’s Branch (p<0.01). Conductivity significantly decreased within Four Mile Creek (p<0.01) and significantly increased within Little Four Mile Creek (p=0.027). Conductivity did not significantly change within Marshall’s Branch (Figure 18 and Table 3).

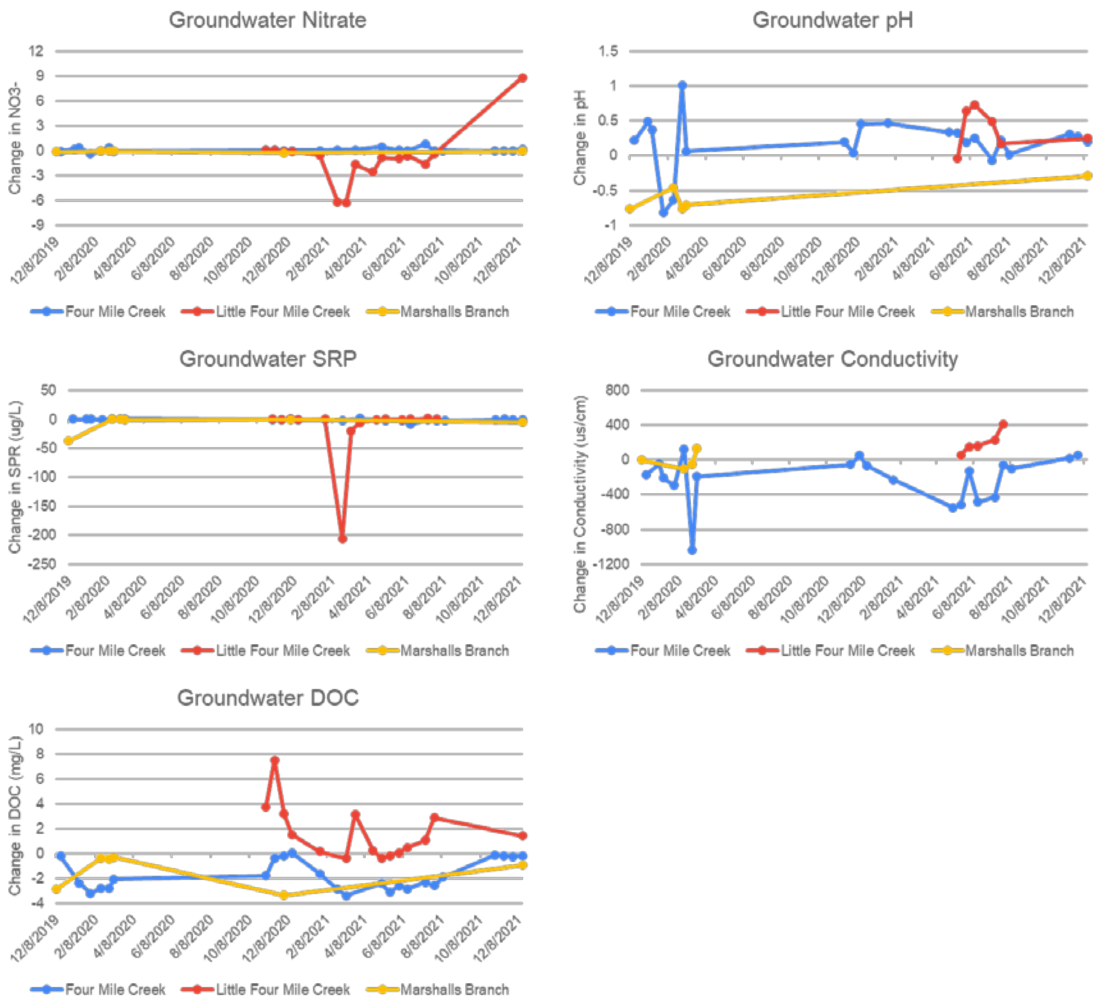

Figure 18. Changes in water quality parameters between upstream and downstream groundwater sampling sites.

			NO3-	SRP	DOC	ph	Conductivity
Four Mile Creek			-- (0.12)	↓(.0691)	↓(<.01)	↑(.034)	↓(<.01)
Little Four Mile Creek			-- (0.34)	-- (0.29)	↑(.011)	↑(.027)	↑ (.027)
Marshall's Branch			↓ (.088)	-- (0.30)	↓(.055)	↓(.003)	-- (0.96)

Table 3. Changes in groundwater concentrations. Green arrows indicate significant decreases and red arrows indicate significant increases. P-values are shown in parentheses.

5.10 Tile Drains

During periods of flow, nutrient concentrations (both nitrate and SRP) and conductivity within tile drains, were consistently higher relative to stream concentrations, while DOC concentrations were generally lower. It is important to note, that direct comparisons of tile drains values to downstream values are difficult, as tile drain flow was highly inconsistent across space and time and the number of samples was limited in comparison to surface water. Furthermore, there was high variability between tile drain parameter values, particularly for nutrients (Figure 19).

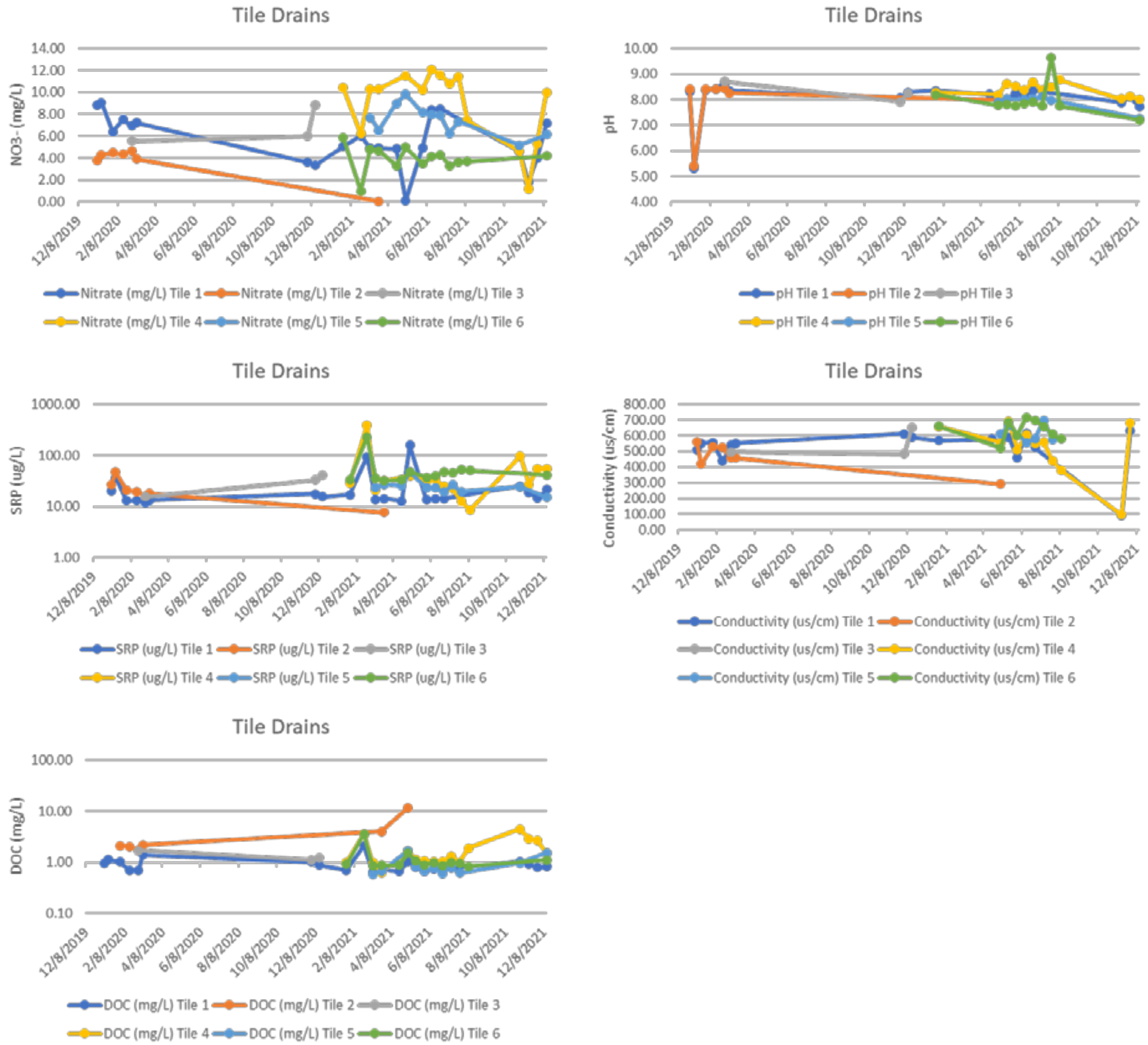

Figure 19. Tile drain water quality values.

6. Discussion

The presence of Hueston Woods State Park within an agricultural landscape has meaningful implications for some water quality variables. After water flows through the park's streams and lake, nitrate concentrations and conductivity decrease, while TP and DOC concentrations increase. Total nitrogen, SRP, and TSS concentrations along with pH were not significantly altered by the presence of the park during the study period. Changes in water quality that occurred within the park were all primarily driven by changes that occur within Acton Lake rather than the streams. For example, water quality parameters that changed significantly within the park also changed significantly in the lake in the same direction and there were no other changes within the lake that did not occur at the park level. Trends in streams did not always match trends within the park. For example, TN EMC decreased within the streams but not at the park level and while TP, DOC, and conductivity all experienced significant changes at the park level, the same changes were not observed within the streams. Nitrate was the only variable that significantly changed within the park and the streams.

While only TN and nitrate EMCs experienced significant changes within the streams, additional significant changes occurred within individual streams. In particular smaller streams experienced more significant changes than larger streams. For example, 10 of 16 water quality parameters changed significantly within Marshall's Branch (7 of 8) and Deer's Ear (3 of 8), while within Little Four Mile Creek (2 of 8) and Four Mile Creek (1 of 8) there were fewer changes. Interestingly, of the 13 significant changes that occurred within the streams, 12 water quality parameters showed decreases while only one (TSS in Four Mile Creek) showed an increase. Overall, when discharge had a significant effect within a stream, a higher flow meant a lower rate of decrease in a water quality parameter (with the exception of TSS and DOC in Deer's Ear). A majority of significant relationships between changes in water quality parameters and discharge again occurred within the 2 smallest streams of Marshall's Branch and Deer's Ear, although the changes were not always directionally consistent between the two streams (Table 2). This indicates that greater changes in water quality occur during lower flows within these streams and that the smaller streams are more sensitive to impacts of discharge. The influence of NDVI was prominent within Marshall's Branch (significant effect for 5 of 8 water quality parameters) and also had an effect on pH in Deer's Ear. NDVI was not found to be a significant driver of any water quality variables within the two largest watersheds of Four Mile Creek and Little Four Mile Creek.

Trends in groundwater were highly variable between sites. For example, nitrate and SRP both marginally decreased within 1 of 3 streams, while DOC, pH, and conductivity each had significant, yet directionally opposite trends within the 3 watersheds. Part of the ambiguity in these results may be due to the relatively low sample sizes in comparison to surface water. There is some evidence that the park is effective at reducing nutrient levels, however, additional data is needed to draw broader conclusions. Future studies with a similar design would benefit from deeper groundwater wells, as these relatively shallow wells frequently had insufficient water to provide the needed volume for a purge and subsequent water sample collection. Additionally, due to the complexity of groundwater dynamics, we encourage future studies to increase the number of wells within watersheds and/or to increase the number of watersheds examined. Not surprisingly the highest nutrient levels occurred within tile drains. Establishing riparian buffers where these tile drains discharge or decreasing nutrient application rates may both be effective methods to reduce these high sources of nutrient concentrations.

We expected the park in decrease all nutrients and sediment concentrations along with conductivity while increasing DOC. It is important to consider the prominent processes that are occurring within the lake that may be driving the observed changes and preventing other hypothesized changes from occurring. Previous research across the United States and additional research that has specifically focused on Acton Lake have identified numerous processes which may have a direct impact on the water quality trends observed here. First, nutrient and carbon cycling within lakes can help explain the increase in DOC and decrease in nitrate. Lakes are notorious for driving denitrification, while also breaking down organic carbon (David et al. 2006; Tranvik et al. 2009). Yet TN did not decrease and TP surprisingly increased. Acton Lake is hypereutrophic and has high levels of algae, particularly within summer month (Knoll et al. 2016). If algae are consuming dissolved nutrients and converting them into solid from, we can expect to see a disconnect between TN and nitrate along with TP and SRP (i.e. particulate vs. dissolved nutrient fractions) as we do in this study. The lack of significant change to SRP is likely driven by Gizzard Shad within the lake which are known sources of dissolved nutrient production, particularly SRP (Kelly et al. 2018; Sharitt et al. 2021). The increase in TP is then likely driven by algae consuming the SRP. The observed decrease in conductivity may be driven by dilution of dissolved ions by the relatively large volume of the lake.

One significant surprise in this study across parameters was how much the lake influenced changes in water quality parameters relative to the streams. When viewed as a connected hydrologic system it is important to consider water residence times within the streams and the lake. While residence times of water during normal flow conditions within the streams is on the order of hours, within the lake it is on the order of weeks-months except during the largest storms (Mike Vanni personal communication). Thus, a majority of the water residence time at the park level, occurs within the lake. This raises interesting questions related to the importance of stream and lake size and how the relative geomorphic characteristics between the two may impact water quality in other areas. We would expect stream "importance" to increase in systems where streams have a larger flow length, or where a lake is smaller. Another way to consider this is simply as a ratio of residence time between the streams and the lake. Unfortunately, detailed residence times under various hydrologic conditions for the period of this study were not able to be calculated. Future studies that compare residence times between connected streams and lakes within forested environments can test if this is a determining factor for the relative impact that streams and lakes have within a connected hydrologic system. Furthermore, this can also be meaningful for management of landscapes if improvements in particular water quality parameters are a goal.

The findings in this study reveal interesting trends in changes to water quality that need to be considered when evaluating potential landscapes areas and their characteristics for conservation. However, it is important to note that these findings are based on one system over a two-year study period and that the trends observed here may vary between sites and under various climatic conditions. Additionally, the drivers of certain processes that impacted water quality in this study may vary within other stream-lake environments due to variability in physical and biological characteristics. Despite this, we outline several considerations below.

What type of land area should we aim to target for conservation if water quality restoration is a goal? This is a question asked by many scientists and conservation minded land managers. Based on the results of our study when conserving streams, it appears that stream morphology is critical. The two small streams within this study experienced the most significant changes in water quality and these were almost universally positive changes. We hypothesize that this is true due to longer residence times and greater connectivity with the riparian zone for the two smallest study streams. Increased time for chemical cycling to occur may allow for greater water quality changes to be detected, while roots from vegetation within connected riparian zones can also pull nutrients from the water. Several important lake characteristics to consider are lake size, residence time, and biotic community. Acton Lake is relatively small and has abundant Gizzard Shad populations. In larger lakes with lower Gizzard Shad abundance, we may expect greater decreases in all nutrients as internal loading of dissolved nutrients would potentially be lower, which would subsequently lower TN and TP levels (e.g. since algae translocate dissolved nutrients from the water column into particulate form). This would then also be expected to decrease TSS as organic matter within the lake tends to be high. DOC within a lake with greater residence time may increase due to additional processing time, yet may also decrease if a lake is larger due to dilution.

Lastly, it is important to consider if the development of recreational reservoirs such as Acton Lake is beneficial for water quality management. The lake in this study area was responsible for increasing both TP and DOC concentrations which may not be desired in eutrophic environments. While management decisions should not be based on one study, our results do indicate that small forested streams are largely producing desirable water quality effects which the lake may be negating. The larger streams in this study may simply not have had sufficient flow length to accomplish significant changes in water quality. It is interesting to ponder what differences in water quality changes may have occurred within the park if the reservoir did not exist and free flowing streams were present instead.

7. Conclusions

- A forested state park in an agricultural landscape had a significant impact on some, but not all, water quality variables.
- In this study, water quality changes at the park level were primarily driven by changes that occurred within the lake rather than the streams.
- Some changes in water quality parameters (e.g. an increase in TP concentrations) may be undesirable in some areas depending on management goals.
- Changes in water quality varied between stream and lake environments.
- Stream morphology appears to be a critical driver of changes in water quality and small streams appear to be particularly beneficial for water quality improvements.
- The greatest improvements in stream water quality occurred during low flow periods.
- Each forested area in the region is unique and may produce variable impacts on changes in water quality. Additional studies need to be completed prior to confidently identifying which agricultural areas to restore into forested environments if water quality improvements are a goal in the region.

8. Acknowledgements

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9. Appendix

Link to Appendix

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