POLLUTION REMOVAL EFFICIENCY IN A RESTORED ANABRANCHING WETLAND

By

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Abstract

Improving water quality is a serious concern of many state and local governments across the U.S. Nutrients, including nitrogen and phosphorus, can significantly impair water quality when found in high concentrations. Constructed and restored wetlands are known to capture pollutants and improve water quality. Anabranching is a new design for restored wetlands in which a primary stream is diverted into smaller braided streams and wetland cells. Its effectiveness at capturing pollutants has not yet been evaluated.

This study investigates the effectiveness of an anabranched wetland at removing total nitrogen and total phosphorus from urban run-off during several winter storm events. The analysis compares the mass balances of total nitrogen and total phosphorus flowing into and out of the restoration area to determine the amount of nutrient reduction. Flow regimes were manipulated to divert water out of or into a stream or wetland cells. Stream and wetland configurations were compared to determine the effectiveness of the wetland cells in nutrient removal compared to streams alone.

Results show that for a given discharge, wetland cells have a residence time up to six times longer than streams. Results indicate that streams may be effective at capturing total phosphorus during low discharge events and ineffective at capturing total phosphorus during high discharge events; the stream configuration does not appear to capture total nitrogen on a consistent basis. Wetland cells appear to be ineffective at retaining total nitrogen over winter storm events; wetland cells may be able to more effectively retain total phosphorus, but this pattern is inconsistent. Results show no clear relationships between discharge and nutrient removal efficiency for the stream or wetland configuration, which is noted in this limited study.

Introduction

Water quality is a major concern for many environmental management departments in the United States. Although many policies designed to protect water quality have been passed, many bodies of water remain impaired and do not meet state and federal regulations. Urban developments and impervious surfaces have been identified as major causes of stream degradation and increased pollutants in nearby bodies of water. “Urban stream syndrome” is a term describing streams that have been physically and/or ecologically impaired by runoff from urban areas. Characteristics of degraded streams in urban areas include altered stream hydrology and geomorphology, reduced residence time, and increased levels of pollutants (Walsh et al 2005).

Streams in or near urbanized areas are particularly vulnerable to nonpoint source pollutants, including nitrogen and phosphorus. These two pollutants are known to cause eutrophication and impairment of bodies of water when found in large concentrations (Carpenter et al 1998). In the North Carolina Piedmont, roadside runoff can have nitrogen and phosphorus loading rates similar to agricultural runoff (Wu et al 1998). Two methods for reducing eutrophication are source reduction and treatment. Because nonpoint source pollutants are more difficult to control than point sources, source reduction is somewhat challenging (Baker 1992).

One method for managing and treating urban runoff is through constructed or restored wetlands. Wetlands are unique and complex ecosystems that offer valuable ecosystem services like improving water quality. Wetlands are known to capture and remove pollutants like suspended solids, phosphorus, different forms of nitrogen, and heavy metals (Stanley 1996;

Johnston *et. al* 1990). Studies indicate that restored and constructed wetlands can effectively capture a variety of pollutants in urban runoff and improve water quality (Mitsch *et. al* 2005; Mitsch and Gosselink 2007; Scholes et al 1998). Because of this, the restoration of wetlands and headwater riparian systems may be useful to improve the quality of impaired waters.

Treatment wetlands may be constructed though many different ways (Vymazal 2008). Different designs for constructed wetlands have different removal rates for nitrogen and phosphorus (Vymazal 2007). "Anabranching" is a relatively new method for restoring wetlands based on evidence that streams in the eastern United States often had an anabranched pattern (Walter and Merritts 2008). In anabranching, dams or weirs are constructed to divide one main stream into multiple smaller streams and/or wetland cells (Nanson and Knighton 1996). Both surface area and hydrologic length of contact between riparian zones and stream sources impact the efficiency of ecosystem services like nitrogen retention in wetlands (Haycock and Pinay 1993). Anabranching is designed to increase the hydrologic connectivity of floodplain wetlands, increase the residence time of storm water, and increase the rate of pollutant removal by the wetland.

One location the North Carolina Department of Environment and Natural Resources has shown concern about water quality in Jordan Lake and its tributary watersheds. The Upper Sandy/New Hope Creek in the North Carolina Piedmont is one tributary of Jordan Lake that has been designated as a Natural Heritage Program Priority Area (NCDENR 2001). Jordan Lake is a reservoir that provides drinking water to several cities in the Triangle Area of North Carolina, including Cary, Apex, and Morrisville. Studies show that Sandy Creek has previously out of compliance with EPA-set nitrogen and phosphorus concentrations (Turley 2001; Elting 2003).

The Duke University Wetland Center has constructed the Stream and Wetland Assessment Management Park (SWAMP) at the upper reaches of Sandy Creek. Here, there are four completed phases of stream and wetland restoration. Phases 1, 2 and 3 have been completed for several years, and results indicate that these effectively capture total phosphorus and nitrate-nitrogen (Richardson et al 2011).

Though a variety of designs for treatment wetlands are known to capture pollutants, the efficiency of anabranched wetlands has not yet been explored. This study is designed to investigate the effectiveness of anabranching as a treatment wetland for capturing pollutants in urban runoff. I expect concentrations of total nitrogen and total phosphorus in the outflow of the wetland and stream to be less than concentrations in the inflowing water. I hypothesize that the anabranched wetland design will capture significantly more total nitrogen and total phosphorus than pollutant removal rates of the stream alone.

Methods and Research Location

The study site for this experiment is Duke University Wetland Center's Stream and Wetland Assessment Management Park (SWAMP) in the Duke Forest of Duke University in Durham, North Carolina, USA; coordinates for this site are latitude 35° 59'27", longitude 78° 56'28". This area is part of Upper Sandy Creek, a headwater piedmont stream of Jordan Lake in the Cape Fear River Basin (shown in Figures 1 and 2), and has a drainage area of approximately 480 hectares (1186 acres). Here, an anabranched wetland system was designed and constructed, having a primary stream and two adjacent hydrologically connected wetland cells (shown in Figure 3). At this site, we can install and remove weirs to manipulate and control the flow of water into wetland cells and/or the stream under high and low flows.

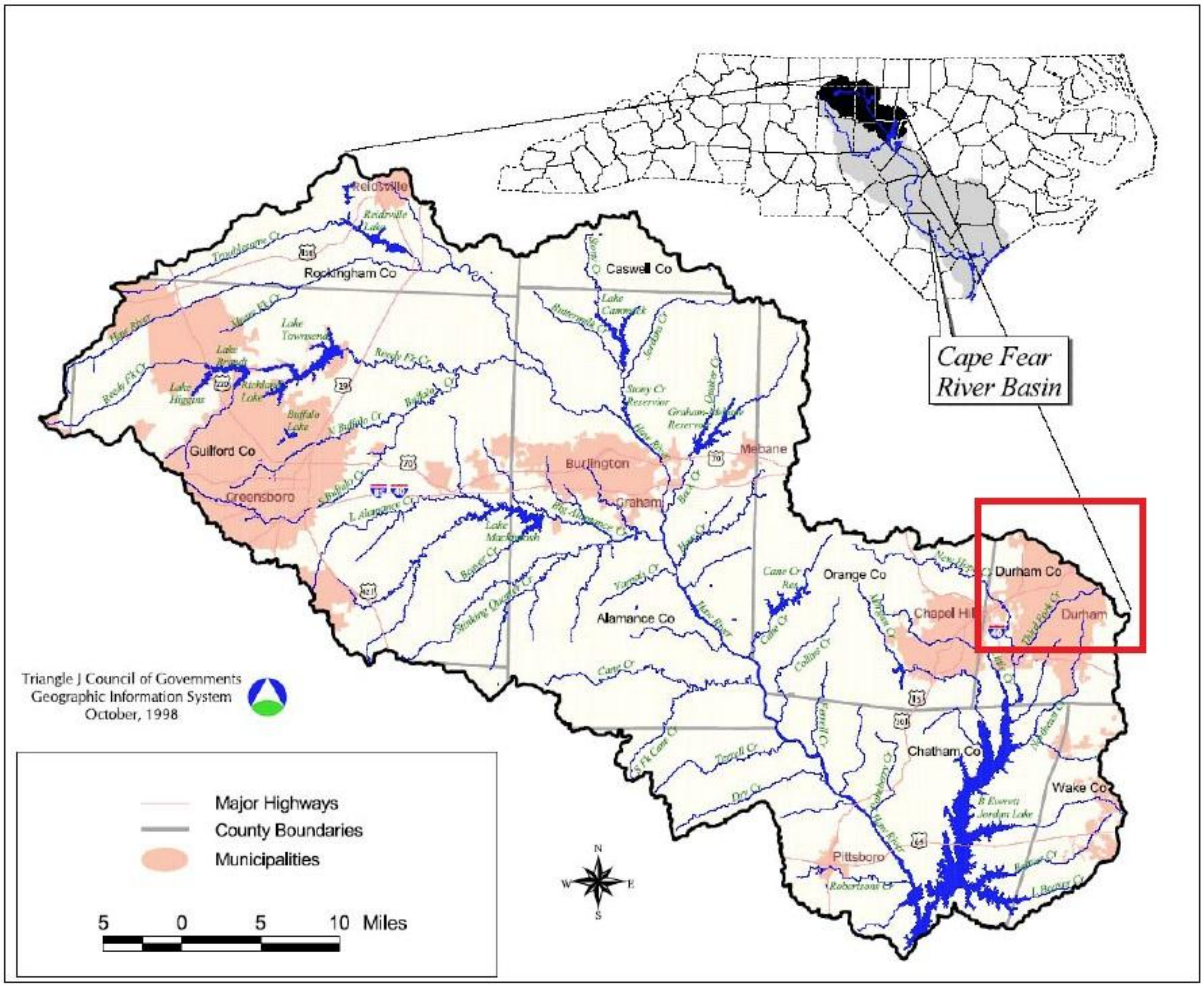

Figure 1. Location of study area in Cape Fear River Basin, North Carolina.

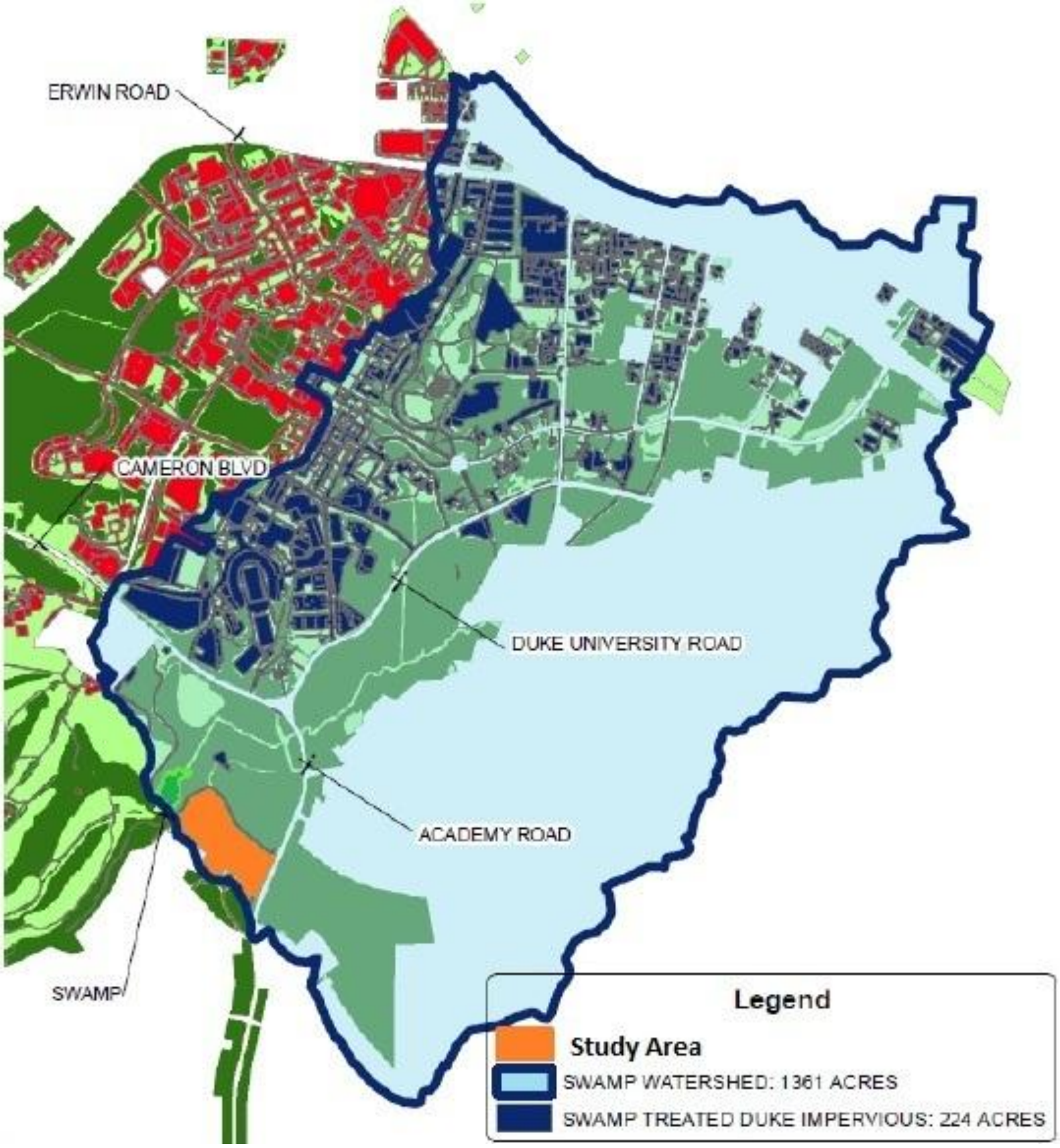

Figure 2. Map of Study Area in the SWAMP Watershed, showing both areas of Duke University impervious surface and the entire watershed for the city of Durham feeding into this branch of Sandy Creek.

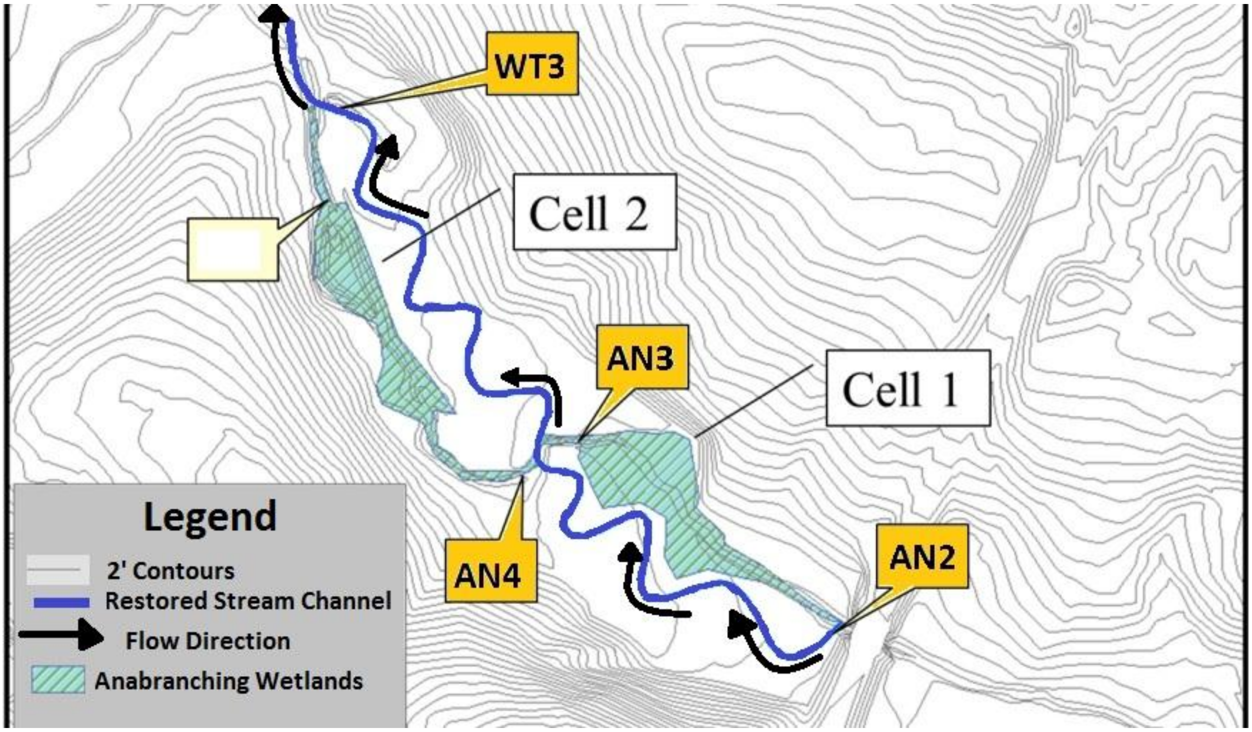

Figure 3. Topographic map of the anabranched wetland. Water flows in at AN2 and flows out at WT3. Flow control devices may be manipulated at AN2, AN3, and AN4. (Figure modified from Flanagan and Richardson).

Two different treatments were created for this study of comparing stream and wetland cells in terms of nutrient efficiency. Four sampling events were performed under the stream configuration and three events under the wetland configuration. I collected three water sample replicates at the inflow point (AN2) under both stream and wetland configurations; WT3 was used as the outflow point for the stream configuration and AN3 was used as the outflow point for the wetland configuration. At the outflow points I collected three to nine water samples. Water samples were collected between December 2012 and February 2013. Specific dates of storm event sampling under the stream configuration were: 17 December 2012, 16 January 2013, 17 January 2013, and 18 January 2013. Dates of storm events under the wetland configuration were: 13 February 2013, 23 February 2013, and 26 February 2013. A time-series of daily precipitation and sampling events is shown in Figure 4.

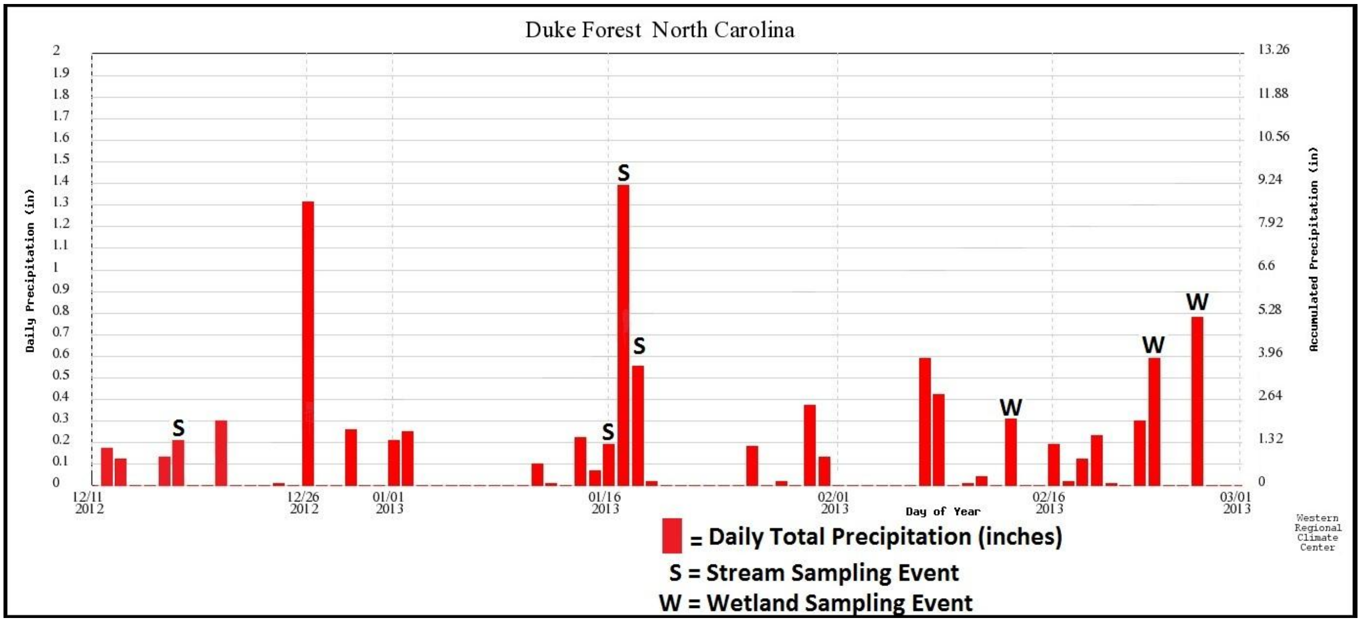

Figure 4. Storm event sampling dates for stream and wetland configurations.

I used a Rhodamine dye tracer and Rhodamine-specific probe to determine stream discharge under the stream configuration. I followed a modified version of Cyrenne and Eng's Flow Measurement Using the Dye Dilution Technique (2002). I performed tracer runs in conjunction with collecting water samples. The Rhodamine tracer was dumped immediately after collecting water samples at the inflow point. The outflow water samples were collected before downstream arrival of the Rhodamine slug at the outflow point; this was to ensure that no Rhodamine will be present in any water samples. Respective stream discharges were multiplied by total nitrogen and total phosphorus concentrations to calculate the mass balance of each pollutant.

To measure the discharge of water under the wetland configuration, I followed the U.S. Department of the Interior's Water Measurements Manual using a V-notch weir (2001). I used a fluorescein dye to measure the residence times of storm water during storm events. The fluorescein dye was used as a marker for collecting water samples; water samples at the outflow point (AN3) were collected just before the arrival of the dye slug downstream. Residence times and discharges were measured for each storm.

Water samples were analyzed for total nitrogen (TN) and total phosphorus (TP) in the Duke University Wetland Center lab. TN content of water sample was analyzed following the EPA's Method 353.2 protocol using persulfate digestion (1993); TP content was analyzed following the EPA's Method 365.2 protocol using persulfate digestion and cadmium column reduction (1971).

I used a t-test to detect differences in TN and TP levels at the inflow and outflow points for both anabranched wetland and stream treatments; TN and TP of each treatment were analyzed individually. I used the concentrations of TN and TP in water samples and stream discharge to calculate their mass balance.

Results

Figure 5 shows the instantaneous discharge values for storm sampling events under stream and wetland configurations. Discharges range from 5.7 L/sec to 259.4 L/sec, which is a substantially wide range; stream configuration discharges range from 5.7 L/sec to 111.8 L/sec and wetland configuration discharges ranged from 12.7 L/sec to 259.4 L/sec. This range of storms provided an appropriate range of discharges for both treatment configurations to test the effectiveness of anabranching on nutrient removal.

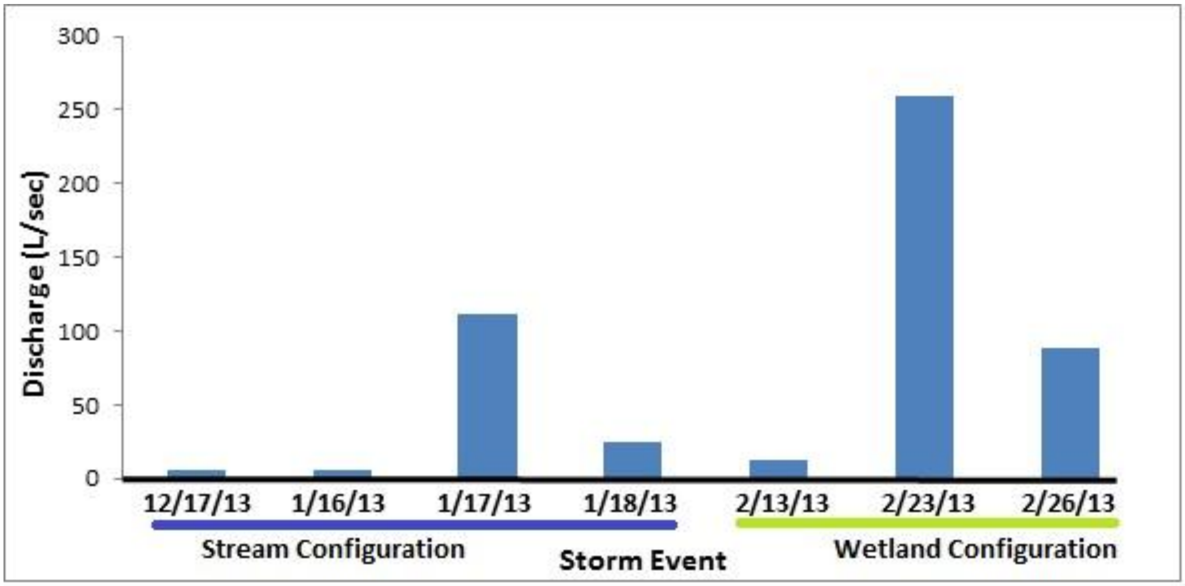

Figure 5. Discharge values for stream and wetland configurations.

Figure 6 shows a scatterplot of residence time vs. discharge comparing stream and wetland configurations. Discharge and residence time appear to be inversely related. Greater discharges have shorter residence times, while smaller discharges have longer residence times. The wetland configuration shows the same inverse relationship between discharge and residence time. For a given discharge, the residence time appears to be longer in the wetland configuration than in the stream configuration.

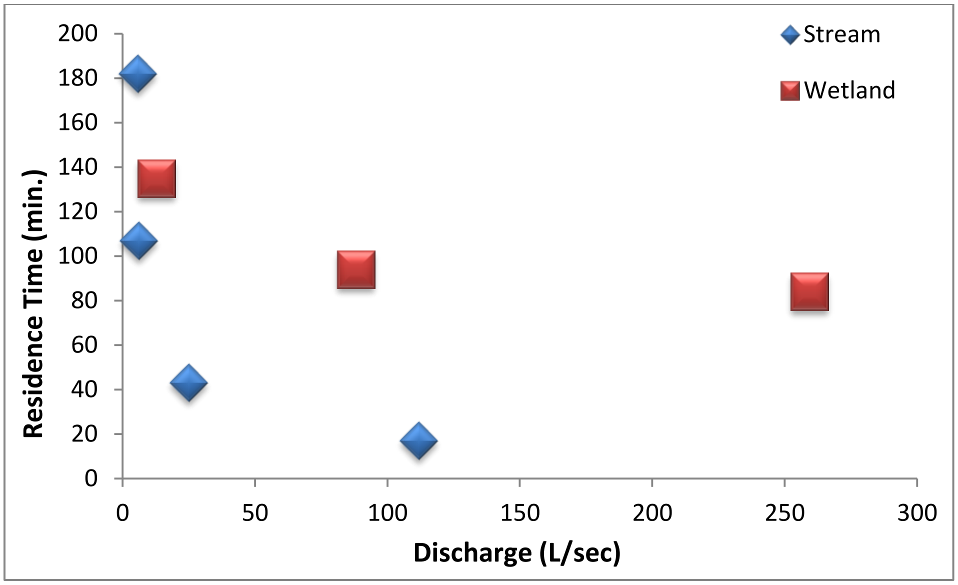

Figure 6. Discharge vs. residence time scatterplot for stream and wetland configurations.

Figure 7 shows the concentrations of TN at inflow and outflow points under the stream configuration. Results for the TN mass balance of the stream configuration are shown in Figure 8. Storm events 1/16, 1/17, and 1/18 each show slight reductions in TN when comparing inflow and outflow values; only events 1/16 (-26%) and 1/18 (-13%) show statistically significant reductions in TN (p-values = 0.021 and 0.014, respectively). Event 12/17 shows a significant increase (+106%) in TN (p-value=0.005); this event had the smallest discharge value, as well as the smallest concentrations of TN flowing in (49.2ug/L).

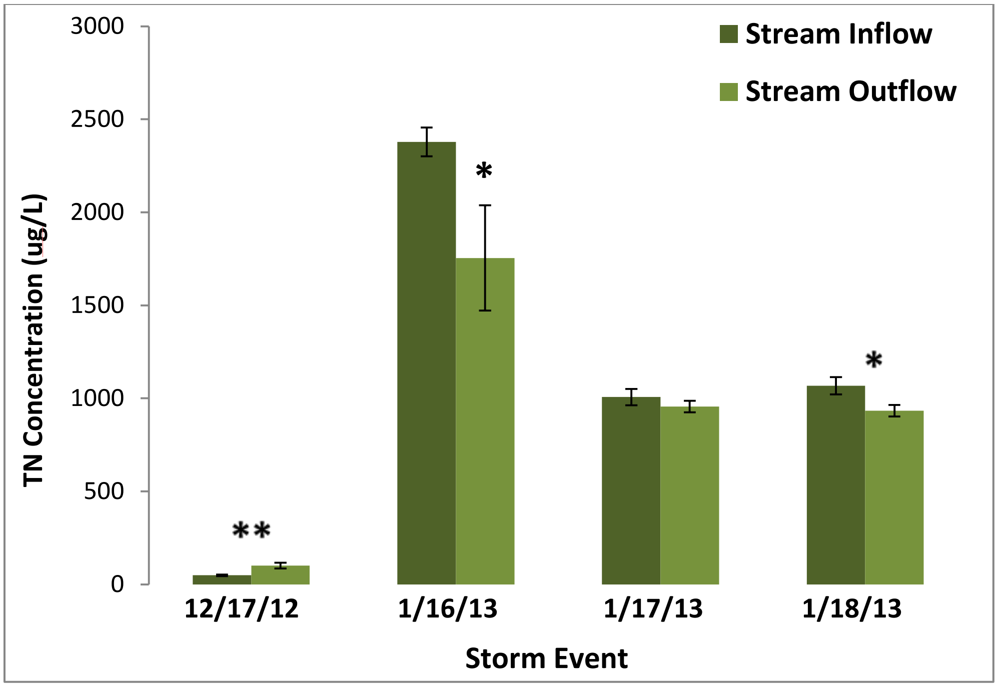

Figure 7. Total nitrogen concentrations for stream configuration. Error bars represent +/- 1 standard deviation; * represents p-value <0.05, ** represents p-value <0.01.

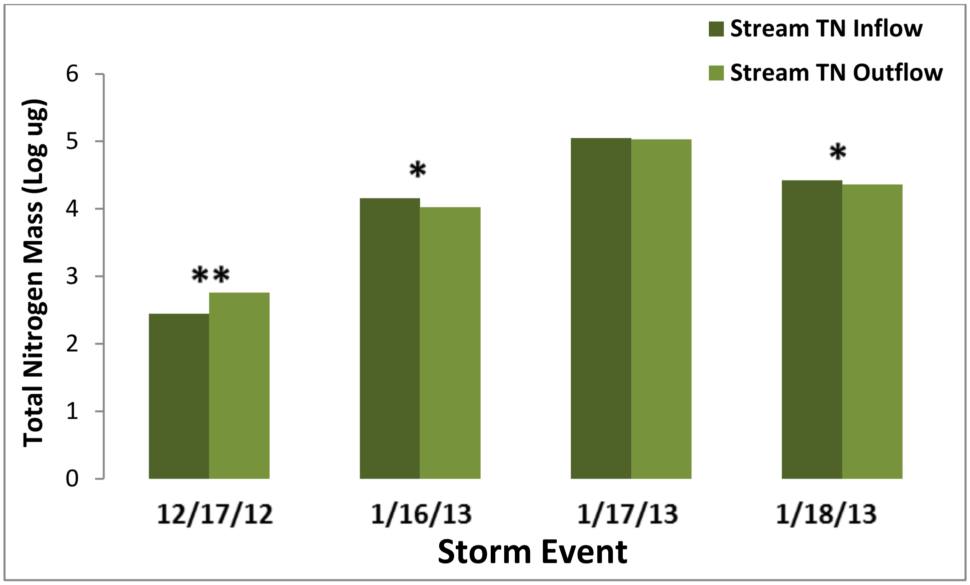

Figure 8. Log of total nitrogen mass balance for stream configuration. (* represents p-value <0.05, ** represents p-value <0.01).

Figure 9 shows the TP concentrations at the inflow and outflow points for the stream configuration. Figure 10 shows the results for the total phosphorus mass balance for the stream configuration. Storm events 12/17, 1/16, and 1/18 show slight decreases in total phosphorus; events 1/16 (-51%) and 1/18(-80%) are statistically significant (both p-values > 0.001), while 12/17 is non-significant (p-value=0.355). Storm event 1/17 shows a significant increase (+44%) in TP (p-value=0.001).

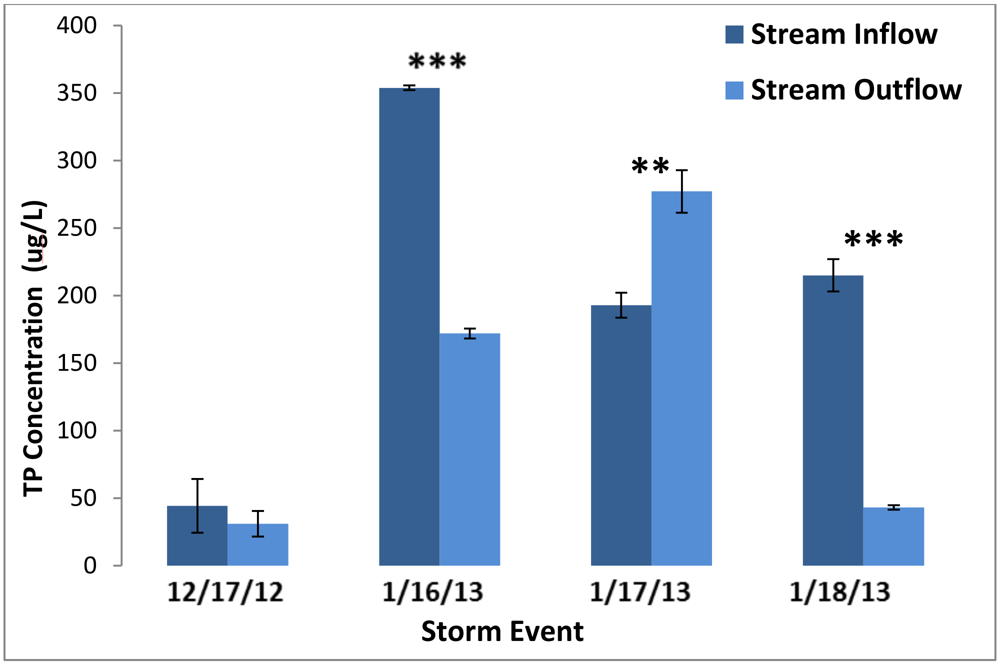

Figure 9. Total phosphorus concentrations for the stream configuration. Error bars represent +/- 1 standard deviation; * represents p-value <0.05, ** represents p-value <0.01.

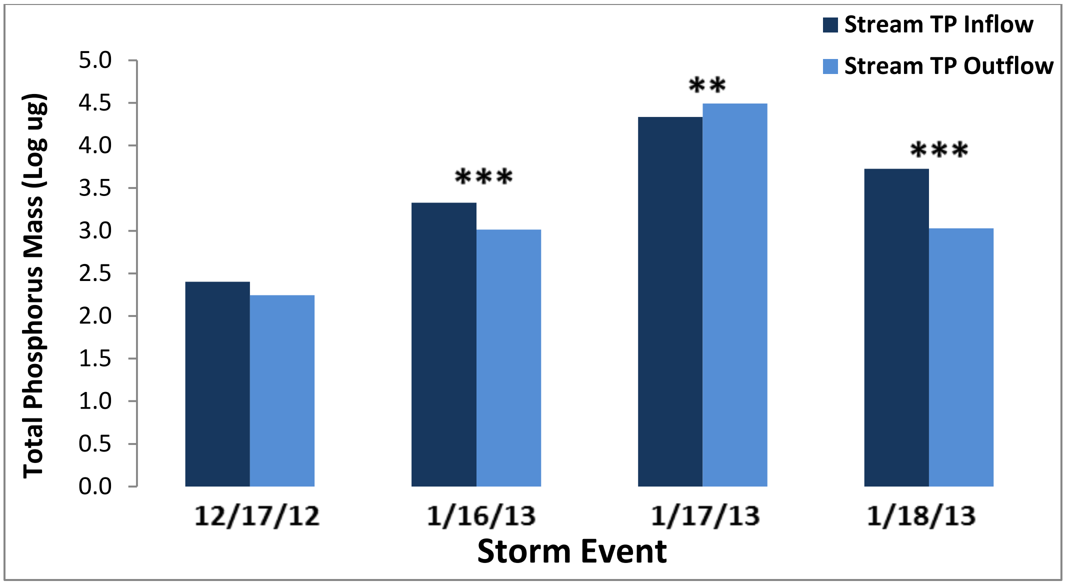

Figure10. Total phosphorus mass balance for stream configuration. (* represents p-value <0.05, ** represents p-value <0.01, *** represents p-value > 0.001).

Figure 11 shows the percent reductions in TN and TP for the stream configuration. Storm events 1/16 and 1/18 show reductions in both TN and TP. Event 12/17 shows a reduction in TP, but a very large increase in TN. Event 1/17 shows a small reduction in TN and a slight increase in TP. Together, these results show no clear patterns in nutrient reductions under the stream configuration.

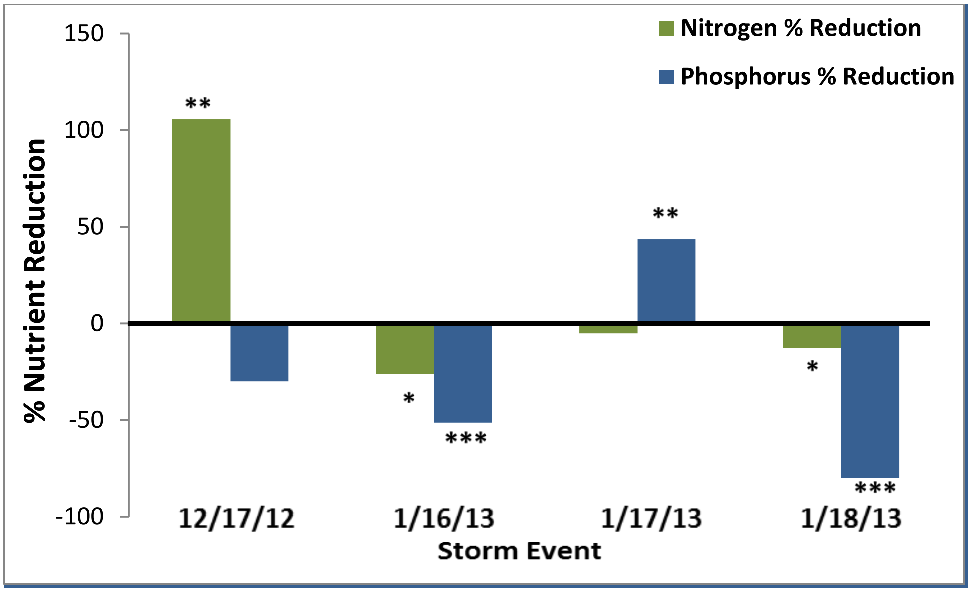

Figure 7. Nutrient percent-reduction in stream configuration. Values below the 0 line represent the percent of reduction and above the 0 line represent percent of increase. (* represents p-value <0.05, ** represents p-value <0.01, * represents p-value > 0.001).**

Figure 12 shows the TN concentrations at the inflow and outflow points of the wetland configuration. Figure 13 shows the mass balance for TN for the wetland configuration. Event 2/13 shows no significant change in TN; events 2/23 and 2/26 show significant increases in TN when comparing inflow and outflow values (p-value = 0.003 and p-value = 0.036, respectively).

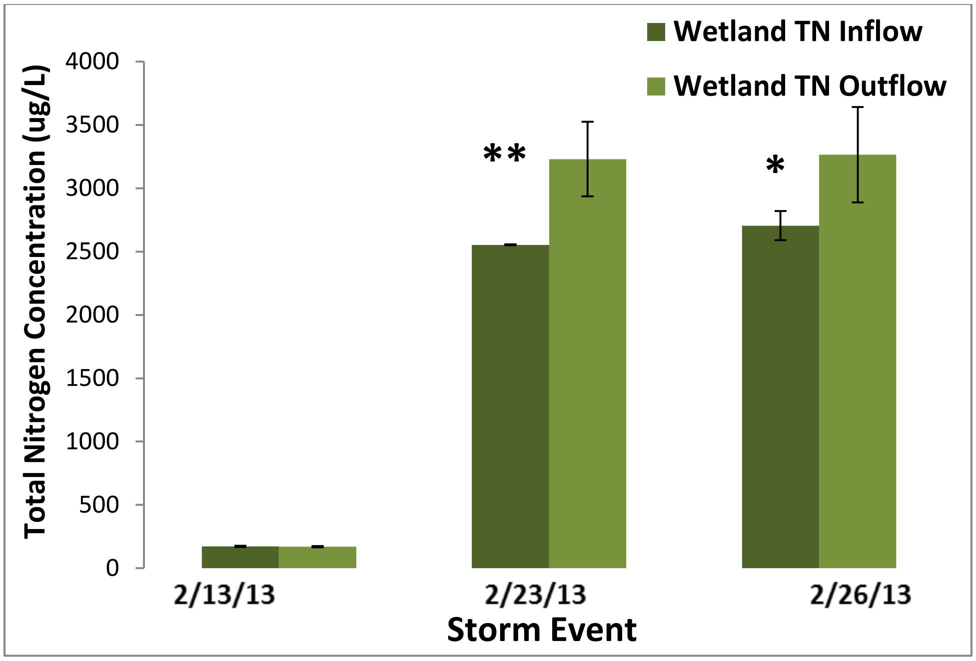

Figure 12. Total nitrogen concentrations under the wetland configuration. Error bars represent +/- 1 standard deviation; * represents p-value <0.05, ** represents p-value <0.01.

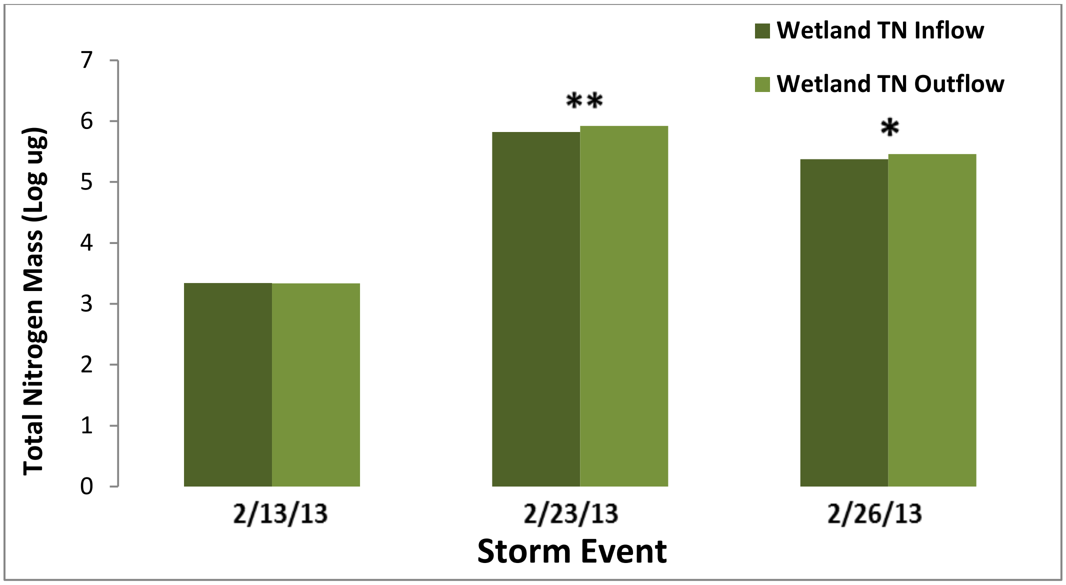

Figure13. Total nitrogen mass balance for the wetland configuration. (* represents p-value <0.05, ** represents p-value <0.01).

Figure 14 shows the TP concentrations at the inflow and outflow points for the wetland configuration. Figure 15 shows the mass balance for TP in the wetland cell configuration. Events 2/13 and 2/23 show reductions in TP, while event 2/26 shows an increase. The reduction in event 2/13 is slight (-24%) and the reduction of event 2/23 is larger (-42%).

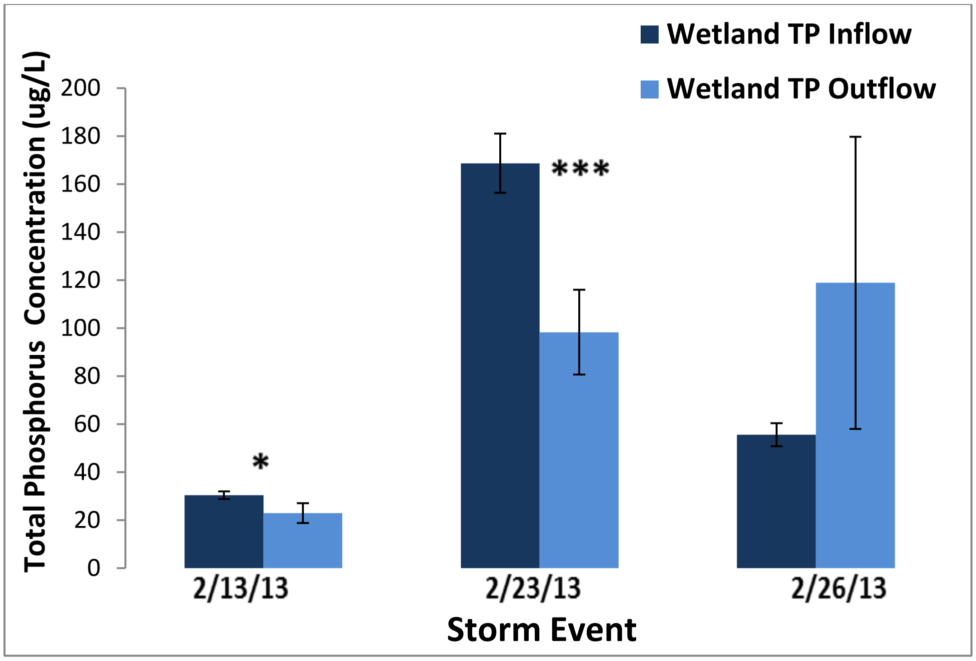

Figure 14. Total phosphorus concentrations at the inflow and outflow points of the wetland configuration. Error bars represent +/- 1 standard deviation ; * represents p-value <0.05, ** represents p-value <0.01, * represents p-value > 0.001.**

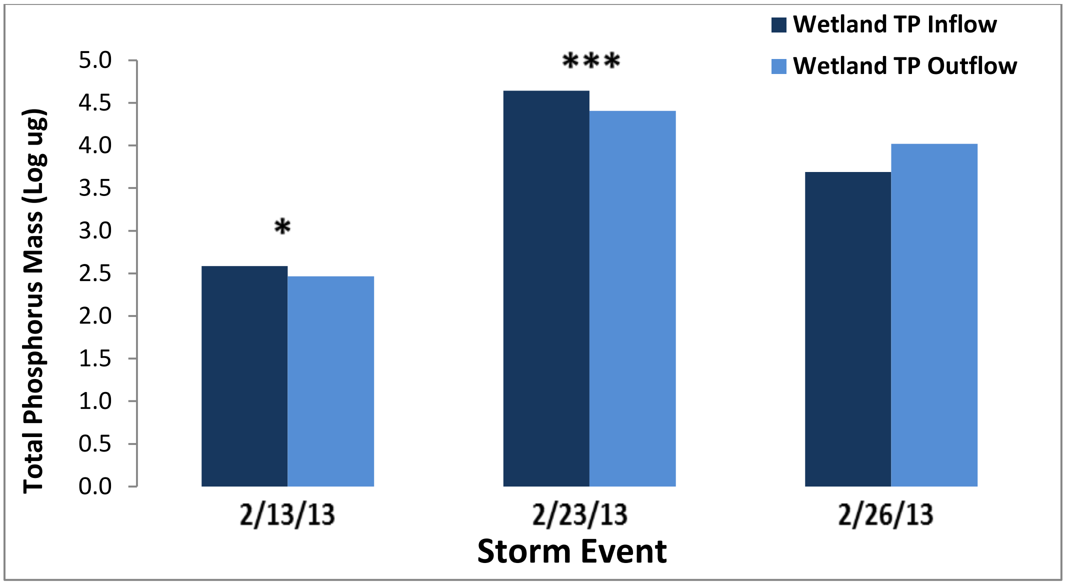

Figure 15. Total phosphorus mass balance for the wetland configuration. (* represents p-value <0.05, ** represents p-value <0.01, * represents p-value > 0.001).**

Figure 16 shows the percent reductions in TN and TP under the wetland configuration. Event 2/13 shows no change in TN and a significant decrease (-24%) in TP; event 2/23 shows a 27% increase in TN and a 42% decrease in TP; event 2/26 shows a 21% increase in TN and a non-significant change in TP.

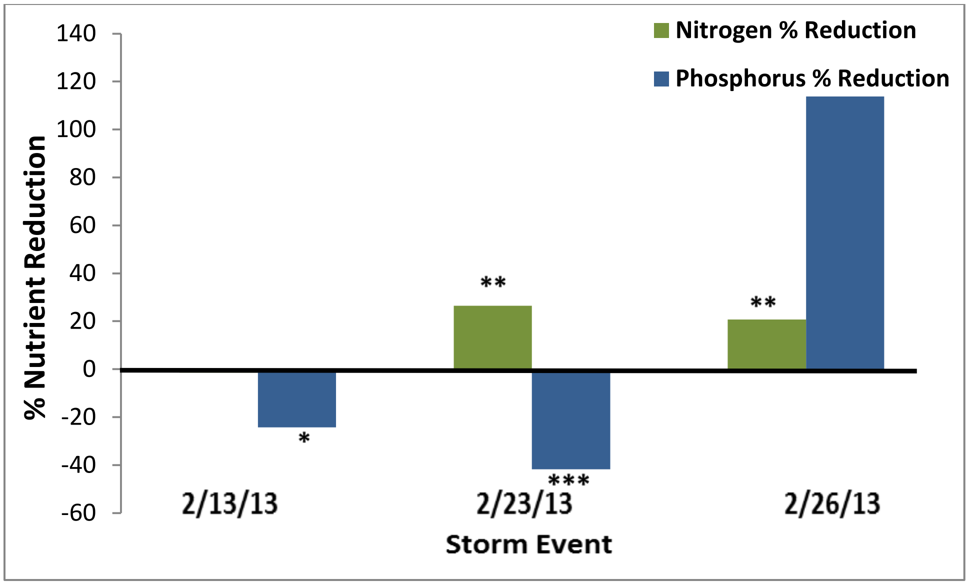

Figure 8. Total nitrogen and total phosphorus percent reduction in the wetland configuration. Values below the 0 line represent the percent of reduction and above the 0 line represent percent of increase. (* represents p-value <0.05, ** represents p-value <0.01, * represents p-value > 0.001).**

Figure 17 shows a scatterplot comparing discharge and % TN reduction for stream and wetland configurations. This shows no clear trends between discharge and TN reduction for the wetland configuration. There may be a very weak trend of smaller discharges and greater TN removal for the stream discharge, however this is unclear. Figure 18 shows a scatterplot comparing discharge and TP removal for stream and wetland configurations. This also shows no clear relationships between discharge and TP removal for either configuration. Consistent patterns may become more apparent with more data points and continued research.

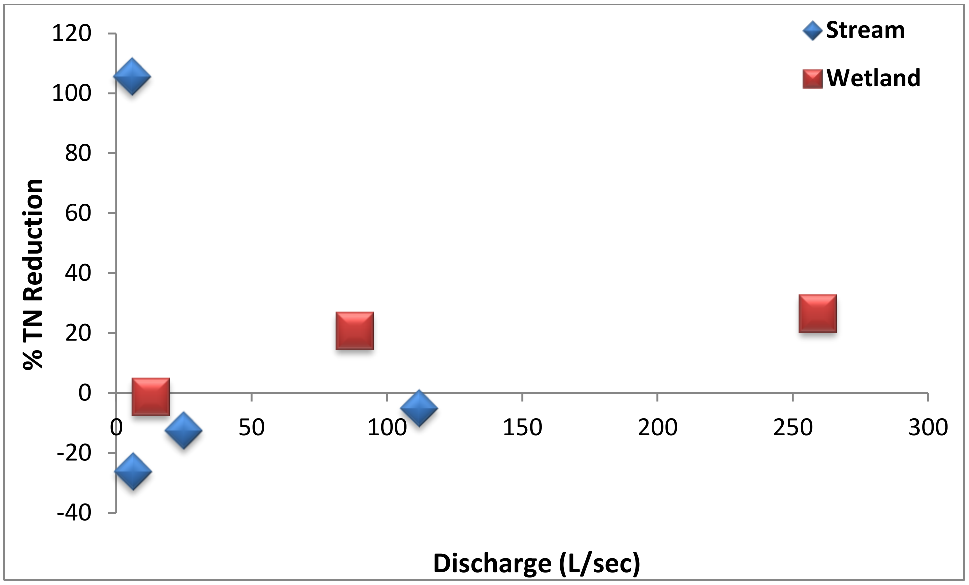

Figure 9. Discharge vs. % total nitrogen reduction scatterplot.

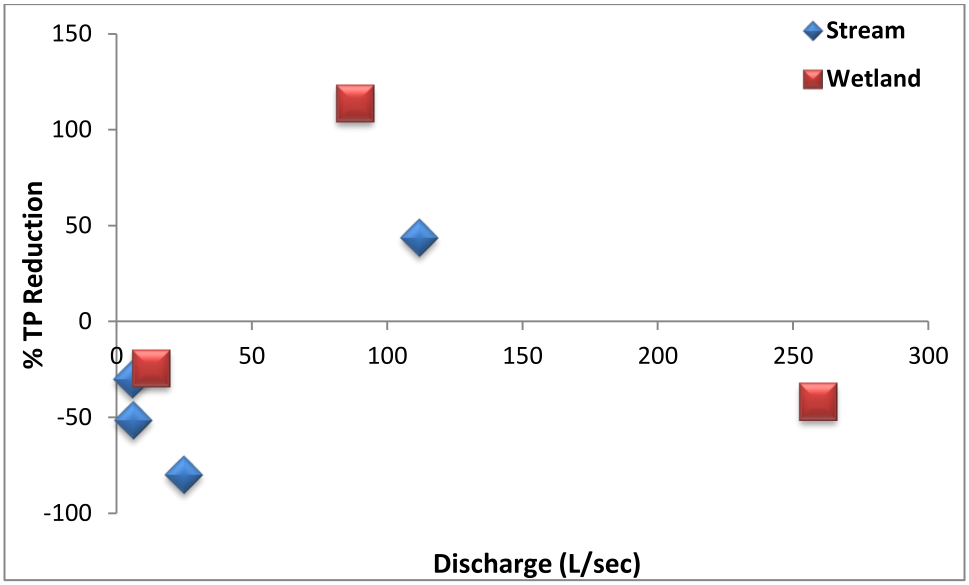

Figure 10. Discharge vs. % total phosphorus reduction scatterplot.

Discussion

There appears to be a clear, inverse relationship between discharge and residence time for both stream and wetland configurations, which was expected. Results indicate that for a given discharge, water in the wetland configuration will have a longer residence time than it would in the stream configuration. Storm water in the stream configuration had a much shorter residence time than those of the wetland configuration. During low discharge events (5-20 L/sec), residence times in wetland cells were approximately 50% longer than in the stream; during high discharge events, residence times in wetland cells were approximately 500% longer that in the stream. This indicates that anabranching, with storm water flow diverted into wetland cells, is effective at increasing the residence time of storm water. The increase in residence time of the wetland cell depends on the discharge; residence times may increase by 50% during low discharge storm events and up to 500% during high discharge events.

Results for the stream configuration give several interesting indications. First, there appear to be no clear trends between inflow and outflow mass balances for TN and TP under the stream configuration. This was expected because the stream is more channelized and less hydrologically connected compared to wetland cells, and therefore TN and TP reductions for the stream configuration we not expected to be significant. Under the stream configuration, storm events 1/16, 1/17, and 1/18 show slight reductions in TN and event 12/17 shows a small increase. For TP, storm events 12/17, 1/16, and 1/18 show reductions, but event 1/17 shows an increase. This increase in TP during event 1/17 may be related to the extremely high discharge and low residence time. Larger discharges should have a greater stream velocity. Large stream velocities may be able to pick up and mobilize sediments on the stream bed. Since phosphorus can bind to sediments, the extremely large discharge may explain the increase in total phosphorus during storm event 1/17 of the stream configuration (Harter 1968). This may indicate that streams are more effective at capturing TP under low nutrient loading rates and ineffective under high nutrient loading rates, however more testing is needed to confirm this.

For the wetland configuration, results show no clear patterns. Event 2/13 shows no change in TN, while events 2/23 and 2/26 show significant increases in TP. The stream configuration appears to capture more TN than the wetland configuration, which was unexpected; these results indicate that the wetland cell may be more of a TN source than a TN sink. It is possible that large loading rates of TN, similar to those of events 2/23 and 2/26, are impacting the ability of the wetland to retain TN. Larger loading rates of TN could be related to wintertime flushing of dead plant exudates. For TP, storm event 2/13 shows a slight decrease, event 2/23 shows a large decrease, and event 2/26 is unclear. More testing may show clearer patterns for TN and TP removal for the wetland cell.

One possible source of variation in this experiment may be in the time of year in which the study was performed. One study indicates that nutrient removal is less efficient under colder temperatures (Kadlec and Reddy 2001). Since sampling events were performed during the winter, colder temperatures may be a factor impacting TN and TP removal rates. Performing this study during the summer may give clearer results since water temperatures would be warmer and nutrient removal may be more efficient. Another possible source of variation in this study may be the variability in inflowing TN and TP concentrations. Figure 19 shows the variation in TN concentration at the inflow point (AN2) during storm event 2/26; concentrations range from 2560 ug/L to 4340 ug/L. Figure 20 shows the variation in TP concentration at the inflow point (AN2) during storm event 2/26; TP concentrations range from 64 ug/L to 188 ug/L. This shows that there is a wide range of loading rates for TN and TP at the inflow point. Figure 21 shows the variation in TN concentration at the wetland outflow point (AN3) during storm event 2/26; TN concentrations range from 2415 ug/L to 4207 ug/L. Figure 22 shows the variation in TP concentration at the wetland outflow point (AN3) during storm event 2/26; TP concentrations range from 60 ug/L to 121 ug/L. This shows that there is a wide range of TN and TP flowing out of the wetland cell; this range is similar to the range of TN and TP flowing into the wetland. It is possible that the differences between inflow and outflow TN and TP may be caused by the pulsing pattern of nutrient input.

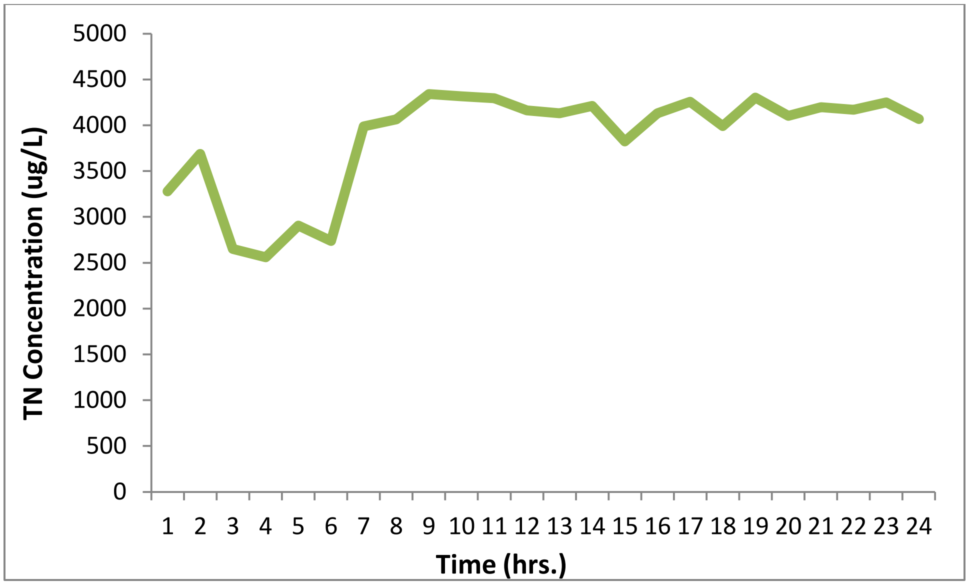

Figure 19.Variation in TN concentration during storm event 2/26 at the inflow point (AN2).

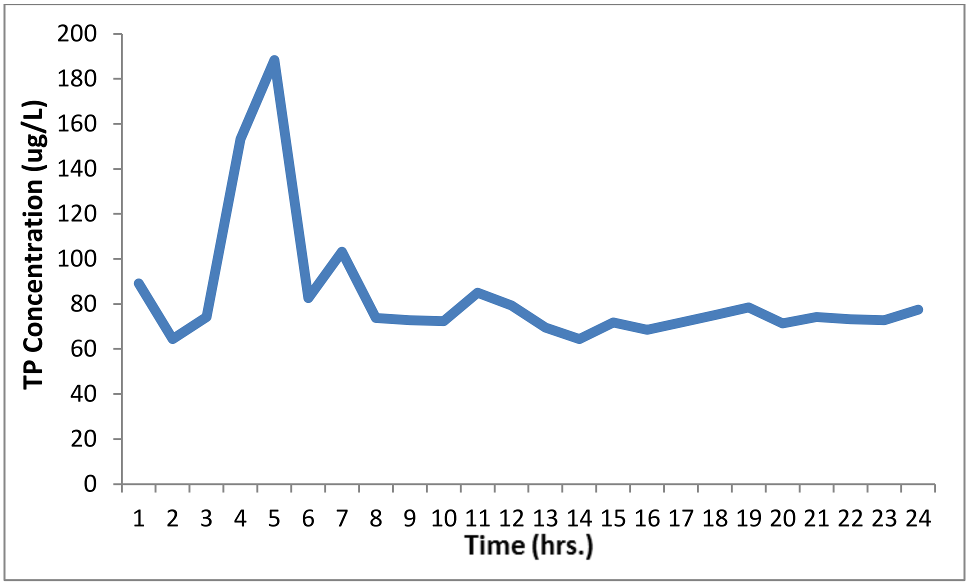

Figure 20. Variation in TP concentration during storm event 2/26 at the inflow point (AN2).

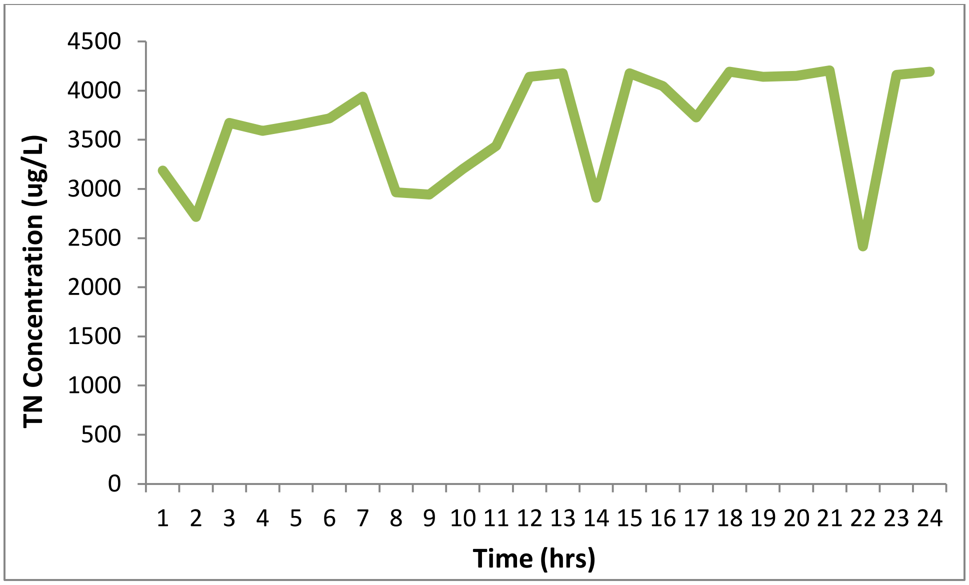

Figure21. Variation in TN concentration during storm event 2/26 at the wetland outflow point (AN3).

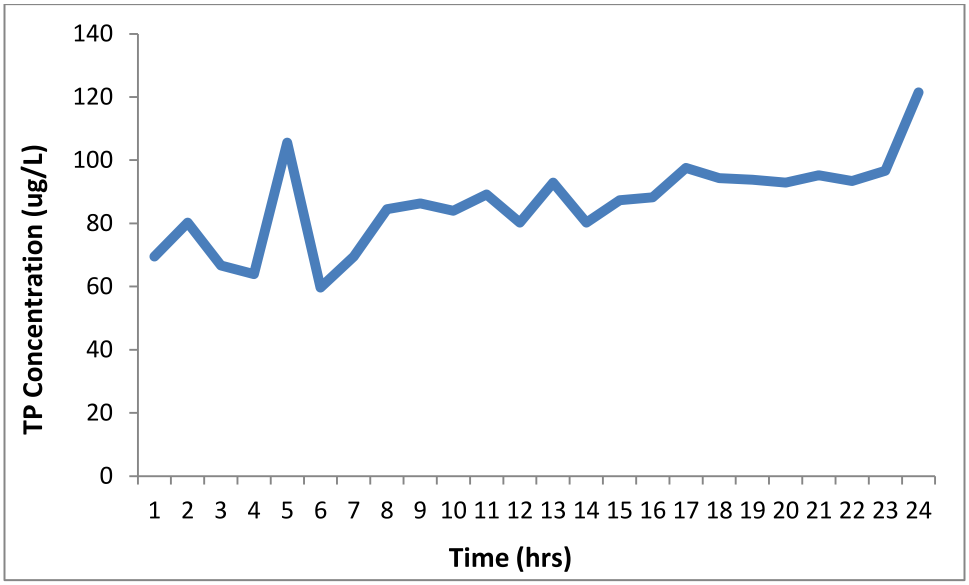

Figure 22. Variation in TP concentration during storm event 2/26 at the outflow point (AN3).

Overall, this studying suggests that both streams and wetlands may potentially capture TN and TP, however the ability to capture these nutrients does not appear to be consistent. Streams may more effectively capture TP while wetland cells may capture TN more effectively. This suggests that an anabranching restoration design, with a stream and wetland cells, may be a more effective design for removing both nitrogen and phosphorus from urban runoff than only a restored stream or restored wetland.

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