Examining the Inter-Storm Variability in Nitrogen Removal Efficiency in a Connecticut Constructed Wetland

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Abstract

Suburban stormwater runoff carries large amounts of nitrogen and other pollutants from fertilized lawns, septic systems, and atmospheric deposition, ultimately contributing to hypoxia (low dissolved oxygen levels) in Long Island Sound and severely perturbing aquatic life. Managers of Long Island Sound have set a goal of achieving a 10% reduction in nitrogen from nonpoint sources in order to mitigate hypoxia. More robust stormwater management practices need to be implemented to both attain this goal and keep pace with the increase in suburban sprawl. Wetlands may provide a valuable, but understudied, ecosystem service by removing nitrogen from this runoff. This study examined the nitrogen removal efficacy of a constructed wetland, located in a suburban area of Hamden, Connecticut. Its position directly upstream of the Lake Whitney public drinking water reservoir makes the quality of the runoff discharged from the site especially critical. Our objective was to evaluate the effectiveness of the constructed wetland at removing nitrogen from runoff, and to assess the inter-storm variability in nitrogen removal, in order to determine which variables (water temperature, residence time, and influent nitrogen concentration) might control this efficiency. The input and output of nitrogen, along with the flow of water, were measured at the site for 73 storm events from June 2011 to December 2011 and from April 2012 to December 2012. Stormwater samples were collected using programmable ISCO 3700 autosamplers over the duration of the storm and composited manually into flow-weighted samples for the influent and effluent in order to determine nitrogen event mean concentrations and loads for each storm event. Results show that the constructed wetland exhibited statistically significant nitrogen removal (nitrate: $p=0.001$, total nitrogen: $p<0.001$), indicating that the site is an effective tool for filtering nitrogen. However, nitrogen removal was highly variable from storm to storm. According to the general linear model, highest removal rates occurred with higher mean influent nitrogen concentrations for both nitrate ($p=0.002$) and total nitrogen ($p<0.001$), as well as with warmer temperatures ($p=0.008$) and longer residence times ($p=0.022$) for nitrate. Continued monitoring of Connecticut constructed wetlands can aid in ensuring more efficient reduction in nitrogen loads to Long Island Sound.

Introduction

As development encroaches upon natural landscapes, maintaining high quality surface waters for the protection of ecosystem and human health becomes increasingly challenging. Suburban stormwater runoff carries large amounts of nitrogen and other pollutants from fertilized lawns, septic systems, and atmospheric deposition (Driscoll et al. 2003). Nitrogen can fuel the growth of algal blooms, leading to the presence of toxic phytoplankton, eutrophication, and a strong odor (Meyer 1985, Collins et al. 2010). In an estuary, eutrophication coupled with seasonal stratification can result in severe problems as the die-off of these algal blooms depletes available oxygen in the bottom water column, sometimes resulting in fish kills (Vitousek 1997).

Seasonal hypoxic conditions in the bottom waters of central and western Long Island Sound (LIS) are a common occurrence, in part due to diffuse pollution delivered from the watershed (Committee on Environment and Natural Resources 2010). While concentrated efforts have been placed on reducing point source nitrogen pollution from sewage treatment plants in the LIS watershed, especially with the LIS Nitrogen Credit Exchange Program targeting 79 sewage treatment plants (Fisher-Vanden and Olmstead 2013), more emphasis needs to be placed on also mitigating nonpoint source nitrogen contaminants (NYSDEC/CTDEP 2000). Stormwater runoff contributes approximately 12,500 metric tons of total nitrogen per year to LIS (Committee on Environment and Natural Resources 2010). The remainder of the total nitrogen loading to LIS comes from the natural processes of weathering and nitrogen fixation adding roughly 10,000 metric tons per year, plus sewage treatment plants generating 38,000 metric tons in point source pollution each year (Committee on Environment and Natural Resources 2010). In western LIS, where hypoxia often has plagued the region for the past four decades due to nutrient enrichment and seasonal stratification (Parker and O'Reilly 1991), studies have indicated that squid, bluefish, and butterfish are among the most vulnerable species with the highest percentage loss in abundance as a result of low dissolved oxygen conditions (Howell and Simpson 1994). LIS hypoxia levels have been continuously monitored and assessed as a major issue of concern since 1985 by the LIS Study, a component of the Environmental Protection Agency National Estuary Program (Committee on Environment and Natural Resources 2010). In conjunction with these efforts, managers of LIS have set a goal of achieving a 10% reduction in nitrogen from nonpoint sources in Connecticut and New York (NYSDEC/CTDEP 2000). A recent study used a Generalized Watershed Loading Functions model to estimate the breakdown of nonpoint source total nitrogen loads reaching LIS as follows: 54% was generated from groundwater baseflow, 17% from urban runoff, 17% from septic systems, 5% from agricultural areas, and 6% from forested areas (Georgas et al. 2009). More robust stormwater management practices need to be implemented to attain the 10% reduction goal in nonpoint source nitrogen pollution, especially in light of continuing suburban sprawl.

Wetlands may provide a valuable–but understudied–ecosystem service by removing nitrogen from stormwater runoff (Hatt et al. 2009). Other measures taken to remove nitrogen from stormwater include bioretention systems, vegetated open channels, and green roofs (Weiss et al. 2007), but studies have shown that constructed wetlands exhibit the highest potential for stormwater management in terms of both efficiency and cost (Meyer 1985, Weiss et al. 2007, Collins et al. 2010, Liang et al. 2011, Tixier et al. 2011, Zhang et al. 2009). Constructed wetlands are manmade ecosystems built to resemble their natural counterparts in terms of function and use (Hogan and Walbridge 2007). Once considered only useful for stormwater storage to slow or prevent flooding, constructed wetlands are now being valued for their pollutant removal capabilities, as well as for the habitat that they provide for aquatic communities both within the wetlands and downstream (Tixier et al. 2011).

Two common nitrogen removal processes that occur in constructed wetlands are plant uptake (ultimately leading to sequestration in wetland organic matter) and denitrification (loss of nitrogen as N_2) (Baker 1998, Bachand and Horne 2000). Wetlands are expected to be ideal environments for both uptake and denitrification because of their high productivity and anoxic conditions, respectively (Cowen et al. 1976, Meyer 1985, Collins et al. 2010, Tixier et al. 2011). Denitrification rates have been found to be directly related to soil carbon levels, with highest levels occurring when the C:N ratio is greater than 5:1 (Baker 1998). A mixed – rather than homogeneous – plant community tends to lead to higher root density, which could enhance the rate of denitrification (Liang et al. 2011).

However, more research is needed to help improve mitigation of nonpoint source pollution and to enhance our understanding of nitrogen removal in Connecticut watersheds. Due to the high solubility of nitrogen, it has often been understudied in the literature with scientists more heavily focused on phosphorus or microbial contaminant levels (Hatt et al. 2009). With constructed wetlands being a widely used stormwater management tool in the region, it is necessary to evaluate their effectiveness with the state's unique climate, soils, and land uses. In addition, few studies have examined the inter-storm factors, e.g. water temperature, residence time, and influent nitrogen concentration, that might control nitrogen removal efficiency, especially under field conditions (Hatt et al. 2009). This knowledge could advance suburban stormwater management practices and provide practical guidelines based on the findings for future constructed wetland implementation projects.

Our study assessed the efficacy of a constructed wetland as a best management practice to remove nitrogen from stormwater runoff. Our objective was to evaluate the effectiveness of the constructed wetland at removing nitrogen from runoff and to assess the inter-storm variability in nitrogen removal in order to determine which variables (water temperature, residence time, and influent nitrogen concentration) might control this efficiency. We predicted that with plant uptake and denitrification being higher during the warmer months (Liang et al. 2011), there would be increased nitrogen removal in these warmer water temperatures, using water temperature as a proxy for determining seasonal variation. Denitrification rates also have been shown to increase with longer water residence times (Nixon et al. 1996), so we predicted that longer water residence times would allow for more nitrogen removal. In addition, previous studies have suggested that higher annual mean influent nitrogen concentrations at a site can result in increased nitrogen removal (Schueler 1996, Anisfeld 2010); thus, we predicted that the highest nitrogen removal would occur during storm events that had the highest influent nitrogen concentrations. In summary, we hypothesized that 1) the constructed wetland studied would have statistically significant nitrogen (N) removal; and 2) N removal would vary from storm to storm based on water temperature, residence time, and influent N concentration.

Methods

Site description

The study was done in Southern New England within the LIS watershed, which is home to more than 8 million people and covers an area of 45,050 km^2 extending through parts of six states and a Canadian province (NYSDEC/CTDEP 2000). The study site selected was a constructed wetland in a suburban area of Hamden, CT, near the intersection of Davis Street and Hartford Turnpike (Figure 1). The wetland is situated upstream of Lake Whitney, which is a source of drinking water for the town's residents (Milone & MacBroom 2002). The site drains an area of approximately 24 acres, with 5.52 acres (roughly 23% of the total drainage area) representing impervious surfaces (Milone & MacBroom 2002). The watershed area contains soils with a high potential for runoff (Milone & MacBroom 2002).

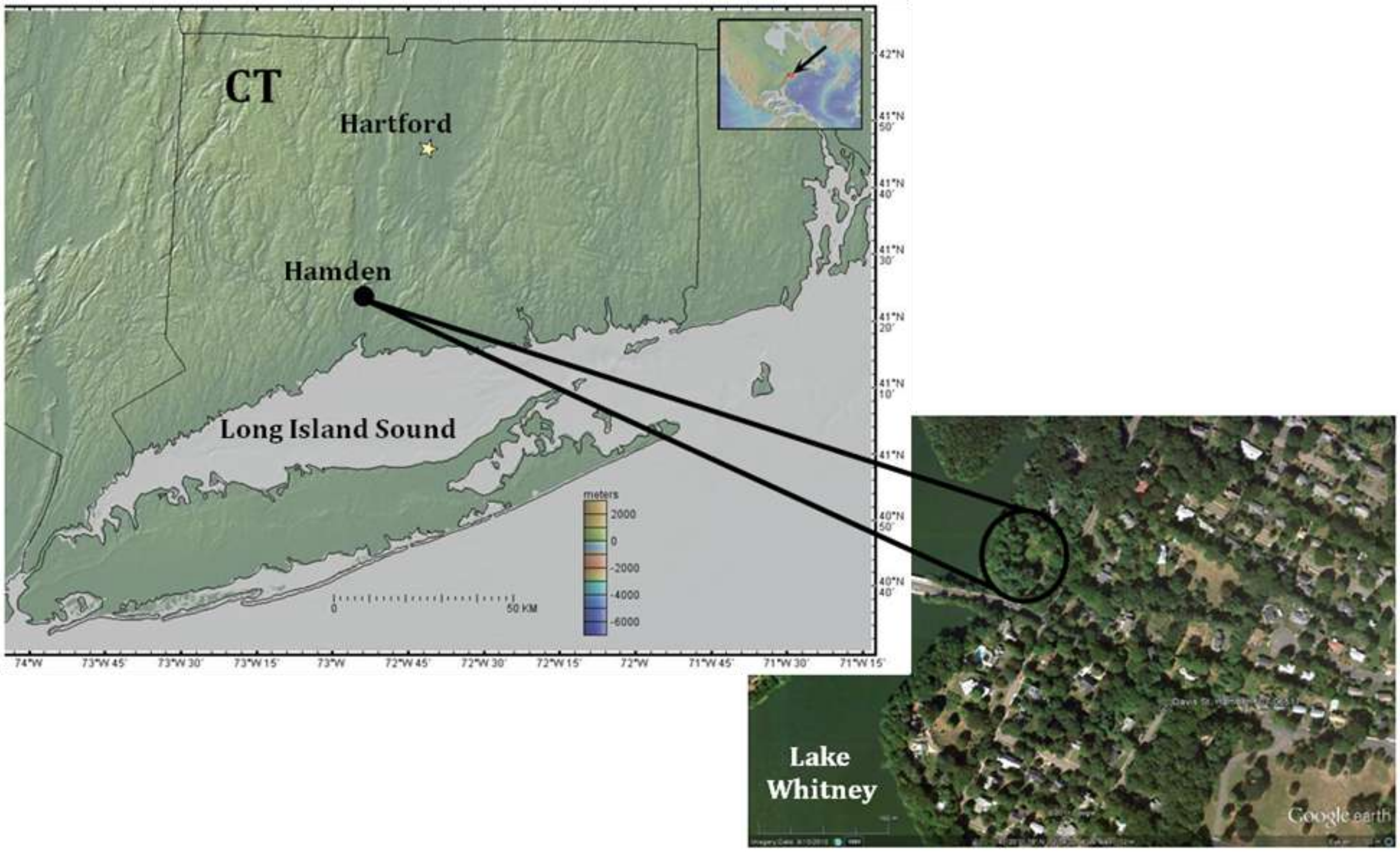


Figure 1: Constructed wetland site location in Hamden, Connecticut, marked with black dot (left) (Note: Left map created using GeoMapApp); Enlarged image of site in black circle (right), adjacent to Lake Whitney and Davis Street (Courtesy of Google Earth Images).

On average, Hamden has received about 50 inches of rain annually over the last ten years (Connecticut Agricultural Experiment Station 2012). The cleanliness of this runoff discharging into the Lake Whitney reservoir is critical. The wetland was constructed in 2002 by Milone and MacBroom, Inc., at the request of its landowner South Central Connecticut Regional Water Authority, so that runoff quality could be improved for the re-opening of the 154-acre Lake Whitney drinking water reservoir (Milone and MacBroom 2002). Previously closed in 1991, the reservoir returned to being used as a public drinking water supply with the accompaniment of a newly renovated water treatment plant in 2002 (Milone and MacBroom 2002). Consequently, our study site was chosen as a helpful model showcasing how to mitigate the spread of nonpoint source pollution in developed areas in order to promote human wellbeing and a healthy LIS.

The constructed wetland site is comprised of a single inlet pipe, three residence ponds, and a single outlet pipe. The three ponds are of varying size and serve different purposes. The first pond is a sediment forebay used to trap large sediments and litter as they enter the wetland after passing through the concrete culvert at the inlet. The second is a large open infiltration pond with no vegetation cover, except for occasional duckweed. The third is smaller than the infiltration pond and filled with mostly cattails (*Typha sp.*) and other native vegetation. After passing through the third pond, water discharges from the concrete culvert at the outlet into a small stream that leads directly to the Lake Whitney reservoir.

Sampling design and measurements

We calculated the input and output of N at the Hamden constructed wetland site for every storm event feasible during the periods of June - December 2011 and April - December 2012. In order to protect the equipment from freezing during the colder winter months, sampling was halted between January 2012 and March 2012. Additionally, there was little rainfall in late winter 2012, which delayed sampling. We measured both the flow of water and the concentration of N at both the influent and the effluent in order to calculate the N flux. A few storm events were missed due to malfunctioning equipment or other unforeseen circumstances, but every attempt possible was made to capture each storm event.

90° V-notch weirs made of wood were installed at both the inlet (20.6 cm high by 36 cm wide) and the outlet (20.4 cm high by 36 cm wide) to measure flow rates using the weir equation ($Q = d^{2.472}/66.8$, where d = depth in notch in cm and Q = flow in L/sec) (U.S. Bureau of Reclamation 2011). We measured the water level of the inlet and outlet at the site every five minutes using Solinst water level loggers. We also checked the weir equation with manual flow measurements.

Stormwater samples were collected at the influent and effluent using programmable ISCO 3700 autosamplers with a liquid level actuator to trigger the autosampler once the water level rose at the start of a storm event. Samples were taken every 6-12 minutes over the duration of the storm with five sub-samples placed in each bottle; thus, a single bottle represented 30-60 minutes of flow. We followed standard automated stormwater sampling protocol by sampling more quickly in the beginning and then staggering the samples over a more extended time interval, so that we could fully capture the first flush of nutrients that occurs at the start of a storm event (Clark et al. 2009). All bottles collected were composited manually into a flow-based composite sample, i.e., one flow-weighted sample per storm for each pipe (influent/effluent). For a few storms, bottles were kept separate in order to analyze the variation in concentration exhibited throughout the storm. Composite samples, along with the individual bottle samples, were filtered in the lab using Millipore Durapure filters with a 0.45 μm pore size. Raw and filtered samples were stored frozen until analysis. Samples were analyzed for: NO_3^-, Cl^-, and SO_4^{2-} (ion chromatography), total N (TN) and total phosphorus (TP) (persulfate digestion; flow analyzer), dissolved and total organic carbon (TOC analyzer), and total suspended solids (TSS) (filtration). The primary focus of analysis was NO_3^- and TN, but other parameters were useful as conservative tracers (Cl^-, SO_4^{2-}) or for assessing removal (TP, OC). Quality control measures included running calibration standards, blanks, lab replicates, spikes, and ultrachecks of known nutrient concentrations for every 10-15% of samples run on all instruments to ensure the accuracy of the nutrient data. During collection of samples, field replicates and field blanks were also collected, usually before a predicted storm event to acquire pre-storm conditions. A total of 73 storm events were captured between June 2011 and December 2012 at the Hamden site, with 369 samples, including dry period and field reps, collected in total.

To measure the three inter-storm parameters, Solinst water loggers recorded water temperature every five minutes at the influent and effluent, while also collecting water depth data. Water temperature was averaged over the duration of the storm event. Water residence times were calculated by dividing the volume of the wetland (sediment forebay and infiltration pond) by the volume inflow rate. Flow-weighted mean influent N concentrations were calculated for each storm event based on the lab analysis and flow data results described earlier.

Data analysis

Two types of statistical analysis were conducted to test our two hypotheses. First, the difference between influent and effluent concentrations was tested using parallel probability plots, as recommended by EPA (Geosyntec Consultants/Wright Water Engineers 2009). A statistically significant difference between influent and effluent, as tested with a paired t-test would support hypothesis 1. Second, we tested the effect of water temperature, residence time, and influent N concentration on N removal using a general linear model and a step-wise regression model, with individual storm removal efficiencies as the dependent variable. At the influent and effluent, this process was done by multiplying the flow rate by the N concentration to determine the N flux at a given time, which was then summed to provide the total N load over the duration of the storm event. Percent removal $[(\text{N Load}_{\text{IN}} - \text{N Load}_{\text{OUT}})/ \text{N Load}_{\text{IN}})*100]$ was then calculated to determine the N removal efficiency per storm event. This procedure was also performed for the other nutrient parameters measured, but the main focus was on N. Water temperature, residence time, and influent N concentration were then tested using the general linear model and a step-wise regression model. These findings tested hypothesis 2 by determining if there was significant variation between storm events based on the three proposed parameters.

Results

Between June 2011 and December 2011 and April 2012 and December 2012, 73 storm events at the Hamden constructed wetland site were sampled (Figure 2), 24 of which had inflow with no outflow. However, due to groundwater discharge, the outlet at the Hamden site continually flows, even during dry periods. Therefore, the N removal estimates presented are conservative values that would have been higher if the baseflow had been subtracted from the results. Still, the success of the site in N removal is evident from the results.

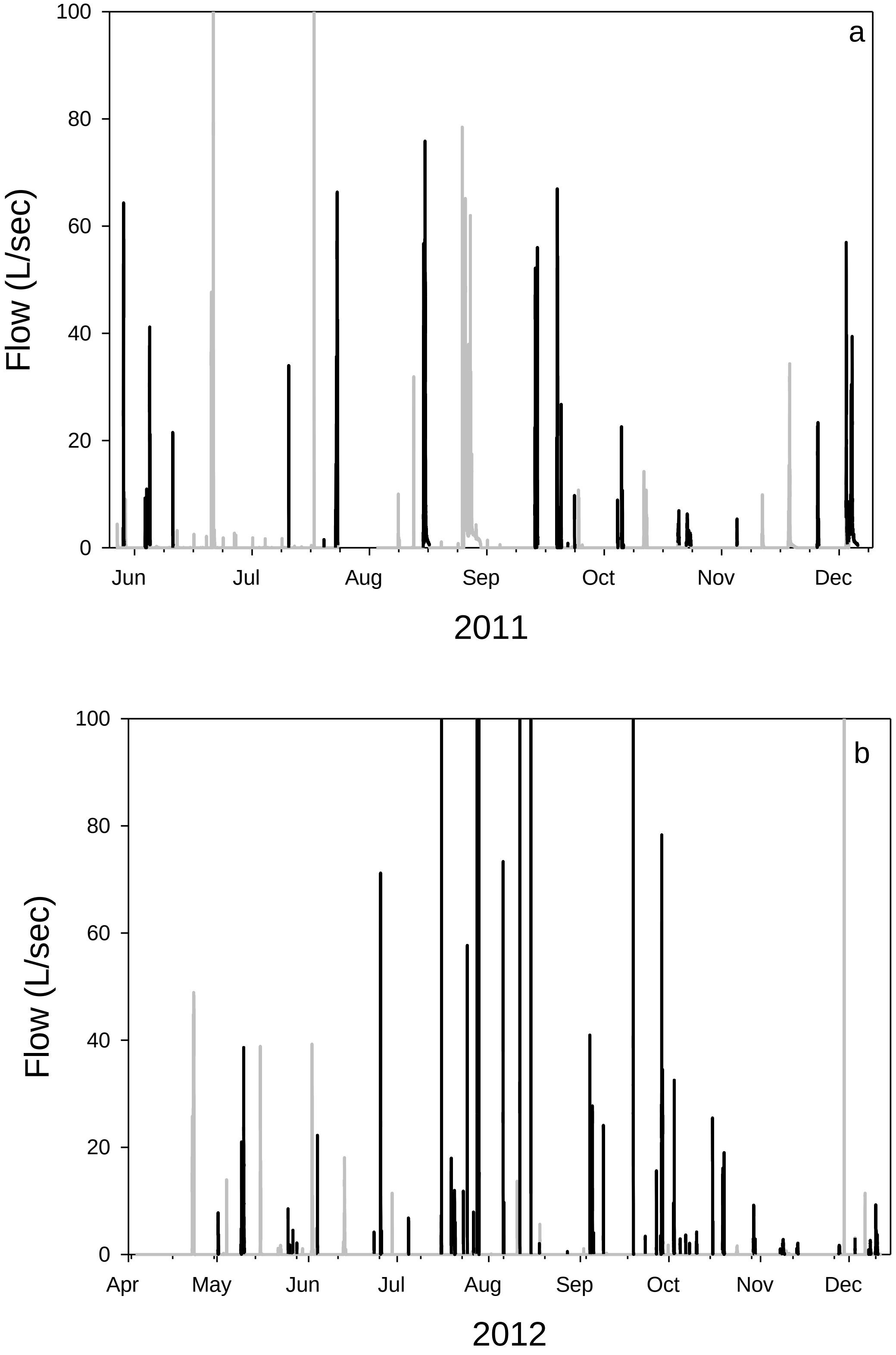


Figure 2: Flow for Davis influent (black lines represent storms sampled): a) Period 1 (6/2011-12/2011) and b) Period 2 (4/2012-12/2012)

In summary, the median storm event removal efficiency for all storms with outflow was approximately 60% for NO_3^- and 56% for TN; however, the removal rate was highly variable with a few storms even exporting N (Figure 3). Cl^- and SO_4^- showed relatively similar removal rates as water removal and were meant to serve as conservative tracers; however, most likely due to the baseflow contribution at the outflow, these nutrients tended to be higher in concentration at the outflow than the inflow.

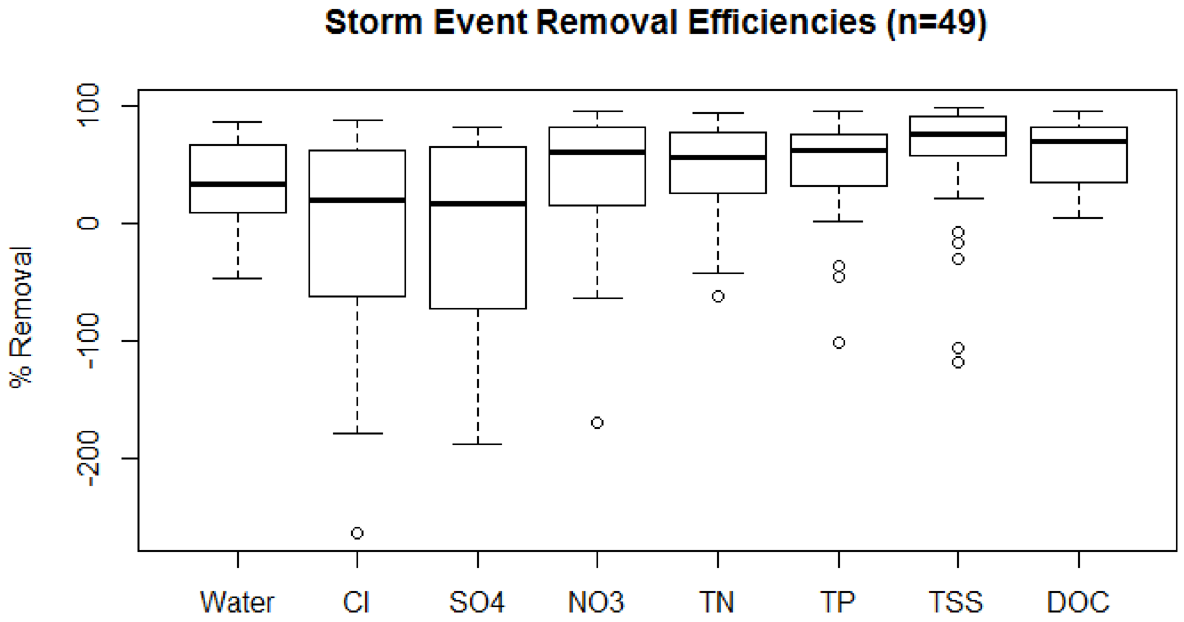
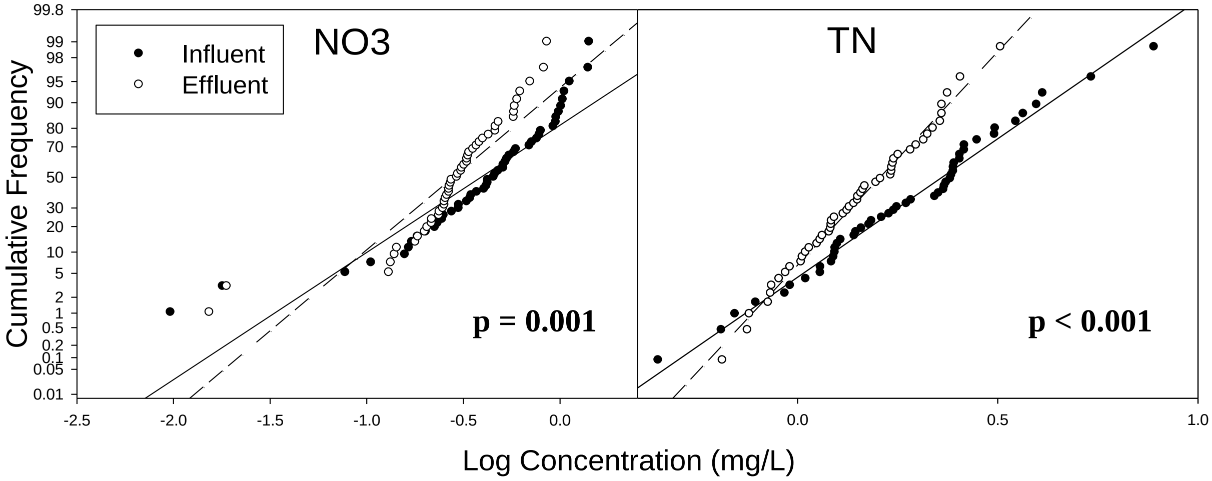


Figure 3: Storm event removal efficiencies (%) shown for all storms with outflow.

The site showed statistically significant N removal, supporting hypothesis 1. The log transformations of event mean concentrations passed the Shapiro-Wilk's normality test and a paired t-test showed statistically significant differences between the means of the influent and effluent for NO_3^- ($p=0.001$), TN ($p<0.001$), Cl^- ($p<0.001$), TSS ($p<0.001$), and SO_4^{2-} ($p<0.001$). A Wilcoxon signed rank test (due to the log transformation of TP and NPOC data failing the Shapiro-Wilk's normality test) showed a statistically significant difference between the influent and effluent mean concentrations for TP ($p<0.001$) and NPOC ($p<0.001$). TP, TSS, and NPOC also showed statistically significant removal rates. The results are displayed in parallel probability plots, which offer an extensive overview of the nutrient event mean concentration compared at the inlet and outlet for each storm event (Figure 4). With this statistical graphing method, the entire range of event mean concentrations observed over the period of sampling can be witnessed.



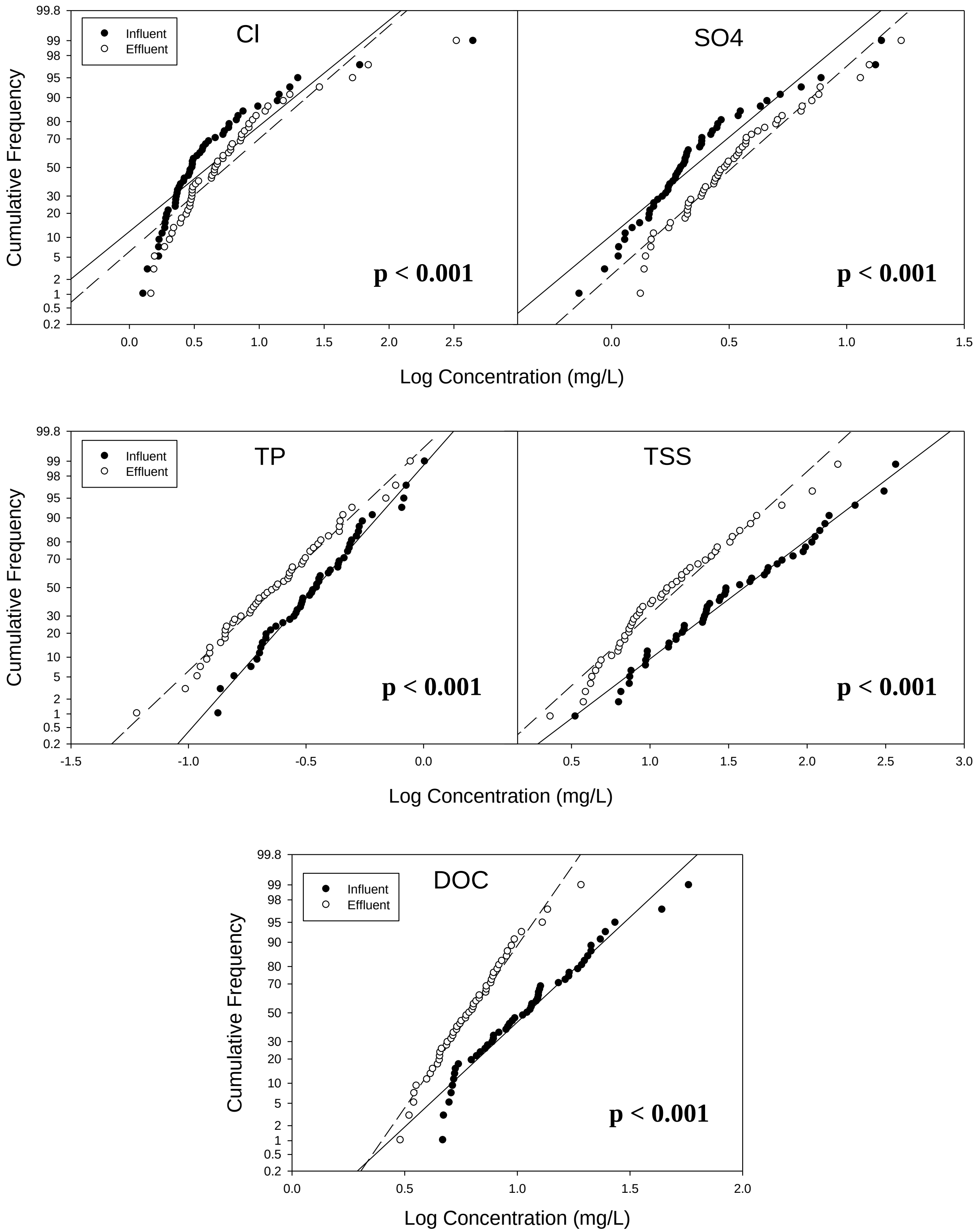


Figure 4: Parallel probability plots, as recommended by EPA, for NO_3^-, TN, Cl^-, SO_4^{2-}, TP, TSS, and DOC. Each dot represents an event mean concentration per storm event. Higher N removal efficiencies occurred when mean N influent concentrations were higher.

When performing a general linear model, mean N influent concentrations showed a statistically significant influence on N removal (NO_3^- : $p=0.002$, TN: $p<0.001$) (Tables 1 and 2). Higher N removal efficiencies occur when mean N influent concentrations are higher. Additionally, mean influent water temperature and residence time also had a statistically significant influence on NO_3^- removal with higher NO_3^- removal efficiencies occurring at warmer temperatures ($p=0.008$) and longer residence times ($p=0.022$) (Table 1). Mean water temperature and residence time did not have a statistically significant effect on TN removal (Table 2).

When conducting a forward step-wise regression model, only mean influent N concentration had a statistically significant effect on N removal ($p<0.001$ for both NO_3^- and TN) (Tables 3 and 4). Mean water temperature and residence time did not have a statistically significant influence on N removal (Tables 3 and 4). These findings support hypothesis 2 for NO_3^- removal, by showing that removal varies from storm to storm based on mean NO_3^- influent concentration according to both statistical tests, as well as mean water temperature and residence time, according to the general linear model. The findings partially support hypothesis 2 for TN removal, by demonstrating that individual storm removal efficiencies are driven by mean TN influent concentration, according to both statistical analyses.

Table 1. General Linear Model Results for NO_3^- Removal

Parameter	**p-value**
Mean Influent NO_3^- Concentration (mg/L)	0.002
Mean Influent Water Temperature (°C)	0.008
Residence Time (s)	0.022

Table 2. General Linear Model Results for TN Removal

Parameter	**p-value**
Mean Influent TN Concentration (mg/L)	<0.001
Mean Influent Water Temperature (°C)	0.719
Residence Time (s)	0.499

Table 3. Forward Step-wise Regression Model Results for NO_3^- Removal

Parameter	**p-value**
Mean Influent NO_3^- Concentration (mg/L)	<0.001
Mean Influent Water Temperature (°C)	0.110
Residence Time (s)	0.406

Table 4. Forward Step-wise Regression Model Results for TN Removal

Parameter	**p-value**
Mean Influent TN Concentration (mg/L)	<0.001
Mean Influent Water Temperature (°C)	0.342
Residence Time (s)	0.266

Tables 1-4: Summary of the influence of the three parameters (mean influent N concentration, water temperature, and residence time) on N removal (NO_3^- and TN). General linear model (Tables 1 and 2) and forward step-wise regression model (Tables 3 and 4) results presented. Higher N removal efficiencies occur at higher mean influent N concentrations.

Discussion

This study showcases the importance of better understanding the inter-storm variability in N removal in CT constructed wetlands to learn which factors control their optimal performance. Once these parameters are known, more well-informed design and management strategies can be instigated in CT, a region in which these tools are frequently used as stormwater best management practices in the LIS watershed.

N removal at the Hamden site is a product of both hydrological and biogeochemical conditions. On the one hand, more water flows into the wetland than out of it due to its successful storage and infiltration abilities. For certain storm events, runoff discharged into the wetland, but no outflow was generated, showing hydrological N removal. On the other hand, plant uptake and denitrification processes enable the effluent N concentration to be less than the influent N concentration. Both types of processes contribute to the overall N removal efficiency for each storm event. It is also important to take into account the pre-storm conditions and capacity of the wetland. Lengthier water residence times can result from smaller magnitude storms and/or larger pre-storm storage capacity in the wetland.

Mean N influent concentration was a significant factor of N removal performance, with higher event mean influent concentrations leading to higher rates of removal. This result shows that the constructed wetland is more efficient when incoming N concentrations are higher and runoff quality conditions are worse. As other past studies have noted, there is an irreducible concentration and wetlands do not have as much room for removal success at lower levels, even though the concentrations being discharged in the effluent are still relatively low (Schueler 1996). Consequently, it is important to look at the event mean concentrations closely, in addition to N removal efficiencies, to more fully grasp the impairment situation from nonpoint sources.

Furthermore, according to the general linear model, warmer temperatures and longer residence times also played an integral role in NO_3^- removal rates, which could be, in part, due to denitrification rates being higher in the summer months and longer residence times allowing for more nutrients to be filtered from the stormwater treatment system.

Conclusion

Constructed wetlands are a common tool in CT to better manage suburban runoff; therefore, they must be tested under field conditions to verify their removal capabilities. Often times, funds are limited to monitor best management practices after they are installed; however, it can lead to ensuring more efficient reduction in N loads to Long Island Sound.

This case study demonstrates that the storm parameters of mean NO_3^- influent concentration, water temperature, and residence time are drivers of NO_3^- removal, while mean TN influent concentration also influences TN removal. Based on this evidence, future work can continue to build upon this study to predict how well constructed wetlands generally will perform under a variety of conditions.

Additional research includes testing more constructed wetlands to make inter-site comparisons in N removal to see if there are statistically significant differences based on vegetation, ratio of watershed area to treatment area, and surrounding land use. These factors also could play pivotal roles in N removal.

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