Water quality before and after watershed-scale implementation of stormwater wet ponds in the coastal plain

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A B S T R A C T

Wet ponds have been used extensively for stormwater control throughout the US, including coastal areas. Despite the widespread application of these water control structures, few studies have investigated how watershed-scale implementation of wet ponds affects downstream water quality or how the pollutant removal efficacy of wet ponds changes over time in a coastal setting. This study utilizes a seven year data set of nutrient, total suspended solid, and chlorophyll-*a* concentration data collected during baseflow and stormflow from two coastal headwater streams draining a developed (28% impervious) and an undeveloped (1.2% impervious) watershed. The seven year record encompasses before, during, and after a large construction project and concurrent implementation of wet ponds in the developed watershed that drain 97% of the watershed area. Additional nutrient, total suspended solid, and chlorophyll-*a* concentration data were collected from within a wet pond in the developed watershed during baseflow over a single spring and summer. A comparison of stream water quality before and after the construction project and wet pond implementation in the developed watershed showed that mean chlorophyll-*a*, nitrate-nitrite (NO_x^-), organic nitrogen, and total suspended solid concentrations significantly increased, the mean orthophosphate (PO_4^{3-}) concentration significantly decreased, and the mean ammonium (NH_4^+) concentration did not change. Over a three year time period after construction and pond implementation, developed stream chlorophyll-*a*, ammonium, and organic nitrogen concentrations decreased, and nitrate-nitrite, orthophosphate, and total suspended solid concentrations increased compared to the reference stream during the same period, indicating changes in pollutant removal capacity. A comparison of baseflow and stormflow samples during the Post period and samples from a wet pond in the developed watershed indicated that ponds were functioning as sources of chlorophyll-*a* and total suspended solids to the stream and sinks for nitrate-nitrite. Overall, watershed-scale implementation of wet ponds in the developed watershed failed to mitigate many negative water quality impacts caused by increased development. This study suggests that centralized stormwater management may not be optimal for maintaining water quality in coastal environments, and that pond retrofits combined with frequent excavation could improve pollutant removal by wet ponds. Further research on the effects of nutrient cycling in coastal wet ponds and wet pond maintenance is needed.

1. Introduction

Nearly 80% of the US population lives in urban areas, and this percentage is increasing (U.S. Census and Bureau, 2010). Concomitantly, the amount of impervious area is increasing due to the expansion of urban and sub-urban areas (Terando et al., 2014). Specifically, the coastal plain of the southeastern US is predicted to experience urban expansion over the next 50 years (Terando et al., 2014). Despite known negative impacts of stormwater runoff from urban areas on coastal stream hydrology and water quality, research on stormwater mitigation techniques in coastal regions is very limited when compared to extensive research in non-coastal regions (Ex. DeLorenzo et al., 2012; EPA National Estuary Program, 2014; Lewitus et al., 2008; Merriman et al., 2016; Serrano and DeLorenzo, 2008). Coastal stormwater managers apply similar stormwater control measures (SCMs) as managers in non-coastal areas and have the same priorities for water quantity and quality (Collins et al., 2010). To test the assumption that stormwater management in coastal systems and non-coastal systems can be approached the same way, it is necessary to determine the effects

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of prevalent types of SCMs, particularly wet ponds, on the water quality of coastal watersheds.

The effects of increased watershed impervious area on streams are well-studied and predictable in most geographic regions of the US, including coastal systems (Ex. O'Driscoll et al., 2009; O'Driscoll et al., 2010). As watershed impervious area increases, more runoff is generated from storm events, and evaporation and infiltration within the watershed decreases. Typically, the total volume of water leaving a watershed increases due to an increase in stormflow and a decrease in baseflow (Booth and Jackson, 1997; O'Driscoll et al., 2010; Paul and Meyer, 2001; Walsh et al., 2005), although the effect of increased impervious area on baseflow dynamics can vary (Price, 2011). Changes in catchment hydrology due to development generally leads to lower stream biota diversity, increased loading of nutrients and other pollutants, and channel incision or enlargement (Goetz and Fiske, 2008; Paul and Meyer, 2001; Walsh et al., 2005). Similar effects have been observed in urban areas within the southeastern coastal plain of the US (O'Driscoll et al., 2009; O'Driscoll et al., 2010; Sanger et al., 2013).

Conventional stormwater management has focused on the objectives of flood mitigation and pollutant removal (Burns et al., 2012; Walsh et al., 2016), and most SCMs have focused on detaining stormwater and slowly releasing it to lower peak flows (Collins et al., 2010). The most prevalent kind of SCM is a wet pond, which is designed to hold a large volume of runoff and retain a permanent pool of water (Collins et al., 2010). Wet ponds are primarily intended to mitigate increased surface runoff from impervious surfaces during storms by lowering peak stormflows and extending the hydrograph (Hancock et al., 2010), but the effects of these ponds on downstream water quality are not well constrained. In some cases wet ponds have been shown to offer valuable ecosystem services, such as increased biodiversity (Hassall and Anderson, 2014; Moore and Hunt, 2012), carbon sequestration (Moore and Hunt, 2012), and nutrient and suspended sediment retention (Bettez and Groffman, 2012; McPhillips and Walter, 2015; Rosenzweig et al., 2011). Conversely, some studies have shown that wet ponds failed to meet regulatory goals for stream channel protection (Hancock et al., 2010), increased nutrient loading at times (Duan et al., 2016; Rosenzweig et al., 2011), created longer periods of erosive stormflow (Tillinghast et al., 2011), increased heavy metal concentrations (Stephansen et al., 2014; Wium-Andersen et al., 2011), and grew harmful algae and bacteria (DeLorenzo et al., 2012; Lewitus et al., 2008).

The implementation of wet ponds may have distinctive effects on water quality in coastal watersheds in the southeastern US due to the landscape's high water table, low relief, soil type, and biogeochemistry. Many coastal watersheds in the southeastern coastal plain have soils and natural hydrologic and biogeochemical processes that produce blackwater streams – streams characterized by large amounts of dissolved organic matter and low concentrations of chlorophyll-*a* and suspended sediments (Meyer, 1990). The optical properties, nutrient concentrations, and suspended sediment concentrations of the blackwater naturally found in coastal streams is significantly different than the water funneled into wet ponds from impervious surfaces (Piehler et al., in prep). Few studies have investigated the effects of watershed-scale implementation of wet ponds on coastal stream water quality, but many of the SCMs in coastal NC counties are wet ponds or dry ponds (NCDEQ, 2017). Previous research on coastal stormwater management has focused on water quality in tidal and brackish water or on single SCMs (Ex. DeLorenzo et al., 2012; Lewitus, 2008; Merriman et al., 2016; Serrano and DeLorenzo, 2008). Improving and broadening the understanding of watershed-scale stormwater management in coastal areas will have clear implications for coastal water quality, public health, and estuarine ecology.

Another unresolved issue is how pollutant removal functions of coastal wet ponds may change over time. Wet ponds fill in with vegetation and sediment over time, but the establishment of vegetation in deeper parts of the ponds is discouraged (Mitsch and Jørgensen, 2004). The excavation of in-filled areas every few years in wet ponds and wetlands is required to maintain water storage capacity and sediment and phosphorus removal (Hunt and Lord, 2006; Merriman and Hunt, 2014). This wet pond maintenance, like most SCM maintenance, is often overlooked but recommended (Blecken et al., 2015). Understanding how stream water quality from a coastal watershed outfitted with stormwater wet ponds changes over time will inform plans for excavation to maximize nutrient and suspended sediment removal and demonstrate the need for maintenance in coastal wet ponds. Few studies have investigated how the pollutant removal function of SCMs changes over extended periods of time (ex. Merriman and Hunt, 2014; Merriman et al., 2016), and none have been conducted on wet ponds in a coastal watershed.

Here we examined the effects of watershed-scale wet pond implementation and increased development on coastal stream water quality by analyzing a time series of nutrient, total suspended solids, and chlorophyll-*a* concentration data. Assessing the efficacy of coastal wet ponds through analysis of data before and after wet pond implementation offers a unique opportunity to understand the role these structures play in shaping coastal water quality and mitigating the negative effects of increased development. Our data span seven years, encompassing before, during, and after increased development and concurrent implementation of wet ponds in a developed coastal watershed and parallel sampling in a minimally developed reference coastal watershed aboard US Marine Corps Base Camp Lejeune in coastal North Carolina.

The goals of this study were to:

1 Quantify the changes in stream chemistry that occurred due to increased development and the watershed-scale implementation of wet ponds.
2 Identify trends in stream nutrient and suspended sediment concentrations after development and the implementation of wet ponds.
3 Determine if wet ponds were functioning as sources or sinks for nitrogen and phosphorus, suspended sediments, and chlorophyll-*a*.
4 Assess implications for future coastal stormwater management and wet pond management along the US Southeastern coast and other similar systems.

2. Site description

Study watersheds sampled were located aboard US Marine Corps Base Camp Lejeune in Jacksonville, NC in the coastal plain of North Carolina (Fig. 1). Camp Lejeune is the largest US Marine base in the world, employing 170,000 people and covering an area of 640 km^2 (http://www.lejeune.marines.mil/About.aspx). Camp Lejeune surrounds the New River Estuary, and has installed over 200 wet ponds to mitigate negative hydrologic impacts of increased impervious area on coastal streams. The New River Estuary, like many other estuaries in NC, has experienced intense eutrophication in the past due to high levels of nutrient loading (Mallin et al., 2005), so understanding the effects of stormwater management on nutrient dynamics is imperative. The two study streams drain into the New River Estuary but did not experience significant tidal fluctuations or any salinity during the study period.

The developed watershed (70 ha, 28% mean imperviousness (Xian et al., 2011)) for this study is located in a residential neighborhood called Tarawa Terrace on the northern boundary of the

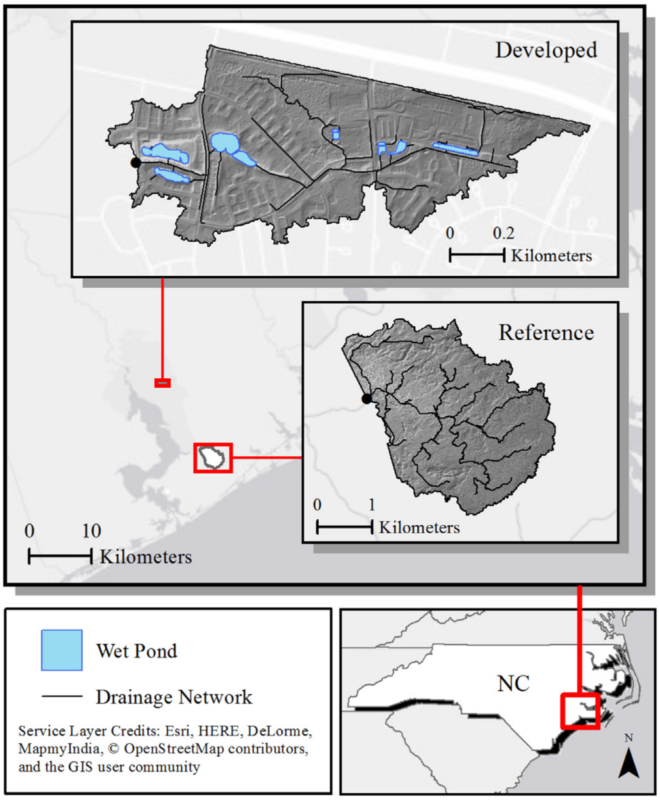

Fig. 1. Location of study watersheds within North Carolina and hillshade with drainage network and wet ponds.

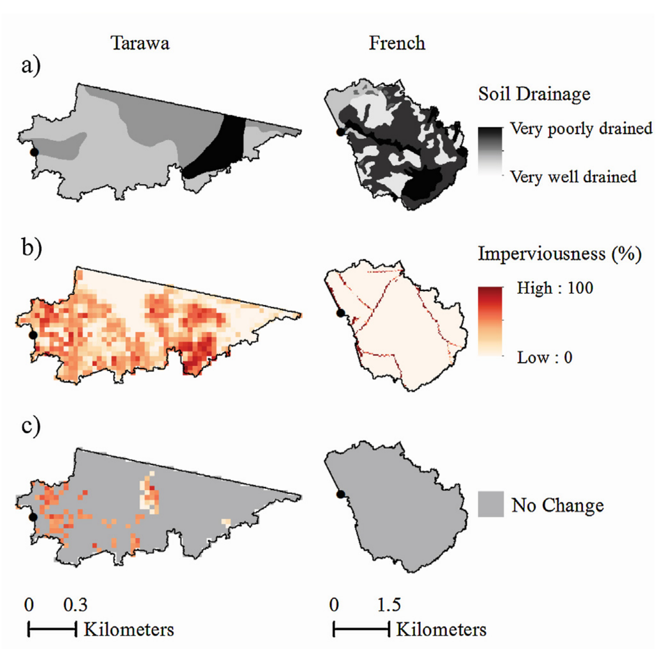

Fig. 2. a) SSURGO soil drainage of the study watersheds b) 2011 National Land Cover Database percent imperviousness c) 2006 – 2011 change in imperviousness.

estuary (Fig. 1). Between January 2009 and March 2011, the existing homes were demolished and completely rebuilt. This development increased the mean imperviousness of the watershed by 5.2% (Fig. 2). Seven wet ponds were constructed during this time period, covering 2.4 ha (3.4% of the watershed area) and receiving nearly all surface water drainage from the watershed (97% of watershed area, 68 ha). By the end of the study, all wet ponds were fringed with marsh vegetation, mainly cattails (*Typha* spp.), and each pond had alligator weed (*Alternanthera philoxeroides*) established at the permanent pond surface that reached into the open water, covering approximately 30% of the pond surface.

The French Creek watershed (835 ha, 1.2% mean imperviousness (Xian et al., 2011)) was the reference watershed for this study (Fig. 1). The watershed has been partially cleared but contains large areas of woody wetlands and shrubs, has very low levels of imperviousness, and exhibits characteristics of an undeveloped blackwater coastal stream system (Fig. 2). This watershed encompasses a bombing range and some gravel roads. The reference watershed is located on the eastern side of the New River Estuary and does not have any SCMs (Fig. 1). This watershed maintained its hydrologic patterns and blackwater characteristics during this study.

The developed watershed's soils are primarily well-drained and moderately well-drained (Soil Survey Staff, 2015), although the soil classification in the developed watershed incorporates the extensive development and storm sewer drainage (Fig. 2). There is a patch of very poorly-drained soil near the top of the watershed. The outlet of the watershed is located next to the outlet of two wet ponds, and a third wet pond is located approximately 0.35 km from the watershed outlet within the stream network (Fig. 1). Four more wet ponds are located higher in the watershed. Reference watershed soils are a mix of poorly-drained and well-drained soils (Soil Survey Staff, 2015), and the natural stream drainage network is unaltered (Fig. 2).

French watershed was selected as a reference in this study because of its proximity to the developed watershed, its low amount of impervious area, and its lack of disturbance during the time period of construction in the developed watershed, despite distinctions in watershed soil types and watershed area. Although not considered a control, this study uses French as a reference with the aim of comparing temporal trends in nutrient, total suspended solids, and chlorophyll-*a* concentrations in each watershed's stream.

3. Methods

Sampling occurred over a period of seven years, beginning in January 2008 and ending in June 2015 for both the developed and reference watersheds. Water samples from each watershed's stream were collected every two weeks during baseflow and throughout the course of one storm event each month. Samples during storm events were collected using Teledyne Isco automatic water samplers programmed to collect samples after the stream velocity passed a certain threshold that was unique for each stream and paced to provide samples from the rising limb, peak, and falling limb of the storm hydrographs. Storm samples collected by Isco's were transported as quickly as possible (always within 48 h of the storm event) for sample processing at the University of North Carolina at Chapel Hill's Institute of Marine Sciences (UNC IMS). Water samples were analyzed for concentrations of nitrate-nitrite (NO_x^--N, μM), ammonium (NH_4^+, μM), orthophosphate (PO_4^{3-}, μM), total nitrogen (TN, μM), organic nitrogen (ON, μM), chlorophyll-*a* (chl-*a*, μg/L), and total suspended solids (TSS, mg/L). All data were Log_{10}-transformed before analysis to fit assumptions for parametric statistical testing. A value of 10^{-6} was added to all data before log transformation due to multiple values of zero (below detection limit) in the data set.

Water quality data for each stream were partitioned into three time periods based on the timing of construction in the developed watershed: Pre-Construction (Pre), Construction (Mid), and Post-Construction (Post) (Table 1). This delineation enabled comparison

Table 1
Sampling dates for each period of development. n represents the number of water samples collected for concentration measurements during each period.

	Start	*End*	*Developed stream sample n*	*Reference stream sample n*
Pre	January - 2008	December - 2008	27	94
Mid	December - 2008	March - 2011	–	–
Post	March - 2011	July - 2015	256	234

among time periods and between watersheds. This study focused on the differences between the Pre and Post periods. While changes in water quality were evident during the Mid period, this study does not offer conclusions about this period because the effects of disturbance from the construction activities and the effects of wet ponds cannot be differentiated. The Mid period was part of the data record, but was not explicitly analyzed as part of this study.

A Student's *t*-test ($\alpha = 0.05$) was performed on the Log_{10}-transformed nutrient, TSS, and chl-*a* data to determine if there were significant differences in any of the water quality variables between Pre and Post development periods for both streams. Nutrient, TSS, and chl-*a* concentration data from the developed stream were parsed into samples collected at baseflow and stormflow, and the same methodology above was used to determine if there were significant differences between time periods for both baseflow and stormflow for each water quality variable.

A linear model was created for each variable measured during the Post period for each stream using the date of sampling as the independent variable and unaltered concentration measurements as the dependent variable. Concentration values were predicted for each variable for each stream using the corresponding linear model for the beginning and end of the Post period. The predicted change in each variable for the reference stream was subtracted from the predicted change in each variable for the developed stream to remove natural trends in concentration data. The reference stream did not experience significant anthropogenic disturbance during this study, so any trends in water quality variables in the reference stream during the Post period were assumed to be trends unrelated to development. These trends in concentration data could hypothetically be driven by changes in precipitation (ex. dilution vs. concentration) or temperature over the course of the Post period. After trends exhibited by the undeveloped watershed were removed, the developed stream's predicted change for each variable was divided by the developed stream's predicted values for the beginning of the Post period and multiplied by 100 to calculate percent relative change.

Finally, a Student's *t*-test ($\alpha = 0.05$) was performed on Log_{10}-transformed nutrient, TSS, and chl-*a* concentration data to compare baseflow and stormflow concentrations during both the Pre and Post periods. To investigate the role of wet ponds as a source or sink for various water quality variables, a paired Student's *t*-test ($\alpha = 0.05$) was performed on Log_{10}-transformed nutrient, TSS, and chl-*a* concentration data to compare water quality concentrations at baseflow from the developed stream and a developed watershed wet pond between mid-March 2015 and the end of June 2015.

All statistical analyses were performed in R (version 3.1.2). Maps were created using Environmental Systems Research Institute (ESRI) ArcMap (version 10.2.2). Imagery, elevation data, and SCM data were provided by US Marine Corps Base Camp Lejeune.

4. Results and discussion

4.1. Impacts of wet pond implementation: comparing pre and post periods

Stormwater managers in both coastal and non-coastal areas utilize similar SCMs and overall management goals (Collins et al., 2010), but the coastal plain presents distinct conditions for stormwater management such as flat topography, high water table, proximity to recreational and ecological resources, high cost of land, and complications associated with tidal influences (EPA National Estuary Program, 2014). To determine the efficacy of wet ponds in a coastal watershed, we examined changes in stream water quality using long-term data collection in 2 representative coastal plain watersheds, one largely undeveloped and one that was further developed and outfitted with wet ponds during the study.

There were significant changes in the mean concentrations of all variables except NH_4^+ in the developed (Tarawa) watershed's stream between the Pre and Post periods (Fig. 3). In the less developed reference (French) watershed's stream, mean chl-*a* and NH_4^+ concentrations both significantly increased between the Pre and Post periods, but the magnitude and percent change in the mean chl-*a* concentration was smaller than in the developed stream and NH_4^+ increased while the developed stream slightly decreased, but not significantly (Fig. 3). This multi-year data record indicates that the installation of the SCMs during the construction phase in the developed watershed did not result in water quality on-par with the Pre conditions.

4.1.1. Nitrogen

Human modification of the nitrogen cycle has been extraordinary (Vitousek et al., 1997). In coastal areas, excessive nitrogen loading has led to impairments of many of the world's estuaries (Bricker et al., 2008). In areas where nitrogen loading to estuaries is excessive, any sinks and/or processes that remove nitrate from the system become increasingly important (Brush, 2008). Coastal stream networks have been shown to be significant sinks for nitrogen, reducing the load delivered to estuaries (Thompson et al., 2000). Wet ponds are presumed to be nitrogen sinks and enhance nitrogen removal, but there are few long-term measurements and fewer still in the coastal plain. In nitrogen-sensitive, eutrophic coastal plain ecosystems, sinks for excess nutrients are ecologically and economically valuable (Piehler and Smyth, 2011). In order to determine whether wet ponds are detrimental or beneficial to estuaries in terms of nitrogen processing, we analyzed a record of nitrogen concentrations before and after the installation of stormwater ponds.

In this study, the mean developed stream NH_4^+ concentration did not change significantly between Pre and Post periods (Fig. 3). The mean concentration did significantly decrease during baseflow but not during stormflow between Pre and Post periods (Fig. 4). The reference stream showed a significant increase in the mean NH_4^+ concentration of 0.22 ± 1.05 μM, or 21.84%, between Pre and Post (Fig. 3, Table A1). The increase of the mean NH_4^+ concentration in the reference stream and decrease in the mean baseflow concentration in the developed stream between Pre and Post indicates that wet ponds or the stream in the developed watershed may have functioned as NH_4^+ sinks (Fig. 3, Fig. 4). Possible mechanisms for the observed decrease of baseflow NH_4^+ concentration could include the storage of NH_4^+ in pond vegetation (Mallin et al., 2002), uptake by pond phytoplankton (Lewitus et al., 2008), or the transformation of NH_4^+ into NO_x^- via nitrification in the pond or stream (Collins et al., 2010).

The mean NO_x^- concentration increased by 1.97 ± 4.85 μM in the developed stream, a 51.8% increase, between Pre and Post

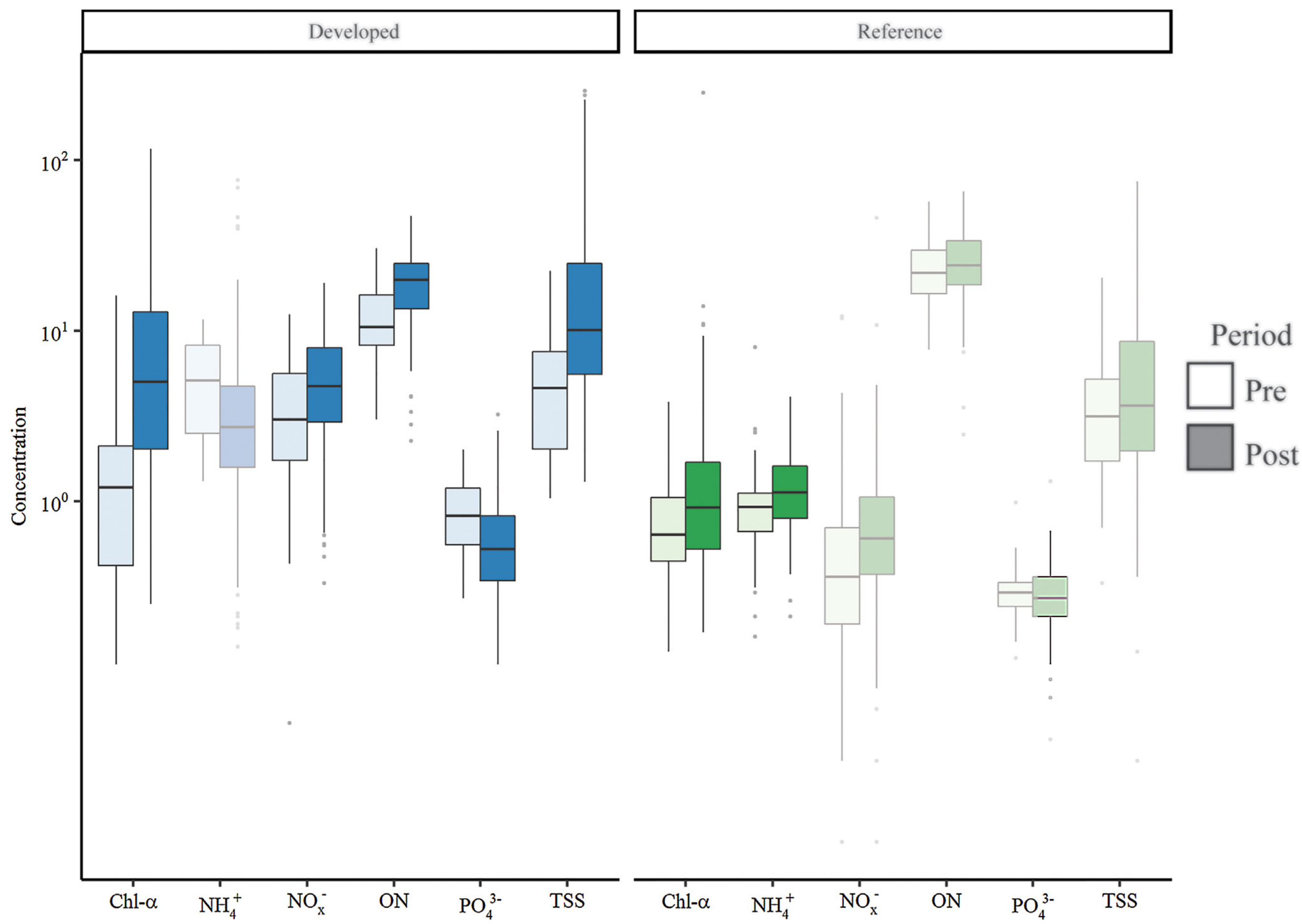

Fig. 3. Nutrient, total suspended solid, and chlorophyll-a concentrations for the Pre and Post periods of development. Full color boxplots indicate water quality variables that changed significantly between Pre and Post periods based on Student's *t*-tests (α = 0.05).

periods (Fig. 3, Table A1). The mean concentration of NO_x^- significantly increased during baseflow but not stormflow in the developed stream between Pre and Post (Fig. 4). There was no significant increase of the mean NO_x^- concentration in the reference stream (Fig. 3). The increased mean baseflow concentration of NO_x^- in the developed stream could be caused by increased impervious and lawn area (Table A4), which can increase NO_x^- inputs from the atmosphere (Kaushal et al., 2011) and fertilizer (Osmond and Hardy, 2004). The majority of nitrogen export in suburban areas occurs during low flows (Groffman et al., 2004; Shields et al., 2008), indicating that sources of nitrogen within the watershed are exported to the stream by high-frequency, low-intensity storm events that bypass stormwater infrastructure (Groffman et al., 2004). Alternatively, channelization of the stream due to increased runoff or elevated wet pond discharge could disconnect the stream from its floodplain, an important area for NO_x^- removal (Newcomer Johnson et al., 2014). A third possible mechanism for the increase in the mean baseflow NO_x^- concentration in the developed stream is the conversion of NH_4^+ into NO_x^- via nitrification (Collins et al., 2010) since the mean baseflow NH_4^+ concentration decreased as well. No change in the mean stormflow concentration of NO_x^- in the developed stream indicates that the ponds are not a source of NO_x^- when flushed during storms (Fig. 4).

The mean ON concentration in the developed stream increased by 7.15 ± 10.38 μM, or 57.93%, between Pre and Post periods (Fig. 3, Table A1). Mean baseflow concentrations and stormflow concentrations significantly increased (Fig. 4). No significant change in mean ON concentrations was observed in the reference stream (Fig. 3). Wet ponds could be sources of ON during baseflow and when flushed during storm events. Possible mechanisms for this increase could be vegetation and algal biomass supported by ponds.

4.1.2. Phosphorus

Excess concentrations of phosphorus in freshwater, specifically orthophosphate (PO_4^{3-}), can cause eutrophication issues much like those caused by nitrogen in ocean or estuarine waters (Correll, 1998). The New River Estuary has historically experienced eutrophication issues with connections to phosphorus enrichment from sewage treatment plants (Mallin et al., 2005), so keeping phosphorus concentrations low is known to be important for maintaining the health of the estuary. Stormwater ponds are thought to remove phosphorus by enhancing settlement of phosphorus-sorbed suspended sediments (Nairn and Mitsch, 2000) or uptake by vegetation (Kadlec, 2016) and algae (Nairn and Mitsch, 2000). Phosphorus removal is thought to be a major benefit of stormwater ponds, but SCMs have been known to become phosphorus saturated over time (Hunt and Lord, 2006; Merriman and Hunt, 2014) and even become sources of phosphorus during low flows due to anoxic sediments (Duan et al., 2016).

Comparing before and after the implementation of wet ponds, the developed stream mean dissolved PO_4^{3-} concentration decreased by 0.30 ± 0.65 μM, or 32.24% (Fig. 3, Table A1). Mean stormflow and baseflow dissolved PO_4^{3-} concentrations in the developed stream both significantly decreased. There was no significant change of the mean dissolved PO_4^{3-} concentration in the reference stream (Fig. 3). The decrease in the developed stream

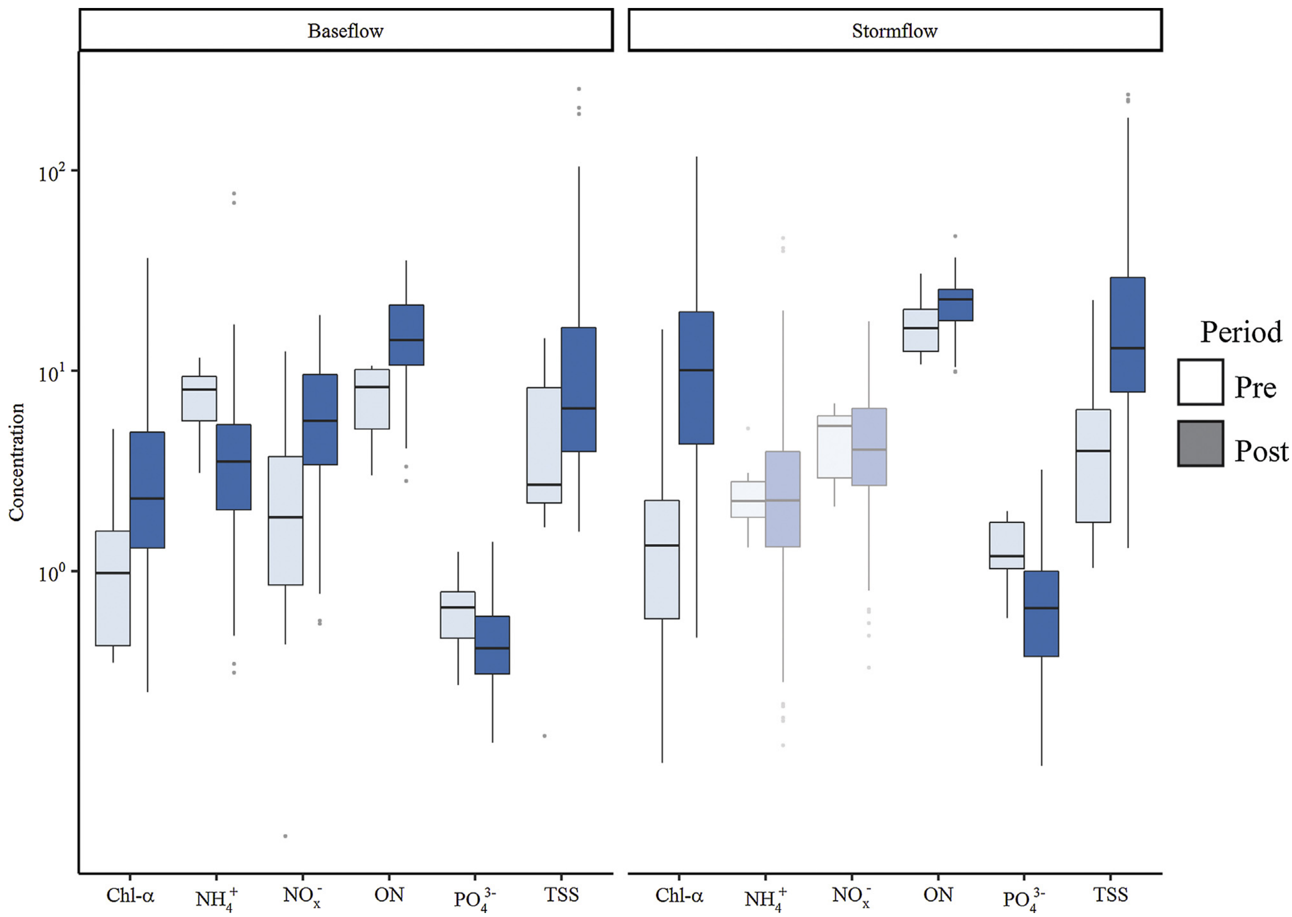

Fig. 4. Nutrient, total suspended solid, and chlorophyll-a concentrations from the developed stream for the Pre and Post periods of development for baseflow and stormflow water samples. Full color boxplots indicate water quality variables that changed significantly between Pre and Post periods based on Student's *t*-tests ($\alpha = 0.05$).

mean dissolved PO_4^{3-} concentration and no change in the reference stream indicates that wet ponds lowered the mean PO_4^{3-} concentration within the stream, especially during storm events (Fig. 3, Fig. 4). These data show that wet ponds may be effective at reducing mean dissolved PO_4^{3-} concentrations either by sorption to suspended sediments that settle out (Nairn and Mitsch, 2000) or uptake from wetland vegetation (Kadlec, 2016) and algae (Nairn and Mitsch, 2000). However, analysis could have been skewed since sample filtration removed sediment-sorbed phosphorus. This could explain the significantly lower mean concentration of dissolved PO_4^{3-} if more PO_4^{3-} was sorbed to sediments in the Post period than the Pre period. Future research should include measurements of total phosphorus in addition to dissolved phosphorus to determine if wet ponds are actually removing phosphorus or supplying it downstream attached to suspended particles.

4.1.3. *Chlorophyll-a*

Nutrient management in coastal regions is most often focused on reducing excessive phytoplankton biomass as measured by chlorophyll-*a*. Pristine blackwater coastal streams are generally understood to be sites with low phytoplankton biomass due to naturally low nutrient concentrations and high amounts of dissolved organic material (Meyer, 1992). However, in coastal streams with a developed watershed, increased nutrient loading can create large amounts of algae and negatively impact downstream water quality (Mallin et al., 2004; Wahl et al., 1997). At our study sites, the mean concentration of chl-*a* increased by 8.23 ± 14.56 μg/L in the developed stream and 0.64 ± 1.93 μg/L in the reference stream, a 349.26% and 76.35% increase, respectively (Fig. 3, Table A1). The increase of the mean chl-*a* concentration in the developed stream was approximately thirteen times larger than the increase in the reference stream. The mean chl-*a* concentration in the developed stream significantly increased during both baseflow and stormflow, although the increase in mean concentration was larger during stormflow (Fig. 4). The larger increase of the mean chl-*a* concentration in the developed stream relative to the reference stream indicates that the increase in the developed stream was not solely due to environmental conditions. Additionally, the larger increase in mean concentration during stormflow compared to baseflow in the developed stream suggests that there is a flushing of chl-*a* from the watershed during storm events, likely from the wet ponds (Fig. 4). Coastal wet ponds have been shown in the past to have high concentrations of algal biomass during certain seasons (DeLorenzo et al., 2012; Lewitus et al., 2008). As a consequence of design, these ponds appear to provide optimal habitat for algal blooms: sufficient irradiance, low flow velocities, and nutrients that flow into ponds from large areas of the watershed after storm events.

4.1.4. *Total suspended solids*

Wet ponds are designed to remove suspended solids by slowing down incoming water and allowing suspended solids to settle out of the water column (NCDENR, 2009). Excess amounts of suspended solids, such as sediments and organic matter, can negatively affect aquatic ecosystems by increasing water column light attenuation (Bilotta and Brazier, 2008), changing water temperature (Bilotta and Brazier, 2008), and reducing dissolved oxygen concentrations by adding organic material to the water column and increasing sediment oxygen demand (Waterman et al., 2011). In the present

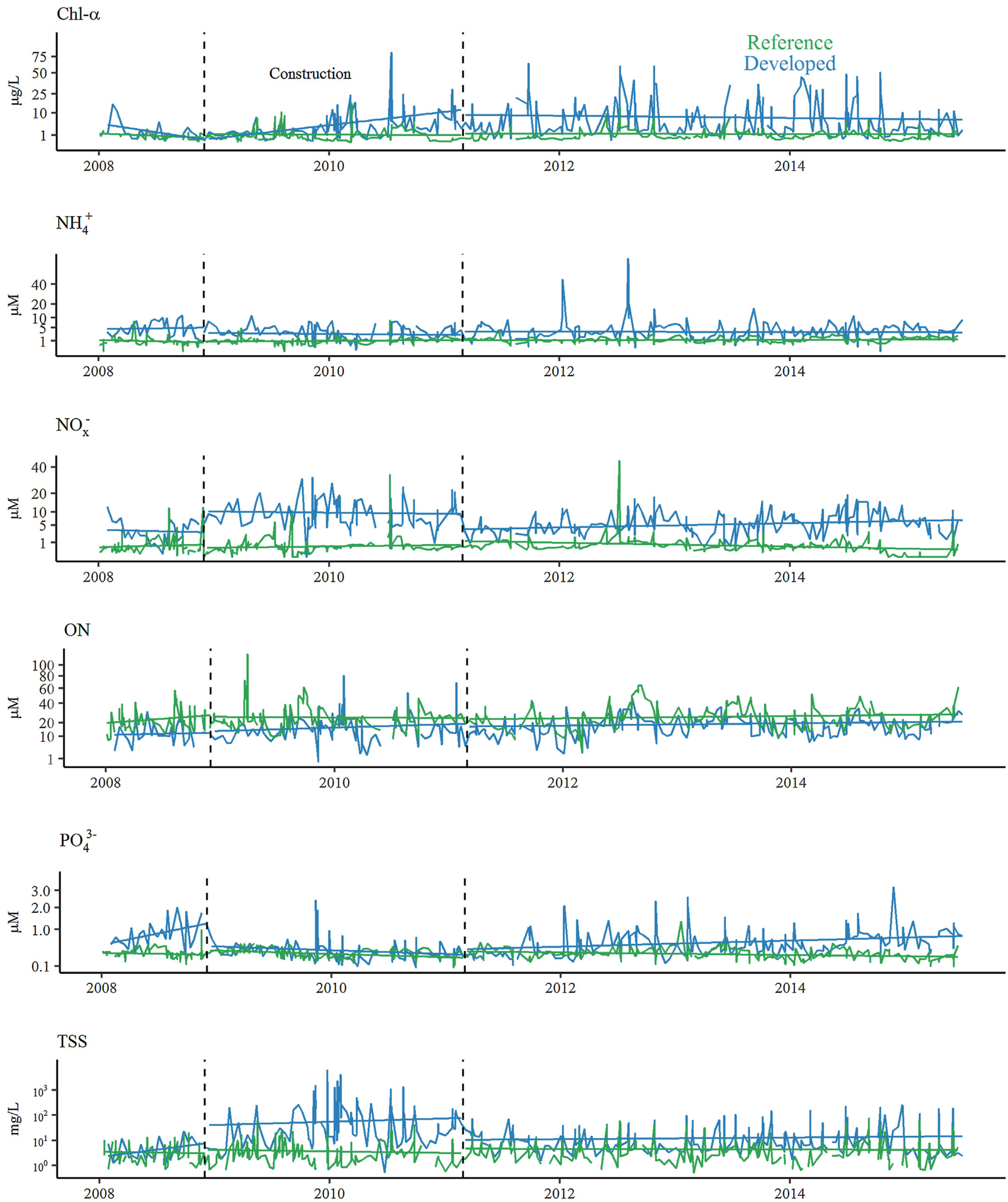

Fig. 5. Time series of nutrient, TSS, and chl-a concentrations for both reference (green) and developed (blue) streams with linear fits for each period of construction. Area between the dotted lines indicates the construction (Mid) period. All y-axes use a square root scale, except TSS which uses a $\log_{10}$ scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

study, mean TSS concentration increased by 18.99 ± 41.51 mg/L in the developed stream between Pre and Post periods, which is a 310.65% increase (Fig. 3, Table A1). After the construction period, the mean TSS concentrations were significantly higher in both baseflow and stormflow in the developed stream (Fig. 4). No significant change in the mean TSS concentration was observed in the refer-

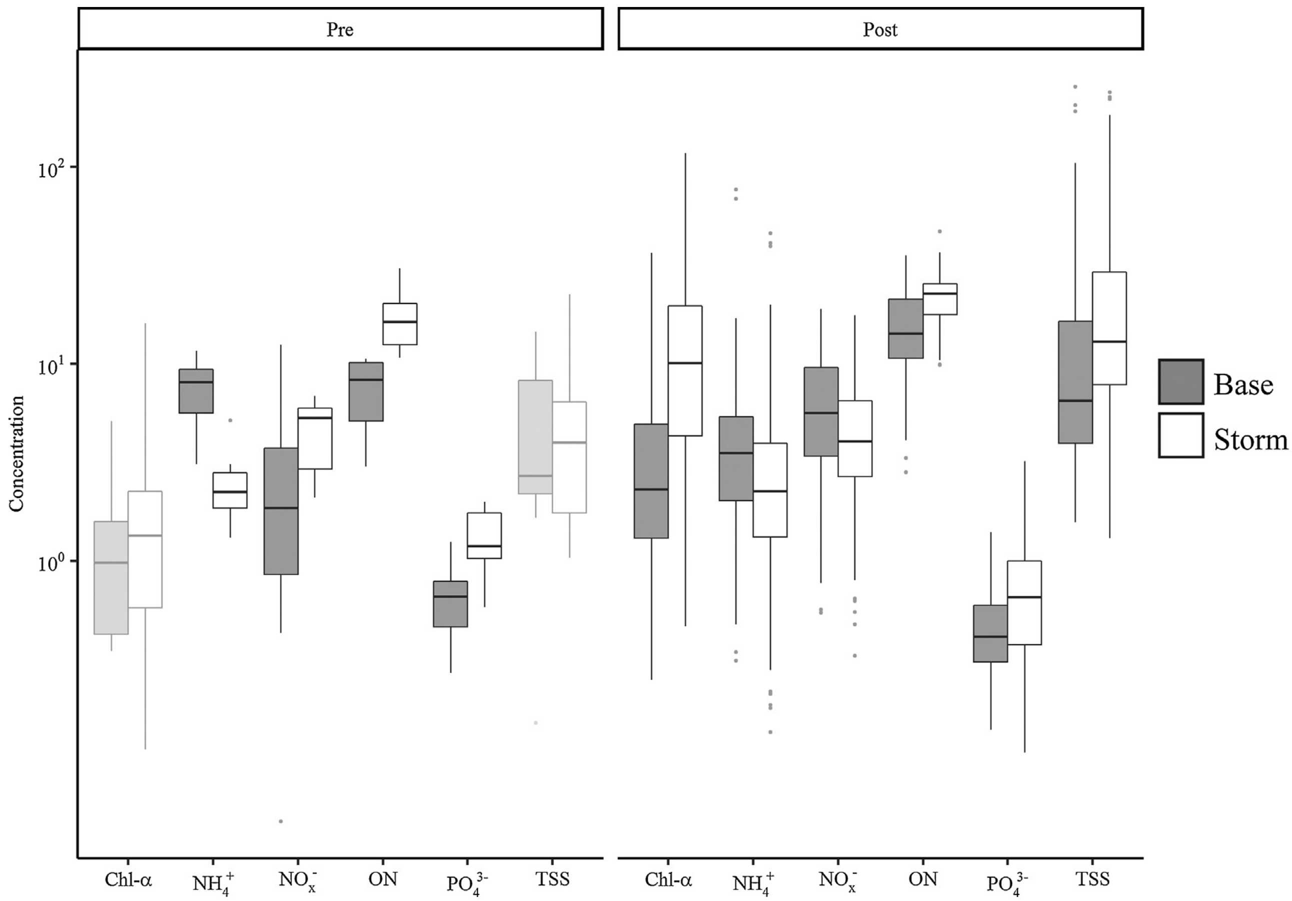

Fig. 6. Developed stream concentrations of nutrient, TSS, and chl-a during baseflow and stormflow conditions for the Pre and Post Periods. Full color boxplots indicate a significant difference determined by a Student's *t*-test ($\alpha = 0.05$). n = 15 for baseflow and 12 for stormflow during the Pre Period, and n = 114 baseflow and 140 for stormflow during the Post period.

ence stream between Pre and Post (Fig. 3). The main purpose of wet ponds is typically to mitigate altered hydrology from development (Hancock et al., 2010) and capture suspended solids that are eroded from the watershed (NCDENR, 2009). It is surprising that the mean TSS concentration in the stream during the Post period was 310% higher than the Pre period (Fig. 3, Table A1). Logically, TSS concentrations will increase while construction is ongoing, but once construction ceased, the wet ponds in this study did not maintain or reduce the mean TSS concentration downstream relative to the Pre period mean concentration. This phenomenon has been documented in the Piedmont of North Carolina by Tillinghast et al. (2011). They showed that lowering the peak flow from storm events using ponds can increase the amount of time that an SCM's discharge exceeds a level that erodes downstream stream channels. An alternative hypothesis is that the wet ponds were actually sources of TSS due to sediment resuspension within the pond.

4.2. Trends in stream water quality after wet pond implementation

Comparing the relative change between the beginning and end of the Post period, concentrations in the developed stream decreased relative to the reference stream for chl-*a*, NH_4^+, and ON and increased relative to the reference stream for NO_x^-, PO_4^{3-}, and TSS (Fig. 5, Table 2). During this 3 year period, chl-*a* decreased by 14.48%, NH_4^+ decreased by 48.76%, and ON decreased by 1.71% relative to the reference stream (Fig. 5, Table 2). Concentrations of NO_x^- increased by 158.23%, PO_4^{3-} increased by 5.23%, and TSS increased by 590.08% (Fig. 5, Table 2). Predicted stream water chl-*a* concentrations decreased slightly through the Post period, which may be explained by an increase in pond vegetation cover over time. An increase in vegetation cover within the ponds over time could compete with algae for nutrients and light within the ponds, possibly also explaining the decrease in NH_4^+ concentrations in the stream over time. The increase in NO_x^- concentrations predicted by the linear regression indicates the wet ponds became less effective at removing NO_x^- as time went on, or channel incision and erosion decreased the stream's ability to remove NO_x^- by disconnecting the stream from its floodplain (Newcomer Johnson et al., 2014). There was no clear trend in ON concentrations between the beginning and end of the Post period. Predicted concentrations of PO_4^{3-} increased slightly through the Post period, which could mean that the sediments in the pond became saturated with PO_4^{3-} within a few years and lowered the pond's ability to remove PO_4^{3-} (Hunt and Lord, 2006; Merriman and Hunt, 2014), or the dissolved oxygen concentrations within the pond decreased over time and allowed particle-bound phosphorus to be released (Duan et al., 2016). Additionally, predicted TSS concentrations increased almost 6-fold during the Post period, indicating that the ponds were removing less TSS over time, having sediments become resuspended within the pond and exported, or scouring material from the streambed. Considered together, these results indicate that wet ponds in the developed watershed became less effective at removing nutrients and TSS over time or negatively impacted the ability of the stream to remove nutrients and TSS. Alternatively, sources of nutrients and TSS could have increased throughout the Post period. To maximize NO_x^-, PO_4^{3-}, and TSS removal within the wet ponds, this study suggests that wet ponds in coastal areas undergo more

Table 2
Relative change, percent relative change, and the relative slope of nutrient, TSS, and chl-a concentrations at the beginning and end of the Post-Construction period.

Natural trends removed	*TSS (mg/L)*	*NO_x^- (μM)*	*NH_4^+ (μM)*	*PO_4^{3-} (μM)*	*ON (μM)*	*Chl-a (μg/L)*
Change	32.35	4.22	−2.66	0.42	−0.31	−1.72
% change	590.08	158.23	−48.76	5.23	−1.71	−14.48
Slope (conc/yr)	7.56	0.99	−0.62	0.10	−0.07	−0.40
Slope (perc/yr)	137.89	36.98	−11.39	1.22	−0.40	−3.38

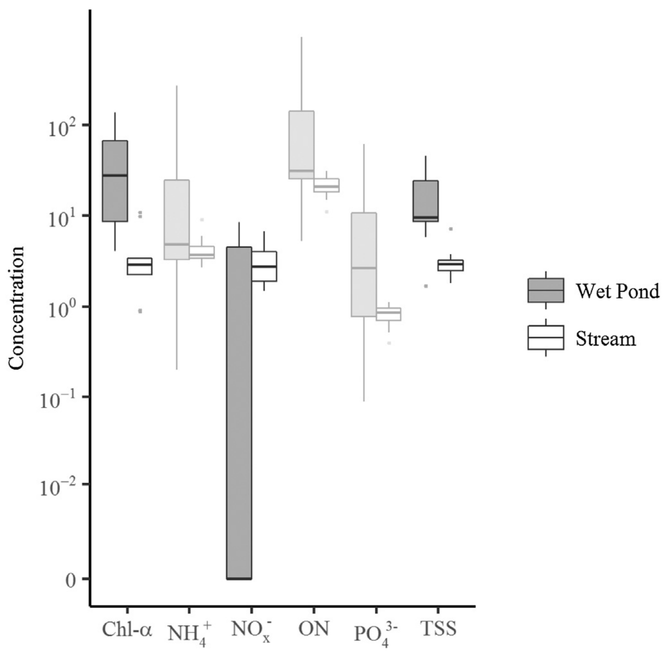

Fig. 7. Developed stream and developed wet pond concentrations of nutrient, TSS, and chl-a. Samples for both sites were taken within 15 min of each other. Full color boxplots indicate a significant difference determined by a paired Student's *t*-test ($\alpha = 0.05$). n = 9 for each location.

frequent excavation. This is in line with the recommendations for wet ponds in the Piedmont of North Carolina and elsewhere that call for sediment excavation every few years to preserve water storage capacity and sediment, nitrogen, and phosphorus removal (Duan et al., 2016; Hunt and Lord, 2006; Sønderup et al., 2016). While stream water concentrations of chl-*a*, NH_4^+, and ON decreased over the Post period, the increases in various water quality concentrations were much larger, percentage-wise, than the reductions (Table 2).

4.3. Stormwater wet ponds as a source of algae and sediments and a sink for NO_x^-

Concentrations of water quality variables during baseflow and stormflow were compared for both Pre and Post periods in the developed stream. During the Pre period, concentrations of all water quality variables, except for chl-*a* and TSS, were significantly different during baseflow and stormflow conditions (Fig. 6). During the Post period, chl-*a* and TSS concentrations became significantly different during baseflow and stormflow, and in both cases had higher stormflow concentrations than baseflow (Fig. 6). NO_x^- concentrations during the Pre period were lower during baseflow than stormflow, but flipped during the Post period to have lower NO_x^- concentrations during stormflow conditions (Fig. 6). Additionally, mean concentrations of chl-*a* and TSS were significantly higher and the mean NO_x^- concentration was significantly lower in the wet pond than in the developed stream during baseflow over the sampling period (Fig. 7). These data indicate that wet ponds in the watershed were likely sources of both chl-*a* and TSS to the stream and sinks for NO_x^-. The variation in each parameter, except chl-*a*, was higher in the wet pond than in the developed stream (Table A3). The extremely low concentrations of pond NO_x^- seem to contrast the fact that NO_x^- concentrations significantly increased in the stream after the implementation of wet ponds (Fig. 3). Based on this observation, and the fact that almost all of the developed watershed drains to a wet pond, NO_x^- may be effectively removed by the ponds, but NO_x^- within the watershed may be infiltrating to groundwater during small storm events and be released to the stream during baseflow. It is also important to note that this comparison between a wet pond and the stream took place between March and the end of June, so it did not capture variability throughout all seasons. All other nutrients in the pond had mean concentrations higher than the stream, but the differences were not significant due to higher variability in nutrient concentrations within the pond. The negative ecological effects of increased chl-*a* and TSS concentrations within coastal wet ponds should be considered in management decisions.

4.4. Implications for stormwater management in the coastal southeastern US

Conventional stormwater management has focused on narrow management goals (Burns et al., 2012) and relied on large, centralized SCMs, such as wet ponds, that collect water from large areas of the landscape (Collins et al., 2010). While most centralized SCMs are made with the primary goal of mitigating the negative hydrologic effects of development, the results from this study show that this typical method of stormwater management in coastal areas may have some negative effects on downstream water quality.

Wet ponds may not be the best choice for stormwater management in the coastal southeastern US. Overall, the installation of wet ponds that drained 97% of the watershed area was unable to mitigate the negative effects of increased development. This is illustrated by the findings of this study that a wet pond was likely a source for TSS and chl-*a* between spring and summer and that water quality generally decreased further after watershed-scale wet pond implementation with increased development. Undeveloped watersheds on the coast of the southeastern US are drained by blackwater streams (Meyer, 1990), but extensive impervious area that accompanies development does not allow precipitation to infiltrate into soils and undergo natural soil biogeochemical processes that supply streams with water rich in dissolved organic matter and low in suspended sediments (Piehler et al., in prep). Rather, the water from developed coastal watersheds have less dissolved organic matter with complex molecular composition (Hosen et al., 2014), more broken-down, bioavailable dissolved organic matter (Hosen et al., 2014), more nutrients (Wahl et al., 1997), and more chl-*a* (Fig. 3, Piehler et al., in prep) than natural watersheds. The installation of wet ponds in the developed watershed did not mitigate many of these negative effects of development, but rather increased them.

Managing stormwater with low-impact development (LID) structures may help restore watershed biogeochemistry and stream water quality by restoring pre-development flow regimes, decreasing surface runoff, and increasing both evapotranspiration and infiltration (Burns et al., 2012; Walsh et al., 2016). Restoring flow paths and biogeochemistry is an optimal approach for improving the water quality of developed coastal watersheds due to importance of dissolved organic matter in streams (Meyer, 1990). LID may be more practical than wet ponds in settings represented by the study watershed due to the large amount of open and low-intensity developed area in the watershed (Table A4) that could support LID infrastructure but not additional wet ponds. Additionally, the higher cost of land and higher water table in coastal areas could make LID more tenable than wet ponds and other large, deep SCMs (EPA National Estuary Program, 2014). LID has improved stormwater quality (Dietz, 2007; Dietz and Clausen, 2008; EPA National Estuary Program, 2014) and quantity (Jarden et al., 2016) in urban or suburban watersheds and could possibly minimize the negative water quality impacts from wet ponds found in this study by decreasing open water area that can promote algae and sediment resuspension. While there is the potential to implement LID in the southeastern coastal plain, more research is needed to determine the efficacy of LID in this region.

Concentrations of NO_x^-, PO_4^{3-}, and TSS increased in the developed stream relative to the reference stream during the period after wet pond implementation, and chl-*a*, NH_4^+, and ON decreased. These changes in stream water quality indicate that the function of wet ponds in the study watershed changed after they were implemented. If other types of SCMs cannot be implemented to replace wet ponds, this study recommends frequent pond excavation to maintain the effective removal of various water quality variables. However, this recommendation may be untenable for some communities due to the high price of maintenance for wet ponds, which are among the most expensive types of SCM to maintain appropriately (Houle et al., 2013). If maintenance cost is not an issue, stormwater wet pond retrofits, such as the implementation of floating wetland vegetation (Tanner and Headley, 2011; Winston et al., 2013), could also be implemented to improve nutrient and suspended sediment removal within a wet pond.

5. Conclusions

After a period of increased development and watershed-scale implementation of stormwater wet ponds in a developed watershed, stream water quality significantly changed and decreased overall. Mean concentrations of chl-*a*, NO_x^-, organic nitrogen, total nitrogen, and TSS in the developed stream significantly increased, while the mean PO_4^{3-} concentration decreased, and the mean concentration of NH_4^+ did not change. Over a three year period after wet pond implementation, the stream water concentrations of NO_x^-, PO_4^{3-}, and TSS increased over time compared to the reference stream, indicating a reduction in pollutant removal efficiency for wet ponds, a negative impact on pollutant removal processes in the stream, or an increase in pollutant sources to the stream throughout the Post period. Concentrations of chl-*a*, NH_4^+, and ON in the developed stream decreased over time after wet pond implementation, but the decreases were much smaller compared to increases of other water quality variables. Comparing baseflow and stormflow water quality concentrations from the developed stream during the Pre and Post period as well as a wet pond within the developed watershed to the developed stream during a single spring and summer showed that the wet ponds were likely functioning as sources of chl-*a* and TSS to the stream and sinks for NO_x^-.

This study demonstrates that the watershed-scale implementation of stormwater wet ponds may not be optimal for nutrient, TSS, and chl-*a* removal in coastal areas within the southeastern US. Distributed stormwater management, such as LID, may be a better method than wet ponds for mitigating the negative effects of development on coastal water quality, but further study of both traditional and LID stormwater structures at the watershed-scale is needed in coastal areas of the southeastern US. In areas where distributed systems cannot be used, our findings indicate that both stormwater pond retrofits and frequent pond excavation to maximize removal efficiency may improve nutrient removal performance.

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Appendix A.

Fig. A1.

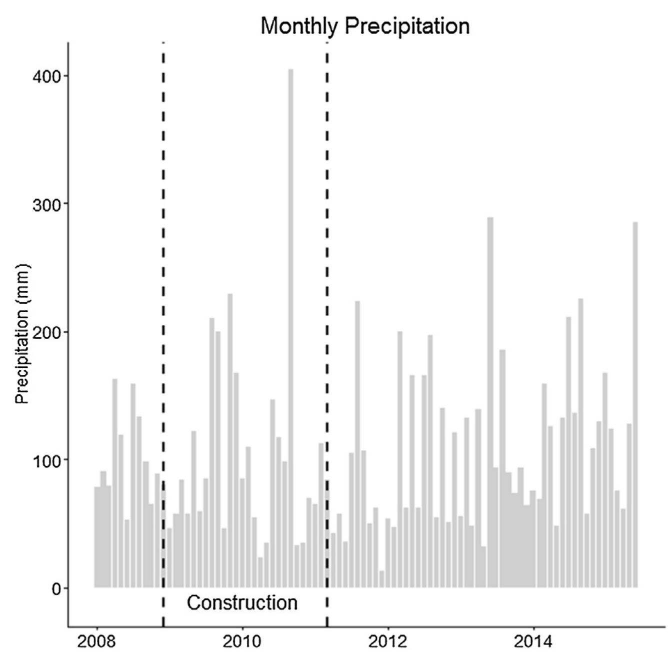

Fig. A1. Monthly Precipitation for both watersheds for Pre-construction (Pre), Construction (Mid), and Post-Construction (Post).

Table A1
Change in mean concentrations of water quality variables between the Pre and Post period and the percent change from the mean concentrations for the Pre period. Only variables that significantly changed are listed.

	Developed	% Change	Reference	% Change
Chl-*a*	8.23 ± 14.56 μg/L	349.26	0.64 ± 1.93 μg/L	76.35
NH_4^+	−0.71 ± 8.60 μM	−13.61	0.22 ± 1.05 μM	21.84
NO_x^-	1.97 ± 4.85 μM	51.80	–	–
ON	7.15 ± 10.38 μM	57.93	–	–
PO_4^{3-}	−0.30 ± 0.65 μM	−32.24	–	–
TSS	18.99 ± 41.51 mg/L	310.65	–	–

Table A2
Predicted values for the beginning and end of the Post, the change over the Post period, and the percent change over the Post period for each stream.

Developed	TSS	NO_x^-	NH_4^+	PO_4^{3-}	ON	Chl-a
3/8/2011	5.48	2.67	5.45	8.07	18.26	11.87
6/18/2015	40.34	5.79	2.95	8.39	21.70	9.84
Change	34.86	3.13	−2.50	0.31	3.44	−2.03
% change	635.69	117.21	−45.90	3.87	18.83	−17.12
Reference	TSS	NO_x^-	NH_4^+	PO_4^{3-}	ON	Chl-a
3/8/2011	8.55	0.39	−0.87	0.41	26.51	2.23
6/18/2015	11.05	−0.70	−0.72	0.30	30.26	1.92
Change	2.50	−1.09	0.16	−0.11	3.75	−0.31
% change	29.25	−279.82	−17.92	−26.48	14.15	−14.02

Table A3
Results of F-test between the variance of Developed and a Developed stormwater wet pond for each water quality variable ($\alpha = 0.05$)

	F Statistic	P-Value
Chl-*a*	2.0936	0.3163
NH_4^+	38.1077	8.618e-05
NO_x^-	124.7187	1.489e-06
ON	25.3087	0.0003381
PO_4^{3-}	37.7774	8.875e-05
TSS	6.704	0.01433

Table A4
National Land Cover Database land cover for each study watershed in percent watershed area and the change between 2006 and 2011.

Developed	2006	2011	Change
Barren Land	0	0.76	0.76
Cultivated Crops	2.80	2.80	0
Developed, High Intensity (80–100% impervious)	0.64	1.40	0.76
Developed, Low Intensity (20–49% impervious)	37.32	36.43	−0.89
Developed, Medium Intensity (50–79% impervious)	9.94	21.02	11.08
Developed, Open Space (0–20% impervious)	30.32	25.35	−4.97
Evergreen Forest	15.41	10.06	−5.35
Shrub/Scrub	3.44	2.16	−1.27
Woody Wetlands	0.13	0	−0.13

Reference	2006	2011	Change
Barren Land	4.66	4.90	0.25
Deciduous Forest	0.06	0.06	0
Developed, Low Intensity (20–49% impervious)	2.81	2.63	−0.18
Developed, Medium Intensity (50–79% impervious)	0.01	0.15	0.14
Developed, Open Space (0–20% impervious)	2.09	2.14	0.04
Emergent Herbaceuous Wetlands	17.50	17.77	0.27
Evergreen Forest	6.64	6.59	−0.05
Herbaceuous	12.82	12.71	−0.11
Mixed Forest	0.78	0.78	0
Open Water	0.24	0.33	0.10
Shrub/Scrub	22.83	22.67	−0.16
Woody Wetlands	29.55	29.26	−0.29

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