RESEARCH & DEVELOPMENT

Evaluating the Hydrologic and Water Quality Benefits Associated with Retrofitting Vegetated Swales with Check Dams

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16. Abstract

Two swales (Mango Creek and I-40) treating highway runoff were retrofitted with simple check dams typically used for construction site sediment and erosion control to determine if these devices might improve post-construction stormwater management. The Mange Creek swale was retrofitted with a pair of standard rock check dams. The I-40 swale was retrofitted with a system of excelsior fiber wattle check dams and bags with proprietary phosphorus-adsorptive media (ViroPhosTM) to investigate if additional treatment for dissolved phosphorus was provided. Each swale was instrumented for approximately six months to collect data prior to the installation of check dams (pre-retrofit period) in March and April of 2014. Monitoring continued for an additional twelve months post-retrofit. Hydrologic data were collected at Mango Creek to examine peak flow mitigation and volume reduction imparted by the check dams due to additional storage and infiltration. Flow-proportional water quality samples were obtained to investigate removal of nitrogen and phosphorus species and total suspended solids (TSS) during the pre- and post-retrofit phases of the research.

The inclusion of rock check dams in the Mango Creek swale did not significantly improve the volume reduction or peak flow mitigation of the SCM; however, these statistics were impacted substantially by the small pre-retrofit data set. Improvements were observed for volume reduction, peak flow mitigation, and hydraulic retention time, especially for small (<0.75 inch) and moderate (0.75-1.5 inch) rainfall events. Rock check dams did not significantly improve the removal rates of nutrients or TSS. However, these statistics were again impacted by the small pre-retrofit data set. Total nitrogen (TN) and total phosphorus (TP) concentrations from the highway were low compared to the literature, limiting the potential for significant reduction. Even so, TN and TP concentrations exiting the swale (0.81 mg/L and 0.13 mg/L, respectively) remained low and generally met "good" water quality conditions based on ambient stream health. Rock check dams were effective in the filtration of gross solids, which led to clogging of the check dams and degradation (due to extensive ponding) of the swale vegetation over time. Inclusion of excelsior fiber wattle check dams at I-40 did not significantly improve any pollutant event mean concentrations (EMCs) compared to pre-retrofit conditions. The ViroPhosTM media amendments did not significantly improve the treatment of O-PO43- in the swale relative to pre-retrofit conditions. Due to their high permeability, visual inspection during rain events showed the wattle check dams did not pond water; therefore, sedimentation was not improved. Overall, results from this study indicate rock check dams are preferable to straw wattles because they are able to pond stormwater, modestly improving swale performance.

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Evaluating the Hydrologic and Water Quality Benefits

Associated with Retrofitting Vegetated Swales with Check Dams

Written in partial fulfilment of NCDOT research project 2014-17:
"Water Quality Benefits Associated with Retrofitting Swales
and Roadside Ditches with Check Dams"

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PREFACE

This final report has been written to partially fulfill the requirements of NCDOT research contract 2014-17: "Water Quality Benefits Associated with Retrofitting Swales and Roadside Ditches with Check Dams." This report will focus on two different monitoring efforts: (1) the implementation of rock check dams in a swale under the bridge deck of Interstate-540 over Mango Creek near Knightdale, North Carolina, and (2) the implementation of straw wattle and media bag check dams in a swale along Interstate-40 near Benson, North Carolina. These swales are referred to as "Mango Creek" and "I-40" herein. The Benson site was previously monitored during two different NCDOT research projects, including 2011-35 (Predicting the Effectiveness of Vegetated Stormwater Control Measures Based on Sediment Size Distribution) and 2007-21 (Research of Hydrologic and Water Quality Performance of Two Linear Wetlands in Eastern North Carolina and House Creek Interchange Retrofits), where it was referred to as "Benson" and "Site A", respectively. The Mango Creek site was previously monitored under NCDOT research project 2009-29 (Monitoring of Prospective Bridge Deck Runoff BMPs: Bioretention and Bioswale). To fully satisfy the requirements of 2014-17, a separate final report is forthcoming detailing the results from the monitoring of a bioswale in Brunswick County, North Carolina. Peer reviewed journal articles will be developed and submitted based on these final reports.

This project provides critical data to the engineering community on the hydrologic and water quality performance of different types of check dams in swales. It could not have been undertaken without funding provided by NCDOT. The authors appreciate NCDOT's support and aid throughout this effort.

EXECUTIVE SUMMARY

Vegetated swales are the most common stormwater control measure (SCM) utilized by Departments of Transportation (DOTs) to drain roads. Typical swale design, however, is determined using hydraulic equations, without considering water quality improvement. By using simple retrofits, such as check dams and engineered media supplements, the performance of these SCMs could potentially be improved. Two swales (Mango Creek and I-40) treating highway runoff were retrofitted with simple check dams typically used for construction site sediment and erosion control to determine if these devices might improve post-construction stormwater management. The Mango Creek swale was retrofitted with a pair of standard rock check dams. The I-40 swale was retrofitted with a system of excelsior fiber wattle check dams and bags with proprietary phosphorus-adsorptive media (ViroPhos^{TM}) to investigate if additional treatment for dissolved phosphorus was provided. Each swale was instrumented for approximately six months to collect data prior to the installation of check dams (pre-retrofit period) in March and April of 2014. Monitoring continued for an additional twelve months post-retrofit. Hydrologic data were collected at Mango Creek to examine peak flow mitigation and volume reduction imparted by the check dams due to additional storage and infiltration. Flow-proportional water quality samples were obtained to investigate removal of nitrogen and phosphorus species and total suspended solids (TSS) during the pre- and post-retrofit phases of the research.

The inclusion of rock check dams in the Mango Creek swale did not significantly improve the volume reduction or peak flow mitigation of the SCM; however, these statistics were probably impacted substantially by the small pre-retrofit data set. Improvements were

observed for volume reduction, peak flow mitigation, and hydraulic retention time, especially for small (<0.75 inch) and moderate (0.75-1.5 inch) rainfall events. Rock check dams did not significantly improve the removal rates of nutrients or TSS. However, these statistics were again impacted by the small pre-retrofit data set; for example, TSS load reduction was -15% pre-retrofit and 74% after the rock check dams were installed. Total nitrogen (TN) and total phosphorus (TP) concentrations from the highway were low compared to the literature, limiting the potential for significant reduction. Even so, TN and TP concentrations exiting the swale (0.81 mg/L and 0.13 mg/L, respectively) remained low and generally met "good" water quality conditions based on ambient stream health. Rock check dams were effective in the filtration of gross solids, which led to clogging of the check dams and degradation (due to extensive ponding) of the swale vegetation over time.

Inclusion of excelsior fiber wattle check dams at I-40 did not significantly improve any pollutant event mean concentrations (EMCs) compared to pre-retrofit conditions. The ViroPhos^{TM} media amendments did not significantly improve the treatment of O-PO_4^{3-} in the swale relative to pre-retrofit conditions. Due to their high permeability, visual inspection during rain events showed the wattle check dams did not pond water; therefore, sedimentation was not improved. Overall, results from this study indicate rock check dams are preferable to straw wattles because they are able to pond stormwater, modestly improving swale performance.

PART 1: EVALUATING THE HYDROLGIC EFFECTS OF RETROFITTING A VEGETATED SWALE WITH ROCK CHECK DAMS

Literature Review

Storm sewer systems provide beneficial mitigation of nuisance flooding, but impact receiving water bodies by efficiently transporting stormwater (Hollis 1975). Because of impervious surfaces associated with urban development, augmented volumes and rates of stormwater cause bed and bank erosion, loss of aquatic habitat, reduced baseflow, and hydromodification, collectively referred to as the "urban stream syndrome" (Schueler et al. 2009; Hamel et al. 2015; Roy et al. 2016; Vietz et al. 2016). Grass swales are open drainage features which may be a suitable Low Impact Development (LID) alternative for hardened infrastructure, such as curb and gutter, catch basins, pipes, and culverts. They are often preferable to curb and gutter systems because (1) they are cheaper to construct and maintain vis-à-vis sewers (Barrett, Irish et al., 1998), (2) provision greater ecosystem services (Bouchard et al. 2013), (3) improve water quality (Winston et al. 2012), and (4) reduce discharge rates through vegetation and soil-based processes (Yousef et al., 1987).

Swales are typically designed with triangular, trapezoidal, or parabolic geometry and to convey runoff from intense, infrequent rainfall events to prevent flooding (e.g., NCDEQ, 2009). They are the most common stormwater control measure (SCM) for road networks because they are simple to design and maintain. While flooding is of concern, the focus of the LID design approach is to control a smaller water quality event (typically the first 19 or 25mm); so, additional studies are needed to determine mechanisms for volume reduction during these smaller events.

Swales design often neglects volume reduction and peak flow mitigation provided by infiltration and evapotranspiration; if these benefits could be quantified, their performance could be properly credited by regulatory agencies. Several factors, such as underlying soil infiltration rate, the presence and density of vegetation, the vegetation type and height, and antecedent soil moisture conditions affect the hydrologic performance of this stormwater control measure (SCM; Yousef et al. 1987; U.S. EPA 2012). Bäckström (2002) found that swales constructed on more permeable soil infiltrated 66% of inflow volume, while swales constructed on less permeable soils performed half as well. Six swales monitored in California reduced runoff volume by 47% on average (Barrett 2005). Two swales studied in Virginia infiltrated the first 0.2-0.28 inches of stormwater runoff; whereas 0.03 inches of rainfall generated runoff at the edge of pavement (Kaighn and Yu, 1996). Water quality-centric swales should be constructed so that flow depth during the design storm does not exceed the grass height, which reduces flow velocity and augments sedimentation and infiltration (U.S. EPA 2012; Bäckström 2003; Winston et al. in press). Davis et al. (2012) studied two swales along highways in Maryland, and they eliminated outflow (through infiltration and evapotranspiration) from one-half of monitored runoff-producing events and significantly reduced runoff volume and peak flow rate during events less than 1.2 in. Above this threshold, the swales simply conveyed flow and had no discernable volume reduction. Knight et al. (2013) measured a 23% runoff volume reduction for a swale over one year of monitoring, lower than adjacent vegetated filter strips because of the concentrated flow prevalent in swales.

Because swales are so common, simple retrofits to existing swales are desired to further ameliorate urban hydrologic impacts. Check dams (Figure 1-1) are often proposed in stormwater design manuals as a method to improve swale hydrologic performance (ODNR 2006; NCDEQ 2009; MPCA 2016). Check dams are structures placed perpendicular to flow to temporarily retain stormwater in the swale during a rainfall event, increasing hydraulic retention time, reducing flow velocity, and potentially improving infiltration (Yu et al. 2001). Davis et al. (2012) found that vegetated check dams reduced the duration of outflow from swales. While effects were not observed for small and large events, volume reduction and flow rate attenuation was improved during moderate-size events (0.9-1.3 inch depth). Perhaps the inclusion of a more robust check dam, built of wood, concrete, or metal, would provide more consistent benefits than vegetated ones? One potential drawback, however, noted by Kaighn and Yu (1996) is that check dams may interfere with highway maintenance operations.

Figure 1-1. Examples of check dams constructed of metal (top left), wood (top right), grass (bottom left, Stagge et al. 2012), and concrete (bottom right).

By applying LID, engineers strive to mimic pre-development hydrology and mitigate adverse downstream effects. There is a need to determine the potential added benefits to runoff reduction and peak flow mitigation provided by simple retrofits to swales. This study evaluated the effectiveness of retrofitting rock check dams, typically used by Departments of Transportation for sediment and erosion control on construction sites, into a grass swale for post-construction stormwater management. The focus herein is on the hydrologic performance of the swale with check dams, but water quality performance should also be weighed to fully quantify the effect of check dams in swales on urban stormwater (see Chapter 2).

Research Goals

This study examined the effectiveness of retrofitting two rock check dams in a swale located in Knightdale, North Carolina, in an easement under a major highway bridge deck (Luell, 2011). Hydrologic data were collected for four months (December 2013 – March 2014) prior to retrofitting the swale with check dams, with monitoring continuing for one year post-retrofit (April 2014 – March 2015). Additional volume reduction and peak flow mitigation provided by the check dams were the focus of this study. Hypotheses of this research were that (1) volume reduction would occur through increased infiltration due to the increased hydraulic retention time provided by check dams and (2) peak flows would be mitigated via flow velocity dissipation and temporary storage created by check dams. This research will further establish whether rock check dams substantially enhance swale hydrology.

Methods and Materials

Site Description

The vegetated swale (hereafter known as Mango Creek) was located in Knightdale, North Carolina, partially underneath the southbound Interstate 540 (I-540) bridge deck (35°47’03”N, 78°30’50”W; Table 1-1; Figure 1-2). A 12-in diameter polyvinyl chloride (PVC) pipe hung from the bridge deck delivered stormwater runoff to the swale. The watershed was 1.13 acres of 100% impervious concrete road with an average annual daily traffic load of 17,000 vehicles per day (URS Corporation, 2012).

The swale was designed to convey the 10-year, 24-hour, storm event (5.04 inches). A Class A riprap-lined forebay provided pretreatment before water entered the swale. The swale had a 1.66% longitudinal slope, triangular cross-section with 8:1 side slopes and 21 ft top width, and a total length of approximately 110 ft. The swale was built on compacted clayey soils (Luell 2011). It was vegetated with tall fescue grass (*Festuca arundinacea*) and remained dry between storm events. Outflow from the swale exited through an 18-in diameter high-density polyethylene (HDPE) pipe. Appendix A provides additional photos of the Mango Creek swale site.

Table 1-1: Summary of Mango Creek site and swale characteristics.

Characteristics	Mango Creek Swale
Latitude and Longitude	35°47’02.5”N, 78°30’49.8”W
Ecoregion	Piedmont
Swale Length (ft)	110
Longitudinal Slope (%)	1.66
Cross-section	Triangular
Side Slopes (H:V)	8:1
Average Top Width (ft)	21
Underlying Soil Infiltration Rate (in/hr)	0.06
Designed Conveyance	10-year, 24-hour storm
Swale Vegetation	Tall fescue sod (*Festuca arundinacea*)
Swale Condition Between Storms	Dry
Drainage Area (ac)	0.19
Drainage Area % Impervious	100
Average Daily Traffic	17,000 vehicles/day

Monitoring Periods and Installation of the Check Dams

The Mango Creek site was monitored for four months (beginning December 2013) during the pre-retrofit period. Nineteen distinct storm events were monitored during this time. On March 28, 2014, the Mango Creek swale was retrofitted with two rock check dams (Figure 1-2 and Figure 1-3), concluding the pre-retrofit monitoring period (NCDOT, 2012). These were constructed using Class B erosion control stone fronted with No. 57 aggregate (0.19-1.0 inch nominal diameter) as a filtration layer (Appendix C). The check dams were 1-ft tall at the thalweg, approximately 12 ft wide, and built at a constant top elevation to promote maximum ponding volume. They were spaced such that the base of the upstream check dam was at the same elevation as the top of the subsequent downstream check dam, again maximizing ponding volume. It should be noted that while installing the rock check dams, NCDOT crews repaired some rutting in the swale (see new sod in Figure 1-2) caused by equipment. Once the check dams were installed, the swale was monitored for an additional twelve months (April 2014 to March 2015), during which sixty-two storm events were observed.

Figure 1-2: View of the Mango Creek swale pre-retrofit (left, looking upstream) and following check dam installation (right, looking upstream).

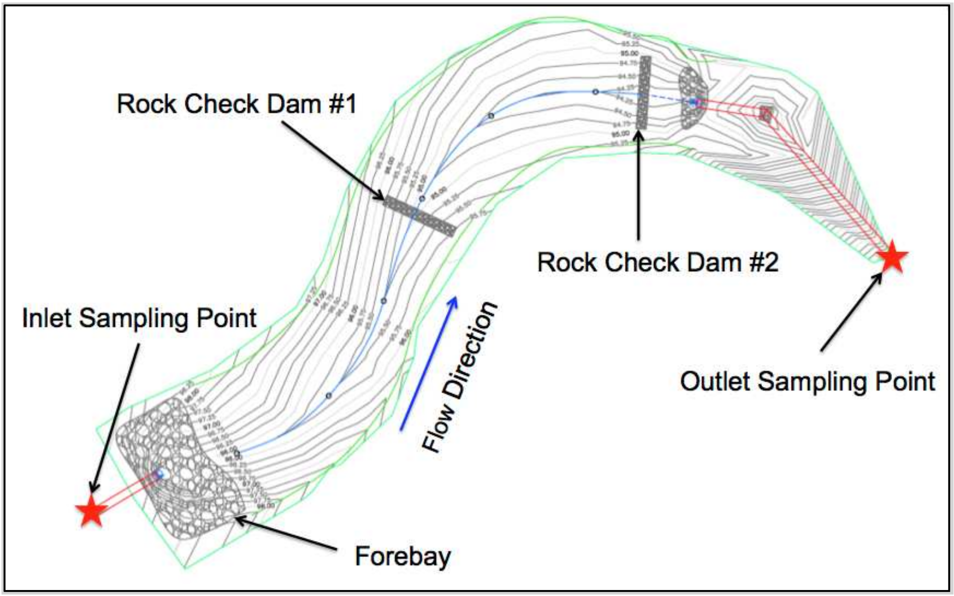

Figure 1-3: Mango Creek swale monitoring schematic with noted check dam locations.

Monitoring Design, Data Collection, and Data Analysis

Weir boxes were installed to measure flow at the inlet to and outlet from the Mango Creek swale (Figure 1-4). A baffle was installed upstream of each weir in an attempt to eliminate turbulent flow over the weir. ISCO 730 bubbler modules (Teledyne Technologies Inc., Lincoln, USA) attached to ISCO 6712 samplers were used to measure stage over each weir on 2-minute intervals. The sampler utilized weir equations for the particular weir geometry at each monitoring location to relate measured depth to flow rate. In a catch basin immediately upstream of the Mango Creek swale, a compound weir was installed and consisted of an 11.4-in tall, 60° v-notch lower portion and a 12.6-in tall, 13-in wide contracted rectangular upper portion (Figure 1-4). Measured flow depth was converted to flow rate using a derived (based on the v-notch and contracted rectangular weir equations), stepwise function given in equations 1-1 and 1-2 (Walkowiak, 2013).

$$Q = 1.443 \times H^{2.5} \quad when\, H \leq 0.95\, ft \tag{1-1}$$

$$Q = 1.27 + 1838(0.335 - 0.2H)H^{1.5} \quad when\ H > 0.95\ ft \tag{1-2}$$

where Q is flow rate (cfs) and H is head on the weir (ft). Because of the unique design of the compound weir used at the inlet, a stage versus discharge table developed using equations 1-1 and 1-2 was input into the ISCO 6712. The outlet weir box was installed where an 18-in diameter HDPE draining the effluent from the swale daylighted into a nearby wooded area. It housed a 24-in tall, 45° v-notch weir and flow rates were calculated using the standard equation (1-3) for this geometry (Figure 1-4; Walkowiak, 2013).

$$Q = 1.035 \times H^{2.5} \tag{1-3}$$

where Q and H have been previously defined. Flow volumes on a storm event basis were determined by integrating under the hydrograph. Swale performance was evaluated based on peak flow rate mitigation and volume reduction using an efficiency ratio, as calculated for storm event *i* (U.S. EPA, 2002):

$$Efficiency\ ratio_i = \frac{(Inlet_i - Outlet_i)}{Inlet_i} \times 100 \tag{1-4}$$

The monitoring design and equipment were the same during pre- and post-retrofit monitoring periods. Appendix B provides additional details regarding weir sizing and stage/discharge calculations for each monitoring location.

Precipitation data were collected during both monitoring periods with an ISCO 674 tipping bucket rain gauge and a manual rain gauge. The rain gauges were mounted on 6-ft tall wooden posts in an area clear of trees and overhead obstructions. Rainfall events were separated by a minimum antecedent dry period of six hours and had rainfall depths of at least 0.10 in. Rainfall depth, duration, antecedent dry period, and peak 5-minute rainfall intensity were determined for each monitored storm event. Total rainfall depths and rainfall intensities from the tipping bucket rain gauge were adjusted with a correction factor developed from the difference in measured rainfall depth between the tipping bucket and manual rain gauge, since tipping bucket rain gauges often under-predict total rainfall depth, especially during intense periods of rainfall. The monitoring equipment used at Mango Creek is summarized in Appendix C.

Figure 1-4: Mango Creek inlet inlet (left) and outlet (right) weirs during a storm event.

On July 21, 2015, double ring infiltration tests were conducted to determine the ability of the soils to transmit water (ASTM 2009). Three infiltration tests were conducted in the thalweg of the swale to capture the variability in soil conditions.

Statistical Analyses

Paired statistical analyses were utilized to determine if influent and effluent volumes and peak flow rates were different across the monitoring periods. Statistical tests were first completed separately on the pre-retrofit and post-retrofit data. These data sets were tested for normality using the Shapiro-Wilk and Kolmorogov-Smirnov tests and visually using histograms and normal quantile-quantile plots. If raw data were normally distributed or could be log-transformed to achieve normality, then a paired t-test determined significance. Otherwise, a Wilcoxon signed-rank test was utilized.

To determine the effects of check dam retrofits on the hydrologic performance of the swale, statistical comparisons between the pre- and post-retrofit data sets were made using Wilcoxon rank-sum tests. These tests compared pre-retrofit influent and effluent volumes and peak flow rates with those post-retrofit. Data were analyzed for significance at the 95% confidence level (α=0.05) unless otherwise noted. R 3.1.3 was used to perform all statistical analyses (R Core Team, 2015).

Results and Discussion

Precipitation

Precipitation was monitored at the Mango Creek site over the entire study (December 1, 2013, to March 6, 2015). During 2014, rainfall at Mango Creek totaled 56.7 inches. The 30-year average annual rainfall for Raleigh, NC, located approximately 0.6 miles from the Mango Creek site, is 46.5 inches (SCONC 2015). Thus, precipitation was approximately 22% greater than the long-term average. Two of the four months during pre-retrofit monitoring had rainfall totals below their respective long-term monthly averages (SCONC 2015); during the post-retrofit period, only 2 of 12 months were drier than normal.

During the pre-retrofit monitoring period nineteen hydrologic events were recorded ranging from 0.1 in to 2.02 in (Table 1-2). Sixty-two hydrologic events ranging from 0.1 in to 4.25 in occurred during the post-retrofit monitoring period. Mean and median rainfall depths and peak rainfall intensities were greater during the post-retrofit monitoring period, perhaps owing to the convective thunderstorms and tropical events that North Carolina experiences during the summer months (Willey et al. 1988).

Table 1-2: Summary of recorded hydrologic events at the Mango Creek swale.

Parameter	Statistic	Pre-Retrofit	Post-Retrofit
Rainfall Events	Number	19	62
Rainfall Depth (in)	Mean	0.58	0.82
	Median	0.34	0.54
	Minimum	0.10	0.10
	Maximum	2.02	4.25
	Total	10.95	51.14
5- Minute Peak Rainfall Intensity (in/hr)	Mean	0.57	1.38
	Median	0.39	0.96
	Minimum	0.11	0.10
	Maximum	1.76	5.30

Storms with rainfall depths of less than 0.10 in, frozen precipitation, and technical difficulties with samplers resulted in some omitted data. Seventy-three percent and 90% of the rainfall depth during the pre- and post-retrofit monitoring periods, respectively, were monitored and reported on herein. The greater proportion of omitted data in the pre-retrofit period is related to freezing temperatures causing equipment malfunction. During the pre-retrofit period, 4 and 15 storms were recorded in the fall and winter seasons, respectively. During the post-retrofit period, 10, 20, 18, and 14 storm events were observed in spring, summer, fall, and winter, respectively.

Swale Hydrology

Volume and peak flow reduction within the swale were the two swale performance metrics used both pre- and post-retrofit with rock check dams. Based on their physical characteristics, the check dams were expected to pond water and dissipate flow velocity, thereby furthering infiltration. Figure 1-5 provides a picture of the upslope check dam during a storm event on April 15, 2014. Visual observations during this and other events showed that a differential head existed across the rock check dams, confirming their ability to retard flow. Observed differences in head from the upstream to downstream end of the rock check dam ranged from 1 to 6 inches and were dependent on the flow rate through the swale. Greater head differences existed at higher flow rates.

Figure 1-5: Two views of the upslope rock check dam in the Mango Creek swale during a storm event.

The pre-retrofit monitoring period was substantially shorter than that of the post-retrofit. Only 19 storm events were recorded pre-retrofit, during which a 20% overall volume reduction and a 7% median volume reduction were measured (Table 1-3). This volume reduction, was statistically significant only at the α=0.10 level, most likely due to the relatively small sample size. The 20% runoff volume reduction in this grass swale was similar to the 23% runoff reduction reported for a 34-ft long swale located in sandy clay loam soils in Wilson, North Carolina (Petre et al. 2013) but lower than the 47% average volume reduction reported for roadside swales in California (Barrett 2005). It was also similar to the

33% volume reduction reported for four swales built on "less permeable soils" in Luleå, Sweden (Bäckström 2003). However, volume reduction declined with increasing rainfall depth, with the swale acting as conveyance-only (i.e., no volume reduction) for events larger than 1.5 inches. The swale reduced runoff volume for events less than 0.75 inches and between 0.75 and 1.5 inches, respectively, by an average of 28% and 13%. This illustrates the inverse relationship between runoff volume reduction and rainfall depth.

Substantial median (27%) and mean (48%) peak flow rate reductions were observed in the Mango Creek swale pre-retrofit. These reductions in peak flow from the inlet to the outlet were statistically significant (p-value = 0.007), suggesting grass swales provide a moderation of flow rates through increased roughness vis-à-vis storm sewers or concrete conveyances (Davis et al. 2012). Davis et al. (2012) found that moderate-to-small storm events (similar to the mean and median events summarized in Table 1-3) had substantially lower peak flow rates after passing through grass swales. During the five largest storm events of the pre-retrofit period, which had rainfall depths between 0.89 and 2.02 inches, the average peak flow reduction was 14%, suggesting that once (1) the grass height is overtopped and (2) the soil infiltration capacity is exceeded, the swale's ability to mitigate flow rate will decline. Thus, similar to other LID SCMs such as bioretention and permeable pavement, volume reduction and peak flow mitigation in swales is inversely related to rainfall depth (Collins et al. 2008; Brown and Hunt 2011; Winston et al. 2016; Winston et al. submitted).

Table 1-3: Summary of Mango Creek swale effects on runoff volume and peak flow rate.

Monitoring Period	Statistic	Influent	Effluent	Reduction (%)
Pre-Retrofit	Median Volume (ft^3)	291	272	7
Post-Retrofit		296	232	21
Pre-Retrofit	Mean Volume (ft^3)	525	422	20^
Post-Retrofit		615	511	17*
Pre-Retrofit	Total Volume (ft^3)	9,984	8,027	20
Post-Retrofit		38,142	31,662	17
Pre-Retrofit	Median Peak Flow (cfs)	0.09	0.07	24
Post-Retrofit		0.18	0.04	75
Pre-Retrofit	Mean Peak Flow (cfs)	0.21	0.11	48*
Post-Retrofit		0.32	0.18	44*

^significant at α=0.1
*significant at α=0.05

During the post-retrofit monitoring period, total (17%) and median (21%) volume reductions were somewhat similar to those of the pre-retrofit period (20% and 7%, respectively). Similar to the pre-retrofit period, volume reduction was statistically significant during the post-retrofit period (p-value <0.0001). Mean post-retrofit peak flow reductions were very similar to pre-retrofit (48% vs. 44%, respectively). Peak flow reduction was significantly reduced (p-value <0.0001) from the inlet to the outlet of the swale. However, it should be noted that the post retrofit period had substantially more large events (defined as greater than 1.5 inches), than the pre-retrofit period (9 versus 2; Table 1-2). These events negatively skew the volume reduction and peak flow rate performance during the post-retrofit period, especially when using the mean as the metric, since these large storms overwhelm the finite ability of the compacted clayey soil to infiltrate stormwater.

To compare pre- and post-retrofit data sets, the Wilcoxon rank sum test was utilized to assess statistical significance between influent hydrologic parameters and (if significant) subsequently effluent hydrologic parameters. No significant difference existed between pre- and post-retrofit influent runoff volume or peak flow rate, suggesting that the runoff hydrology was similar prior to treatment by the swale. Follow-up tests comparing effluent runoff volume and peak flow rates showed no significant differences from pre- to post-retrofit (all p-values >0.40). These results suggested that the check dams did not substantially or significantly affect swale hydrology. However, this statistical result is skewed by (1) the relatively limited data set (19 storms) during the pre-retrofit period, and (2) the greater number of large storm events during the post-retrofit period. On average, the volume reduction provided by the swale improved post-retrofit for small and moderate storm events (Table 1-4 and Figure 1-6), suggesting that statistical significance may have been prevented by the small pre-retrofit data set. Additionally, the addition of check dams increased the size of the largest storm that was completely captured (i.e., produced no outflow) from 0.19 to 0.24 inches. Post-retrofit peak flow reduction also appeared, on average, to improve for small, moderate, and large events (Table 1-4). These results differ slightly from those of Davis et al. (2012), who saw a significant improvement in swale hydrology only for moderate-size storm events (0.9-1.3 inch) after retrofitting with check dams.

Table 1-4: Swale hydrologic performance during pre- and post-retrofit periods by rainfall depth.

Rainfall Depth	Volume Reduction (%)		Peak Flow Reduction (%)	
	Pre-Retrofit	Post-Retrofit	Pre-Retrofit	Post-Retrofit
Small (<0.75 in)	28.0	53.3	30.1	67.7
Moderate (0.75-1.5 in)	12.7	22.4	26.1	39.2
Large (>1.5 in)	0.0	0.9	1.0	25.4

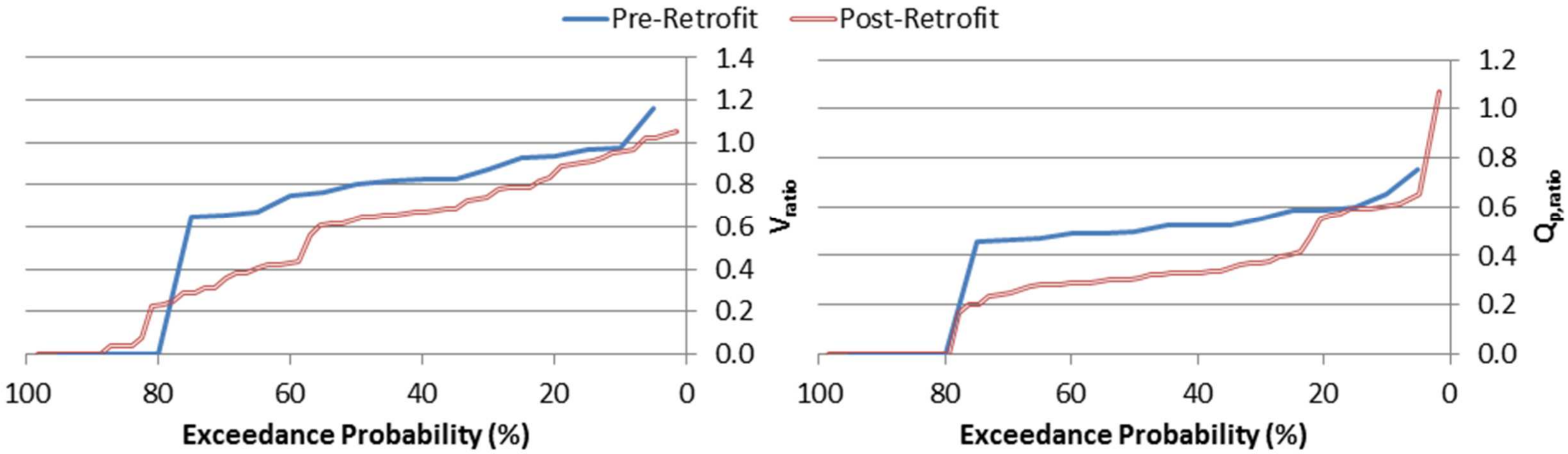

Figure 1-6: Exceedance probability plots of runoff volume ratio (V_{ratio}) and peak flow rate ratio ($Q_{p,ratio}$) for the Mango Creek swale. V_{ratio} and $Q_{p,ratio}$ are defined as the ratio of inlet to outlet runoff volume and as the ratio of inlet to outlet peak flow rate, respectively.

The compacted clay soils within the swale limited the potential for volume reduction. Measured infiltration rates along the swale thalweg ranged from 0.03 in/hr to 0.08 in/hr, with a mean of 0.06 in/hr. An analysis of the swale topography found that approximately 31% of its surface area was exposed to ponding at the brink of overflow of the check dams (Figure 1-7). Assuming an average ponding depth of 3.7 in, or one-third of the height of the check dams, and using the average measured infiltration rate, the swale would take 2.6 days to dewater (Appendix E). The total storage of the retrofitted swale was calculated to be approximately 500 ft^3. This was similar to influent volumes for 0.6- to 0.8-in rainfall events. This maximum potential storage volume was not utilized for most storms, as the aggregate check dams only temporarily detained water, rather than forcing all detained water to infiltrate.

When the check dams became clogged (subsequently discussed in the "clogging of the check dams" section), a greater fraction of runoff volumes were captured upslope of the check dams. Plus, because of greatly reduced check dam permeability, additional time was available for infiltration and evapotranspiration. The largest volume reduction (728 ft^3) was recorded during a 1.4-in storm event from August 9-11, 2014 (2.7 day duration), which occurred after the check dam face had partially blinded.

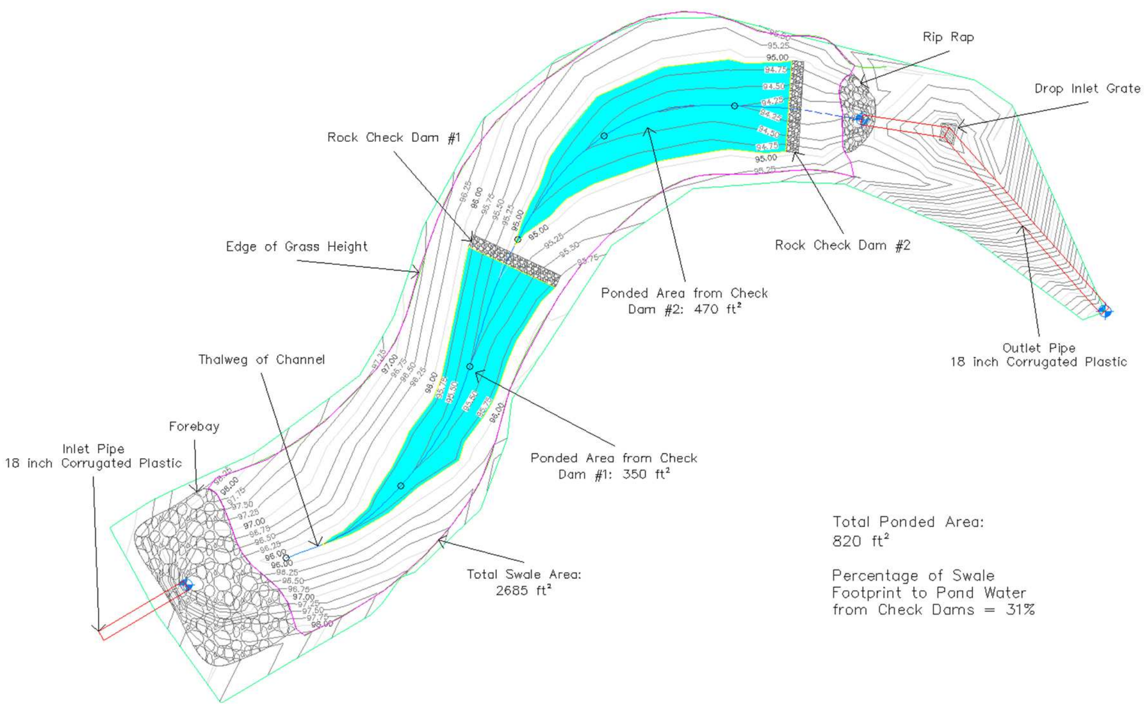

Figure 1-7: Overview of the Mango Creek Swale. Surface area with ponded water at the brink of overflow of the check dams is shaded in blue.

Performance during Design Storm Events

Mitigation of peak flows for large, high-intensity storm events, such as the 2-year and 10-year storms, is a common goal in urban stormwater management because flooding.

Therefore, peak flow rate reduction was calculated during events exceeding design rainfall intensities. For this analysis, a rainfall duration of 10 minutes was utilized, as this was similar to the time of concentration for the bridge deck watershed (12 minutes; Luell 2011), determined through U.S. EPA Stormwater Management Model (SWMM) simulations and direct observation. The 1-, 2-, and 5-yr rainfall intensities for Raleigh, NC were 3.86, 4.51, and 5.20 in/hr, respectively (NOAA 2014). During the pre-retrofit period, no storms exceeded these thresholds (Table 1-2). Post-retrofit, 1, 2, and 5 storms, respectively, exceeded the 5-, 2-, and 1-yr design rainfall intensities (Table 1-5).

The retrofitted swale exhibited a wide range of effectiveness in reducing peak flows during these larger design events. Peak flow mitigation appeared directly related to rainfall intensity and inversely to antecedent dry period. For the three events with short (<1 day) antecedent dry periods, the swale with check dams provided no meaningful peak flow mitigation. With longer antecedent dry periods, the soil in the swale abstracted additional water through infiltration. Additionally, the timing of the peak rainfall intensity is an important contributor to peak flow mitigation (Winston et al. 2016). The peak rainfall intensity occurred approximately 10 minutes into both the May 15th and July 24th storms, with these two storms having disparate effects on peak flow rate. The critical factor delineating the performance of the swale is the amount of rainfall that occurred before this peak intensity was reached. Three-tenths of an inch of rainfall fell prior to the peak rainfall intensity on May 15th, while on July 24th, one inch of rainfall occurred prior to this point. Because there was less runoff volume for the May 15th events prior to the peak intensity, there was still available storage behind the check dams to mitigate peak flow. This is contrasted with the event on August 12th, where 1.7 inches of rainfall fell prior to the peak intensity 30 minutes into the event. This storm likely filled the storage volume behind the check dams before the peak intensity occurred. Once this volume is filled, no peak flow reduction would be expected. Thus, the shape of the hyetograph impacts substantially the peak flow mitigation potential of swales (similar to other LID SCMs, such as bioretention and permeable pavement; Muthanna et al. 2008; Fassman and Blackbourn 2010; Winston et al. 2016). This suggests center-weighted design hyetographs may not be representative of true conditions, and may result in over-design of SCMs.

Table 1-5: Peak flow values for high-intensity storm events monitored at the Mango Creek swale.

Storm Date	Antecedent Dry Period (days)	Rainfall (in)	5-min Peak Intensity (in/hr)	Influent Peak Flow Rate (cfs)	Effluent Peak Flow Rate (cfs)	Reduction (%)
4/30/2014	0.6	1.19	3.9	0.89	0.68	24
5/15/2014	15	4.25	4.0	0.98	0.54	45
7/15/2014	4.84	2.03	3.9	1.18	0.73	38
7/24/2014	0.4	1.57	4.3	1.29	1.11	14
8/12/2014	0.8	2.87	5.3	2.22	2.37	-7

Clogging of the Check Dams

The forebay of the Mango Creek swale was not successful in capturing large debris or gross solids, because it did not have adequate storage (Figure 1-8). Because of this, the first check dam in the swale began filtering and collecting gross solids upon installation. The mass of gross solids began to blind, or cover the surface of, the first check dam within two months of installation. The second check dam functioned as designed due to the "effectiveness" of the first check dam acting as a forebay (Figure 1-9).

Figure 1-8: The forebay failed to pond a substantial water volume during storm events, partly because it was overwhelmed by gross solids.


Figure 1-9: The first check dam in the Mango Creek swale blinded by debris and gross solids (left) and the second check dam in the Mango Creek swale (right), with photographs taken in May 2014, two months after check dam installation.

After approximately six months, the first check dam fully clogged and the rate water transmission was reduced to a very slow seep. The second check dam began to show similar signs of blinding towards the end of the twelve-month monitoring period. Upon clogging, flow passed around the edges or over the top of the check dams rather than through the rocks. Because the grassed area upslope of the check dams was consequently inundated for extended periods of time, swale vegetation did not remain healthy (Figure 1-10).

Additionally, long-term ponding behind the check dams reduces the available storage volume for subsequent storms, limiting the ability of the check dams to mitigate peak flow.

These observations suggest that maintenance of check dams is a critical to their ability to properly function over time. Clogged check dams will negatively impact the health of the vegetation in the swale, subsequently undermining the water quality performance of the swale, specifically with respect to reduced sedimentation and filtration of sediment-bound pollutants (Barrett et al. 2004; Winston et al. 2012). Saturated soils upslope of clogged check dams maintenance by mowers. Debris removal from check dams will thus be a critical factor to ensure these systems augment the hydrologic (and water quality) performance of grass swales. Appendix F provides further photographic evidence comparing vegetation health in the swale before and after check dam clogging.

Figure 1-10: Clogged first check dam (left) and view of the swale upstream of the clogged check dam (right). Pictures taken in November 2014, approximately seven months after check dam installation. Note vegetation loss along thalweg of channel.

Hydraulic Retention Time

Swales are often designed based upon hydraulic retention time (HRT), or the amount of time water is retained within the SCM (Barrett 2008). The HRT, defined herein as the duration between peak inflow and outflow, was determined for each rainfall event, with storm events that did not produce outflow discarded from the analysis (Appendix G).

The check dams were expected to increase swale HRT by temporarily detaining water and lowering flow velocity, which was generally supported by the data (Table 1-6). Median HRT increased by 29% from 14.1 to 18 min when rainfall depth for small events (<0.75 in). For events greater than 0.75 inches, HRT increased by 50% from 8 to 12 minutes. As expected, median and mean HRT were lower for larger storm events because these events quickly saturate the soil of the swale and fill the available storage volume behind the check dams. Ferguson (1998) suggested a HRT of 9 minutes or more for substantial pollutant removal to occur. While this threshold was met, especially post-retrofit, the improvement in HRT due to the installation of the check dams did not significantly improve the water quality performance of the swale (See Chapter 2).

Table 1-6: Summary of hydraulic retention times at the Mango Creek swale.

Statistic	<0.75 inch rainfall		>0.75 inch rainfall	
	Pre-Retrofit	Post-Retrofit	Pre-Retrofit	Post-Retrofit
Median	14.1	18.0	8.0	12.0
Mean	17.1	19.7	10.0	12.5

Summary and Conclusions

This study examined the effectiveness of retrofitting rock check dams in a vegetated swale to improve the swale's hydrologic performance. Rock check dams were installed at the Mango Creek swale located in Knightdale, North Carolina, in an easement under the I-540 highway bridge deck. The following conclusions were drawn:

1) The existing grass swale provided 20% volume reduction (significant at α=0.10), while the grass swale with rock check dams reduced runoff volume by 17% (significant at α=0.05). Statistical tests showed retrofitted rock check dams did not significantly improve volume reduction. However, further analysis of the data demonstrated that statistical testing may be skewed by (1) a small pre-retrofit data set and (2) the fact that 9 large storm events (>1.5" depth) occurred in the post-retrofit period, while only 2 such events occurred pre-retrofit. Volume reduction during small (<0.75 in) and moderate (0.75-1.5 in) storms approximately doubled with the addition of check dams. This suggests that for the water quality event, check dams may improve runoff volume mitigation by grass swales. For the largest events (>1.5 in), runoff reduction was not improved when adding check dams to the swale. Post-check dam retrofit, hydraulic retention time was shown to improve by 30% for small storms (<0.75 inches) and by 50% for large storms (>0.75 inches).
2) Significant peak flow rate reductions were observed during both pre- (48%) and post-retrofit (44%) periods. No significant improvement was again provided by the addition of the check dams. However, these statistics were compromised by the (1) larger and more intense events during the post-retrofit period and (2) smaller data set of the pre-retrofit period. For example, for the smallest events (those <0.75 in), the check dams substantially improved peak flow mitigation. Peak flow mitigation also modestly improved for moderate (0.75-1.5 in) and large (>1.5 in) events.

3) The swale with check dams provided modest peak flow attenuation (i.e., less than 50%) for some storm events exceeding design rainfall intensities (e.g., 1- and 5-yr ARI) for Raleigh, North Carolina. Longer antecedent dry periods and lower rainfall intensities positively impacted peak flow mitigation. Additionally, the timing of the peak rainfall intensity was critical, since the check dams provide no attenuation of peak flow once the storage upslope of them is filled. Thus, peak flows were attenuated for events with peak rainfall intensities that occurred prior to the check dams' maximum ponding. For one storm, 1.7 inches of rainfall occurred prior to the peak rainfall intensity occurring, leading to zero peak flow mitigation.
4) Debris, litter, and coarse sediment clogged the check dams, with the first check dam fully blinding in six months. Ponding due to clogging led to a loss of swale vegetation upstream of the check dam. At the rate of gross solids accumulation for this highway watershed, maintenance should be conducted approximately every four months to remove captured gross solids and prevent detrimental blinding.

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PART 2: ROCK AND STRAW WATTLE CHECK DAMS: DO THEY IMPROVE GRASS SWALE WATER QUALITY PERFORMANCE?

Literature Review

Stormwater runoff is a significant source of pollution to surface waters (U.S. EPA, 2007). The construction of impervious surfaces due to urbanization cause imbalances in the hydrologic cycle, allowing more stormwater runoff to be carried to streams and rivers, thereby increasing pollutant loading (Schueler et al. 2009; Vietz et al. 2014; Walsh et al. 2016). Highway stormwater runoff, which entrains pollutants deposited through atmospheric deposition, leaking of vehicular fluids, combustion of fuel, wear of vehicular parts, road surface deterioration, and dustfall (Barrett, Irish et al. 1998; Kayhanian et al. 2003; Kayhanian et al. 2007; Kayhanian et al., 2012), is often disconnected from receiving waters through the use of stormwater control measures (SCMs) such as vegetated filter strips (VFS) and grass swales. Highway runoff research has shown that swales and filter strips mute pollutant loads prior to discharge from the right-of-way (Barrett, Walsh et al. 1998; Deletic and Fletcher 2006; Winston et al. 2012; Winston et al. in press). Other SCMs, such as wet ponds, bioretention cells, and permeable pavement, have also been characterized for highway stormwater treatment (Luell et al. 2011; Eck et al. 2012; Winston et al. 2013). However, these treatment practices are often (1) costly and/or (2) require the purchase of additional right-of-way.

Vegetated swales are the most common SCM utilized by Departments of Transportation to drain stormwater from roads. They are typically designed to prevent inundation of the road by conveying runoff from large, intense design storms. Often water quality treatment is overlooked (Winston et al. in press), but ancillary treatment of stormwater runoff does occur. Bäckström (2002) and Willis et al. (2013) showed that TSS removal within a swale was primarily due to sedimentation and secondarily filtration. Bäckström (2003) found that TSS removal efficiencies increased with influent concentration, achieving removal rates above 50% when influent TSS was above 100 mg/L. A swale studied by Knight et al. (2013) achieved greater than 75% TSS load reduction, partly owing to 23% reduction in runoff volume. However, Bäckström (2003) and Allen et al. (2015) observed that captured sediments may not be permanently sequestered and may re-suspend during subsequent runoff events.

The concentration of sediment in swales appears to exponentially decay with swale length (Deletic and Fletcher 2006). For instance, Kachchu Mohamed et al. (2014) showed that 50-75% TSS removal occurred within the first 10 m of swale length; beyond this, only a further 20% TSS reduction could be expected regardless of the total swale length. In another study, TSS removal did not increase beyond a swale length of 75 m (Yu et al. 2001). Modeling results in Winston et al. (in press) suggested that the majority of TSS removal occurs within the first 15 meters of swale length.

Vegetation is critical to sediment reduction in swales. Bäckström (2002) found that well-vegetated swales had TSS removal rates greater than 90%, while 80% of TSS was removed in poorly vegetated swales. Sparse vegetation in swales can lead to channel erosion and subsequent increases in sediment concentration through a swale (Bäckström 2002; Winston et al. 2012). Barrett et al. (2004) suggested a minimum 80% vegetation coverage for sediment trapping in grass filters. Deletic and Fletcher (2006) showed that taller grass heights within a swale produced lower effluent sediment concentrations.

Nutrient removal from dry grass swales in past studies has been highly variable (Winston et al. 2012; Kachchu Mohamed et al. 2014). Lucke et al. (2014) found that at typical stormwater concentrations, sequestration of TN and TP was not expected. Willis et al. (2013) found that swale effluent concentrations of TN and total Kjeldahl nitrogen (TKN) were significantly and substantially (approximately 75%) lower than adjacent asphalt runoff. Particulate pollutants were well mitigated, while dissolved pollutants such as nitrate-nitrite nitrogen ($NO_{2\text{-}3}$) and orthophosphorus ($O\text{-}PO_4^{3-}$) showed similar concentrations in the swale outflow as untreated asphalt runoff. Pollutant loading of TN, TP, and TSS after treatment by the swale was at minimum 67% less than untreated runoff (Willis et al. 2013). Knight et al. (2013) observed that a swale was able to achieve significant reductions in TN concentrations, although TN was found to be “irreducible” at concentrations below 1 mg/L.

Various modifications to swales have been proposed to improve their water quality performance: soil amendments to increase infiltration (Bean and Dukes 2015), installation of soil media and a drain to create a bioswale (Kazemi et al. 2011; Ingvertsen, Cederkvist, Régent, et al. 2012, Ingvertsen, Cederkvist, Jensen, et al. 2012), vegetation treatments (Mazer et al. 2001), creation of wetland conditions (Winston et al. 2012; Tang et al. 2016), and installation of check dams (Stagge et al. 2012; Davis et al. 2012). Winston et al. (2012) found that wetland swales produced significantly and substantially (0.4 mg/L) lower effluent TN concentrations than traditional dry swales. Retrofits promoting infiltration are desired, since Bäckström (2002) observed that swales situated on permeable soil had improved pollutant removal efficiencies.

Check dams are often proposed in stormwater design manuals (e.g., ODNR 2006; NCDEQ 2009a) as simple modifications which can improve the water quality performance of a grass swale (Figure 1-1). They are installed perpendicular to flow to reduce velocity and temporarily detain runoff (NCDEQ, 2009a), thereby theoretically improving sediment trapping efficiency. Line and White (2001) and McLaughlin et al (2009) have shown rock and straw wattle check dams to be effective turbidity-reduction strategies for construction sites. For a post-construction grass swale, Davis et al. (2012) found that check dams provided improved hydraulic retention time (or the amount of time water is retained within a swale) for rainfall events of less than 1.2 inches. Kaighn and Yu (1996) found that two nearby swales, one with and one without a check dam, removed 87% and 23% of TSS load, respectively. Yu et al. (2001) showed 77% and 50% TP capture for swales with and without check dams. Stagge et al. (2012) concluded that vegetated check dams (pictured in Figure 1-1) had a negligible effect on overall water quality treatment, improving only nitrate treatment. The check dams in this study actually detracted from TSS treatment. Mixed results from previous studies show that further research is needed on check dams so that design guidance can be refined.

The abatement of dissolved phosphorus in stormwater is particularly important since it may lead to eutrophication and algal blooms (Correll 1998; Nogaro et al. 2016), substantially impacting the intended uses of surface waters (Brooks et al. 2015). Much recent research has focused on the removal of dissolved phosphorus from urban stormwater

(Erickson et al. 2012; LeFevre et al. 2014; Winston et al. submitted), with research showing water treatment residuals and other iron and aluminum oxide-containing filter media can provide significant O-PO_4^{3-} removal. One such media, ViroPhos™, has been previously evaluated during an evaluation of vegetated filter strips (VFS); VFS amended with Virophos™ emitted lower effluent TP concentrations and reduced TP loads (Knight et al. 2013). This type of phosphorus-adsorptive media could be incorporated into a check dam to improve the water quality performance of existing swales.

Research Goals

This study examined the effectiveness of two different types of check dams for improvement of post-construction highway stormwater quality. Rock check dams were retrofitted into a previously monitored swale draining runoff from a bridge deck on Interstate-540 (Luell, 2011; Winston et al. 2014). A second swale was monitored along Interstate-40, where straw wattles and polypropylene bags filled with Virophos™ were used as check dams. A pre/post monitoring design was used to quantify the impact of check dams on swale water quality performance (Spooner and Line 1993). This research will inform swale design guidance by quantifying the water quality benefits of rock check dams, excelsior fiber wattle check dams, and phosphorus-adsorptive check dams as swale enhancement features.

Methods and Materials

Site Descriptions

Two swales were monitored for the improvement of stormwater runoff quality before and after retrofit with check dams (Table 2-1). The first swale (hereafter referred to as Mango Creek) was located in Knightdale, North Carolina, and treated the southbound Interstate 540 (I-540) bridge deck runoff (35°47’03”N, 78°30’50”W), which has an annual average daily traffic load of 17,000 vehicles per day (URS Corporation, 2012). The swale was installed beneath the bridge deck in 2009 (Luell 2011). Forty-three existing bridge scupper drains were connected to a 12-in diameter polyvinyl chloride (PVC) pipe which conveyed stormwater runoff to the inlet of the swale. It drained 1.13 acres of 100% impervious surface and was designed to convey the 10-year, 24-hour storm (5.04 inches; Figure 2-1). A forebay lined with Class A riprap dissipated velocity and removed large debris as stormwater entered the swale. The swale had a 1.66% longitudinal slope and a length of 110 ft. It was triangular in cross-section, with 8:1 side slopes and an average top width of 21 ft, was vegetated with tall fescue grass (*Festuca arundinacea*), and remained dry between storm events. Appendix A provides additional photos of the Mango Creek swale.

The second swale (hereafter referred to as I-40) was located near Benson, North Carolina, along the eastbound lanes of I-40 (35°22’01.1”N, 78°29’36.0”W) at mile marker 330 (Table 2-1). This monitoring site was previously described in Winston et al. (2012), Eck et al. (2012), and Winston and Hunt (in press). The annual average daily traffic load was 20,000 vehicles per day (NCDOT, 2013). The I-40 swale drainage area included the road, adjacent wooded buffer and grassed backslope, and a portion of the nearby agricultural land beyond the wooded buffer (Appendix H). The catchment was approximately 1.07 ha and 16% impervious.

The I-40 swale had a 1% longitudinal slope and a length of 378 ft (Figure 2-1). It was triangular in cross-section with 7:1 side slopes and an average top width of 21 ft. Volunteer warm-season grasses and weeds dominated. It remained dry during inter-event periods in warm-season months (May through October), while high water tables existed during cold-season months (December through April). During these months, water was up to 6 inches deep during inter-event periods.

Table 2-1: Mango Creek and I-40 catchment and swale characteristics.

Characteristic	Mango Creek	I-40
Location	35°47’02.5”N, 78°30’49.8”W	35°22’01.1”N, 78°29’36.0”W
Ecoregion	Piedmont	Coastal
Swale Length (ft)	110	378
Longitudinal Slope (%)	1.66	1
Cross-section	Triangular	Triangular
Side Slopes (H:V)	8:1	7:1
Average Top Width (ft)	21	21
Underlying Soil Infiltration Rate (in/hr)	0.06	Not Measured
Designed Conveyance	10-year, 24-hour storm	10-year, 24-hour storm
Swale Vegetation	Tall fescue sod (*Festuca arundinacea*)	Warm season grasses
Swale Condition Between Storms	Dry	Seasonally Wet
Drainage Area (ac)	0.19	0.43
Drainage Area % Impervious	100	16
Annual Average Daily Traffic	17,000 vehicles/day	20,000 vehicles/day

Figure 2-1: Pre-retrofit photographs of the Mango Creek swale (left) and the I-40 swale (right).

Monitoring Periods and Installation of the Check Dams

Stormwater monitoring locations and the locations of the retrofitted check dams are shown at Mango Creek and I-40 in Figure 2-2. At Mango Creek, pre-retrofit monitoring began in December 2013 to compare inlet and outlet pollutant concentrations and loads. Four months of hydrologic data were collected and seven storms were sampled prior to check dam installation. On March 28, 2014, the Mango Creek swale was retrofitted with two NCDOT standard 1633.01 temporary rock silt check dams (NCDOT, 2012). These were constructed with Class B rip-rap fronted with #57 aggregate (Figure 2-3). The check dams were 1-ft tall at the channel thalweg, approximately 12 ft wide, and built with a flat top for increased storage (Figure 2-3). The check dams were spaced so that the upstream dam toe was at the same elevation as the top of the proximate downstream dam to ensure maximum ponded volume within the swale (U.S. EPA 2006). Post-retrofit swale monitoring continued for an additional twelve months (April 2014 to March 2015), during which twenty-three storm events were sampled.

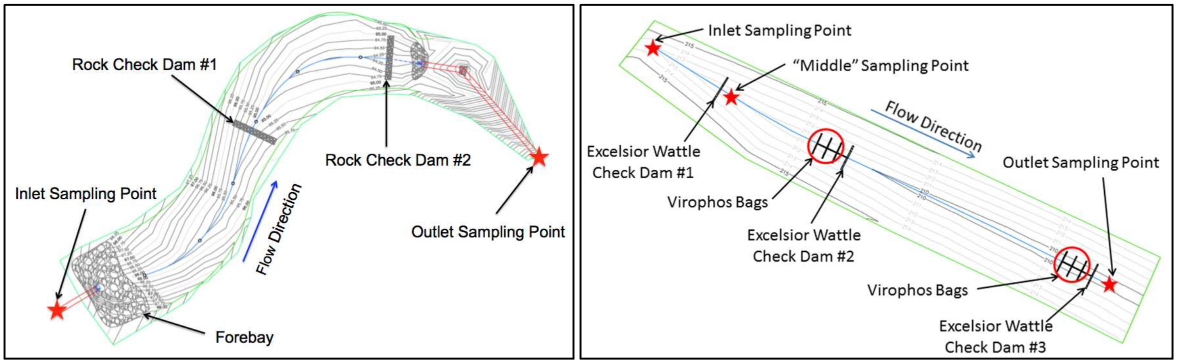

Figure 2-2: Mango Creek (left) and I-40 (right) monitoring schematics with check dam locations.

At I-40, the pre-retrofit monitoring began in September 2013 and spanned seven months during which twelve storm events were sampled for water quality. On April 24, 2014, the I-40 swale was retrofitted with three wood excelsior fiber (i.e., wattle) check dams and two sets of polypropylene multifilament supplemental bags installed at the two downstream-most wattle check dams (Figure 2-3). These bags were filled with Virophos™, a porous material designed to remove dissolved phosphorus. ViroPhos™ is made from a solid waste residue termed "red mud" and is composed of 20-30% hematite (Fe_2O_3), 10-20% hydrated alumina ($Al_2O_3 \bullet H_2O$), 10-20% sodalite ($Na_4Al_3Si_3O_{12}Cl$), <10% quartz (SiO_2), and other components (ViroTec, 2009). The check dams were spaced to maximize ponding using the same methods as at Mango Creek. Wattles were held in place with 2 in x 2 in x 24 in wood grade stakes. The retrofitted I-40 swale was monitored for twelve months (April 2014 to March 2015) post-retrofit.

During the pre-retrofit monitoring period, sampling points were located at the I-40 swale inlet and outlet. Post-retrofit, the "Middle" sampling point was added to isolate the effects of a single straw wattle check dam from those of the two sets of Virophos™ bags and straw wattles (Figure 2-2). Eighteen storm events were sampled post-retrofit. Further details and photos of monitoring challenges at Mango Creek and I-40 are provided in Appendices C, D, E, I, and J.

Figure 2-3. Rock check dam at Mango Creek (top), standard excelsior fiber wattle check dam at I-40 (bottom left), and an excelsior wattle with ViroPhos™ supplement bags check dam at I-40 (bottom right).

Monitoring Scheme and Sampling Procedure

Automated samplers (ISCO 6712, Teledyne ISCO, Lincoln, Nebraska, USA) were used to monitor each swale and were powered by a 12-volt deep cycle marine battery trickle charged by a 5-watt solar panel. At Mango Creek, ISCO 730 bubbler modules measured water level and were relayes to the ISCO 6712. Flow depths were measured on a 2-minute interval at inlet and outlet weir boxes (which included a baffle). In a catch basin just upstream of the Mango Creek swale, a compound weir was installed consisting of an 11.4-in tall, 60° v-notch lower portion and a 12.6-in tall, 13-in wide contracted rectangular upper portion (Figure 2-4). Measured flow depth was converted to flow rate using a derived (based on the v-notch and contracted rectangular weir equations), stepwise function (Walkowiak, 2013):

$$Q = 1.443 \times H^{2.5} \quad when\, H \leq 0.95\, ft \tag{2-1}$$
$$Q = 1.27 + 1838(0.335 - 0.2H)H^{1.5} \quad when\, H > 0.95\, ft \tag{2-2}$$

where Q is flow rate (cfs) and H is head on the weir (ft). Because of the unique design of the compound weir used at the inlet, a stage versus discharge table developed and input into the ISCO 6712. The outlet weir box was installed where an 18-in diameter pipe draining swale effluent daylighted into a nearby wooded area. It housed a 24-in tall, 45° v-notch weir, with flow rates calculated using the standard equation for this geometry (Figure 2-4; Walkowiak, 2013):

$$Q = 1.035 \times H^{2.5} \tag{2-3}$$

where Q and H have been previously defined. The ISCO sampler used measured flow depths and aforementioned weir equations to quantify the hydrograph. The sampler determined flow volume by integrating under the hydrograph, thus allowing flow-proportional, composite samples to be obtained from inlet and outlet weir boxes during wet-weather flow. Appendix B provides additional details regarding weir sizing and stage/discharge calculations for each monitoring location.

Figure 2-4: Mango Creek inlet (left) and outlet (right) weirs during a storm event.

The I-40 swale did not have the slope necessary to incorporate weirs without causing substantial backwater conditions; therefore, ISCO 674 tipping bucket rain gauges were utilized to trigger water quality samples during storm events (Figure 2-2). At the inlet, middle, and outlet sampling points, sample strainers were installed within shallow depressions in the thalweg of the swale (Appendix C). Sample collection was enabled after 0.17 in of rainfall in three hours. Samplers obtained a 200 mL aliquot after each subsequent 0.03 in of rainfall.

At both sites, sample aliquots were obtained through strainers with 3/8” diameter apertures located in areas of well-mixed flow. Samples represented at least 90% of the hydrograph, providing representative data to draw conclusions about swale performance (U.S. EPA 2002). All samples were collected from the samplers and distributed into laboratory bottles within 24 hours of the cessation of rainfall. A 500-mL plastic bottle and a 125-mL pre-acidified plastic bottle were filled for TSS and nutrient (except O-PO_4^{3-}) analysis, respectively. A syringe was used to remove approximately 20 mL from the TSS bottle and then field-filter the sample through a 0.45-µm filter into a 60-mL amber glass bottle for O-PO_4^{3-} analysis. After all samples were collected, they were chilled to ≤ 4°C for transport to the laboratory. All samples were transported to the North Carolina State University Center for Applied Aquatic Ecology (CAAE) lab in Raleigh, NC, for analysis. Samples were analyzed for: TKN, $NO_{2\text{-}3}$, total ammoniacal nitrogen (TAN), TP, O-PO_4^{3-}, and TSS. Organic nitrogen (ON) was calculated as the difference between TKN and TAN, particle bound phosphorus (PBP) as the difference between TP and O-PO_4^{3-}, and TN as the sum of TKN and $NO_{2\text{-}3}$. Table 2-2 summarizes the laboratory analysis methods, sample preservation methods, and laboratory reporting limits.

Table 2-2: Laboratory testing methods and reporting limits for nutrients and sediment.

Constituent	Preservation	Laboratory Testing Method	Reporting Limit
TKN	H_2SO_4 (<2 pH), <4˚C	EPA Method 351.2[a]	0.28 mg/L
$NO_{2\text{-}3}$	H_2SO_4 (<2 pH), <4˚C	Std Method 4500 NO3 F[b]	0.0056 mg/L
TN	N/A	= TKN + $NO_{2\text{-}3}$	N/A
TAN	H_2SO_4 (<2 pH), <4˚C	Std Method 4500 NH3 G[b]	0.007 mg/L
ON	N/A	= TKN – TAN	N/A
TP	H_2SO_4 (<2 pH), <4˚C	Std Method 4500 P F[b]	0.01 mg/L
O-PO_4^{3-}	<4˚C	Std Method 4500 P F[b]	0.006 mg/L
PBP	N/A	= TP – O-PO_4^{3-}	N/A
TSS	<4˚C	Std Method 2540 D[b]	1 mg/L

[a]U.S. EPA 1983
[b]APHA et al. 2012

Precipitation data were collected during pre- and post-retrofit monitoring periods with ISCO 674 tipping bucket and manual rain gauges located at both the Mango Creek and I-40 sites. The rain gauges were mounted on 6-ft tall wooden posts in an area free from overhead obstructions and trees. Rainfall events were separated by a minimum antecedent dry period of six hours and had rainfall depths of at least 0.10 in. Tables and photos summarizing monitoring equipment used at each site are presented in Appendix C.

Data Analysis

Because tipping bucket rain gauges often under-predict total rainfall depth during intense rainfall (Winston et al. 2011), these data were adjusted based upon the manual rain gauge data at each site. A correction factor was developed from the difference in rainfall depth between the tipping bucket and manual rain gauge. Rainfall duration, antecedent dry period, peak 5-minute rainfall intensity, and rainfall depth were determined for each storm event.

Since rainfall-paced or flow-paced samples were composited for each sampled rainfall event, water quality data were representative of event mean concentrations (EMCs). Swale water quality performance was evaluated using two (I-40) or three (Mango Creek) metrics. First, the reduction in the EMC of each pollutant, also known as the efficiency ratio (ER), was calculated (U.S. EPA, 2002):

$$\text{Median ER} = \frac{(\text{Median Inlet EMC} - \text{Median Outlet EMC})}{\text{Median Inlet EMC}} \qquad (2\text{-}4)$$

where either the mean or median EMCs were used to calculate the respective median ER or mean ER. The second method considered the concentrations entering and emitted from the swales pre- and post-retrofit. These concentrations were compared against established targets for ambient water quality based on benthic macroinvertebrate health (McNett et al, 2010). If influent pollutant concentrations were already meeting concentrations associated with healthy streams, then the swale may not be expected to provide additional treatment.

Finally, pollutant loads were determined for the Mango Creek swale on an event basis as the product of EMC and flow volume at each monitoring location. Minimum, median, mean, and maximum pollutant loads were compared between the inlet and outlet of the swale. The ER for pollutant loads, for *n* storm events, was calculated as (U.S. EPA, 2002):

$$\text{Load ER} = \frac{\sum_{i=1}^{n}(\text{Inlet Load}_{\text{i}} - \text{Outlet Load}_{\text{i}})}{\sum_{i=1}^{n}\text{Inlet Load}_{\text{i}}} \tag{2-5}$$

Statistical Analyses

Water quality data were statistically analyzed to compare paired influent and effluent concentration (both sites) and pollutant loading (Mango Creek) data. Statistical testing was completed separately for the pre-retrofit and post-retrofit data sets. Normality testing utilized the Shapiro-Wilk and Kolmorogov-Smirnov methods as well as visual inspection of quantile–quantile plots. If raw data were normally distributed or could be log-transformed to achieve normality, then a paired t-test was utilized. Otherwise, a Wilcoxon signed-rank test was utilized on the untransformed data.

To determine the effects of check dams on the water quality performance of the swale, statistical comparisons between the pre- and post-retrofit data sets were made using Welch's two-sample t-test for normal and lognormal data sets. For non-parametric data sets, a Wilcoxon rank-sum test was performed. Seasonality was analyzed using the Kruskal-Wallis K-Sample test with follow up paired comparisons with Dunn's test with a Bonferroni correction. Except where noted, data were analyzed for significance at the 95% confidence level (α=0.05). The statistical software R (version 3.1.3) was used to perform all statistical analyses (R Core Team 2015).

Results and Discussion

Precipitation

At Mango Creek, 7 rainfall events (ranging from 0.28 in to 1.26 in) and 23 rainfall events (ranging from 0.47 in to 4.25 in) were sampled during the pre- and post-retrofit periods, respectively (Table 2-3). These represented 35% and 53% of the rainfall events during the monitoring periods, respectively. Kruskal-Wallis K-sample tests showed no significant seasonality in rainfall depth, but rainfall intensity during the winter was significantly less than during the fall (α=0.05) and summer and spring (α=0.10). At I-40, twelve rainfall events (ranging from 0.47 in to 2.13 in) and eighteen rainfall events (ranging from 0.28 in to 3.62 in) were sampled during the pre- and post-retrofit periods, respectively. These were representative of 45% of the rainfall events during both periods. Samples at both sites were well distributed among the four astronomical seasons (Table 2-4).

Table 2-3: Summary statistics for sampled rainfall events at Mango Creek and I-40.

Parameter	Mango Creek		I-40	
	Pre-Retrofit	Post-Retrofit	Pre-Retrofit	Post-Retrofit
Number of sampled events	7	23	12	18
Mean rainfall (in)	0.71	1.29	1.06	1.30
Median rainfall (in)	0.55	1.10	0.94	1.18
Minimum rainfall (in)	0.28	0.47	0.47	0.28
Maximum rainfall (in)	1.26	4.25	2.13	3.62
Total rainfall (in)	4.93	29.71	12.95	23.74
Mean 5-min peak intensity (in/hr)	0.63	2.32	1.38	2.44
Median 5-min peak intensity (in/hr)	0.59	2.13	0.79	2.56
Minimum 5-min peak intensity (in/hr)	0.24	0.24	0.28	0.47
Maximum 5-min peak intensity (in/hr)	1.26	5.31	4.57	5.94

Table 2-4: Seasonal distribution of sampled water quality events at Mango Creek and I-40.

Monitoring Phase	Site	Spring	Summer	Fall	Winter
Pre-Retrofit (12/1/13 – 3/27/14)	Mango Creek	0	0	2	5
Post-Retrofit (3/28/14 – 3/6/15)		6	8	4	5
Pre-Retrofit (9/16/13 – 4/23/14)	I-40	3	0	3	6
Post-Retrofit (4/24/14 – 3/6/15)		4	5	3	6

During 2014, rainfall totaled 1440 mm and 1456 mm at Mango Creek and I-40, respectively. The 30-year mean annual rainfall for Raleigh, NC and Benson, NC (within 15 km of each site) was 1182 mm and 1161 mm, respectively (State Climate Office of North Carolina, 2015). Thus, both sites experienced approximately 25% greater rainfall than long-term average conditions during the monitoring periods.

Mango Creek Swale Pollutant Concentrations

Seven and 23 storm events were sampled for water quality during the pre- and post-retrofit periods at Mango Creek (Table 2-5). For almost all nutrient forms and TSS (except O-PO_4^{3-}), no significant difference existed between influent and effluent concentrations during the pre-retrofit period, suggesting the grass swale provided little treatment (Figure 2-5). These results were similar to those from a previous study on this swale (Luell 2011), where the swale only significantly reduced TSS. Mean and median influent concentrations during the pre-retrofit period were less than 0.8 mg/L TN, 0.2 mg/L TP, and 60 mg/L TSS. These concentrations are relatively low compared to other highway runoff studies (Thomson et al. 1997; Kayhanian et al. 2007; Kayhanian et al. 2012; Winston et al. 2012), perhaps hindering the ability of the swale to further reduce nutrient and sediment concentrations (Lucke et al. 2014). Median $NO_{2\text{-}3}$ concentrations increased through the swale, which may be related to the aerobic conversion of TAN through nitrification (Chen et al. 2012). Orthophosphate was the only pollutant that significantly increased through the swale; influent orthophosphate concentrations were on average 0.02 mg/L, well below effluent concentrations from swales in past research (Knight et al. 2013), perhaps indicating an irreducible concentration.

The median TSS ER of 46% was lower than other studies on grass swales, which have shown 60-95% removal (Barrett et al. 1998; Yu et al. 2001; Bäckström 2003; Stagge et al. 2012). Median and mean TP and PBP concentrations increased through the swale. The increases in PBP were related to the three largest and most intense rainfall events, where concurrent substantial increases in TSS were observed, probably due to resuspension of particulate matter. However, this could also be influenced by the winter-dominated pre-retrofit sampling period, when grass hardiness and stiffness is reduced and senescence of warm season grasses reduces vegetation coverage (Dunn and Dabney 1996).

In contrast to the pre-retrofit period, significant differences between influent and effluent EMCs were observed for all analytes except ON and PBP following the installation of the check dams (Figure 2-5 and Table 2-5). TSS concentrations significantly decreased through the swale by 70% following the installation of the check dams; however this was in the range of TSS removal for past swale studies without check dams (Barrett et al. 1998; Yu et al. 2001; Bäckström 2003; Stagge et al. 2012). TSS concentrations were reduced through the post-retrofit swale during all 23 sampled post-retrofit storm events, including during the winter months. However, statistical testing showed no significant improvement when comparing pre- and post-retrofit effluent TSS concentrations. These results are supported by

Stagge et al. (2012), who found that the inclusion of a pre-treatment vegetated filter strip provided statistically improved TSS removal, while check dams actually slightly increased TSS concentrations.

Nutrient removal performance suffered following the installation of the check dams, with TKN, $NO_{2\text{-}3}$, TN, TAN, TP, and O-PO_4^{3-} significantly increasing post-retrofit. ON concentrations were not significantly affected by the swale, while TSS concentrations decreased, suggesting sedimentation of silicate, non-organic particles. While no significant seasonality in effluent TSS concentrations was observed, the significant export of nutrient species intensified during spring and summer months (Table 2-6); swale nutrient ERs toward the end of the monitoring period (fall and winter) were often significantly (α values shown in Table 2-6) better than those during spring and summer. The observed 70% TSS removal and the lack of ON export suggested that particle resuspension was not the culprit. Additionally, NCDOT does not fertilize its grass swales as part of its standard maintenance procedures (NCDOT 2010). However, due to equipment passing through the swale, wheel ruts were observed in February 2014. On March 28, 2016, 500 ft^2 of the swale, 18.6% of its surface area, was regraded and re-sodded to repair the rutting in conjunction with the installation of the check dams. The first post-retrofit water quality samples were obtained 2 weeks after the installation of the sod. The growing medium of the sod was probably the source of nutrients released during the spring and summer months, either in the form of slow-release fertilizer or compost. As the source of nutrients in the sod was depleted, nutrient sequestration (except for $NO_{2\text{-}3}$) within the swale improved with time. This highlights the important temporal impacts that maintenance or lack of maintenance can have on SCM performance (Winston et al. 2012; Brown and Hunt 2012; Blecken et al. 2015; Winston et al. 2016).

Even with the significant export of some nutrient forms during the post-retrofit period, comparisons between pre- and post-retrofit effluent nutrient concentrations showed no significant differences at the Mango Creek swale. This suggested that the installation of the two rock check dams did not impact water quality performance. However, based on the standard deviation, the check dams reduced the variability of swale effluent concentrations for TKN, TAN, ON, TP, PBP, and TSS by 50-67% pre- versus post-retrofit. So, the check dams produced more consistent effluent concentrations, perhaps furthering the ability of swales to attenuate the peaks in pollutant loads, first described by Bäckström et al. (2006). The lack of statistical significance could certainly be related to the small (n=7) pre-retrofit data set.

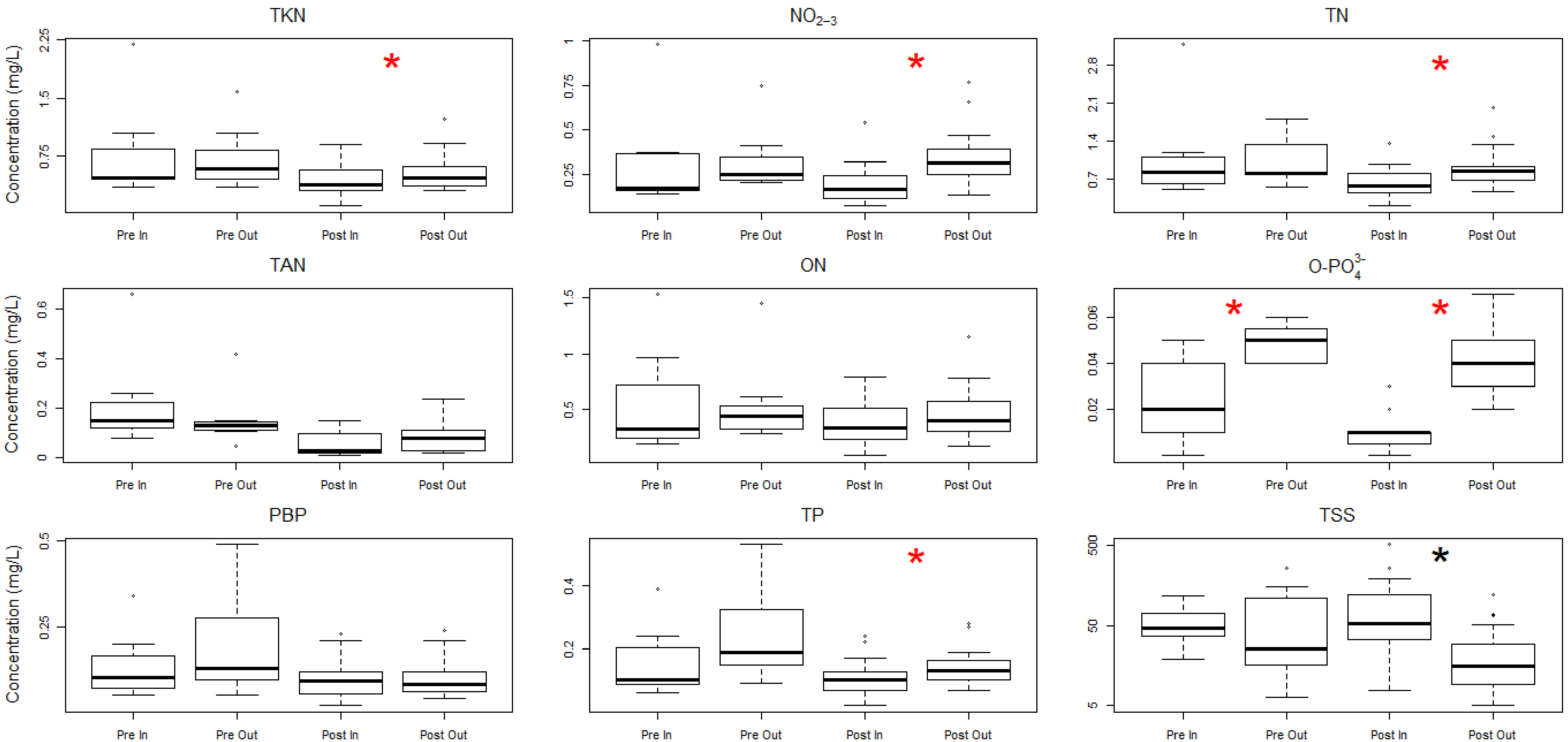

Figure 2-5: Pre- and post-retrofit nutrient and sediment concentrations at Mango Creek. Asterisks (*) located between data sets indicate singificant differences between them at the α=0.05 level, with red asterisks indicating significant increases in pollutant EMC.

Table 2-5: Statistics for pollutant EMCs and loads at the Mango Creek swale.

Pollutant	Monitoring Period and Location	Concentrations (mg/L) Range	$\bar{x}$	$\tilde{x}$	s	ER_{median}	ER	Loads (lb/ac/in) Range	$\bar{x}$	$\tilde{x}$	s	ER_{loads}
TKN	Pre-In	0.35-2.19	0.8	0.47	0.65	-24	10	0.09-0.50	0.24	0.15	0.18	0.23
	Pre-Out	0.34-1.58	0.72	0.58	0.44			0.05-0.50	0.18	0.14	0.15	
	Post-In	0.1-0.9	0.38	0.44	0.21	-24	-24*	0.01-0.3	0.12	0.10	0.07	0.08
	Post-Out	0.3-1.23	0.47	0.55	0.23			0.02-0.29	0.11	0.09	0.07	
NO_{2-3}	Pre-In	0.14-0.98	0.33	0.17	0.30	-49	1	0.04-0.21	0.090	0.069	0.064	0.16
	Pre-Out	0.2-0.75	0.33	0.25	0.20			0.03-0.15	0.076	0.067	0.038	
	Post-In	0.07-0.54	0.16	0.19	0.11	-90	-76*	0.01-0.11	0.05	0.04	0.03	-0.26
	Post-Out	0.13-0.77	0.31	0.34	0.15			0.02-0.11	0.06	0.06	0.03	
TN	Pre-In	0.5-3.17	1.13	0.83	0.93	3	7	0.12-0.68	0.33	0.21	0.22	0.21
	Pre-Out	0.54-1.8	1.05	0.81	0.52			0.08-0.57	0.26	0.20	0.16	
	Post-In	0.2-1.35	0.57	0.63	0.26	-47	-40*	0.03-0.33	0.17	0.15	0.08	-0.02
	Post-Out	0.47-2	0.84	0.88	0.36			0.04-0.37	0.17	0.14	0.09	
TAN	Pre-In	0.08-0.66	0.23	0.15	0.20	16	30	0.03-0.14	0.059	0.044	0.038	0.36*
	Pre-Out	0.05-0.42	0.16	0.13	0.12			0.01-0.08	0.038	0.035	0.023	
	Post-In	0.01-0.15	0.03	0.06	0.05	-152	-43	0-0.05	0.016	0.008	0.013	-0.12
	Post-Out	0.02-0.24	0.08	0.08	0.06			0-0.06	0.018	0.013	0.015	
ON	Pre-In	0.2-1.53	0.57	0.33	0.50	-34	2	0.04-0.46	0.18	0.11	0.16	0.19
	Pre-Out	0.29-1.45	0.56	0.44	0.41			0.04-0.46	0.15	0.11	0.14	
	Post-In	0.09-0.79	0.34	0.38	0.20	-17	-21	0.01-0.26	0.10	0.09	0.06	0.11
	Post-Out	0.18-1.15	0.4	0.46	0.21			0.02-0.25	0.09	0.06	0.06	
TP	Pre-In	0.06-0.39	0.16	0.1	0.12	-85	-55	0.015-0.114	0.05	0.03	0.04	-0.30
	Pre-Out	0.09-0.53	0.25	0.19	0.16			0.019-0.168	0.07	0.05	0.06	
	Post-In	0.02-0.24	0.1	0.1	0.06	-26	-35*	0.004-0.074	0.028	0.025	0.018	-0.04
	Post-Out	0.07-0.28	0.13	0.14	0.05			0.005-0.089	0.029	0.018	0.021	
$O\text{-}PO_4^{3-}$	Pre-In	0-0.05	0.02	0.02	0.02	-118	-93*	0.0013-0.0179	0.008	0.005	0.006	-0.45
	Pre-Out	0.04-0.06	0.05	0.05	0.01			0.0077-0.0168	0.011	0.011	0.003	
	Post-In	0.001-0.029	0.01	0.01	0.008	-476	-309*	0-0.009	0.003	0.002	0.003	-1.87*
	Post-Out	0.022-0.073	0.04	0.04	0.014			0.003-0.018	0.008	0.007	0.004	
PBP	Pre-In	0.05-0.34	0.14	0.1	0.10	-35	-48	0.012-0.096	0.042	0.033	0.033	-0.28
	Pre-Out	0.05-0.49	0.2	0.13	0.16			0.011-0.156	0.054	0.032	0.054	
	Post-In	0.02-0.23	0.09	0.09	0.05	4	-4	0.003-0.071	0.025	0.020	0.017	0.16
	Post-Out	0.04-0.24	0.08	0.1	0.05			0.002-0.078	0.021	0.013	0.019	
TSS	Pre-In	19-119	57.4	46.9	35.0	46	-34	4.62-56.8	18.9	16.0	17.6	-0.15
	Pre-Out	6-258	77.0	25.5	94.8			1.37-82.3	21.9	6.8	30.1	
	Post-In	7.8-510.6	52.2	91.1	110.7	71	70*	1.75-166.9	25.5	12.2	35.5	0.74*
	Post-Out	5-121	15.3	27.0	28.8			0.3-38.8	6.6	2.5	9.5	

*Significant at the 95% confidence level.

Table 2-6. Statistical testing for seasonality of nutrient effluent concentrations.

Pollutant	Kruskal Wallis p-value	Spring ER Better than…	Summer ER Better than…	Fall ER Better than…	Winter ER Better than…
TKN	<0.05	-	-	-	Sp[a], F[b], Su[b]
NO_{2-3}	<0.1	F[b]	F[b]	-	F[b]
TN	<0.1	-	-	-	Sp[a]
TAN	<0.05	-	-	-	Sp[a]
ON	<0.1	-	-	Sp[b]	-
TP	<0.05	-	-	-	Su[a], Sp[b]
$O\text{-}PO_4^{3-}$	<0.01	-	-	Su[b]	Su[a]
PBP	<0.05	-	-	-	Su[b], Sp[b]
TSS	NSD	-	-	-	-

[a,b] significant at α=0.05 and α=0.10 levels, respectively.

Statistical tests of pre- versus post-retrofit effluent concentrations were impacted by the small (n=7) pre-retrofit data set. To increase the statistical power, the post-retrofit data set was also compared against data collected by Luell (2011) in 2009-2010 at the Mango Creek swale, during which 31 storm events were sampled (Table 2-7). During Luell's study, influent nutrient concentrations were not significantly different from the pre-retrofit influent data herein except for TAN. Luell's effluent quality data (2011) were compared to the post-retrofit effluent concentrations, with no significant differences observed. These statistical comparisons further demonstrate that the rock check dams did not improve pollutant retention within the swale.

Table 2-7: Comparison of Luell (2011) and post-retrofit median pollutant EMCs and efficiency ratios for the Mango Creek swale.

Constituent	Luell (2011) Inlet (mg/L)	Luell (2011) Outlet (mg/L)	Luell (2011) Reduction (%)	Post-Retrofit Inlet (mg/L)	Post-Retrofit Outlet (mg/L)	Post-Retrofit Reduction (%)
TKN	0.60	0.54	10	0.38	0.47	-24
NO_{2-3}	0.28	0.24	14	0.16	0.31	-90
TN	0.89	0.83	7	0.57	0.84	-47
TAN	0.05	0.05	0	0.03	0.08	-152
TP	0.11	0.13	-18	0.10	0.13	-26
TSS	55	30	45	52	15	71

After approximately six months, the first check dam at Mango Creek fully clogged with debris, reducing its hydraulic conductivity substantially. Similarly, the second check dam clogged toward the end of the twelve-month post-retrofit monitoring period. However, no significant temporal trend was observed for swale hydraulic retention time (see Chapter 1). Check dam clogging caused the loss of swale vegetation due to extended inundation, although no resultant significant seasonal trend in effluent TSS concentration was observed (Table 2-6). Healthy vegetation is desired to promote nutrient uptake, filtration, and channel stability. Channel erosion caused a net export of TSS in one swale (Winston et al. 2012) where sediment deposited in the swale and exposed bed material are easily suspended. To reduce maintenance needs, check dams could be allowed to clog, allowing for hydrophytic vegetation and wetland hydrology to establish, which has been shown to improve swale water quality performance, particularly for TN (Winston et al. 2012); in this case, maintenance may still needed to reduce the potential for mosquito-borne disease (Hunt et al. 2006). Otherwise, maintenance (in this case at less than 6 month intervals) to remove debris and rubbish will be required to prevent loss of turfgrass or other upland vegetation.

Mango Creek Pollutant Loads

The distribution of rainfall depths and intensities during the two monitoring periods was substantially different (Table 2-3). For example, mean rainfall depth was 0.71 and 1.3 inches during the pre- and post-retrofit periods, respectively. Additionally, total rainfall during the pre-retrofit period was one-sixth that of the post-retrofit period. Resulting pollutant loads during these periods would not be comparable, since rainfall depth is directly related to runoff volume. Therefore, all pollutant loads were normalized by watershed area and rainfall depth (e.g., lb/ac/in) to account for differences in rainfall distribution. This method has three distinct advantages: (1) pollutant loads can be estimated for any rainfall event, (2) pollutant loads during the monitoring periods can be determined using the total rainfall in Table 2-3 and (2) long-term average pollutant loading can be estimated given a historical rainfall data set.

Pre- and post-retrofit pollutant loading data for the Mango Creek swale are shown in Table 2-5 and Figure 2-6. These were positively impacted by 20% and 17% runoff volume reductions, respectively, observed during the pre- and post-retrofit monitoring periods (see Chapter 1). During the pre-retrofit monitoring period, only TAN loads significantly decreased through the swale. Similarly, Luell (2011) did not observe significant load reduction for N or P during monitoring of the Mango Creek swale in 2009-2010. A roadside swale studied by Stagge et al. (2012) significantly reduced the load of nitrite, while TKN, $NO_{2\text{-}3}$, TN, TP, and TSS loads were not significantly reduced from those in road runoff. A grass swale in the Coastal Plain of North Carolina was only able to significantly reduce PBP and TSS loads (Knight et al. 2013). Thus, long-term pollutant load reduction for grass swales appears inconsistent, furthering the need for retrofits to improve their performance. Load ERs for the pre-retrofit Mango Creek swale did not exceed 40% for N species. Other than TAN, very little change in nitrogen species loading occurred through the swale, but the variability in event loads often declined (Figure 2-6). For both P species and TSS, load ERs for the pre-retrofit swale were negative; in fact, TSS loading increased in 2 of 7 sampled events. This was unusual, since TSS load reduction in grass swales is often greater than 50% (Barrett et al. 1998; Yu et al. 2001; Bäckström et al. 2003; Luell 2011; Knight et al. 2013).

During the post-retrofit period, O-PO_4^{3-} loads significantly increased through the swale (Figure 2-6 and Table 2-5). This is probably related to the concurrent installation of the sod and check dams, with the sod contributing nutrients during spring and summer. However, effluent loads of O-PO_4^{3-} during the post-retrofit period were still significantly lower than those of the pre-retrofit period.

Load ERs supported the statistical findings that the addition of the check dams did not improve nitrogen load reduction (apart from TAN). TAN effluent loads were significantly lower during the post-retrofit period. However, the ER for TAN loads was negative during the post-retrofit period (Table 2-5). At the 90% confidence level, PBP and TP post-retrofit effluent loads were also significantly lower than pre-retrofit, although load ERs for TP were still near zero.

While TSS effluent loads were not statistically different between the two monitoring periods (probably due to small pre-retrofit sample size), significant load reduction did occur during the post-retrofit period (74% ER), while similar results did not occur pre-retrofit (-15% ER). TSS load reduction for the swale with rock check dams was similar to the 83%

and 68% TSS removal observed for two swales in Maryland with vegetated check dams (Stagge et al. 2012) and the 75% removal for a swale with a check dam in Taiwan (Yu et al. 2001). These results suggest additional sedimentation may be occurring during the post-retrofit period, but that the small pre-retrofit sample size may have confounded statistical significance.

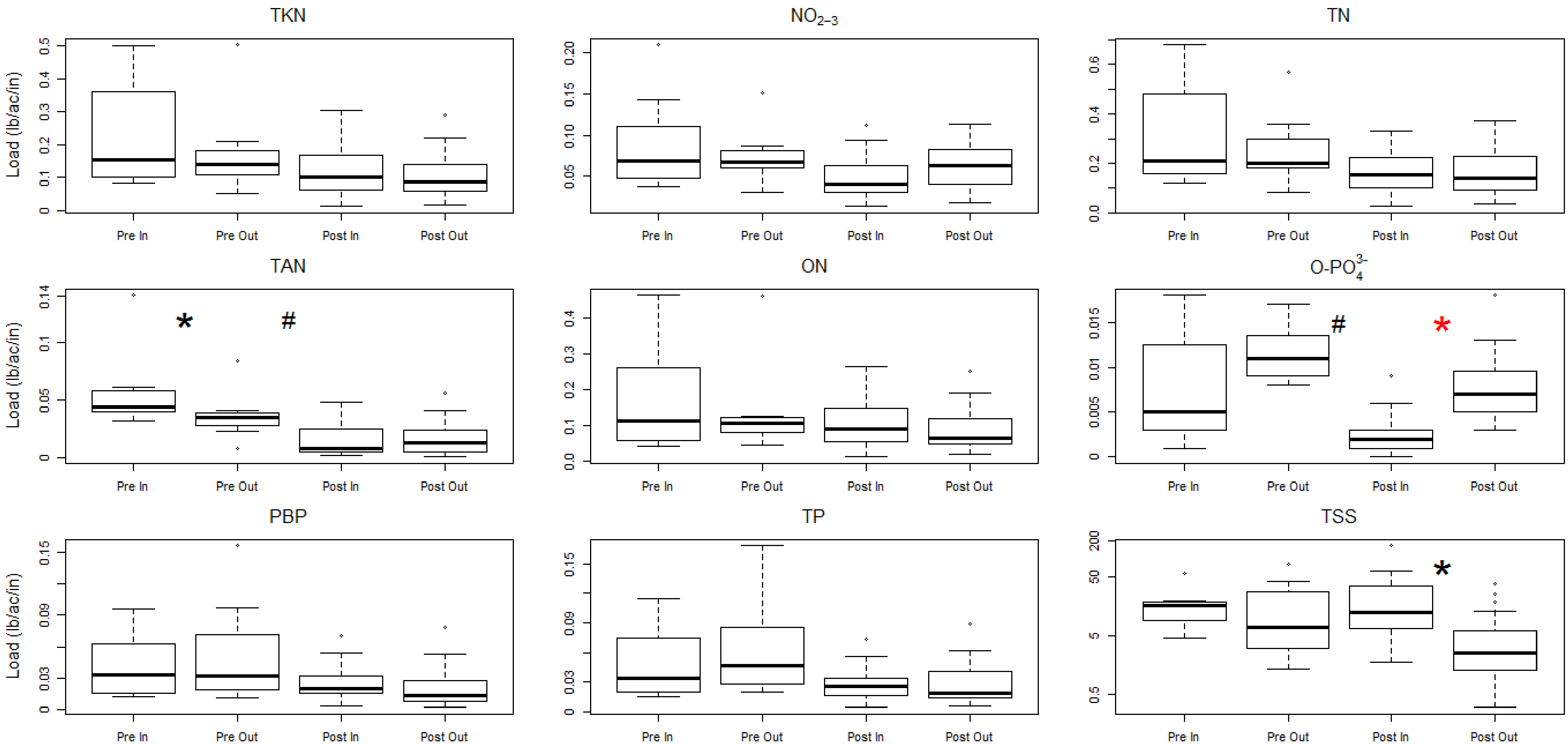

Figure 2-6: Pre- and post-retrofit nutrient and sediment loads at Mango Creek. Asterisks (*) located between data sets indicate significant differences between them at the α=0.05 level. The pound sign (#) indicates significant difference between effluent load pre- and post-retrofit. Red sybmols indicate significant increases in pollutant load.

I-40 Swale Pollutant Concentrations

The I-40 swale was located adjacent to and drained an interstate highway, and was described in Winston et al. (2012) as "site A." Table 2-8 and Figure 2-7 display statistics for and distributions of EMCs in stormwater runoff at the inlet, middle (post-retrofit only), and outlet of the I-40 swale. The pre-retrofit monitoring period consisted of twelve sampled storm events, during which significant differences were observed between all paired influent and effluent EMCs except TN and TAN (Figure 2-7). $NO_{2\text{-}3}$ concentrations significantly increased through the swale, while TKN, ON, TP, O-PO_4^{3-}, PBP, and TSS concentrations significantly decreased. The combination of significant and substantial ON, PBP, and TSS reduction within the swale suggested it was successfully trapping sediment, as observed in other swale research (Bäckström 2002; Barrett 2008). Mean ERs for these parameters were 63%, 77%, and 86%, respectively, meeting the 85% TSS removal required for post-construction stormwater management in North Carolina (NCDEQ 2009b) and far exceeding the 35% TSS removal credit that swales receive (NCDEQ 2009a). While ON and TKN decreased, probably due to settling of organic particulates, aqueous phase nitrogen was generally not well mitigated, similar to past grass swale research (Knight et al. 2013). It appears that aerobic transformation of TAN to $NO_{2\text{-}3}$ occurred through microbially-mediated nitrification, as mean $NO_{2\text{-}3}$ concentrations nearly tripled after passing through the swale; this type of $NO_{2\text{-}3}$ export has not been observed in other studies of grass swales (Winston et al. 2012; Stagge et al. 2012; Knight et al. 2013).

Table 2-8: Summary statistics for pollutant EMCs at the I-40 swale.

Pollutant	Monitoring Period and Location	Concentrations (mg/L)					
		Range	$\bar{x}$	$\tilde{x}$	s	ER_{median}	ER
TKN	Pre-In	0.62-9.09	2.46	1.28	2.49	14	61*
	Pre-Out	0.24-1.54	0.97	1.10	0.40		
	Post-In	0.4-4.97	1.38	1.08	1.06	-44[@]	-31*
	Post-Mid	0.7-5.22	1.81	1.55	1.17	18[^]	-3
	Post-Out	0.37-6.88	1.87	1.27	1.71	-17[$]	-35
NO_{2-3}	Pre-In	0.07-1.04	0.42	0.39	0.26	-127	-183*
	Pre-Out	0.19-2.75	1.18	0.89	0.94		
	Post-In	0.05-1.04	0.29	0.20	0.25	-16	8
	Post-Mid	0.08-0.64	0.26	0.23	0.16	-235	-223*
	Post-Out	0.03-2.89	0.85	0.77	0.77	-290	-196*
TN	Pre-In	0.99-9.64	2.87	1.69	2.55	-22	25
	Pre-Out	0.79-3.88	2.15	2.06	0.97		
	Post-In	0.53-5.02	1.67	1.29	1.12	-37	-24
	Post-Mid	0.86-5.46	2.07	1.76	1.22	-29	-31
	Post-Out	0.81-8.08	2.72	2.26	1.76	-76	-63*
TAN	Pre-In	0.03-0.29	0.12	0.10	0.08	29	16
	Pre-Out	0.03-0.3	0.10	0.07	0.08		
	Post-In	0.01-0.28	0.07	0.06	0.06	-24	-25*
	Post-Mid	0.03-0.24	0.09	0.07	0.06	-18	-321
	Post-Out	0.03-2.17	0.39	0.09	0.60	-46	-426*
ON	Pre-In	0.57-8.8	2.34	1.14	2.43	15	63*
	Pre-Out	0.15-1.32	0.87	0.96	0.37		
	Post-In	0.39-4.9	1.31	1.02	1.04	-45	-31
	Post-Mid	0.65-5.03	1.72	1.48	1.15	26	14
	Post-Out	0.28-4.72	1.48	1.09	1.24	-7	-13
TP	Pre-In	0.11-1.37	0.49	0.21	0.48	55	76*
	Pre-Out	0.03-0.34	0.12	0.09	0.08		
	Post-In	0.054-0.787	0.26	0.21	0.21	-42	-25*
	Post-Mid	0.097-0.981	0.33	0.29	0.21	52	36*
	Post-Out	0.042-0.697	0.21	0.14	0.18	31	20
$O\text{-}PO_4^{3-}$	Pre-In	0.008-0.074	0.04	0.04	0.02	58	61*
	Pre-Out	0.001-0.03	0.015	0.02	0.01		
	Post-In	0.02-0.28	0.051	0.076	0.07	39	32*
	Post-Mid	0.01-0.2	0.031	0.052	0.05	57	59*
	Post-Out	0-0.13	0.014	0.021	0.03	73	72*
PBP	Pre-In	0.04-1.36	0.45	0.16	0.49	48	77*
	Pre-Out	0.03-0.32	0.10	0.08	0.08		
	Post-In	0.04-0.74	0.13	0.19	0.20	-61	-47*
	Post-Mid	0.08-0.95	0.20	0.28	0.22	38	32
	Post-Out	0.04-0.69	0.13	0.19	0.17	0	-1
TSS	Pre-In	4.4-848.4	238.4	93.3	281.8	76	86*
	Pre-Out	4.1-182	32.6	22.1	48.2		
	Post-In	6.5-691.4	84.7	25.7	175.8	-278	-97*
	Post-Mid	8.1-827.6	166.5	97.2	210.7	83	65*
	Post-Out	3.3-413.3	58.8	16.6	104.2	35	31

*Significant at the 95% confidence level.

[@]ER compares in vs. middle monitoring locations

[^]ER compares middle vs. out monitoring locations

[$]ER compares in vs. out monitoring location

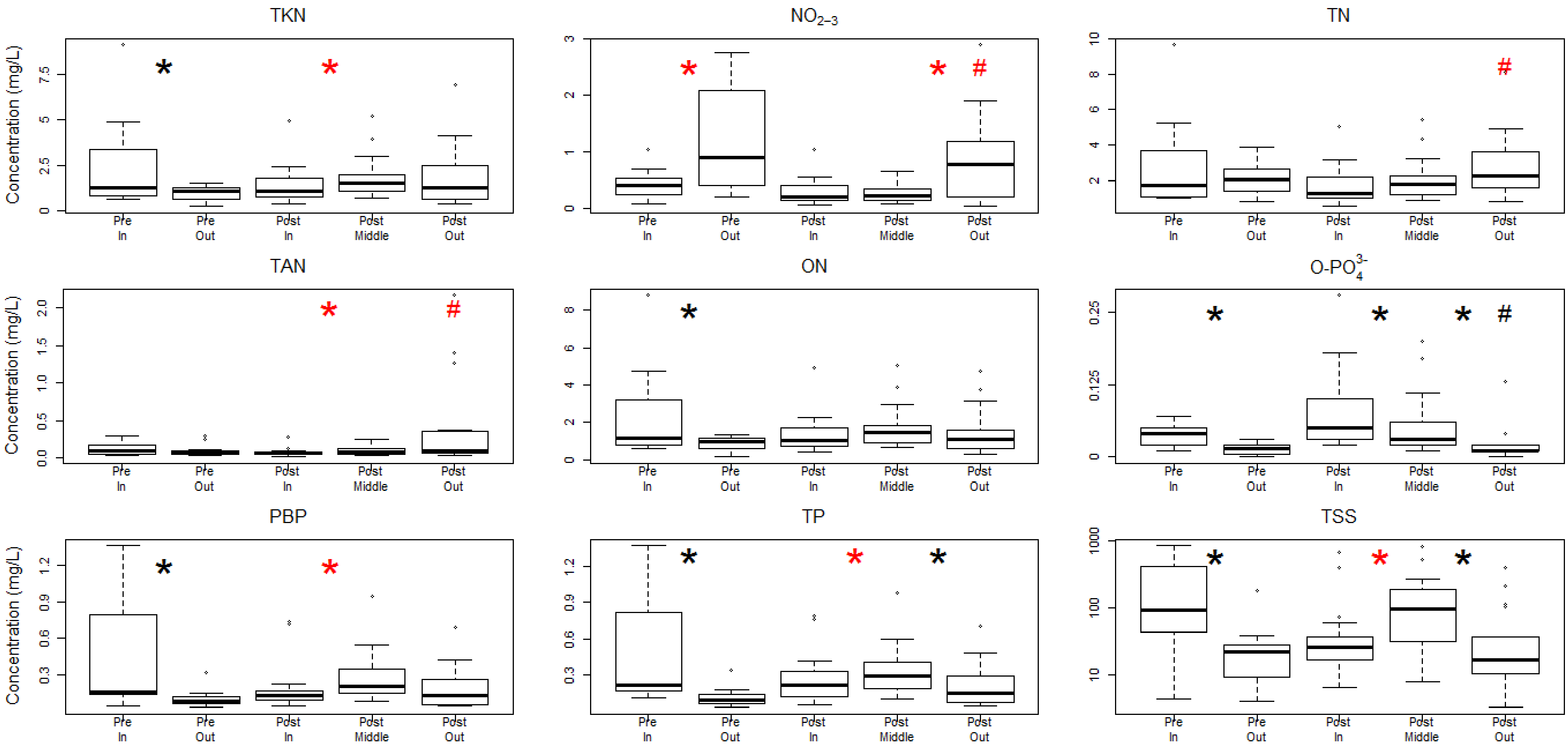

Figure 2-7: Pre- and post-retrofit nutrient and sediment concentrations at I-40. Asterisks (*) located between data sets indicate significant differences between them at the α=0.05 level, with red asterisks indicating significant increases in pollutant EMC. Pound signs (#) indicate significant differences over the length of the swale (i.e., from inlet to outlet) during the post-retrofit period.

Following the installation of the check dams, an additional monitoring station (i.e., middle) was established after the first straw wattle check dam and upslope of the first straw wattle/media bag check dam (Figure 2-2). This isolated the performance of the single straw wattle check dam from the P-adsorptive media bags. Statistical analysis for the post-retrofit monitoring period was broken into three separate comparisons: inlet vs. middle (testing the effects of the single straw wattle check dam), middle vs. outlet (testing the effects of the straw wattle/media bag check dams), and inlet vs. outlet (testing the effects of all check dams). Eighteen storm events were sampled post-retrofit.

The straw wattle check dam had little impact on swale performance; only O-PO_4^{3-} concentrations were significantly reduced (Figure 2-7 and Table 2-8), perhaps related to sorption of dissolved P to sediment suspended in the stormwater. Concentrations of TKN, TAN, PBP, TP, and TSS significantly increased. The excelsior fiber wattle check dams were 30 lbs dry weight (Figure 2-8). While they were properly installed, the wattle check dams' light weight caused them to float slightly off the ground during wet weather, providing negligible impedance to flow. Observations during storm events indicated no differential head across the straw wattles (Figure 2-9). Thus, the wattle check dams did not substantially extend the detention time within the swale, explaining the lack of significant treatment benefits. This is in contrast to results presented by Kang et al. (2013) for construction sites, who found that excelsior wattles provided greater ponding than rock check dams, perhaps because the wattles clog and restrict flow more quickly in this higher turbidity environment.

Figure 2-8: Close up view of an excelsior fiber wattle (left) and an excelsior fiber wattle installed in the I-40 swale with wood grade stakes.

Figure 2-9: Close up view of an excelsior wattle during a storm event (9/8/14). Note that water levels are the same on both sides of the check dam, indicating minimal flow impedance.

While TKN, TAN, PBP, TP, and TSS significantly increased through the section of swale with the straw wattle, the check dam was not the pollutant source; rather, this segment of the swale experienced channel erosion during the post-retrofit period (Figure 2-10), first observed after a 3.6-in rainfall event on May 15, 2014. The check dam was not a contributor to channel degradation as the lack of ponding meant there was no impact on vegetation health. Maintaining healthy and vigorous vegetation in swales is perhaps the most critical factor to prevent suspension of soil particles and associated pollutants (Barrett et al. 2004; Winston et al. 2012).

Figure 2-10: Channel degradation between the inlet and first check dam of the I-40 swale.

The straw wattle/media bag check dams significantly reduced concentrations of O-PO_4^{3-}, TP, and TSS when compared to those observed immediately downslope of the first straw wattle check dam. TP and TSS reductions were probably related to settling and/or trapping of the re-suspended sediment in the upper portion of the swale (Figure 2-7). However, significant and nearly three-fold increases in NO_{2-3} concentrations in this portion of the swale were similar to those observed pre-retrofit; perhaps the adjacent agricultural field was contributing NO_{2-3} along this portion of the swale. Similarly elevated NO_{2-3} concentrations were not observed in previous monitoring of this swale (Winston et al. 2012).

When considering the combined effects of all check dams, the retrofitted swale significantly increased NO_{2-3}, TN, and TAN concentrations, while no significant difference was observed from the inlet to the outlet of the swale for TKN and ON. Taken together, the check dams had no positive impact on nitrogen retention in this swale, similar to results in Yu et al. (2001). These results modestly diverged from those in Stagge et al. (2012), who observed significant improvement of NO_{2-3} treatment when check dams were installed in a swale, but no improvement in TKN. PBP, TP, and TSS concentrations were not significantly different through the post-retrofit I-40 swale. Furthermore, significant differences were not observed between pre- and post-retrofit swale effluent concentrations for any of the pollutants monitored. This suggested that in terms of water quality discharged to nearby receiving streams, the straw wattle and media bag check dams provided no benefit.

The ViroPhos™ supplements incorporated in the media bag check dams were designed to remove $O\text{-}PO_4^{3-}$. Post-retrofit, a significant reduction (73%) in $O\text{-}PO_4^{3-}$ concentration was observed between the swale inlet and outlet. The median inlet EMC of 0.051 mg/L was reduced to 0.031 mg/L at the middle sampling point (prior to ViroPhos™ treatment) and to 0.014 mg/L at the swale outlet. The pre-retrofit swale significantly reduced (by 61%) $O\text{-}PO_4^{3-}$ concentration, with a median effluent concentration of 0.015 mg/L at the swale outlet. When comparing pre- and post-retrofit swale performance, $O\text{-}PO_4^{3-}$ effluent concentrations were not significantly different. Thus, ViroPhos™ did not improve $O\text{-}PO_4^{3-}$ removal within the swale; similar results were observed for vegetated filter strips in Knight et al. (2013). This may be related to irreducible effluent $O\text{-}PO_4^{3-}$ concentrations in the pre-retrofit period (Figure 2-7 and Table 2-8; Lenhart and Hunt, 2011). The contact time between the media and the stormwater could have been too short since the straw wattles did not pond water over the media bags.

Research by Stagge et al. (2012) also showed that check dams had a negligible effect on the overall ability of swales to sequester or otherwise reduce pollutant concentrations. In their study, vegetated check dams only improved $NO_{2\text{-}3}$ removal, while slightly increasing TSS concentrations. Kaighn and Yu (1996) observed that a roadside swale with a check dam had nearly twice the TSS removal efficiency of one without a check dam. However, this check dam ponded stormwater, while wattles at the I-40 site failed to do so. Based on results herein, in Stagge et al. (2012) and Kaighn and Yu (1996), check dam installations should ensure detention of stormwater during wet weather, but release water within 24 hours of the cessation of rainfall to prevent turfgrass mortality (Beard and Martin 1970).

Comparison of Pollutant Concentrations with Ambient Stream Health

Although SCM pollutant treatment efficiency is often evaluated based on reductions in EMCs and pollutant loads, these metrics do not consider the limited potential to achieve pollutant reduction when influent concentrations are already low (Strecker et al., 2001). Under these circumstances, unit processes within the SCM may not be able to provide substantial improvement to “irreducible” concentrations; however, discharged water may be of high enough quality to have no negative impact on receiving waters. Nonetheless, this analysis considers only the impact of pollutant concentrations; one must also consider the impact of stormwater volume and flow rate on stream geomorphology (Walsh et al. 2016).

Due to the range of benthos sensitivity to pollution, benthic macroinvertebrates may be used as indicators to assess water quality and assign levels of impairment in streams and rivers (Barbour et al., 1999). McNett et al. (2010) correlated ambient nutrient and sediment concentrations in streams across North Carolina to the sensitivity of their benthic macroinvertebrate populations. These metrics have been employed as baselines for SCM performance (e.g., Lenhart and Hunt, 2011; Winston et al., 2011; Knight et al., 2013).

The Mango Creek and I-40 swales were located in the Piedmont and Coastal Plain ecoregions of North Carolina. For streams in the North Carolina Piedmont, McNett et al. (2010) established “good” water quality thresholds for TN and TP at 0.99 mg/L and 0.11 mg/L, respectively. For streams in the Coastal Plain, “good” water quality thresholds were 0.73 mg/L and 0.09 mg/L, respectively (McNett et al., 2010). “Good” water quality is associated with sensitive benthos populations, including mayflies and caddisflies (Barbour et al., 1999). A target TSS effluent concentration for SCMs of 25-30 mg/L is often used (e.g., Barrett et al. 2004; Stagge et al. 2012). These target concentrations provide benchmarks for comparison against SCM influent and effluent quality.

Influent concentrations at Mango Creek were below the respective TN and TP “good” water quality thresholds, suggesting runoff from the I-540 bridge deck was relatively clean. After passing through the swale, median pre- and post-retrofit TN concentrations (between 0.8-0.85 mg/L) were still below this threshold. Median TP effluent concentrations for the pre- and post-retrofit periods (0.19 mg/L and 0.13 mg/L, respectively) increased through the swale to concentrations associated with “fair” and “good/fair” water quality, respectively (McNett et al., 2010). Median influent TSS concentrations (pre- and post-retrofit of 47 mg/L and 52 mg/L, respectively) were reduced to near (pre-retrofit) or below (post-retrofit) the 25 mg/L target concentration. The inability of the Mango Creek swale to provide significant treatment of nutrients may have been a result of irreducible concentrations entering the SCM (Lenhart and Hunt, 2011).

To illustrate the relative frequency that target concentrations were met, cumulative probability plots were generated by ranking storm event mean concentrations for each monitoring period and plotting each against its relative probability of exceedance (Figure 2-11). Pre-retrofit influent TN, TP, and TSS EMCs met their respective “good” water quality targets 57%, 57%, and 14% of the time. Comparatively, pre-retrofit effluent met water quality goals 14%, 0%, and 29% more often, respectively, suggesting improved TN and TSS effluent quality. Post-retrofit influent met the “good” target for TN, TP, and TSS, respectively for 96%, 65%, and 22% of events. Post-retrofit effluent EMCs met their water quality targets during 0%, 0%, and 48% more often than pre-retrofit, respectively. For nutrients, this suggested unreliable treatment. For TSS, treatment was observed across the range of influent concentrations (Figure 2-11).

Stormwater entering the I-40 swale contained elevated nutrient concentrations when compared to target water quality conditions of coastal streams. Median TN influent (1 mg/L) and effluent (2 mg/L) concentrations were above the 0.73 mg/L target “good” concentration. The median influent TP concentration improved from 0.21 mg/L to 0.09 mg/L (pre-retrofit) and 0.14 mg/L (post-retrofit) as water passed through the swale, with effluent meeting the “good” water quality threshold pre-retrofit. Median influent TSS concentrations were above the target threshold pre- and post-retrofit (93 mg/L and 26 mg/L, respectively), while the swale effectively trapped sediment during these periods (22 mg/L and 17 mg/L, respectively) periods, reducing concentrations below the target threshold. Reliable sediment removal was observed both before and after check dams retrofit.

Pre-retrofit influent TN, TP, and TSS EMCs met “good” water quality thresholds during 0%, 0%, and 8% of events. Pre-retrofit effluent EMCs met their water quality targets 0%, 50%, and 50% more often, respectively. For post-retrofit influent concentrations, 17%, 11%, and 50% of events met the “good” targets, respectively. Post-retrofit effluent EMCs met their water quality targets 0%, 17%, and 17% more frequently than pre-retrofit, respectively. Collectively, these results suggested this swale was effective (both pre- and post-retrofit) at sequestering TP and TSS but not TN. The swale offered no treatment of TN with or without the inclusion of check dams. If TN is of concern, other retrofits to swales, such as those promoting denitrification, filtration, or plant uptake, should be the focus of management plans (Winston et al. 2012; Ingvertsen, Cederkvist, Régent, et al. 2012; Ingvertsen, Cederkvist, Jensen, et al. 2012).

When comparing effluent quality, the check dams at Mango Creek improved the percentage of storm events meeting target water quality conditions for TN, TP, and TSS by 7%, 25%, and 27%, respectively. The check dams at I-40 did not improve the percentage of events meeting the target conditions for TN and TP, and only improved those for TSS by 9%. Perhaps these contrasting results are related to the greater impedance to flow produced by the rock check dams vis-à-vis the straw wattles. Especially in light of the fact that potentially irreducible influent concentrations were observed at Mango Creek, this supports the notion that check dams should be designed as hardened structures that maximize hydraulic retention time without jeopardizing motorist safety or increasing maintenance burden.

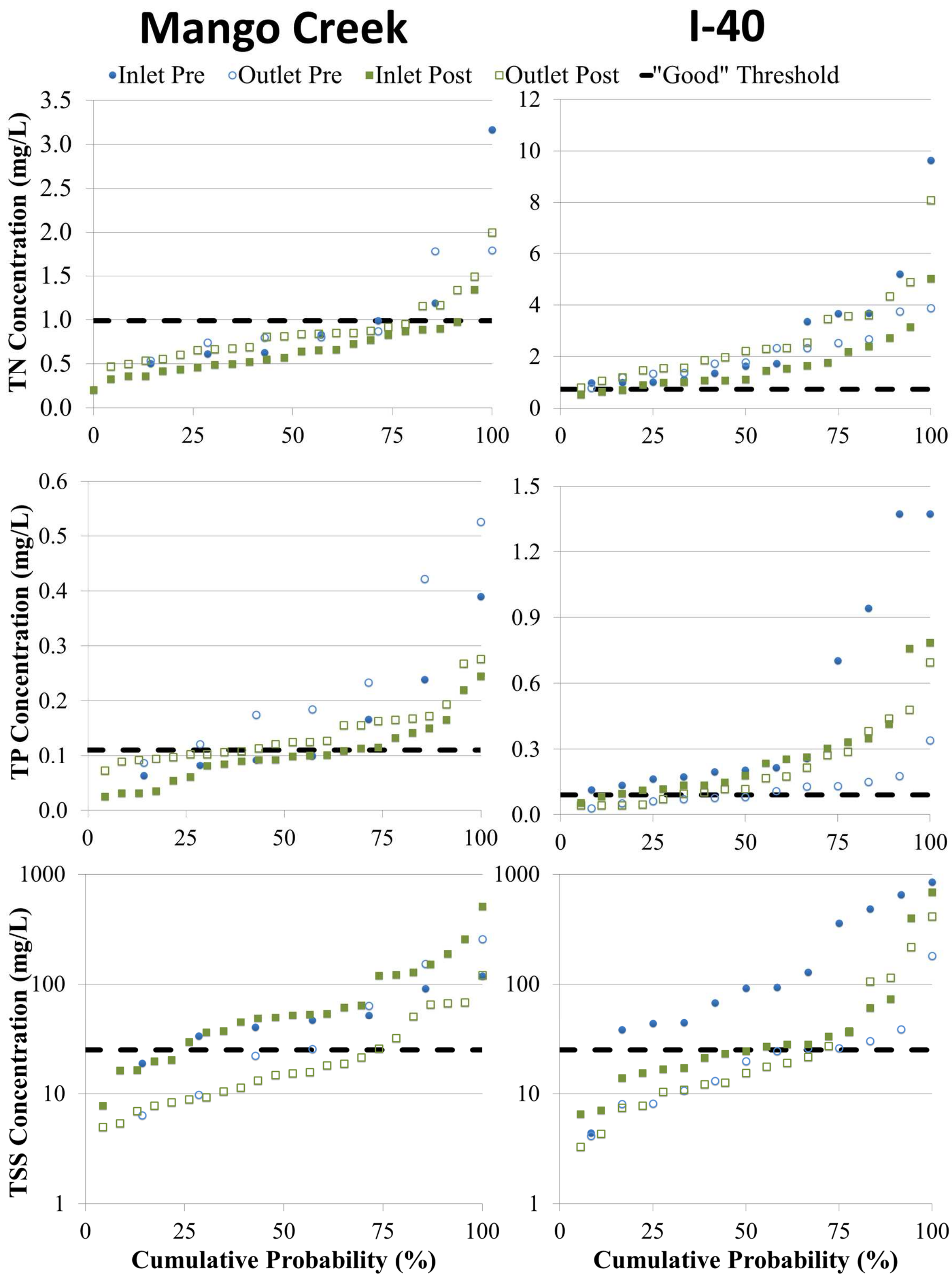

Figure 2-11: Cumulative probability plots for TN, TP, and TSS for Mango Creek and I-40. "Good" water quality thresholds (based on McNett et al. 2010) are shown as dashed horizontal lines.

Summary and Conclusions

This study examined the effectiveness of retrofitting various types of check dams, including rock, straw wattle, and phosphorus-adsorptive media bags, in vegetated swales to augment nutrient and sediment retention. The following conclusions were drawn:

1) The pre-retrofit grass swale at Mango creek was unable to significantly reduce nutrient concentrations or TSS ER concentrations. After installing the rock check dams, total suspended solids EMCs were significantly reduced by 71%; however, effluent concentrations during the pre- and post-retrofit periods were not significantly different. Because the pre-retrofit data set was small, data (31 sampled storm events) from Luell (2011) were also compared to the post-retrofit data. Statistical analysis showed no significant improvement in nutrient or TSS removal by the swale with check dams. However, post-retrofit effluent TSS concentrations (15 mg/L) met the ambient water quality target of 25 mg/L, while pre-retrofit EMCs did not (26 mg/L). Nutrient concentrations often increased in the post-retrofit swale due to the impact of newly installed sod and nutrients associated with its growing media.
2) Pollutant load reduction at the Mango Creek swale was aided by the 20% and 17% volume reductions observed during the pre- and post-retrofit periods. Even so, the pre-retrofit swale was only able to significantly reduce TAN loads. Post-retrofit, TSS loads were reduced by 74%, while TSS loads increased by 15% pre-retrofit. However, only TAN and O-PO_4^{3-} loads were significantly lower post-retrofit. The post-retrofit swale was, however, able to

mitigate the variability in effluent pollutant loading, providing more consistent effluent water quality.

3) Influent runoff at Mango Creek contained low nutrient concentrations when compared to target water quality conditions developed for local streams. Both pre- and post-retrofit median TN and TP inflow concentrations were below "good" water quality thresholds. Therefore, the swale's inability to treat nutrients may have been a result of "irreducible" concentrations entering the SCM (Lenhart and Hunt, 2011). Pollutant concentrations exiting the swale were found to generally meet "good" water quality.

4) Debris, litter, and sediment caused clogging of the rock check dams at Mango Creek. Clogged check dams contributed to the loss of healthy swale vegetation from extended periods of inundation. Check dams should be designed of hardened materials to detain stormwater during a rainfall event, but should drain to prevent turfgrass mortality and the potential for suspension of bed material.

5) In contrast to the Mango Creek swale, the influent concentrations to the I-40 swale were substantially higher, and the pre-retrofit I-40 swale significantly reduced concentrations of all pollutants studied except TAN, $NO_{2\text{-}3}$, and TN. This suggests that swales provide mitigation of elevated pollutant concentrations (especially P and TSS), but perhaps struggle to reduce more typical urban stormwater pollutant concentrations. The post-retrofit swale provided significant reduction for only O-PO_4^{3-} from the inlet to outlet.

However, effluent concentrations of $O\text{-}PO_4^{3-}$ pre- (0.014 mg/L) and post-retrofit (0.015 mg/L) were not significantly different. Furthermore, when comparing pre- and post-retrofit data sets, the addition of the excelsior fiber wattle check dams and ViroPhos supplement bags (either separately or as a group) did not significantly improve TSS or nutrient concentrations, because the wattle check dams failed to impound water during wet weather due to their high permeability and low weight.

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PART 3: SUMMARY AND RECOMMENDATIONS

Summary of Studies

Two swales (Mango Creek and I-40) draining highway runoff in North Carolina were retrofitted with simple check dams to determine if these devices might improve hydrologic and/or water quality performance of swales. Common check dam designs were evaluated for improvement of pollutant removal and infiltration provided by the swale. The Mango Creek swale was retrofitted with a pair of standard rock check dams, while the I-40 swale was retrofitted with a system of standard excelsior fiber wattle check dams. Furthermore, proprietary phosphorus-adsorptive aggregate (ViroPhos^{TM}) media bags were incorporated to supplement the check dams at I-40. Each swale was monitored for approximately six months to collect "pre-retrofit" data prior to the installation of check dams in March-April of 2014. Monitoring of the "post-retrofit" swales followed for twelve months. Hydrologic data were collected from the Mango Creek site to examine peak flow mitigation and volume reduction caused by storage and infiltration due to the addition of check dams. Inflow and outflow flow-proportional (Mango Creek) and rainfall-proportional (I-40) water quality samples were obtained from both swales to investigate removal of nitrogen and phosphorus species and total suspended solids (TSS) during the pre- and post-retrofit phases of the research.

The inclusion of rock check dams in the Mango Creek swale did not significantly improve the hydrologic performance of the SCM; neither volumes nor peak flows mitigation was furthered by the check dams. However, this was substantially impacted by the small pre-retrofit data set. Greater than 50% and 20% volume reduction was observed during small (<0.75inch) and moderate (0.75-1.5 inch) rainfall events post-retrofit, nearly double the runoff volume reduction for these events before the installation of the rock check dams. Similar improvements in peak flow mitigation were observed. No improvement in volume reduction for large events (>1.5 inch) was observed, while modest peak flow mitigation was observed post-retrofit due to the inclusion of the check dams. Rock check dams did not significantly improve the removal rates of sediment-bound pollutants or aqueous nutrients. Again, this may be related to the small pre-retrofit data set, as pre-retrofit reduction in TSS concentration was -34%, while post-retrofit it improved to 74%. Additionally, TSS loads were significantly reduced post-retrofit, while no significant difference was observed pre-retrofit. Compared to concentrations found in healthy Piedmont streams, nutrient concentrations were generally low entering the swale, limiting the potential for significant reduction. Total nitrogen and TP effluent concentrations were found to generally meet "good" water quality conditions based on ambient stream health. The rock check dams increased hydraulic retention time by 29-50% depending on rainfall depth. Rock check dams were effective in the filtration of gross solids, which led to clogging of the check dams and loss of swale vegetation over time (due to lengthy ponding). Check dams should be designed for ease of maintenance and to dewater between evens to prevent vegetation loss.

Inclusion of excelsior fiber wattle check dams in the I-40 swale did not significantly improve pollutant EMCs compared to pre-retrofit conditions. While dramatically improving 'in swale' orthophosphate ($O\text{-}PO_4^{3-}$) concentrations, ViroPhos™ supplements did not significantly improve the treatment of $O\text{-}PO_4^{3-}$ in the swale relative to pre-treatment concentrations, as both pre- and post-retrofit concentrations (<0.02 mg/L) were low, possibly approaching "irreducible" concentrations. Due to their high permeability, the wattle check dams did not pond water; therefore, sedimentation was not improved. Overall, results from this study indicate that rock check dams are preferable to straw wattles because they ponded stormwater and provided modest benefits.

Design Considerations

Both check dams types studied herein offered one major benefit: the filtration of coarse sediments, gross solids, and debris. The rock check dams, in particular, were so effective at collecting gross solids that they clogged within six months. Rock check dams could be utilized as "portable forebays" in swales receiving excessive gross solids and debris. The wattle check dams also captured gross solids, but not to the same extent as the rock dams. The weaker structure and lighter weight make them less desirable in capturing gross solids.

Some design guidance for check dams can be gleaned from the this work. First, the shape of the check dam should be parabolic as detailed in NCDOT standard 1633.01 to encourage bypass over the weir and not around the check dam (Figure 3-1). The check dams herein were flat across the top to promote more ponding than the NCDOT standard detail, but this design caused erosion around the edges of the check dam from during high flow rates. Second, to maintain the health of typical swale grass vegetation, check dams must be easily maintained to remove detritus and debris. It is recommended that rock check dams be regularly inspected (e.g., once every four months) for any sediment/gross solids/debris removal. This preventative maintenance is particularly important for check dams used for gross solids capture. Alternatively, check dams could be allowed to clog (by design) under appropriate conditions. Prepping soils to be loose (rather than compacted) and planting hydrophytic wetland vegetation in the swale (versus typical warm season grasses) would enhance infiltration and sedimentation provided by check dams, while maintaining healthy swale vegetation. With water-tolerant plants in the swale, extended periods of ponded water would not cause plant mortality, increasing channel stability. Allowing check dams to clog by design would also reduce the amount of maintenance required for these retrofits.

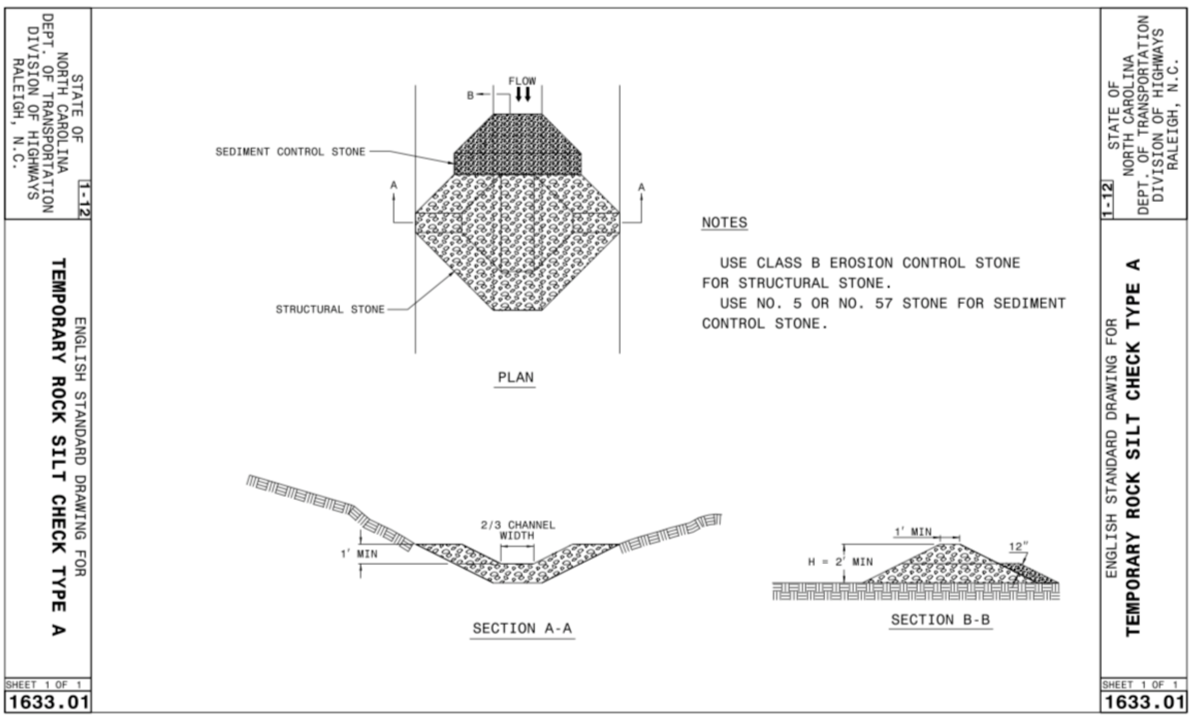

Figure 3-1: NCDOT standard 1633.01 temporary rock silt check dam design drawing (NCDOT, 2012).

There were several notable improvements that could be made to the design of the wattles for enhanced functionality as check dams in post-construction grass swales. First, the excelsior fiber was too light in weight, allowing flow to easily travel underneath the check dam and float the wattle. Because of high excelsior fiber permeability, flows passed through the wattles with negligible flow impedance. A wattle with a heavier and less porous filling material might substantially improve the ability of the check dam to filter stormwater and impound flow. The wooden stakes used to hold the wattles in place were inefficient and allowed the wattles to float in place, rather than holding them on the ground. Using landscape staples to staple wattles on the ground through their netting might provide a more effective method for installation. Finally, for both check dam types including a designation (such as flagging or bollards) on each end of the check dams is critical to ensure they are made visible to mowers. Particularly in swales with tall vegetation, mowing personnel may not be able to see check dams and this could damage the mower and the check dam.

The ViroPhos bags utilized at the I-40 swale proved to be durable throughout the twelve-month post-retrofit monitoring period. The media bags were heavy enough that they were not moved during heavy flows. It makes sense to incorporate the ViroPhos bags upstream of check dams to increase contact time with runoff; however, the system of ViroPhos bags used at each check dam in this study was too complicated for real-world application. A more reasonable approach would be to incorporate only the “thalweg” media bag(s) upstream of each check dam. This way, it would be easier to replace the bag(s) when necessary and less complicated to maintain and mow around the check dam.

Of the two check dams studied, the rock check dam is recommended as an effective swale retrofit for the filtration of gross solids and debris, hydrologic and water quality improvement. While the rock check dams showed potential to enhance stormwater treatment in swales, the low number of pre-retrofit storms collected herein limited the chance to prove significance when comparing to post-retrofit.

Research Recommendations

Additional research is needed on different types of check dams. This study provided design guidance regarding rock and excelsior fiber wattle check dams; however, there are other materials (wood railroad ties, filter socks, different types of wattles) that can be used to build check dams that have not been evaluated as swale retrofits. Stagge et al. (2012) evaluated swales with vegetated berm check dams, but these seem difficult or impractical to distinguish from other vegetation in a swale.

The effectiveness of rock check dams that are maintained (as they were not in this study) and under higher influent nutrient concentrations is unknown. Additionally, research on other P-sorbtive media for targeted phosphorus removal in swales is needed. Research should be conducted to test the incorporation of ViroPhos within a check dam that effective ponds stormwater to increase contact time. Finally, check dams designed to clog should be implemented with hydrophytic vegetation to evaluate if clogged check dams might offer improved treatment of stormwater.

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PART 4: APPENDICES

Appendix A: Mango Creek Site Photos

Figure 4-1: I-540 bridge deck PVC runoff conveyance pipe downspout (left) and view of pipe extending towards Mango Creek (right).

Figure 4-2: Upstream view of the Mango Creek swale forebay.


Figure 4-3: View from the top edge of the Mango Creek swale forebay.


Figure 4-4: View of the Mango Creek swale outlet pipe.

Appendix B: Mango Creek Weir Stage/Discharge Calculations

The inlet weir box housed a compound weir consisting of a 29.0-cm, 60° V-notch weir and a 32.0-cm high, 33.5-cm wide contracted rectangular weir. Flow depths in the inlet weir box were converted to flow rates using a derived (based on the V-notch and contracted rectangular weir equations), stepwise function given in Eqs. (B-1) and (B-2) (Walkowiak, 2013).

$$Q = 796.7 \times H^{2.5} \quad when\ H \leq 0.29\ m \tag{B-1}$$
$$Q = 35.9 + 1838(0.335 - 0.2H)H^{1.5} \quad when\ H > 0.29\ m \tag{B-2}$$

Where,
Q = flow rate (L/s)
H = head on the weir (m)

The stepwise function calculated flow through the 60° V-notch [Eq. (B-1)] and then over the contracted rectangular weir [Eq. (B-2)]. Because of the unique design of the compound weir used at the inlet, stage/discharge data points developed using Eqs. (B-1) and (B-2) were entered into the ISCO 6712 automated sampler to determine flow rates based on flow depths in the weir box (Table 4-1).

Table 4-1: Programmed stage/discharge relationship used for the Mango Creek swale inlet weir.

Point	Head (ft)	Q (cfs)	Head (m)	Q (L/s)
1	0.000	0.000	0.000	0.000
2	0.040	0.000	0.012	0.013
3	0.080	0.003	0.024	0.074
4	0.120	0.007	0.037	0.204
5	0.160	0.015	0.049	0.418
6	0.200	0.026	0.061	0.731
7	0.240	0.041	0.073	1.153
8	0.280	0.060	0.085	1.695
9	0.320	0.084	0.098	2.367
10	0.360	0.112	0.110	3.177

11	0.400	0.146	0.122	4.135
12	0.440	0.185	0.134	5.247
13	0.480	0.230	0.146	6.523
14	0.520	0.281	0.158	7.967
15	0.560	0.339	0.171	9.589
16	0.600	0.402	0.183	11.394
17	0.640	0.473	0.195	13.389
18	0.680	0.550	0.207	15.581
19	0.720	0.635	0.219	17.974
20	0.760	0.727	0.232	20.575
21	0.800	0.826	0.244	23.390
22	0.840	0.933	0.256	26.425
23	0.880	1.048	0.268	29.684
24	0.920	1.171	0.280	33.173
25	0.950	1.269	0.290	35.943
26	1.000	1.310	0.305	37.092
27	1.040	1.367	0.317	38.697
28	1.080	1.437	0.329	40.689
29	1.120	1.518	0.341	42.988
30	1.160	1.608	0.354	45.543
31	1.200	1.706	0.366	48.319
32	1.240	1.811	0.378	51.287
33	1.280	1.922	0.390	54.426
34	1.320	2.038	0.402	57.717
35	1.360	2.159	0.415	61.143
36	1.400	2.285	0.427	64.692
37	1.440	2.414	0.439	68.350
38	1.480	2.546	0.451	72.108
39	1.520	2.682	0.463	75.953
40	1.560	2.821	0.475	79.879
41	1.600	2.962	0.488	83.875
42	1.640	3.105	0.500	87.935
43	1.680	3.251	0.512	92.050
44	1.720	3.398	0.524	96.215
45	1.760	3.546	0.536	100.422
46	1.800	3.696	0.549	104.665
47	1.840	3.847	0.561	108.940
48	1.880	3.999	0.573	113.239
49	1.920	4.152	0.585	117.559
50	2.000	4.458	0.610	126.237

The outlet weir box housed a 61.0-cm, 45° V-notch weir. Flow rates at the outlet weir box were calculated using a standard 45° V-notch weir equation [Eq. (B-3)] (Walkowiak, 2013).

$$Q = 571.4 \times H^{2.5} \tag{B-3}$$

Where,

Q = flow rate (L/s)
H = head on the weir (m)

Appendix C: Summary and Photos of Monitoring Equipment Utilized at the Mango Creek and I-40 Sites

Mango Creek Site

Table 4-2: Summary of Mango Creek monitoring equipment.

Equipment	Mango Creek Inlet	Mango Creek Outlet
Sampler Device	ISCO 6712 automated sampler	ISCO 6712 automated sampler
Weir Box Structure	29 cm - 60° V-notch to 33.5 cm wide rectangular weir, 32 cm high (baffle included)	61 cm - 45° V-notch weir (baffle included)
Flow Monitoring Device	ISCO 730 Bubbler Module	ISCO 730 Bubbler Module
Power Source	12-volt deep cycle marine battery charged by 20-watt solar panel	12-volt deep cycle marine battery charged by 20-watt solar panel
Rainfall Monitoring Device	ISCO 674 Tipping Bucket and Manual Rain Gauge	ISCO 674 Tipping Bucket and Manual Rain Gauge

Figure 4-5: ISCO 6712 automated sampler and a 12-volt deep cycle battery in housing (left) and a mounted 20-watt solar panel (right).


Figure 4-6: Automatic, tipping bucket and manual rain gauges at Mango Creek site.

Figure 4-7: Clockwise from top left: Mango Creek inlet monitoring point showing ISCO sampler housing and catch basin, weir box with baffle placed within the catch basin, and the mounted sampler head with a bubbler attachment for measuring flow rates.

Figure 4-8: Clockwise from top left: Mango Creek outlet monitoring point showing ISCO sampler housing and weir box, weir box from above with baffle placed inside, and the outlet weir during a storm event.

I-40 Site

Table 4-3: Summary of I-40 monitoring equipment.

Equipment	I-40 Inlet*	I-40 Middle	I-40 Outlet	I-40 Road
Sampler Device	ISCO 6712 sampler w/ 0.95 cm strainer intake sampler head	ISCO 6712 sampler w/ 0.95 cm strainer intake sampler head	ISCO 6712 sampler w/ 0.95 cm strainer intake sampler head	ISCO 6712 sampler w/ 0.95 cm strainer intake sampler head
Weir Box Structure	N/A	N/A	N/A	30 cm – 30° V-notch weir (baffle included)
Sample Pacing Device	ISCO 674 Tipping Bucket	ISCO 674 Tipping Bucket	ISCO 674 Tipping Bucket	ISCO 730 Bubbler Module

Power Source	12-volt deep cycle marine battery charged by 20-watt solar panel	12-volt deep cycle marine battery charged by 20-watt solar panel	12-volt deep cycle marine battery charged by 20-watt solar panel	12-volt deep cycle marine battery charged by 20-watt solar panel
Rainfall Monitoring Device	ISCO 674 Tipping Bucket	ISCO 674 Tipping Bucket	ISCO 674 Tipping Bucket and Manual Rain Gauge	N/A

*Monitoring Locations shown on Figure 2-2.

Figure 4-9: ISCO 6712 automated sampler and a 12-volt deep cycle battery in housing (left) and a mounted 5-watt solar panel (right).

Figure 4-10: ISCO 674 rain gauges and manual rain gauge at the I-40 site.

Figure 4-11: Mango Creek inlet monitoring point showing ISCO sampler housing and catch basin (top left), weir box with baffle placed within the catch basin (top right), and the mounted sampler intake with a bubbler attachment for detecting flow rates.

Figure 4-12: Mango Creek outlet monitoring point showing ISCO sampler housing and weir box (top left), weir box from above with baffle placed inside (top right), outlet weir during a storm event (bottom).

Figure 4-13: A sampler intake strainer set up for monitoring at the I-40 swale inlet (left) and a view of the sampler intake during a storm event (right).

Figure 4-14: Slot drains installed alongside the highway (left) and the weir box used to collect highway runoff water quality samples (right).

Appendix D: Mango Creek Monitoring Challenges

Several challenges were encountered throughout the monitoring phases at the Mango Creek swale. There were several occasions that either one or both of the monitoring stations experienced power failure. This issue was particularly common during the winter months of the year, when cold temperatures inhibited the performance of the 12-volt batteries. Furthermore, the positioning of the 20-watt solar panels, which were used to maintain the charge of the batteries, did not provide the optimal amount of direct sunlight throughout the day. The solar panels were installed next to the swale in between the northbound and southbound highway bridge decks, limiting the exposure to direct sunlight. During cloudy days, the solar panels received very little sunlight and were not able to provide additional charge of the batteries for the ISCO 6712 samplers. The overlapping of cold temperatures in the winter with cloudy days on which storm events typically occurred, presented a difficult challenge for maintaining power at both monitoring stations. Due to such circumstances, hydrologic data for some storm events were lost due to power failures throughout the monitoring process.

Freezing temperatures and snow presented additional challenges during the winter months. When subjected to freezing temperatures, the water in the weir boxes would freeze, leading to inaccurate water level readings with the bubbler module. Because of this, there was no way to properly determine the volumes and flow rates of runoff through the system and such snow events were not included in the analysis of hydrologic data. Additionally, snowmelt would often times continue for several days after a snow event had concluded, occasionally overlapping with new rainfall events, leading to inaccurate runoff volumes for that storm event. These factors were accounted for when analyzing hydrologic data for winter storms.

Gross solids occasionally lodged in the inlet weir (Figure 4-15), leading to inaccurate flow measurement. A grabber tool was used to remove all larger debris from the weir box during each site visit. Debris and litter consisted mostly of plastic bottles, Styrofoam cups, plastic bags, mulch, pine straw, cigarettes, and occasional large pieces of wood. The instances when the weir became clogged were obvious in the recorded hydrology data and typically occurred during the tail of the hydrograph for larger storm events. A correction was applied to the hydrology data for storm events that encountered this issue in order to cut off the false portion of the hydrograph due to weir clogging.

Figure 4-15: The inlet weir box clogged with debris and litter (left) and a pile of the debris and litter removed from the weir box (right).

During the pre-retrofit monitoring period of this study, two separate disconnections of the PVC pipes used for routing runoff from the highway bridge deck to the swale were observed. The first disconnection was observed on October 22, 2013. On December 3, 2013, a second disconnection was observed. NCDOT crew mended all pipe disconnections on January 14, 2014 (Figure 4-16). While the pipes were disconnected, the swale received runoff volumes similar to those of rainfall events before and after the disconnections were observed, indicating that only a small portion of the runoff volume was leaking from the pipes. Data collected while the pipes were disconnected were included in analyses.

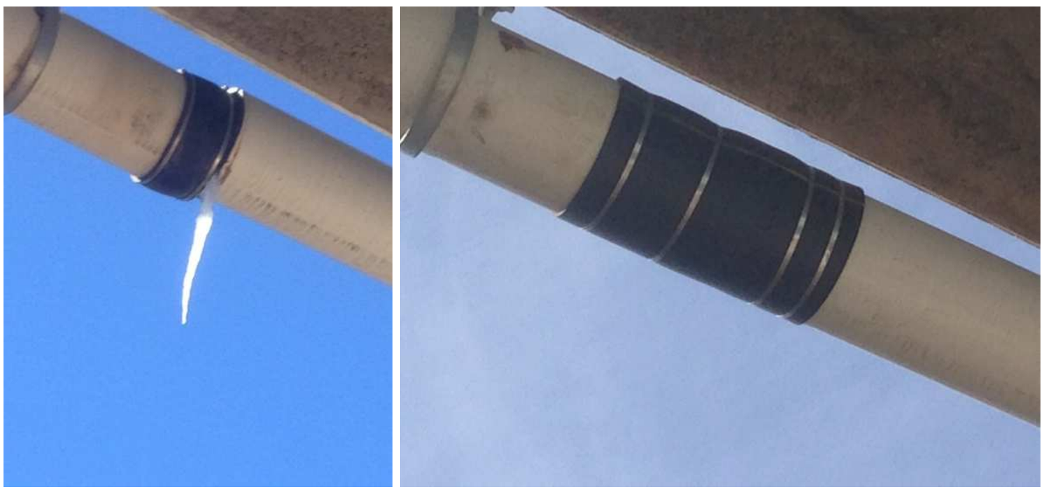

Figure 4-16: The first observed disconnected PVC drainage pipes leaking on 10/22/13 (left) and the same PVC pipes mended on 1/14/14 (right).

On February 4, 2014, during a site visit, it was observed that a vehicle had driven through the swale, leaving two rutted tracks and damaging the established grass. On March 28, 2014, NCDOT crew dug out the ruts and laid down new turfgrass sod. Figure 4-17 displays the observed damage to the swale along with the repair of the swale by NCDOT crew. This damage may have contributed slightly to increased ponding of water within the rutted tracks as well as increased suspended sediment concentrations during the short period before repair occurred.

Figure 4-17: Rutted track damage caused by a large vehicle driving across the swale on 2/4/14 (left) and the repair of this damage by NCDOT on 3/28/14 (right).

The final challenge faced during the monitoring of this site involved the functionality of the ISCO 674 rain gauge. The bucket would collect bird feces, sometimes causing it to clog (Figure 4-18). The addition of a wire extension around the edge of the bucket provided an alternative place for birds to sit, appreciably mitigating this problem. Additionally, the rain gauge did also experience technical issues with data not properly logging into the data logger on a few occasions for unknown reasons. It is possible that this had something to do with a bad battery or the magnetic connection of the tipping bucket. This issue was inconsistent throughout the study.

Figure 4-18: ISCO 674 rain gauge bucket clogged due to bird feces.

Appendix E: Mango Creek Swale Check Dam Installation

Installation of the rock check dams at the Mango Creek swale occurred on March 28, 2014. North Carolina Department of Transportation (NCDOT) worked in conjunction with North Carolina State University to complete the swale retrofit. Figure 4-19 depicts the procedure used to install the check dams.

Figure 4-19: Installation of a rock check dam at the Mango Creek swale (proceeds clockwise from top left).

Appendix F: Mango Creek Swale Storage and Infiltration Calculations

Step 1: **AutoCAD Civil 3D was used to determine the areas of the swale that ponded water due to the rock check dams.**

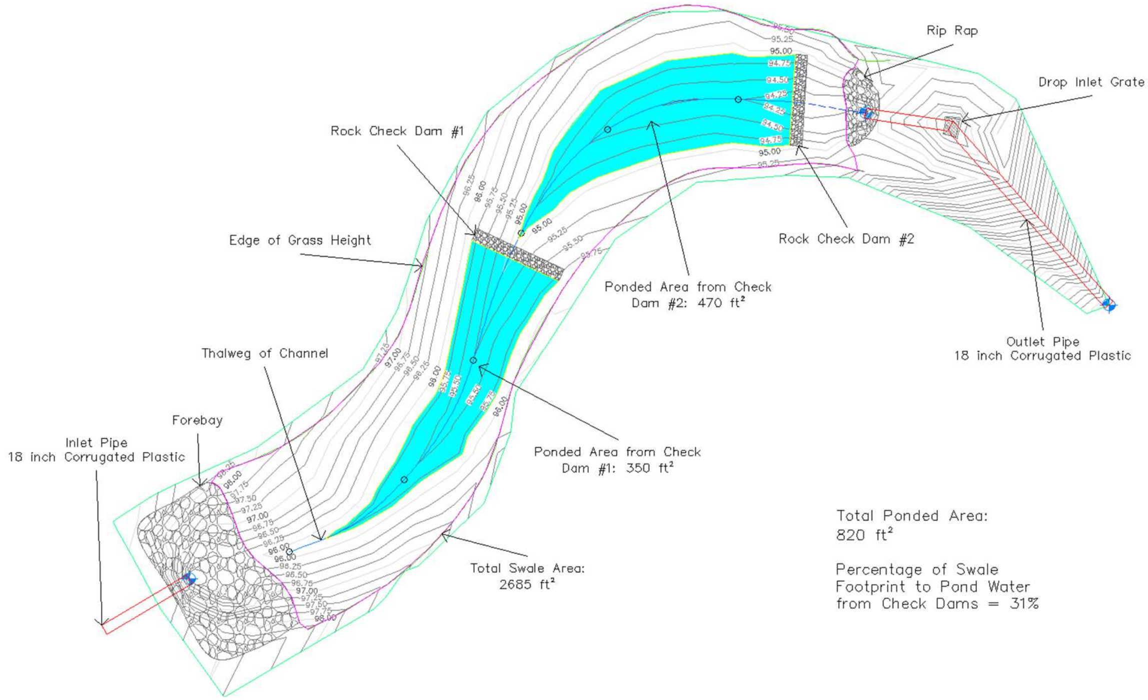

Figure 1-7 displays the footprint of the swale that could pond water from the check dams. This analysis found that approximately 76 m^2, or 31%, of the swale surface area was exposed to ponding water when the check dams were filled to the brink. Below are the areas from AutoCAD used to make these calculations:

Total Swale Surface Area =	249.5	m^2
Check Dam 1 Ponded Area =	32.7	m^2
Check Dam 2 Ponded Area =	43.4	m^2
Total Ponded Area Footprint =	76.1	m^2
Percentage of Swale Footprint Ponded =	31	%

Step 2: The maximum potential storage volume of the swale was calculated. Check dams were designed to be 0.28 m (11.0 in) in height. To calculate an approximation of the maximum volume that could be ponded in the swale, an average height of 2/3 the height of

the check dams was used (due to the triangular shape of the ponded water when viewing the profile of the swale). This height (0.19 m) was multiplied by the ponded area created by each check dam to determine individual storage volumes. Finally, these two volumes were added together to provide an estimate of the total swale storage volume. The values used in this calculation are shown below:

Average Water Height for Max Volume =	0.19	m
Check Dam 1 Ponded Volume =	6.1	m^3
Check Dam 2 Ponded Volume =	8.1	m^3
Total Ponded Volume =	14,175	L

Step 3: Finally, the maximum drawdown time of clogged, fully ponded check dams was estimated. A ponding depth of 93 mm (3.7 in), or 1/3 the height of the check dams, was used as an estimate of the average water level over the period of time while the full ponding depth was infiltrated. The average ponding depth was then divided by the average, minimum, and maximum infiltration rates (determined using the ASTM D3385-09 Double-Ring Infiltrometer Standard Test Method) to provide a range of potential drawdown times that could be experienced in the swale (when check dams are clogged). The infiltration rates and calculated drawdown times are provided below:

Average Infiltration Rate =	1.51	mm/hr
Minimum Infiltration Rate =	0.75	mm/hr
Maximum Infiltration Rate =	2.06	mm/hr

Average Drawdown Time =	2.6	hrs
Maximum Drawdown Time =	5.2	hrs
Minimum Drawdown Time =	1.9	hrs

Appendix G: Photos of Mango Creek Swale Vegetation Health

Degradation of swale vegetation was observed after the rock check dams fully clogged (due to extensive ponding). Figure 4-20 displays swale vegetation upstream of the first check dam in the summer after check dams were installed. Photos were taken over four months after the check dams were installed on March 28, 2014. Prior to the clogging of the check dam, swale vegetation remained generally healthy.

Figure 4-20: Mango Creek swale vegetation upstream of the first check dam prior to clogging (photos taken August 12, 2014). Photos are in order moving downstream (clockwise from top left).

The first check dam was observed to fully clog approximately six months after installation. The effects of the clogged check dam on swale vegetation health over time are shown in Figure 4-21. Photos were taken the following summer (at the end of the study), nearly ten months after the first check dam was observed to fully clog. Healthy swale vegetation was not sustained with the absence of periodic check dam maintenance to remove clogged sediment and debris.

Figure 4-21: Mango Creek swale vegetation upstream of the first check dam after clogging had been present for approximately ten months (photos taken July 21, 2015). Photos are in order moving downstream (clockwise from top left).

Appendix H: Mango Creek Swale Hydraulic Retention Time Calculations

Hydraulic retention time (HRT) was measured as the length of time from when peak flow occurred at the inlet of the swale until peak flow occurred at the outlet for each rainfall event. Only storm events large enough to produce outflow from the swale were considered for the analysis. Storm events with rainfall depths of 5.0 mm (0.2 in) or greater met this constraint. Table 4-4 and Table 4-5 display calculated estimates of hydraulic retention times for each rainfall event pre- and post-retrofit, respectively.

Table 4-4: Pre-Retrofit calculated hydraulic retention times for the Mango Creek swale.

Storm	Rainfall	5-min Peak Int.	Time of Peak Discharge		HRT
Number	(mm)	(mm/hr)	Inflow	Outflow	(min)
3	23	17	12/10/13 3:16	12/10/13 3:24	8
4	25	19	12/14/13 17:22	12/14/13 17:38	16
5	40	45	12/23/13 9:14	12/23/13 9:20	6
7	32	32	1/10/14 22:34	1/10/14 22:38	4
8	6	22	1/11/14 14:14	1/11/14 14:22	8
9	9	7	1/14/14 11:52	1/14/14 12:16	24
11	5	7	2/3/14 10:42	2/3/14 10:50	8
12	14	11	2/4/14 17:56	2/4/14 18:06	10
13	13	11	2/19/14 6:00	2/19/14 6:18	18
14	15	44	2/21/14 12:36	2/21/14 12:48	12
15	11	15	3/3/14 10:40	3/3/14 11:02	22
16	51	7	3/7/14 3:22	3/7/14 3:38	16
17	7	6	3/16/14 22:54	3/16/14 23:32	38
18	7	3	3/17/14 22:48	3/17/14 23:02	14

Table 4-5: Post-Retrofit calculated hydraulic retention times for the Mango Creek swale.

Storm	Rainfall	5-min Peak Int.	Time of Peak Discharge		HRT
Number	(mm)	(mm/hr)	Inflow	Outflow	(min)
1	36	40	4/15/14 17:20	4/15/14 17:32	12
2	15	6	4/19/14 6:54	4/19/14 7:08	14
3	6	31	4/29/14 20:06	4/29/14 20:22	16
4	30	99	4/30/14 12:28	4/30/14 12:40	12
5	108	101	5/15/14 13:02	5/15/14 13:14	12
7	19	96	6/9/14 22:26	6/9/14 22:38	12

8	22	53	6/11/14 16:36	6/11/14 16:40	4
10	12	68	6/19/14 22:58	6/19/14 23:14	16
12	6	41	6/25/14 19:52	6/25/14 20:10	18
15	21	24	7/10/14 17:44	7/10/14 17:56	12
16	52	99	7/15/14 17:00	7/15/14 17:08	8
18	18	70	7/24/14 9:14	7/24/14 9:28	14
19	40	110	7/24/14 18:22	7/24/14 18:28	6
20	14	59	7/27/14 9:36	7/27/14 9:50	14
21	9	14	8/1/14 13:42	8/1/14 14:18	36
22	16	35	8/2/14 12:36	8/2/14 12:52	16
23	35	8	8/9/14 13:04	8/9/14 13:18	14
24	73	135	8/12/14 18:56	8/12/14 19:00	4
25	13	48	8/18/14 19:04	8/18/14 19:24	20
28	35	80	9/4/14 21:12	9/4/14 21:22	10
29	88	40	9/8/14 21:30	9/8/14 21:38	8
31	37	N/A	9/24/14 11:38	9/24/14 11:52	14
33	15	45	10/4/14 0:18	10/4/14 0:28	10
34	13	N/A	10/10/14 20:44	10/10/14 21:02	18
35	8	N/A	10/11/14 16:46	10/11/14 17:06	20
36	11	N/A	10/14/14 11:26	10/14/14 11:48	22
37	51	N/A	10/15/14 7:50	10/15/14 8:08	18
39	7	6	11/1/14 5:22	11/1/14 5:46	24
40	8	17	11/6/14 20:04	11/6/14 20:32	28
42	6	20	11/17/14 18:58	11/17/14 19:30	32
43	19	73	11/23/14 23:12	11/23/14 23:22	10
44	59	19	11/26/14 5:20	11/26/14 5:44	24
47	13	6	12/9/14 19:08	12/9/14 19:32	24
48	8	16	12/16/14 11:32	12/16/14 12:04	32
49	20	14	12/22/14 4:52	12/22/14 5:22	30
50	58	35	12/24/14 9:30	12/24/14 9:44	14
51	19	14	12/29/14 7:32	12/29/14 7:46	14
53	62	44	1/12/15 8:08	1/12/15 8:16	8
54	17	10	1/18/15 6:14	1/18/15 6:32	18
55	28	10	1/24/15 7:38	1/24/15 7:56	18
56	16	N/A	2/2/15 5:00	2/2/15 5:14	14
57	17	N/A	2/9/15 22:32	2/9/15 22:52	20
60	25	7	2/26/15 4:54	2/26/15 5:04	10
61	10	3	2/27/15 11:40	2/27/15 11:58	18
62	28	N/A	3/5/15 13:36	3/5/15 13:50	14

Appendix I: I-40 Watershed Delineation

Orthoimagery and contour data for the project site were retrieved from Johnston County, NC Geographic Information Systems website (Table 4-6). Orthoimagery of the I-40 swale and surrounding area is displayed in Figure 4-22. The contour lines overlaid the orthoimagery for use in delineation of the watershed (Figure 4-23).

Table 4-6: Data retrieved for the I-40 study site in Benson, NC.

Dataset Name	Source	Projection	Datum	Resolution	Notes
Johnston County Contours – 2 ft	Johnston County, North Carolina Geographic Information Systems http://www.johnstonnc.com/gis2/content.cfm?PD=data	Lambert Conformal Conic	NAD83	2 feet	The original source for this data was the NCDOT.
Johnston County, North Carolina Digital Orthoimagery 2013	Johnston County, North Carolina Geographic Information Systems http://www.johnstonnc.com/gis2/content.cfm?PD=data	State Plan Coordinate System 1983	NAD83	6 inch	Orthos were flown early (January - April) in 2013. Mapsheet 1558 - 01 was used for the intended study area.

Figure 4-22: The I-40 study site with the swale outlined with the yellow box.

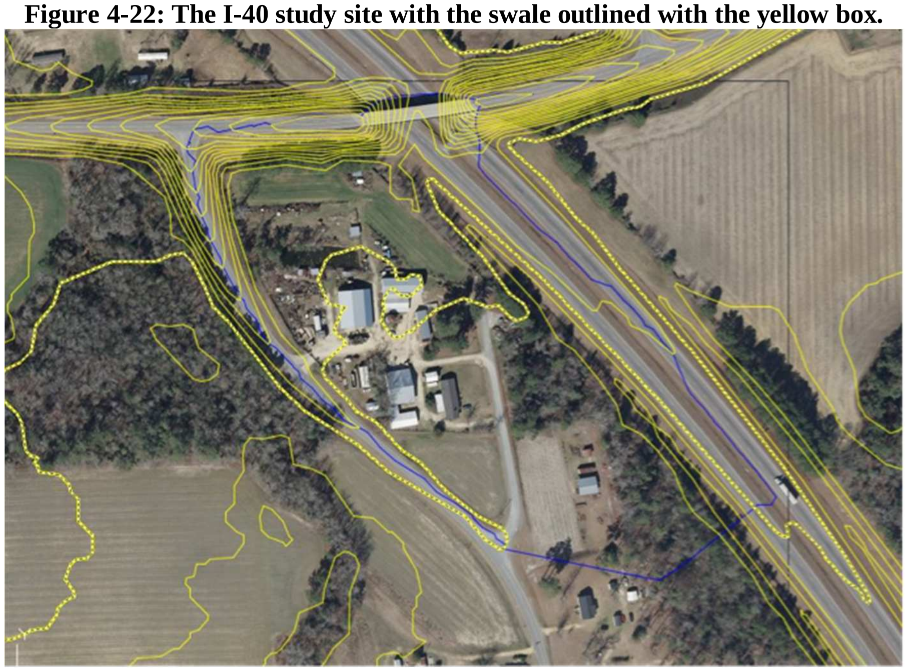

Figure 4-23: Two-foot contour lines overlaying the I-40 study site.

The contributing watershed draining to the swale was delineated using AutoCAD Civil 3D. A combination of utilizing the AutoCAD *Water Drop* function to determine flow paths based on contour data and good judgment based on the site's orthoimagery were used in the process. It was determined that the watershed area for the swale was approximately 1.07 ha, of which 0.17 ha (16%) was impervious. The impervious roads contributing to the watershed included the southbound lanes of I-40, a portion of the bridge overpass road (Stricklands Crossroads Rd), and a small section of Hannah Creek Rd near the intersection with Stricklands Crossroads Rd. The remainder of the contributing watershed consisted of a combination of agricultural plots, wooded land, and vegetated filter strips bordering the nearby roads.

Figure 4-24: Delineated watershed for the I-40 swale.

Appendix J: I-40 Monitoring Challenges

Several challenges were encountered throughout the monitoring phases at the I-40 swale. On two separate occasions during post-retrofit monitoring, a vehicle drove off the highway and through the monitored portion of the I-40 swale, causing damage to the swale, check dams, and/or monitoring equipment. In the first incident (June 28, 2014), a vehicle drove through the "Road" sampler housing box. The impact destroyed all of the ISCO monitoring equipment within the job box, along with the weir box at this sampling location (Figure 4-25). Additionally, the vehicle drove over the set of steel reflector beams surrounding the job box and left some minor rut damage within the swale. The check dams were unscathed through this incident. A new job box, ISCO 6712 sampler, and weir box were reinstalled at the swale on July 8th, 2014.

Figure 4-25: Clockwise from top left: Job box housing and ISCO 6712 sampler remains from vehicle incident on June 28, 2014, rut damage in the swale, the damaged weir box from the Road Runoff sampling point, and bent steel reflector beams.

On January 13, 2015, a second incident occurred in which a vehicle drove off the highway and through the swale. The vehicle drove through the second excelsior wattle check dam when driving across the swale. When the vehicle was removed from the swale, the tow truck pulled it through the third check dam, leading to the displacement and destruction of both wattles (Figure 4-26). Fortunately, the vehicle did not come into contact with any of the monitoring equipment and the tire tracks left minor damage to the swale vegetation. New excelsior fiber wattles were purchased and reinstalled in the swale on January 23rd, 2015.

Figure 4-26: Clockwise from top left: Vehicle tracks running through the second check dam from incident on January 13, 2015, the remains of the third check dam, vehicle tracks from the tow truck pulling the vehicle out, and a newly reinstalled replacement wattle check dam on January 23, 2015.

Mowing events provided a further challenge, as mowers were unaware of the monitoring research within the swale and tall grasses hid the check dams from eyesight. On several occasions throughout monitoring, mowers ran over the outer edges of the wattle check dams, shredding those portions of the check dams (Figure 4-27). Additionally, during a mowing event in May of 2014, a mower ran over the intake sampler head at the inlet sampling location (Figure 4-28). The sampler head was replaced during the subsequent site visit.

Figure 4-27: Photographs of damage to wattle check dams from mowers.

Figure 4-28: Damage to the inlet sampler head from a mower.

Finally, the ISCO 674 rain gauges experienced complications with occasional clogging from bird feces and frozen precipitation during winter months (Figure 4-29). Infrequent technical difficulties were also experienced with the tipping buckets when malfunctions would occur and cause improper triggering of rainfall-paced samples.

Figure 4-29: ISCO 674 rain gauges clogged from bird feces (left) and from frozen precipitation (right).

Appendix K: I-40 Check Dam Installation

Installation of excelsior wattle check dams and ViroPhos bags at the I-40 swale occurred on April 24, 2014. North Carolina Department of Transportation (NCDOT) worked in conjunction with North Carolina State University to install the excelsior fiber wattle check dams in the swale. EnviRemed Construction supplied and installed the supplemental ViroPhos media bags. Figure 4-30 provides photos of the installation.

Figure 4-30: Installation of excelsior fiber wattle check dams and ViroPhos media bags at the I-40 swale.

Appendix L: Mango Creek Swale Rainfall and Hydrology – Raw Data

Table 4-7: Pre-Retrofit Mango Creek swale rainfall and hydrologic event data.

Storm Date	Rainfall (mm)	Duration (hrs)	5-min Peak Int. (mm/hr)	Ant. Dry Period (days)	Volume (L)		Peak Flow (L/s)	
					Inf	Eff	Inf	Eff
12/7/13	5	5.7	9.9	7.6	3,434	0	7.2	0.0
12/8/13	5	10.9	9.9	0.9	1,620	0	1.1	0.0
12/9/13	23	24.6	16.5	0.8	18,388	11,666	3.5	2.8
12/14/13	25	8.8	19.0	4.0	19,441	20,511	5.3	4.7
12/22/13	40	31.4	44.6	8.0	67,943	26,889	33.6	15.4
1/5/14	4	14.2	7.1	3.0	8,710	0	9.6	0.0
1/10/14	32	20.3	31.7	4.0	37,147	34,518	16.5	8.7
1/11/14	6	5.4	22.2	0.3	4,810	6,555	2.6	2.3
1/14/14	9	12.1	6.7	2.3	6,738	3,963	1.1	1.1
1/29/14	4	4.5	2.8	14.9	1,490	0	0.6	0.0
2/3/14	5	4.2	7.1	3.8	5,238	4,558	2.2	2.0
2/4/14	14	20.4	10.5	1.0	18,289	12,264	2.0	1.9
2/19/14	13	2.2	10.6	3.7	21,204	11,907	3.5	3.4
2/21/14	15	1.7	43.5	2.2	14,155	14,534	17.9	11.7
3/3/14	11	2.9	15.2	9.9	8,230	7,693	5.0	1.1
3/6/14	51	28.4	6.9	3.1	32,764	54,255	1.3	2.1
3/16/14	7	14.0	6.0	3.8	4,675	4,839	0.4	0.5
3/17/14	7	12.6	3.0	0.4	6,336	10,101	0.4	0.7
3/19/14	3	3.0	3.5	1.3	2,113	3,032	0.5	0.7

Table 4-8: Post-Retrofit Mango Creek swale rainfall and hydrologic event data.

Storm Date	Rainfall (mm)	Duration (hrs)	5-min Peak Int. (mm/hr)	Ant. Dry Period (days)	Volume (L)		Peak Flow (L/s)	
					Inf	Eff	Inf	Eff
4/15/14	36	16.3	40.4	7.7	43,528	23,514	13.9	4.8
4/18/14	15	15.4	6.4	3.0	6,314	7,180	0.7	0.6
4/29/14	6	4.3	30.6	3.9	3,818	2,043	5.4	1.2
4/30/14	30	3.5	98.7	0.6	25,061	32,640	25.1	19.1
5/15/14	108	14.9	101.1	15.0	89,789	84,283	27.7	15.3
6/4/14	3	0.4	13.8	19.5	1,867	0	2.8	0.0
6/9/14	19	4.0	96.4	5.3	18,912	10,762	27.2	7.7

6/11/14	22	2.2	52.6	1.6	17,391	17,762	18.1	16.1
6/13/14	5	4.2	42.7	1.2	2,737	1,609	7.6	1.2
6/19/14	12	5.8	67.6	6.8	8,571	4,508	17.7	3.2
6/21/14	4	5.3	25.6	1.5	2,199	77	4.8	0.1
6/25/14	6	0.9	41.4	3.9	7,875	1,515	10.2	1.2
7/3/14	4	9.6	6.4	7.7	247	0	0.5	0.0
7/9/14	5	0.6	28.8	5.7	526	72	1.7	0.1
7/10/14	21	2.2	24.0	1.1	14,053	9,205	6.0	3.4
7/15/14	52	10.0	98.5	4.8	52,814	43,004	33.4	20.6
7/20/14	4	2.3	18.5	4.3	1,958	68	2.8	0.1
7/24/14	18	1.2	69.8	3.9	18,006	14,409	17.7	11.8
7/24/14	40	3.1	109.7	0.4	35,842	38,587	36.6	31.6
7/27/14	14	3.0	59.4	2.5	9,290	6,675	13.0	4.7
8/1/14	9	9.4	14.1	5.0	4,718	694	3.0	0.4
8/2/14	16	4.5	35.3	0.6	11,485	6,755	7.6	2.1
8/9/14	35	64.9	8.3	6.5	26,571	6,554	2.5	1.0
8/12/14	73	8.6	134.6	0.8	79,915	91,476	63.0	67.2
8/18/14	13	3.4	48.0	5.7	8,365	6,471	11.9	3.4
8/20/14	6	0.2	24.6	1.8	3,949	2,768	7.9	2.1
8/29/14	4	0.2	27.7	8.3	2,591	166	5.8	0.2
9/4/14	35	5.6	80.0	6.7	35,134	37,054	25.4	16.3
9/8/14	88	29.8	40.0	3.0	83,861	85,617	14.0	11.1
9/13/14	4	N/A	N/A	3.7	16	0	0.0	0.0
9/24/14	37	N/A	N/A	11.0	30,907	15,884	6.8	4.0
10/3/14	3	11.3	9.5	9.0	1,944	0	1.9	0.0
10/4/14	15	1.2	44.5	0.5	11,866	9,642	10.6	6.6
10/10/14	13	N/A	N/A	5.9	11,899	7,452	7.0	3.5
10/11/14	8	N/A	N/A	1.0	5,684	3,753	12.9	1.9
10/14/14	11	N/A	N/A	3.0	5,952	2,145	5.2	0.8
10/15/14	51	N/A	N/A	1.0	55,220	43,014	14.8	8.9
10/29/14	6	N/A	N/A	14.0	4,479	969	2.7	0.8
11/1/14	7	4.1	6.3	3.2	6,971	1,045	1.3	0.3
11/6/14	8	6.1	16.9	5.3	4,758	1,198	3.7	0.8
11/16/14	3	6.9	3.3	9.8	3,008	0	1.0	0.0
11/17/14	6	6.2	19.6	0.6	7,226	935	3.4	0.4
11/23/14	19	14.0	73.4	5.7	21,797	12,446	33.9	10.5
11/25/14	59	18.9	19.2	1.7	43,229	41,324	5.8	3.2
12/6/14	5	8.7	9.6	9.8	2,787	612	1.8	0.6
12/8/14	3	8.0	3.1	2.1	787	0	0.3	0.0
12/9/14	13	8.5	6.2	0.3	6,737	6,595	1.0	0.7

12/16/14	8	5.6	15.7	6.4	3,599	1,996	3.1	0.6
12/22/14	20	7.8	13.9	5.5	15,917	8,157	2.3	1.2
12/23/14	58	24.1	34.9	1.4	44,622	48,259	8.4	4.8
12/29/14	19	11.7	13.9	4.3	8,378	7,780	1.9	1.3
1/4/15	6	3.7	10.5	5.9	3,407	2,413	4.4	1.2
1/12/15	62	16.3	43.5	7.4	47,627	52,733	12.9	14.2
1/18/15	17	7.2	10.1	5.3	5,711	12,604	1.7	1.4
1/23/15	28	24.5	10.1	5.1	28,289	12,395	1.8	0.9
2/2/15	16	N/A	N/A	6.7	9,823	6,435	3.0	2.3
2/9/15	17	N/A	N/A	7.0	18,442	9,535	1.4	1.0
2/18/15	6	7.3	2.6	8.4	182	0	0.1	0.0
2/25/15	4	1.2	6.7	6.7	834	605	0.1	0.2
2/26/15	25	18.1	6.7	0.6	15,598	24,470	1.0	1.2
2/27/15	10	4.3	3.4	0.5	1,790	2,408	0.1	0.2
3/5/15	28	N/A	N/A	5.4	33,194	24,308	3.3	1.7

Appendix M: Mango Creek Pollutant Event Mean Concentrations – Raw Data

Table 4-9: Pre-Retrofit Mango Creek swale nitrogen species EMCs.

Storm	Rain	TKN (mg/L)		NO_{2-3} (mg/L)		TN (mg/L)		TAN (mg/L)		ON (mg/L)	
Date	(mm)	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff
12/9/13	23	0.35	0.34	0.15	0.20	0.50	0.54	0.13	0.05	0.22	0.29
12/14/13	25	0.47	0.58	0.16	0.22	0.63	0.80	0.19	0.15	0.28	0.44
1/10/14	32	0.45	1.58	0.17	0.21	0.61	1.79	0.12	0.13	0.33	1.45
2/4/14	14	0.63	0.59	0.36	0.28	0.99	0.87	0.15	0.14	0.48	0.45
2/19/14	13	1.05	0.49	0.14	0.25	1.19	0.74	0.08	0.12	0.97	0.37
3/3/14	11	2.19	1.04	0.98	0.75	3.17	1.80	0.66	0.42	1.53	0.62
3/16/14	7	0.46	0.40	0.37	0.41	0.83	0.81	0.26	0.11	0.20	0.29

Table 4-10: Pre-Retrofit Mango Creek swale phosphorus species and TSS EMCs.

Storm	Rain	TP (mg/L)		$O\text{-}PO_4^{3-}$ (mg/L)		PBP (mg/L)		TSS (mg/L)	
Date	(mm)	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff
12/9/13	23	0.06	0.12	0.014	0.050	0.05	0.07	19	10
12/14/13	25	0.09	0.23	0.012	0.041	0.08	0.19	47	64
1/10/14	32	0.10	0.53	0.004	0.037	0.10	0.49	52	258
2/4/14	14	0.17	0.18	0.037	0.054	0.13	0.12	40	26
2/19/14	13	0.24	0.42	0.037	0.062	0.20	0.36	119	153
3/3/14	11	0.39	0.19	0.047	0.055	0.34	0.13	91	22
3/16/14	7	0.08	0.09	0.023	0.037	0.06	0.05	34	6

Table 4-11: Post-Retrofit Mango Creek swale nitrogen species EMCs.

Storm	Rain	TKN (mg/L)		NO_{2-3} (mg/L)		TN (mg/L)		TAN (mg/L)		ON (mg/L)	
Date	(mm)	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff
4/15/14	36	0.61	0.60	0.21	0.21	0.83	0.81	0.02	0.03	0.59	0.57
4/18/14	15	0.10	0.41	0.10	0.13	0.20	0.54	0.01	0.03	0.09	0.39
4/30/14	30	0.39	0.91	0.13	0.26	0.53	1.17	0.02	0.13	0.37	0.78
5/15/14	108	0.31	0.87	0.12	0.47	0.42	1.34	0.08	0.24	0.23	0.63
6/9/14	19	0.59	0.83	0.31	0.66	0.90	1.49	0.04	0.20	0.55	0.63
6/19/14	12	0.80	1.23	0.54	0.77	1.35	2.00	0.02	0.08	0.78	1.15
7/10/14	21	0.59	0.44	0.30	0.40	0.89	0.84	0.03	0.02	0.56	0.42
7/15/14	52	0.34	0.60	0.16	0.36	0.50	0.95	0.04	0.08	0.29	0.51
7/24/14	40	0.20	0.63	0.13	0.25	0.33	0.88	0.02	0.03	0.18	0.59
7/27/14	14	0.16	0.41	0.20	0.29	0.36	0.69	0.03	0.02	0.13	0.38
8/2/14	16	0.23	0.30	0.21	0.31	0.44	0.61	0.02	0.03	0.21	0.26
8/9/14	35	0.34	0.33	0.32	0.33	0.66	0.66	0.01	0.02	0.33	0.31
8/12/14	73	0.55	0.59	0.11	0.25	0.66	0.85	0.08	0.08	0.47	0.51
8/18/14	13	0.30	0.46	0.27	0.47	0.57	0.92	0.03	0.06	0.27	0.40
9/24/14	37	0.28	0.33	0.08	0.17	0.36	0.50	0.01	0.02	0.26	0.31
10/15/14	51	0.38	0.37	0.11	0.30	0.49	0.67	0.02	0.09	0.35	0.28
11/23/14	19	0.90	0.71	0.08	0.45	0.98	1.16	0.11	0.12	0.79	0.59
12/9/14	13	0.38	0.34	0.08	0.22	0.46	0.56	0.13	0.11	0.25	0.23
1/12/15	62	0.80	0.34	0.07	0.14	0.87	0.47	0.12	0.16	0.67	0.18

1/23/15	28	0.34	0.35	0.21	0.32	0.55	0.68	0.12	0.09	0.23	0.26
2/2/15	16	0.55	0.53	0.18	0.33	0.73	0.85	0.13	0.12	0.41	0.40
2/9/15	17	0.50	0.47	0.28	0.38	0.77	0.86	0.15	0.08	0.34	0.39
3/5/15	28	0.48	0.53	0.16	0.28	0.64	0.82	0.09	0.10	0.40	0.43

Table 4-12: Post-Retrofit Mango Creek swale phosphorus species and TSS EMCs.

Storm Date	Rain (mm)	TP (mg/L) Inf	TP (mg/L) Eff	$O\text{-}PO_4^{3-}$ (mg/L) Inf	$O\text{-}PO_4^{3-}$ (mg/L) Eff	PBP (mg/L) Inf	PBP (mg/L) Eff	TSS (mg/L) Inf	TSS (mg/L) Eff
4/15/14	36	0.09	0.13	0.006	0.027	0.09	0.10	45	21
4/18/14	15	0.03	0.07	0.007	0.023	0.02	0.05	16	7
4/30/14	30	0.13	0.28	0.007	0.034	0.13	0.24	152	121
5/15/14	108	0.08	0.17	0.010	0.054	0.07	0.12	49	32
6/9/14	19	0.11	0.12	0.006	0.035	0.11	0.09	129	26
6/19/14	12	0.10	0.17	0.005	0.044	0.10	0.12	62	9
7/10/14	21	0.10	0.11	0.013	0.054	0.09	0.05	53	13
7/15/14	52	0.12	0.16	0.003	0.030	0.11	0.13	122	51
7/24/14	40	0.06	0.19	0.001	0.031	0.06	0.16	120	66
7/27/14	14	0.03	0.09	0.003	0.033	0.03	0.06	37	9
8/2/14	16	0.04	0.10	0.004	0.054	0.03	0.04	20	5
8/9/14	35	0.02	0.09	0.002	0.057	0.02	0.04	8	5
8/12/14	73	0.17	0.17	0.001	0.022	0.16	0.14	511	67
8/18/14	13	0.05	0.13	0.006	0.056	0.05	0.07	54	15
9/24/14	37	0.10	0.11	0.025	0.059	0.08	0.05	37	8
10/15/14	51	0.09	0.16	0.008	0.073	0.08	0.08	64	11
11/23/14	19	0.22	0.27	0.008	0.062	0.21	0.21	190	68
12/9/14	13	0.11	0.10	0.021	0.044	0.09	0.06	30	11
1/12/15	62	0.24	0.13	0.013	0.041	0.23	0.09	258	15
1/23/15	28	0.08	0.09	0.029	0.033	0.05	0.06	20	19
2/2/15	16	0.14	0.11	0.014	0.034	0.13	0.08	52	18
2/9/15	17	0.09	0.10	0.020	0.027	0.07	0.08	17	8
3/5/15	28	0.15	0.16	0.025	0.051	0.13	0.10	50	16

Appendix N: I-40 Pollutant Event Mean Concentrations – Raw Data

Table 4-13: Pre-Retrofit I-40 swale nitrogen species EMCs.

Storm	Rain	TKN (mg/L)			NO_{2-3} (mg/L)			TN (mg/L)		
Date	(mm)	Road	In	Out	Road	In	Out	Road	In	Out
9/21/13	54	-	0.68	1.13	-	0.69	2.75	-	1.37	3.88
12/9/13	20	0.38	0.62	1.19	0.68	0.39	0.19	1.06	1.01	1.38
12/14/13	34	0.31	0.81	0.89	0.11	0.31	0.45	0.41	1.11	1.35
1/10/14	54	0.28	0.86	0.71	0.21	0.13	0.50	0.49	0.99	1.21
2/4/14	15	1.86	1.22	0.45	0.74	0.42	2.23	2.59	1.64	2.68
2/19/14	18	0.89	1.34	0.59	0.61	0.40	1.95	1.50	1.74	2.53
2/21/14	12	0.63	2.33	1.09	0.32	1.04	1.25	0.95	3.37	2.34
3/3/14	13	-	9.09	1.34	-	0.55	2.43	-	9.64	3.76
3/17/14	18	0.44	4.87	1.11	0.60	0.34	1.24	1.03	5.21	2.34
3/28/14	32	0.43	3.53	0.24	0.40	0.17	0.54	0.83	3.70	0.79
4/15/14	31	0.46	3.19	1.54	0.32	0.49	0.24	0.78	3.68	1.78
4/18/14	28	0.17	0.95	1.38	0.24	0.07	0.36	0.41	1.02	1.74

Table 4-14: Pre-Retrofit I-40 swale nitrogen species and TSS EMCs.

Storm	Rain	TAN (mg/L)			ON (mg/L)			TSS (mg/L)		
Date	(mm)	Road	In	Out	Road	In	Out	Road	In	Out
9/21/13	54	-	0.09	0.24	-	0.59	0.89	-	4	11
12/9/13	20	0.11	0.05	0.06	0.27	0.57	1.12	5	38	8
12/14/13	34	0.15	0.10	0.09	0.16	0.70	0.81	10	44	39
1/10/14	54	0.05	0.03	0.03	0.22	0.83	0.67	11	92	24
2/4/14	15	0.09	0.18	0.05	1.76	1.04	0.40	249	94	4
2/19/14	18	0.12	0.11	0.03	0.77	1.24	0.55	42	68	8
2/21/14	12	0.08	0.07	0.05	0.55	2.26	1.04	41	129	26
3/3/14	13	-	0.29	0.08	-	8.80	1.26	-	654	30
3/17/14	18	0.06	0.15	0.08	0.38	4.72	1.03	6	848	20
3/28/14	32	0.03	0.22	0.10	0.40	3.31	0.15	8	485	13
4/15/14	31	0.07	0.05	0.30	0.39	3.14	1.24	8	359	182
4/18/14	28	0.01	0.05	0.06	0.16	0.90	1.32	4	45	26

Table 4-15: Pre-Retrofit I-40 swale phosphorus species EMCs.

Storm	Rain	TP (mg/L)			$O\text{-}PO_4^{3-}$ (mg/L)			PBP (mg/L)		
Date	(mm)	Road	In	Out	Road	In	Out	Road	In	Out
9/21/13	54	-	0.11	0.07	-	0.074	0.015	-	0.04	0.06
12/9/13	20	0.04	0.13	0.13	0.012	0.039	0.021	0.03	0.10	0.11
12/14/13	34	0.04	0.20	0.15	0.010	0.060	0.016	0.03	0.14	0.13
1/10/14	54	0.03	0.20	0.11	0.007	0.044	0.012	0.03	0.16	0.10
2/4/14	15	0.19	0.17	0.03	0.003	0.010	0.001	0.19	0.16	0.03
2/19/14	18	0.16	0.22	0.05	0.041	0.064	0.006	0.12	0.15	0.05
2/21/14	12	0.08	0.26	0.06	0.014	0.008	0.004	0.07	0.25	0.06
3/3/14	13	-	1.37	0.08	-	0.017	0.005	-	1.36	0.07
3/17/14	18	0.06	1.37	0.08	0.026	0.035	0.018	0.04	1.34	0.06
3/28/14	32	0.06	0.94	0.13	0.012	0.037	0.023	0.05	0.91	0.11
4/15/14	31	0.05	0.70	0.34	0.008	0.032	0.026	0.04	0.67	0.32
4/18/14	28	0.03	0.16	0.18	0.009	0.025	0.030	0.02	0.14	0.15

Table 4-16: Post-Retrofit I-40 swale nitrogen species EMCs.

Storm	Rain	TKN (mg/L)				$NO_{2\text{-}3}$ (mg/L)			
Date	(mm)	Road	In	Mid	Out	Road	In	Mid	Out
4/29/14	42	-	2.38	5.22	1.88	-	0.36	0.24	0.35
5/15/14	92	0.58	1.36	3.01	4.11	0.28	0.19	0.22	0.23
6/9/14	33	0.87	2.12	2.00	3.71	0.39	1.04	0.64	1.18
6/19/14	23	0.66	1.86	1.85	6.88	0.45	0.55	0.39	1.20
7/10/14	18	0.80	1.79	1.53	1.65	0.35	0.40	0.31	0.65
7/24/14	28	0.42	1.00	1.07	1.01	0.20	0.12	0.14	0.19
7/27/14	13	0.60	0.87	1.26	1.90	0.33	0.21	0.16	0.08
8/9/14	44	0.31	0.60	0.78	1.50	0.24	0.11	0.08	0.07
8/12/14	7	2.13	4.97	1.18	3.44	0.38	0.05	0.16	0.14
10/15/14	49	0.69	1.39	1.66	1.03	0.14	0.07	0.09	0.03
11/23/14	31	0.48	0.95	1.30	2.48	0.41	0.14	0.33	1.14
12/16/14	12	0.56	1.23	1.74	0.55	0.82	0.54	0.49	1.79
1/12/15	79	0.37	0.88	1.98	0.67	0.18	0.15	0.27	1.19
1/23/15	37	0.15	0.40	0.87	0.59	0.21	0.13	0.09	0.89
2/2/15	17	0.40	0.75	0.70	0.66	0.61	0.26	0.35	1.89
2/9/15	15	0.64	1.16	3.92	0.58	1.27	0.50	0.43	2.89
2/25/15	46	0.47	0.52	0.94	0.37	0.18	0.13	0.12	0.44
3/5/15	17	0.51	0.69	1.57	0.66	0.49	0.23	0.21	0.90

Table 4-17: Post-Retrofit I-40 swale TN and TAN EMCs.

Storm	Rain	TN (mg/L)				TAN (mg/L)			
Date	(mm)	Road	In	Mid	Out	Road	In	Mid	Out
4/29/14	42	-	2.73	5.46	2.23	-	0.12	0.19	0.35
5/15/14	92	0.86	1.54	3.22	4.34	0.15	0.04	0.07	0.36
6/9/14	33	1.26	3.15	2.64	4.89	0.42	0.28	0.14	1.41
6/19/14	23	1.11	2.40	2.24	8.08	0.16	0.06	0.05	2.17
7/10/14	18	1.15	2.19	1.84	2.30	0.27	0.05	0.05	0.04
7/24/14	28	0.62	1.12	1.22	1.20	0.11	0.03	0.04	0.03
7/27/14	13	0.93	1.08	1.42	1.98	0.18	0.05	0.13	0.37
8/9/14	44	0.55	0.71	0.86	1.57	0.07	0.03	0.09	0.10
8/12/14	7	2.51	5.02	1.33	3.58	0.18	0.07	0.24	0.34
10/15/14	49	0.83	1.45	1.74	1.07	0.06	0.06	0.09	0.07
11/23/14	31	0.89	1.09	1.63	3.62	0.15	0.04	0.05	1.27
12/16/14	12	1.38	1.77	2.23	2.34	0.11	0.07	0.08	0.08
1/12/15	79	0.55	1.03	2.25	1.87	0.08	0.06	0.06	0.07
1/23/15	37	0.36	0.53	0.96	1.48	0.07	0.01	0.03	0.03
2/2/15	17	1.01	1.01	1.05	2.55	0.10	0.04	0.05	0.03
2/9/15	15	1.91	1.66	4.35	3.46	0.19	0.09	0.07	0.06
2/25/15	46	0.65	0.65	1.06	0.81	0.18	0.12	0.13	0.09
3/5/15	17	0.99	0.91	1.78	1.56	0.11	0.07	0.09	0.08

Table 4-18: Post-Retrofit I-40 swale TP and O-PO_4^{3-} EMCs.

Storm	Rain	TP (mg/L)				O-PO_4^{3-} (mg/L)			
Date	(mm)	Road	In	Mid	Out	Road	In	Mid	Out
4/29/14	42	-	0.76	0.98	0.27	-	0.040	0.031	0.013
5/15/14	92	0.07	0.24	0.60	0.44	0.022	0.122	0.054	0.017
6/9/14	33	0.07	0.35	0.31	0.29	0.031	0.181	0.108	0.044
6/19/14	23	0.07	0.31	0.28	0.70	0.003	0.086	0.024	0.009
7/10/14	18	0.07	0.33	0.22	0.17	0.016	0.164	0.071	0.017
7/24/14	28	0.03	0.13	0.14	0.12	0.001	0.043	0.027	0.014
7/27/14	13	0.05	0.13	0.20	0.17	0.016	0.064	0.036	0.025
8/9/14	44	0.02	0.08	0.11	0.21	0.007	0.028	0.031	0.044
8/12/14	7	0.06	0.79	0.41	0.48	0.013	0.052	0.198	0.129
10/15/14	49	0.06	0.26	0.37	0.12	0.012	0.050	0.021	0.021
11/23/14	31	0.06	0.42	0.31	0.10	0.025	0.282	0.170	0.005
12/16/14	12	0.06	0.26	0.32	0.04	0.015	0.096	0.032	0.005
1/12/15	79	0.06	0.18	0.46	0.07	0.017	0.054	0.062	0.016
1/23/15	37	0.02	0.05	0.18	0.38	0.009	0.017	0.016	0.006
2/2/15	17	0.02	0.11	0.10	0.10	0.012	0.019	0.013	0.005
2/9/15	15	0.04	0.15	0.52	0.05	0.012	0.017	0.008	0.002
2/25/15	46	0.10	0.12	0.19	0.04	0.021	0.031	0.014	0.004
3/5/15	17	0.09	0.10	0.22	0.04	0.022	0.021	0.014	0.005

Table 4-19: Post-Retrofit I-40 swale PBP and TSS EMCs.

Storm	Rain	PBP (mg/L)				TSS (mg/L)			
Date	(mm)	Road	In	Mid	Out	Road	In	Mid	Out
4/29/14	42	-	0.72	0.95	0.26	-	400	828	106
5/15/14	92	0.05	0.11	0.55	0.42	10	14	269	218
6/9/14	33	0.04	0.17	0.20	0.25	11	27	36	37
6/19/14	23	0.07	0.22	0.26	0.69	6	61	76	413
7/10/14	18	0.05	0.17	0.15	0.15	9	24	23	19
7/24/14	28	0.03	0.09	0.11	0.10	7	28	24	18
7/27/14	13	0.04	0.07	0.16	0.15	6	16	22	22
8/9/14	44	0.02	0.05	0.08	0.17	4	7	8	10
8/12/14	7	0.04	0.74	0.21	0.35	7	691	41	115
10/15/14	49	0.05	0.21	0.35	0.10	14	73	166	15
11/23/14	31	0.03	0.13	0.14	0.10	24	37	40	12
12/16/14	12	0.04	0.16	0.29	0.04	12	21	191	8
1/12/15	79	0.04	0.12	0.40	0.05	20	33	250	11
1/23/15	37	0.01	0.04	0.16	0.38	2	7	153	27
2/2/15	17	0.01	0.09	0.08	0.09	5	17	32	7
2/9/15	15	0.03	0.13	0.52	0.04	3	23	533	13
2/25/15	46	0.08	0.09	0.18	0.04	20	28	118	4
3/5/15	17	0.07	0.08	0.21	0.04	18	17	185	3