Evaluation of Nutrient Reduction Crediting Strategies for Stream Restoration

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NC State University (NCSU) Department of Biological and Agricultural Engineering (BAE)

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Executive Summary

The NC Division of Water Resources (DWR) has developed draft standards for awarding nutrient credits for stream restoration efforts. The proposed guidance borrows heavily from the current Chesapeake Bay Protocol (CBP). The credit considers three potential nutrient credit elements for stream restoration projects including (1) prevented sediment during storm flow, (2) instream denitrification during base flow and (3) floodplain reconnection. NC Sea Grant and NCSU conducted a review of the draft standards and tested the proposed nutrient credit calculation methods on four case study restoration projects in order to: 1) quantify the level of effort necessary to prepare nutrient credit estimates, 2) identify opportunities to address shortcomings and simplify the proposed credit standards and 3) where appropriate, develop modified nutrient credit standards for improving application and accuracy of reduction estimates. In addition, USGS gage station data analysis was conducted at five streams to evaluate relationships in channel size, hydrology, watershed size and floodplain flow frequency. The existing CBP provides a first attempt to assign nutrient removal credits to stream restoration. As the stream restoration field is currently a $1 billion/yr industry and growing, interest in providing nutrient credits in addition to mitigation credits will also continue growing. NC Sea Grant and NCSU BAE applied the existing CBP to four case study streams to (1) assess credit opportunities for restored streams in NC, (2) determine level of effort required for application of the protocol, (3) identify areas for improvement in the existing protocol, and (4) propose potential revisions to the CBP for possible implementation by NC DWR.

Applying the Chesapeake Bay Protocol to four case study sites, comparing restored and unrestored reaches, resulted in TN removal credit of 589 – 1,236 lb/yr and TP credit ranging from 6 – 48 lb/yr. The main factor influencing TN credit in the existing CBP is Protocol 2, a continuous denitrification rate applied to a theoretical hyporheic box. TP credit is mainly determined by preventing streambank erosion accounted for in CBP 1. CBP Protocol 1 assigns a 50% efficiency adjustment factor to credit. This study found predicted streambank erosion reductions ranging from 44-98%. The greatest estimated reduction in streambank erosion was at the only case study site with pre- and post-restoration data available.

Protocol 2 was found to overestimate the hyporheic box based on depth. TN credit assigned via the original CBP ranged from 470-1,133 lb/yr. Case study sites were assessed for the presence of a confining layer below riffles. Average depth to confining layer was 2 feet instead of 5 ft prescribed by CBP 2. Baseflow monitoring at two case study sites found conflicting results.

Higgins Trail significantly reduced NO3-N and TP concentrations. TN and TP concentrations at Austin Creek increased between upstream and downstream locations, albeit changes were not statistically significant.

Application of CBP 3 was labor intensive and disjointed. TN credit ranged from 8-41 lb/yr while TP credit ranged from 3-12 lb/yr. Treatment efficiency is determined using curves provided by the CBP; however, little resolution at the lower end of curves, where most restoration projects will lie, results in interpolation. Further, CBP resulted in little overall credit when compared to other protocols. A flood flow frequency analysis was performed to compare observed hydrologic connectivity to floodplains to estimated connectivity in CBP 3. USGS gage data from 5 streams was analyzed and load reductions were computed using water quality data provided by local partners. Predicted TN load reductions were similar to those predicted by CBP 3. New curves were produced with higher resolution at a more reasonable practice-based scale.

Potential revisions to the CBP include (1) retaining CBP 1 with NC specific streambank concentrations similar to those reported in the 2013 Tetra Tech report and combining CBP 2 and 3 to calculate an areal denitrification partitioned by streambed area and floodplain area; or (2) allowing credit solely based on prevented streambank erosion following CBP 1 with NC specific streambank concentrations.

Introduction

The NC Division of Water Resources (DWR) has developed draft standards for awarding nutrient credits for stream restoration efforts. The proposed guidance borrows heavily from the current Chesapeake Bay Protocol (CBP). The credit considers three potential nutrient credit elements for stream restoration projects including (1) prevented sediment during storm flow, (2) instream denitrification during base flow and (3) floodplain reconnection. The first element concerns lowering nutrients by reducing stream bank and bed erosion, the second by enhancing the hyporheic zone of the stream and the third by reducing channel size and/or increasing floodplain area. NC Sea Grant and NC State University Biological & Agricultural Engineering Department will review and refine the draft protocol in an effort to assist DWR in developing a practical and appropriate nutrient crediting framework for eligible stream restoration projects with a goal of achieving nutrient reductions in Nutrient Management Strategy watersheds. Specifically, Sea Grant and NCSU will conduct a review of the draft standards and test the proposed nutrient credit calculation methods on four case study restoration projects in order to: 1) quantify the level of effort necessary to prepare nutrient credit estimates, 2) identify opportunities to address shortcomings and simplify the proposed credit standards and 3) where appropriate, develop modified nutrient credit standards for improving application and accuracy of reduction estimates. In addition, USGS gage station data analysis will be conducted at five streams in order to evaluate relationships in channel size, hydrology, watershed size and floodplain flow frequency. Field survey, assessment and modeling of case study restored streams and modeling of USGS gaged streams will be conducted for this effort.

Goals and Objectives

The overall goal of this project is to assist NC Division of Water Resources with developing a practical and appropriate nutrient crediting framework for eligible stream restoration projects to achieve nutrient reductions in DWR watersheds currently under a Nutrient Management Strategy. Specific objectives include:

1. Determine the estimated nutrient reduction and the associated credit that would be allocated for typical urban stream restoration projects based on DWR’s draft “Stream Restoration Nutrient Credit Standards & Design Conditions” guidelines. Evaluate the feasibility of the protocol and the accuracy of the estimates based on the literature values reported.

2. Quantify the level of effort necessary for applicants to prepare nutrient credit estimates for stream restoration projects based on the current proposed standards.
3. Identify opportunities to address shortcomings and simplify the proposed credit standards to improve the accuracy of the credit values as well as improving the feasibility and likelihood of public and private entities pursuing stream restoration measures.
4. Work with DWR to develop modified nutrient credit standards where opportunities for improving application and accuracy of reduction estimates have been identified. Revised information will include text, diagrams and calculation examples for consideration by DWR to be included in the nutrient credit guidelines.

Deliverables

- Synthesis of existing literature on stream restoration and nutrient processing.
- Critical review, testing and summary of the CBP nutrient and sediment crediting protocols for stream restoration at four case study sites.
- Recommendations for the application of nutrient and sediment protocols in North Carolina.
- New simplified and validated nutrient management reduction credit estimation procedures.

Review of Literature

Stream restoration is quickly becoming a major industry in environmental and ecological engineering, as well as in land development, resulting in greater than $1 billion/year of activity (Lammers and Bledsoe, 2017). As such, an impetus has been placed on quantifying nutrient treatment to develop crediting guidelines to encourage restorations and design practices that maximize stream benefits. However, previous research has shown that fewer than 10% of restorations have conducted post-restoration monitoring for nutrients (Bernhardt et al., 2005).

In effort to develop nutrient crediting guidelines for stream restorations, previous literature reviews by Tetra Tech (2013) and the Chesapeake Bay Protocol (Schueler and Stack, 2012) have explored published literature on nutrient removal in restored streams. For North Carolina specifically, a previous review of literature was conducted by Tetra Tech (2013) for the Division of Water Quality. The contents of the review of literature herein will build on these previous literature reviews and explore research presented subsequently.

It is widely agreed that streams prevent or remove nutrient loads from receiving watersheds by three main mechanisms: (1) prevention of erosion and related introduction of sediment bound nutrients, (2) reduction of nitrogen through denitrification in the hyporheic zone of the stream bed, and (3) through hydrologic connection to floodplains and riparian zones adjacent to streams. Consequently, the Chesapeake Bay Protocol (CBP) for nutrient crediting for stream restorations, has designated these three mechanisms as separate pieces to the cumulative nutrient removal puzzle which must be ascertained by consultants and regulators (Schueler and Stack, 2012). As research, and crediting, focuses on each of these processes individually, the review of literature herein will also be structured to examine each process separately.

Prevention of Erosion and Sediment Nutrient Concentrations

The main focus of classical stream restoration has been to ameliorate the effects of “urban stream syndrome,” or streambank erosion, incision, degraded water quality, and loss of habitat (Walsh et al., 2005). Channel enlargement introduces sediment bound nutrients to surface waters, which in dissolved forms can lead to downstream water quality degradation. While some species of nitrogen are found sorbed to soil, most attention is focused on dissolved inorganic fractions of nitrogen. Phosphorus, however, is the main focus of sediment loss prevention, as phosphorus is readily sorbed to soils high in metal hydroxides (Hesterberg, 2010).

Streambank erosion due to erosive flows and channel enlargement introduce sediments and associated bioavailable P to downstream water bodies. Sediment inputs from eroding streambanks can constitute up to 95% of total watershed yield (Fox et al., 2016). Lenhart et al. (2018) recently compared sediment loads from streambank erosion and field erosion in an agricultural stream and found the main source of sediment is from streambank erosion. These sediment inputs can contribute between 10-40% of total phosphorus load in a watershed (Fox et al., 2016; Sekely et al., 2002). As a result, much effort has been made to understand and predict phosphorus concentrations in streambanks and erosion potential.

In simulations of the impact of various stream restoration practices on nutrient removal, Lammers and Bledsoe (2017) reported that bank stabilization provided the greatest potential for the prevention/removal of TP (609 kg P/km/yr). Selvakumar et al. (2010) conducted pre- and post-restoration monitoring of an urban stream in Virginia, finding that restoration improved bank stabilization and prevented sloughing and further incision of the channel. Multiple methods can be used for bank stabilization, including engineered in-stream structures and bank armoring; however, research has shown that protecting the bank toe-region can reduce erosion by 90% (Simon et al., 2009).

Hyporheic Exchange and Denitrification

The hyporheic zone is best defined by Harvey and Bencala (1993) as, "a subsurface flowpath along which water recently from the stream will mix with subsurface water to soon return to the stream." Triska et al. (1989) went further and define the hyporheic zone as an interactive layer consisting of at least 10% and no greater than 98% surface water. As hyporheic exchange involves hydrologic, geologic, geomorphic, geochemical, and ecological processes, the impact of stream restoration is difficult to quantify and broadly predict (Boano et al., 2014; Cardenas, 2015).

Not only is the hyporheic zone difficult to quantify and dependent on a wide range of variables, denitrification within the hyporheic zone is additionally difficult to quantify. Biogeochemical factors impacting processes and denitrification rates vary spatially and temporally, while measurement of denitrification itself is costly and time demanding. As such, research attempting to quantify the denitrification potential of restored streams and hyporheic zones is highly varied, and often relies on modeling efforts.

Hester et al. (2018) modeled nitrate removal in streams via the hyporheic zone and found the controlling factors for denitrification to be streambed hydraulic conductivity, stream topography and slope, and groundwater levels. Further, earlier modeling of a stream reach in Virginia found that restoration with in-stream structures resulted in hyporheic based denitrification only removed 3.1% of N received by the restored reach (Hester et al., 2016). However, research by Tuttle et al. (2014) found significantly greater denitrification rates associated with more geomorphically complex streams. Geomorphic complexity exists in the form of grade control structures and deep pools. The authors compared their results to the CBP and concluded that Protocol 2 overestimated N removal due to hyporheic exchange. Filoso and Palmer (2011) examined urban streams in Maryland and reported the greatest N removal occurred in restored streams with low discharge and high N concentrations. This is similar to findings of up to 50% removal of watershed dissolved inorganic nitrogen (DIN) in small headwater streams (Peterson et al., 2001).

Lammers and Bledsoe (2017) examined 69 peer-reviewed studies to determine streambed denitrification rates and the primary factors that influence denitrification. The authors reported a median streambed denitrification rate of 1.85 mg N/m^2/hr (Lammers and Bledsoe, 2017). Further, the authors found nitrate concentrations to be the most significant factor, which agrees with Tuttle et al. (2014). The authors proposed an equation to predict denitrification rates based on in-stream nitrate concentrations as,

$$Denitrification\ Rate = 0.012 \times [NO_3^-]^{0.722};\ R^2 = 0.45,$$

where the denitrification rate is reported as mg N/m^2/hr and nitrate concentrations are reported as µg N/L.

Paradoxically, restored streams may have lower denitrification rates than unrestored reaches as restoration activities can result in compaction of the streambed, coarser streambed material, and loss of organic carbon in the hyporheic zone (Gabriele et al., 2013; Gift et al., 2010).

As stream restoration goals and guidance continue to evolve to include ecological and nutrient removal goals, research is needed to quantify the impact of various stream restoration techniques. Ultimately, syntheses agree that hyporheic exchange does not provide enough treatment relative to the size of streams to provide significant impact on nitrogen removal (Hester and Gooseff, 2013; Lammers and Bledsoe, 2017; Merill and Tonjes, 2014).

Nutrient Removal Through Floodplains and Riparian Zones

Riparian zones and floodplain wetlands provide additional opportunity for nutrient treatment of overbank flows and watershed loads; however, attempts to quantify treatment capabilities has been highly variable.

Protocol 3 of the CBP, assumes floodplain nutrient removal during overbank flow events, as the credit assumes floodplains behave similar to wetlands during periods of inundation. However, not all floodplain flow is treated, as floodplains act as an additional conduit with minimal contact time for flow during high intensity events (Jordan et al., 2003; Kadlec and Wallace, 2008; Kovacic et al., 2000). To receive nutrient removal credit in North Carolina, wetlands must be sized to capture and retain received loads for two to five days; consequently, applying a similar approach to floodplain treatment of storm flows would require substantial floodplain areas. Nonetheless, some degree of treatment will be realized in riparian zones adjacent to streams.

Kaushal et al. (2008), measured denitrification rates at the riparian zone-stream interface in restored and unrestored reaches of an urban stream in Baltimore, Maryland. The authors found that denitrification rates varied spatially and temporally, while mean denitrification rates were significantly greater in the restored reach (77.4 ug N/kg/day) compared to the unrestored reach (34.8 ug N/kg/day). The authors concluded that the introduction of soil organic carbon and hydrologic pathways in restored riparian zones were important to increasing potential nitrate removal in restored reaches (Kaushal et al., 2008). Lammers and Bledose (2017) reported areal riparian N removal rates of 1.01 mg N/m^2/hr.

These findings support previous research showing the denitrification potential increases within riparian zones where stream water can move laterally up to 18 m inland (Triska et al., 1993).

McMillan and Noe (2017) observed that inset floodplains at four restored reaches had higher sedimentation and nutrient removal rates than floodplains at higher elevations.

Further, McMillan and Noe (2017) found that the age of the riparian zone significantly impacted nutrient removal. Riparian vegetation is removed during restoration efforts and grading and compaction often remove organic carbon needed for biogeochemical transformations. This organic carbon is replenished over time during the maturation of the riparian zone.

Previous research has also explored the ability of riparian zones and floodplains to remove sediment and nutrients via sedimentation and transformations. Schenk et al. (2013) found that sedimentation rates were negatively correlated to the ratio of bank height to floodplain width. As bank heights are shorter and floodplain widths are wider, more flow is able to access the floodplain over a larger surface area. Conversely, McMillan and Noe (2017) report the opposite relationship; however, the authors concluded that high sedimentation rates occurring downstream of deeply incised streams were the result of significant bank erosion providing larger loads to be subject to sedimentation compared to other streams. In simulations of the impact of various stream restoration practices on nutrient removal, Lammers and Bledsoe (2017) reported that riparian restoration provided the greatest potential for N removal in stream restorations (1,086 kg N/km/yr) while floodplain reconnection provided a potential N removal of 86 kg N/km/yr. The authors attributed this difference to larger surface areas provided by riparian zones than small floodplain wetlands.

In North Carolina, riparian buffer protection is required along nutrient sensitive waters. Consequently, buffers in North Carolina have been researched extensively. King et al. (2016) reported findings of significant difference in NO_3-N treatment as riparian buffer width increased in a comprehensive review of 12-years of buffer research in eastern North Carolina. However, landscape position is vital to buffer performance, as Johnson et al. (2013) indicate that buffers in upland positions do not improve nitrate removal.

Existing Protocol

Protocol 1: Credit for Prevented Sediment During Storm Flow

Protocol 1 provides nutrient removal credit for prevented erosion, thereby reducing the introduction of nutrients bound to streambank sediment. The current credit for Protocol 1 is calculated as follows.

Step 1: Estimate stream sediment erosion rate

- Use BANCS and NBS, BSTEM, or appropriate method to calculate annual erosion rates
- Calculate annual sediment load as,

$$S = \frac{\sum(cAR)}{2000} \qquad (1)$$

where,

S = annual sediment load (tons/yr)

c = bulk density of streambank (lb/ft^3)

A = area subject to erosion (ft^2)

R = erosion rate (ft/yr)

Step 2: Calculate nutrient load by multiplying nutrient concentrations and sediment load estimate

- Multiply sediment load (Equation 1) by soil nitrogen and phosphorus concentrations (lb/ton).
  - Soil N and P concentrations either measured directly via onsite sampling, or with Tetra Tech (2013) proposed concentrations (TP = 0.46 lb/ton; TN = 1.78 lb/ton).

Step 3: Estimate reduction attributable to restoration

- CBP and Tetra Tech recommend a conservative estimate of 50% efficiency in preventing sediment during storm flows
- Multiply sediment and nutrient loads by reduction factor of 0.5

Protocol 2: Credit for In-Stream and Riparian Nutrient Processing within the Hyporheic Zone During Base Flow

Protocol 2 provides credit for enhanced biogeochemical processing of nitrogen via denitrification within the hyporheic zone during baseflow.

Step 1: Determine the total post construction stream length with a bank height ratio of 1.0 or less

Step 2: Determine the cross sectional area of the hyporheic box

$$A_{hb} = (10 + Bankfull\ Width) \times 5 \qquad (2)$$

Where,

A_{hb} = cross sectional area of the hyporheic box (ft^2)

- The CBP designated the hyporheic box to be the area 5 feet below the stream bed and 5 feet into each side of the stream bank (Figure 1).

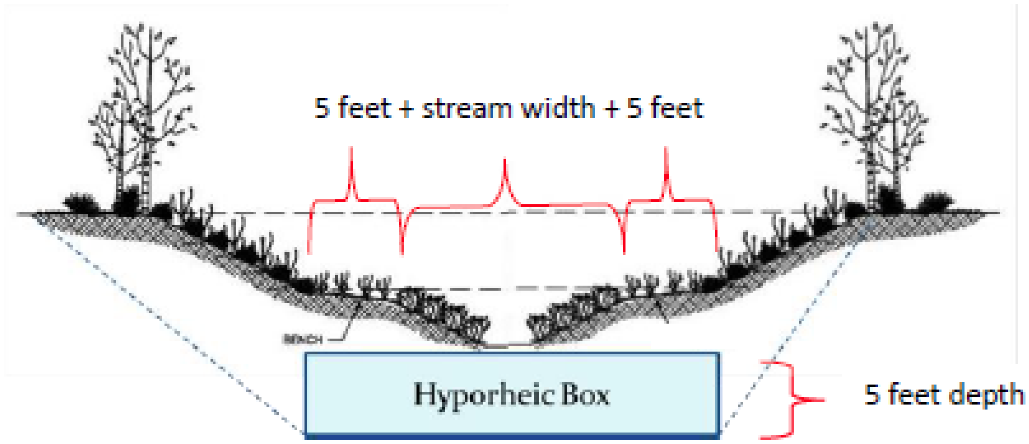


Figure 1. Hyporheic box as defined by the CBP (Schueler and Stack, 2012).

Step 3: Determine the volume of the "hyporheic box"

$$V_{hb} = A_{xs} \times L \quad (3)$$

where,

V_{hb} = volume of the hyporheic box (ft^3)

A_{hb} = cross sectional area of the hyporheic box

L = total length of post-construction stream with bank height ration of 1.0 or less

Step 4: Determine density of streambed sediments and denitrification rate

- Sediment samples may be collected and density determined using laboratory methods
  - Tetra Tech default value of 1.1 g/cm^3 (0.0343 ton/ft^3) may be used.
- Default denitrification rate provided by CBP is 1.06×10^{-4} lbs N/ton of soil/day

Step 5: Calculate nitrogen reduction via denitrification in the hyporheic box

$$N\ Removed = \frac{V_{hb} \times \rho_{bd} \times r_{denit} \times 365}{2000} \quad (4)$$

Where,

ρ_{bd} = bulk density of the streambed (lb soil/ft^3)

r_{denit} = denitrification rate (lb N/ton of soil/day)

Protocol 3: Credit for Floodplain Reconnection Volume

Protocol 3 assigns credit for stream restorations that reconnect streams to floodplains and riparian zones. Floodplain reconnection will enhance nutrient and sediment removal during storm flows via physical and biogeochemical processes. Protocol 3 provides credit based on the annual volume of storm flow that is connected and stored on the flood plain for treatment.

Step 1: Estimate the floodplain connection volume in the available floodplain area.

Step 2: Estimate the nitrogen and phosphorus removal rate attributable to floodplain reconnection for the floodplain connection volume achieved.

Step 3: Compute the annual N, P, and TSS load delivered to the project.

Step 4: Multiply the pollutant load by the project removal rate to define the reduction credit.

Case Study Application of Existing Protocol

Case Study Sites

Four restored streams were selected to serve as case studies for this project. The existing Chesapeake Bay Protocol credit standards were applied to the four case study sites to assess feasibility and applicability to North Carolina streams. All four streams are located in urban areas and were restored using natural channel design principles. In addition, a USGS gage analysis was performed on five gaged streams in effort to improve the calculation of Protocol 3.

Table 1. Site descriptions for four case study streams.

Site	Location	Drainage Area (mi^2)	Reach Length (ft)	Year Restored
Higgins Trail	Cary, NC	0.8	3,225	2012
Austin Creek	Wake Forest, NC	8.6	3,074	2002
Sandy Creek	Durham, NC	1.7	2,461	2003
Torrence Creek	Huntersville, NC	3.6	1,620	2013

Higgins Trail

Located in a suburban setting along the Higgins Trail Greenway in Cary, NC, a UT to Swift Creek drains a 0.8 mi^2 watershed. Three reaches were restored in 2012. The overall goal of the restoration project was to enhance water quality by restoring ecological function and structural stability. Project objectives included establishing an adequate floodplain; reducing bank erosion and sedimentation; improving aquatic habitat through the use of natural materials, stabilization techniques and a riparian buffer; protecting approximately 4.5 acres of riparian buffer within the Neuse River Basin; mitigating for future off-site stream impacts within the Town of Cary; and providing space for naturalized stormwater BMPs (part of a different project) to improve water quality. Historically, the stream had been altered by the increased flow velocity and non-point pollution associated with highly urbanized areas in the watershed. The land use in the drainage area of the stream is over 80% developed with residential, commercial and industrial land uses. The pre-construction condition was a highly entrenched stream with moderately erosive banks and other characteristics indicative of unstable.

Figure 2. UT to Swift Creek (Cary, NC) - Higgins Trail case study site. Restored reach (left) and degraded reach (right).

Austin Creek

The Austin Creek case study site is located in northern Wake County, approximately 1 mile southeast of the Town of Wake Forest adjacent to the Heritage Development and Golf Course. Restored in 2002, the case study focuses on 3,074 ft of restored reach extending downstream from box culverts under Forestville Road to the confluence with Smith Creek. The primary goals of the stream restoration were stabilization, improvement of aquatic habitat via in-stream structures, and the establishment of a forested riparian buffer and wildlife corridor. The upstream portion of the case study was enhanced based on a Priority 3 approach while the downstream section was replaced with a meandering channel with bankfull stage at the existing floodplain elevation.

Figure 3. Austin Creek (Wake Forest, NC) case study site. Restored reach (left) and degraded reach (right).

Sandy Creek

The Sandy Creek case study site is located in the City of Durham, approximately 3.5 miles southwest of downtown. Sandy Creek was enhanced as part of Environmental Enhancement Program project in 2003. The enhancement consisted of the installation of log vanes to create pool features to enhance habitat and water quality along 2,461 ft of stream. In addition to the stream enhancement, flood plain wetlands along the project were restored and subject to research by Duke University. Sandy Creek is described in great detail by Richardson et al. (2011).

Figure 4. Sandy Creek (Durham, NC) case study site. Restored reach (left) and degraded reach (right).

Torrence Creek

The Torrence Creek case study site is located in the Town of Huntersville, NC. The case study reach was restored in 2013 as a North Carolina Clean Water Management Trust Fund project. The objective of the restoration was to restore a geomorphically degraded stream that was contributing high sediment loads to the primary drinking water supply for the Charlotte, NC, metropolitan area. Restoration efforts focused on creating a geomorphically stable stream with floodplain connection, reducing streambank erosion, improving the biological health of the stream, creating appropriate aquatic and terrestrial habitat, and restoring a forested riparian buffer where absent.

Figure 5. Torrence Creek (Huntersville, NC) case study site. Restored reach (left) and degraded reach (right).

Protocol 1

Protocol 1 provides nutrient removal credit for prevented erosion, thereby reducing the introduction of nutrients bound to streambank sediment. The Tetra Tech report summarized Protocol 1 using the following conceptual model.

$$\begin{aligned} Nutrient\ Load &= Mass\ of\ eroded\ material \\ &\quad \times Mass\ concentration\ of\ nutrient\ in\ the\ eroded\ material \end{aligned}$$

Sediment Nutrient Concentrations

Rather than use literature values for nitrogen and phosphorus concentrations in streambank sediment, 3 samples were taken from eroding banks along each restored reach (n=12). Cores were also collected to determine streambank bulk density. Samples were analyzed following EPA standards at the Environmental Analysis Laboratory within the BAE department.

The CBP provides default values for TN and TP concentrations in streambank sediment of 2.28 and 1.05 lb/ton, respectively. Tetra Tech analyzed 128 streambed soil samples for TN (n=19) and TP (n=109) concentrations in the NC Piedmont region from the National Water Information System (NWIS) and suggested the use of median concentrations from that analysis. Median concentrations for TN and TP were 1.78 and 0.46 lb/ton, respectively, which more closely align with concentrations reported in this study. Mean concentrations were calculated from the three streambank samples taken at each study site to use for Protocol 1 calculations (Table 2). Streambank N and P concentrations varied, but were close to values proposed by Tetra Tech.

Observed streambank TN concentrations ranged from 1.01-2.64 lb/ton and streambank TP concentrations ranged from 0.30-1.57 lb/ton. The greatest TP concentrations were observed at Austin Creek. A newly developing watershed constructed over legacy agricultural sediment is hypothesized to result in the higher TP concentrations in streambank sediment. Standard concentrations provided by the CBP were much higher than observed at the case study sites. TN concentrations given by the CBP were 60% greater than the median TN concentrations from the case study sites. Similarly, TP concentrations given by the CBP were 61% higher than the median of observed TP concentrations.

Table 2. Total Phosphorus, Total Nitrogen, and Bulk Density values for case study sites compared to previous guidance.

Site/Study	TN (lb/ton soil)	TP (lb/ton soil)	Bulk Density (lb/ft^3)
Higgins Trail	1.75	0.82	70.16
Austin Creek	1.05	0.41	51.95
Sandy Creek	1.57	0.86	87.82
Torrence Creek	1.01	0.51	58.59
Case Study Mean	1.34[a]	0.65[a]	67.13
Case Study Median	1.23[a]	0.56[a]	59.45
CBP Standard Conc.	2.28	1.05	N/A
Tetra Tech Median	1.78[b]	0.46[c]	N/A

[a] n = 12
[b] n = 19
[c] n = 109

Sediment Loss Estimation

To assess Protocol 1, case study sites were examined for streambank erosion and sediment nutrient concentrations. Site visits were conducted and the Bank Assessment for Non-Point Source Consequences of Sediment (BANCS) method was performed utilizing the Bank Erosion Hazard Index (BEHI) and Near Bank Stress (NBS) to assess erosion potential of the previously restored streams. Assessments were performed using BEHI and NBS worksheets. For comparison, the BANCS method was also applied to adjacent unrestored reaches and assessed using Protocol 1 methods, except for Torrence Creek, where pre-restoration data for the case study reach was available. North Carolina Piedmont Region Bank Erosion Prediction curves were used to estimate annual bank erosion rates.

Overall, all four restored reaches appeared to be exporting minimal sediment. When applying CBP and Tetra Tech values to the pre- and post-restoration comparisons, average reductions decrease slightly. Average TN and TP reductions using CBP concentrations were both 68% and 72%, respectively. Thus, using standard concentrations rather than sampling each individual site would result in slightly less credit, but still greater than a maximum of 50%, as provided by the current guidance.

Sandy Creek had the greatest potential for streambank erosion, with 11.9 ton/yr predicted. Estimated erosion rates for Austin Creek, Higgins Trail, and Torrence Creek were 4.0, 7.0, and 1.2 tons/yr, respectively. In addition to using the BANCS method to predict sediment loads, the Sandy Creek restoration included the installation of bank pins in May 2006. Bank pins were measured during site survey for this project in April 2018. Bank pin data was then used to estimate erosion and sediment loads over the 12-year period. Decent agreement existed between the bank pin data and the BANCS method. The BANCS method predicted 11.9 ton/yr of sediment due to erosion, while erosion from the bank pins indicated an average annual sediment load of 10.5 ton/yr, resulting in a 12% difference. For the sake of comparison with other case studies, the BANCS method predictions were used for additional analysis.

For comparison, the BANCS method was applied for each case study to nearby reaches within each stream that were deemed degraded and assumed to be similar to pre-restoration values. At Torrence Creek, BEHI and NBS data was available from pre-restoration surveys. Due to differences in reach length, erosion rates were normalized over the length of each reach for the three case study sites without pre-restoration data. In each case, less erosion was predicted for the restored reach. Percent reductions were calculated for the hypothetical restorations (Table 3). The largest reduction in predicted sediment loads was observed at Torrence Creek where pre-restoration data was actually available. The pre-restoration reach was predicted to erode at a rate of 85.5 lb/ft/yr while the restored reach was predicted to erode at a rate of only 1.5 lb/ft/yr. Actual data shows a 98% reduction in annual sediment load.

Table 3. Comparison of restored and unrestored reaches for predicted sediment and nutrient loss.

Reach	Predicted Erosion (lb/100 ft/yr)	% Reduction	TN Loss (lb/yr)	% Reduction	TP Loss (lb/yr)	% Reduction
Higgins Trail Restored	435	50%	12	41%	6	41%
Higgins Trail Degraded	875		21		10	
Austin Creek Restored	259	95%	6	96%	3	95%
Austin Creek Degraded	5649		144		67	
Sandy Creek Restored	969	44%	13	64%	5	70%
Sandy Creek Degraded	1731		35		16	
Torrence Creek Restored	149	98%	1	99%	1	99%
Torrence Creek Pre-Restoration	8554		121		57	
	Mean	72%		75%		76%
	Median	73%		80%		83%

Discussion

The effect of the discrepancy in sediment nutrient concentrations between the CBP, observed values, and Tetra Tech values is realized in the calculation of credit for reduced sediment loads and associated TN and TP. The CBP states that restorations will not reach 100% efficiency in preventing sediment loss due to erosion; therefore, the CBP assigns an adjustment factor of 0.5 to calculated loads, which translates to an average 50% reduction in erosion due to restoration. However, predicted reductions in nutrient loss were greater for this study than allowed in the CBP.

As previously mentioned, pre- and post-restoration data were not available for each reach; therefore, comparisons were made assuming the same restoration practices were applied to unrestored reaches as were already applied to the restored sections (Table 3). Considering these assumptions, average reductions in TN and TP loss due to streambank erosion were 73% and 75%, respectively. The greatest reductions in TN and TP were observed for Torrence Creek, where pre- and post-restoration data was available. Predicted streambank erosion at Torrence Creek was reduced by 98%, subsequently, both TN and TP loads would be reduced by 99%. When applying CBP and Tetra Tech values to the pre- and post-restoration comparisons, average reductions decrease slightly. Average TN and TP reductions using CBP concentrations were both 68% and 72%, respectively. Thus, using standard concentrations rather than sampling each individual site would result in slightly less credit, but still greater than a maximum of 50%, as provided by the current guidance.

Credit prescribed by Protocol 1 assumes a net difference in TN, TP, and sediment resulting from the protection of streambanks via stream restoration. While a typical case would estimate predicted erosion rates for an existing degraded channel being restored and subsequently assign a 50% removal rate for the entirety of the estimated erosion, for the case study application, the difference in predicted erosion between the paired degraded reaches and restored reaches was adjusted by the 50% conversion factor to determine credit received as part of CBP 1 (Table 4). Using the CBP sediment TN and TP concentrations, TN credit ranged from 8.1 – 94.4 lb/yr while TP credit ranged from 3.7 – 43.5 lb/yr. Further, credit was calculated using the observed concentrations and Tetra Tech values in addition to the CBP concentrations (Table 4; Figure 6). Using observed concentrations resulted in an average of 25% less credit being received for TN and TP at each site. Using Tetra Tech concentrations, TN credit was reduced by 25% and TP credit was reduced by 78%.

Table 4. Credits for Protocol 1.

Method	Constituent	Higgins Trail	Austin Creek	Sandy Creek	Torrence Creek
All	Sed (ton/yr)	3.5	41.4	4.7	34.0
CBP	TN (lb/yr)	8.1	94.4	10.7	77.6
	TP (lb/yr)	3.7	43.5	4.9	35.7
Observed Concentrations	TN (lb/yr)	6.2	72.5	8.2	59.6
	TP (lb/yr)	2.9	34.0	3.8	27.9
Tetra Tech	TN (lb/yr)	6.3	73.7	8.3	60.6
	TP (lb/yr)	1.6	19.1	2.2	15.7

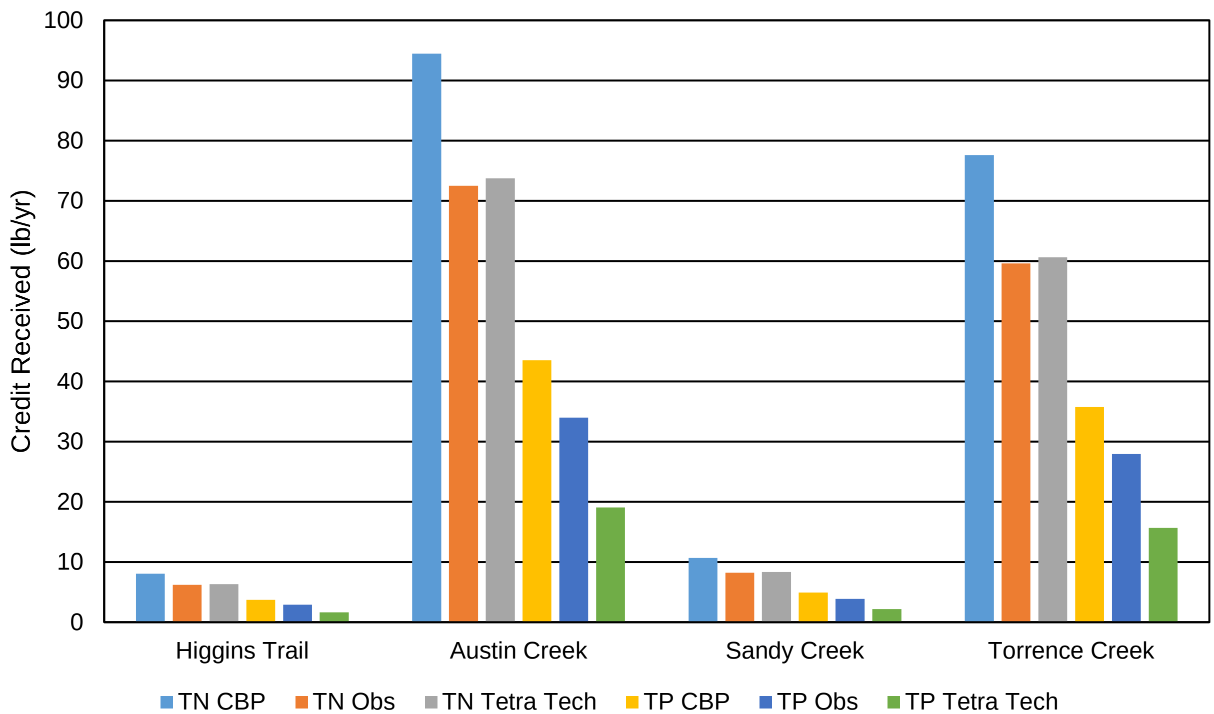


Figure 6. Comparison of Protocol 1 credit using difference sediment nutrient concentrations.

Protocol 2

Protocol 2 provides credit for enhanced biogeochemical processing of nitrogen via denitrification within the hyporheic zone during baseflow. The protocol consists of defining the hyporheic box and a standard denitrification rate within the hyporheic box. In essence, Protocol 2 follows the following model.

$$\begin{aligned} &Stream\ Reach\ Denitrification \\ &\qquad = Volume\ of\ the\ hyporheic\ box\ \times Density\ of\ streambed\ sediment \\ &\qquad \times Denitrification\ rate\ of\ streambed\ sediment \end{aligned}$$

Application

Each case study site was surveyed to capture multiple cross sections. The CBP specifies that Protocol 2 can only be applied to reaches with a bank height ratio (BHR) less than or equal to one, and each restored reach met this constraint while only a single 55 ft section of pre-restored Torrence Creek met this requirement. From surveys, average bankfull widths were determined to use for the calculation of the hyporheic box. In addition to bankfull widths, Protocol 2 also includes denitrification in riparian zones by adding five feet into each streambank to the bankfull width.

Using the existing methods for Protocol 2, nitrogen removal due to denitrification in the hyporheic box was calculated for each restored case study site as well as for unrestored reaches (Table 5). As it was intended, the degraded streams would receive no credit for Protocol 2, except for a small section of pre-restored Torrence Creek. For the restored case study reaches, N removal attributed to denitrification ranged from 470 lb/yr to 1133 lb/yr, with the smallest credit given to Torrence Creek as it had the smallest hyporheic box. Austin Creek would receive the largest credit as its average bankfull width of 34 feet over 3,074 feet of stream results in the largest hyporheic box.

Protocol 2 states that to receive full credit for N removal, practitioners must check with a designated official to ensure that a project does not receive credit for removing more N than what is received from its watershed. This is checked by comparing N removal to predicted N loads using a nutrient model.

Using Depth to Confining Layer

North Carolina Piedmont soils are known for their clay content. As such, it is difficult to imagine a uniform depth of 5 feet for the hyporheic box, which is specified in Protocol 2, in Piedmont soils. To assess this concern, an auger was used to measure the distance to a confining clay layer beneath the streambed at each case study site. Streambeds were augured at each alternating riffle until a clay layer was reached and the corresponding depth was subsequently measured. Depth to confining layers were then averaged to determine a depth of hyporheic box for Protocol 2.

Average depth to the confining layer ranged from 0.9 feet to 3.0 feet, all below the 5 feet assigned in Protocol 2. Overall depths to the confining layer ranged from 0.2 feet to 5.0 feet, with a depth greater than 5 feet occurring only twice among 35 augured riffles. The average depth to confining layer for all augured locations was 2.0 feet.

Using average depths to confining layer at each case study site reduced N removal by an average of 437 lb N/yr at each site (Table 6). N removal using actual depths to a confining layer ranged from 140 lb N/yr at Torrence Creek to 703 lb N/yr at Austin Creek. Higgins Trail is predicted to remove 176 lb N/yr and Sandy Creek is predicted to remove 293 lb N/yr.

Table 5. Computed N removal using Protocol 2 of the Chesapeake Bay Protocol.

Stream	Higgins Trail Restored	Higgins Trail Degraded	Austin Creek Restored	Austin Creek Degraded	Sandy Creek Restored	Sandy Creek Degraded	Torrence Creek Restored	Torrence Creek Unrestored
L (ft)	3225	408	3074	415	2461	658	1620	338
L_{BHR1} (ft)	3225	0	3074	0	2461	0	1620	55
W_{bkf} (ft)	19	20	34	15.5	22	30	24	10.5
W_{hb} (ft)	29	30	44	25.5	32	40	34	20.5
D_{hb} (ft)	5	5	5	5	5	5	5	5
A_{hb} (ft^2)	145	150	220	127.5	160	200	170	102.5
V_{hb} (ft^3)	467625	0	676280	0	393760	0	275400	5637.5
ρ_{bd} (lb/ft^3)	88.2	88.2	86.6	86.6	86.6	86.6	88.2	88.2
r_{denit} (lb N/ton soil/day)	0.000106	0.000106	0.000106	0.000106	0.000106	0.000106	0.000106	0.000106
N Removed (lb/yr)	798	0	1133	0	659	0	470	10
N Credit (lb/ft/yr)	0.247	0.000	0.369	0.000	0.268	0.000	0.290	0.028

Table 6. Comparison of N removal using standard and observed depths for hyporheic box.

Stream	CBP Credit (lb/yr)	CBP Credit with Confining Layer (lb/yr)	Δ (lb/yr)
Higgins Trail Restored	798	176	623
Austin Creek Restored	1133	703	431
Sandy Creek Restored	659	293	367
Torrence Creek Restored	470	140	330

Protocol 3

Protocol 3 assigns credit for stream restorations that reconnect streams to floodplains and riparian zones. Floodplain reconnection will enhance nutrient and sediment removal during storm flows via physical and biogeochemical processes. Protocol 3 provides credit based on the annual volume of storm flow that is connected and stored on the flood plain for treatment.

Estimating Sediment and Nutrient Loads using STEPL (Spreadsheet Tool for Estimating Pollutant Load)

STEPL is a US EPA funded pollutant loading model that was developed by Tetra Tech, Inc. STEPL employs simple algorithms to calculate nutrient and sediment loads from different land uses and the load reductions that would result from the implementation of various best management practices (BMPs). For this application, STEPL was used without BMP functions to estimate the nutrient and sediment loads supplied to each stream restoration project. For each watershed, the annual nutrient loading is calculated based on the runoff volume and the specified pollutant concentrations from each land use type. The annual sediment load (sheet and rill erosion only) is calculated based on the Universal Soil Loss Equation (USLE) and the sediment delivery ratio.

The primary model inputs and methods for development were:

1. Total area of each watershed landuse type (Urban, Cropland, Pastureland or Forest) and local normal annual precipitation characteristics.
2. Universal Soil Loss Equation (USLE) for each watershed landuse type.
3. The average (dominant) Hydrologic Soil Group (HSG) in the watershed.

The study watersheds were manually delineated using ArcGIS and the most recent aerial imagery (2016 – 2017) to document and quantify each landuse type (Table 7 and Table 8). Overall, the study watersheds were relatively urban / suburban with very little cropland or pastureland and no documented livestock operations. Substantial forest cover was observed for the Austin Creek and Torrence Creek project watersheds. Urban land was further delineated into Commercial, Industrial, Institutional, Transportation, Multi-family and Single-Family categories. This was done so that specific TN, TP and TSS concentrations could be applied by STEPL to each urban landuse type. Standard TN, TP and TSS concentrations used by STEPL are included in Table 9 and predicted loads are included in Table 10. Runoff concentrations for urban landuses in STEPL are all higher than concentrations assigned in the NCDEQ SNAP Tool (NC DEQ, 2017).

Table 7. Watershed landuse summary by STEPL input type in acres and (%).

Watershed	Total	Urban	Cropland	Pastureland	Forest
Austin	5,901	1,786 (30)	907 (15)	434 (7)	2,774 (47)
Higgins Trail	426	419 (98)	0 (0)	0 (0)	7 (2)
Sandy Creek	859	721 (84)	2 (0)	0 (0)	137 (16)
Torrence Creek	1,911	1,073 (56)	123 (6)	153 (8)	562 (29)

Table 8. Urban landuse summary by detailed STEPL input type in acres and (%).

Watershed	Total	Comm.	Indust.	Instit.	Transport.	Multi-Family	Single-Family
Austin Creek	1,786	5 (0)	14 (1)	30 (2)	32 (2)	11 (1)	1,694 (95)
Higgins Trail	419	33 (8)	5 (1)	36 (9)	0 (0)	83 (20)	263 (63)
Sandy Creek	721	35 (5)	0 (0)	307 (43)	47 (7)	138 (19)	194 (27)
Torrence Creek	1,073	146 (14)	171 (16)	202 (19)	128 (12)	13 (1)	414 (38)

Table 9. Nutrient and sediment concentration inputs for STEPL urban landuse types (mg/L).

Constituent	Commercial	Industrial	Institutional	Transportation	Multi-Family	Single-Family
TN	2.0	2.5	1.8	3.0	2.2	2.2
TP	0.2	0.4	0.3	0.5	0.4	0.4
TSS	75	120	67	150	100	100

Table 10. Summary of nutrient and sediment loads predicted by STEPL.

Site	N Load		P Load		Sediment Load	
	(lb/yr)	(lb/ac/yr)	(lb/yr)	(lb/ac/yr)	(TN/yr)	(TN/ac/yr)
Austin Creek	22,586	3.8	4,670	0.8	1,450	0.25
Higgins Trail	1,891	4.4	317	0.7	41	0.10
Sandy Creek	6,393	7.4	1,104	1.3	147	0.17
Torrence Creek	12,428	6.5	2,185	1.1	564	0.26
Neuse Basin TMDL	N/A	3.6	N/A	N/A	N/A	N/A
Tar-Pam TMDL	N/A	4.0	N/A	0.4	N/A	N/A
Jordan Lake TMDL	N/A	2.2-4.4	N/A	0.78-1.43	N/A	N/A
Falls Lake TMDL	N/A	2.2	N/A	0.33	N/A	N/A

Application

Protocol 3 assumes that sediment and nutrient removal occurs only for that volume of annual flow that is effectively in contact with the floodplain up to a 1-foot depth. A series of conceptual curves were developed by the Chesapeake Bay Expert Panel that relate the floodplain reconnection volume to the effective depth of rainfall treated in the floodplain. Nutrient and sediment removal rates are then applied to the watershed supplied loads. The extent of the removal rate depends on the elevation of the streambed relative to the stage at which the floodplain is effectively accessed. Designs that divert more stream runoff onto the floodplain during smaller storm events (e.g., 0.25 or 0.5 inches) receive greater removal rates than designs that interact with the floodplain during infrequent events, for example the 1.5-year storm event. To receive the full sediment and nutrient removal rates, the floodplain area must be at least 1% of the total watershed area. The credit is discounted proportionally for projects that cannot meet this criterion.

The primary steps for determining the nutrient and sediment load removed through floodplain connection under the CB Expert Panel's Protocol 3 are described below:

1. Determine the project's floodplain area and floodplain area to watershed area ratio.
2. Estimate the floodplain connection volume up to a 1-foot depth and normalize by watershed area to obtain "Watershed Inches".
3. Compute the annual TN, TP and TSS load delivered to the project (see STEPL summary).
4. Estimate the nitrogen and phosphorus removal rate attributable to floodplain reconnection from the TN, TP and TSS curves developed by the CB Export Panel.
5. Multiply the pollutant load by the project removal rate to define the reduction credit.

ArcGIS was used to delineate the available floodplain area. The most recent QL2 LiDAR dataset was obtained from the North Carolina Floodplain Mapping Program and converted to a TIN Surface. From the TIN surface the total floodplain area up to a 1-foot depth was estimated and delineated with a polygon. The floodplain area to watershed area ratio (FA / WA) was then calculated for all sites (Table 11). FA / WA was less than 1% for all sites, which means the criterion for full removal rate for floodplain connection was not met. As anticipated, sites with larger watersheds (Austin Creek and Torrence Creek) resulted in lower FA / WA values, compared to sites with smaller watersheds (Higgins Trail and Sandy Creek). Floodplain connection volume for a 1-foot depth was determined and convert to watershed inches by dividing by the total watershed area and converting units. For all sites, the floodplain connection volume in WA in ranged from 0.01 in up to 0.10 inches. Similar to FA / WA ratio, sites with larger watersheds (Austin Creek and Torrence Creek) resulted in lower WA in values, compared to sites with smaller watersheds

(Higgins Trail and Sandy Creek). This suggests watershed area may a limiting factor in nutrient and sediment removal credit under the current Protocol 3 guidance.

Table 11. Summary of Protocol 3 parameters and calculations.

Site	Watershed Area (ac)	Floodplain Area (ac)	FA / WA	1.0 ft Floodplain Volume (ft^3)	WA in	Design Storm to Access Floodplain (in)
Austin Creek	5,901	6.7	0.12%	291,852	0.01	1.25
Higgins Trail	426	4.1	0.84%	178,596	0.10	1.00
Sandy Creek	859	8.1	0.74%	352,836	0.09	1.25
Torrence Creek	1,911	5.2	0.22%	224,334	0.03	0.50

Finally, HEC-HMS and HEC-RAS were used to determine discharges for a range of design storms (0.5 inches to 2.0 inches in 0.25 inch increments) and the design storm that results in overbank flows (Table 11). The design storm depth required to access the floodplain determines the TN, TP and TSS curve used to assign removal rates to each project (Figures 7– 9). Red boxes have been included in Figures 7– 9 to show the general area that sites fall on the curves.

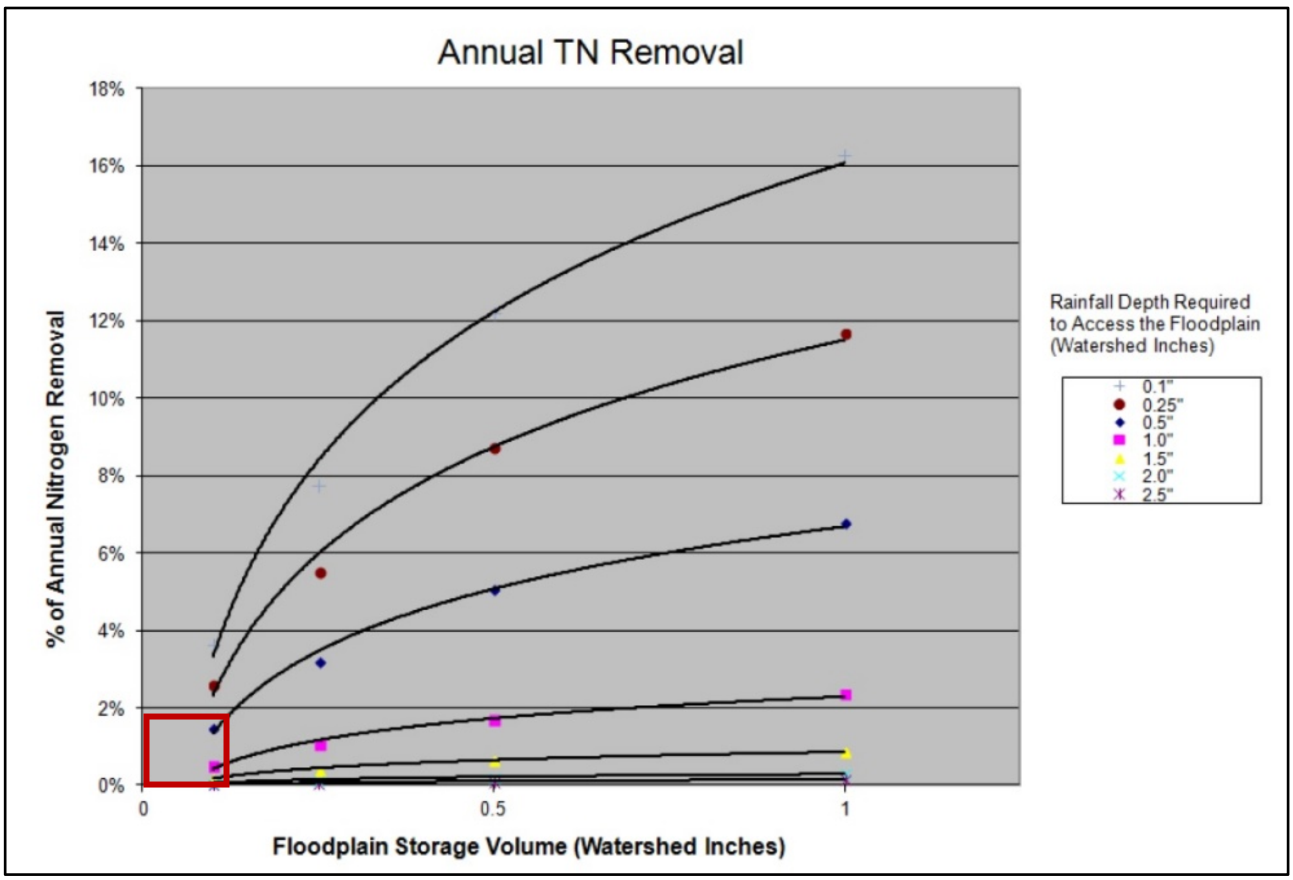


Figure 7. Protocol 3 annual TN removal.

Table 12. Protocol 3 TN removal rate summary.

Calculation Parameter	Higgins Trail	Austin Creek	Sandy Creek	Torrence Creek
Watershed Load (lb/yr)	1,891	22,586	6,393	12,428
% Removed	0.5%	0.3%	0.3%	1.5%
Load Removed (lb/yr)	9.5	67.8	19.2	186.4
FA / WA Factor	0.84	0.12	0.74	0.22
Corrected Removal (lb/yr)	**8.0**	**8.1**	**14.2**	**41.0**
Corrected % Removed	**0.4%**	**0.0%**	**0.2%**	**0.3%**

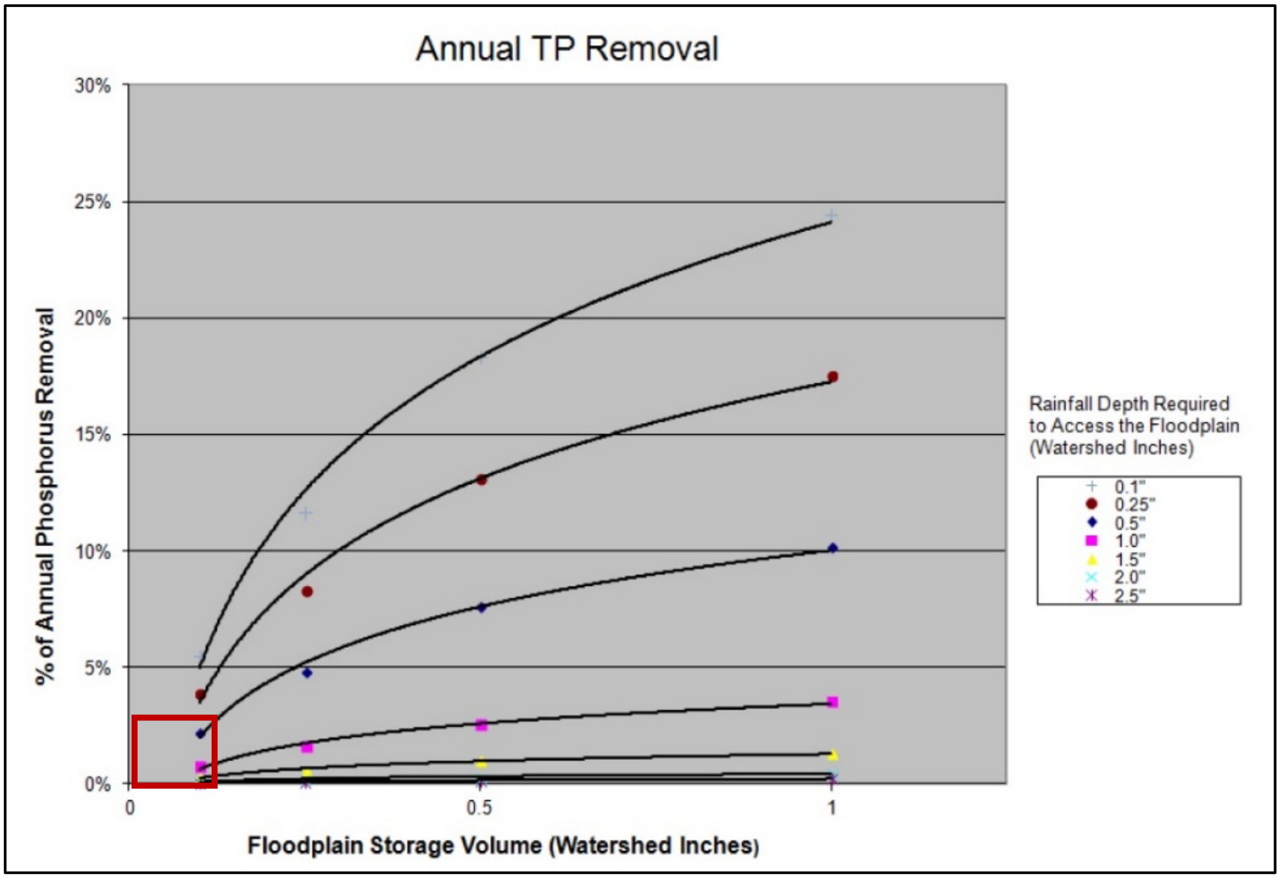


Figure 8. Protocol 3 annual TP removal.

Table 13. Protocol 3 TP removal rate summary.

Calculation Parameter	Higgins Trail	Austin Creek	Sandy Creek	Torrence Creek
Watershed Load (lb/yr)	317	4,670	1,104	2,185
% Removed	1.0%	0.5%	0.5%	2.5%
Load Removed (lb/yr)	3.2	23.3	5.5	54.6
FA / WA Factor	0.84	0.12	0.74	0.22
Corrected Removal (lb/yr)	**2.7**	**2.8**	**4.1**	**12.0**
Corrected % Removed	**0.8%**	**0.1%**	**0.4%**	**0.5%**

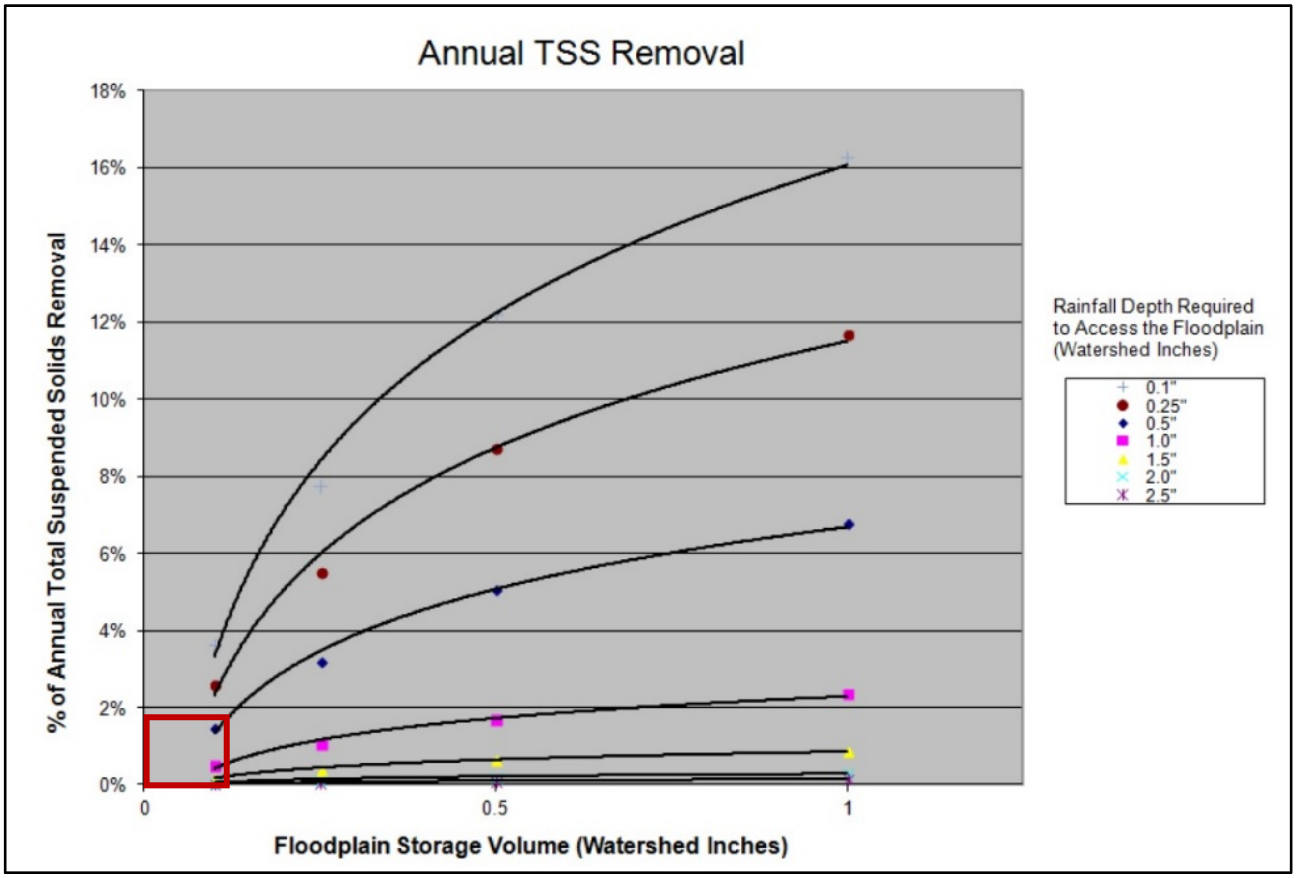


Figure 9. Protocol 3 annual TSS removal.

Table 14. Protocol 3 TSS removal rate summary.

Calculation Parameter	Higgins Trail	Austin Creek	Sandy Creek	Torrence Creek
Watershed Load (lb/yr)	41	1,450	147	564
% Removed	0.5%	0.3%	0.3%	1.5%
Load Removed (lb/yr)	0.2	4.4	0.4	8.5
FA / WA Factor	0.84	0.12	0.74	0.22
Corrected Removal (lb/yr)	**0.2**	**0.5**	**0.3**	**1.7**
Corrected % Removed	**0.4%**	**0.0%**	**0.2%**	**0.2%**

In general, very little TN, TP or TSS removal (0.0% to 0.8% for all constituents across all sites) was calculated using the current Protocol 3 guidance (see Tables 12-14). This is primarily because the floodplain storage volume in units of watershed inches is very small for all sites (0.01 – 0.10 in). Torrence Creek had the greatest removal rates due because it floods at smaller design storm (0.5 in) while Austin Creek and Sandy Creek had the lowest removal rates because the 1.25-inch design storm was required for the channel to flood.

This is little to no resolution on the curves at WA in values less than 0.1, which is where all of the study sites lie. Additionally, very little removal credit is given for sites that require a 1-inch design storm or greater to flood. This methodology is not consistent with current stream restoration design standards and may lead to or incentivize grossly undersized channels that flood extremely frequently. While this may be desirable for water quality under the Protocol 3 guidance, it deviates from natural channel functions and decreases the channel's ability to move water and sediment and perform geomorphic processes under bankfull flow conditions.

Total Credit

CBP credits are additive, and an individual stream restoration project may quality for credit under one or more of the protocols, depending on its design and overall restoration approach. For the analysis herein, it is assumed that each case study reach will receive credit under all three protocols. As such, individual credit for each protocol was summed to determine total nutrient removal credit assigned to each case study site (Table 15).

Table 15. Total credits assigned under CBP to case study sites.

Protocol	Credit	Higgins Trail	Austin Creek	Sandy Creek	Torrence Creek
Watershed Loads + Erosion	TN (lb/yr)	1916	22738	6431	12549
	TP (lb/yr)	329	4741	1122	2242
	Sediment (ton/yr)	14	88	21	70
Protocol 1	TN Credit (lb/yr)	8	94	11	78
	TP Credit (lb/yr)	4	43	5	36
	Sediment Credit (ton/yr)	4	41	5	34
Protocol 2	TN Credit (lb/yr)	757	1133	659	470
Protocol 3	TN Credit (lb/yr)	8	8	14	41
	TP Credit (lb/yr)	3	3	4	12
	Sediment Credit (ton/yr)	0.2	0.5	0.3	1.7
Total Credit	**TN Credit (lb/yr)**	**773**	**1236**	**684**	**589**
	TP Credit (lb/yr)	**6**	**46**	**9**	**48**
	Sediment Credit (ton/yr)	**4**	**42**	**5**	**36**
% Removed	**TN**	**40%**	**5%**	**11%**	**5%**
	TP	**2%**	**1%**	**1%**	**2%**
	Sediment	**27%**	**48%**	**24%**	**51%**

Total nitrogen credits ranged from 589 – 1,236 lb/yr while TP credits varied from 6 – 48 lb/yr. Assigned credits were compared to the sum of watershed loads calculated by the aforementioned STEPL Tool and nutrients associated with predicted annual streambank erosion. Removal rates were highest for Higgins Trail, as it is the smallest watershed (0.8 mi^2) and receives the smallest load. Removal rates for TP were minimal and ranged from less than 1% to 2% of watershed load.

For additional analysis, TN, TP, and sediment credits were partitioned based on protocol (Figure 10-Figure 12). The preponderance of TN credit is associated with CBP 2 while TP and sediment removal is mainly awarded by CBP 1. Protocol 2 accounts for >92% of TN reduction at Higgins Trail, Austin Creek, and Sandy Creek and 80% of TN credit at Torrence Creek. Torrence Creek received 13% of its TN credit from Protocol 1 mainly as a function of receiving less credit from Protocol 2 due to a shorter reach length. Torrence Creek also received 7% of its TN credit from Protocol 3 as it displayed the smallest “design storm” providing access to the floodplain.

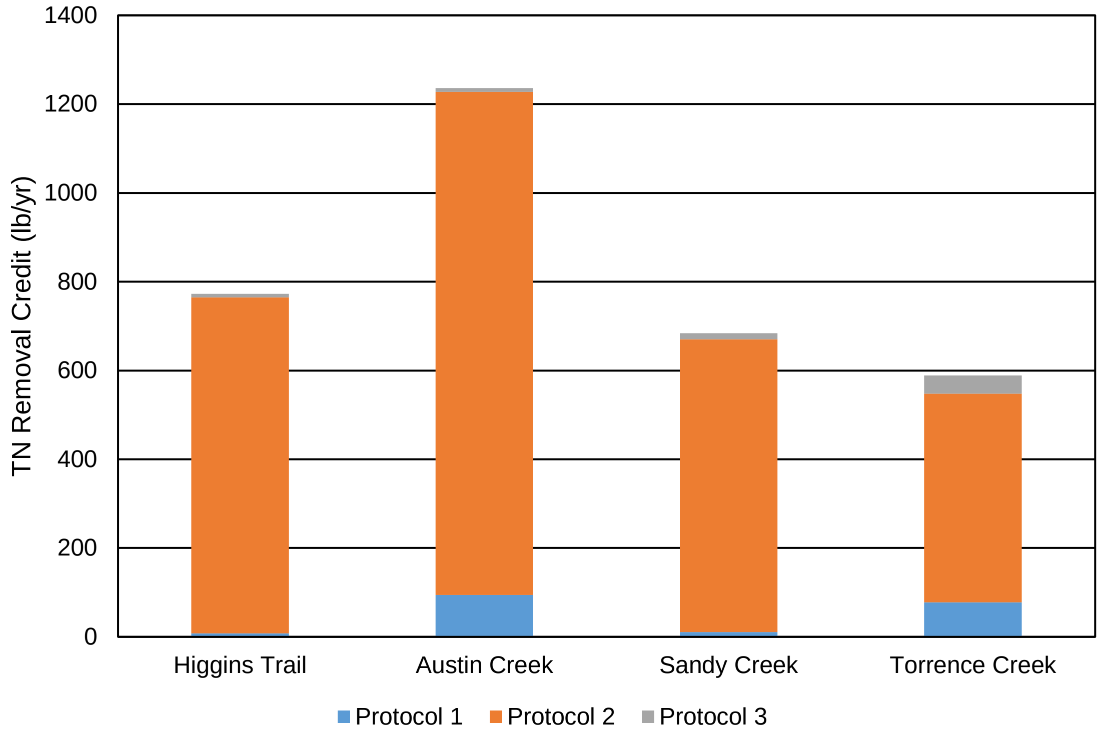


Figure 10. TN credit partitioned by CBP.

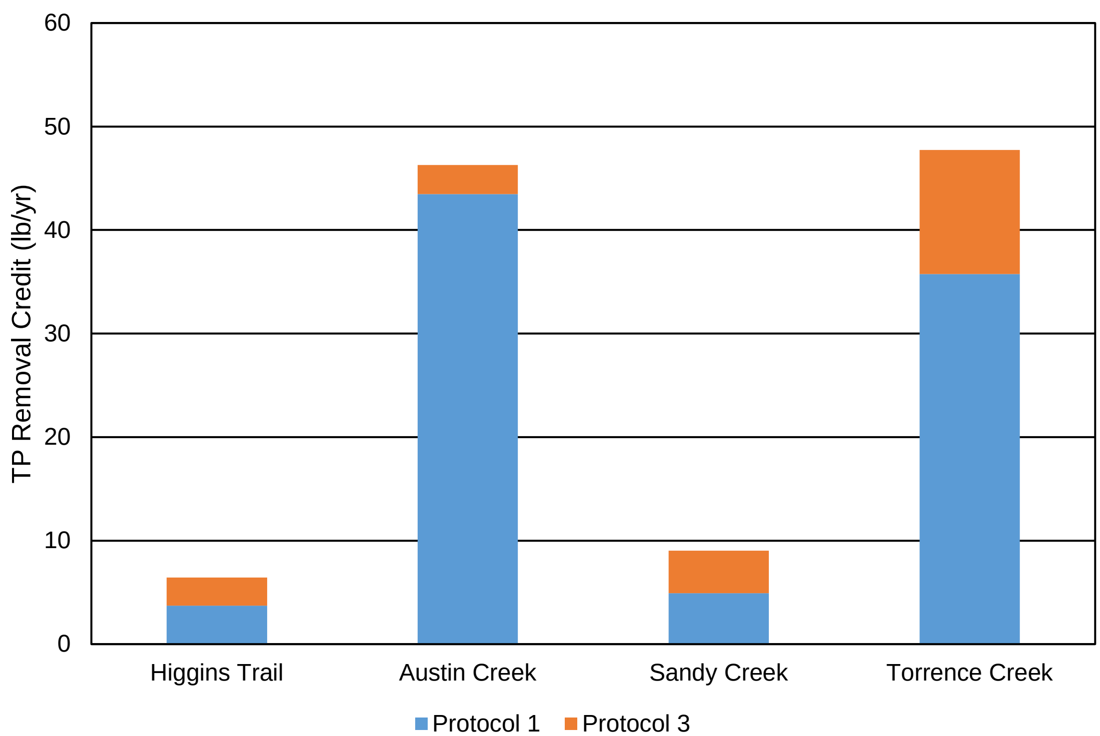


Figure 11. TP credit partitioned by CBP.

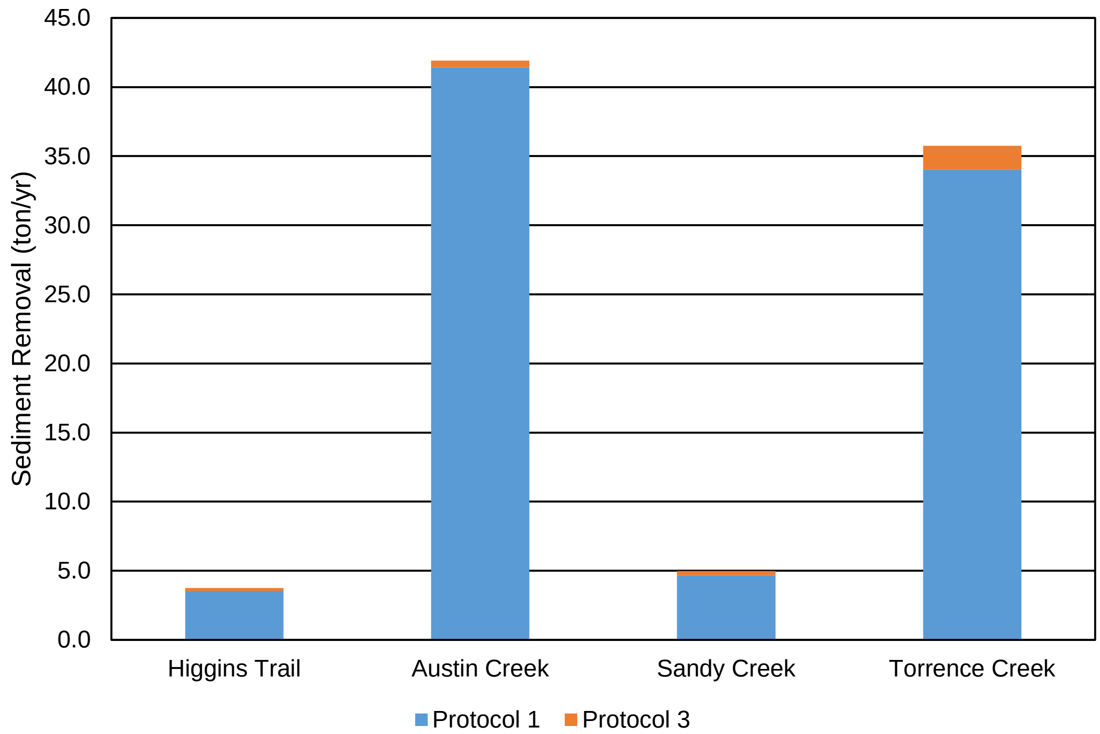


Figure 12. Sediment credit partitioned by CBP.

Water Quality Monitoring

Baseflow monitoring and sampling occurred at two of the case study sites, Higgins Trail and Austin Creek. Monitoring occurred from January – July 2018. As hyporheic exchange occurs during baseflow conditions, water quality samples were taken solely during baseflow conditions.

Two Teledyne ISCO 6712 portable automatic samplers were installed at upstream and downstream locations at both case study sites to compare concentrations and mass reductions in TN and TP. Water levels were measured with staff gauges and ISCO 720 submerged probe flow modules to determine baseflow conditions and calculate flow volumes for mass calculations via rating curves. Rating tables were generated following flow observations during various conditions using a Pygmy flow meter. Automatic samplers were programmed to sample every eight hours during baseflow conditions. Baseflow conditions were determined by programming a sampling enable condition in the automatic samplers. Composite samplers were collected biweekly and transported to the NCSU BAE Environmental Analysis Lab for analysis. Samples were analyzed for TKN, NO_3-N, TP, and TSS. TN concentrations were calculated as the sum of TKN (NH_4-N and Organic N) and NO_3-N.

During the 7-month monitoring period, 11 samples were collected at Higgins Trail and 8 samples were collected at Austin Creek. Fewer samples were collected at Austin Creek due to a greater frequency of high flow events that interfered with equipment. Following the monitoring period, observed flow levels were analyzed in Flowlink® software to calculate a total volume of baseflow observed during the monitoring period. TN and TP loads were then calculated for each sampling period and summed to calculate total TN and TP masses observed at upstream and downstream locations.

A statistical analysis was performed on baseflow sample concentrations. Analysis was performed using R statistical software (R Core Team, 2016). Concentrations were inspected for normality visually and using the Shapiro-Wilk test of normality. Concentrations were uniformly lognormal. Concentration means were statistically compared using Welch two sample t-tests with significance indicated by $\alpha = 0.05$.

Water quality analysis found opposing results between the two case study sites (Table 16). At the Higgins Trail case study site, median TN concentrations observed at upstream and downstream sampling locations were 2.07 and 1.61 mg/L, respectively, with observed concentrations ranging from 0.97 to 7.28 mg/L. While TN and TKN concentrations were not significantly different, nitrate concentrations significantly decreased between the upstream and downstream locations ($p = 0.019$). Similarly, median TP concentrations at upstream and downstream locations were 0.32 and 0.08 mg/L, respectively, and ranged from 0.01 to 5.64 mg/L. TP concentrations were also significantly reduced between the upstream and downstream sample locations ($p = 0.003$). Mean percent reductions and mass reductions were 19% for TN and 88% for TP.

At Austin Creek, mean concentrations for both TN and TP increased between upstream and downstream monitoring locations. At Austin Creek, median TN concentrations for upstream and downstream sampling locations were 2.12 and 2.76 mg/L, respectively, with concentrations ranging from 1.65 to 5.23 mg/L. For TP, upstream and downstream median concentrations were 0.17 and 0.22 mg/L, respectively. TP concentrations ranged from 0.01 to 2.43 mg/L. Overall, reductions in mean concentrations were -27% and -227% for TN and TP, respectively. Mass reductions were -10% for TN and -141% for TP. Even though substantial increases in concentrations were observed at Austin Creek, there was no significant difference between concentrations at upstream and downstream sample locations. It should be noted that Austin Creek was relatively large with baseflow of greater than 1200 gallons per minute and as such had a complex watershed. Streams of this size would require at least 18-24 months of monitoring before trends can be documented with a reasonable level of uncertainty.

Table 16. Summary statistics for baseflow water quality monitoring at two case study sites.

Case Study Site	Statistic	TKN		NO3		TN		TP	
		Up	Down	Up	Down	Up	Down	Up	Down
Higgins Trail	Mean ± SD	2.76 ± 2.04	2.01 ± 1.19	0.14 ± 0.11	0.07 ± 0.05	2.91 ± 2.12	2.08 ± 1.17	0.92 ± 1.78	0.09 ± 0.06
	Median	1.96	1.47	0.12	0.06	2.07	1.61	0.32	0.08
	Min	0.95	0.91	0.05	0.03	1.06	0.97	0.1	0.01
	Maximum	6.87	4.62	0.41	0.16	7.28	4.65	5.64	0.21
Austin Creek	Mean ± SD	1.67 ± 0.64	2.17 ± 1.42	0.70 ± 0.27	0.84 ± 0.21	2.37 ± 0.69	3.01 ± 1.36	0.19 ± 0.11	0.61 ± 0.89
	Median	1.58	1.87	0.61	0.89	2.12	2.76	0.17	0.22
	Min	0.78	0.86	0.37	0.57	1.65	1.81	0.08	0.01
	Maximum	2.74	4.26	1.13	1.09	3.48	5.23	0.4	2.43

Mass removal rates were calculated for comparison to literature values. Using stream morphology data gathered for previous analysis, an areal removal rate was calculated using the difference in nutrient masses at each site. At Higgins Trail, a TN removal rate of 0.35 mg N/m^2/hr was observed, while TN increased at Austin Creek by 13.17 mg N/m^2/hr. TN removal at Higgins Trail falls between values reported by Mulholland et al. (2004) (0.168 mg N/m^2/hr) and Lammers and Bledsoe (2017) (1.85 mg N/m^2/hr) and below values reported by McMillan et al. (2014).

TP was removed from baseflow at Higgins Trail by a rate of 0.45 mg P/m^2/hr while TP increased at Austin Creek by a rate of 11.73 mg P/m^2/hr. It is hypothesized that significant removal of TP at Higgins Trail is due in part to two possible factors: (1) soils at Higgins Trail had a much higher clay content than Austin Creek, which could lead to increased sorption and (2) a negative correlation between phosphate uptake and canopy cover was observed by McMillan et al. (2014), and for the case study sites, a larger and more mature riparian zone at Austin Creek resulted in a large canopy cover, while a relatively small and young riparian zone at Higgins Trail provided less canopy cover. Increasing concentrations at Austin Creek are hypothesized to be a result of legacy agriculture in the developing watershed. Legacy nutrients in the groundwater may be entering Austin Creek along the monitored reach resulting in increasing concentrations. Further, a manicured soccer park is located adjacent to Austin Creek. Fertilization of soccer fields may also contribute to increased baseflow concentrations.

Stream Gage Data Analysis

Purpose and Site Selection

To evaluate nutrient removal potential of a floodplain, the flow regime and connectivity of the floodplain with the channel must be considered. Five USGS gage stations were selected to determine the frequency that the floodplain is inundated with overbank flow. The location, gage station number and basic watershed characteristic for the five study streams is provided below in Table 17. A map of the study site locations is provided in Figure 13. Ten years of discharge data for each station was evaluated from January 2008 to December 2017. Three of the gages (Rocky Branch, Sandy and Torrence) are located downstream of a restoration project. For these sites, both the pre-restoration and restored scenarios were considered to evaluate the change in overbank flow frequency and volume that resulted from the restoration effort. The remaining two sites (Marsh and Swift) are located on un-restored streams. These sites were selected due to the presence of a wide forested floodplain adjacent to the stream. The un-restored sites are currently suffering from streambank erosion and poor floodplain connection that is likely the result of urbanization, channel incision and/or historical channel modifications. Floodplain flow frequency and volume at these un-restored sites was also evaluated using a theoretical stream restoration approach of reconfiguring the channel to improve floodplain connection. This theoretical restoration scenario was intended to mimic a typical natural channel design restoration similar to what was applied at the three restored study sites. Therefore, all five gage sites were evaluated to determine the changes in frequency of floodplain flow and associated nutrient reduction that could be realized through floodplain reconnection efforts.

Table 17. Basic watershed and channel characteristics for five USGS stream gages analyzed for floodplain flow frequency and potential nutrient treatment.

Stream Name	Location	Watershed Area (sq.mi.)	Percent Impervious	USGS Station Number
Marsh Creek	Raleigh	6.84	25%	0208732885
Rocky Branch	Raleigh	0.98	40%	0208735012
Sandy Creek	Durham	1.72	17%	0209722970
Swift Creek	Apex	21	16%	02087580
Torrence Creek	Charlotte	3.6	16%	0214265808

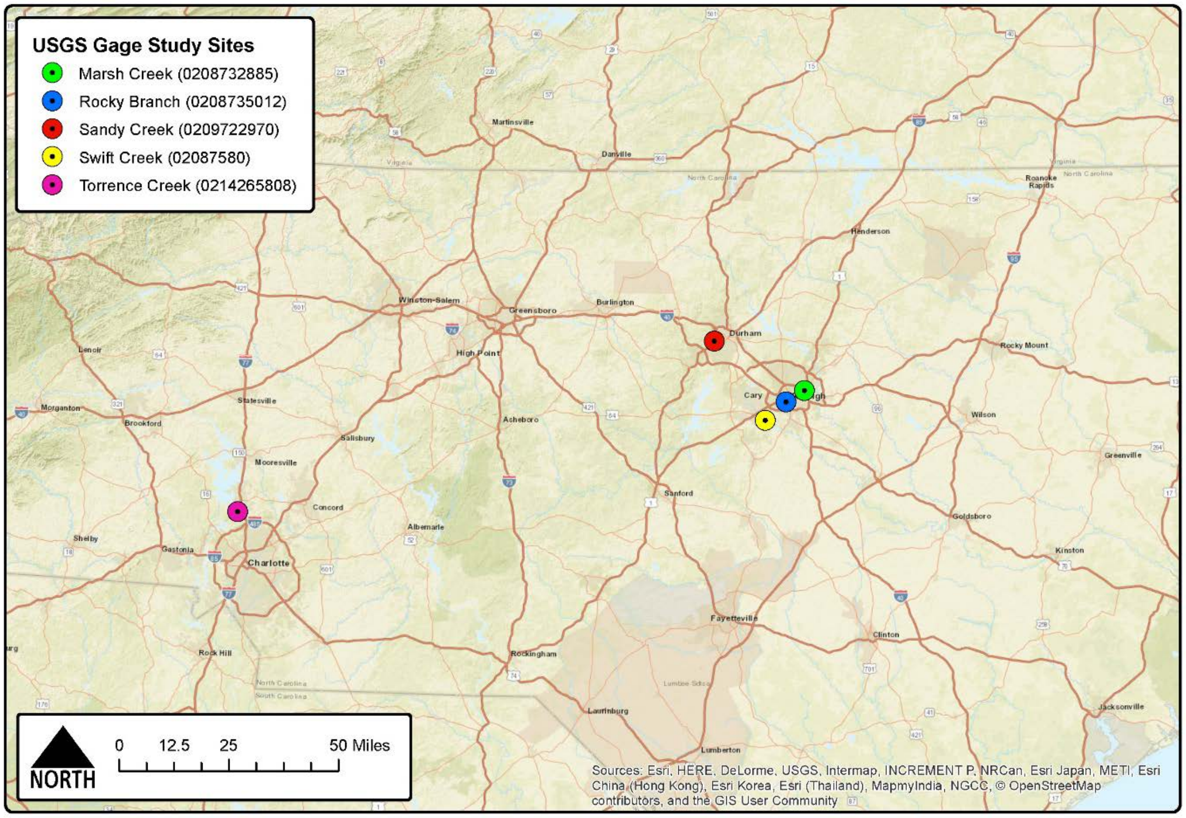


Figure 13. USGS gage study site locations.

Methods

Bankfull and Top of Bank Discharge Determinations

To evaluate the frequency of flows accessing the floodplain both before and after restoration, it was first necessary to determine the discharge associated with both the top of bank (pre-restoration condition) and the bankfull stage associated with the post-restoration condition for the five gages. For the two un-restored streams (Marsh and Swift), the gage sites were visited and both top of bank and bankfull stage was identified in the field. A riffle cross-section and streambed longitudinal profile were surveyed to estimate channel slope, the bankfull and top of bank cross-sectional areas. These hydraulic parameters were used to calculate the bankfull discharge using Manning's equation. Annual peak discharges for the entire gage record were downloaded and used to analyze the flood frequency. The calculated bankfull discharge was compared to the one-year return interval discharge estimated from the flood frequency analysis. At Sandy and Torrence creeks, the design bankfull discharge was obtained from restoration design documents. Finally, for Rocky Branch, the five-year post-restoration morphological monitoring cross-sectional area and channel slope were used to calculate the bankfull discharge using Manning's equation.

To further evaluate bankfull and top of bank discharge at each stream reach, the effective river hydraulic flood model was obtained from the NC Flood Risk Information System (https://fris.nc.gov/fris/) for Swift, Marsh, Torrence and Sandy Creek. An effective model is not available for Rocky Branch. Using HEC-RAS, the hydraulic model was executed at various discharges to identify the flow that would just fill the existing channel without overtopping its banks. This discharge was set as the top of bank discharge. The pre-restoration top of bank for Sandy Creek and Rocky Branch were calculated using Manning's equation based on cross-section and longitudinal surveys of the creeks conducted prior to restoration by NC State University and by engineering consultants contracted by Duke University, respectively. Because the gage is located a considerable distance downstream (approximately 1.3 and 0.8 miles, respectively) of the restoration projects at Sandy and Torrence creeks, the effective hydraulic model was also used to determine the discharge at the gage location that corresponds to the bankfull channel flowing full in the restoration project reach upstream.

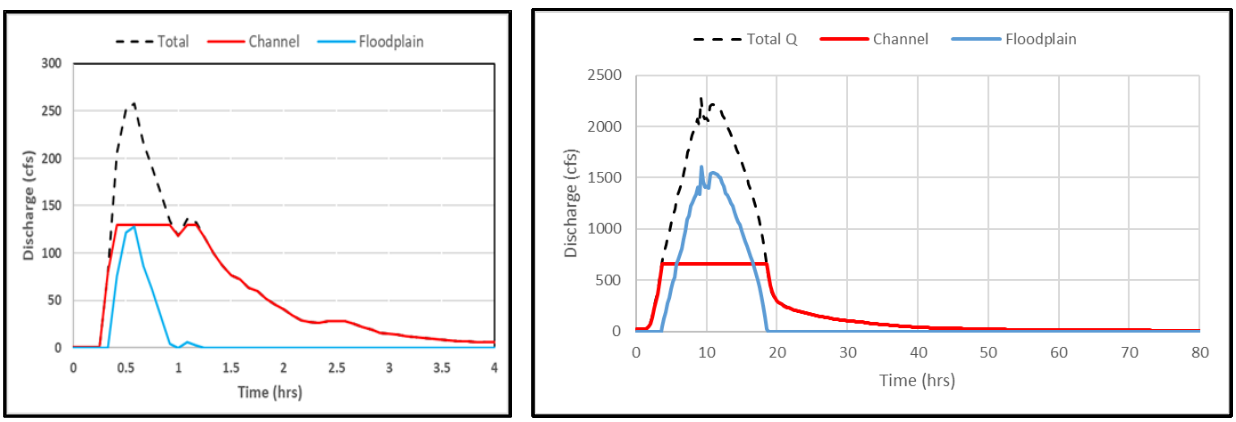


Figure 14. Hydrograph for storm event at Rocky Branch in June of 2006 and on Swift Creek in September 2008 showing flow for floodplain and channel.

Annual Flow Volume on the Floodplain

To determine the percentage of the flow volume that comes in contact with the floodplain in a typical year, the total flow volume that passes the gage and the volume of flow for each time period when total discharge exceeded either bankfull (post- restoration) or top of bank (pre-restoration) discharge were calculated. To evaluate floodplain flow volumes, high frequency 5-minute and 15-minute flow data was downloaded for each USGS gage. The high-frequency discharge data allows for a more accurate calculation of flow volume particularly for small streams with more urbanized watersheds that exhibit flashy hydrologic responses. Figure 14 above provides an example of a hydrograph for a storm that occurred in June of 2006 at Rocky Branch with a rapid time-to-peak and relatively short duration response (i.e. two-hour storm event with a 260 cfs maximum discharge). In contrast, Figure 14 also shows a much longer duration (20-hour) storm on Swift Creek with a peak of 2210 cfs that occurred in September 2008.

The high-frequency discharge data was filtered to only examine the flows that exceeded the bankfull and top of bank discharge. Floodplain flow was assumed to occur during any discharge in excess of the bankfull or top of bank flow being evaluated. For example, if the bankfull discharge is 70 cfs for the restored stream, any flow greater than 70 (e.g. 71 cfs) would be considered to have flow in contact with the floodplain. Next, the cumulative volume of flow for each storm event that exceeded the flow of interest and the annual flow volume on the floodplain were calculated by summing the incremental flow volumes.

The total annual flow volume at each USGS gage was calculated from the daily mean flow measurements rather than from the high-frequency flow data. The percentage of flow volume on the floodplain on an annual basis was then calculated as the ratio of the floodplain flow volume to the overall flow volume. For Rocky Branch, some of the 5-minute observations were missing during bankfull events so the event flow volume could not be calculated. The missing flow volumes were infilled by fitting a quadratic regression of daily maximum floodplain flow versus total floodplain flow volume for all storm events (r^2=0.74, see Appendix E).

Total Nitrogen Load Removed by the Floodplain

To estimate the total nitrogen loads that would be delivered to each stream reach, an event mean concentration (EMC) was calculated by averaging measured water quality data for each stream. Water quality data was obtained from the City of Raleigh for Marsh Creek and Rocky Branch, from the City of Charlotte for Torrence Creek, from USGS for Swift Creek and from Duke University (Richardson et al., 2011) for Sandy Creek. The overall EMC was then multiplied by the total annual flow volumes from the USGS gage to obtain an annual load in pounds. It should be noted that, assuming an overall EMC is very approximate and in reality the TN and TP concentrations likely vary widely over the range of flow conditions.

Nitrogen removal on the floodplain is only possible when discharge exceeds bankfull discharge. However, not all flow volume in excess of bankfull discharge will be treated by the floodplain and any surface depressions or wetlands present on the floodplain because high flow events can overwhelm the floodplain and bypass with very little contact time (Jordan et al., 2003; Kovacic et al., 2000). For example, high flow events in excess of a wetland’s storage capacity limit retention time and the thus decrease treatment efficiency (Kadlec and Wallace, 2008). To determine the nitrogen removal, the actual flow volume that can potentially be treated during a storm event was calculated. For this calculation, a potential storage of 12 inches was assumed across the floodplain based on the measured available floodplain area. Flow volume in excess of this depth was assumed to move through the system with negligible treatment occurring due to limited retention time. The assumed 12 inches of storage multiplied by the floodplain surface area to quantify an event-based treatment volume (see Figure 15). While this is likely an oversimplification of the hydrologic and biogeochemical processes occurring, the approach follows the general method used to calculate nutrient removal for the Chesapeake Bay Protocol (Schueler and Stack, 2012).

Assuming that the load is delivered proportional to flow (i.e. relatively constant influent TN concentration). The load that could be potentially treated was calculated by multiplying the total annual nitrogen load by the percentage of flow volume that could potentially be treated by the floodplain. The potential removal of total nitrogen from the floodplain was then calculated by multiplying the load subject to treatment by a removal efficiency. 20% was used by Schueler and Stack (2012) for the Chesapeake Bay Protocol and was implemented for this analysis.

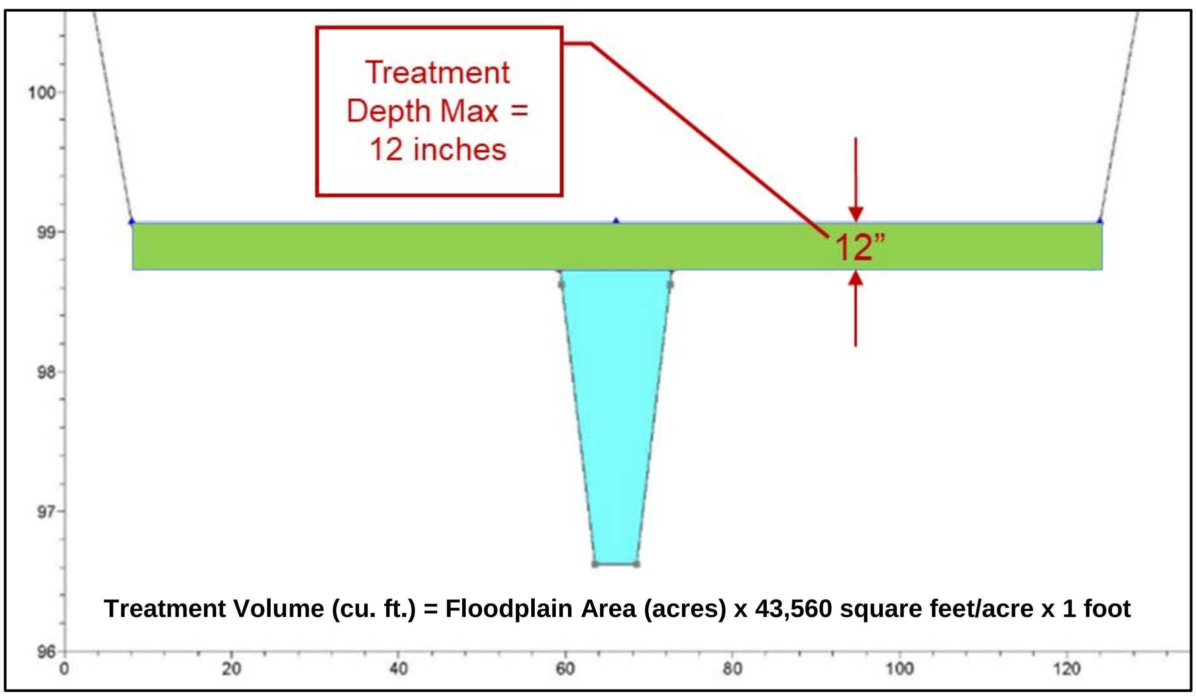


Figure 15. Floodplain treatment volume capped at 12 inches of flow depth.

The area of the available floodplain for the restored stream or for the stream reach at the USGS gage was measured using Arc GIS. The treatment volume was calculated by multiplying the floodplain area by the 1-foot depth. The annual total potential treatment volume was calculated for each year by summing all storm event volumes of less than or equal to the floodplain treatment volume. The treatment volume was then divided by the annual total flow volume that passes the gage to determine the percentage of the total flow that could potentially be treated.

Channel Size and Floodplain Area Sensitivity Analysis

Channel size has an impact on the frequency at which channel flow will access the floodplain. And once the water is on the floodplain, the size of the area that the water has to spread out will have an effect on the nitrogen treatment capacity. Therefore, in order to identify the possible range of total nitrogen removal that can be achieved by the five gaged streams, a sensitivity analysis of channel size combined with floodplain area was evaluated to determine the resulting % of total nitrogen load that could be removed. The analysis was conducted using R Statistical Software (R Core Team, 2016) and involved varying channel size and floodplain area to calculate the resulting % total nitrogen load removed. For each stream, a range of channel sizes was evaluated as a proportion of the predicted bankfull discharge based on the published rural North Carolina Piedmont regional hydraulic geometry relationships of watershed area to bankfull discharge (Doll et al. 2002). Each channel discharge tested ($Q_{departure}$) was defined as a proportion (or fraction) of the predicted regional curve bankfull discharge ($Q_{expected}$). $Q_{departure}$ values of 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2 times $Q_{expected}$ were tested. In addition, the floodplain area was varied by changing the length of channel and the floodplain width. The channel length started with 500 feet and was increased by increments of 1000 feet. Channel floodplain width started at 50 feet and was increased by increments of 50 feet. Both variables were increased until the resulting % total nitrogen removed reached a point of diminishing returns. The floodplain flow volume, treatment volume, nitrogen load and treatment efficiency were all calculated according to the procedures outlined in the methods above.

Results

An example of the floodplain delineation to determine floodplain area that was completed using ArcGIS is provided for Sandy Creek in Figure 16 below. The resulting floodplain area for each stream is provided in Table 18. In addition, the floodplain treatment volume that corresponds to a flow depth of 1 foot on the delineated floodplain area is also provided in Table 18.

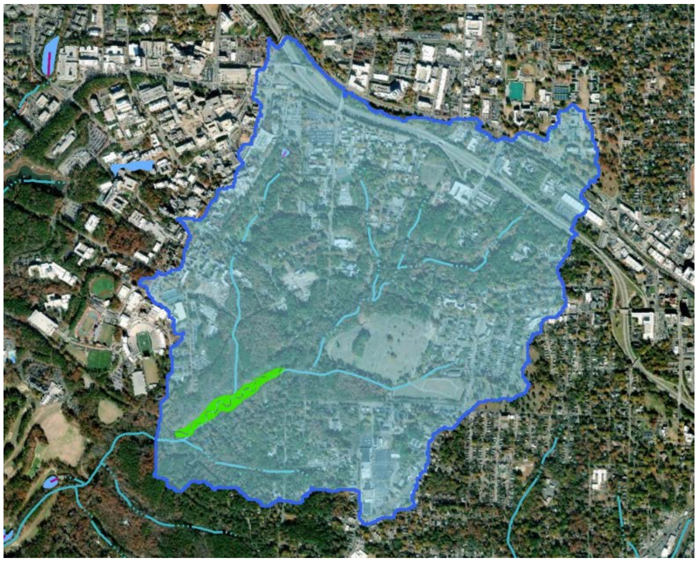


Figure 16. Sandy Creek watershed (1.72 sq. mi.) shown in blue and the floodplain area (8.1 acres) associated with the Sandy Creek Phase I stream restoration project show in green.

Table 18. Floodplain area, floodplain percent of watershed ratio, and floodplain treatment volume.

Stream	Watershed Area (sq.mi.)	Floodplain Area (acres)	% of Watershed Area	Treatment Volume (cu.ft.)
Marsh Creek	6.84	17	0.39%	740,500
Rocky Branch	0.98	8.4	1.34%	365,900
Sandy Creek	1.72	8.1	0.70%	352,800
Swift Creek	21	41.3	0.31%	1,799,000
Torrence Creek	3.6	5.2	0.23%	226,500

The bankfull discharge for the restored condition and the top of bank discharge associated with the pre-restoration (or existing) condition for the five gaged streams is provided below in Table 19. For Marsh Creek, the bankfull discharge calculated from the field-survey data was too large and the one-year storm discharge estimated from flood frequency analysis was used for the gage station flow analysis instead. The results of the flood frequency analysis of annual peak flows for Marsh Creek is provided in Figure 17 below.

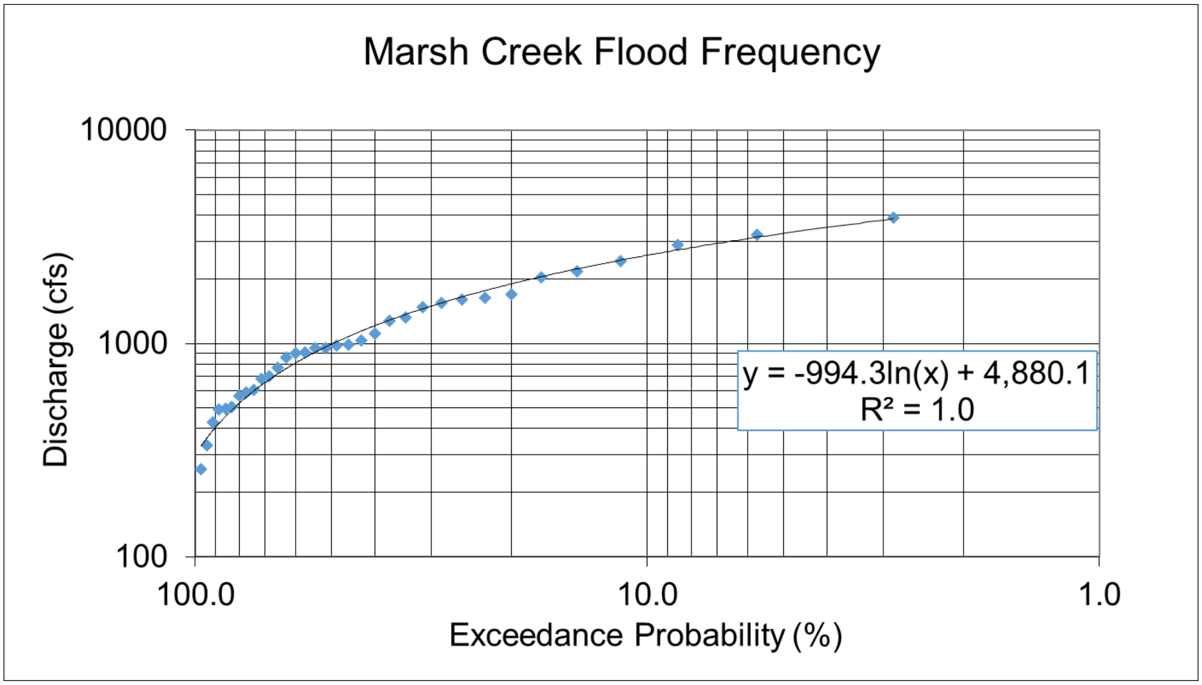


Figure 17. Annual peak discharge flood frequency analysis for Marsh Creek, Raleigh, NC.

The average number of storm events accessing the floodplain annually and the total average percentage of flow volume on the floodplain all five gages are also presented in Table 19. The average number of storm events that accessed the floodplain at bankfull stage ranged from 4.6 at Swift Creek to as many as 18.2 at Rocky Branch with an average of 12.1 events exceeding bankfull discharge each year. On average, these bankfull or greater events resulted in 9.9% of the flow being exposed to the floodplain with Torrence Creek at 6.2% and Rocky Branch with the highest percentage at 16.9%. For the pre-restoration top of bank scenario, only Swift Creek experienced any storm events exceeding the top of bank discharge during the ten-year period of 2008 to 2017. On average, there were 2.3 storms per year above top of bank at Swift Creek in its un-restored condition. For post restoration, Swift Creek experienced an average of 4.6 flow events above bankfull discharge. The range of annual percentage of total flow that could potentially be treated (i.e. flow depth less than 12 inches) was 1.0 % at Swift Creek to 5.7 % at Rocky Branch with an average of 2.3 %, which was a substantial decline over the 9.9% average of flow that is exposed to the floodplain.

Table 19. Summary of the average annual number of storm events where bankfull and top of bank discharge were exceeded and the percent of the average annual total flow volume that is exposed to the floodplain and that is potentially treated by the floodplain.

Stream	Top of Bank *Discharge (cfs)	# Events >Qtob	Bankfull *Discharge (cfs)	# Events >Qbkf	% Volume on Floodplain	% Treatment Volume
Marsh Creek	2300	0	300	9.1	9.4%	2.0%
Rocky Branch	335	0	130	18.2	16.9%	5.7%
Sandy Creek	1130	0	150	10.9	7.7%	1.4%
Swift Creek	1500	2.3	660	4.6	9.0%	1.0%
Torrence Creek	376	0	70	17.8	6.2%	1.7%
Average				**12.1**	**9.9%**	**2.3%**

The EMC for total nitrogen that was estimated by averaging measured water quality data at each site and the average annual load is provided below in Table 20.

Table 20. Total nitrogen concentration and unit load per watershed acre.

Stream	Watershed Area (sq.mi.)	TN Concentration (mg/L)	TN Load (lbs/ac/yr)
Marsh Creek	6.84	0.78	3.36
Rocky Branch	0.98	1.83	12.36
Sandy Creek	1.72	0.835	9.17
Swift Creek	21	0.62	1.99
Torrence Creek	3.6	0.556	2.48

The load of nitrogen that is delivered in the treatment volume as a result of applying the EMC values ranges from 101 to 437 lbs/yr (see Table 21). However, with the 20% removal efficiency applied, the resulting total nitrogen load removed ranges from as low as 20 lbs/year at Torrence Creek up to 120 pounds/year at Swift Creek with an average of 63 lbs/year for all five streams. This equates to a percentage of total nitrogen removal rate of 0.3% at Swift and Torrence creeks to as high as 1.1% at Rocky Branch. The ratio of watershed to floodplain for these five streams ranges from 77:1 to over 440:1. It is generally assumed that in order to provide water quality benefits the wetland area should occupy at least 1% of the watershed area to allow adequate retention time (Jordan et al., 2007). Thus, the 20% removal efficacy could over-estimate the removal rate. As such, Schueler and Stack (2012) recommend reducing the treatment efficiency if the watershed to floodplain ratio is less than 100:1.

The TN load and the % of TN removed from the USGS gage data analyses were also compared to the load estimated using STEPL for the Chesapeake Bay Protocol (CBP) 3 and the associated

% total nitrogen removed for Sandy and Torrence creeks (see Table 21). In addition, the total pounds removed according to Protocol 3, which reflects the adjustment required for floodplain to watershed area ratios of less than 1% is also reported in Table 21. The percent removal for Sandy Creek matches the protocol 3 removal at 0.3%, however, the adjusted pounds removed is less for CBP because the STEPL load is significantly less than the EMC-based load and due to the floodplain size adjustment. For Torrence Creek, the STEPL load is more than double the EMC load, however, flood frequency analysis results in a higher removal rate of 3% compared to only 1.5% for the CBP estimate. Despite the increased removal rate, the total pounds removed based on the EMC is only half that of the CBP 3 estimated load removed despite the deduction applied for floodplain area size.

Table 21. Estimates of total nitrogen load, and load removed by the floodplain at five gaged USGS streams compared to estimates produced by the Spreadsheet Tool for Estimating Pollutant Load (STEPL) and the estimated % total nitrogen removal as determined.

	USGS Gage Data Analysis (2008-2017)					**Existing Protocol 3**		
Stream	**TN Load (lbs/yr)**	**Floodplain Load (lbs/yr)**	**Treatment Load (lbs/yr)**	**Total Load Removed (lbs/yr)**	**% N Removed**	**STEPL Load (lbs/yr)**	**%N Removed**	**Total Load Removed (lbs/yr)***
Marsh	14726	1383	291	58	0.4%			
Rocky Branch	7752	1367	437	87	1.1%			
Sandy	10100	822	141	28	0.3%	6393	0.3%	14.2
Swift	26699	2537	268	120	0.4%			
Torrence	5719	371	101	20	0.3%	12428	1.5%	41
Average	**12999**	**1296**	**247**	**63**	**0.5%**			

* The reported total load removed reflects the correction that is applied based on the floodplain area to watershed area ratio

The relatively low removal percentages (0.2 to 1.1%) found for these five streams is the result of the high flow volumes entering the floodplain during storm events, which limits retention time and results in most of the flow "bypassing" treatment in the floodplain wetlands. A majority of the flow occurs during several high flow events each year, and drives the very low removal rates. An example of this is shown for Torrence Creek in Figure 18. For the year 2010, the majority of the flow volume in the floodplain (95%) occurred in just four major events that would have mostly exceeded the treatment capacity of the floodplain.

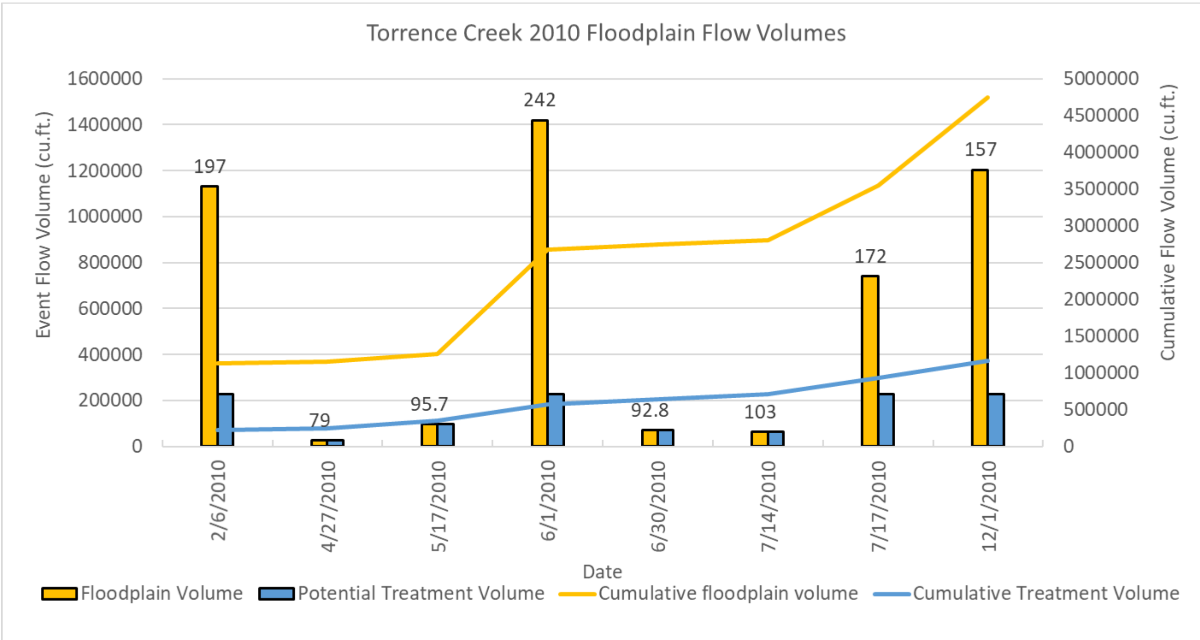
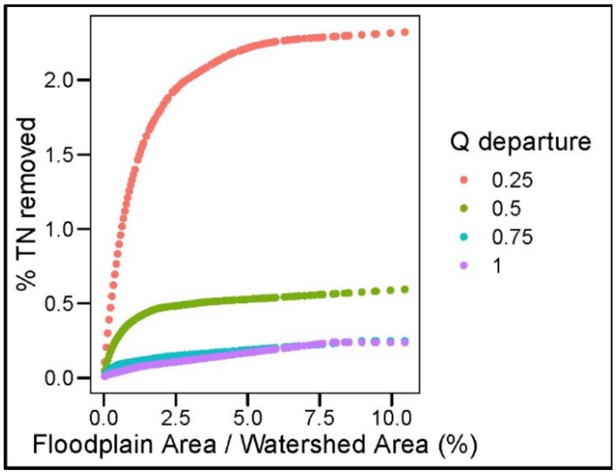


Figure 18. Cumulative and event volume for Torrence Creek in 2010. Maximum discharge for each event and percentage of floodplain volume that could potentially be treated for each event is also shown based on the assumed 5.2 acre-feet of treatment volume.

The results of the sensitivity analysis for each stream is provided in the graphs below (see figures Figure 19 and Figure 20). In addition, comparisons of the five gaged streams for a $Q_{departure}$ of 0.25, 0.5 and 1 times the $Q_{predicted}$ are provided in Figure 21. The sensitivity analysis reveal as expected that as the $Q_{departure}$ is reduced and the floodplain area to watershed area % is increased, that the % total nitrogen removal increases. Due to a small watershed size combined with high percent impervious (40%) that produces the highest annual occurrence of flows exceeding the bankfull discharge, the Rocky Branch floodplain produces the highest potential % TN removal rates (>7% TN rate for $Q_{departure}$=0.25). Torrence Creek, in contrast produces the lowest potential removal rates with a maximum of just over 2%. This is likely due to Torrence having a lesser volume of flow reaching the floodplain. The maximum discharge recorded at Torrence Creek during the 10-year study period is 244 cfs, which is only 1.08 times the $Q_{expected}$ value of 227 cfs for a 3.6 square mile watershed. As such, nitrogen treatment curves are not shown for $Q_{departure}$ ratios of greater than 1 at Torrence Creek. The restored stream at Torrence carries approximately 70 cfs at bankfull, which is equal to a $Q_{departure}$ ratio of 0.3. This smaller channel size should help to maximum the removal percentage for the available floodplain. Marsh, Sandy and Swift creeks produce very similar removal curves with the highest potential removal rate just above 4%.



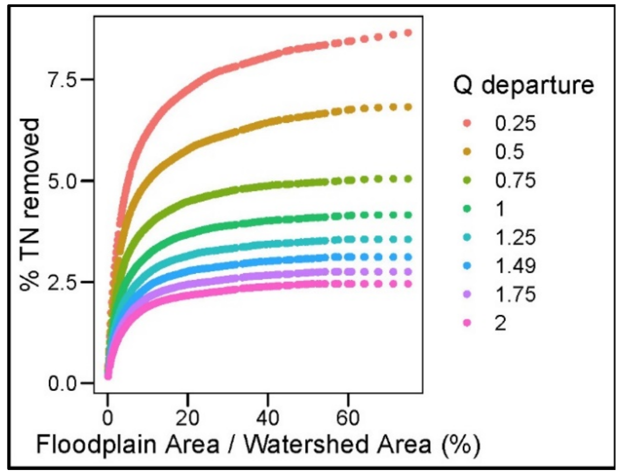


Figure 19. % TN removed estimates based on a range of floodplain area to watershed area ratios and channel sizes as indicted by $Q_{departure}$ for Torrence (left) and Rocky Branch (right) creeks.

Table 22. Basic watershed and floodplain characteristics and floodplain flow and total nitrogen removal percentages for Torrence and Rocky Branch creeks.

Torrence		**Rocky Branch**
3.6	Watershed Area (sq. mi.)	0.98
16	% Impervious	40
5.2 acres = 0.23%	Floodplain Area & % of Watershed Area	8.4 acres = 1.3%
0.31	$Q_{departure}$ ratio	1.44
17.8	Average $Q>Q_{bkf}$ events	18.2
1.7%	% Volume treated	5.7%
0.3%	%TN Removed	1.1%

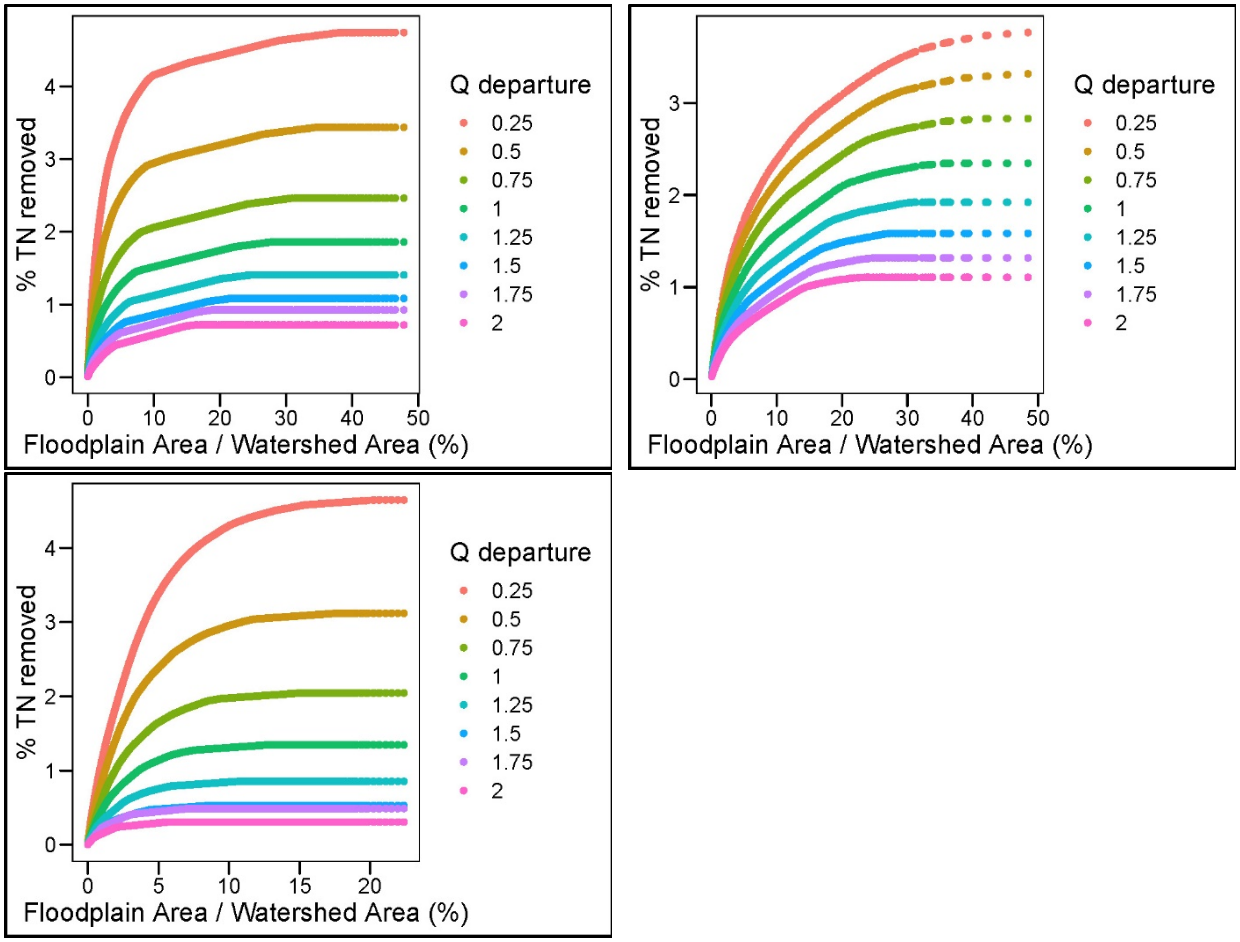


Figure 20. % TN removed estimates based on a range of floodplain area to watershed area ratios and channel sizes as indicted by $Q_{departure}$ for Marsh (upper left), Sandy (upper right) and Swift (bottom) creeks.

Table 23. Basic watershed and floodplain characteristics and floodplain flow and total nitrogen removal percentages for Marsh, Sandy and Swift creeks.

	Marsh	**Sandy**	**Swift**
Watershed Area (sq. mi.)	6.84	1.72	21
% Impervious	25	17	16
Floodplain Area & % of Watershed Area	17 acres = 0.4%	8.1 acres = 0.7%	41.3 acres = 0.3%
$Q_{departure}$ ratio	0.84	1.08	0.83
Average $Q>Q_{bkf}$ events	9.1	10.9	4.6
% Volume treated	2.0%	1.4%	0.9%
%TN Removed	0.4%	0.3%	0.2%

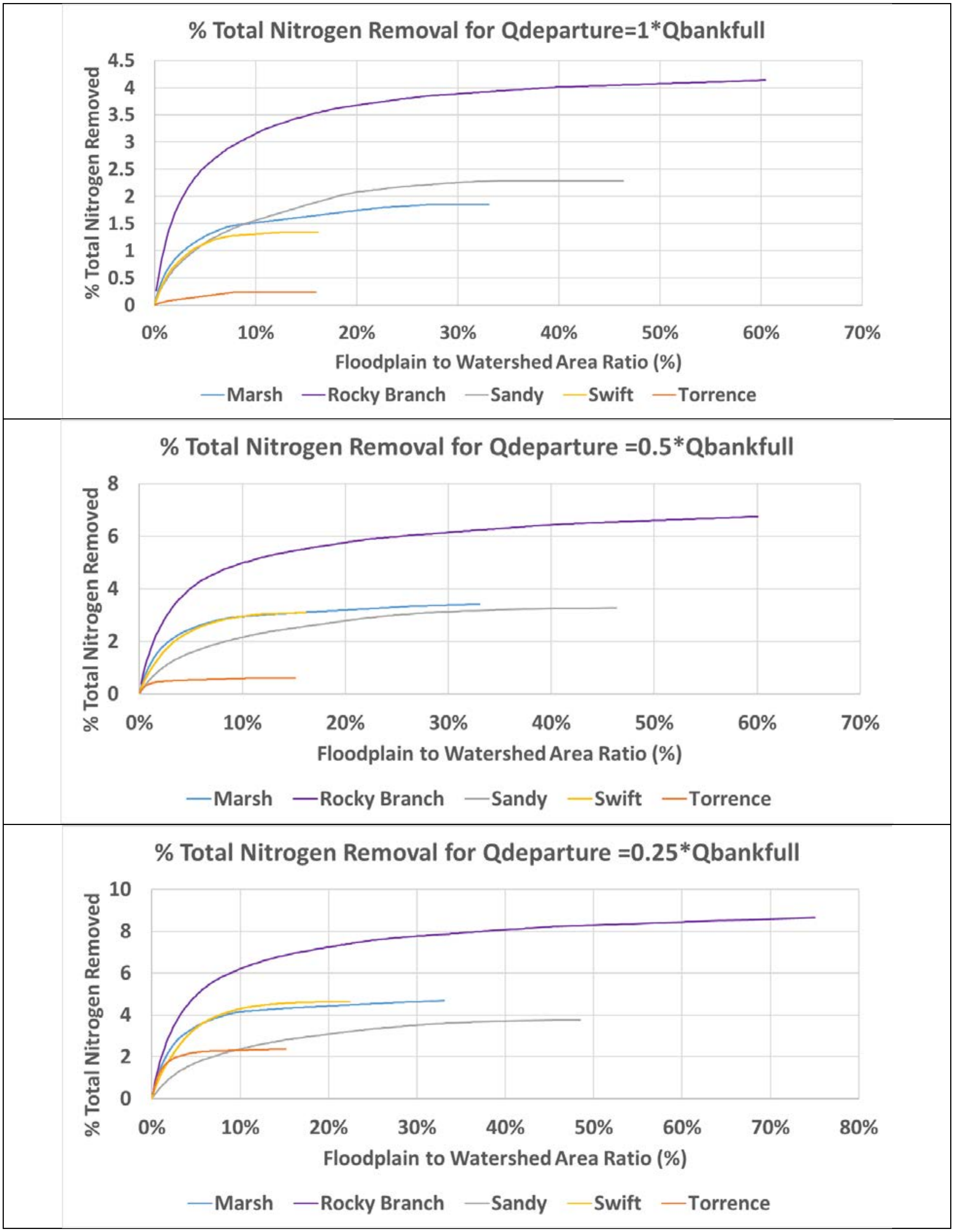


Figure 21. Percent of total nitrogen load removed in relation to the ratio of floodplain area to watershed area (%) for channel sizes that can carry 0.25, 0.5 and 1 times the expected bankfull discharge as estimated from the hydraulic geometry regional curve for rural North Carolina streams (Doll et al., 2002).

Discussion and Conclusions

In reality, the assumed 20% TN treatment efficiency of the floodplain may be an overestimate of the actual treatment capability for some floodplains due to stormwater inflow from adjacent culverts that may fill up any wetlands and depressions on the floodplain prior to overbank flow occurring. Also, it is possible that much of the flow volume would not be in contact with the floodplain long enough to receive significant treatment. In contrast, during lower volume overbank events the floodplain may be able to potentially treat a majority of the floodplain flow. However, there is a wide range of removal rates reported for TN. For example, EPA reported 28% removal efficiency for stormwater wetlands (USEPA, 1999), while Lee et al. (2009) reports 45% removal of TN and other have reported higher rates. If a higher removal efficiency is used (45%), this would result in a range of 0.4% to 2.6% removal efficiency.

Revised Protocol

Following the application of the CBP to the four case study sites, gage analysis, and monitoring, NCSU BAE proposes the following revisions to the CBP for consideration for application to Nutrient Crediting for Stream Restoration in North Carolina.

Revised Protocol 1

Protocol 1 provides the greatest nutrient removal credit for restoration projects. Bank stabilization and prevention of streambank erosion has the greatest impact on the prevention of nutrient introduction to downstream waters. As seen in the application of the Torrence Creek case study, with pre- and post-restoration data, streambank erosion was minimized following restoration and reduced TN, TP, and sediment loads by at least 98%. As such, the greatest emphasis should be placed on maximizing credit under Protocol 1.

Following application of CBP 1, methods and reduction values are deemed appropriate for crediting in North Carolina. BANCS or BSTEM methods provide are the most applicable and reasonable for consultants and regulators to implement. However, soil concentration values provided by the CBP are too high for North Carolina soils. In their place, the values suggested by Tetra Tech should be implemented for use in NC. Moreover, concentrations from this study may be combined with Tetra Tech's analysis of Piedmont streambank concentrations to expand the database to develop new standards. Similar methods to those employed by Tetra Tech can be used to develop standard concentrations for each of North Carolina's ecoregions.

Tetra Tech concentration values were applied to Protocol 1 (Table 4). Using Tetra Tech concentrations, TN credit was reduced by 25% and TP credit was reduced by 78%. While there is a reduction in available credit, using NC specific streambank concentrations would be more prudent.

Revised Protocol 2/3

Following analysis of CBP 2 and 3, removal rates associated with the hyporheic box appear inflated due to the allowed dimensions of the hyporheic box. As previously discussed, the average depth to a confining clay layer among all four case study sites was 2 feet. Further, Protocol 3 resulted in the removal of less than 0.1 lb TN/ac/yr and 0.03 lb TP/ac/yr among all four case study sites. It was determined that the level of effort necessary for both designers and regulators to calculate and cross-check credits, for Protocol 3 in particular, was inappropriate for the level of removal actually realized.

Consequently, it is proposed that CBP 2 and 3 be combined into a single protocol to calculate nutrient removal in the streambed and in riparian zones using a designated areal uptake rate. For the streambed portion, the constraint that bank height ratios be less than or equal to 1.0 would remain from the CBP. Lammers and Bledsoe (2017) collected separate denitrification rates for streambed and riparian zones from 98 peer-reviewed studies covering 249 stream systems including agricultural, urban, and reference streams. The authors reported median denitrification rates for stream and riparian zones as 1.85 and 1.01 mg $N/m^2/hr$, respectively. As this recently published study includes the most robust analysis of stream denitrification rates in various settings, their median rates are proposed for use in revised Protocol 2/3.

When applied to the four case study streams, the revised Protocol 2/3 results in an average of 3% reduction in watershed N load (Table 24). TN credit assigned from the revised protocol ranges from 527-875.8 lb/yr. When compared to CBP 1, the revised protocol reduces TN credit at Higgins Trail and Austin Creek, but increases credit at Sandy Creek and Torrence Creek (Table 25). Under the revised Protocol 2/3, a smaller denitrification rate is used resulting in less credit being given to streambed denitrification; however, a constant denitrification rate is given to the floodplain, resulting in a much larger credit when compared to CBP 3.

No credit is given for TP removal in the proposed revised Protocol 2/3. TP credit given by CBP 3 is minimal. Further, uptake of phosphorus by vegetation and storage is only temporary, and removed P can be reintroduced to the system, resulting in no net difference.

Table 24. Revised Protocol 2/3 results.

Stream	Higgins Trail	Austin Creek	Sandy Creek	Torrence Creek
L (ft)	3225	3074	2461	1620
L (m)	983	937	750	494
W_{bkf} (ft)	19	34	22	24
W_{bkf} (m)	5.8	10.4	6.7	7.3
A_{hb} (m^2)	5692.6	9709.9	5030.0	3612.1
$r_{denit,stream}$ (mg N/m^2/hr)	1.85	1.85	1.85	1.85
Streambed N Removed (kg/yr)	92.3	157.4	81.5	58.5
Streambed N Removed (lb/yr)	**203.4**	**346.9**	**179.7**	**129.1**
Floodplain Area (ac)	4.1	6.7	8.1	5.2
Floodplain Area (m^2)	16592.2	27114.0	32779.7	21043.7
$r_{denit,riparian}$ (mg N/m^2/hr)	1.01	1.01	1.01	1.01
Floodplain N Removed (kg/yr)	146.8	239.9	290.0	186.2
Floodplain N Removed (lb/yr)	**323.6**	**528.9**	**639.4**	**410.5**
Total N Removed (lb/yr)	**527.0**	**875.8**	**819.1**	**539.5**
% Removed	**2%**	**4%**	**4%**	**2%**

Table 25. CBP 2 and Revised Protocol 2/3 comparisons.

Site	TN (lb/yr)			TP (lb/yr)			Sediment (ton/yr)		
	CBP	Revised	Δ	CBP	Revised	Δ	CBP	Revised	Δ
Higgins Trail	772.6	6	-766	6.4	1.6	-5	3.7	3.5	0
Austin Creek	1235.9	74	-1162	46.3	19.1	-27	41.9	41.4	-1
Sandy Creek	684.2	8	-676	9.0	2.2	-7	5.0	4.7	0
Torrence Creek	588.6	61	-528	47.7	15.7	-32	69.8	68.1	-2

Eliminate Protocols 2 and 3

Much uncertainty exists in the literature about (1) the effectiveness of stream restorations at providing a net removal of TN and TP compared to pre-restored conditions, (2) the ability to quantify nutrient removal, and (3) predicting spatial and temporal changes in removal. Boano et al. (2014) explored uncertainty in hyporheic exchange and listed 10 main questions driving uncertainty. These unsolved questions range from how to scale up individual measured uptake rates to a reach scale to microbiology questions surrounding denitrifying bacteria populations to hydrodynamic processes in pore water where nutrient removal would take place. Consequently, rather than assign a credit based on an assumed net removal extrapolated from scaled observations, it may be more prudent to only provide credit under Protocol 1 until the science behind the impacts of restoration on the hydrologic, geologic, geomorphic, geochemical, and ecological processes that influence in-stream and riparian nutrient removal.

Total Credit for Proposed Revisions

TN and TP credits were calculated for each of the proposed revisions and summed to compare total credits against the CBP.

Revised Protocol 1 and 2/3

If credit is given for both revised protocols 1 and 2/3, TN credit ranges from 533 – 950 lb/yr while TP credit ranges from 2 – 19 lb/yr (Table 26). Under the CBP, Higgins Trail TN credit represented a 40% reduction in the watershed load, while the revisions reduce that to 28%. Austin Creek, Sandy Creek, and Torrence Creek percent removal of watershed loads remains relatively unchanged when compared to the total credit from the CBP. As previously discussed, Sandy Creek and Torrence Creek receive more TN credit with the revised protocols. The portion of TP credit associated with CBP 3 is removed across all sites, while Protocol 1 credit for TP is reduced due to using lower streambank sediment TP concentrations in the calculations.

Table 26. Total credit for revised protocols 1 and 2/3.

Protocol	Credit	Higgins Trail	Austin Creek	Sandy Creek	Torrence Creek
Watershed Loads + Erosion	TN (lb/yr)	1916	22738	6431	12549
	TP (lb/yr)	329	4741	1122	2242
	Sediment (ton/yr)	14	88	21	70
Protocol 1	TN Credit (lb/yr)	6	74	8	61
	TP Credit (lb/yr)	2	19	2	16
	Sediment Credit (ton/yr)	4	41	5	34
Protocol 2/3	TN Credit (lb/yr)	527	876	819	540
Total Credit	**TN Credit (lb/yr)**	**533**	**950**	**827**	**600**
	TP Credit (lb/yr)	**2**	**19**	**2**	**16**
	Sediment Credit (ton/yr)	**4**	**41**	**5**	**34**
% Removed	**TN**	**28%**	**4%**	**13%**	**5%**
	TP	**0.5%**	**0.4%**	**0.2%**	**0.7%**
	Sediment	**25%**	**47%**	**22%**	**49%**

Revised Protocol 1 Only

Should only Protocol 1 assign credit for stream restorations, credit would be diminished greatly; however, bank stabilization methods are well known and the physical processes of bank erosion and stabilization make efforts to quantify net changes in nutrient introduction to waters easier. Revised Protocol 1 would result in TN credit of 6 – 74 lb/yr due to prevented erosion and TP credit would range from 2 – 19 lb/yr (Table 27). While these numbers are much smaller than aforementioned credits with other protocols, it is important to note that confidence in properly quantifying and accounting for reductions associated with protocol 1 is much higher.

Table 27. Total credit for revised protocol 1 only.

Protocol	**Credit**	**Higgins Trail**	**Austin Creek**	**Sandy Creek**	**Torrence Creek**
Watershed Loads + Erosion	TN (lb/yr)	1916	22738	6431	12549
	TP (lb/yr)	329	4741	1122	2242
	Sediment (ton/yr)	14	88	21	70
Protocol 1	TN Credit (lb/yr)	6	74	8	61
	TP Credit (lb/yr)	2	19	2	16
	Sediment Credit (ton/yr)	4	41	5	34
% Removed	**TN**	**0.3%**	**0.3%**	**0.1%**	**0.5%**
	TP	**0.5%**	**0.4%**	**0.2%**	**0.7%**
	Sediment	**25%**	**47%**	**22%**	**49%**

Conclusions

The existing CBP provides a first attempt to assign nutrient removal credits to stream restoration. As the stream restoration field is currently a $1 billion/yr industry and growing, interest in providing nutrient credits in addition to mitigation credits will also continue growing. This study applied the existing CBP to four case study streams to (1) assess credit opportunities for restored streams in NC, (2) determine level of effort required for application of the protocol, (3) identify areas for improvement in the existing protocol, and (4) propose potential revisions to the CBP for possible implementation by NC DWR. The following are the main conclusions reached in this study:

(1) Applying the Chesapeake Bay Protocol to four case study sites, comparing restored and unrestored reaches, resulted in TN removal credit of 589 – 1,236 lb/yr and TP credit ranging from 6 – 48 lb/yr. The main factor influencing TN credit in the existing CBP is

Protocol 2, a continuous denitrification rate applied to a theoretical hyporheic box. TP credit is mainly determined by preventing streambank erosion accounted for in CBP 1.

(2) CBP Protocol 1 assigns a 50% efficiency adjustment factor to credit. This study found predicted streambank erosion reductions ranging from 44-98%. The greatest estimated reduction in streambank erosion was at the only case study site with pre- and post-restoration data available.

(3) Observed sediment TN and TP concentrations more closely aligned with values reported in the 2013 Tetra Tech report to NC DWR. It is recommended that NC DWR use NC specific concentrations while following a similar method to Tetra Tech to develop specific concentrations for the Mountain and Coastal Plain ecoregions of NC.

(4) Protocol 2 was found to overestimate the hyporheic box based on depth. TN credit assigned via the original CBP ranged from 470-1,133 lb/yr. Case study sites were assessed for the presence of a confining layer below riffles. Average depth to confining layer was 2 feet instead of 5 ft prescribed by CBP 2.

(5) Baseflow monitoring at two case study sites found conflicting results. Higgins Trail significantly reduced NO3-N and TP concentrations. TN and TP concentrations at Austin Creek increased between upstream and downstream locations, albeit changes were not statistically significant and the duration of monitoring was too short to document trends with an acceptable level of uncertainty.

(6) Application of CBP 3 was labor intensive and disjointed. TN credit ranged from 8-41 lb/yr while TP credit ranged from 3-12 lb/yr. Treatment efficiency is determined using curves provided by the CBP; however, little resolution at the lower end of curves, where most restoration projects will lie, results in interpolation. Further, CBP resulted in little overall credit when compared to other protocols.

(7) A flood flow frequency analysis was performed to compare observed hydrologic connectivity to floodplains to estimated connectivity in CBP 3. USGS gage data from 5 streams was analyzed and load reductions were computed using water quality data provided by local partners. Predicted TN load reductions were similar to those predicted by CBP 3. New curves were produced with higher resolution at a more reasonable practice-based scale.

(8) Potential revisions to the CBP include (1) retaining CBP 1 with NC specific streambank concentrations similar to those reported in the 2013 Tetra Tech report and combining CBP 2 and 3 to calculate an areal denitrification partitioned by streambed area and floodplain

area or (2) allowing credit solely based on prevented streambank erosion following CBP 1 with NC specific streambank concentrations.

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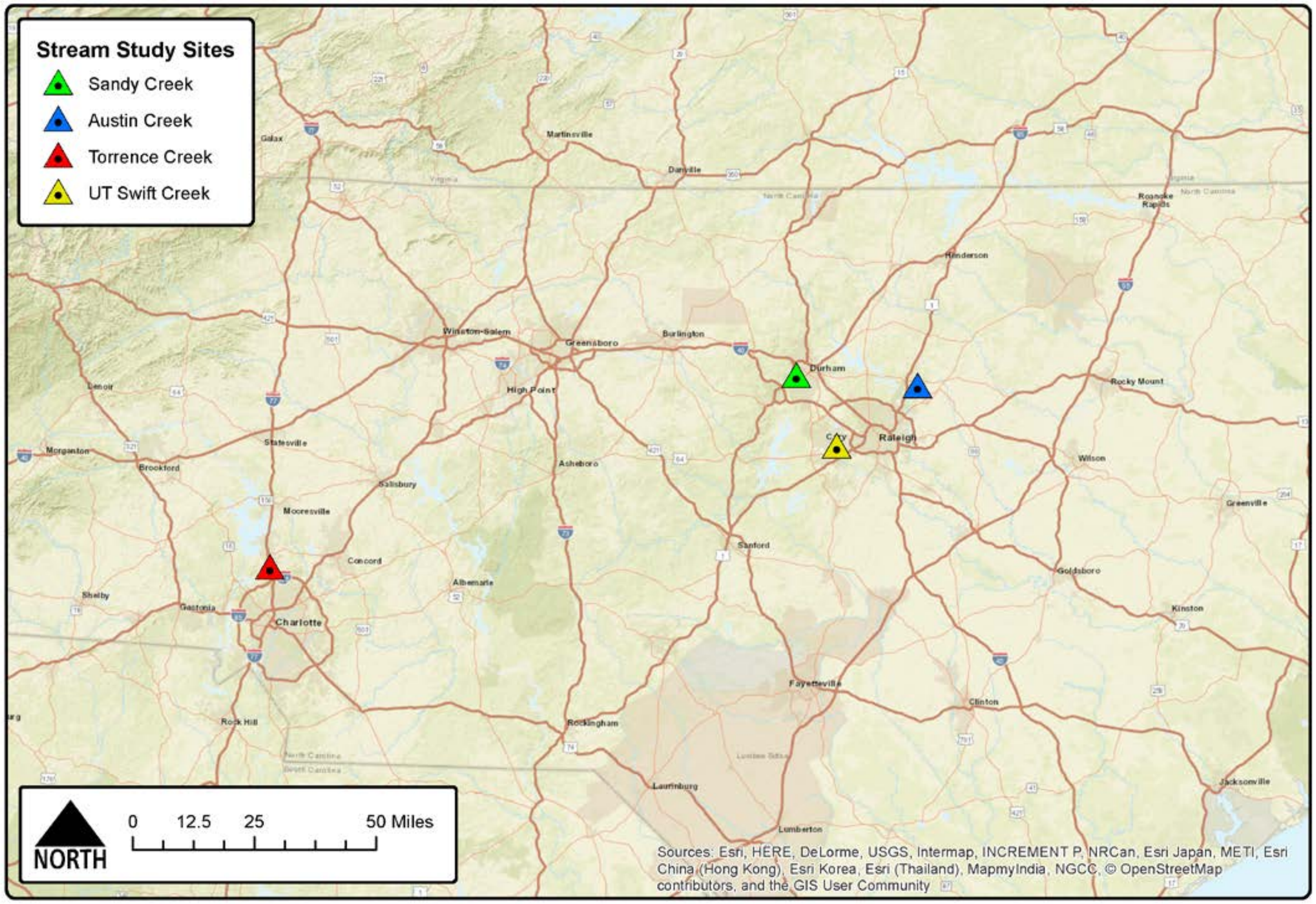
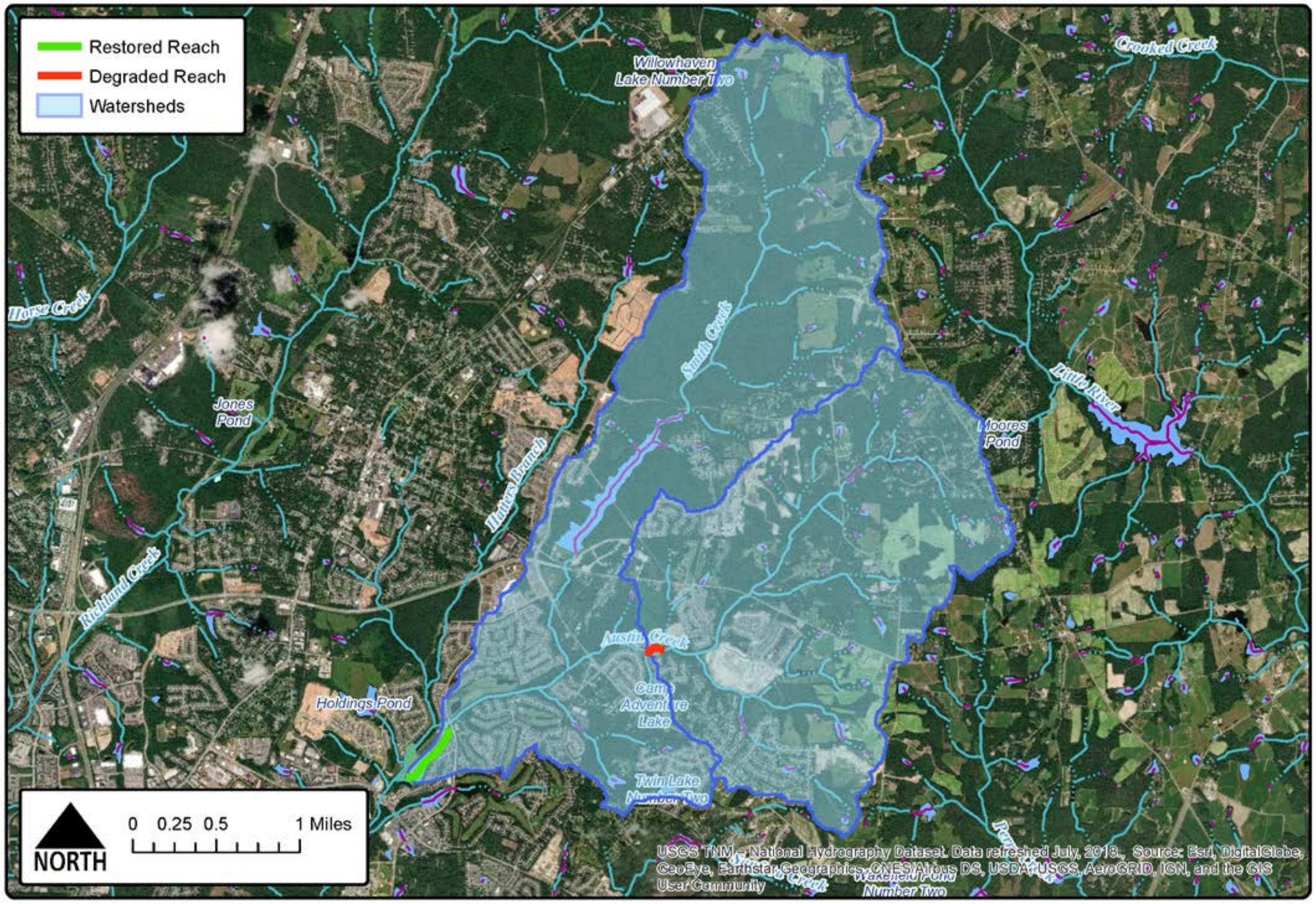
Appendices

Appendix A: Maps, Figures, and Photos

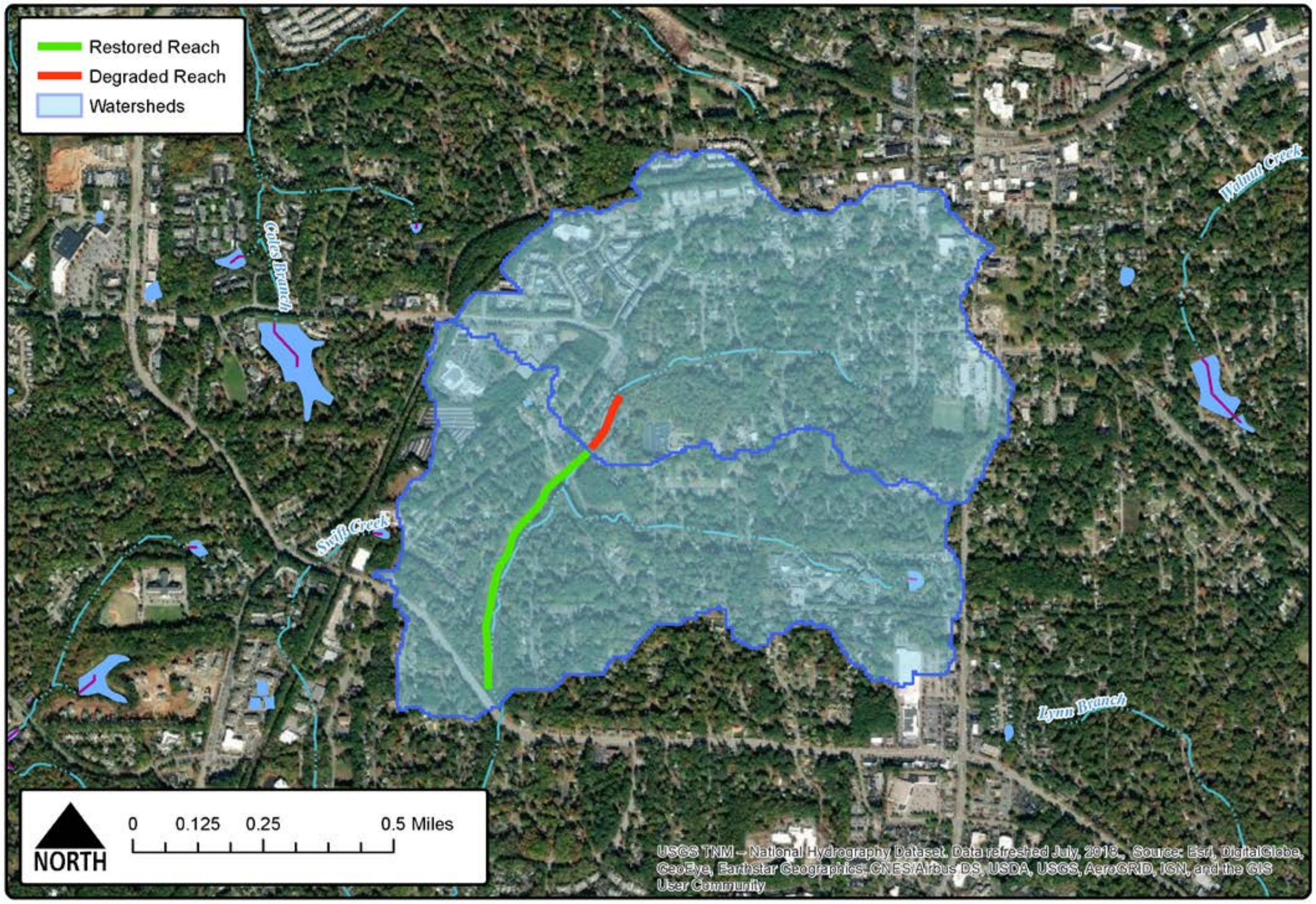


NC DEQ Evaluation of Nutrient Reduction Crediting Strategies for Stream Restoration
Stream Study Sites



NC DEQ Evaluation of Nutrient Reduction Crediting Strategies for Stream Restoration

Austin Creek - Wake Forest, NC



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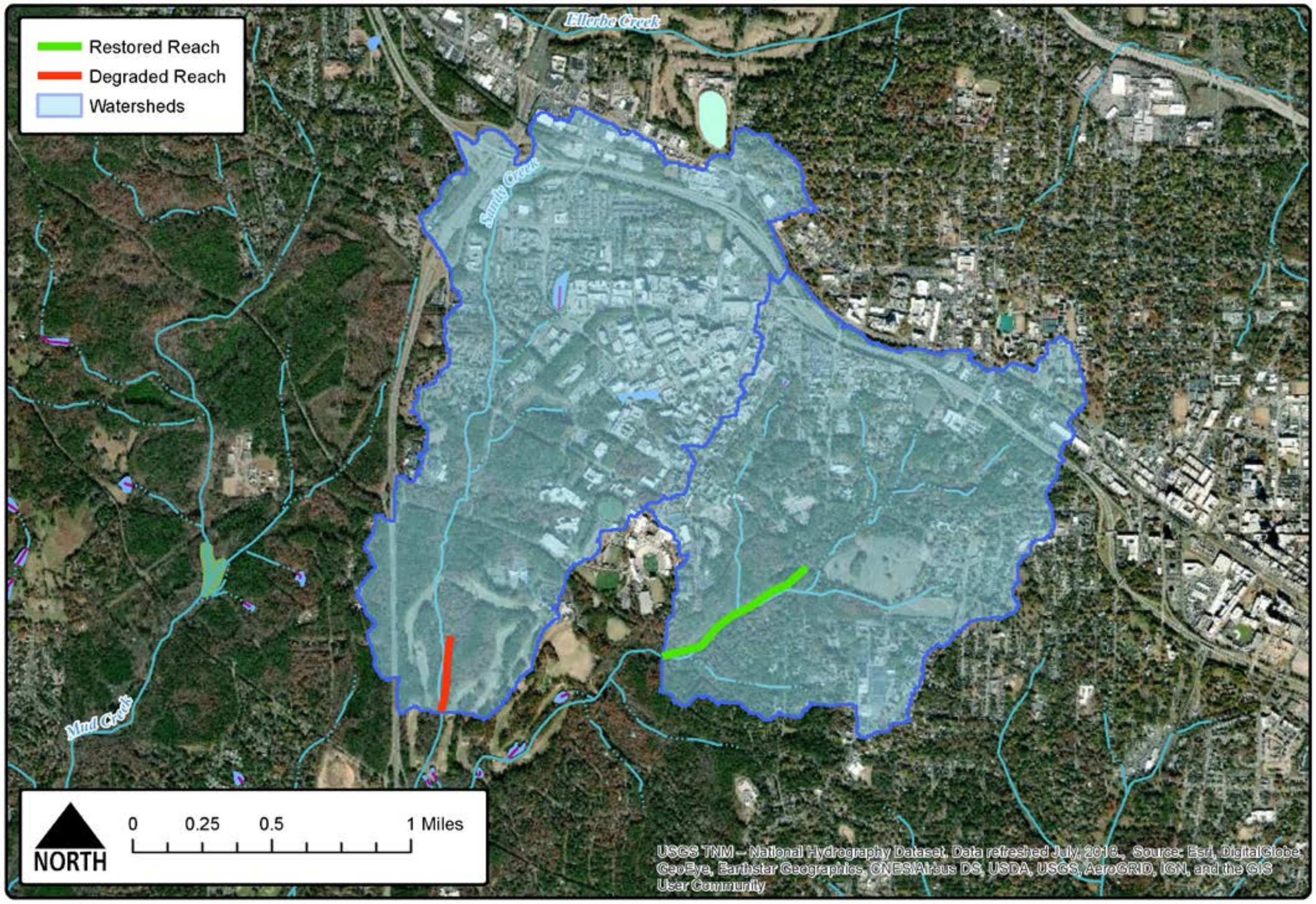
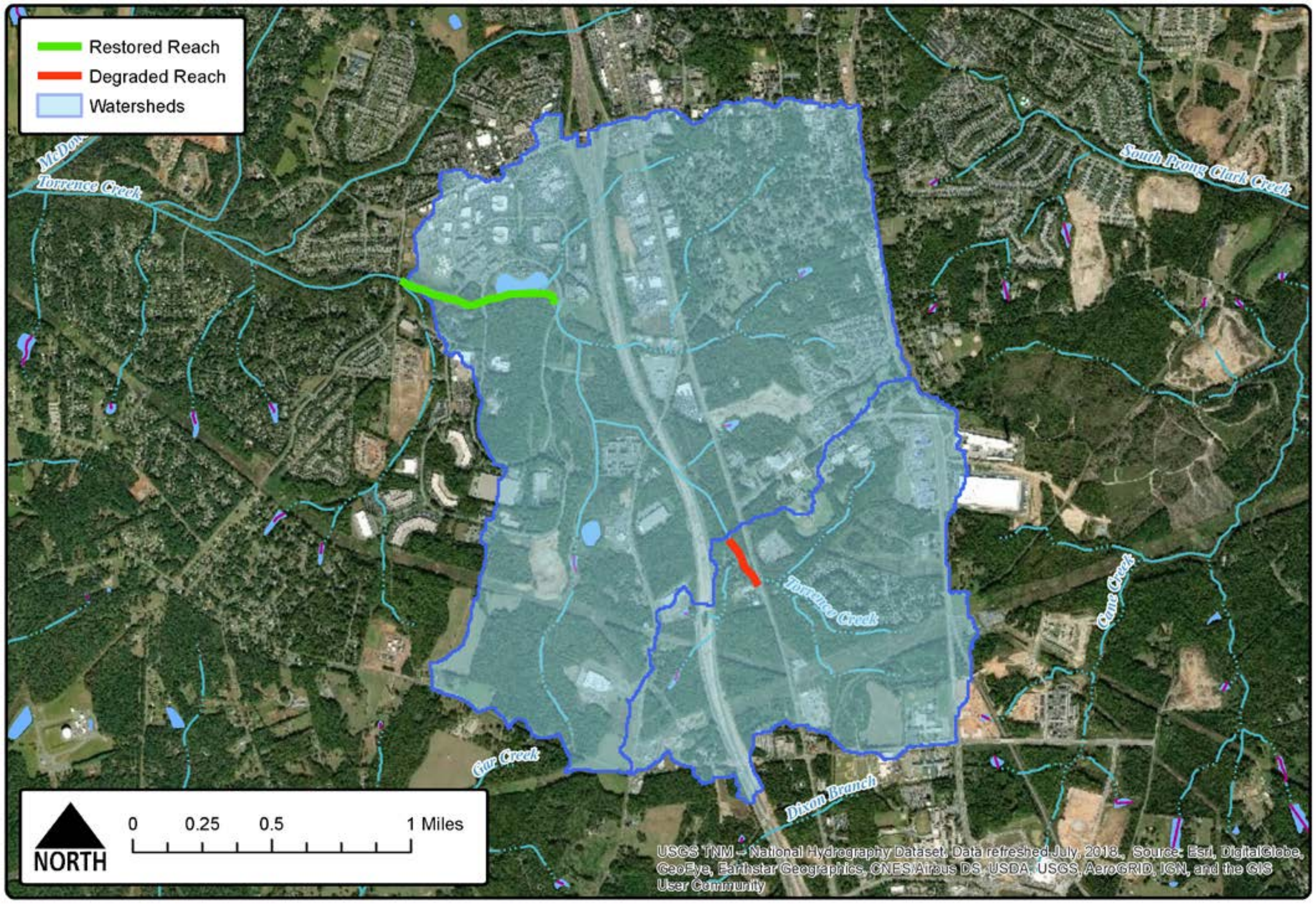
UT Swift Creek - Cary, NC



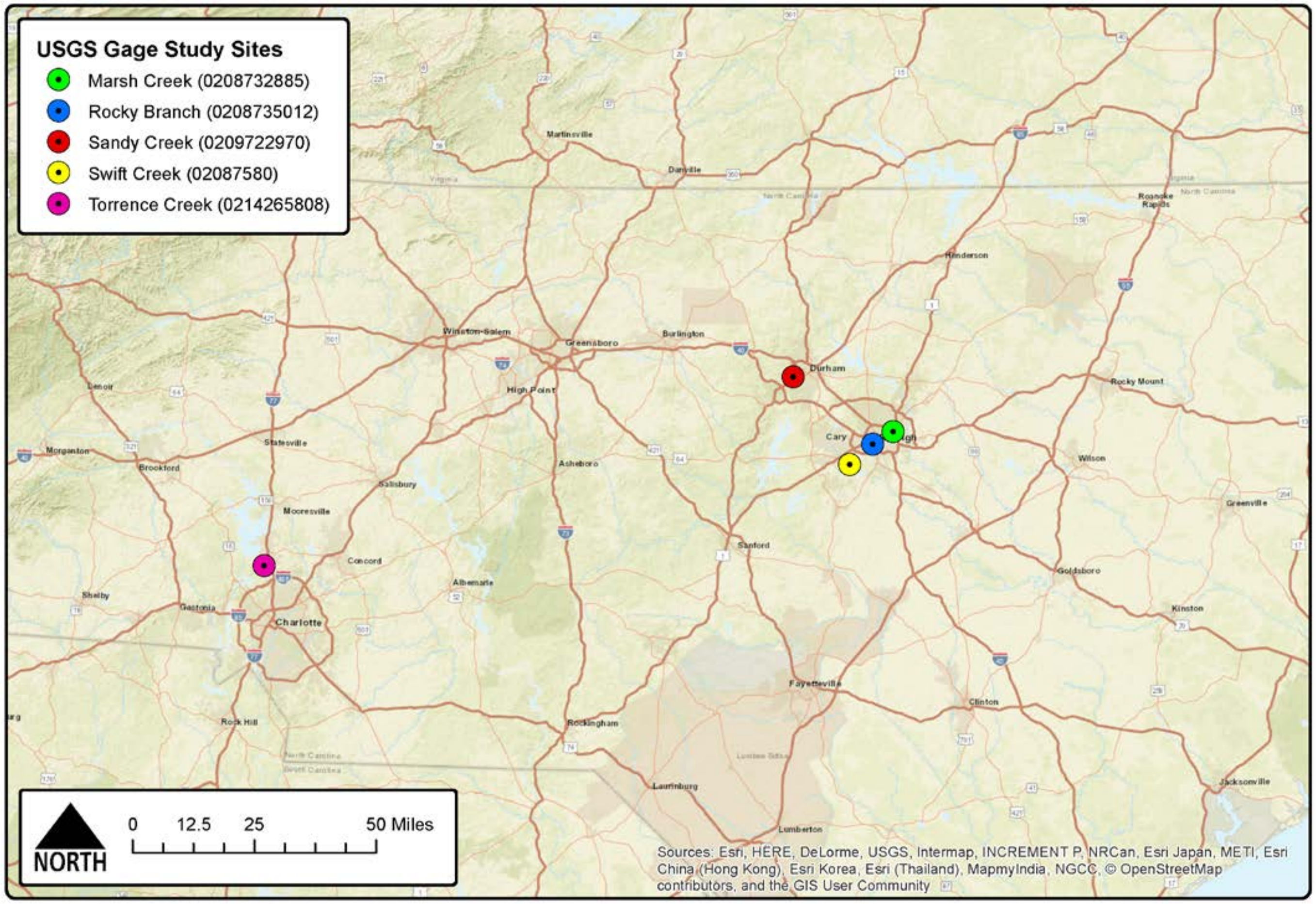
NC DEQ Evaluation of Nutrient Reduction Crediting Strategies for Stream Restoration

Sandy Creek - Durham, NC



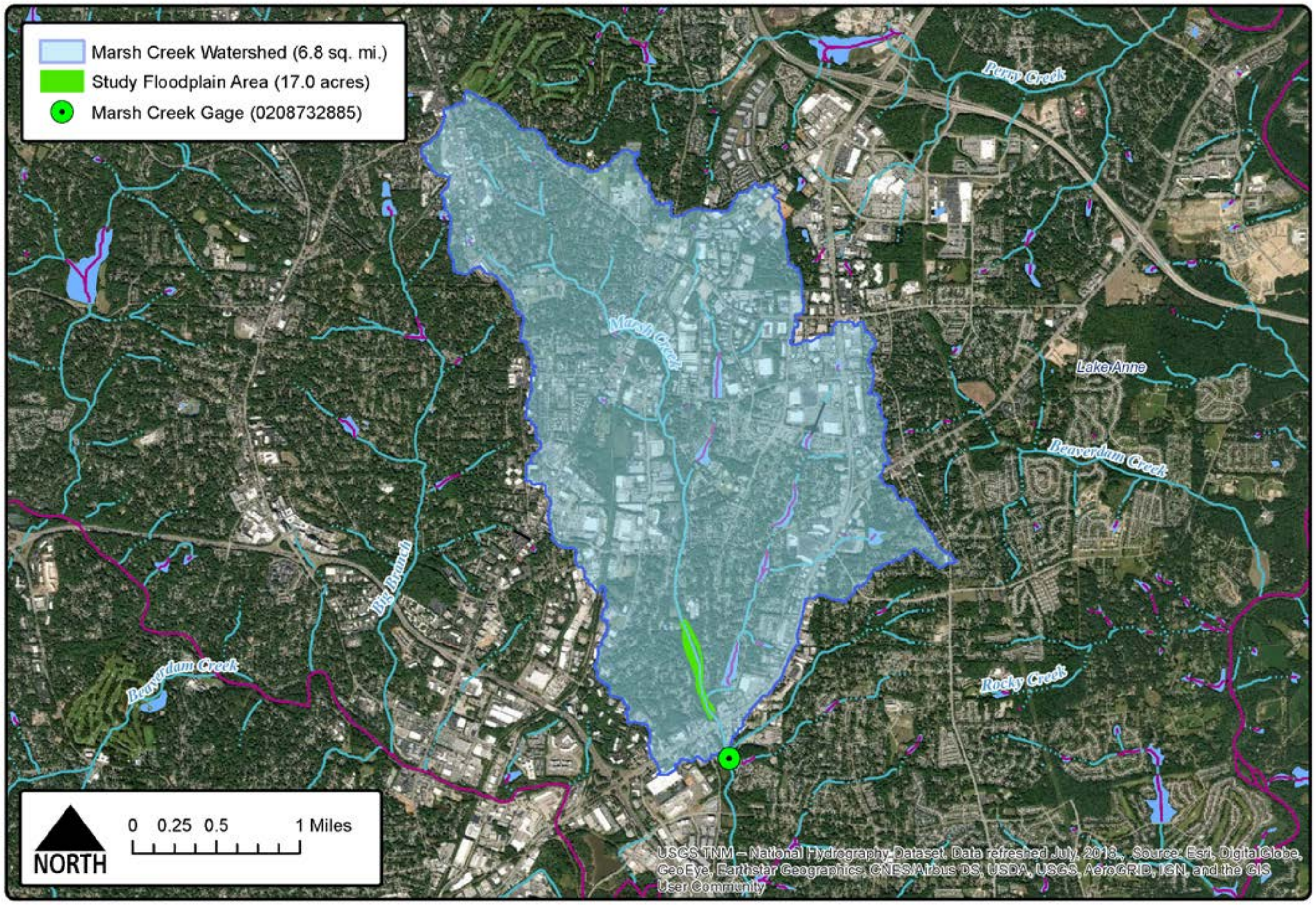
NC DEQ Evaluation of Nutrient Reduction Crediting Strategies for Stream Restoration

Torrence Creek - Huntersville, NC



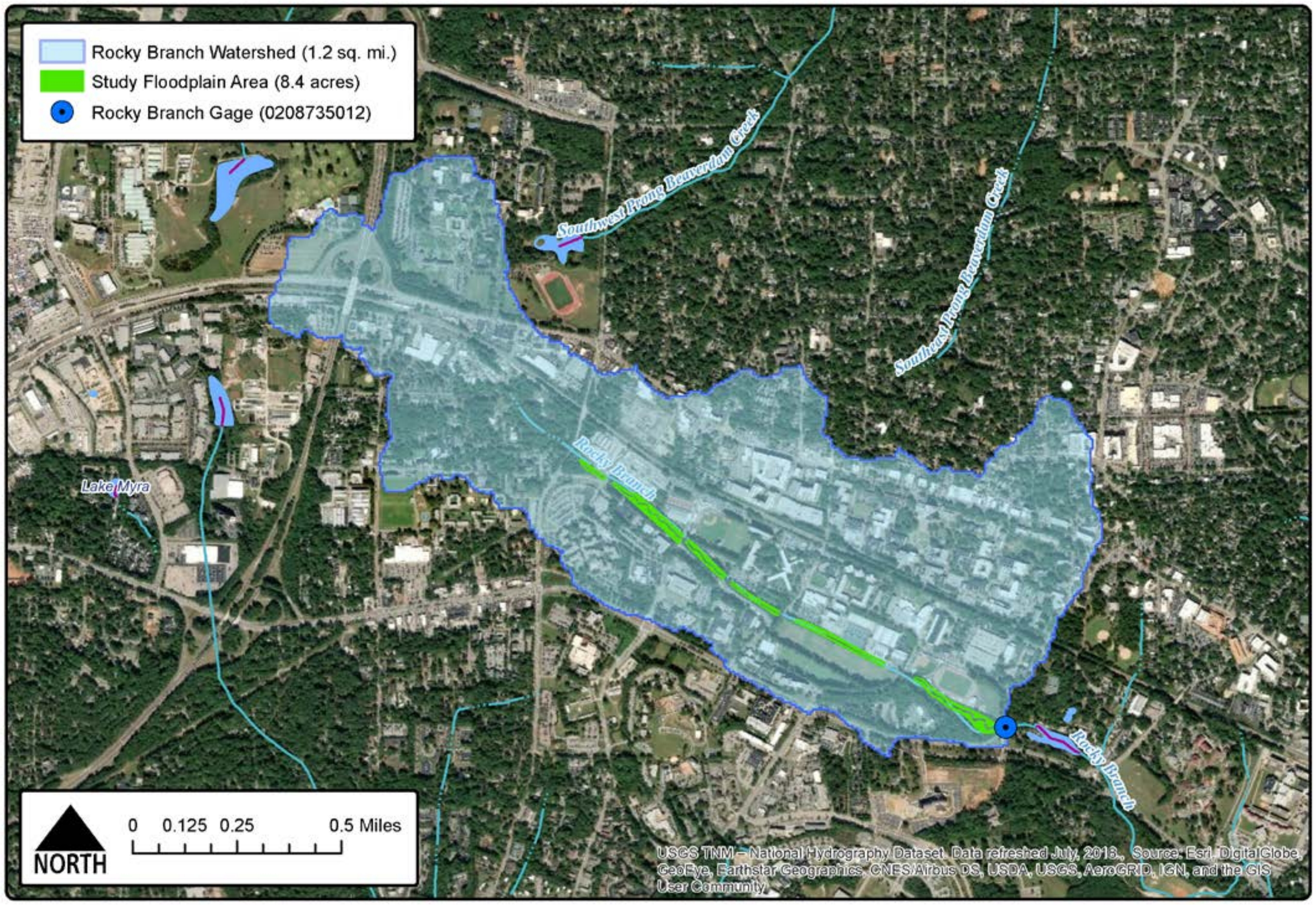
NC DEQ Evaluation of Nutrient Reduction Crediting Strategies for Stream Restoration

USGS Gage Study Sites



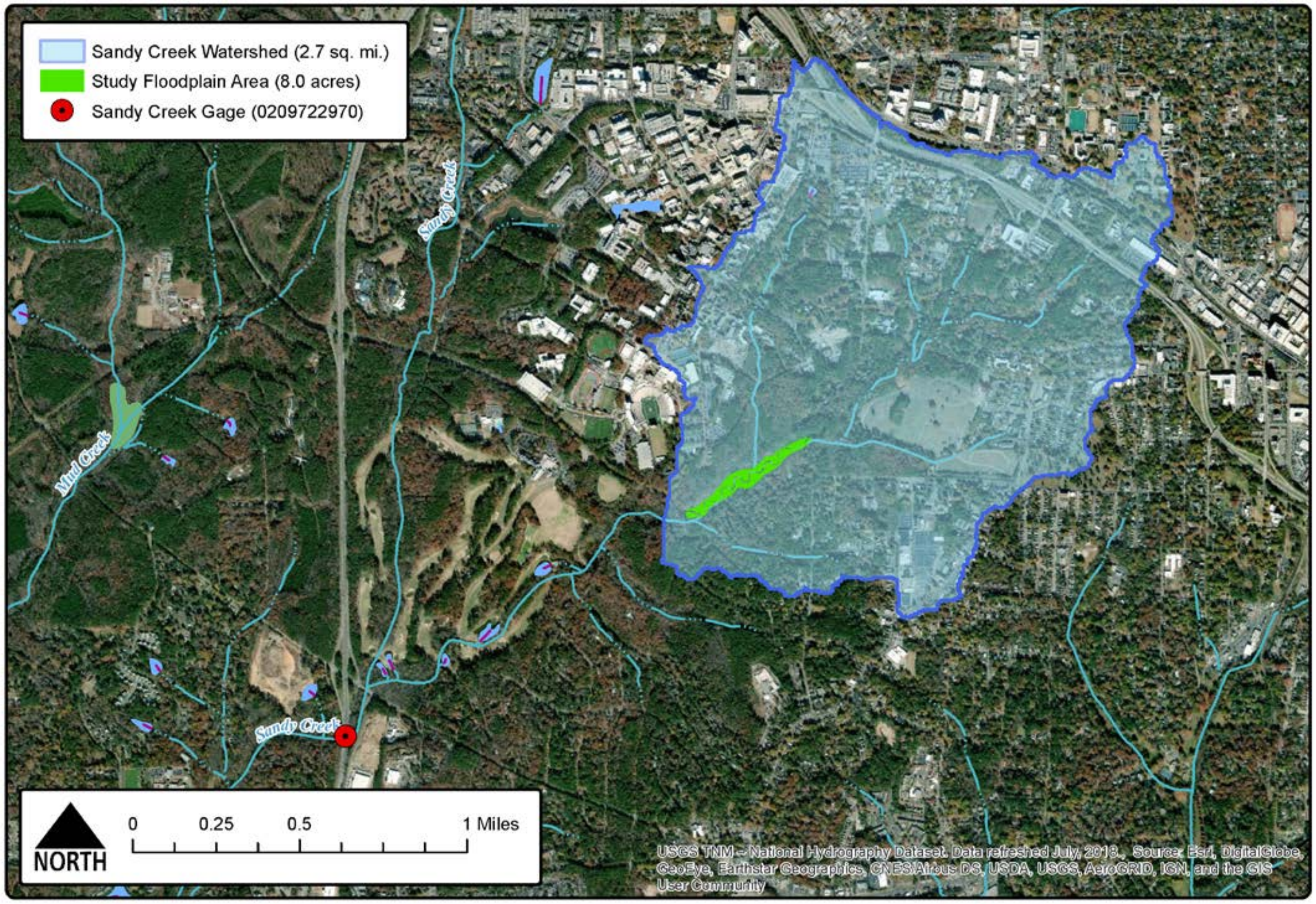
NC DEQ Evaluation of Nutrient Reduction Crediting Strategies for Stream Restoration

Marsh Creek - Raleigh, NC



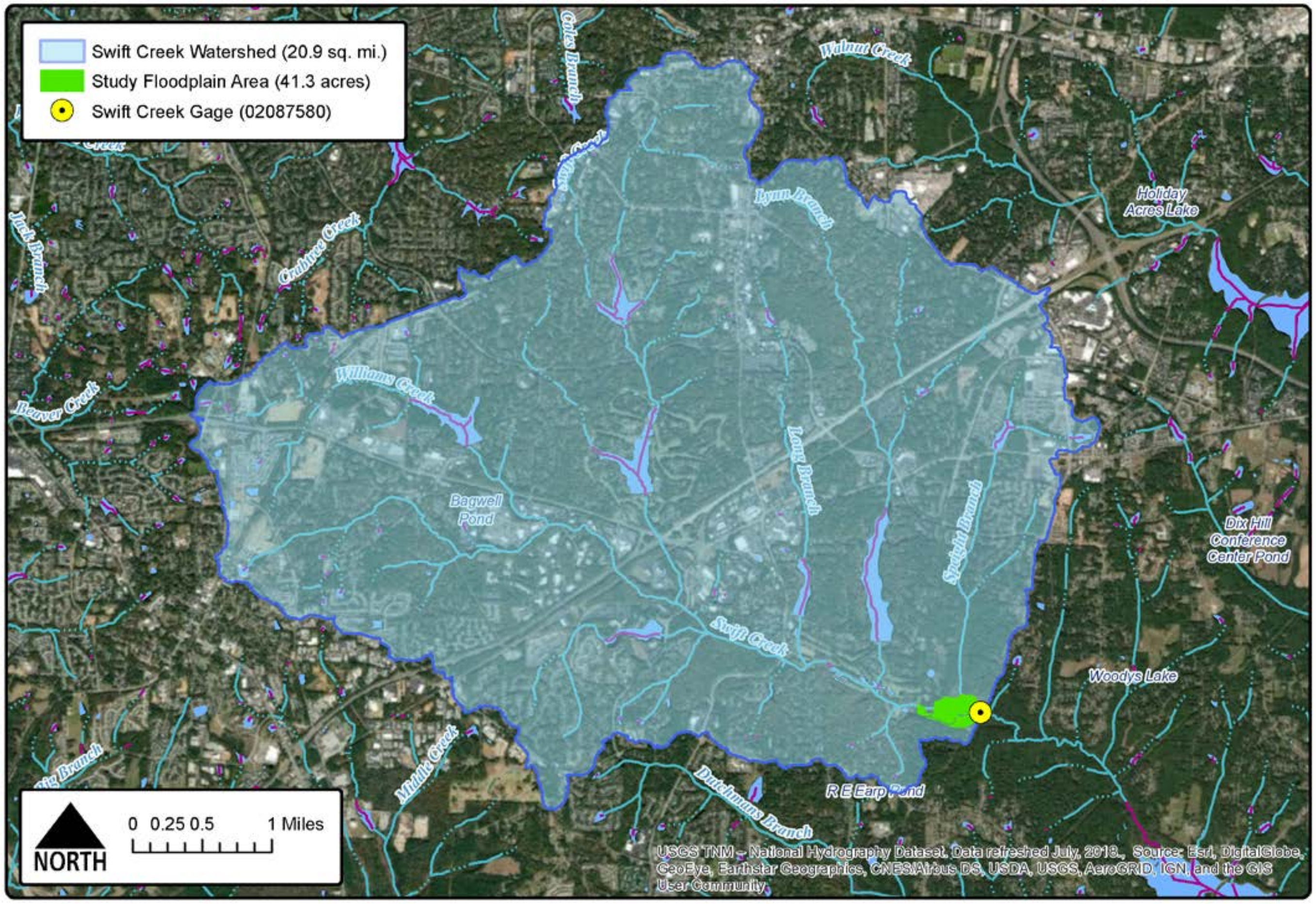
NC DEQ Evaluation of Nutrient Reduction Crediting Strategies for Stream Restoration

Rocky Branch - Raleigh, NC



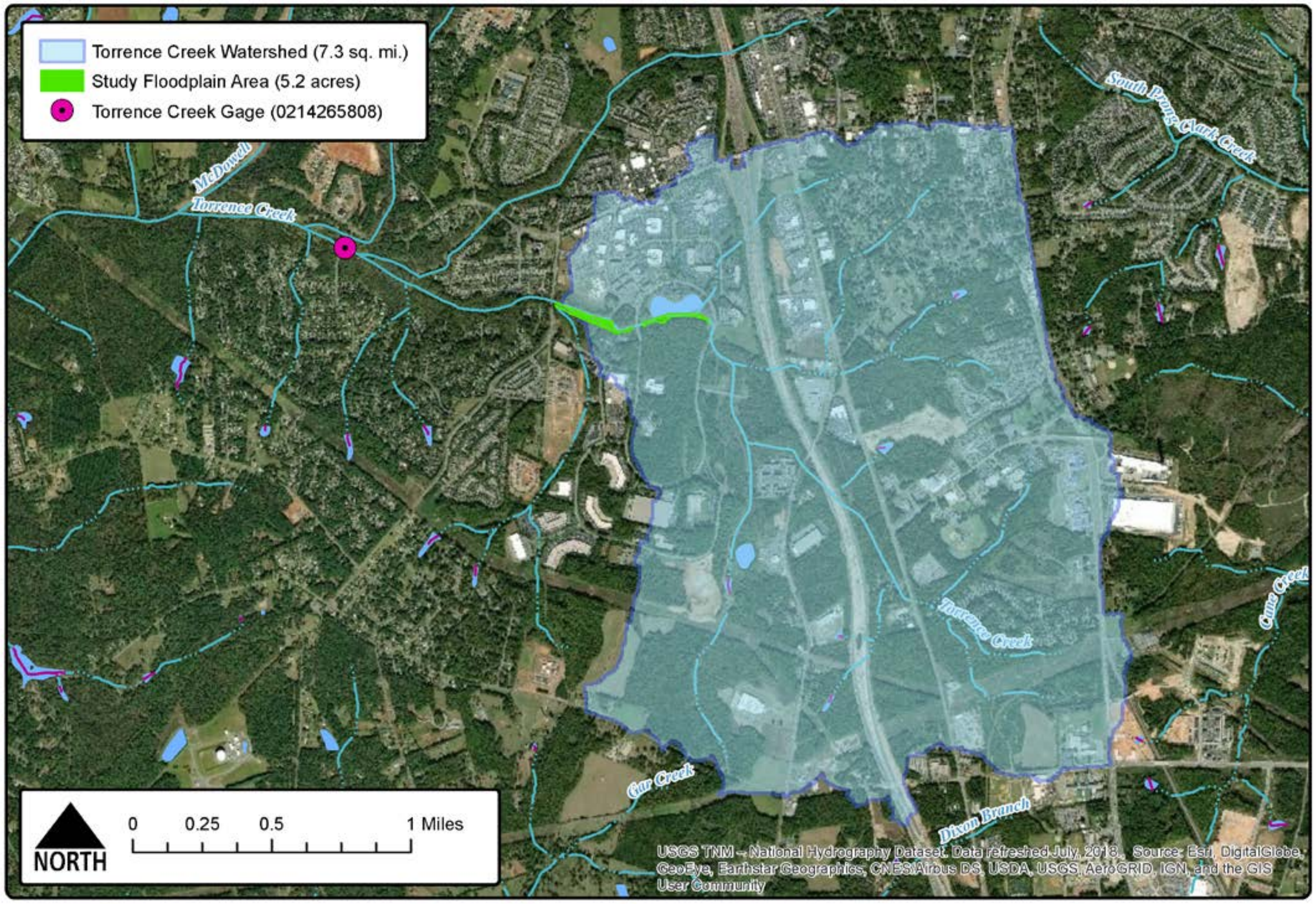
NC DEQ Evaluation of Nutrient Reduction Crediting Strategies for Stream Restoration

Sandy Creek - Durham, NC



NC DEQ Evaluation of Nutrient Reduction Crediting Strategies for Stream Restoration

Swift Creek - Apex, NC



NC DEQ Evaluation of Nutrient Reduction Crediting Strategies for Stream Restoration

Torrence Creek - Huntersville, NC

Appendix B: CBP 1 Supporting Data

Table 28. Results of streambank and streambed soil testing.

Sample ID	TN (lb/ton)	TP (lb/ton)	Streambank BD (lb/ft^3)	Streambed BD, lb/ft3
AUST-UP	1.34	0.58	51.97	86.45
AUST-MID	1.12	0.42	49.43	86.45
AUST-DN	2.25	1.57	54.44	86.99
HT-UP	1.65	0.97	91.08	86.91
HT-MID	2.64	0.90	53.27	88.04
HT-DN	0.96	0.59	66.14	89.73
SC-UP	1.03	0.53	84.00	
SC-MID	1.71	0.38	78.04	86.55
SC-DN	0.41	0.30	101.41	
TC-UP	0.63	0.43	61.59	88.97
TC-MID	1.97	0.58	56.87	87.37
TC-DN	0.43	0.52	57.32	88.32
Mean	1.34	0.65	67.13	87.58
Std. Dev.	0.72	0.35	17.27	1.14
Median	1.23	0.56	59.45	87.18
Min	0.41	0.30	49.43	86.45
Max	2.64	1.57	101.41	89.73

Table 29. Summary of CBP 1 calculations.

Method	Constituent	Higgins Trail				Austin Creek				Sandy Creek				Torrence Creek			
		Degraded	Restored	Δ	Credit	Degraded	Restored	Δ	Credit	Degraded	Restored	Δ	Credit	Degraded	Restored	Δ	Credit
All	Sed (ton/yr)	14	7	7	4	87	4	83	41	21	12	9	5	69	1	68	34
CBP	TN (lb/yr)	32	16	16	8	198	9	189	94	49	27	21	11	158	3	155	78
	TP (lb/yr)	15	7	7	4	91	4	87	43	22	13	10	5	73	1	71	36
Obs	TN (lb/yr)	25	12	12	6	152	7	145	73	37	21	16	8	121	2	119	60
	TP (lb/yr)	12	6	6	3	71	3	68	34	17	10	8	4	57	1	56	28
Tetra Tech	TN (lb/yr)	25	12	13	6	155	7	147	74	38	21	17	8	123	2	121	61
	TP (lb/yr)	6	3	3	2	40	2	38	19	10	5	4	2	32	1	31	16

Stream	Reach	Reach Length	Bank Height	Erosion Rate	Bulk Density	Sediment Load	
		ft	ft	ft/yr	lb/ft3	lb/yr	
Higgins Trail Restored	0+17 - 0+32	15	3.5	0.05	70.16	184.2	
	0+95 - 1+10	15	2.9	0.05	70.16	152.6	
	1+80 - 1+90	10	2.5	0.05	70.16	87.7	
	2+52 - 2+75	23	3	0.05	70.16	242.1	
	3+20 - 3+60	40	4.7	0.05	70.16	659.5	
	3+74 - 4+05	31	4	0.05	70.16	435.0	
BEHI Length	405	ft			BEHI Sediment Load	1761.0	lb/yr
Restored Length	3225	ft				0.9	ton/yr
Scaling Factor	7.96						
					Scaled Sediment Load	14022.9	lb/yr
						7.0	ton/yr
						0.002174094	ton/yr/ft

Stream	Reach	Reach Length	Bank Height	Erosion Rate	Bulk Density	Sediment Load	
		ft	ft	ft/yr	lb/ft3	lb/yr	
Austin Creek Restored	0+60 - 0+75	15	3.8	0.02	51.95	59.221097	
	1+65 - 1+73	8	3.2	0.05	51.95	66.493863	
	1+73 - 2+00	27	5.2	0.02	51.95	145.87091	
	2+30 - 2+64	34	3.2	0.02	51.95	113.03957	
	2+64 - 3+00	36	3.3	0.02	51.95	123.42923	
	3+34 - 3+45	11	3.7	0	51.95	0	
	3+45 - 4+36	91	3	0.05	51.95	709.09472	
	5+33 - 5+50	17	4.7	0.05	51.95	207.53358	
BEHI Length	550	ft			BEHI Sediment Load	1424.683	lb/yr
Restored Length	3074	ft				0.7	ton/yr
Scaling Factor	5.59						
					Scaled Sediment Load	7962.7	lb/yr
						4.0	ton/yr
						0.0012952	ton/ft/yr

Stream	Reach	Reach Length	Bank Height	Erosion Rate	Bulk Density	Sediment Load	
		ft	ft	ft/yr	lb/ft3	lb/yr	
Sandy Creek Restored	0+30 - 0+38	8	6.5	0.02	87.82	91.3	
	0+79 - 0+89	10	5	0.02	87.82	87.8	
	0+98 - 1+31	33	5.5	0.05	87.82	797.0	
	1+60 - 2+11	51	6	0.05	87.82	1343.6	
	2+37 - 2+43	6	4.5	0.02	87.82	47.4	
	2+67 - 2+89	22	5	0.1	87.82	966.0	
	3+19 - 3+34	15	4.8	0.02	87.82	126.5	
	3+34 - 3+77	43	4.5	0	87.82	0.0	
	3+83 - 4+03	20	4.8	0.02	87.82	168.6	
	4+13 - 4+65	52	3.8	0	87.82	0.0	
	4+51 - 4+82	31	4.5	0.02	87.82	245.0	
	4+90 - 5+33	43	5	0.1	87.82	1888.1	
	5+52 - 5+88	36	4	0.02	87.82	252.9	
	6+24 - 6+65	41	3.5	0.1	87.82	1260.2	
	6+65 - 7+15	50	2.5	0	87.82	0.0	
	7+34 - 7+51	17	4	0	87.82	0.0	
BEHI Length	751	ft			BEHI Sediment Load	7274.5	lb/yr
Restored Length	2461	ft				3.6	ton/yr
Scaling Factor	3.28						
					Scaled Sediment Load	23838.3	lb/yr
						11.9	ton/yr
						0.004843	ton/ft/yr

Stream	Reach	Reach Length	Bank Height	Erosion Rate	Bulk Density	Sediment Load	
		ft	ft	ft/yr	lb/ft3	lb/yr	
Torrence Creek Restored	0+43 - 0+47	4	3	0.041	58.59	28.6	
	0+29 - 0+42	13	3	0.000	58.59	0.0	
	0+91 - 0+96	5	2.6	0.000	58.59	0.0	
	3+81 - 3+85	4	3.2	0.016	58.59	11.7	
	3+94 - 4+06	12	3.2	0.016	58.59	35.2	
	4+23 - 4+29	6	3.4	0.470	58.59	562.0	
BEHI Length	429	ft			BEHI Sediment Load	637.55	lb/yr
Restored Length	1620	ft				0.3	ton/yr
Scaling Factor	3.78						
					Scaled Sediment Load	2407.5	lb/yr
						1.2	ton/yr

Stream	Reach	NBS	BEHI	Erosion Rate	Reach Length	Bank Height	Bulk Density	Sediment Load
				ft/yr	ft	ft	lb/ft3	lb/yr
Higgins Trail Degraded	0+38 - 0+71	1	Moderate	0.01	33	5	70.16	69.4
	0+71 - 1+05	1	Moderate	0.01	34	6	70.16	85.8
	1+12 - 1+65	2	Moderate	0.02	53	6	70.16	348.6
	2+00 - 2+12	1	High	0.08	12	4.8	70.16	314.6
	2+12 - 2+19	1	High	0.08	7	4.8	70.16	183.5
	2+19 - 2+53	1	High	0.08	34	4.8	70.16	891.3
	2+19 - 2+53	1	Moderate	0.01	34	6.8	70.16	97.2
	2+53 - 2+92	1	Moderate	0.01	39	4.7	70.16	77.1
	3+07 - 3+26	1	High	0.08	19	5.3	70.16	550.0
	3+17 - 3+57	1	Moderate	0.01	40	5.1	70.16	85.8
	3+32 - 3+41	1	High	0.08	9	5.7	70.16	280.2
BEHI Length	341	ft			BEHI Sediment Load	2983.3	lb/yr	
Reach Length	408	ft				1.5	ton/yr	
Restored Length	3225	ft				0.00437	ton/yr/ft	
					Scaled Sediment Load =		14.1	ton/yr

Stream	Reach	NBS	BEHI	Erosion Rate	Reach Length	Bank Height	Bulk Density	Sediment Load
				ft/yr	ft	ft	lb/ft3	lb/yr
Austin Creek Degraded	0+00 - 1+15	2	High	0.11	115	3	51.95	1925.4
	0+17 - 0+34	3	Moderate	0.04	17	4.8	51.95	172.6
	0+45 - 0+60	5	Moderate	0.28	15	4.8	51.95	1034.4
	0+72 - 0+90	4	High	0.20	18	5.3	51.95	1014.2
	1+20 - 1+68	3	Moderate	0.04	48	5.2	51.95	527.9
	1+53 - 1+99	1	Moderate	0.01	46	4.5	51.95	64.5
	2+15 - 2+54	1	Moderate	0.01	39	4.4	51.95	53.4
	2+49 - 2+65	2	High	0.11	16	4.6	51.95	410.8
	3+12 - 3+56	1	Very High	0.47	44	5.2	51.95	5588.8
	3+56 - 3+93	4	Very High	0.91	37	6.5	51.95	11407.1
BEHI Length	393	ft			BEHI Sediment Load	22199.1	lb/yr	
Reach Length	415	ft				11.1	ton/yr	
Restored Length	3074	ft				0.02824	ton/ft/yr	
					Scaled Sed. Load	86.8195	ton/yr	

Stream	Reach	NBS	BEHI	Erosion Rate	Reach Length	Bank Height	Bulk Density	Sediment Load
				ft/yr	ft	ft	lb/ft3	lb/yr
Sandy Creek Degraded	0+00 - 0+21	2	Moderate	0.02	21	6.4	87.82	184.4
	0+31 - 0+43	4	High	0.20	12	6.6	87.82	1423.4
	0+68 - 0+81	1	High	0.08	13	7.8	87.82	693.2
	1+00 - 1+30	3	Moderate	0.04	30	7.1	87.82	761.6
	1+38 - 1+70	3	Moderate	0.04	32	7.2	87.82	823.8
	1+60 - 1+91	1	Moderate	0.01	31	6.3	87.82	102.8
	2+50 - 2+67	4	Moderate	0.11	17	7.3	87.82	1156.5
	3+40 - 4+00	3	Moderate	0.04	60	6.8	87.82	1458.8
	3+68 - 3+70	3	High	0.15	2	6.7	87.82	174.5
	4+22 - 4+35	5	High	0.28	13	6.9	87.82	2224.9
	5+10 - 5+54	3	Moderate	0.04	44	7.2	87.82	1132.8
	5+96 - 6+18	3	Moderate	0.04	22	7.1	87.82	558.5
BEHI Length	618	ft			BEHI Sediment Load	10695.1	lb/yr	
Reach Length	658	ft				5.3	ton/yr	
Restored Length	2461	ft				0.00865	ton/ft/yr	
					Scaled Sed. Load	21.295	ton/yr	

Torrence Creek BEHI/NBS - Pre-Restoration

Left Bank	TOTAL FT3/YR	Right Bank	TOTAL FT3/YR
	0		0
	0		0
	0		0
	56.7		0
	0		0
	0		0
Total ft3/yr	56.7	Total ft3/yr	0
Total yd3/yr	2.1	Total yd3/yr	0
Total TONS/YR	2.7	Total TONS/YR	0.0

TOTAL SEDIMENT LOADS		
LB	61.3	
RB	52.6	
SUM	113.9	TONS/YR

TOTAL SEDIMENT LOADS		
LB	1273.1	ft3/yr
RB	1092.1	ft3/yr
SUM	2365.2	ft3/yr
BD	58.59	lb/ft3
LOAD	138577.07	lb/yr
	69.29	ton/yr

LEFT BANK 2		RIGHT BANK 2		LEFT BANK 3		RIGHT BANK 3		LEFT BANK 4		RIGHT BANK 4	
	TOTAL FT3/YR		TOTAL FT3/YR		TOTAL FT3/YR		TOTAL FT3/YR		TOTAL FT3/YR		TOTAL FT3/YR
	1		0		67.5		0		0		48.8
	3.6		8.1		0		22.7		94		0
	1.5		3.8		0		69.6		98		16.7
	2.3		2		0		8.3		60.8		38
	7.1		2		27.9		9		0		42
	3		8.2		21.6		100.8		0		35
	5.4		2.2		13.5		56.7				
	1.7		1.9		5.8		36.5				
	50.6		38.8		100.8		0				
	10.9		24.2		5.2		19.5				
	58.7		20.4		0		22.2				
	3.2		50.4		4.8		5.1				
	124.8		0		0		94.5				
	0		92		0		0				
	78.2		0		68.4		0				
	63.4		46.8		0		19.4				
	5.3		24.8		52.4		54.7				
	16.3		0		40.8		9.8				
	31.6		12.3		5.3		13.2				
	0		0		15.5		0				
	0		9.8		4.5		0				
	0		21.9		10.8		0				
	14.6		0								
	35.6		0								
Total ft3/yr	518.8	Total ft3/yr	369.6	Total ft3/yr	444.8	Total ft3/yr	542	Total ft3/yr	252.8	Total ft3/yr	180.5
Total yd3/yr	19.21481481	Total yd3/yr	13.68888889	Total yd3/yr	16.47407407	Total yd3/yr	20.07407407	Total yd3/yr	9.362962963	Total yd3/yr	6.685185185
Total TONS/YR	25.0	Total TONS/YR	17.8	Total TONS/YR	21.4	Total TONS/YR	26.1	Total TONS/YR	12.2	Total TONS/YR	8.7

Figure 22. BEHI and NBS from pre-restoration at Torrence Creek.

Appendix C: CBP 2 Supporting Data

Table 30. Existing CBP 2 credit calculations.

Stream	Higgins Trail Restored	Higgins Trail Degraded	Austin Creek Restored	Austin Creek Degraded	Sandy Creek Restored	Sandy Creek Degraded	Torrence Creek Restored	Torrence Creek Unrestored
L (ft)	3225	408	3074	415	2461	658	1620	338
L_{BHR1} (ft)	3225	0	3074	0	2461	0	1620	55
W_{bkf} (ft)	19	20	34	15.5	22	30	24	10.5
W_{hb} (ft)	29	30	44	25.5	32	40	34	20.5
D_{hb} (ft)	5	5	5	5	5	5	5	5
A_{hb} (ft^2)	145	150	220	127.5	160	200	170	102.5
V_{hb} (ft^3)	467625	0	676280	0	393760	0	275400	5637.5
ρ_{bd} (lb/ft^3)	88.2	88.2	86.6	86.6	86.6	86.6	88.2	88.2
r_{denit} (lb N/ton soil/day)	0.000106	0.000106	0.000106	0.000106	0.000106	0.000106	0.000106	0.000106
N Removed (lb/yr)	798	0	1133	0	659	0	470	10
N Credit (lb/ft/yr)	0.247	0.000	0.369	0.000	0.268	0.000	0.290	0.028

Table 31. Depth to confining layers measured at each case study site.

	Location	AC	HT	SC	TC
Depth to Confining Layer (ft)	Riffle 1	3.2	0.6	0.8	1.6
	Riffle 2	2.5	1.3	3.2	1.5
	Riffle 3	5.0	0.9	2.3	1
	Riffle 4	3.0	0.8	4.4	1.4
	Riffle 5	3.3	1.2	0.4	1.3
	Riffle 6	2.2	0.9		1.9
	Riffle 7	2.1	1.3		1.7
	Riffle 8	2.1	0.2		
	Riffle 9	4.6	1.2		
	Riffle 10		2.7		
	Riffle 11		0.3		
	Riffle 12		5		
Avg		3.10	1.37	2.22	1.49
Std. Dev.		1.07107	1.31033	1.66193	0.29114
Median		3.0	1.1	2.3	1.5
Min		0.2	0.2	0.4	1.0
Max		5.0	5.0	4.4	1.9

Table 32. CBP 2 calculations with depth to confining layer instead of Dhb = 5 ft.

Stream	Higgins Trail Restored	Higgins Trail Degraded	Austin Creek Restored	Austin Creek Degraded	Sandy Creek Restored	Sandy Creek Degraded	Torrence Creek Restored	Torrence Creek Unrestored
L (ft)	3225	408	3074	415	2461	658	1620	338
L_{BHR1} (ft)	3225	0	3074	0	2461	0	1620	55
W_{bkf} (ft)	19	20	34	15.5	22	30	24	10.5
W_{hb} (ft)	29	30	44	25.5	32	40	34	20.5
D_{hb} (ft)	1.1	1.1	3.1	3.1	2.22	2.22	1.49	1.49
A_{hb} (ft^2)	31.9	33.0	136.4	79.1	71.0	88.8	50.7	30.5
V_{hb} (ft^3)	102877.5	0.0	419293.6	0.0	174829.4	0.0	82069.2	1680.0
ρ_{bd} (lb/ft^3)	88.2	88.2	86.6	86.6	86.6	86.6	88.2	88.2
r_{denit} (lb N/ton soil/day)	0.000106	0.000106	0.000106	0.000106	0.000106	0.000106	0.000106	0.000106
N Removed (lb/yr)	176	0	703	0	293	0	140	3
N Credit (lb/ft/yr)	0.054	0.000	0.229	0.000	0.119	0.000	0.086	0.008

Table 33. Revised protocol 2 calculations.

Revised Protocol 2

Stream	**HT Rest**	**AC Rest.**	**SC Rest.**	**TC Rest.**
L (ft)	3225	3074	2461	1620
L (m)	983	937	750	494
W_{bkf} (ft)	19	34	22	24
W_{bkf} (m)	5.8	10.4	6.7	7.3
A_{hb} (m^2)	5692.6	9709.9	5030.0	3612.1
$r_{denit,stream}$ (mg N/m^2/hr)	1.85	1.85	1.85	1.85
Streambed N Removed (kg/yr)	92.3	157.4	81.5	58.5
Streambed N Removed (lb/yr)	203.4	346.9	179.7	129.1
Floodplain Area (ac)	4.1	6.7	8.1	5.2
Floodplain Area (m^2)	16592.2	27114.0	32779.7	21043.7
$r_{denit,riparian}$ (mg N/m^2/hr)	1.01	1.01	1.01	1.01
Floodplain N Removed (kg/yr)	146.8	239.9	290.0	186.2
Floodplain N Removed (lb/yr)	323.6	528.9	639.4	410.5
Total N Removed (lb/yr)	**527.0**	**875.8**	**819.1**	**539.5**
% Removed	**2%**	**4%**	**4%**	**2%**

Appendix D: Baseflow Monitoring Data

Table 34. Higgins Trail baseflow monitoring results.

Higgins Trail Baseflow Monitoring Results (all in mg/L)										
	TKN		NO3		TN		TP		TSS	
Date	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
1/31/2018	0.95	0.95	0.11	0.09	1.06	1.04	0.1	0.12	3.91	34.78
2/13/2018	6.87	0.91	0.41	0.11	7.28	1.02	5.64	0.03		11.9
2/27/2018	1.31	0.94	0.17	0.03	1.48	0.97	0.62	0.21		7.69
3/16/2018	1.86	1.92	0.07	0.08	1.93	2	0.23	0.15	28.25	14.29
3/27/2018	2.56	2.59	0.13	0.06	2.69	2.65	0.11	0.08	18.75	5.08
4/19/2018		2.91		0.04		2.95		0.01		12.28
5/7/2018	1.6	3.21	0.05	0.03	1.65	3.24	0.41	0.1	33.05	9.48
5/21/2018	5.58	4.62	0.12	0.03	5.7	4.65	0.51	0.05	25.4	87.8
6/4/2018		1.47		0.14		1.61		0.08		19.79
6/18/2018	2.21	1.19	0.13	0.03	2.34	1.22	0.32	0.11	24.71	6.38
7/5/2018	1.96	1.37	0.11	0.16	2.07	1.53	0.3	0.06	37.37	35.04
Mean	**2.77**	**2.01**	**0.14**	**0.07**	**2.91**	**2.08**	**0.92**	**0.09**	**24.49**	**22.23**
Std. Dev.	**2.04**	**1.19**	**0.11**	**0.05**	**2.12**	**1.17**	**1.78**	**0.06**	**10.88**	**24.11**
Median	**1.96**	**1.47**	**0.12**	**0.06**	**2.07**	**1.61**	**0.32**	**0.08**	**25.40**	**12.28**
Min	**0.95**	**0.91**	**0.05**	**0.03**	**1.06**	**0.97**	**0.10**	**0.01**	**3.91**	**5.08**
Maximum	**6.87**	**4.62**	**0.41**	**0.16**	**7.28**	**4.65**	**5.64**	**0.21**	**37.37**	**87.80**
Mean % Reduction	**27%**		**50%**		**29%**		**90%**		**9%**	

Table 35. Austin Creek baseflow monitoring results.

Austin Creek Baseflow Monitoring Results (all in mg/L)										
	TKN		NO3		TN		TP		TSS	
Date	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
1/25/2018		0.91		1.04		1.95		0.12		
2/13/2018	1.14	0.86	1	1.09	2.14	1.95	0.08	0.01		
3/2/2018	1.88	3.93	0.64	0.6	2.52	4.53	0.4	1.15	75	1430
3/13/2018	0.78	4.26	0.87	0.97	1.65	5.23	0.3	2.43		
4/19/2018	2.74		0.58		3.32		0.09		15	
5/21/2018	2.35	1.87	1.13	0.89	3.48	2.76	0.08	0.03	55.05	77.81
6/4/2018	1.74	2.26	0.37	0.57	2.11	2.83	0.17	0.33	63.46	67
6/18/2018	1.42		0.54		1.96		0.17		45.83	
7/5/2018	1.33	1.09	0.44	0.72	1.77	1.81	0.21	0.22	34.69	38.46
Mean	**1.67**	**2.17**	**0.70**	**0.84**	**2.37**	**3.01**	**0.19**	**0.61**	**48.17**	**403.32**
Std. Dev.	**0.64**	**1.42**	**0.27**	**0.21**	**0.69**	**1.36**	**0.11**	**0.89**	**21.39**	**684.66**
Median	**1.58**	**1.87**	**0.61**	**0.89**	**2.13**	**2.76**	**0.17**	**0.22**	**50.44**	**72.41**
Min	**0.78**	**0.86**	**0.37**	**0.57**	**1.65**	**1.81**	**0.08**	**0.01**	**15.00**	**38.46**
Maximum	**2.74**	**4.26**	**1.13**	**1.09**	**3.48**	**5.23**	**0.40**	**2.43**	**75.00**	**1430.00**
Mean % Reduction	**-30%**		**-21%**		**-27%**		**-227%**		**-737%**	

Higgins Trail Baseflow Monitoring Loads																		
	TKN				NO3				TN				TP				TSS	
Date	Conc. Up (mg/L)	Mass Up (kg)	Conc. Down (mg/L)	Mass Down (kg)	Conc. Up (mg/L)	Mass Up (kg)	Conc. Down (mg/L)	Mass Down (kg)	Conc. Up (mg/L)	Mass Up (kg)	Conc. Down (mg/L)	Mass Down (kg)	Conc. Up (mg/L)	Mass Up (kg)	Conc. Down (mg/L)	Mass Down (kg)	Conc. Up (mg/L)	Conc. Down (mg/L)
1/31/2018	0.95	1.4	0.95	1.4	0.11	0.0	0.09	0.13	1.06	1.5	1.04	1.5	0.1	0.1	0.12	0.2	3.91	34.78
2/13/2018	6.87	8.5	0.91	1.1	0.41	0.0	0.11	0.14	7.28	9.0	1.02	1.3	5.64	7.0	0.03	0.0		11.9
2/27/2018	1.31	1.7	0.94	1.3	0.17	0.0	0.03	0.04	1.48	2.0	0.97	1.3	0.62	0.8	0.21	0.3		7.69
3/16/2018	1.86	3.0	1.92	3.1	0.07	0.0	0.08	0.13	1.93	3.1	2	3.2	0.23	0.4	0.15	0.2	28.25	14.29
3/27/2018	2.56	2.7	2.59	2.7	0.13	0.0	0.06	0.06	2.69	2.8	2.65	2.8	0.11	0.1	0.08	0.1	18.75	5.08
4/19/2018		4.3	2.91	6.4		4.3	0.04	0.09		4.5	2.95	6.5		0.7	0.01	0.0		12.28
5/7/2018	1.6	2.7	3.21	5.5	0.05	0.0	0.03	0.05	1.65	2.8	3.24	5.6	0.41	0.7	0.1	0.2	33.05	9.48
5/21/2018	5.58	7.5	4.62	6.2	0.12	0.0	0.03	0.04	5.7	7.6	4.65	6.2	0.51	0.7	0.05	0.1	25.4	87.8
6/4/2018		2.6	1.47	2.0		2.6	0.14	0.19		2.8	1.61	2.2		0.4	0.08	0.1		19.79
6/18/2018	2.21	3.0	1.19	1.6	0.13	0.0	0.03	0.04	2.34	3.1	1.22	1.6	0.32	0.4	0.11	0.1	24.71	6.38
7/5/2018	1.96	3.2	1.37	2.2	0.11	0.0	0.16	0.26	2.07	3.4	1.53	2.5	0.3	0.5	0.06	0.1	37.37	35.04
Sum		40.6		33.4		6.9		1.2		42.7		34.6		11.9		1.4		
Mean	2.77		2.01		0.14		0.07		2.91		2.08		0.92		0.09		24.49	22.23
Std. Dev.	2.04		1.19		0.11		0.05		2.12		1.17		1.78		0.06		10.88	24.11
Median	1.96		1.47		0.12		0.06		2.07		1.61		0.32		0.08		25.40	12.28
Min	0.95		0.91		0.05		0.03		1.06		0.97		0.10		0.01		3.91	5.08
Maximum	6.87		4.62		0.41		0.16		7.28		4.65		5.64		0.21		37.37	87.80
% Reduction	18%				83%				19%				88%				18%	

Figure 23. Higgins Trail baseflow monitoring load calculations.

Austin Creek Baseflow Monitoring Loads																		
	TKN				NO3				TN				TP				TSS	
Date	Conc. Up (mg/L)	Mass Up (kg)	Conc. Down (mg/L)	Mass Down (kg)	Conc. Up (mg/L)	Mass Up (kg)	Conc. Down (mg/L)	Mass Down (kg)	Conc. Up (mg/L)	Mass Up (kg)	Conc. Down (mg/L)	Mass Down (kg)	Conc. Up (mg/L)	Mass Up (kg)	Conc. Down (mg/L)	Mass Down (kg)	Conc. Up (mg/L)	Conc. Down (mg/L)
1/25/2018		303.0	0.91	174.5		117.0	1.04	199.4		407.5	1.95	373.9		32.6	0.12	23.0		
2/13/2018	1.14	259.6	0.86	195.8	1	227.7	1.09	248.2	2.14	487.3	1.95	444.0	0.08	18.2	0.01	2.3		
3/2/2018	1.88	383.0	3.93	800.7	0.64	130.4	0.6	122.2	2.52	513.4	4.53	922.9	0.4	81.5	1.15	234.3	75	1430
3/13/2018	0.78	102.8	4.26	561.6	0.87	114.7	0.97	127.9	1.65	217.5	5.23	689.5	0.3	39.5	2.43	320.4		
4/19/2018	2.74	1215.0		829.2	0.58	257.2		394.7	3.32	1472.2		1223.9	0.09	39.9		97.6	15	
5/21/2018	2.35	901.3	1.87	717.2	1.13	433.4	0.89	341.3	3.48	1334.6	2.76	1058.5	0.08	30.7	0.03	11.5	55.05	77.81
6/4/2018	1.74	291.9	2.26	379.2	0.37	62.1	0.57	95.6	2.11	354.0	2.83	474.8	0.17	28.5	0.33	55.4	63.46	67
6/18/2018	1.42	238.3		313.8	0.54	90.6		149.3	1.96	328.9		463.1	0.17	28.5		36.9	45.83	
7/5/2018	1.33	271.0	1.09	222.1	0.44	89.6	0.72	146.7	1.77	360.6	1.81	368.8	0.21	42.8	0.22	44.8	34.69	38.46
Sum		3965.9		4194.1		1522.7		1825.4		5476.1		6019.5		342.3		826.1		
Mean	1.67		2.17		0.70		0.84		2.37		3.01		0.19		0.61		48.17	403.32
Std. Dev.	0.64		1.42		0.27		0.21		0.69		1.36		0.11		0.89		21.39	684.66
Median	1.58		1.87		0.61		0.89		2.13		2.76		0.17		0.22		50.44	72.41
Min	0.78		0.86		0.37		0.57		1.65		1.81		0.08		0.01		15.00	38.46
Maximum	2.74		4.26		1.13		1.09		3.48		5.23		0.40		2.43		75.00	1430.00
% Reduction	-6%				-20%				-10%				-141%				-6%	

Figure 24. Austin Creek baseflow load calculations.

Table 36. Areal mass removal rate calculations for baseflow monitoring.

Higgins Trail						
TN Reduction				TP Reduction		
Mass In	42.71	kg		Mass In	11.9	kg
Mass Out	34.58	kg		Mass Out	1.4	kg
% Red	19%			% Red	88%	
Δ	8.13	kg		Δ	10.45	kg
Time Span	170	days		Time Span	170	days
	4080	hrs			4080	hrs
Reduction Rate	1992.2	mg/hr		Reduction Rate	2562.2	mg/hr
	47.8	g/day			61.5	g/day
Streambed Area	5692.6	m^2		Streambed Area	5692.6	m^2
N Removal Rate	0.35	mg $N/m^2/hr$		P Removal Rate	0.45	mg $P/m^2/hr$
Austin Creek						
TN Reduction				TP Reduction		
Mass In	5476.07	kg		Mass In	342.3	kg
Mass Out	6019.46	kg		Mass Out	826.1	kg
% Red	-10%			% Red	-141%	
Δ	-543.39	kg		Δ	-483.82	kg
Time Span	177	days		Time Span	177	days
	4248	hrs			4248	hrs
Reduction Rate	-127916.3	mg/hr		Reduction Rate	-113894.6	mg/hr
	-3070.0	g/day			-2733.5	g/day
Streambed Area	9709.9	m^2		Streambed Area	9709.9	m^2
N Removal Rate	-13.17	mg $N/m^2/hr$		P Removal Rate	-11.73	mg $P/m^2/hr$

Appendix E: Gage Analysis Supporting Data

Table 37: Marsh Creek gage, watershed and stream characteristics

Stream Name	Marsh Creek
Location	Raleigh, NC
USGS Gage Number	0208732885
Watershed Area (sq. mi.)	6.84
% Impervious	25
Floodplain Area & % of Watershed Area	17 acres = 0.4%
Bankfull Discharge (Qbkf)	300
Top of Bank Discharge (Qtob)	2300
Qdeparture ratio	0.84
Average Q>Qbkf events	9.1

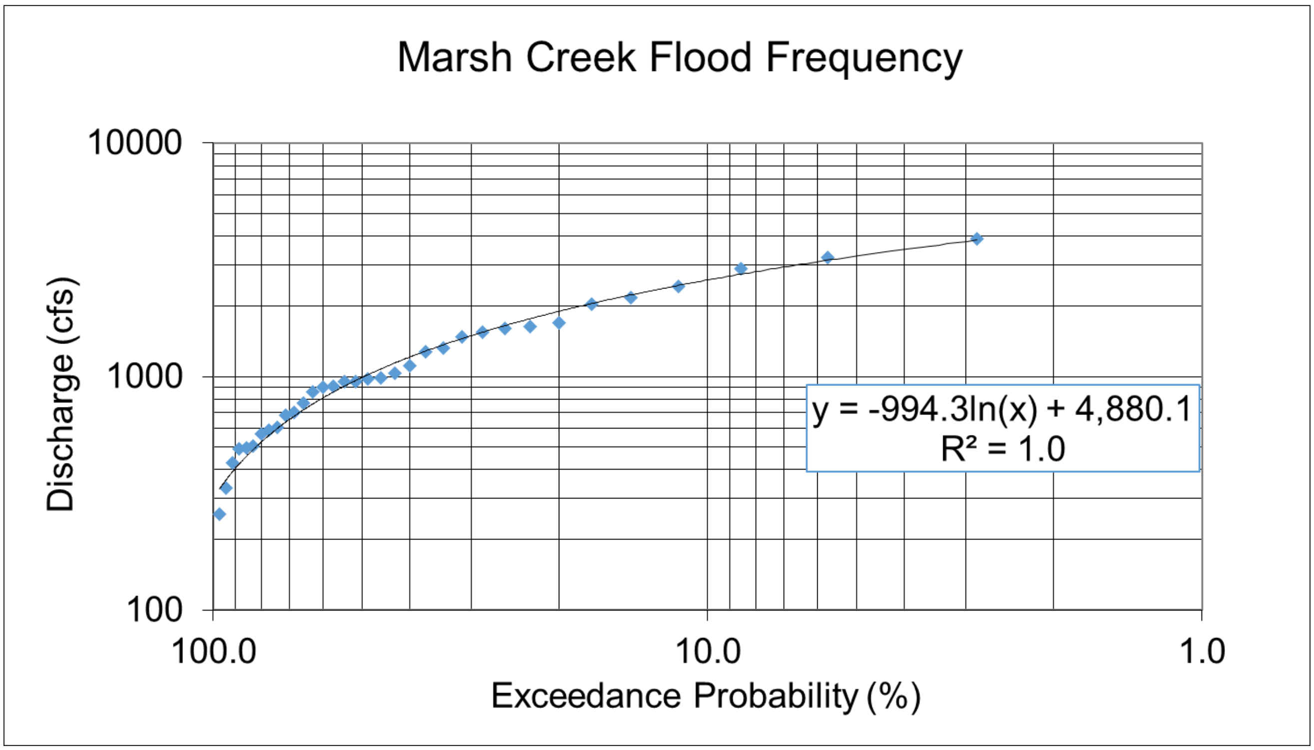
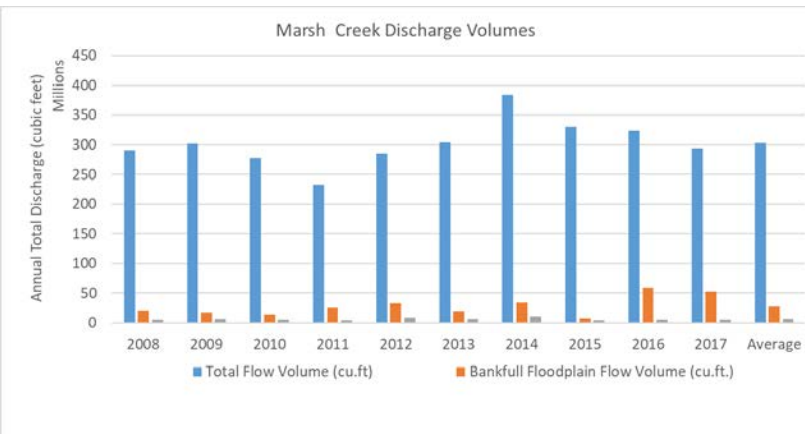


Figure 25: Flood frequency curve for Marsh Creek for annual peaks obtained from USGS gaging station for 34 years of record (1984 to 2017).

Table 38. Annual and average floodplain flow and nutrient removal totals for Marsh Creek.

Year	Total Flow Volume (cu.ft)	Bankfull Floodplain Flow Volume (cu.ft.)	Bankfull Treatment Volume (cu.ft.)	Number of Storm Events at Bankfull Stage or Greater	% Volume on Floodplain	% Treatment Volume/ Total Volume	Total Nitrogen Load (lbs)	Floodplain Nitrogen Load (lbs)	Treatment Nitrogen Load (lbs)	Total Load Removed (lbs)	% Total Nitrogen Removed
2008	290911392	20311200	5111100	7	7.0%	1.8%	14166	989	249	50	0.4%
2009	301937760	17375400	5895000	10	5.8%	2.0%	14703	846	287	57	0.4%
2010	278087904	13584600	4914180	10	4.9%	1.8%	13541	661	239	48	0.4%
2011	232362432	26375400	4153860	5	11.4%	1.8%	11315	1284	202	40	0.4%
2012	284824512	32727600	8451540	13	11.5%	3.0%	13869	1594	412	82	0.6%
2013	303516288	19830600	6402420	9	6.5%	2.1%	14779	966	312	62	0.4%
2014	384226848	34217100	10374480	15	8.9%	2.7%	18709	1666	505	101	0.5%
2015	330613056	7727400	3952260	9	2.3%	1.2%	16099	376	192	38	0.2%
2016	323714880	58798800	5591880	7	18.2%	1.7%	15763	2863	272	54	0.3%
2017	293989824	52976700	4859100	6	18.0%	1.7%	14315	2580	237	47	0.3%
Average	**302418490**	**28392480**	**5970582**	**9**	**9.4%**	**2.0%**	**14726**	**1383**	**291**	**58**	**0.4%**



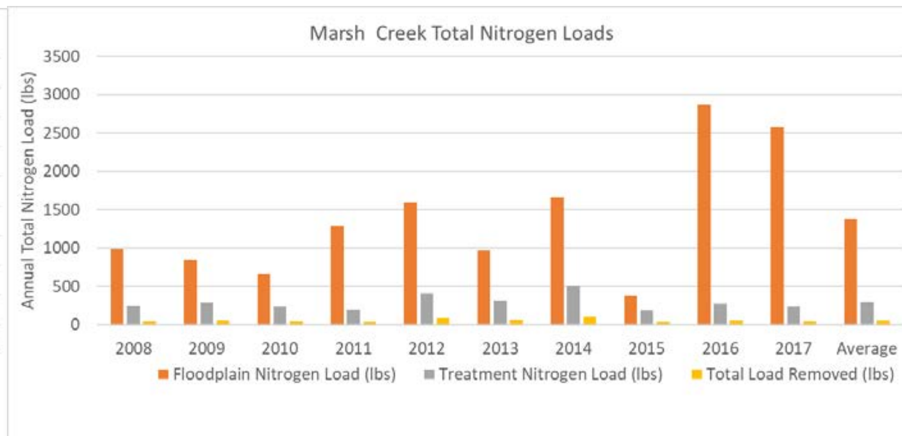


Figure 26: Graphical summary of discharge volumes (left) and nutrient load (right) totals for Marsh Creek

Table 39.Rocky Branch gage, watershed and stream characteristics.

Stream Name	Rocky Branch
Location	Raleigh, NC
USGS Gage Number	0208735012
Gage Watershed Area (sq. mi.)	1.17
Watershed Area (sq. mi.)	0.98
% Impervious	40
Floodplain Area & % of Watershed Area	8.4 acres = 1.3%
Bankfull Discharge (Qbkf)	130
Top of Bank Discharge (Qtob)	335
Qdeparture ratio	1.44
Average Q>Qbkf events	18.2

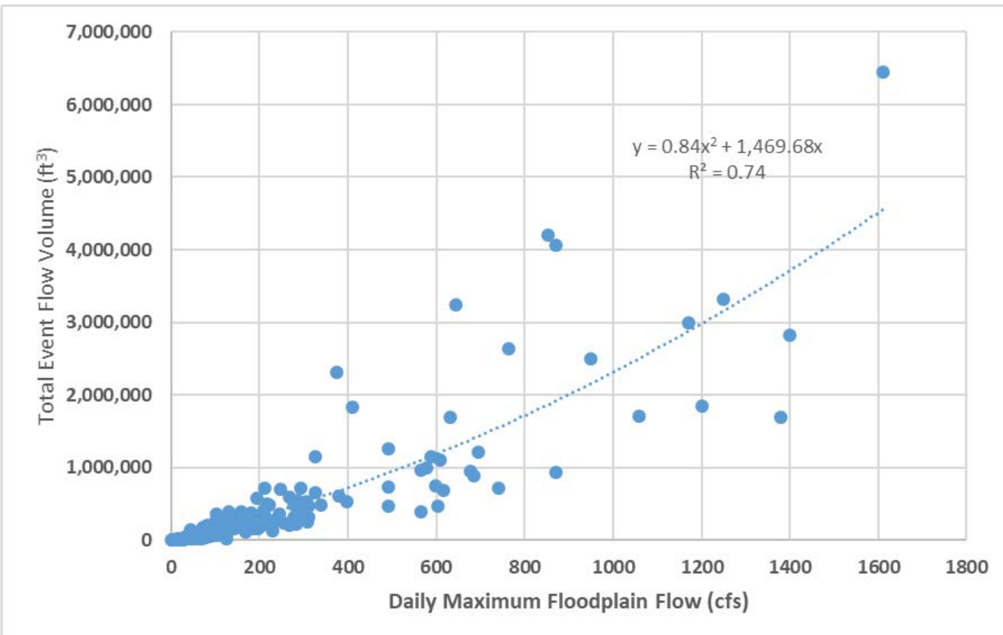


Figure 27. Quadratic regression of total event flow volume versus daily maximum floodplain flow. Three tropical storm events were removed as outliers.

Table 40. Annual and average floodplain flow and nutrient removal totals for Rocky Branch.

Year	Total Flow Volume (cu.ft)	Bankfull Floodplain Flow Volume (cu.ft.)	Bankfull Treatment Volume (cu.ft.)	Number of Storm Events at Bankfull Stage or Greater	% Volume on Floodplain	% Treatment Volume/ Total Volume	Total Nitrogen Load (lbs)	Floodplain Nitrogen Load (lbs)	Treatment Nitrogen Load (lbs)	Total Load Removed (lbs)	% Total Nitrogen Removed
2008	57960576	9086100	2698224	16	15.7%	4.7%	6622	1038	308	62	0.9%
2009	72853344	10176600	3845124	19	14.0%	5.3%	8323	1163	439	88	1.1%
2010	57765312	4017900	2963316	16	7.0%	5.1%	6599	459	339	68	1.0%
2011	54416448	7080600	3629916	20	13.0%	6.7%	6217	809	415	83	1.3%
2012	59488128	9002775	4257528	22	15.1%	7.2%	6796	1029	486	97	1.4%
2013	63293184	10328905	3461476	14	16.3%	5.5%	7231	1180	395	79	1.1%
2014	84284928	17406291	4829619	20	20.7%	5.7%	9629	1989	552	110	1.1%
2015	78747552	6326340	4535677	20	8.0%	5.8%	8996	723	518	104	1.2%
2016	87322752	31865100	4321332	21	36.5%	4.9%	9976	3640	494	99	1.0%
2017	62445600	14342100	3730128	15	23.0%	6.0%	7134	1638	426	85	1.2%
Average	**67857782.4**	**11963271**	**3827234**	**18**	**16.9%**	**5.7%**	**7752**	**1367**	**437**	**87**	**1.1%**

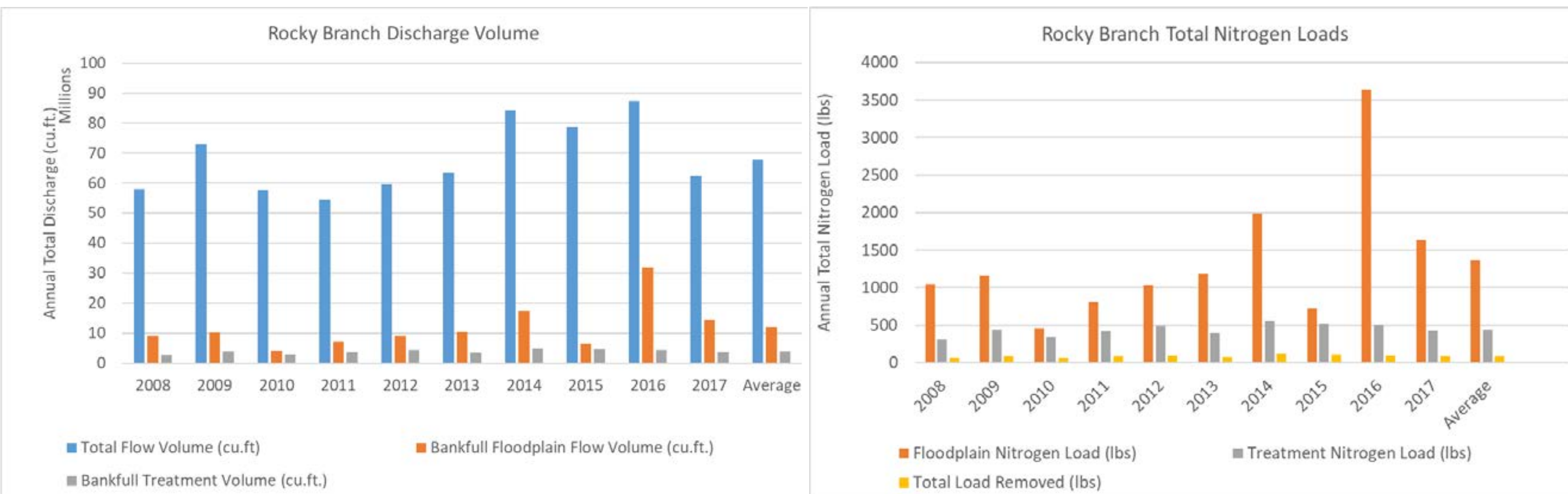


Figure 28: Graphical summary of discharge volumes (left) and nutrient load (right) totals for Rocky Branch

Table 41. Sandy Creek gage, watershed and stream characteristics.

Stream Name	Sandy Creek
Location	Durham, NC
USGS Gage Number	209722970
Gage Watershed Area (sq. mi.)	2.65
Watershed Area (sq. mi.)	1.72
% Impervious	17
Floodplain Area & % of Watershed Area	8.1 acres = 0.74%
Bankfull Discharge (Qbkf)	150
Top of Bank Discharge (Qtob)	1130
Qdeparture ratio	1.11
Average Q>Qbkf events	10.9

Table 42. Annual and average floodplain flow and nutrient removal totals for Sandy Creek.

Year	Total Flow Volume (cu.ft)	Bankfull Floodplain Flow Volume (cu.ft.)	Bankfull Treatment Volume (cu.ft.)	Number of Storm Events at Bankfull Stage or Greater	% Volume on Floodplain	% Treatment Volume/ Total Volume	Total Nitrogen Load (lbs)	Floodplain Nitrogen Load (lbs)	Treatment Nitrogen Load (lbs)	Total Load Removed (lbs)	% Total Nitrogen Removed
2008	113821632	3650400	1703340	8	3.2%	1.5%	5933	190	89	18	0.3%
2009	314659296	14738700	2748900	12	4.7%	0.9%	16402	768	143	29	0.2%
2010	240814080	2582280	1787760	7	1.1%	0.7%	12553	135	93	19	0.1%
2011	114438528	1477380	967740	6	1.3%	0.8%	5965	77	50	10	0.2%
2012	115846848	5086020	1282080	7	4.4%	1.1%	6039	265	67	13	0.2%
2013	212488704	32247000	4375800	16	15.2%	2.1%	11076	1681	228	46	0.4%
2014	226094112	29051100	4720140	16	12.8%	2.1%	11786	1514	246	49	0.4%
2015	230973984	24201900	3958020	16	10.5%	1.7%	12040	1262	206	41	0.3%
2016	201961728	27675000	3210660	12	13.7%	1.6%	10528	1443	167	33	0.3%
2017	166391712	17015100	2296500	9	10.2%	1.4%	8674	887	120	24	0.3%
Average	**193749062.4**	**15772488**	**2705094**	**11**	**7.7%**	**1.4%**	**10100**	**822**	**141**	**28**	**0.3%**

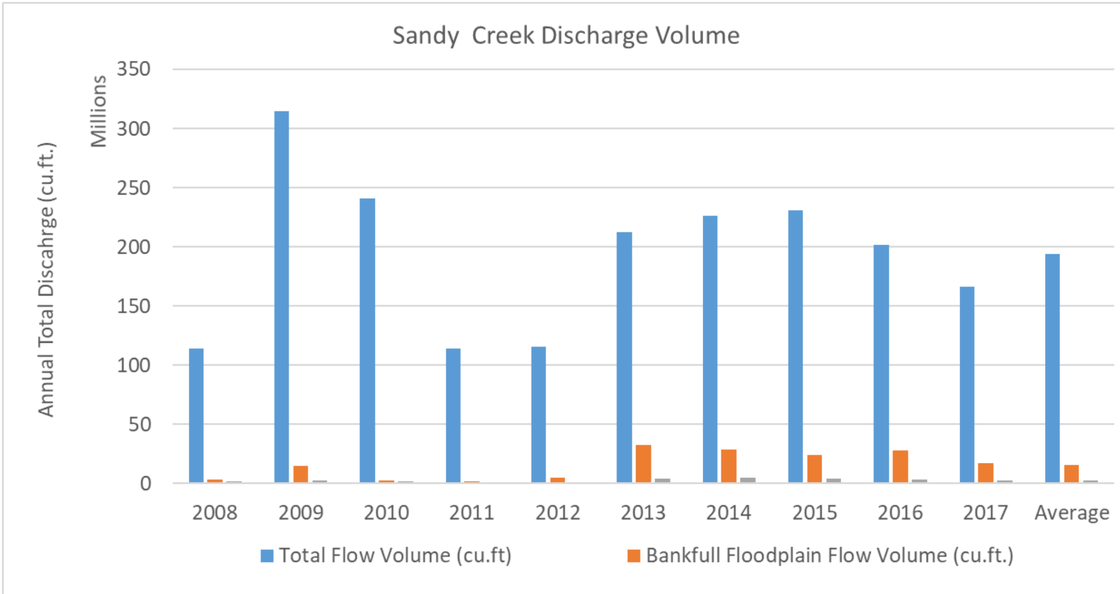


Figure 29: Graphical summary of discharge volumes for Sandy Creek

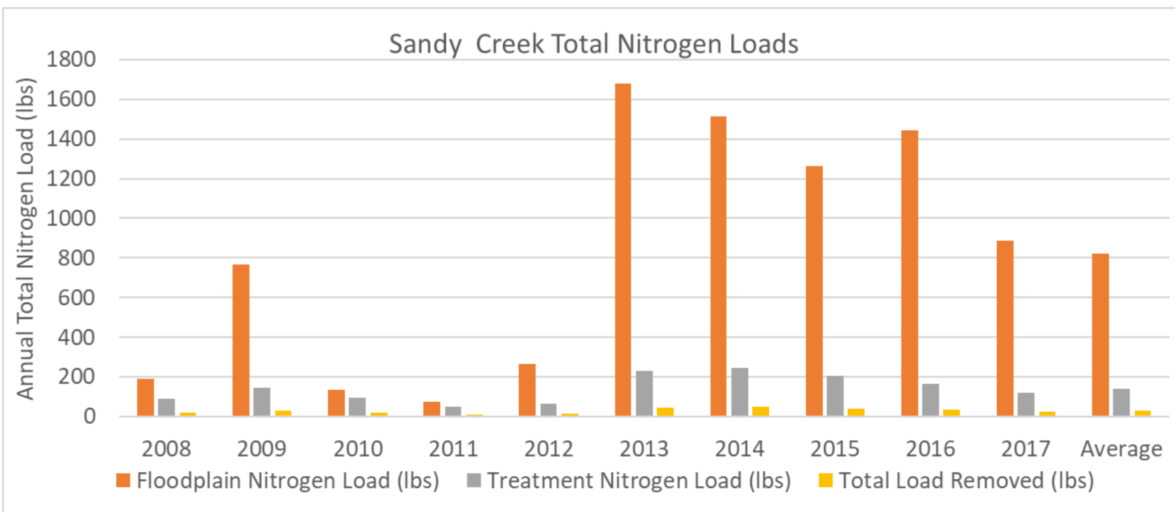


Figure 30: Graphical summary of nutrient load (right) totals for Sandy Creek

Table 43. Swift Creek gage, watershed and stream characteristics.

Stream Name	Sandy Creek
Location	Apex, NC
USGS Gage Number	2087580
Gage Watershed Area (sq.mi.)	21
% Impervious	16
Floodplain Area & % of Watershed Area	41.3 acres = 0.31%
Bankfull Discharge (Qbkf)	660
Top of Bank Discharge (Qtob)	1200
Qdeparture ratio	0.83
Average Q>Qbkf events	4.6

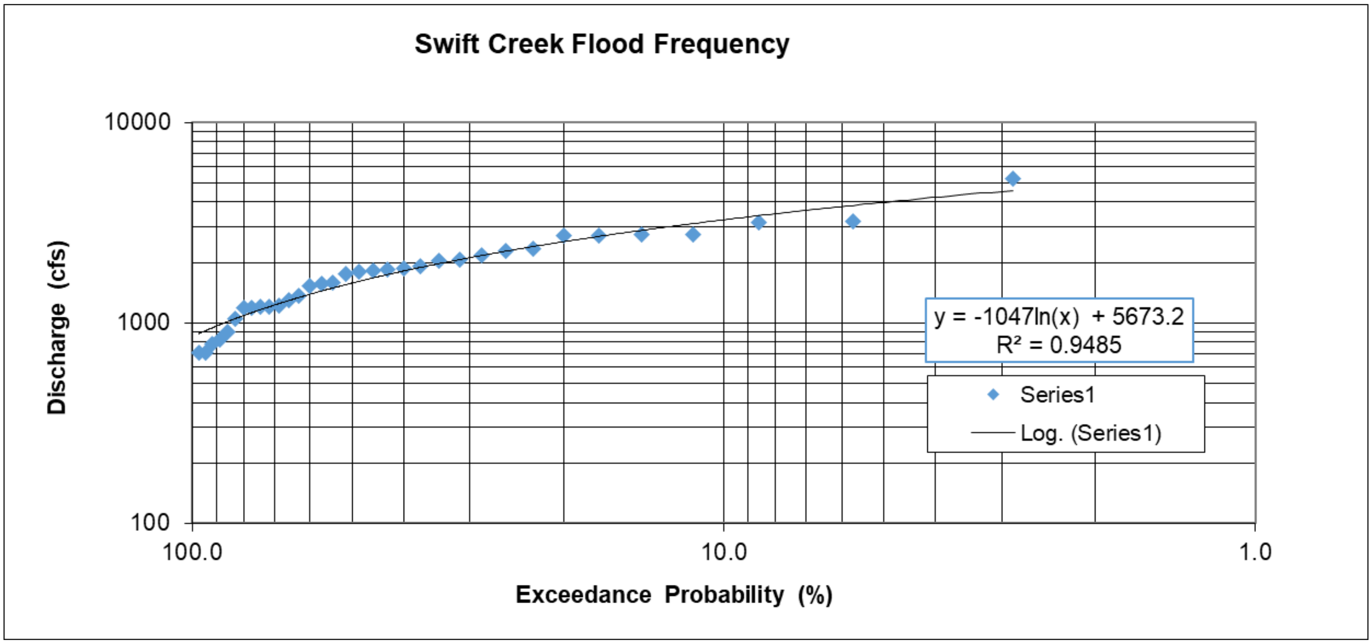


Figure 31: Flood frequency curve for Swift Creek for annual peaks obtained from USGS gaging station for 34 years of record (1954-1971 and 2001- 2017)

Table 44. Annual and average floodplain flow and nutrient removal totals for Swift Creek (existing un-restored condition).

Year	Total Flow Volume (cu.ft)	Existing Floodplain Flow Volume (cu.ft)	Existing Annual Treatment Volume (cu.ft.)	Number of Storm Events above TOB	% Volume on Existing Floodplain	% Treatment Volume/ Total Volume	Existing Floodplain Nitrogen Load (lbs)	Existing Treatment Nitrogen Load (lbs)	Existing Total Load Removed (lbs)	% Total Nitrogen Removed
2008	649631232	36396000	3598056	2	5.6%	0.6%	1409	139	28	0.1%
2009	804408192	37908000	5101056	4	4.7%	0.6%	1467	197	39	0.1%
2010	654138720	4383000	2213028	2	0.7%	0.3%	170	86	17	0.1%
2011	410565888	72000	72000	2	0.0%	0.0%	3	3	1	0.0%
2012	461436480	603000	603000	1	0.1%	0.1%	23	23	5	0.0%
2013	590268384	9576000	1799028	1	1.6%	0.3%	371	70	14	0.1%
2014	909774720	23292000	6621084	5	2.6%	0.7%	902	256	51	0.1%
2015	998221536	2691000	2691000	3	0.3%	0.3%	104	104	21	0.1%
2016	874806048	71343000	3598056	2	8.2%	0.4%	2761	139	28	0.1%
2017	544758048	13095000	1799028	1	2.4%	0.3%	507	70	14	0.1%
Average	**689800925**	**19935900**	**2809534**	**2**	**2.6%**	**0.4%**	**771.6**	**108.7**	**22**	**0.1%**

Table 45. Annual and average floodplain flow and nutrient removal totals for Swift Creek (post-restoration condition). The change in the treated nutrient load in pounds and percentage that result from the theoretical floodplain reconnection at the bankfull stage are provided in the last two columns.

Year	Total Flow Volume (cu.ft)	Bankfull Floodplain Flow Volume (cu.ft.)	Bankfull Treatment Volume (cu.ft.)	Storm Events at Bankfull Stage or Greater	% Volume on Floodplain	% Treatment Volume/ Total Volume	Total Nitrogen Load (lbs)	Floodplain Nitrogen Load (lbs)	Treatment Nitrogen Load (lbs)	Total Load Removed (lbs)	% Total Nitrogen Removed	Delta Load	Delta %
2008	649631232	83375100	3598056	2	12.8%	0.6%	25144	3227	139	62.7	0.2%	34.8	0.1%
2009	804408192	104976000	10794168	6	13.1%	1.3%	31135	4063	418	188.0	0.6%	148.5	0.5%
2010	654138720	36399600	4519656	5	5.6%	0.7%	25319	1409	175	78.7	0.3%	61.6	0.2%
2011	410565888	25428600	5397084	3	6.2%	1.3%	15891	984	209	94.0	0.6%	93.4	0.6%
2012	461436480	20462400	3598056	2	4.4%	0.8%	17860	792	139	62.7	0.4%	58.0	0.3%
2013	590268384	31635900	3799656	4	5.4%	0.6%	22847	1224	147	66.2	0.3%	52.3	0.2%
2014	909774720	123435000	12593196	7	13.6%	1.4%	35213	4778	487	219.3	0.6%	168.1	0.5%
2015	998221536	49893300	11432268	8	5.0%	1.1%	38637	1931	442	199.1	0.5%	178.3	0.5%
2016	874806048	131877900	9798012	6	15.1%	1.1%	33860	5104	379	170.7	0.5%	142.8	0.4%
2017	544758048	47939400	3599856	3	8.8%	0.7%	21085	1856	139	62.7	0.3%	48.8	0.2%
Average	**689800925**	**65542320**	**6913001**	**4.6**	**9.0%**	**1.0%**	**26699**	**2537**	**268**	**120**	**0.4%**	**99**	**0.4%**

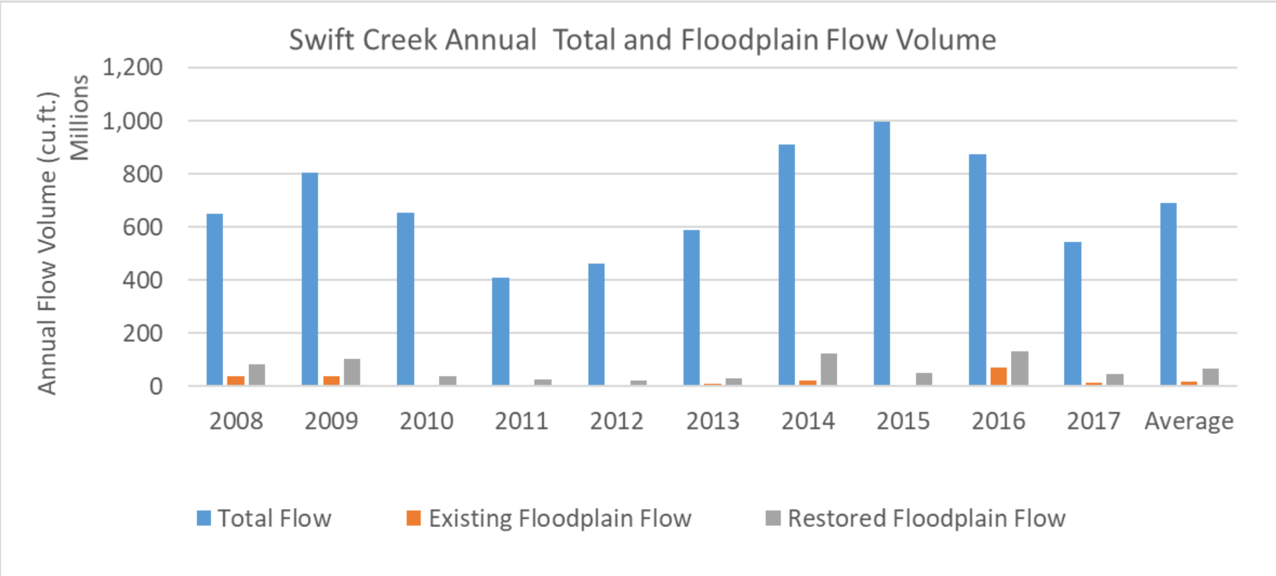


Figure 32: Graphical summary of total and floodplain discharge volumes for existing and theoretical restoration at Swift Creek

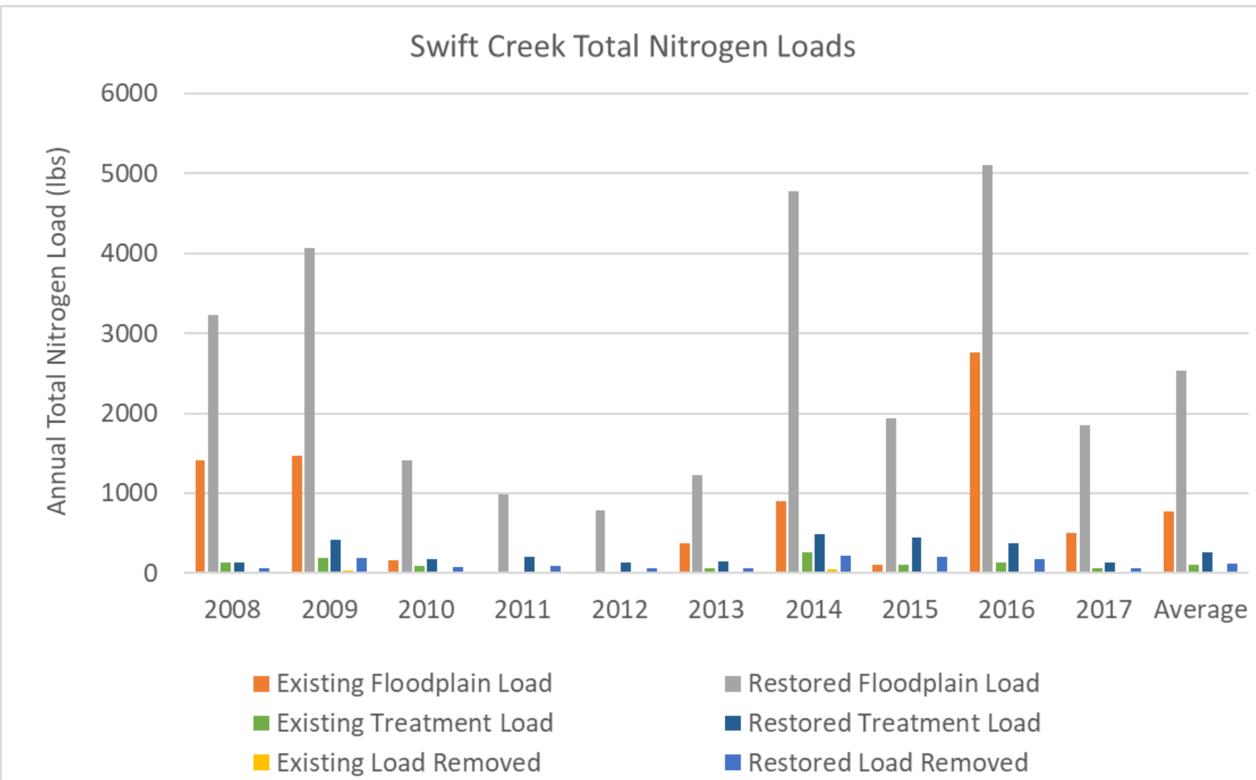


Figure 33: Graphical summary of floodplain, treatment and removed total nitrogen loads for existing and theoretical restoration at Swift Creek

Table 46. Torrence Creek gage, watershed and stream characteristics.

Stream Name	Sandy Creek
Location	Huntersville, NC
USGS Gage Number	214265808
Gage Watershed Area (sq. mi.)	7.29
Watershed Area (sq. mi.)	3.6
% Impervious	16
Floodplain Area & % of Watershed Area	5.2 acres = 0.23%
Bankfull Discharge (Qbkf)	70
Top of Bank Discharge (Qtob)	376
Qdeparture ratio	0.31
Average Q>Qbkf events	17.8

Table 47. Annual and average floodplain flow and nutrient removal totals for Torrence Creek.

Year	Total Flow Volume (cu.ft)	Bankfull Floodplain Flow Volume (cu.ft.)	Bankfull Treatment Volume (cu.ft.)	Number of Storm Events at Bankfull Stage or Greater	% Volume on Floodplain	% Treatment Volume/ Total Volume	Total Nitrogen Load (lbs)	Floodplain Nitrogen Load (lbs)	Treatment Nitrogen Load (lbs)	Total Load Removed (lbs)	% Total Nitrogen Removed
2008	133683264	7468140	3019668	17	5.6%	2.3%	4642	259	105	21	0.5%
2009	187010208	11281524	2900028	20	6.0%	1.6%	6494	392	101	20	0.3%
2010	126989856	4750200	1161648	8	3.7%	0.9%	4410	165	40	8	0.2%
2011	167282496	7046550	3346704	22	4.2%	2.0%	5809	245	116	23	0.4%
2012	119357280	4153140	1465182	9	3.5%	1.2%	4145	144	51	10	0.2%
2013	212537952	14842680	3670122	24	7.0%	1.7%	7381	515	127	25	0.3%
2014	215464320	15981240	3519504	24	7.4%	1.6%	7482	555	122	24	0.3%
2015	186211872	14193360	3092064	16	7.6%	1.7%	6466	493	107	21	0.3%
2016	133697952	6697710	2168856	13	5.0%	1.6%	4643	233	75	15	0.3%
2017	164732832	20338382	4599768	25	12.3%	2.8%	5720	706	160	32	0.6%
Average	**164696803.2**	**10675293**	**2894354**	**18**	**6.2%**	**1.7%**	**5719**	**371**	**101**	**20**	**0.3%**

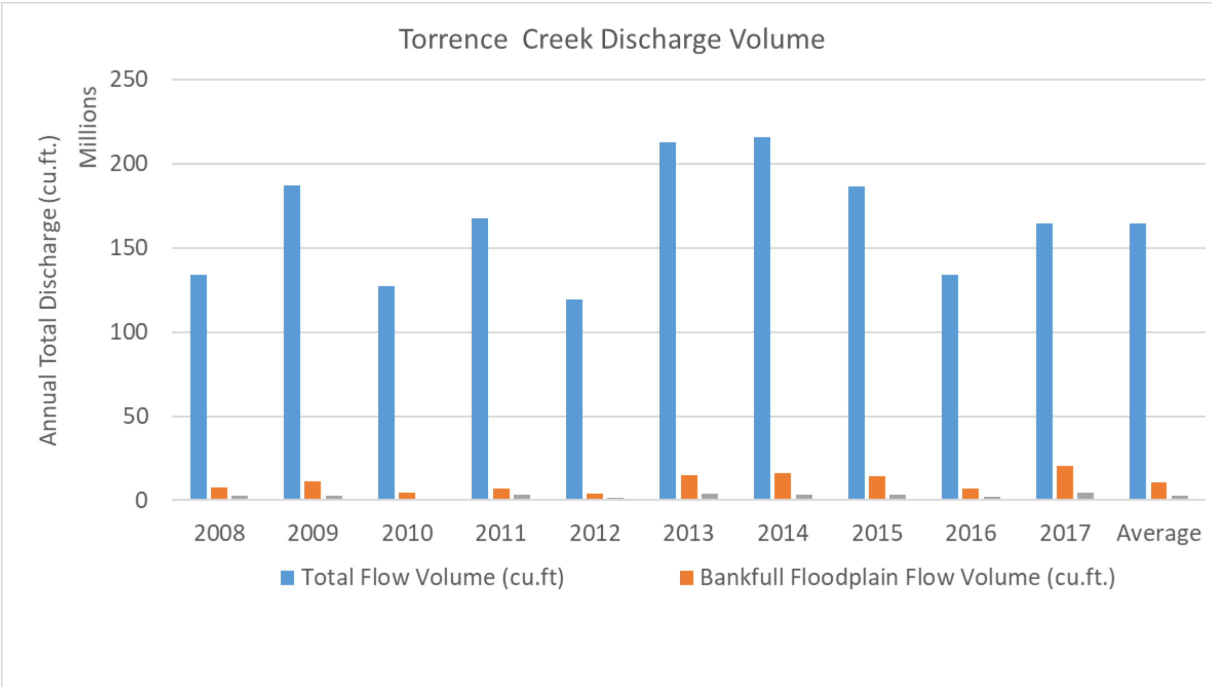


Figure 34: Graphical summary of discharge volumes for Torrence Creek

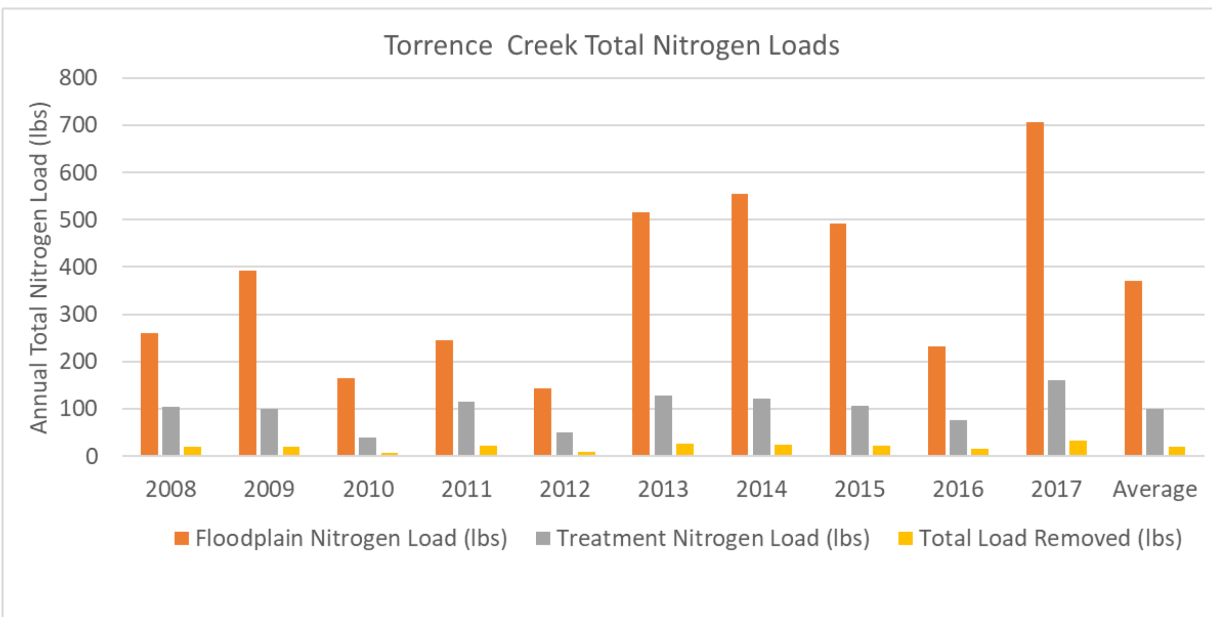


Figure 35: Graphical summary of nutrient loads for Torrence Creek