Evaluation of Nutrient Reduction Crediting Strategies for Stream Restoration

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Background and Objectives

Background

- NC DWR interested in developing standards for awarding nutrients credits for stream restorations based on Chesapeake Bay Protocol (CBP) credit

Objectives

1. Estimate nutrient reduction and the associated credit for typical urban stream restoration projects
2. Evaluate the feasibility and accuracy of the protocol
3. Quantify the level of effort
4. Identify opportunities to simplify and address shortcomings
5. Develop modified nutrient credit standards applicable to NC

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Study Elements

- Reviewed Literature
- Tested CBP Protocols 1-3 at four Restored Streams
- Analyzed Gage Data to Evaluate Flood Flow Frequency (5 USGS Gages)

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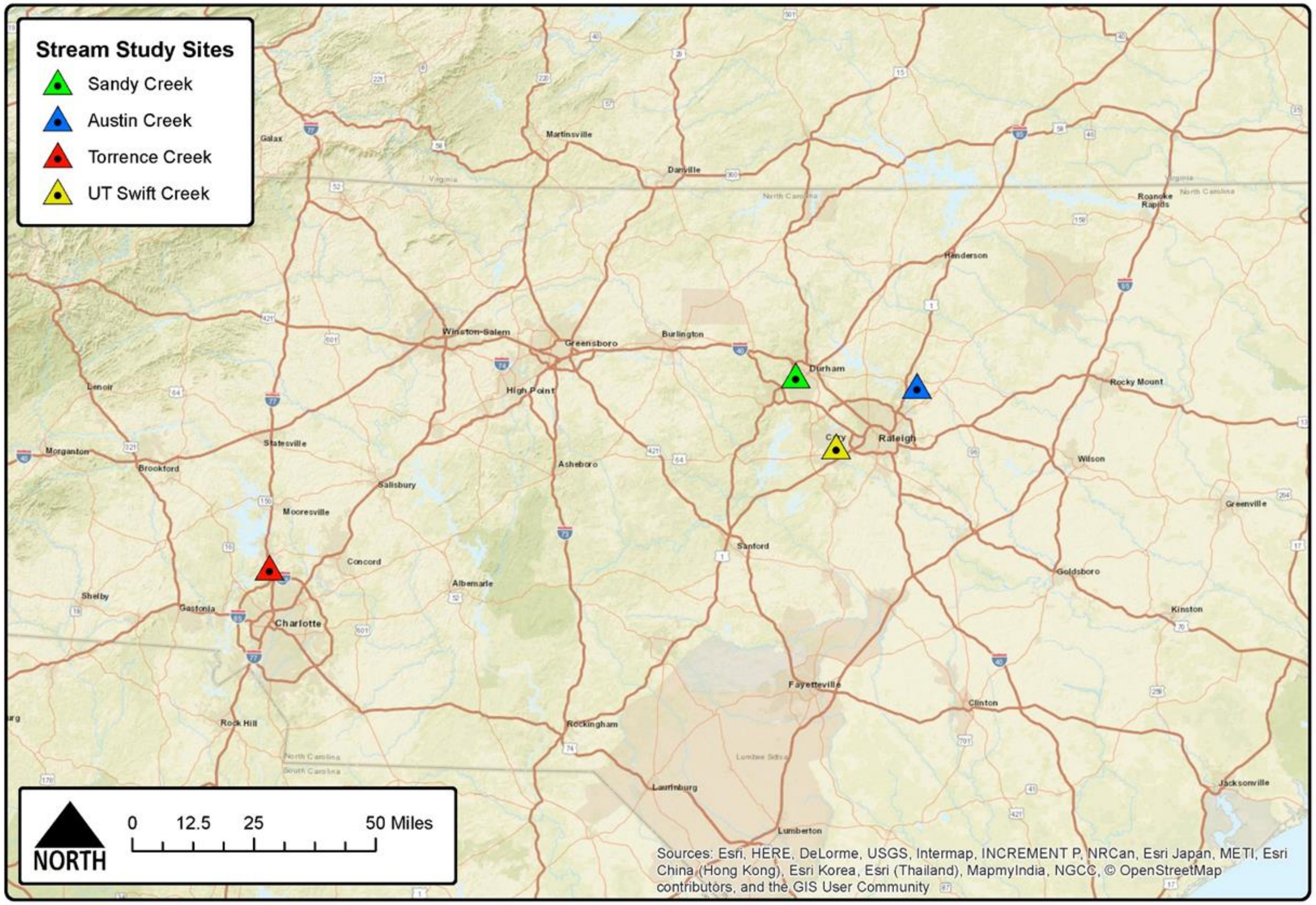
Literature Review Summary

- Nutrient removal via stream restoration literature is limited
- Lack of pre- and post-restoration studies
- Main nutrient removal processes:
  - Phosphorus
    - Bank erosion
  - Nitrogen
    - Biogeochemical transformations
      - Streambed
      - Riparian zones
- Bank stabilization works for preventing the introduction of nutrients via erosion
- In-stream and floodplain nutrient removal highly variable and complicated
- Recent review (2017) by Lammers and Bledsoe provides best overview of nutrient removal via stream restorations
  - Lammers, R.W., Bledsoe, B.P., 2017. What role does stream restoration play in nutrient management? Crit. Rev. Environ. Sci. Technol. 47, 335–371. doi:10.1080/10643389.2017.1318618



Case Study Application

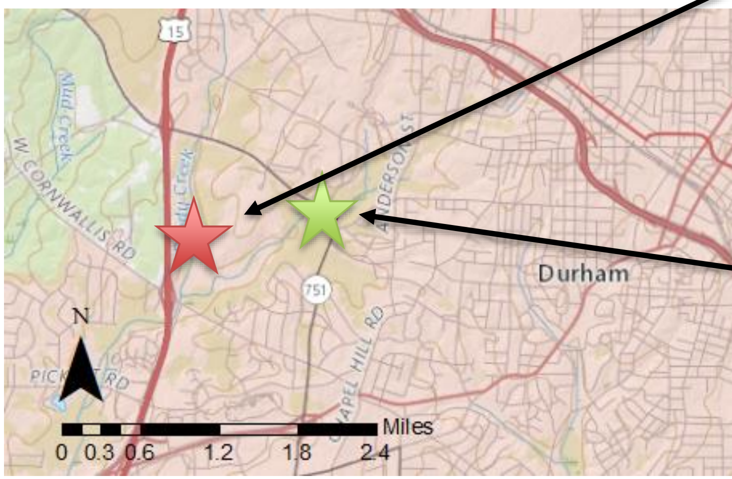
Site	Location	Drainage Area (mi^2)	Reach Length (ft)	Year Restored
Higgins Trail	Cary, NC	0.8	3,225	2012
Austin Creek	Wake Forest, NC	8.6	3,074	2002
Sandy Creek	Durham, NC	1.7	2,461	2003
Torrence Creek	Huntersville, NC	3.6	1,620	2013

Case Study Work - Protocol 1

- Applied BANCS and NBS method to each case study site and paired with nearby degraded reach
  - Pre-restoration BANCS and NBS data available for Torrence Creek
- Collected sediment samples from streambanks
  - Analyzed for TN and TP
- Collected soil cores from streambank for bulk density analysis

Sandy Creek

- Durham, Durham County
- Urban watershed



	Drainage Area (sq. mi)
Degraded	2.0
Restored	1.7

Protocol 1: Sediment Concentrations

Method	TN (lb/ton sediment)	TP (lb/ton sediment)
Observed	1.34 ± 0.72 *	0.65 ± 0.35 *
CBP	2.28	1.05
Tetra Tech**	1.78	0.46

*3 samples taken from each stream (n=12)

** Tetra Tech sampled 128 streambed soil samples TN (n=19) and TP (n=109) concentrations in the NC Piedmont region)

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Protocol 1: Sediment Associated Nutrient Loss

- Applied BANCS and NBS method to case study sites and nearby degraded reaches
- Pre and post-retrofit BANCS and NBS available at Torrence only

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 Degraded	8554		121		57	
Mean		72%		75%		76%
Median		73%		80%		83%

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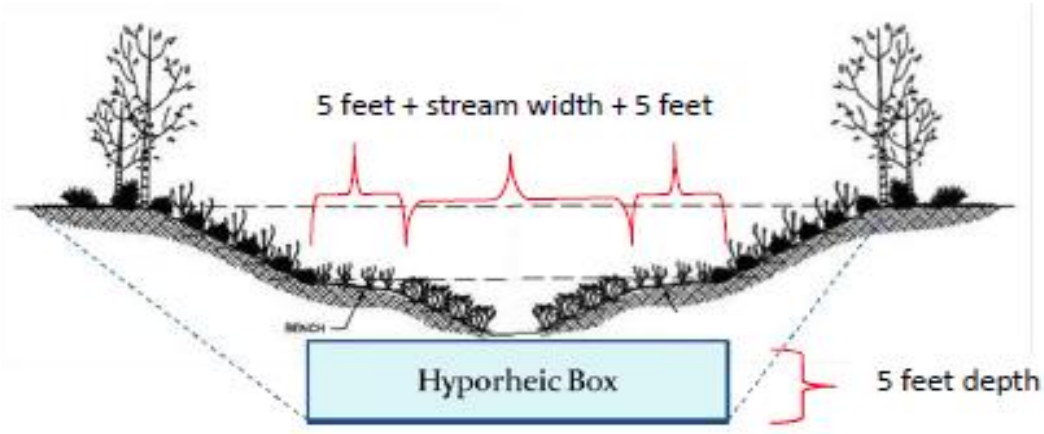
BANCS method vs. Bank Pin Data

- Sandy Creek at Duke University Bank Pin Study
- Pins installed May 2006.
- NCSU measured April 2018
- 12-year period average sediment load = 10.5 ton/yr
- BANCS method predicted 11.9 ton/yr
- 12% Difference → reasonable agreement

Case Study Work - Protocol 2

- Surveyed case study reaches and nearby degraded reaches
- Collected streambed samples to determine bulk density
- Applied to CBP 2 for BHR ≤ 1.0
- Augured riffles at each case study site to determine depth to confining layer to characterize hyporheic box
- Installed water quality sampling of baseflow for mass balance nutrient uptake rates



Protocol 2: Existing 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)	0.25	0.00	0.37	0.00	0.27	0.00	0.29	0.03

Protocol 2: Confining Layers

	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	1.0
	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		5.0		
Avg		3.1	1.4	2.2	1.5
Std. Dev.		1.1	1.3	1.7	0.3
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

- Average depth to confining layer (n = 33) was 2.0 ft
- Bottom of Higgins Trail restricted by bedrock
- CBP hyporheic box depth = 5 ft

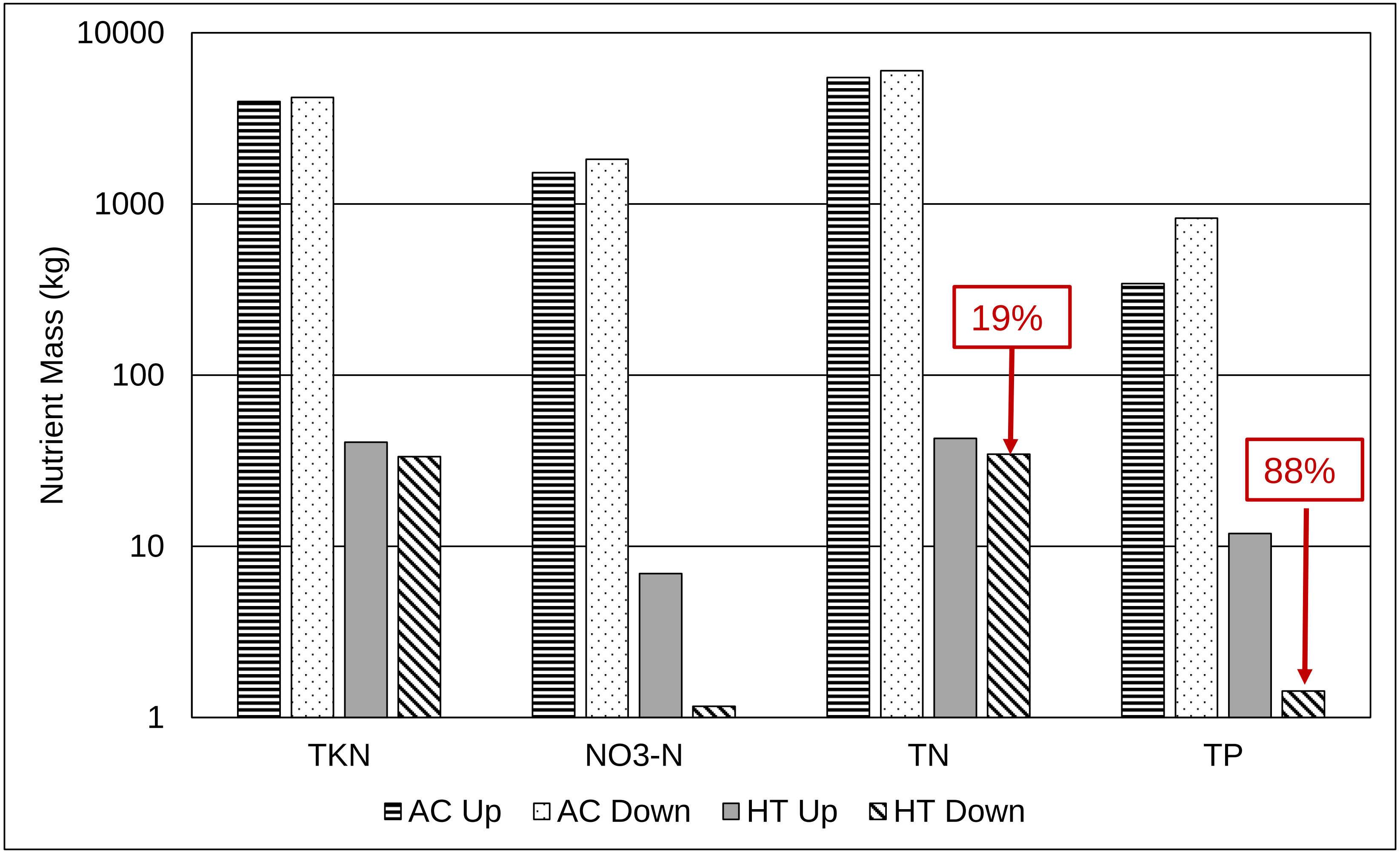
Protocol 2: Comparisons

Stream	CBP Credit (lb N/yr)	CBP Credit with Confining Layer (lb N/yr)	Δ (lb N/yr)
Higgins Trail Restored	757	176	-581
Austin Creek Restored	1133	703	-431
Sandy Creek Restored	659	293	-367
Torrence Creek Restored	470	140	-330

- CBP limits credit to 40% of watershed load
- Higgins Trail watershed N load = 1,891 lb/yr
  - 40% = 757 lb/yr
  - Calculated denitrification via CBP 2 = 798 lb/yr
- N cap not an issue with confining layer

Protocol 2: Baseflow Monitoring

Sampling from January – July 2018
Higgins Trail (HT) n = 11 and Austin Creek (AC) n = 8



Case Study Work - Protocol 3

- **Delineated the floodplain** area
- **Estimated floodplain volume** at 1 ft depth
- Conducted **landuse analysis** for each watershed (**ArcGIS**)
- **Estimated Watershed Loads** for TN, TP and TSS using EPA **STEPL** tool
- **Conducted watershed modeling** (**HEC-HMS**) to generate discharge volumes for various design storms (0.25 to 2 inches of r/f in 0.25" increments)
- **Conducted hydraulic modeling** (**HEC-RAS**) to determine the amount of rainfall that produces floodplain flow
- Used CBP curves to determine % of TN, TP and TSS load removed

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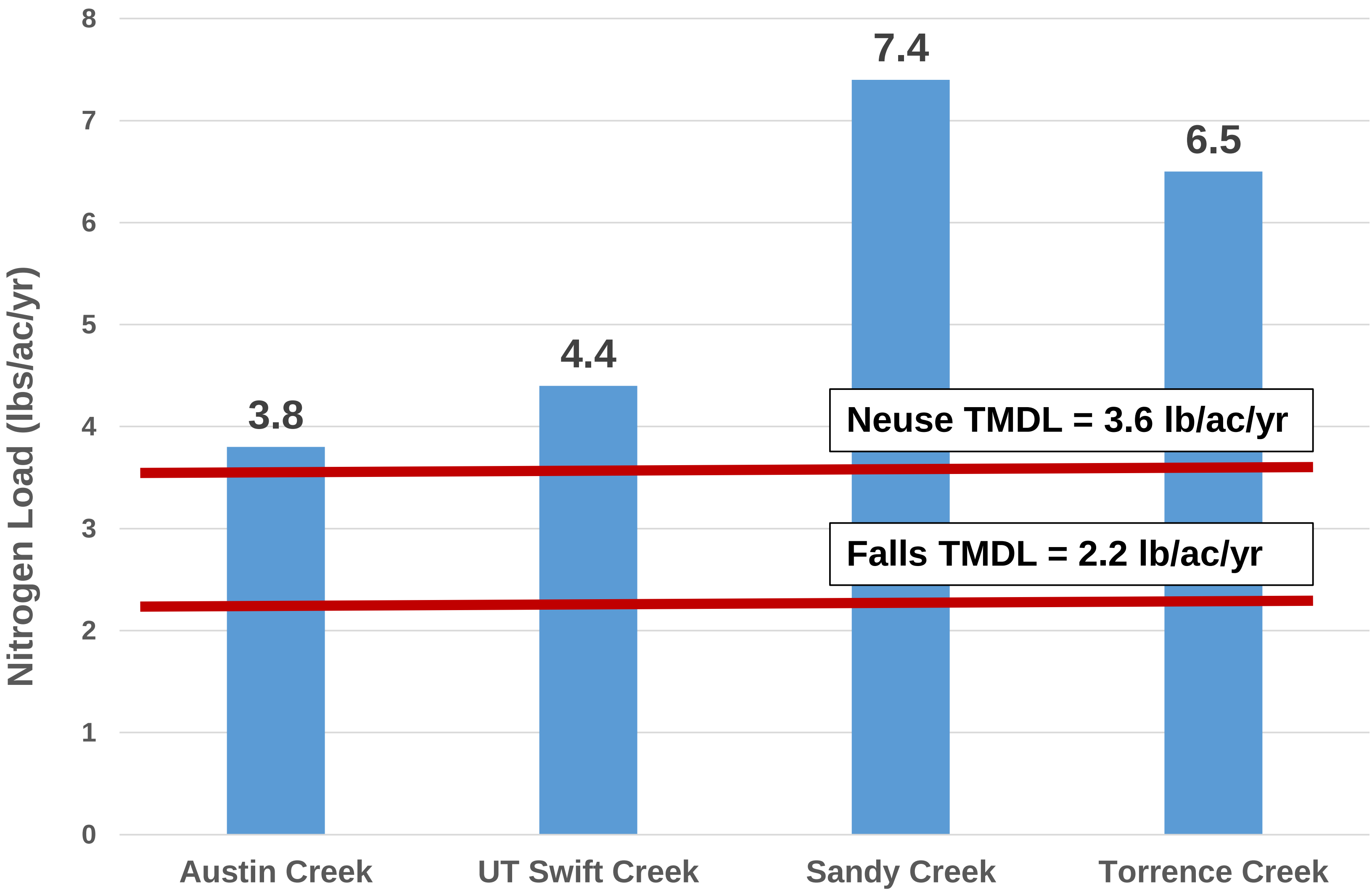
Watershed Total Nitrogen Load - EPA STEPL Model



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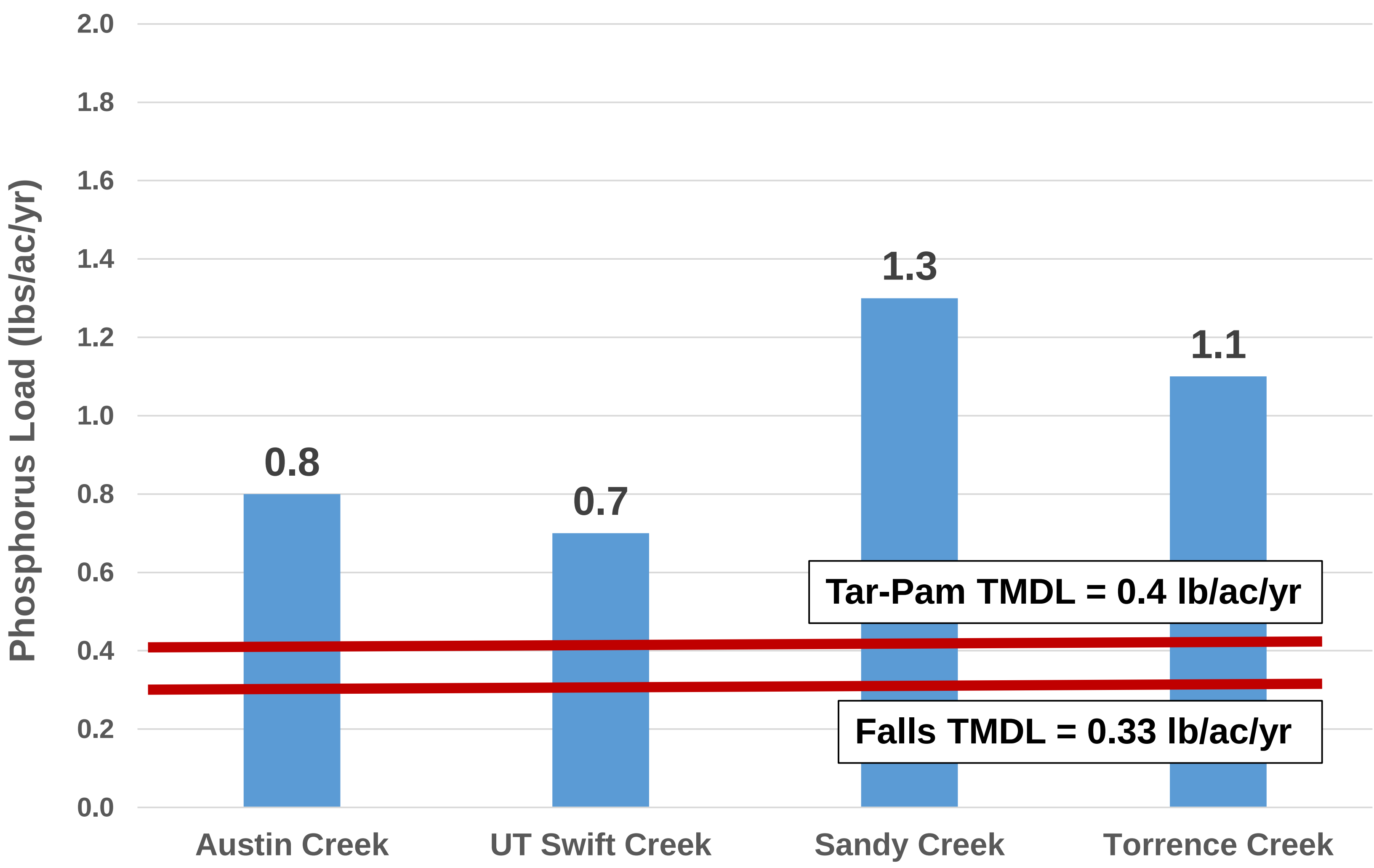
Watershed Total Phosphorus Load - EPA STEPL Model



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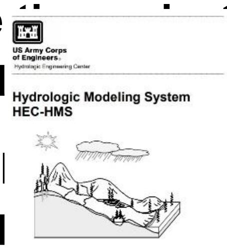
Existing Protocol 3: Inputs

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	5,517	6.7	0.12%	291,852	0.01	1.25
Higgins Trail	486	4.1	0.84%	178,596	0.10	1.00
Sandy Creek	1,094	8.1	0.74%	352,836	0.09	1.25
Torrence Creek	2,317	5.2	0.22%	224,334	0.03	0.50

1. **Determine t… …'s watershed area, floodplain area a… …ain area to watershed…**

2. **Estimate t… in connection volume up to a 1 foot … normalize by watershed… tain "Watershed Inches".**

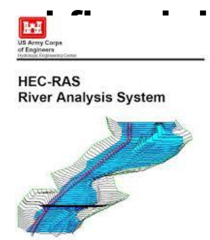
3. **Determine "design storm" depth to generate overbank flows.**



HEC-HMS

Watershed Hydrology

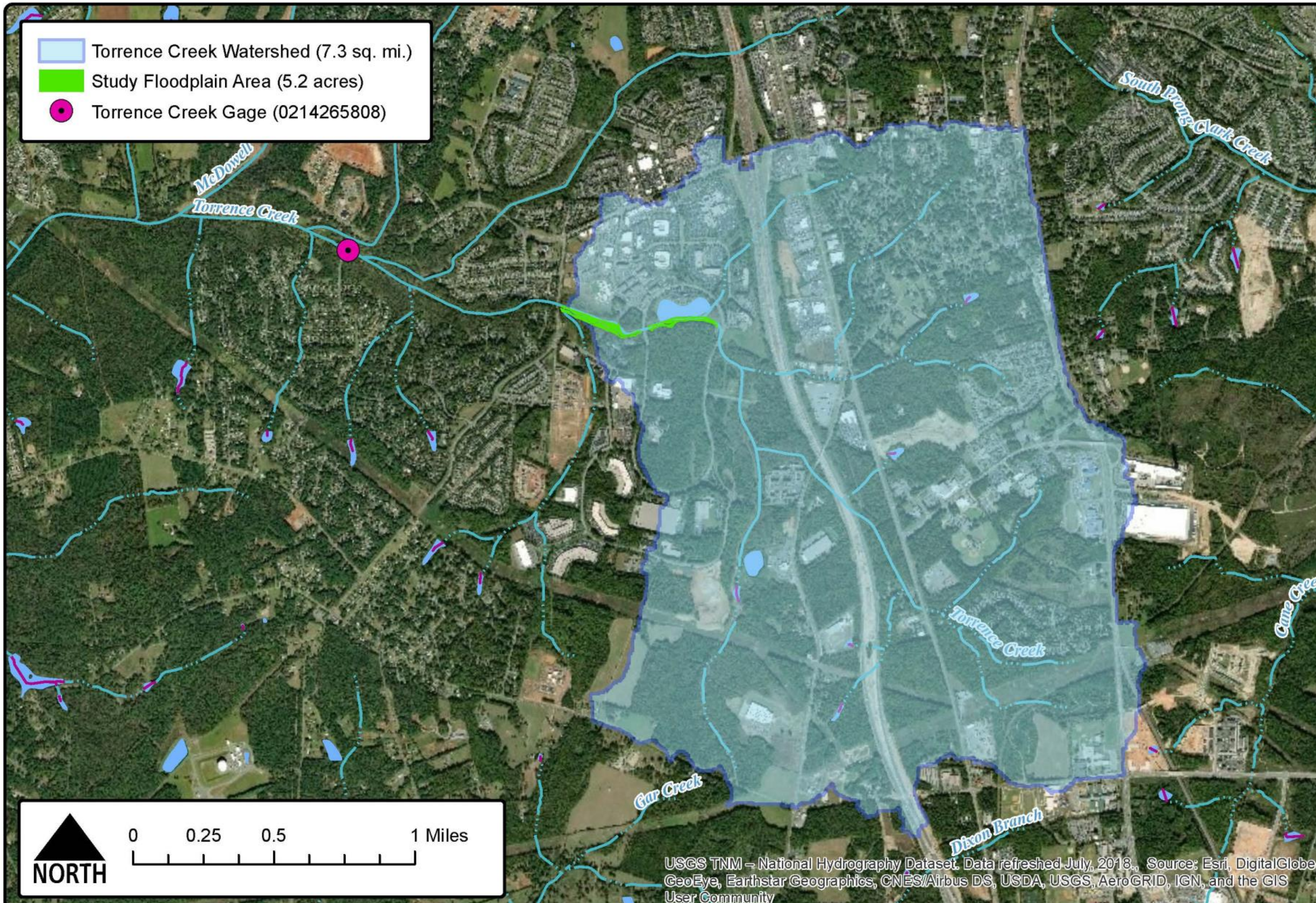
Design Storm Discharge



HEC-RAS

Stream Hydraulics

WSE / Overbank Flow

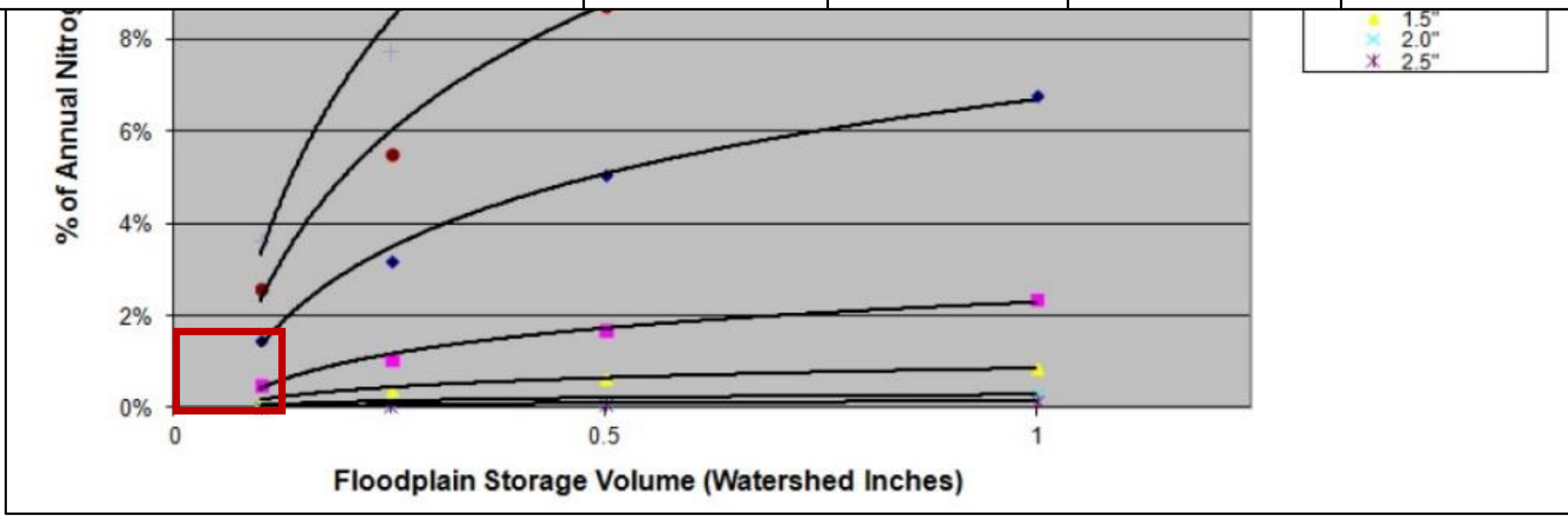


NC DEQ Evaluation of Nutrient Reduction Crediting Strategies for Stream Restoration

Torrence Creek - Huntersville, NC

Annual TN Removal

	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



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Annual TN Removal

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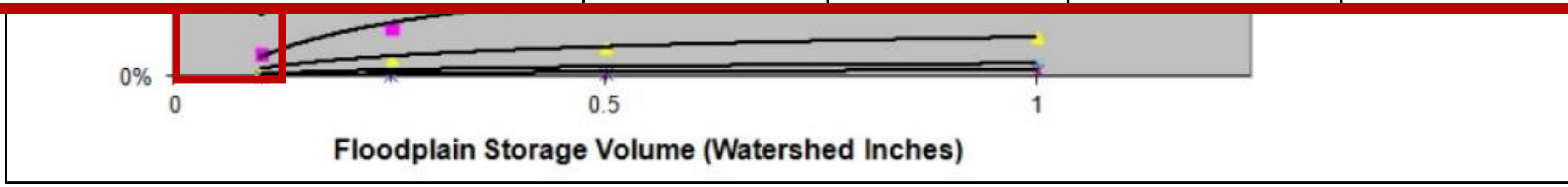
Watershed Load (lb/yr)	1,891	22,586	6,393	12,428
% Removed	0.5%	0.3%	0.3%	1.5%
Load Removed (lb/yr)	9.5	67.8	19.2	186.4
FA / WA Factor	0.84	0.12	0.74	0.22
Corrected Removal (lb/yr)	**8.0**	**8.1**	**14.2**	**41.0**
Corrected % Removed	**0.4%**	**0.0%**	**0.2%**	**0.3%**



Existing Protocol 3

- Floodplain Area to Watershed Area is small in most cases
- This is little to no resolution at the lower end of the curves
- Little nutrient and sediment retention achieved (0.0% - 0.8%)

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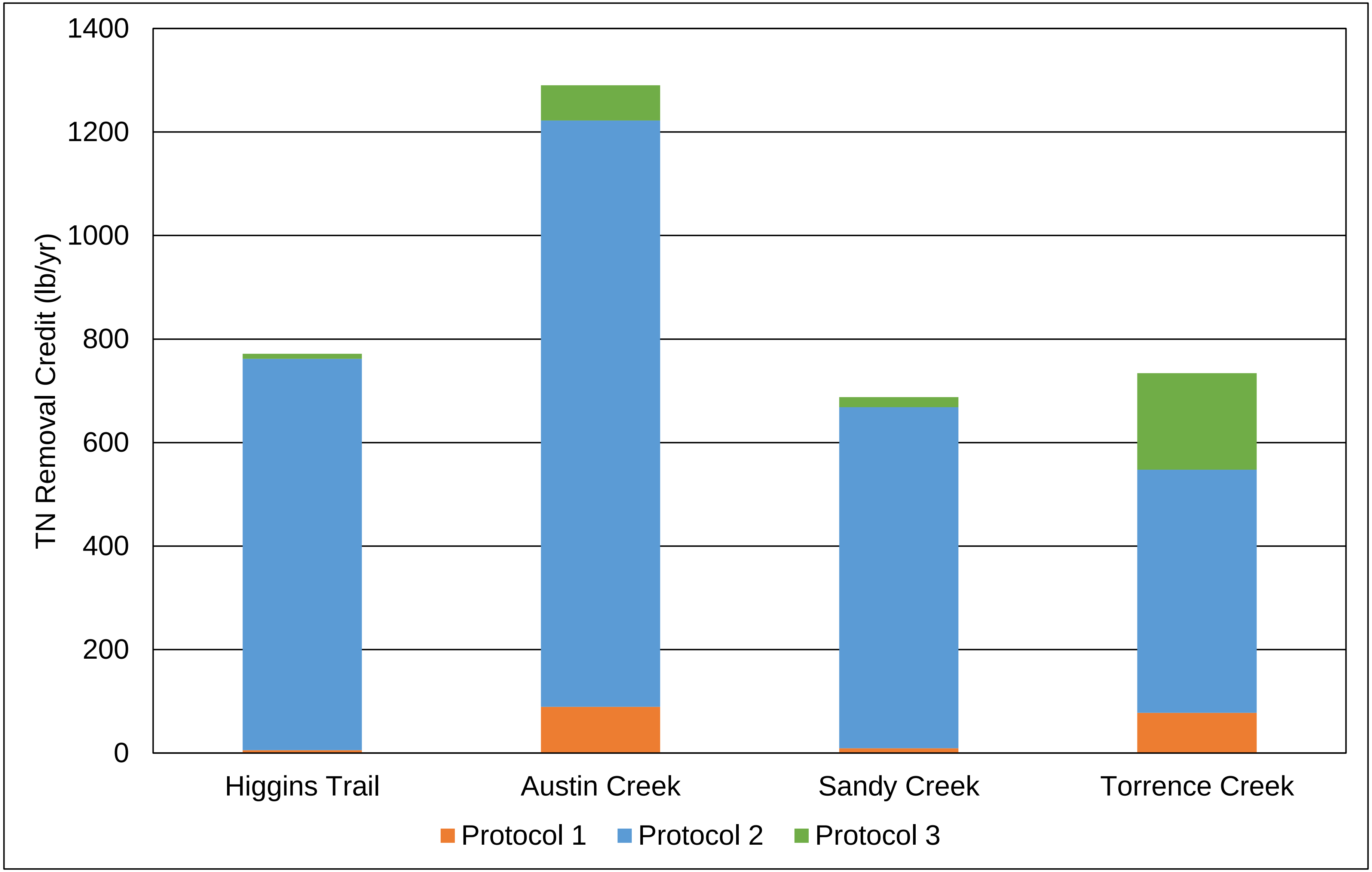
CBP Application Results

		Higgins Trail	Austin Creek	Sandy Creek	Torrence Creek
	Reach Length	3,225	3,074	2,461	1,620
	Constituent	**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 (lb/yr)	8	94	11	78
	TP (lb/yr)	4	43	5	36
	Sediment (ton/yr)	4	41	5	34
Protocol 2	TN (lb/yr)	757	1133	659	470
Protocol 3	TN (lb/yr)	8	8	14	41
	TP (lb/yr)	3	3	4	12
	Sediment (ton/yr)	0.2	0.5	0.3	1.7
Total Credit	**TN (lb/yr)**	**773**	**1236**	**684**	**589**
	TP (lb/yr)	**6**	**46**	**9**	**48**
	Sediment (ton/yr)	**4**	**42**	**5**	**36**
% Removed	**TN**	**40%**	**5%**	**11%**	**5%**
	TP	**2.0%**	**1.0%**	**0.8%**	**2.1%**
	Sediment	**27%**	**48%**	**24%**	**51.1%**

TN Credit


1400
1200
1000
800
600
400
200
0
TN Removal Credit (lb/yr)
Higgins Trail
Austin Creek
Sandy Creek
Torrence Creek
Protocol 1
Protocol 2
Protocol 3

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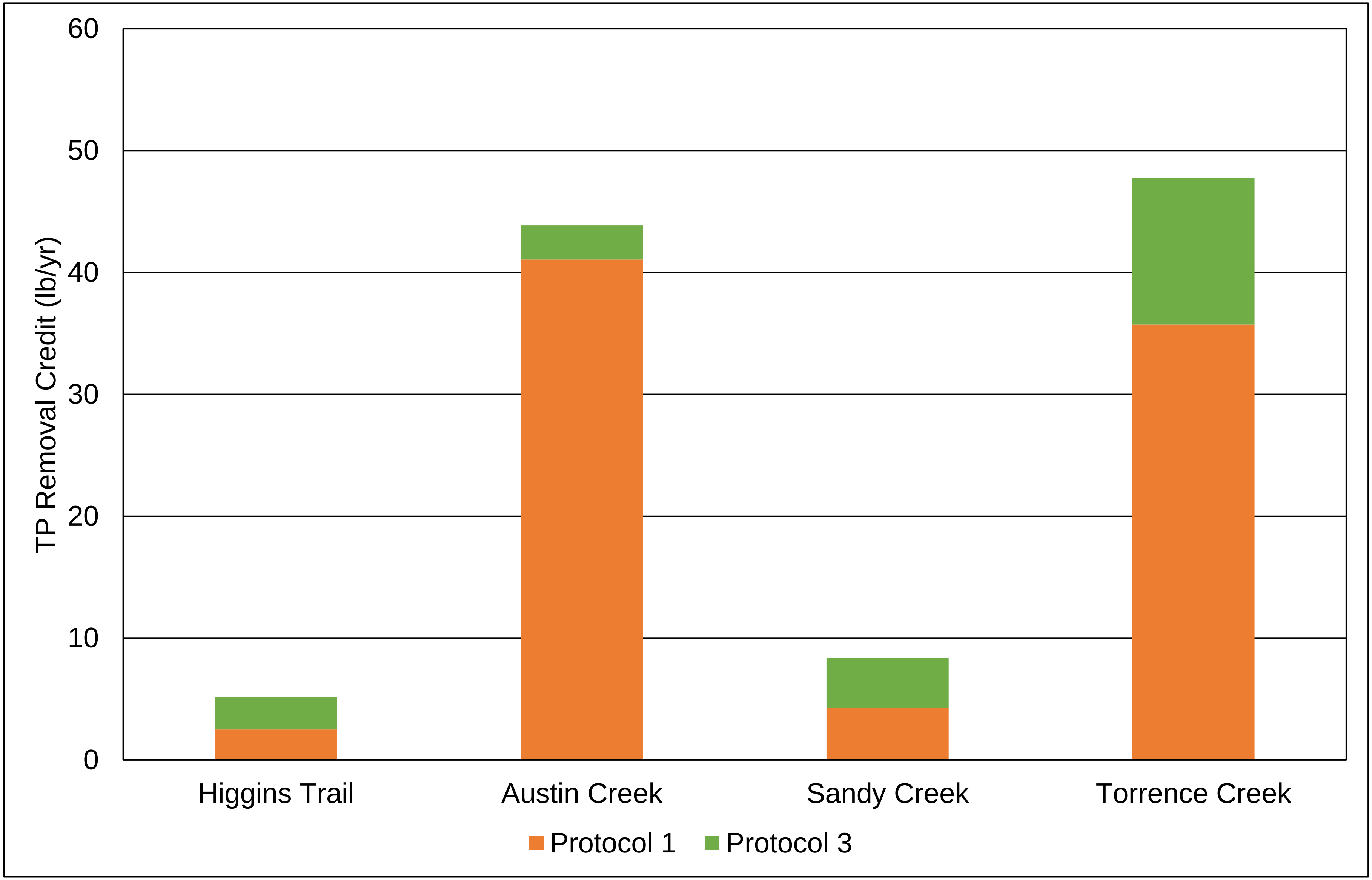
TP Credit



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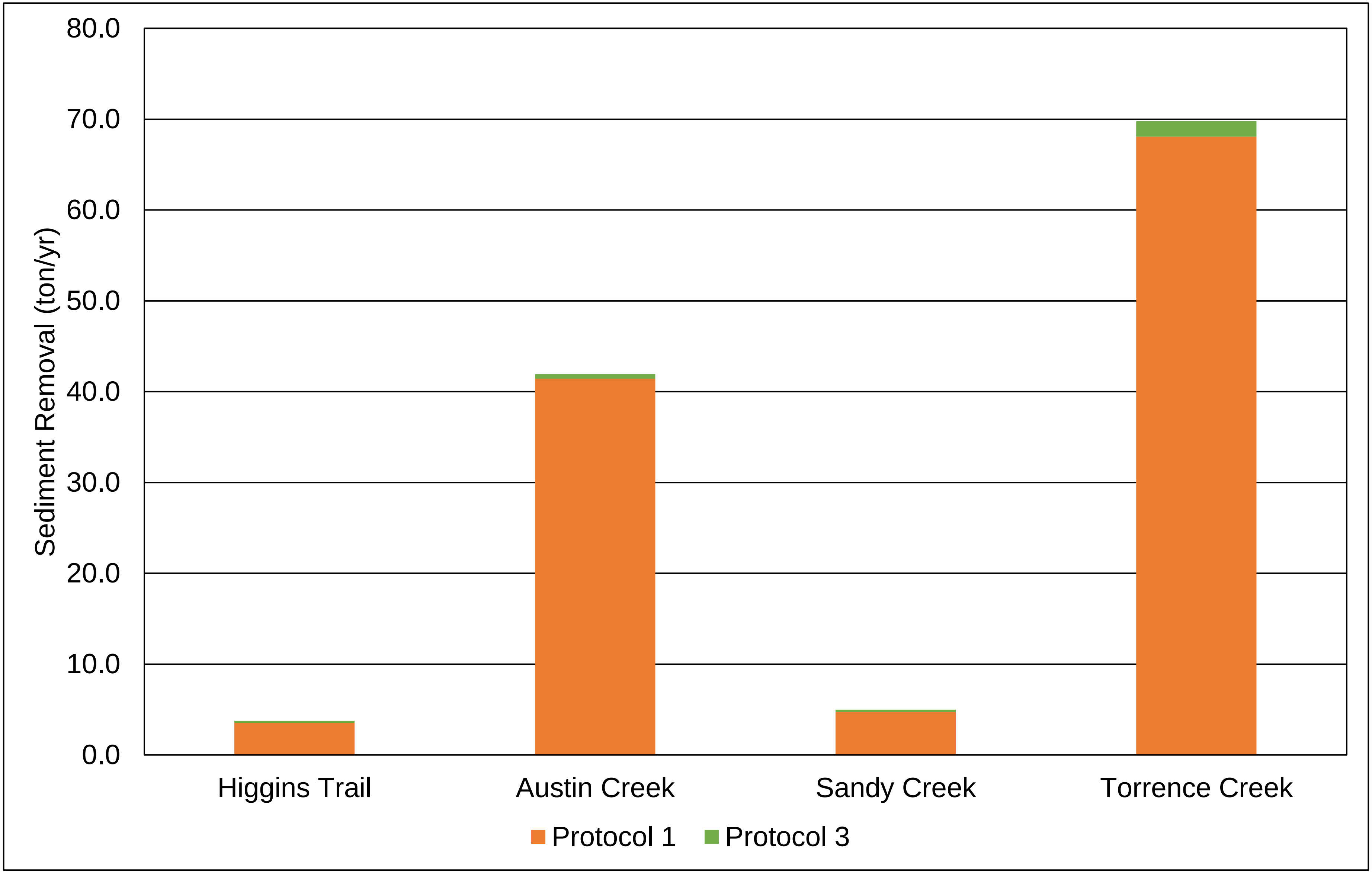
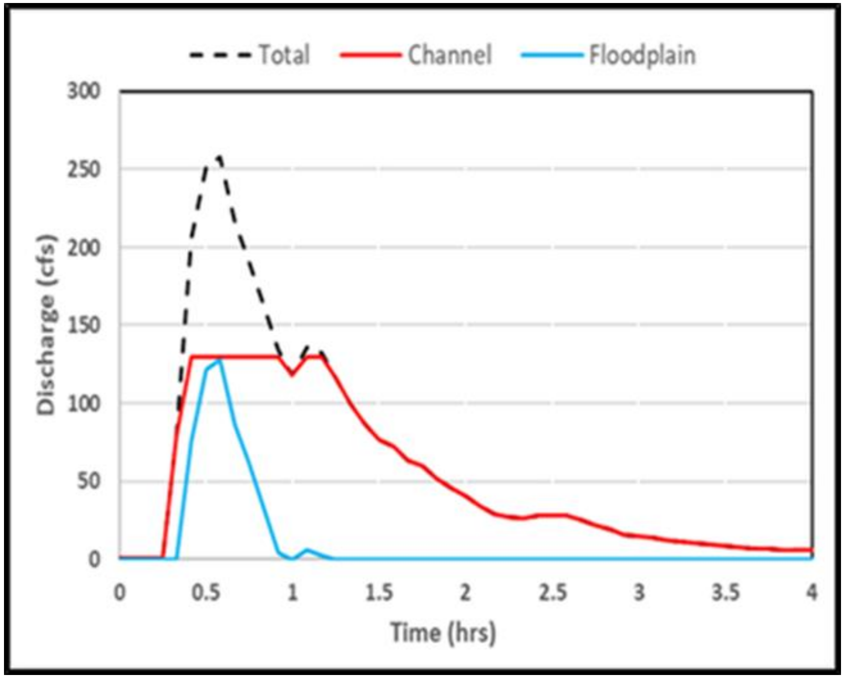
Sediment Credit



Flood Flow Frequency Analysis

Purpose:

- Determine the frequency of flows accessing the floodplain
- Evaluate the relationship between channel size and floodplain flow frequency.
- Compare results to CBP Protocol 3.



Method:

- Evaluated 10 years of discharge data at 5 USGS gage stations
- 3 gages downstream of restored streams and 2 located on un-restored reaches

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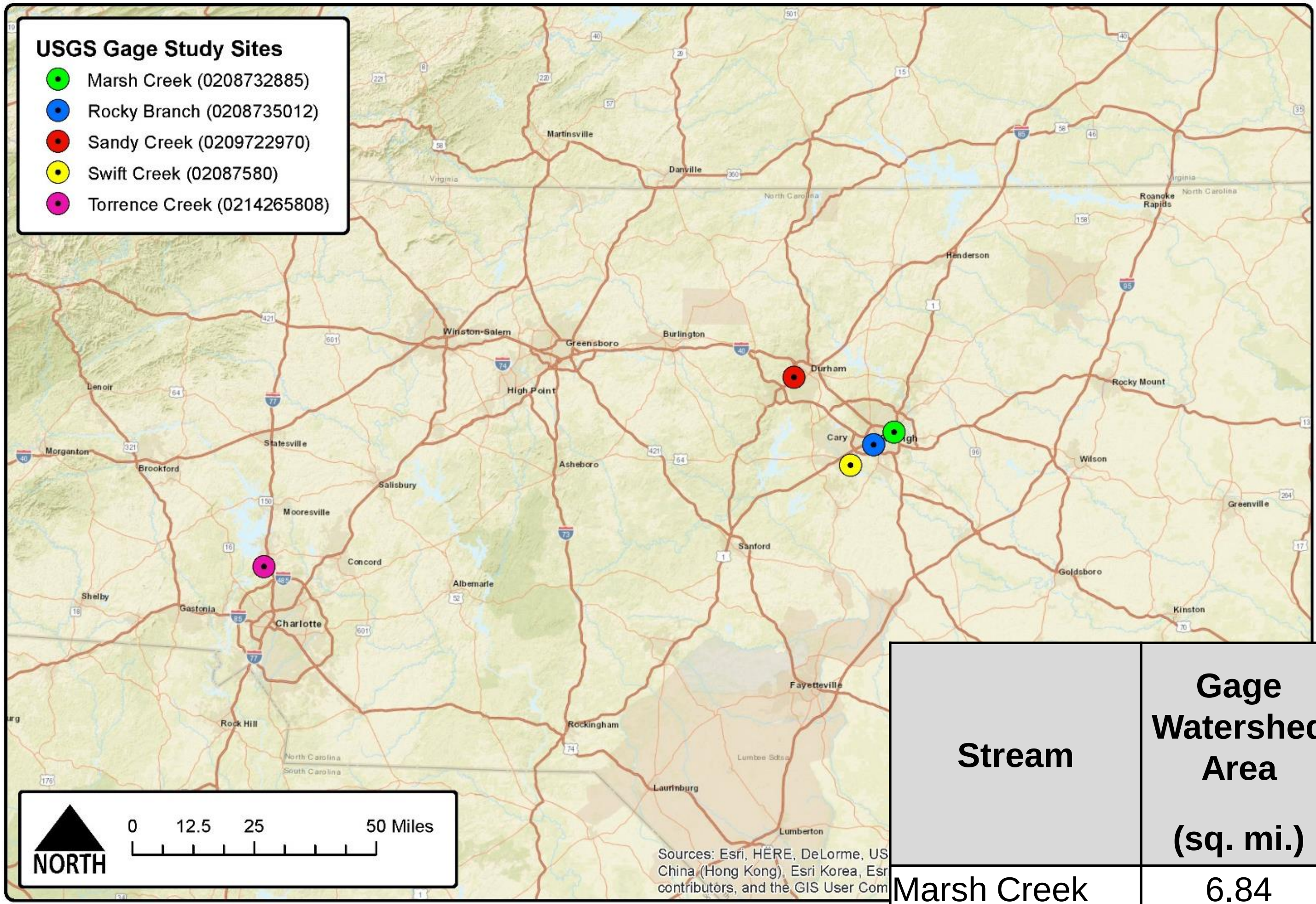
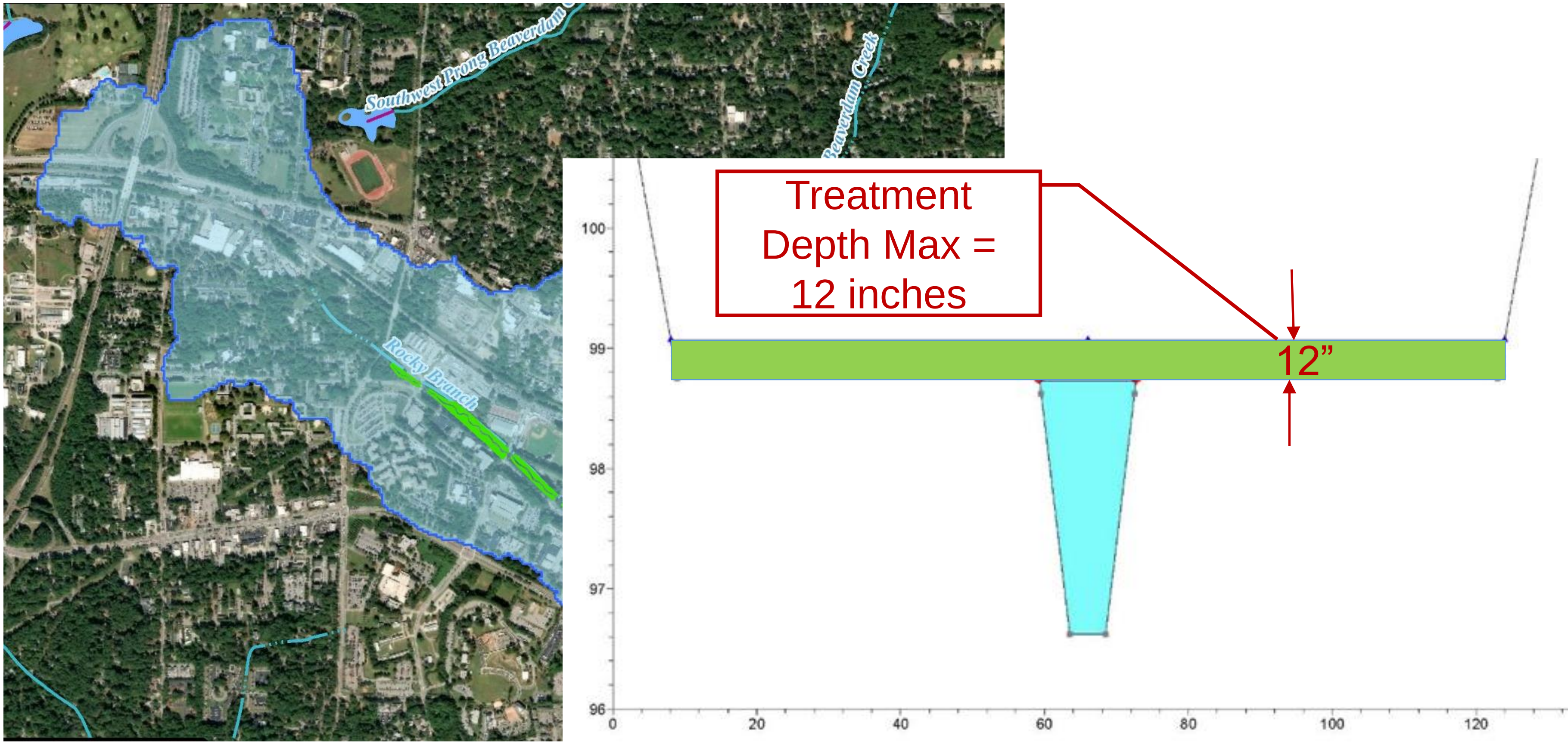


Stream	Gage Watershed Area (sq. mi.)	Restoration Project Drainage Area (sq. mi.)	Floodplain Area (acres)
Marsh Creek	6.84		17
Rocky Branch	1.17	0.98	8.4
Sandy Creek	2.65	1.7	8.1
Swift Creek	21		41.3
Torrence Creek	7.29	3.6	5.2

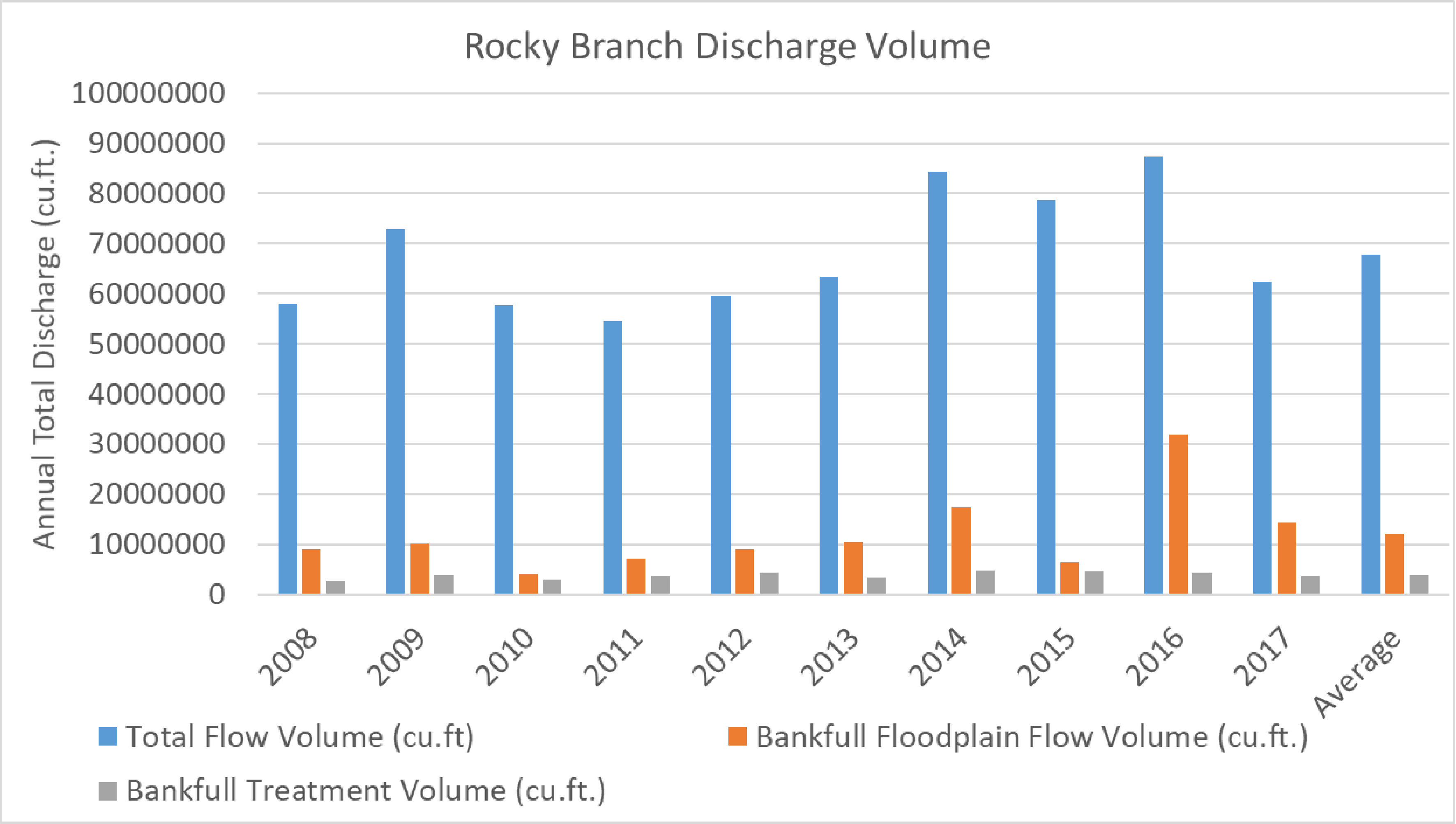
Determine Treatment Volume



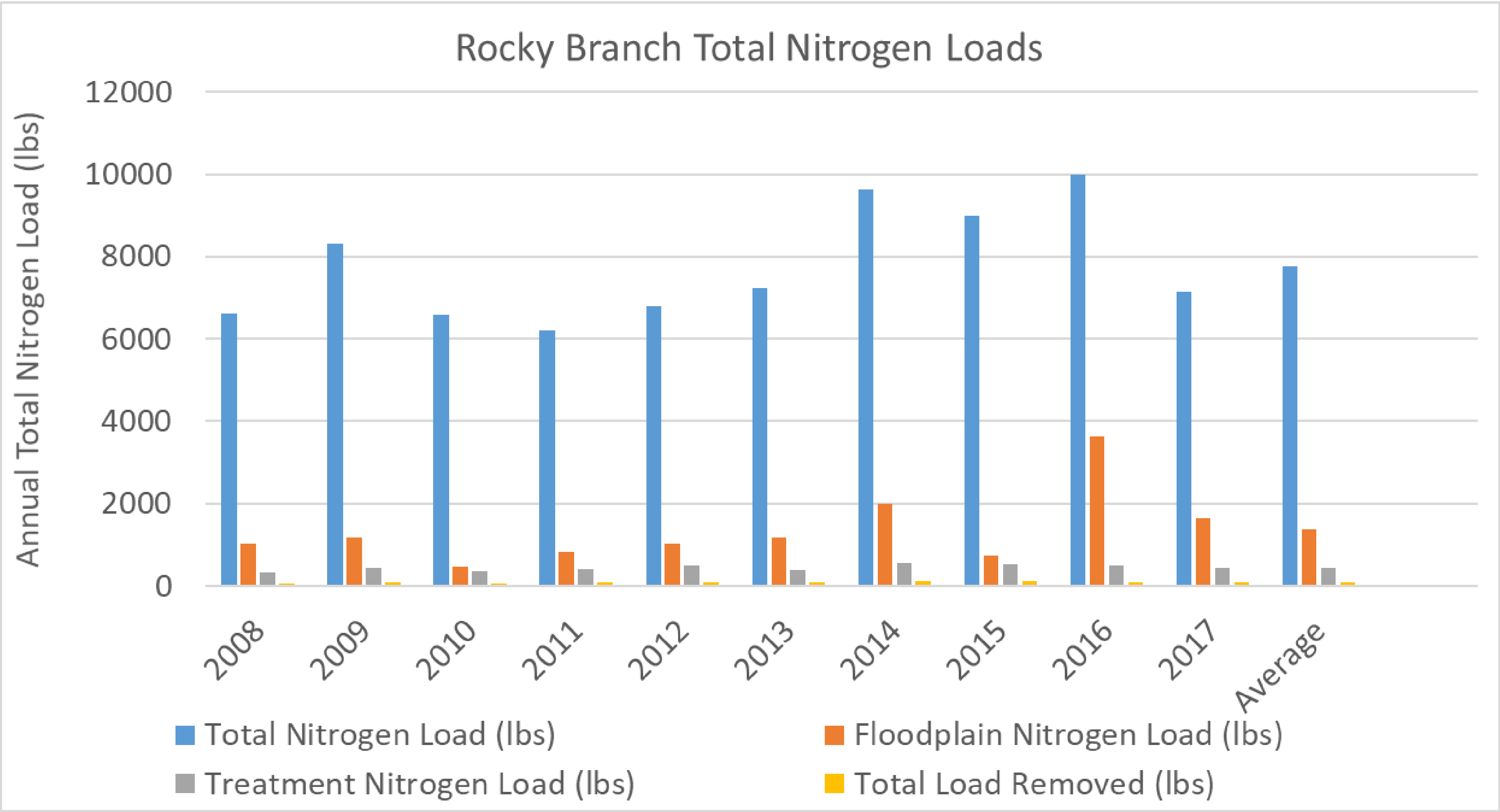
Treatment Volume (cu.ft.) = Floodplain Area (acres) x 43,560 square feet/acre x 1 foot

Results of Flood Frequency Analysis for 10-years of data (2008 to 2017)

Stream	FA/WA	# Events $>Q_{tob}$	# Events $>Q_{bkf}$	% Volume on Floodplain	% Treatment Volume
Marsh	0.4%	0	9.1	9.4%	2.0%
Rocky Branch	1.3%	0	18.2	16.9%	5.7%
Sandy	0.7%	0	10.9	7.7%	1.4%
Swift	0.3%	2.3	4.6	9.0%	1.0%
Torrence	0.23%	0	17.8	6.2%	1.7%
Average			**12.12**	**9.9%**	**2.3%**


Rocky Branch Discharge Volume
Annual Total Discharge (cu.ft.)
100000000
90000000
80000000
70000000
60000000
50000000
40000000
30000000
20000000
10000000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Average
Total Flow Volume (cu.ft)
Bankfull Floodplain Flow Volume (cu.ft.)
Bankfull Treatment Volume (cu.ft.)

- Obtain measured TN concentration data (Municipalities, USGS, Duke Univ.)
- Calculate annual TN load assuming constant concentration
- Calculate the total pounds of nitrogen in the treatment volume
- Apply removal efficiency rate of 20% (CBP)



TN Load Removal Potential

				USGS Gage Data Analysis					Existing Protocol 3	
Stream	**Watershed Area (sq.mi.)**	**TN Concentra-tion (mg/L)**	**TN Load (lbs/ac/yr)**	**TN Load (lbs/yr)**	**Flood-plain Load**	**Treat-ment Load**	**Total Load Removed**	**% N Removed**	**STEPL Load**	**%N Removed**
Marsh	6.84	0.78	3.36	14726	1383	291	58	0.4%		
Rocky Branch	0.98	1.83	12.36	7752	1367	437	87	1.1%		
Sandy	1.8	0.835	8.77	10100	822	141	28	0.3%	6393	0.3%
Swift	21	0.62	1.99	26699	2537	268	120	0.4%		
Torrence	0.8	0.556	11.17	5719	371	101	20	0.3%	12428	1.5%
Average				**12999**	**1296**	**247**	**63**	**0.5%**		

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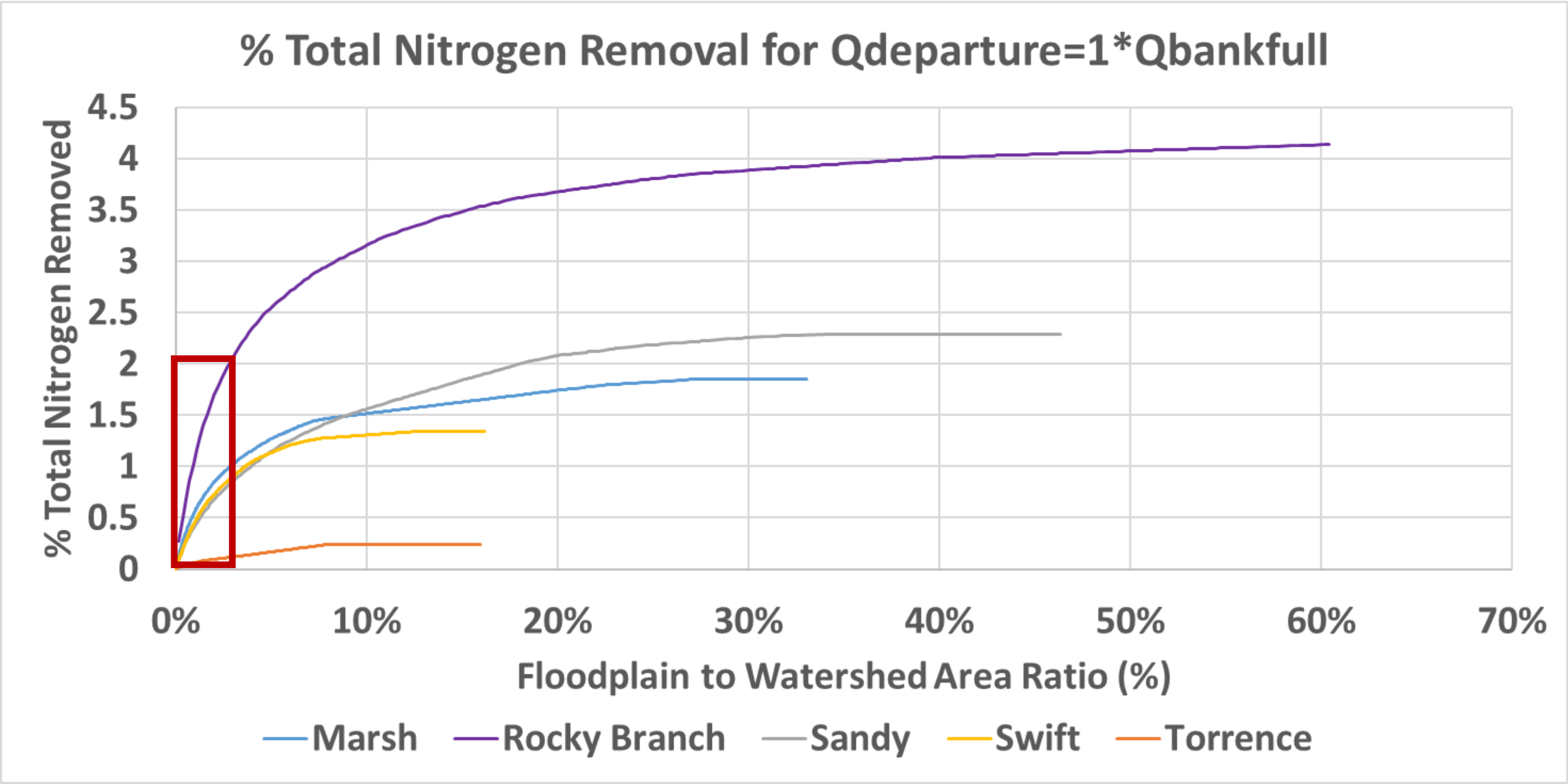
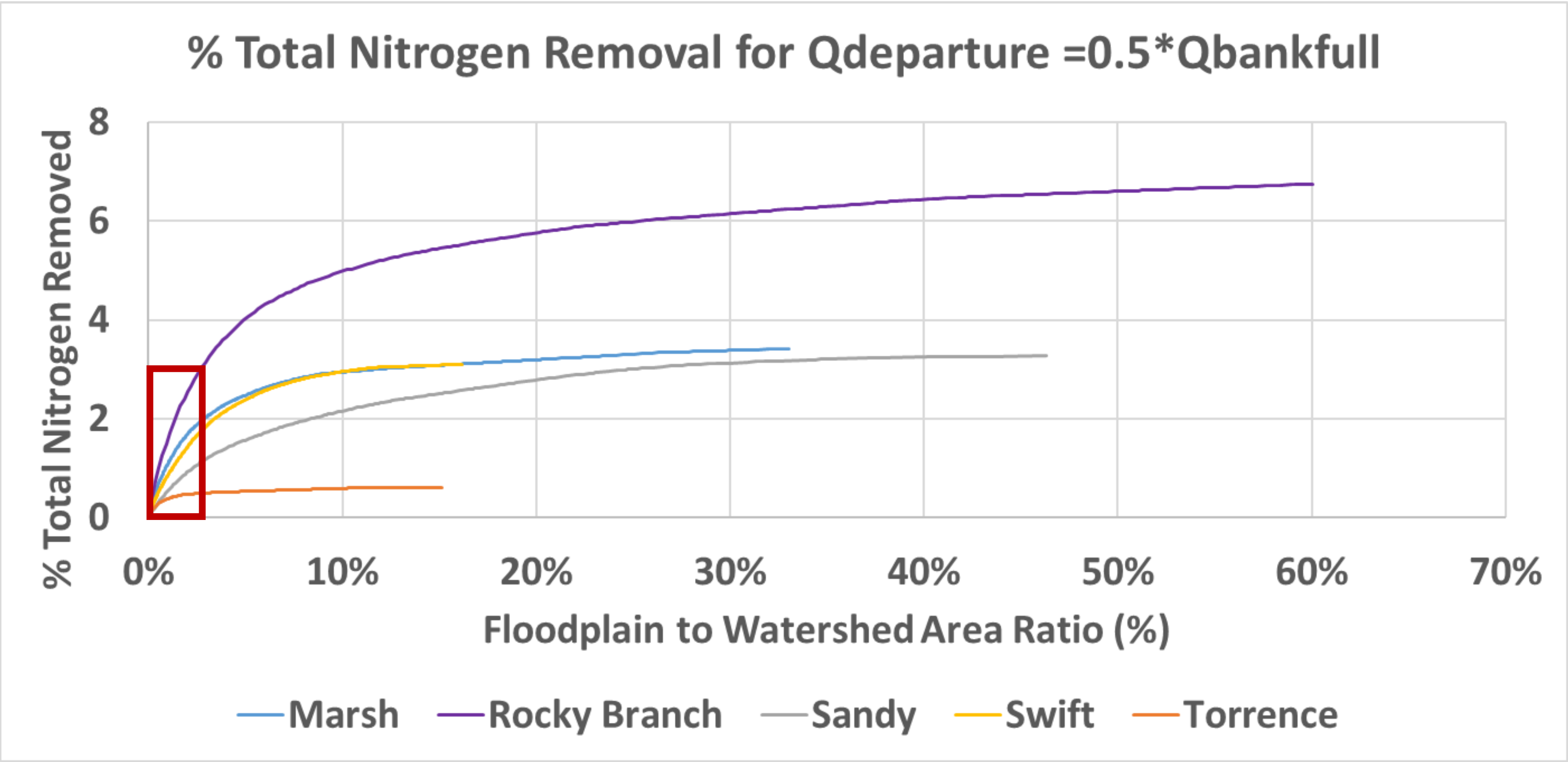
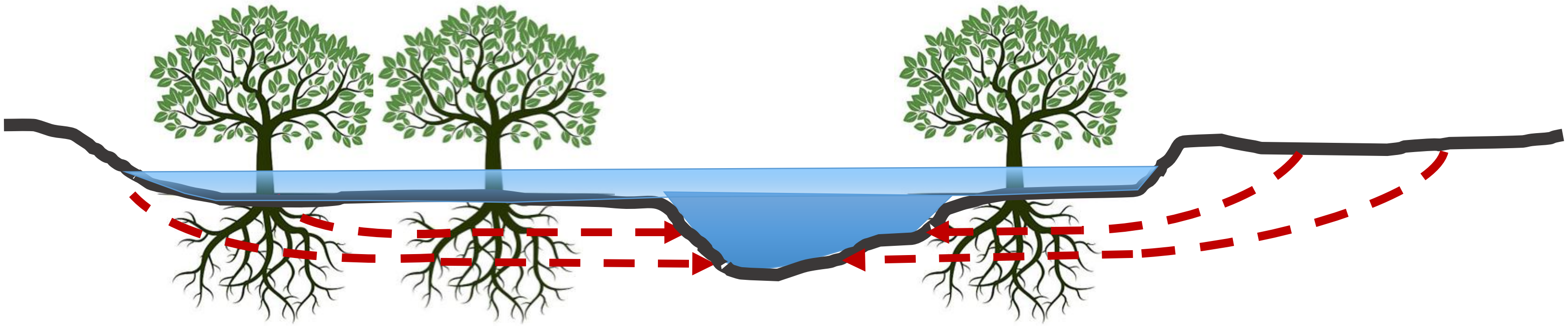
Sensitivity Analysis of % TN Load Removal

- Vary channel size and floodplain area to evaluate effects on % TN removal rate
  - Smaller channel = more flows on floodplain
  - Larger floodplain = larger treatment volume
- Channel Size Range
  - Vary as a fraction (0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2) of the expected Qbkf from published hydraulic geometry regional curves = Qdeparture
- Treatment Volume = channel length x Floodplain width x 12 inches
  - Channel length: Start at 500 feet and increase by increments of 1000 feet
  - Floodplain width: Start at 50 feet and increase by increments of 50 feet
  - Continued increasing both variables until reach a point of diminishing returns


% Total Nitrogen Removal for Qdeparture=1*Qbankfull
% Total Nitrogen Removed
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0%
10%
20%
30%
40%
50%
60%
70%
Floodplain to Watershed Area Ratio (%)
Marsh
Rocky Branch
Sandy
Swift
Torrence


% Total Nitrogen Removal for Qdeparture =0.5*Qbankfull
% Total Nitrogen Removed
8
6
4
2
0
0%
10%
20%
30%
40%
50%
60%
70%
Floodplain to Watershed Area Ratio (%)
Marsh
Rocky Branch
Sandy
Swift
Torrence



Potential Revisions

- Protocol 1
  - Leave as is with BANCS and NBS
  - Consider adjusting 50% efficiency factor
  - Recommend using Tetra Tech soil concentrations

Potential Revisions

- Combine Protocol 2 and 3
  - Intensive process for consultants and reviewers
  - Hyporheic box will be highly variable across NC
  - Consider using an areal denitrification
    - Lammers and Bledsoe (2017) collected denitrification rates from streambed and riparian zones from 98 peer-reviewed studies covering 249 stream systems including urban, agricultural, and reference streams
    - Streambed denitrification rate = 1.85 mg $N/m^2/hr$
    - Riparian denitrification rate = 1.01 mg $N/m^2/hr$

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Potential Total Protocol 2/3 Revisions

	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%**

Potential Revisions: Credit Differences

Protocol	Credit	Higgins Trail	Austin Creek	Sandy Creek	Torrence Creek
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**

- CBP Credits

Protocol	Credit	Higgins Trail	Austin Creek	Sandy Creek	Torrence Creek
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**

- Revised Credit

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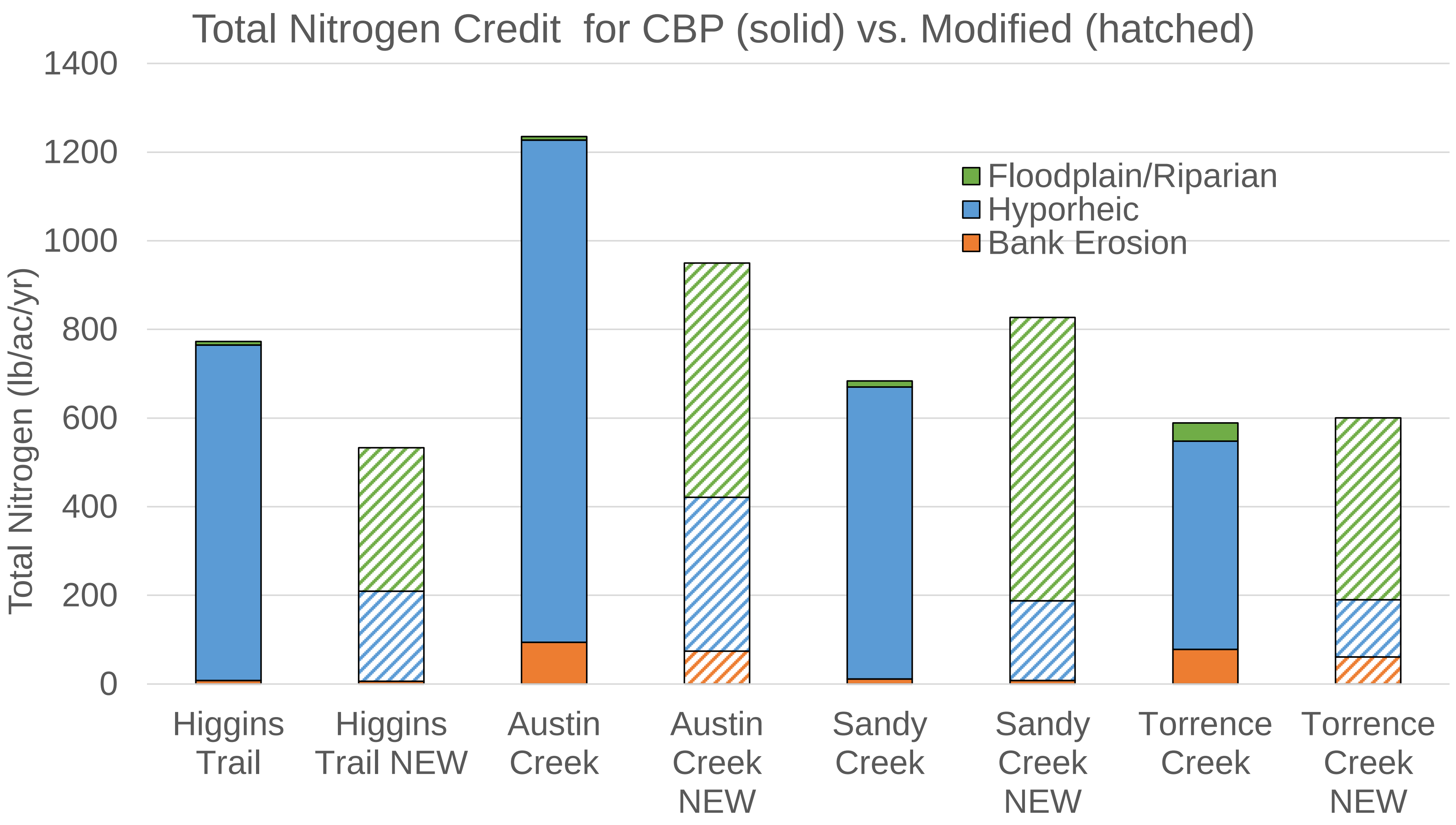

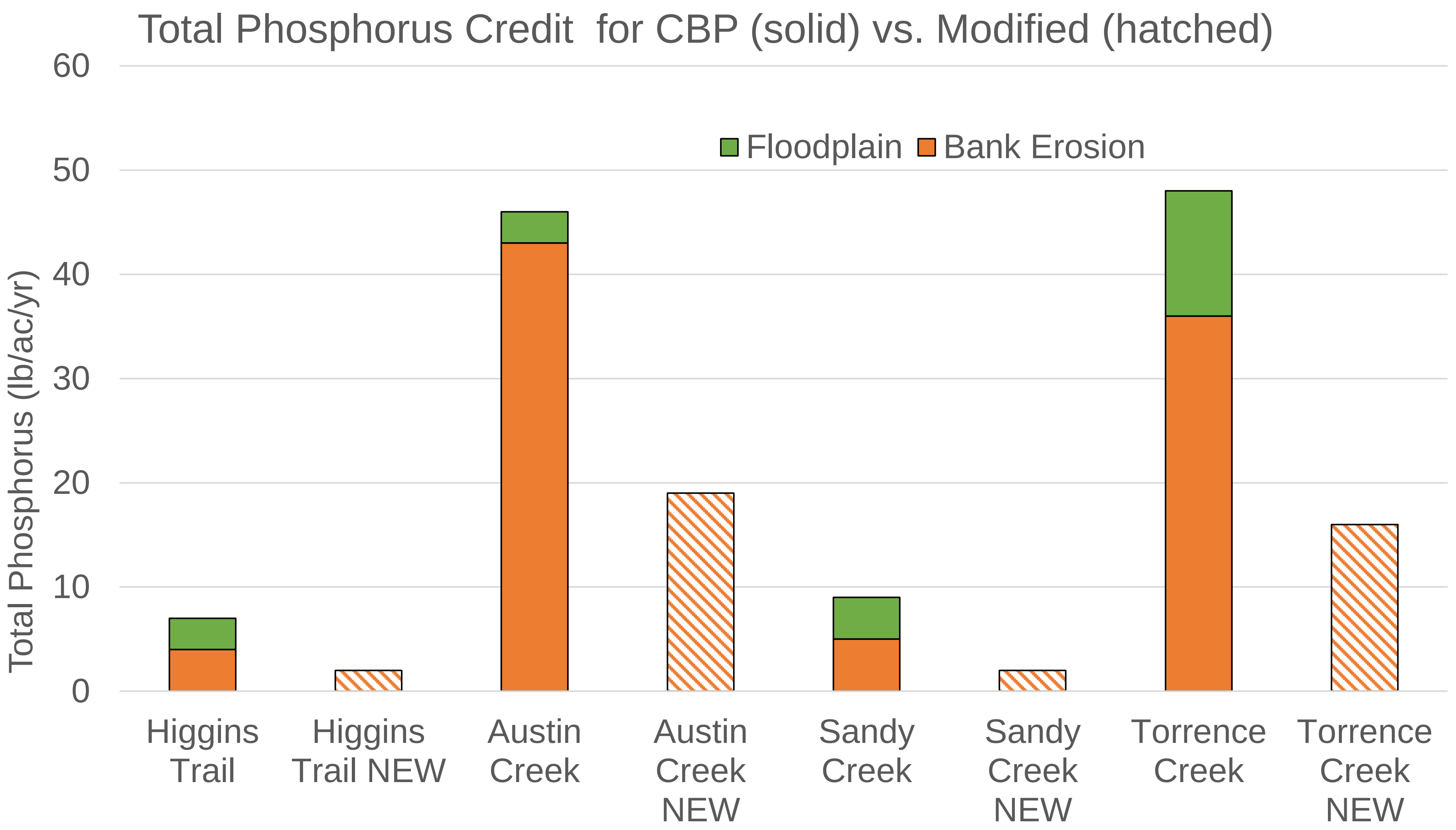

Total Phosphorus Credit for CBP (solid) vs. Modified (hatched)
Floodplain
Bank Erosion
Total Phosphorus (lb/ac/yr)
0
10
20
30
40
50
60
Higgins Trail
Higgins Trail NEW
Austin Creek
Austin Creek NEW
Sandy Creek
Sandy Creek NEW
Torrence Creek
Torrence Creek NEW

Conclusions

- BANCS method easy to implement and produces reasonable values (e.g. Duke bank pins)
- Tetra Tech TN & TP concentrations reasonable for NC Piedmont
- Much uncertainty in quantifying biogeochemical processes for N removal for CBP protocol 2/3
- Applying published areal denitrification rates to streambeds and riparian zones (Lammers & Bledsoe, 2017) in place of CBP 2 & 3 simplifies approach and results in reasonable TN removal (2-4%)
- More study of urban stream buffer function and hyporheic treatment is needed