Innovative and Integrative Best Management Practices (BMPs) for Surface and Groundwater Protection

BDV24-977-25

Principal Investigator:

Dr. Kelly Kibler
University of Central Florida
4000 Central Florida Blvd.
Orlando, FL 32816-2993
Email Address: kelly.kibler@ucf.edu
Phone Number: (407) 823-4150

Project Manager:

Jennifer Green
Florida Department of Transportation
Office: Roadway Design
Address: 605 Suwannee Street, MS 32, Tallahassee, FL 32399
Email Address: Jennifer.Green@dot.state.fl.us
Phone Number: (850) 414-4351

Report prepared by: Dr. Kelly M. Kibler, Dr. Ni-Bin Chang, Dr. Dingbao Wang, Dr. Martin P. Wanielista, Mr. Mohammad Shokri, Ms. Diana Ordonez, Mr. Yuan Gao, Ms. Andrea Valencia, Mr. Christopher Hagglund, and Mr. Andrew Corrado.

August 2020

Final Report

DISCLAIMER

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation.

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation's University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

The CTS Bold and Gold® Filtration Media tested herein is a proprietary product patented by UCF. Other media tested herein are under development by UCF.

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
ºF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	ºC

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
lbf	pounds force	4.45	Newtons	N
lbf/in^2	pounds force per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds mass	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
ºC	Celsius	1.8C+32	Fahrenheit	ºF

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
N	Newtons	0.225	pounds force	lbf
kPa	kilopascals	0.145	pounds force per square inch	lbf/in^2

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Innovative and Integrative Best Management Practices (BMPs) for Surface and Groundwater Protection		5. Report Date 8/2020
		6. Performing Organization Code
7. Author(s) Dr. Kelly M. Kibler, Dr. Ni-Bin Chang, Dr. Dingbao Wang, Dr. Martin P. Wanielista, Mr. Mohammad Shokri, Ms. Diana Ordonez, Mr. Yuan Gao, Ms. Andrea Valencia, Mr. Christopher Hagglund, and Mr. Andrew Corrado.		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Central Florida 4000 Central Florida Blvd. Orlando, FL 32816-2993		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. BDV24-977-25
12. Sponsoring Agency Name and Address Florida Department of Transportation 605 Suwannee Street, MS 30 Tallahassee, FL 32399		13. Type of Report and Period Covered Final Report 6/6/2017 – 8/21/2020
		14. Sponsoring Agency Code
15. Supplementary Notes N/A		

16. Abstract

In this project, development of innovative methods for the integrated evaluation of surface and groundwaters inform practical applications for stormwater best management practices (BMPs) aimed at remediating stormwater nutrient impacts. To explore innovative uses of engineered media, five novel chemically activated media (CAM) were developed and tested for nutrient removal and recovery. Inclusion of bio-sorption activated media (BAM) filters within roadway shoulder vegetated filter strips (VFS) was found to effectively remediate nitrogen when subjected to controlled testing at field scale under a range of hydrologic conditions. The BMP Trains model, widely applied to the permitting, planning, and design of stormwater BMPs, was overhauled to integrate runoff discharged to surface and groundwater, facilitate complex catchment configurations, and ease the user experience, all with continued support of regulatory agencies. Finally, a groundwater flow and nutrient transport model was developed within a region of complex karst hydrogeology and used to explore integrated processes of stormwater runoff, surface water, and groundwater nutrient transport. The modelling study found that the maximum cumulative water quality benefits to Silver Springs from many individual BAM-based BMPs may be negligible. A critical knowledge gap regarding the relative nutrient remediation potential of BAM versus soils of variable properties should be addressed before making investments into BAM-based BMPs.

17. Key Word stormwater BMPs, roadway runoff, Vegetated filter strips, Biosorption Activated Media, chemically activated media, BMP Trains, Silver Springs, karst, groundwater model, tracer, nitrogen, nitrate, phosphorus		18. Distribution Statement No restrictions	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 115	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EXECUTIVE SUMMARY

Innovative best management practices (BMPs) and assessment tools that integrate seamlessly across surface and groundwater management are needed to mitigate nutrient loading to Florida's waterbodies from urban and roadway runoff. In this project, innovative methods for the integrated evaluation of surface and groundwaters inform practical applications for BMPs aimed at remediating stormwater nutrient impacts.

First, to explore innovative advances in engineered media, novel chemically activated media (CAM) were developed and tested for nutrient removal and recovery. Physical characterization of each new medium confirmed appropriate hydraulic conductivities, surface areas, and porosities to maintain acceptable drainage rates and environments for microbial growth. Using batch isotherm testing, column studies, and sorption experiments, five novel CAM mixes (including three iron-based media, IFGEM-1, IFGEM-2, and IFGEM-3, and two aluminum-iron-based media, AGEM-1 and AGEM-2) were tested for removal of nitrogen and phosphorus. Nutrient removal efficiency was compared to bio-sorption activated media (BAM) and unaltered soils. Synergies among clay minerals and iron-aluminum oxides led to optimum nutrient removals in AGEM mixes (up to 95% removal of nitrate and up to 99% removal of total phosphorus (TP)). By contrast, removal of nutrients by unaltered soils (22 Candler sands) was lower (up to 73% removal of TN) and generation of nitrate and TP was often observed. The most promising two novel CAM mixes (IFGEM-3 and AGEM-2) were tested in sorption and desorption experiments for nutrient recovery potential. Results suggested that in situ regeneration of media and recovery of phosphate and ammonia from IFGEM-3 may be possible. The desorption process in AGEM-2 slowed the infiltration rate through the media considerably, suggesting in situ regeneration may not be possible.

Second, the inclusion of BAM filters within roadway shoulder vegetated filter strips (VFS) to create 'self-filtering roadways' was subjected to controlled testing at field scale. Experiments were designed to query (1) the hydraulic performance of the BAM VFS to efficiently infiltrate precipitation and runoff and (2) the performance of BAM to effectively remove nutrients from infiltrated runoff. Two 1:1-scale physical models of vegetated roadway shoulders, one with and one without BAM, were tested against rainfall and runoff from 1-lane and 2-lane roadways. The hydraulic capacity of a 20-ft-wide BAM VFS was exceeded only during the highest-intensity testing while capacity of the control was never exceeded. With regard to phosphorus removal, both the BAM and control test beds performed well, reducing TP respectively by 84±9% and 82±12% at 5 ft from the pavement. However, the BAM VFS strongly outperformed the control in terms of nitrogen removal. A 20-ft BAM VFS removed a mean 94±6% of nitrate while nitrate was consistently generated in the control. TN concentrations were reduced by a mean 80±5% in the treatment model as compared to 38±23% in the control. Nitrogen generation was also observed in the BAM VFS at shorter filter lengths, suggesting that a minimum 20-ft BAM VFS width should be the design standard to ensure adequate nitrogen removal performance.

Third, the BMP Trains model, widely applied to permitting and the planning and design of stormwater BMPs, was overhauled to integrate runoff discharged to surface and groundwater, facilitate complex catchment configurations, and ease the user experience, all with continued support of regulatory agencies. The resulting BMP Trains 2020 computer program is a significant improvement to the prior EXCEL-based model, notably because of the move to a

more robust computational programming that allows for a user-friendly graphical user interface (GUI), greater stability, and reduced computation times. The user may now investigate an unlimited number of catchments (25 have been tested) in a variety of configurations (series, parallel, combinations). Through extensive testing with user focus groups (360 professionals attended 14 workshops across the state of Florida), the BMP Trains 2020 model has been deemed acceptable by stormwater professionals and all water management districts, the Florida Department of Environmental Regulation for Environmental Resource Permits (ERP) and Basin Management Action Plans (BMAP). The model and user manual are now maintained and available for download on the UCF STARS data repository, where the program is consistently one of the top 10 downloads, downloaded over 3,000 times in its first 15 months of availability.

Fourth, a groundwater flow and nutrient transport model was developed within a region of complex karst hydrogeology and used to explore integrated processes of stormwater runoff, surface water, and groundwater nutrient transport. The model was applied to investigate the potential cumulative impact of implementing many individual BAM-based BMPs, including BAM blanket filters in stormwater management areas and roadway shoulder BAM VFS within the Silver Springs springshed. Various implementation scenarios of BAM-based BMPs were compared based on potential to mitigate nitrate, TN, and TP concentrations in Silver Springs. This modelling study indicates that the spring water quality benefits accruing from even large-scale implementation of BAM-based stormwater BMPs are ambiguous. Outcomes ranged from nominal water quality improvements to net degradation.

This equivocal result points to a critical knowledge gap regarding the relative nutrient remediation potential of BAM versus soils of variable properties. This knowledge gap should be addressed before investments are made in BAM-based BMPs. In some places, replacing the soil profile with BAM will lead to greater removal of nutrients; in other cases, the natural remediation of the unaltered soil profile will exceed that of BAM. The spatial heterogeneity of soil nutrient remediation properties introduces considerable uncertainty to the potential cumulative water quality improvements offered by BAM BMPs. The uncertainty related to soil heterogeneity can be resolved, but only after achieving greater understanding of nutrient transformations within soils of variable properties and then understanding how those variable soils are distributed spatially. However, the modeling study suggests that even when this is accomplished, the maximum expected water quality benefits of BAM BMPs may be nominal. When uncertainty from soil removals is eliminated, at best, realistic implementation scenarios would lead to maximum net spring water quality improvement of 0.3% to 0.7% for TP, 0.6% to 2.3% for nitrate, and 0.4% to 3.4% for TN. Given the modest improvements that can be expected with realistic BAM BMP implementation scenarios, water quality in Silver Springs would still fall quite short of restoration targets. To achieve restoration goals in Silver Springs, non-transportation sources of nutrients (such as agricultural applications and septic tanks) must also be controlled or treated.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. **Introduction**

Urban and roadway runoff contributes excess loads of nutrients and other pollutants to surface and groundwater resources, causing water quality and ecosystem degradation (Suthar et al. 2009; Mallin et al. 2009; Trenouth and Gharabaghi 2016; Eller and Katz 2017). Historically, discharges to surface waters were of primary concern to regulators. However, in recent decades, scientific and management communities have increasingly acknowledged the profound connectivity between runoff, surface water, and groundwater resources. The FDOT is thus challenged to reduce nutrient concentrations in stormwater runoff before discharge to most surface and groundwater bodies. As such, management needs have shifted to require innovative assessment tools and best management practices that integrate seamlessly across surface and groundwater management.

In this project, development of innovative methods for the integrated evaluation of surface and groundwaters facilitate practical applications for best management practices (BMPs) aimed at remediating stormwater nutrient impacts. Past research has indicated that the inclusion of media engineered for nutrient removal, such as bio-sorption activated media (BAM), within stormwater BMPs may enhance nutrient removal performance. To explore innovative uses of engineered media, five novel chemically activated media (CAM) were developed and tested for nutrient removal and recovery. Inclusion of BAM filters within roadway shoulder vegetated filter strips (VFS) to create 'self-filtering roadways' was subjected to controlled testing at field scale under a range of hydrologic conditions to assess hydraulic and nutrient removal performance. The BMP Trains model, widely applied to permitting and planning and design of stormwater BMPs, was overhauled to integrate runoff discharged to surface and groundwater, facilitate complex catchment configurations, and ease the user experience, all with continued support of regulatory agencies. Finally, a groundwater flow and nutrient transport model was developed within a region of complex karst hydrogeology and used to explore integrated processes of stormwater runoff, surface water, and groundwater nutrient transport. The model was used to investigate the potential cumulative impact of implementing many individual BAM-based BMPs, including BAM blanket filters in stormwater management areas and roadway shoulder BAM VFS, within the Silver Springs springshed. Various implementation scenarios of BAM-based BMPs were compared based on potential to mitigate nitrate, total nitrogen, and total phosphorus concentrations in Silver Springs.

Projects goals were facilitated by the following research tasks:

Task 1: Literature review and experimental preparations

Task 2: Testing and interim results

Task 3: Testing and interim results

Task 4: Project Draft Final Report

Task 5: Project Final Report.

Interim reporting on project tasks (Kibler et al. 2018a; 2018b; 2020a) is available on the UCF STARS data repository (https://stars.library.ucf.edu/fdot/).

CHAPTER 2. Chemically activated media (CAM) for the removal of nitrogen and phosphorus

2.1 Research objectives

The research objective was to investigate the nitrogen and phosphorus removal and recovery potential of new chemically activated media (CAM) mixes. Three new iron-based media, Iron-Filing Green Environmental Media (IFGEM), and two new aluminum-iron based media, Advanced Green Sorption Media (AGEM) were developed and tested alongside BAM and unaltered soils.

2.2 Development of chemically activated media (CAM) mixes

Bio-sorption activated media (BAM) was used as a baseline for development of CAM mixes (Table 2.1). The iron-based media mixes (denoted as IFGEM-1, IFGEM-2 and IFGEM-3) are composed of either sand or BAM with the addition of iron filings. The mixes including aluminum and iron (AGEM-1 and AGEM-2) additionally include aluminum in either flake or powder form, due to the positive effect of aluminum to enhance nutrient removal and recovery (Sousa et al. 2012).

Manufacturing of CAM mixes tested in this study was performed by a certified vendor, given the importance of safe materials handling, the homogeneity of the media mix and the utilization of the correct components. Likewise, the in situ preparation of media mixes for field applications should be avoided. Aluminum flakes and powder, ingredients in AGEM, are highly flammable and combustible materials, which can also lead to scarring of human lung tissue if inhaled. Furthermore, additional research is needed to assess release of iron and aluminum ions in AGEM-2 effluent due to potential public health hazards (see Appendix A).

Table 2.1. Composition (% material by volume) of CAM mixes developed and tested in study, as compared to BAM

Material	**BAM**	**IFGEM-1 (CAM-1)**	**IFGEM-2 (CAM-2)**	**IFGEM-3 (CAM-3)**	**AGEM -1 (CAM-4)**	**AGEM-2 (CAM-5)**
Sand (%)	85	96.2	80	83	78	85
Tire Crumb (%)	10	--	10	10	10	--
Clay (%)	5	--	5	2	2	3
Iron filings (%)	--	3.8	5	5	5	7.5
Aluminum flakes (%)	--	--	--	--	5	--
Aluminum powder (%)	--	--	--	--	--	4.5

In this study, five CAM mixtures were tested alongside BAM and soils (unaltered soils) collected from stormwater management basins (Basin 9B and Basin 2 located near Ocala, FL) as a baseline comparison for nutrient removal. Both soil samples utilized in this study have been characterized by the USGS as 22 Candler sand (0 to 5 percent slopes). The physical characteristics of the five CAM mixes (i.e., IFGEM-1, IFGEM-2, IFGEM-3, AGEM-1, and AGEM-2), BAM, and soils were analyzed by an external certified laboratory (EMSL) (Table 2.2, Figure 2.1).

Table 2.2. Characteristics of soil and media mixes (Chang et al., 2019; Ordonez et al., 2020 a, b; Valencia et al., 2019; Valencia et al., 2020)

Properties	**Unaltered Soil**	**BAM**	**IFGEM-1 (CAM-1)**	**IFGEM-2 (CAM-2)**	**IFGEM-3 (CAM-3)**	**AGEM -1 (CAM-4)**	**AGEM-2 (CAM-5)**
Bulk Density (g/cm^3)	2.36	1.39	2.73	2.60	1.37	1.42	1.52
Surface Area (m^2/g)	9.37	0.71	0.31	1.40	0.70	1.27	1.71
Porosity (%)	40.43	40.10	36.16	37.31	25.53	30.54	29.07
Saturated Hydraulic Conductivity (cm/s)	0.003	0.026	0.028	0.017	0.031	0.030	0.027

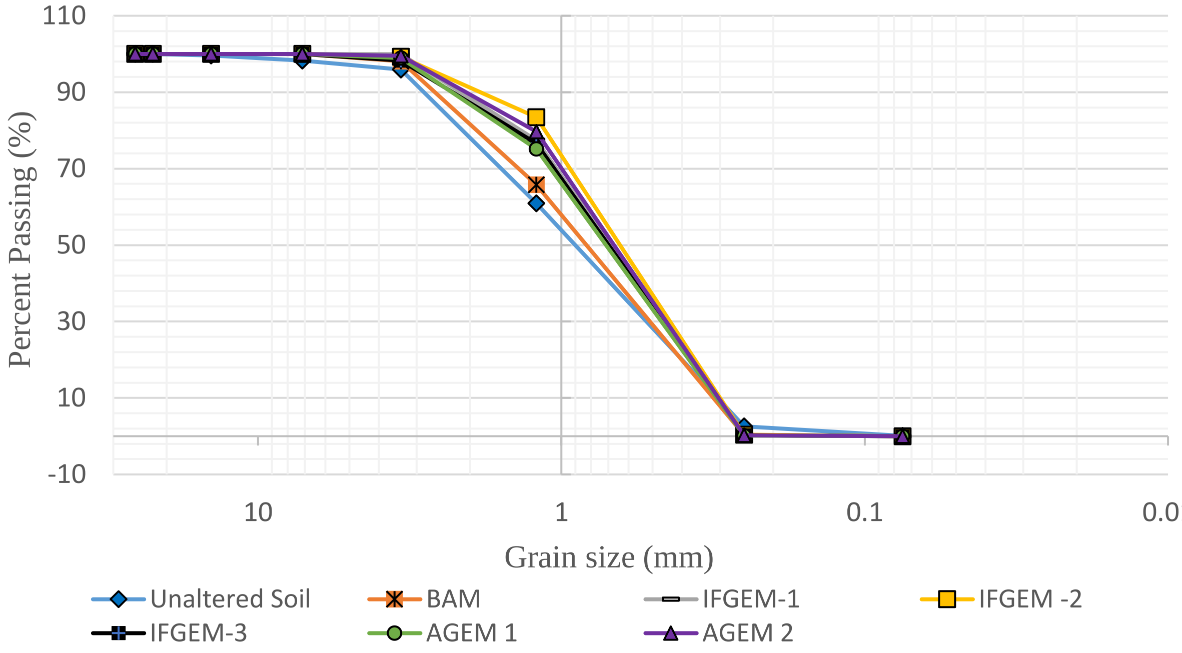


Figure 2.1. Grain size distributions of CAM, BAM, and soils from sieve analysis (Chang et al., 2019; Ordonez et al., 2020 a, b; Valencia et al., 2019; Valencia et al., 2020)

For a media (soil) to be well graded, its uniformity coefficient (C_u) must be greater than 4 and the coefficient of gradation (C_c) should be in the range of 1 to 3. Given that the uniformity coefficient for all media lays under 4, all medias can be categorized as uniformly graded, in the sense the particle sizes with-in the media are similar. While, based on the C_u value AGEM-1 has a wider range of particle followed by IFGEM-3 and lastly AGEM 2. Furthermore, a smaller surface area was found in IFGEM-3, followed by AGEM-1 and AGEM-2, respectably. Lastly, the removal of tire crumb from AGEM-2, and inclusion of aluminum powder triggered the decreased in hydraulic conductivity, however compared to natural soil, the hydraulic conductivity of AGEM-2 remains adequate.

2.3 CAM nutrient removal

The nutrient removal effectiveness of the five new CAM mixes were investigated and compared to BAM and unaltered soils via a series of batch and column studies (Table 2.3, Chang et al., 2019; Ordonez et al., 2020 a, b; Valencia et al., 2019; 2020). In BAM, nitrate reduction is achieved via the interaction between sand/clay and nitrate. Conjunctly, phosphate removal in BAM is primarily obtained via adsorption, while tire crumb can further aid in phosphate adsorption (Hood et al, 2013) as well as contribute to the infiltration and distribution of water. The introduction of iron filings as a component of the media mixes contributes to nitrate and phosphate removal by increasing nitrate reduction, phosphate precipitation and ion exchange from interactions between iron oxide and nitrate while clay minerals provide basic binding capacity. The results from column studies indicated that the nutrient removals obtained from the five CAM mixes were comparable to BAM (Table 2.3).

However, better total nitrogen and phosphate removals were achieved from IFGEM-3 and AGEM-2. Removals obtained in a batch study performed with AGEM-1 and AGEM-2 indicated that aluminum powder was a more effective component as compared to aluminum flakes, as less contact time was required for the reactions to occur. Thus, the results (Table 2.3) show better removal efficiencies of nitrate and TP within the AGEM-2 mix containing aluminum powder. For comparison of nutrient removal between unaltered soils and CAM mixes, a batch analysis and two column studies indicated that the soil samples (22 Candler sand (0 to 5 percent slopes)) poorly treated nutrients and its treatment was unreliable.

The most promising two CAM mixes (IFGEM-3 and AGEM-2) were selected for an integrated sorption and desorption study to observe nitrate and phosphate removal dynamics and determine the maximum adsorption capacity of the media (Figures 2.2 and 2.3). The results indicated that IFGEM-3 removed about 42% of the total nitrate load fed in 64,275 minutes, while AGEM-2 removed about 52% of the total nitrate load fed in the same period of time (Table 2.3). However, IFGEM-3 and AGEM-2 exhibited high phosphate removals, obtaining total phosphate removals of 98% and 97%, respectively, within 64,275 minutes (Table 2.3, Figures 2.2 and 2.3). Because aluminum contributed to the reduction of nitrate and phosphate precipitation, greater nitrate and phosphate removals were observed from the AGEM-2 mix.

Table 2.3. Nutrient removal efficiencies of CAM, BAM and soils. Negative removal indicates nutrient generation.

Media name	TN Removal	Nitrate removal	TP Removal	References
Unaltered Soil (Ocala, FL)	--	-166% to 0.27%	-108% to 4.8%	Chang et al. (2019)
	46% to 73%	--	-176% to 63%	Valencia et al. (2020)
	--	-28% to -14%	-333% to 8%	Ordonez et al. (2020b)
BAM	--	45% to 80%	-165% to 54%	Chang et al. (2019)
	48% to 70%	--	4% to 93%	Valencia et al. (2020)
IFGEM-1	--	91% to 95%	54% to 83%	Chang et al. (2019)
	85% to 94%	--	60% to 92%	Valencia et al. (2020)
IFGEM-2	--	88% to 94%	26% to 62%	Chang et al. (2019)
IFGEM-3	91% to 94%	--	81% to 92%	Valencia et al (2019)
	81% to 97%	--	50% to 92%	Valencia et al. (2020)
	--	82% to 85%	80% to 99%	Ordonez et al. (2020b)
	--	*42%	*96%	Ordonez et al. (2020a)
AGEM-1	--	90% to 94%	77% to 99%	Ordonez et al. (2020b)
AGEM-2	--	90% to 95%	89% to 99%	Ordonez et al. (2020b)
	--	*52%	*98%	Ordonez et al. (2020a)

*Cumulative nutrient removal over sorption study

2.4 CAM nutrient recovery

After the most promising two CAM mixes (IFGEM-3 and AGEM-2) were fully saturated during the sorption study (signifying that the sorption media could not take up more nutrients) they were then subjected to a desorption process to determine nutrient recovery potential. In this process, a desorbing agent (1% NaOH, sodium hydroxy solution) was fed to columns containing 500 grams of fully saturated IFGEM-3 or AGEM-2 mixes. The effluent water samples were collected and analyzed for nitrate, phosphate, and ammonia concentrations.

The results indicated that a desorption process on saturated IFGEM-3 and AGEM-2 mixes allow for the recovery of up to 57% and 60% of the phosphate, respectively (Table 2.4). Furthermore, the generation of ammonia is a by-product of nitrate reduction in the media. Respectively, 68.03 mg and 93.4 mg of ammonia was recovered from IFGEM-3 and AGEM-2 (Table 2.4). The desorption process in AGEM-2 slowed the infiltration rate through the media considerably, due to reactions of aluminum and NaOH that resulted in formation of H+ and the precipitation of NaAlO2. This suggests that in situ regeneration of AGEM-2 may not be possible.

However, after use in BMPs, saturated media mixes can be utilized as soil amendment to reduce the cost associated with disposal after media saturation.

These preliminary desorption results are promising and suggest that in situ regeneration of media and recovery of phosphate and ammonia from IFGEM-3 may be possible. However, work must be done to understand the logistical and economic feasibility of undertaking desorption at field scale. Finally, additional research is needed to assess release of iron and/or aluminum ions in IFGEM-3 and AGEM-2 effluent due to potential public health hazards (see Appendix A).

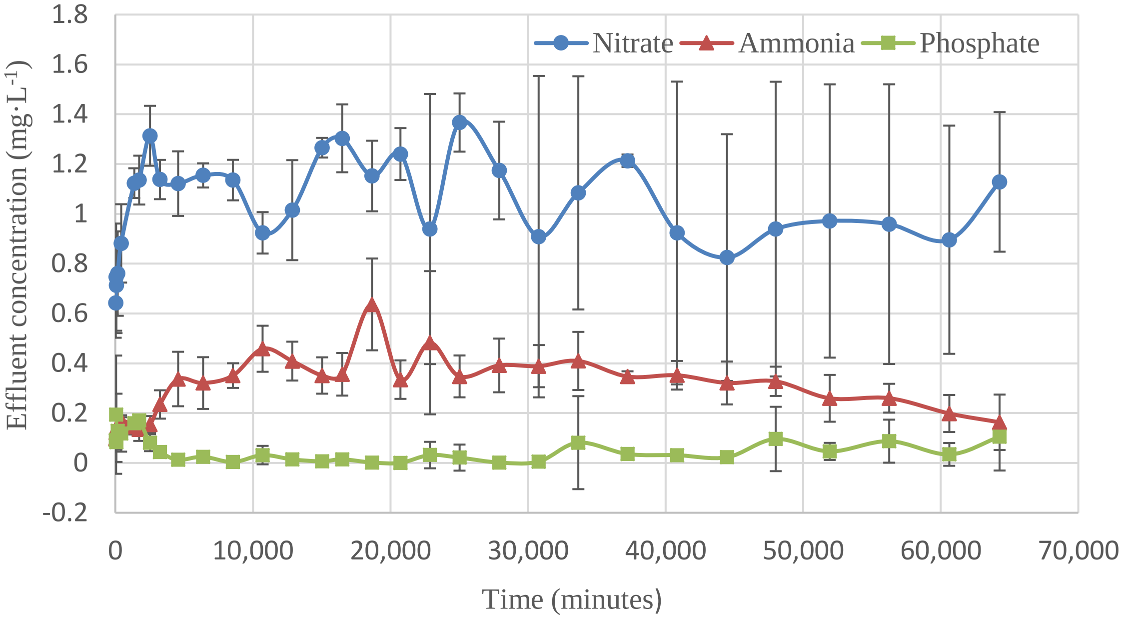


Figure 2.2. Nitrate, phosphate, and ammonia IFGEM-3 adsorption curves (Ordonez et al., 2020a)

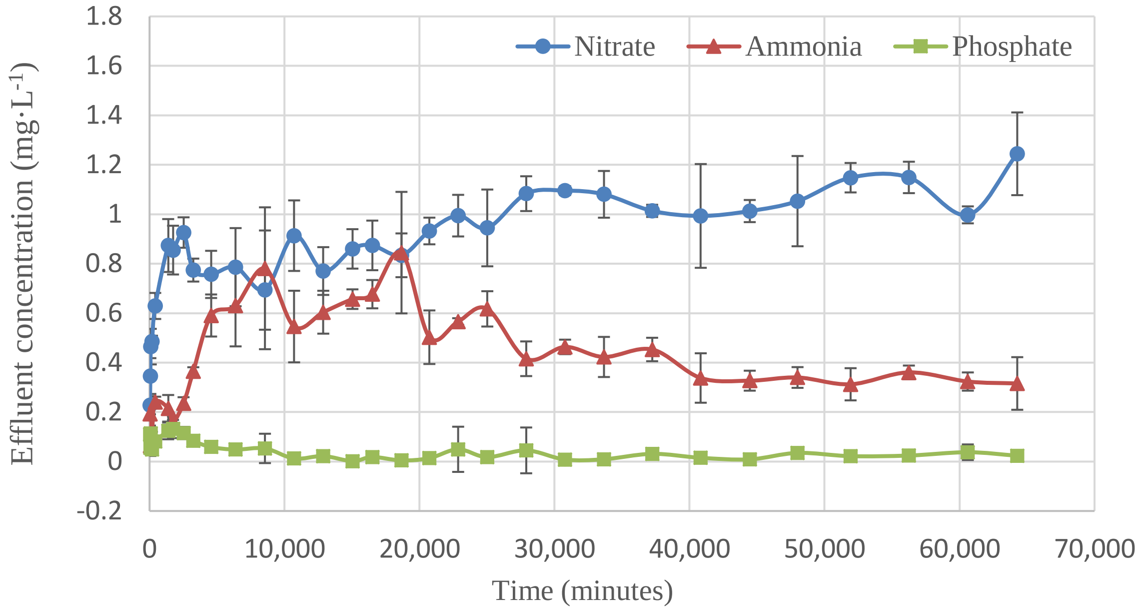


Figure 2.3. Nitrate, phosphate, and ammonia AGEM-2 adsorption curves (Ordonez et al., 2020a)

Table 2.4. Summary adsorption and desorption quantities from IFGEM-3 and AGEM-2 (Ordonez et al., 2020a)

Nutrient	**Total nutrient loading (mg)**[a]	**Nutrient adsorbed (mg)**	**Maximum sorption capacity (mg/g)**	**Nutrient produced and released during adsorption (mg)**[b]	**Nutrient released during desorption**[c] **(mg)**	**Nutrient generated (recovered) (mg)**[d]
			IFGEM-3			
NO_3^-	385.65	161.42	0.32	--	4.33	--
PO_4^{-3}	385.64	377.56	0.76	--	215.98	--
NH_3^+	0	--	--	68.03	1.13	69.16*
			AGEM-2			
NO_3^-	385.65	200.61	0.40	--	2.03	--
PO_4^{-3}	385.64	371.20	0.74	--	84.29	--
NH_3^+	0	--	--	93.4	2.49	95.89*

[a] Cumulative quantity of nutrient supplied over experiment run (64,275 min)

[b] Nutrient produced and released in the effluent by the media during sorption stage calculated from regression curve

[c] Nutrient released in the effluent by the media during desorption stage calculated from regression curve

[d] Sum of ammonia released during sorption stage and amount recovered from media during desorption stage

* Reflects approximation ammonia generated in adsorption stage as the quantity of ammonia released in desorption stage was not complete

CHAPTER 3. **Effectiveness of BAM-based BMPs applied in roadway shoulder filters**

3.1 Research objectives

The research objective was to investigate the drainage and nutrient removal effectiveness of vegetated filter strips (VFS) containing BAM when applied in shoulders of 1- and 2-lane roadways for the purpose of treating roadway runoff. Overall performance of BAM VFS in removing nutrients from stormwater runoff hinges upon two processes: 1) the hydraulic performance of the VFS to efficiently infiltrate precipitation and runoff and 2) the performance of the engineered media to effectively remove nutrients from infiltrated runoff. Experiments were designed to query the effectiveness of both processes within two 1:1 scale physical models of vegetated roadway shoulders: a treatment model containing BAM (CTS BOLD & GOLD^{TM}), and an identical control model containing AASHTO A-3 sandy soils. Drainage and nutrient removal performance of the BAM VFS is thus compared to that of A-3 sandy soils.

3.2 Design of experiments

Road shoulder models were constructed following standard specifications for 1- and 2-lane roadways in Florida (Florida Department of Transportation, 2012). The treatment model was filled with a 2-ft layer of BAM, overlain by a 1-ft layer of an A-3 sandy soil (Figure 3.1, material testing in Appendix B). The control model bed was filled with a 3-ft depth of A-3 sandy soil. All media were compacted to within the range of standard bulk density required for roadway shoulders in Florida (80 to 100 lb/ft^3, see Appendix B), with the exception of the top 0.5 ft, to allow vegetation establishment. Water was able to drain freely from the bottom of the models, simulating infinite depth to the groundwater table. A 10-ft impervious surface (6% slope) was poured at the upstream of each model to simulate a portion of the roadway and the paved shoulder. From the edge of the pavement, a 5 ft vegetated shoulder (6% slope) was followed by 15 ft of vegetated embankment (16.6% slope). Roadway shoulder and embankment areas of both models were cultivated from seed with Bahia grasses (Figure 3.2a). Bahia vegetation was cultivated over a period of 9 months to ensure a mature vegetative canopy before testing began. In a series of experiments, rainfall was simulated using a calibrated rainfall simulator (Figure 3.2b) while roadway runoff was introduced upstream as a sheet flow dispersed over the concrete (Figure 3.2c). Model construction is described in more detail in Kibler et al. 2018a and b.

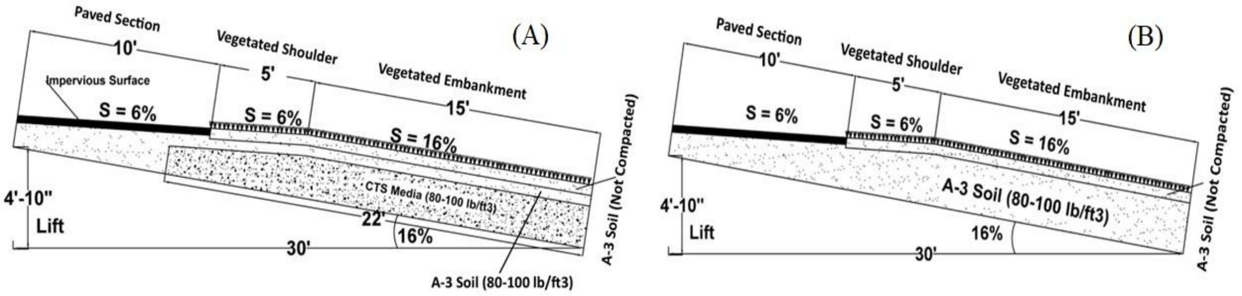


Figure 3.1. (a) Treatment and (b) control vegetated road shoulder models.

Figure 3.2. (a) Treatment and control model roadway shoulders, (b) lifted rainfall simulator, (c) roadway runoff delivered over paved section, (d) covered waterproof tarpaulin to exclude natural rainfall, and (e) water tank for supply water.

Thirty controlled experiments were performed to test hydraulic and nutrient removal performance of the BAM VFS. Each experiment consisted of identical testing in treatment and control models, and each tested design storm was replicated to simulate runoff from both 1- and 2-lane roadways. Hydraulic and nutrient removal performance was tested across varied design storms. The hydraulic performance of engineered media (e.g. partitioning inflows into infiltration vs. runoff) is likely to vary with storm duration, cumulative depth and rainfall intensities. Therefore, frequency analysis of long-term (1984-2013) rainfall data gauged in Central Florida was undertaken (Appendix B, detailed in Kibler et al. 2018a) to understand parameters of frequent storms (e.g. rainfall depth, duration, and patterns of occurrence). Partitioning of volumetric inflow (Q_{in}, consisting of precipitation and roadway runoff) into infiltrated water (Q_{inf}) and surface runoff (Q_{RO}) were accomplished using a water mass balance as below:

$$Q_{in} = Q_{inf} + Q_{RO} + Q_E \qquad \text{(Eq. 3.1)}$$

where evapotranspiration (Q_E) is considered negligible at event scale. Testing under frequently-occurring storm conditions indicates hydraulic and nutrient removal performance during rainfall events likely to produce high cumulative loadings of nutrients to receiving water bodies. Hydraulic performance was also tested under high-intensity rainfall conditions to indicate the maximum 1-hour storm intensities under which minimum hydraulic performance criteria are met.

Nutrient removal performance of VFS was examined for a range of rainfall depths (0.5 in, 0.75 in, 1 in, 1.5 in, and 3 in). Runoff nutrient loads of nitrate-nitrite (NO_x), ammonia (NH_3), total nitrogen (TN), and total phosphorus (TP) were designed based on review of literature citing concentrations of each constituent in roadway runoff (Table 3.1; Driscoll et al., 1990; Thomson et al., 1997; Barrett et al., 2004; Kayhanian et al., 2007; Harper and Baker, 2007; Winston et al. 2011; Winston and Hunt, 2016, Kibler et al., 2020b). Background nutrient concentrations in city water were measured (Appendix B), and standard solutions of 1,000 mg/L nitrogen-nitrate (NO_3-N), nitrogen-ammonia (NH_3-N), and phosphorus (P) were used to achieve target concentrations of NO_x, NH_3, and TP, respectively. Following the method applied by Caruso (2014), glycine ($C_2H_5NO_2$, 99% reagent) was used to create a stock solution of 1,000 mg/L as an organic nitrogen source to bring the solution into the target range for TN concentrations.

Table 3.1. Mean and range of Event Mean Concentrations of nutrients observed in runoff from roadways in Florida, Minnesota, California, and North Carolina.

Nutrient species	NO_x	NH_3	TN	TP
Mean EMC (mg/L)	0.58	0.11	1.75	0.21
Range of variation (mg/L)	0.23 – 1.32	0.07 – 0.15	0.68 – 3.20	0.07 – 0.56

Each experiment was completed on treatment and control test beds on the same day, or in the case of long event durations, on consecutive days. Input runoff was sampled at the start of each experiment, and infiltrate samples were collected from drainage ports underneath each model at varied intervals downstream, over a period of up to 72 hours. The test beds were covered when needed to exclude natural precipitation (Figure 3.2d). Samples were tested in triplicate for dissolved oxygen concentration (DO) and temperature immediately after sample collection using a YSI Pro 20i DO meter calibrated to the local DO saturation. pH was measured in triplicate within 24 hours of sample collection using a YSI Pro 1030 Water Quality Meter, calibrated before each use with a 3-point calibration using pH 4, 7, and 10 buffer solutions. Samples analyzed for nutrient concentration were kept cool ($T < 5°C$) and delivered to a certified lab (Environmental Research & Design) within 24 hours of collection. Each sample was tested in triplicate within 48 hours for concentrations of TN, NO_x, NH_3, and TP.

To ensure independence between experiments, all surfaces, vegetation, soils, and media of each test bed were washed with 2,000 L of water (approximately 40% of available pore volume) at the conclusion of each test. Rinsing was completed exactly 90 hours before the start of each experiment, providing identical drainage time to ensure similar media water content at the start of each experiment. The test beds were covered when needed to exclude natural precipitation. Vegetation canopy height was maintained before each experiment and vegetation density was monitored regularly within 12 in by 12 in (144 in^2) quadrats in seven randomly-selected locations in each test bed. Monitoring suggests that vegetation density was similar in control and treatment test beds over the period of experimentation (Figure 3.3).

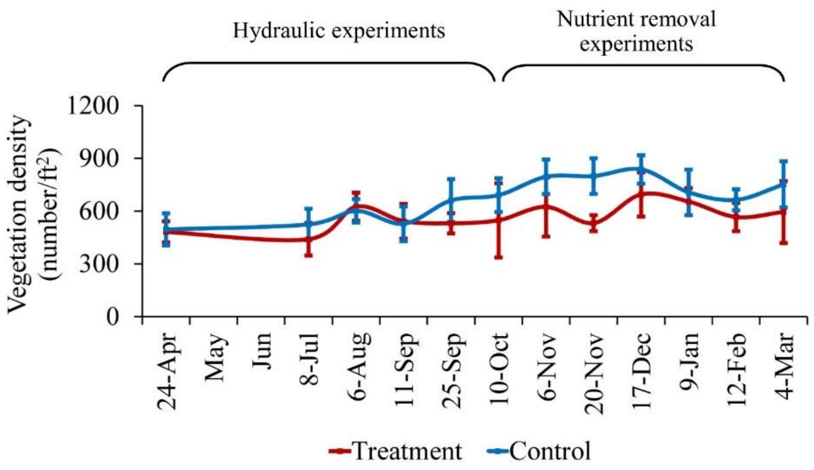


Figure 3.3. Mean vegetation density over the treatment and control test beds. Error bars indicate the range over seven random quadrat samples.

3.3. BAM VFS hydraulic performance

As storms progressed, overland flow initially generated where roadway runoff flowed from the pavement to the vegetated section of test beds and usually infiltrated further along the test beds. The length over which overland flow generated increased with storm intensity (Figures 3.4 and 3.5), until the entire model length generated overland flow. During identical storm events, overland flow was consistently generated at greater lengths in the treatment system as compared to the control (Figures 3.4 and 3.5, Tables 3.2-3.5). Additionally, surface runoff was collected at the downstream of the treatment model, but never in the control model (Tables 3.2-3.5).

Surface runoff generated to the end of the treatment model during high rainfall intensities. All surface runoff recorded was generated as Hortonian overland flow, signifying that infiltration rate was lower than the water input rate. During 1-lane roadway simulations, surface runoff at the downstream of the treatment test bed was recorded during the highest intensity storm, 3 in/h (76.2 mm/h) (Table 3.2 and Figure 3.4). Approximately 35% of inflow water did not infiltrate into the filter during this storm and left the treatment system as Hortonian surface water runoff. During 2-lane roadway simulations, respectively 22% and 35% of input water ran off as Hortonian flow at the downstream of the treatment test bed during storm intensities of 2 in/h and 3 in/h (Table 3.3 and Figure 3.4). At an intensity of 2 in/hr, Hortonian surface water runoff generated over the entire 20 ft BAM VFS approximately 30 min from the beginning of storm (Table 3.3). This time decreased to about 20 min at the higher storm intensity of 3 in/h.

By comparison, surface runoff was never recorded in the downstream of the control test bed (Table 3.2-3.5, Figures 3.4 and 3.5). For the same storm intensity, overland flow infiltrated closer to pavement in the control than the treatment model. The generally lower lengths of overland flow in the control test bed and lack of Hortonian surface runoff at the downstream of the control test bed suggests that infiltration rates through BAM were slightly lower relative to the A-3 soil.

Results of the high-intensity testing indicate that the hydraulic capacity of a 20-ft wide BAM VFS similar to the model is likely to be exceeded only rarely, given sufficient depth to the groundwater table. For reference, in the Silver Springs vicinity a storm with 1-h duration and 3 in/h intensity would have a recurrence interval of once every 62.5 years. Hydraulic experiments for 1-lane and 2-lane roadways during storm events with more typical parameters suggest complete infiltration before 20 ft (Figure 3.4 Tables 3.4-3.5).

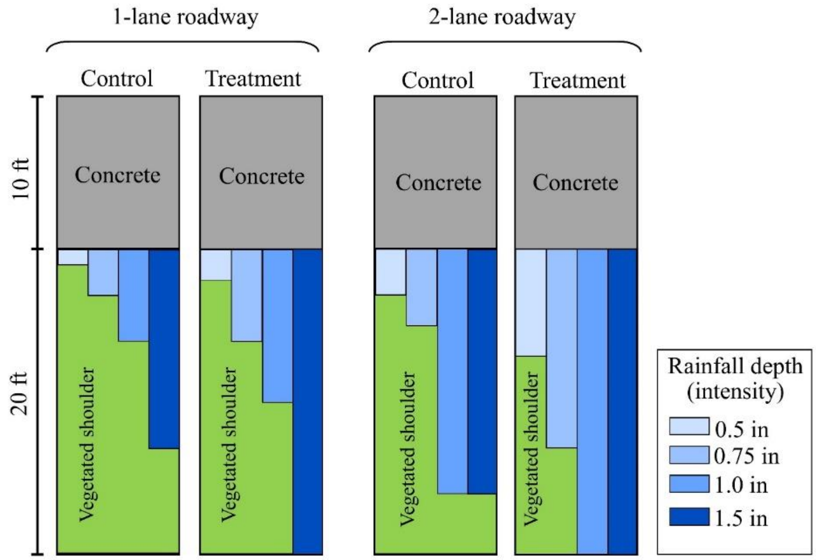


Figure 3.4. High-intensity hydraulic testing: overland flow generation length over control and treatment test beds during 1- and 2-lane simulations.

Table 3.2. High-intensity hydraulic testing results: 1-lane roadways

		treatment test bed				control test bed			
Storm depth in (mm)		1 (25.4)	1.5 (38.1)	2 (50.8)	3 (76.2)	1 (25.4)	1.5 (38.1)	2 (50.8)	3 (76.2)
Storm duration, (h)		1	1	1	1	1	1	1	1
Mean intensity, in/h (mm/h)		1 (25.4)	1.5 (38.1)	2 (50.8)	3 (76.2)	1 (25.4)	1.5 (38.1)	2 (50.8)	3 (76.2)
Q_{in}	Rainfall, ft^3 (L)	19.9 (566)	29.9 (849)	40.0 (1133)	59.9 (1699)	19.9 (566)	29.9 (849)	40.0 (1133)	59.9 (1699)
	Roadway runoff, ft^3 (L)	7.9 (226)	12.0 (340)	15.9 (452)	23.9 (678)	7.9 (226)	12.0 (340)	15.9 (452)	23.9 (678)
	Total, ft^3 (L)	27.9 (792)	41.9 (1189)	55.9 (1585)	83.9 (2377)	27.9 (792)	41.9 (1189)	55.9 (1585)	83.9 (2377)
Q_{out}	Infiltrated water, ft^3 (L)	30.7 (870)	27.1 (770)	52.9 (1500)	54.5 (1545)	25.8 (731)	22.1 (626)	55.7 (1578)	83.9 (2377)
	Surface runoff, ft^3 (L)	0.0	0.0	0.0	29.3 (832)	0.0	0.0	0.0	0.0
	Total, ft^3 (L)	30.7 (870)	27.1 (770)	52.9 (1500)	83.9 (2377)	25.8 (731)	22.1 (626)	55.7 (1578)	83.9 (2377)
	Infiltration %	100	100	100	65	100	100	100	100
	Runoff %	0.0	0.0	0.0	35	0.0	0.0	0.0	0.0
Time to flow generation at 20 ft (h)		-	-	-	0.5	-	-	-	-
Overland flow length ft (m)		2 (0.6)	5-6 (1.5 – 2)	10 (3)	20 (6)	1 (0.3)	3 (1)	5-6 (1.5 – 2)	13 (3.9)

Table 3.3. High-intensity hydraulic testing results: 2-lane roadways

		treatment test bed				control test bed			
Storm depth, in (mm)		1 (25.4)	1.5 (38.1)	2 (50.8)	3 (76.2)	1 (25.4)	1.5 (38.1)	2 (50.8)	3 (76.2)
Storm duration, (h)		1	1	1	1	1	1	1	1
Mean intensity, in/h (mm/h)		1 (25.4)	1.5 (38.1)	2 (50.8)	3 (76.2)	1 (25.4)	1.5 (38.1)	2 (50.8)	3 (76.2)
Q_{in}	Rainfall, ft^3 (L)	19.9 (566)	29.9 (849)	40.0 (1133)	59.9 (1699)	19.9 (566)	29.9 (849)	40.0 (1133)	59.9 (1699)
	Roadway runoff, ft^3 (L)	15.9 (452)	24 (679)	31.9 (904)	47.8 (1356)	15.9 (452)	24 (679)	31.9 (904)	47.8 (1356)
	Total, ft^3 (L)	35.8 (1018)	53.9 (1528)	71.9 (2037)	107.8 (3055)	35.8 (1018)	53.9 (1528)	71.9 (2037)	107.8 (3055)
Q_{out}	Infiltrated water, ft^3 (L)	35.8 (1018)	53.9 (1528)	55.7 (1580)	70.4 (1995)	35.8 (1018)	53.9 (1528)	71.9 (2037)	107.9 (3055)
	Surface runoff, ft^3 (L)	0	0	16.1 (458)	37.4 (1060)	0	0	0.0	0.0
	Total, ft^3 (L)	35.8 (1018)	53.9 (1528)	71.9 (2038)	107.8 (3055)	35.8 (1018)	53.9 (1528)	71.9 (2037)	107.9 (3055)
	Infiltration %	100	100	78	65	100	100	100	100
	Runoff %	0	0	22	35	0	0	0.0	0.0
Time to flow generation at 20 ft (h)		-	-	0.5	0.3	-	-	-	-
Overland flow length ft (m)		7 (2.1)	13 (3.9)	20 (6)	20 (6)	2-3 (0.6 -1)	5 (1.5)	16 (5)	15-16 (4.5- 5)

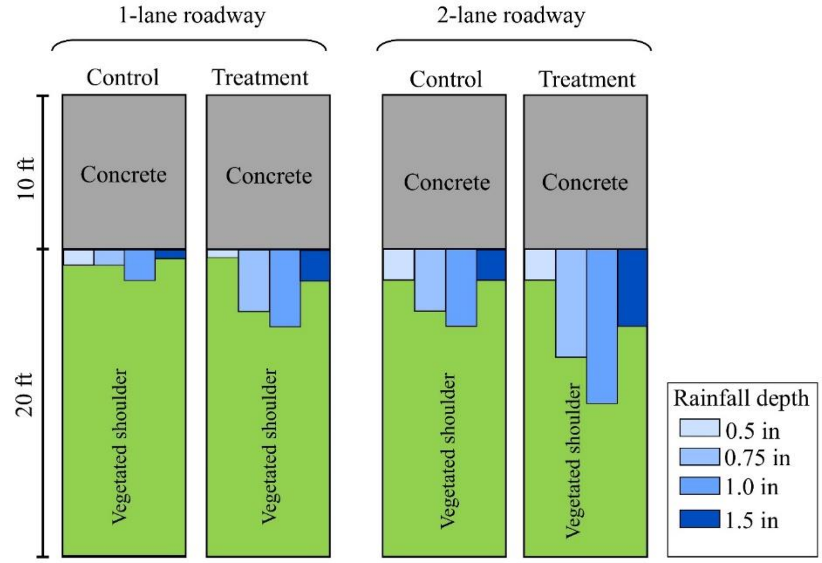


Figure 3.5. Lower-intensity hydraulic testing: overland flow generation length over control and treatment test beds during 1- and 2-lane simulations.

Table 3.4. Lower-intensity hydraulic testing results: 1-lane roadways

		treatment test bed				control test bed			
Storm depth in (mm)		0.5 (12.7)	0.75 (19.05)	1 (25.4)	1.5 (38.1)	0.5 (12.7)	0.75 (19.05)	1 (25.4)	1.5 (38.1)
Storm duration, (h)		0.5	0.75	0.75	3.75	0.5	0.75	0.75	3.75
Mean intensity, in/h (mm/h)		1 (25.4)	1 (25.4)	1.3 (33.0)	0.4 (10.16)	1 (25.4)	1 (25.4)	1.3 (33.0)	0.4 (10.16)
Q_{in}	Rainfall, ft^3 (L)	10 (283)	15 (425)	20 (566)	30 (849)	10 (283)	15 (425)	20 (566)	30 (849)
	Roadway runoff, ft^3 (L)	4 (113)	6 (170)	8 (226)	12 (340)	4 (113)	6 (170)	8 (226)	12 (340)
	Total, ft^3 (L)	14 (396)	21 (595)	28 (792)	42 (1189)	14 (396)	21 (595)	28 (792)	42 (1189)
Q_{out}	Infiltrated water, ft^3 (L)	14 (396)	21 (595)	28 (792)	42 (1189)	14 (396)	21 (595)	28 (792)	42 (1189)
	Surface runoff, ft^3 (L)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Total, ft^3 (L)	14 (396)	21 (595)	28 (792)	42 (1189)	14 (396)	21 (595)	28 (792)	42 (1189)
	Infiltration %	100	100	100	100	100	100	100	100
	Runoff %	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Time to flow generation at 20 ft (h)		-	-	-	-	-	-	-	-
Overland flow length ft (m)		0.5 (0.15)	3-4 (0.9 - 1.2)	5 (1.5)	1-2 (0.3-0.6)	0.5-1 (0.15-0.3)	1 (0.3)	1-2 (0.3-0.6)	0.5 (0.15)

Table 3.5. Lower-intensity hydraulic testing results: 2-lane roadways

		treatment test bed				control test bed			
Storm intensity in/h (mm/h)		0.5 (12.7)	0.75 (19.05)	1 (25.4)	1.5 (38.1)	0.5 (12.7)	0.75 (19.05)	1 (25.4)	1.5 (38.1)
Storm duration, (h)		0.5	0.75	0.75	3.75	0.5	0.75	0.75	3.75
Mean intensity, in/h (mm/h)		1 (25.4)	1 (25.4)	1.3 (33.0)	0.4 (10.16)	1 (25.4)	1 (25.4)	1.3 (33.0)	0.4 (10.16)
Q_{in}	Rainfall, ft^3 (L)	10 (283)	15 (425)	20 (566)	30 (849)	10 (283)	15 (425)	20 (566)	30 (849)
	Roadway runoff, ft^3 (L)	8 (226)	12 (340)	16 (452)	24 (680)	8 (226)	12 (340)	16 (452)	24 (680)
	Total, ft^3 (L)	18 (509)	27 (765)	36 (1018)	54 (1529)	18 (509)	27 (765)	36 (1018)	54 (1529)
Q_{out}	Infiltrated water, ft^3 (L)	18 (509)	27 (765)	36 (1018)	54 (1529)	18 (509)	27 (765)	36 (1018)	54 (1529)
	Surface runoff, ft^3 (L)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Total, ft^3 (L)	18 (509)	27 (765)	36 (1018)	54 (1529)	18 (509)	27 (765)	36 (1018)	54 (1529)
	Infiltration %	100	100	100	100	100	100	100	100
	Runoff %	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Time to flow generation at 20 ft (h)		-	-	-	0.5	-	-	-	-
Overland flow length ft (m)		1-2 (0.3-0.6)	7 (2)	10 (3)	5 (1.5)	2 (0.6)	4 (1.2)	5 (1.5)	1-2 (0.3-0.6)

3.4 BAM VFS nutrient removal performance

The 20 ft BAM VFS strongly outperformed the control in terms of nitrogen removal performance (Figures 3.6 and 3.7, Tables 3.6-3.9). With regard to phosphorus removal, both the treatment and control test beds performed well, reducing TP by respectively 84±9% and 82±12% by 5 ft from the pavement. Similar patterns of nutrient removal were observed across all experiments (various design storms and 1- and 2-lane roadway designs, shown individually in Appendix B), suggesting that VFS nutrient removal was most strongly related to runoff nutrient concentration and subsurface conditions and less affected by storm depth or roadway type.

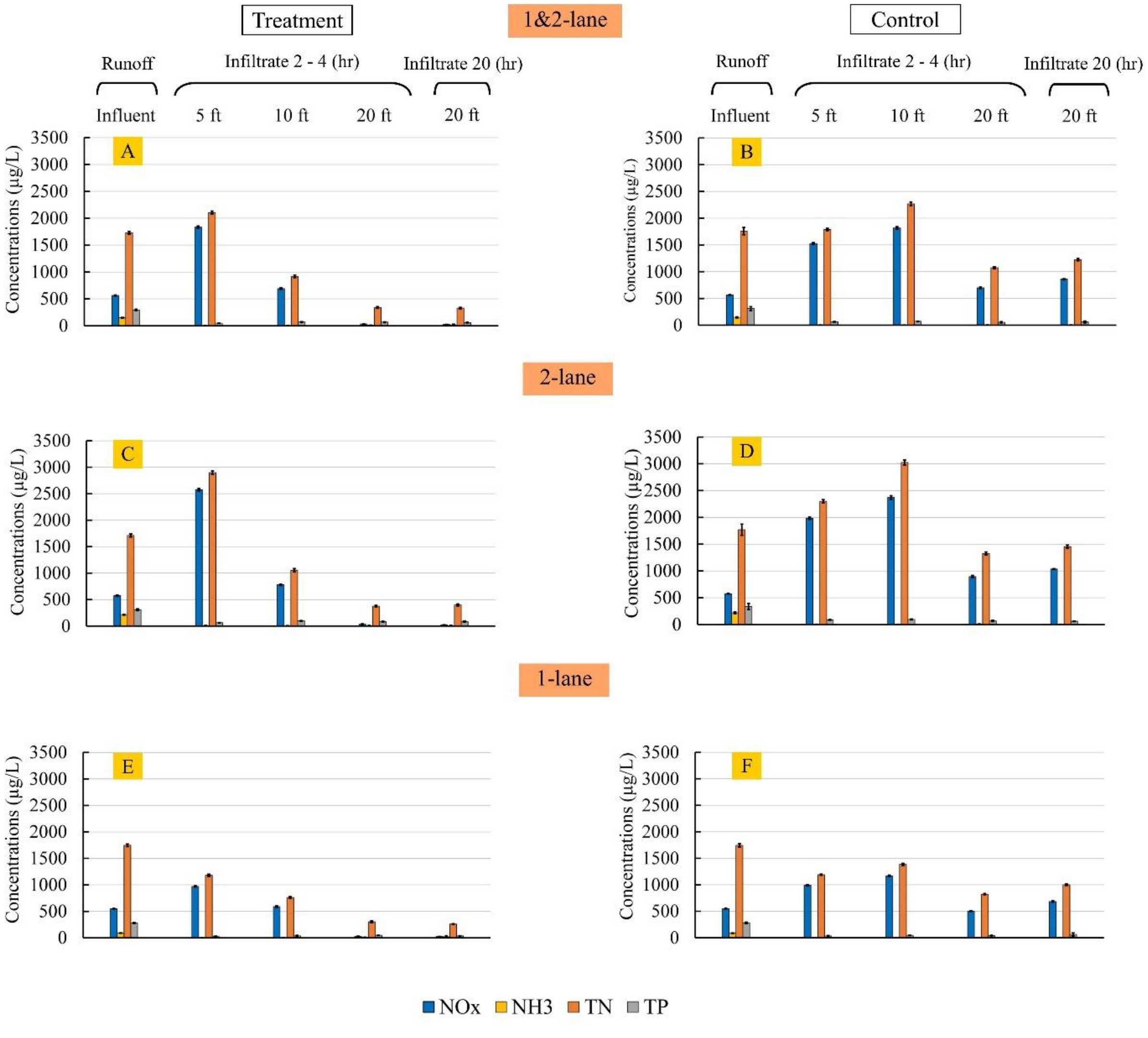


Figure 3.6. Mean ± SD nutrient concentrations in simulated roadway runoff (influent) and infiltrate sampled from 5, 10 and 20 ft along the treatment (a, c, and e) and control (b, d, and f) models. Top figures combine data from all experiments; data are shown separately for 1- and 2-lane roadway experiments below.

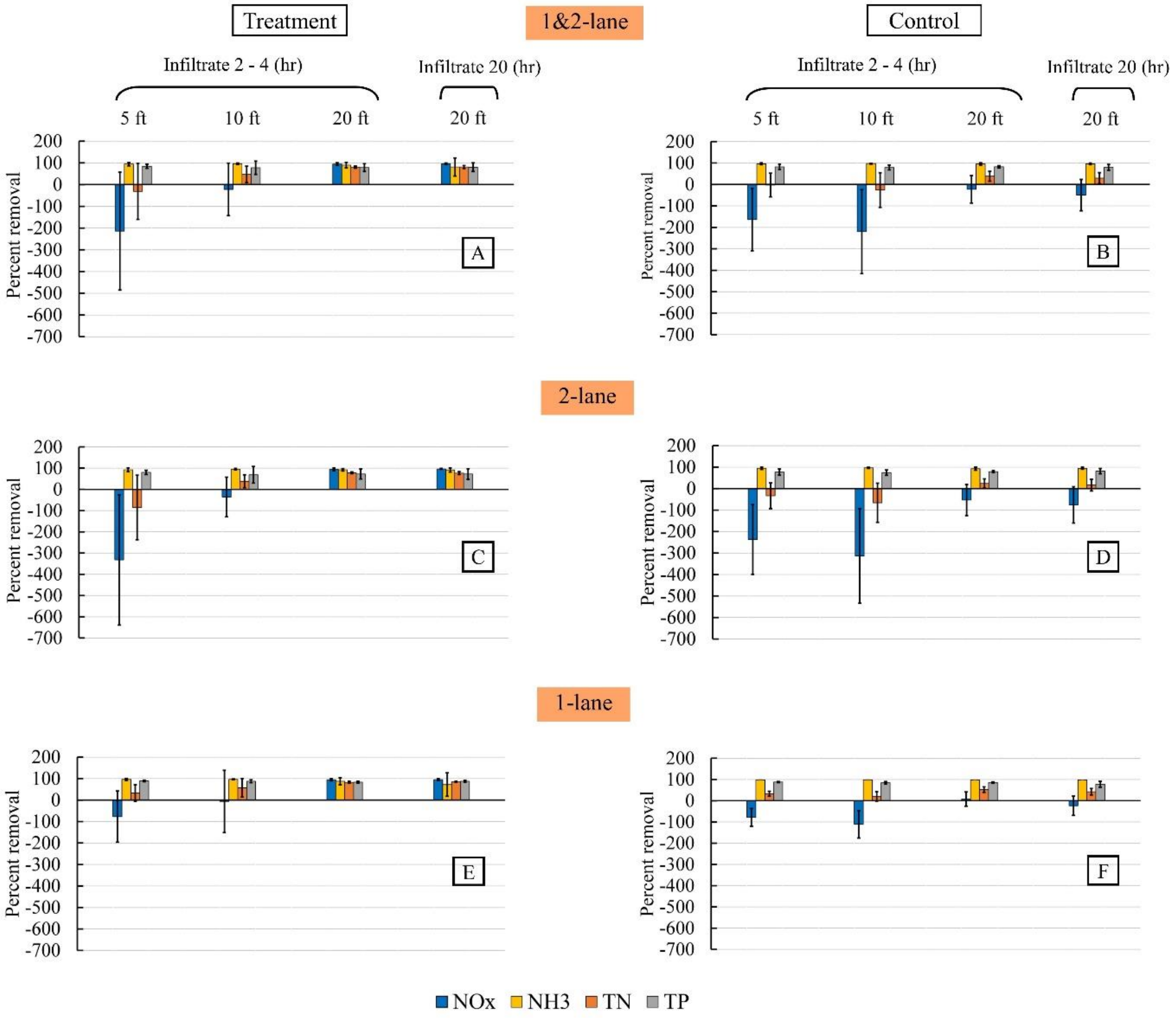


Figure 3.7. Mean ± SD percent nutrient removal with respect to influent of infiltrate sampled from 5, 10 and 20 ft along the treatment (a, c, and e) and control (b, d, and f) models. Top figures combine data from all experiments; data are shown separately for 1- and 2-lane roadway experiments below. Negative removal indicates nutrient generation relative to influent.

The most striking difference between treatment and control models was related to nitrate removal performance. Across all experiments, nitrate concentrations in the control increased relative to the influent concentration, at every sampled location and time. For instance, nitrate increased by 220±196% by 10 ft and remained elevated by 50±73% at 20 ft (Table 3.6). In the treatment model, nitrate generation was also observed at 5 ft and 10 ft, with mean respective nitrate concentration increases of 214±271% and 22±121%. However, by 20 ft, nitrate had been all but removed by the treatment model, decreasing by a mean 94±6% relative to influent by four hours after the experiment start. While nitrate behavior in 5 ft and 10 ft positions varied from test to test, the strong decrease in nitrate concentration by 20 ft in the treatment model was highly consistent between tests. Independent-sample t-test analysis ($\alpha = 0.05$) confirmed that nitrate and TN concentrations were significantly lower in the treatment model (Table 3.9).

The treatment model also removed TN more effectively than the control (Table 3.9). Similar to nitrate, TN generation was observed at 5 ft in the treatment and at 5 ft and 10 ft in the control. However, both models had decreased TN concentrations by 20 ft. At 20 ft, TN concentrations were reduced by a mean 80±5% in the treatment model as compared to 38±23% in the control. Nitrate generation in the first 10 ft of the road shoulder models is likely at least partially explained by rapid conversion of ammonia to nitrate by nitrification. Ammonia concentrations decreased consistently and abruptly within the first 5 ft of both models, by 94±7% and 96±4%, respectively, in treatment and control models. Mean infiltrate DO concentrations at 20 ft 72 hours after the experiments' starts were 6.3±1.3 mg/L and 8.1±1.3 mg/L in treatment and control models (Table 3.10), well above thresholds of hypoxia. However, DO levels and pH decreased significantly through the treatment model (Table 3.11) while DO saturation increased in the control (Figure 3.8), potentially indicating increased oxygen demand through microbial activity in the treatment model.

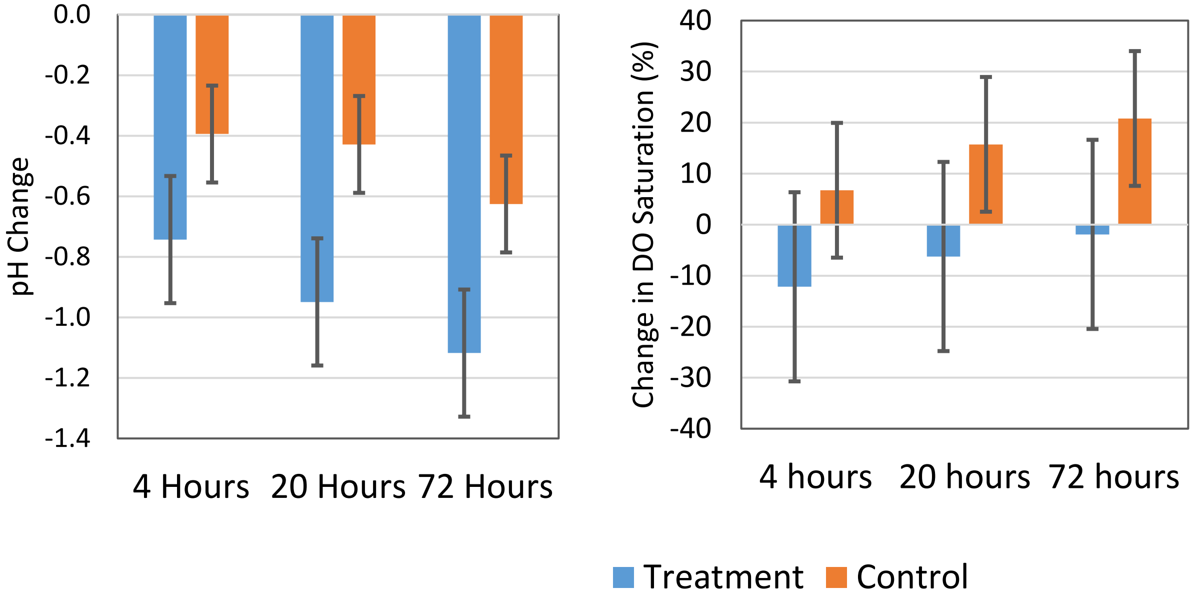


Figure 3.8. Mean ± SD change in pH and DO saturation relative to runoff in treatment and control models.

Table 3.6. Mean ± SD nutrient concentrations and percent removal across all experiments. Negative removal indicates nutrient generation relative to influent.

			Mean Concentration (µg/l)				% removal			
			NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP
1- and 2-lane roadways	treatment	Roadway runoff	563±10	149±6	1729±27	295±12	-	-	-	-
		Infiltrate 5 ft (4 hr)	1835±19	6±1	2105±26	48±4	-214±271	94±7	-31±129	84±9
		Infiltrate10 ft (4 hr)	692±14*	4±1	919±25*	69±7	-22±121*	96±3	47±38*	78±31
		Infiltrate 20 ft (4 hr)	32±4**	10±1	339±16**	66±6	94±6**	90±12	80±5**	78±18
		Infiltrate 20 ft (20 hr)	23±3**	16±11	329±12**	61±8	96±3**	81±42	81±7**	80±20
	control	Roadway runoff	565±7	147±10	1758±69	309±36	-	-	-	-
		Infiltrate 5 ft (4 hr)	1526±17	4±1	1788±22	63±6	-164±146	96±4	-3±55	82±12
		Infiltrate 10 ft (4 hr)	1816±23*	3±0	2267±35*	72±4	-220±196*	97±2	-26±81*	79±11
		Infiltrate 20 ft (4 hr)	700±14**	6±1	1074±20**	54±10	-23±64**	95±5	38±23**	82±5
		Infiltrate 20 ft (20 hr)	859±9**	4±1	1226±23**	62±17	-50±73**	96±4	29±26**	80±13

*indicates statistically significant difference between treatment and control

**indicates highly statistically significant difference between treatment and control

Table 3.7. Mean ± SD nutrient concentrations and percent removal across all 2-lane roadway experiments. Negative removal indicates nutrient generation relative to influent.

			Mean Concentration (µg/l)				% removal			
			NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP
2-lane roadways	treatment	Roadway runoff	575±13	215±10	1711±28	308±17	-	-	-	-
		Infiltrate 5 ft (4 hr)	2575±25	9±1	2898±30	63±5	-332±307	92±9	-85±152	80±10
		Infiltrate 10 ft (4 hr)	780±13*	6±1	1053±33*	98±4	-36±93*	95±4	38±30*	69±39
		Infiltrate 20 ft (4 hr)	34±5**	8±2	377±15**	84±8	94±6**	92±6	78±4**	73±23
		Infiltrate 20 ft (20 hr)	20±4**	10±2	398±18**	86±11	97±3**	91±9	77±7**	72±25
	control	Roadway runoff	578±6	218±16	1770±104	338±58	-	-	-	-
		Infiltrate 5 ft (4 hr)	1984±20	6±1	2299±31	88±6	-237±162	95±6	-33±59	77±14
		Infiltrate 10 ft (4 hr)	2371±33*	4±0	3024±46*	95±6	-314±220*	96±3	-66±91*	74±13
		Infiltrate 20 ft (4 hr)	896±21**	10±2	1326±29**	67±10	-54±72**	93±7	24±22**	79±5
		Infiltrate 20 ft (20 hr)	1035±6**	7±1	1453±30**	62±4	-76±85**	95±5	16±27**	81±12

*indicates statistically significant difference between treatment and control

**indicates highly statistically significant difference between treatment and control

Table 3.8. Mean ± SD nutrient concentrations and percent removal across all 1-lane roadway experiments. Negative removal indicates nutrient generation relative to influent.

			Mean Concentration (µg/l)				% removal			
			NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP
1-lane roadways	treatment	Roadway runoff	550±8	91±3	1747±25	281±8	-	-	-	-
		Infiltrate 5 ft (4 hr)	971±12	3±0	1180±21	31±2	-77±119	96±5	33±38	89±3
		Infiltrate 10 ft (4 hr)	590±16	3±1	763±15	36±10	-6±145	97±2	57±43	88±7
		Infiltrate 20 ft (4 hr)	29±3	12±1	302±16	47±4	95±5	88±16	83±5	83±4
		Infiltrate 20 ft (20 hr)	25±1	21±18	260±7	35±5	95±4	72±55	85±2	88±5
	control	Roadway runoff	552±8	86±5	1745±34	281±13	-	-	-	-
		Infiltrate 5 ft (4 hr)	992±12	2±0	1191±10	34±7	-78±42	98±1	33±11	88±2
		Infiltrate 10 ft (4 hr)	1169±13	2±0	1383±22	44±2	-111±65	98±1	20±22	84±6
		Infiltrate 20 ft (4 hr)	504±8**	2±0	823±11**	40±9	8±34**	98±1	52±13**	85±3
		Infiltrate 20 ft (20 hr)	682±12**	2±0	1000±15**	61±30	-24±46**	98±0	42±15**	78±14

*indicates statistically significant difference between treatment and control

**indicates highly statistically significant difference between treatment and control

Table 3.9. Results of hypothesis testing comparing mean nutrient concentrations in treatment and control models: 2-tailed p-values of independent-sample t-test analysis with 95% confidence interval. **Bolded** values are statistically significant. Values in ***italics*** are highly statistically significant.

		NO$_x$	NH$_3$	TN	TP
1 & 2 lane roadway	Roadway runoff	0.851	0.884	0.637	0.471
	Infiltrate 5 ft (4 hr)	0.609	0.339	0.589	0.489
	Infiltrate 10 ft (4 hr)	**0.009**	0.184	**0.021**	0.940
	Infiltrate 20 ft (4 hr)	***0.000***	0.195	***0.000***	0.454
	Infiltrate 20 ft (20 hr)	***0.000***	0.170	***0.000***	0.743
2-lane roadway	Roadway runoff	0.901	0.873	0.596	0.422
	Infiltrate 5 ft (4 hr)	0.535	0.407	0.483	0.492
	Infiltrate 10 ft (4 hr)	**0.011**	0.296	**0.034**	0.969
	Infiltrate 20 ft (4 hr)	***0.000***	0.920	***0.000***	0.572
	Infiltrate 20 ft (20 hr)	***0.001***	0.435	***0.000***	0.516
1-lane roadway	Roadway runoff	0.862	0.618	0.975	0.970
	Infiltrate 5 ft (4 hr)	0.959	0.400	0.981	0.729
	Infiltrate 10 ft (4 hr)	0.221	0.194	0.208	0.614
	Infiltrate 20 ft (4 hr)	***0.000***	0.092	***0.000***	0.312
	Infiltrate 20 ft (20 hr)	***0.001***	0.264	***0.000***	0.150

Table 3.10. Mean ± SD pH and DO in runoff and infiltrate at 20 ft in treatment and control models, 72 hours after experiment start.

Parameter	**Runoff**		**Infiltrate**	
	treatment	control	treatment	control
pH	8.06 ± 0.12	8.01 ± 0.10	7.31 ± 0.15**	7.62 ± 0.12**
DO (mg/L)	8.39 ± 1.29	8.29 ± 1.28	6.28 ± 1.30*	8.05 ± 1.28*
DO (%sat)	79.88 ± 10.58	80.09 ± 9.45	67.97 ± 12.54*	86.24± 11.50*

*indicates statistically significant difference between treatment and control

**indicates highly statistically significant difference between treatment and control

Table 3.11. Results of hypothesis testing comparing mean pH and DO in treatment and control models: 2-tailed p-values of independent-sample t-test analysis with 95% confidence interval. **Bolded** values are statistically significant. Values in ***italics*** are highly statistically significant.

		DO (mg/L)	DO saturation (%)	pH
1 & 2 lane roadway	Roadway runoff	0.853	0.930	0.159
	Infiltrate 5 ft (4 hr)	0.783	0.648	***0.000***
	Infiltrate 10 ft (4 hr)	0.220	0.178	***0.000***
	Infiltrate 20 ft (4 hr)	**0.002**	***0.001***	***0.000***
	Infiltrate 20 ft (20 hr)	**0.007**	**0.002**	***0.000***
	Infiltrate 20 ft (46 hr)	**0.006**	***0.001***	0.890
	Infiltrate 20 ft (72 hr)	**0.006**	**0.002**	***0.000***
2-lane roadway	Roadway runoff	0.529	0.547	0.450
	Infiltrate 5 ft (4 hr)	0.522	0.407	***0.000***
	Infiltrate 10 ft (4 hr)	0.926	0.997	***0.001***
	Infiltrate 20 ft (4 hr)	0.060	0.069	**0.012**
	Infiltrate 20 ft (20 hr)	**0.024**	**0.035**	***0.000***
	Infiltrate 20 ft (46 hr)	0.067	**0.023**	***0.000***
	Infiltrate 20 ft (72 hr)	**0.043**	**0.029**	**0.010**
1-lane roadway	Roadway runoff	0.248	0.560	0.383
	Infiltrate 5 ft (4 hr)	0.842	0.670	***0.000***
	Infiltrate 10 ft (4 hr)	0.052	**0.002**	***0.000***
	Infiltrate 20 ft (4 hr)	**0.002**	***0.000***	***0.000***
	Infiltrate 20 ft (20 hr)	**0.049**	**0.024**	***0.000***
	Infiltrate 20 ft (46 hr)	0.072	**0.024**	0.871
	Infiltrate 20 ft (72 hr)	0.096	0.056	0.083

3.5 Recommendations

The enhanced nitrogen removal performance of the BAM VFS model indicates greater capacity for nutrient uptake and transformation within the BAM filter as compared to the soils of the control test bed. This finding suggests that road shoulder BAM VFS may be effective BMPs for stormwater nitrogen removal. The addition of BAM may be particularly effective at remediating nitrate concentrations before stormwater reaches receiving water bodies. While promising, the nitrogen removal benefits of BAM VFS concluded in this study are strictly relative to the nutrient removal performance of the control soils tested in this experiment. Soil properties (e.g. texture, organic matter content) are naturally spatially heterogeneous and influence the transformation of nitrogen through the soil profile. Therefore, nitrogen remediation that can be expected within unaltered soil profiles also varies from place to place. In some places, replacing the unaltered soil profile with a filtration media such as BAM will lead to greater and more consistent transformation and removal of nitrogen (as observed in this study); in other cases, the natural remediation of the unaltered soil profile will equal or exceed that of BAM. Better understanding of nutrient transformation within BAM relative to soils of variable properties will allow managers to make more precise predictions of when replacing part of the soil profile in a VFS with BAM may lead to greater net benefits of nutrient remediation. Controlled, field-scale experimental applications of BAM BMPs are necessary to gain further knowledge to this end.

Given the observed generation of nitrate and TN at 5 ft and 10 ft widths, a BAM VFS filter width greater than 10 ft is recommended to ensure sufficient nutrient removal performance. A minimum width of 20 feet should ensure adequate performance in removing both nitrate and TN. The State water management districts recommend a media depth of no less than one foot with two feet of media (as tested herein) preferred. Study findings suggest that stormwater-media contact times of 4 hours or less should be sufficient to attain considerable nutrient transformation. Within the treatment model, there was very little change in nutrient concentrations of infiltrate sampled at 20 ft at 4 hrs vs. 20 hrs after the start of precipitation.

Overall VFS effectiveness must be understood in terms of potential to both intercept and treat nutrient loads. Design of VFS should be focused on infiltration of the events with potential to deliver the greatest loading of nutrients, which are frequently-occurring rainfall-runoff events. These events tend to be small with respect to cumulative rainfall depth. Larger events occur less frequently and will thus deliver overall smaller loading of nutrients from roadways. Events with larger cumulative depth are therefore potentially of lesser importance to VFS design. High-intensity hydraulic testing confirmed that the capacity of 20 ft-wide VFS with sandy soil textures and/or BAM are unlikely to be exceeded during typical and even lower-frequency events. Although the infiltration rate through the BAM VFS was slightly lower than the control sandy soils, the reduction in drainage rates in the BAM filter were not sufficient to produce surface runoff during event sizes that would occur with regularity. Again, given the spatial heterogeneity of soils, it should be understood that these results are partially controlled by the sandy soils tested. While BAM will behave similarly from place to place, soils used to overlay BAM may vary with respect to properties that control drainage. When infiltration is not impeded by a shallow water table, and when soil hydraulic conductivities are similar to those tested, hydraulic capacity is not necessarily a limitation to annual average nutrient remediation by a 20-ft roadway shoulder BAM VFS.

Rainfall-runoff lab experimentation as reported herein represents areas with a relatively deep (> 3 ft) vadose zone, such that surface infiltration into the VFS is not impeded by saturation from below by the groundwater table. Thus, any surface runoff observed within the vegetated sections of the test beds was generated as infiltration-excess (Hortonian) overland flow and was not saturation-excess overland flow. Outcomes of these experiments will therefore not necessarily apply to situations when infiltration is impeded the groundwater table. In these situations, partitioning of runoff and infiltration will become site- and event-specific, and thus cannot be tested for generally. Prospective sites for BAM VFS installation should be monitored to determine seasonal depth to the groundwater table. Since the BAM filter cannot treat stormwater that does not infiltrate, calculation of potential annual nutrient removal benefit should consider whether reduced vadose zone capacity will limit stormwater infiltration and thus treatment.

CHAPTER 4. Improvement of BMP Trains model for integrated assessment of surface and groundwater BMPs

4.1 Research objectives

The research objective was to overhaul the BMP Trains program to produce a model that could integrate groundwater and surface discharges, include more complex catchment configurations, and ease the user experience, all with continued support of regulatory agencies. This Chapter describes development of the improved BMP Trains model, results of testing the updated BMP Trains model and the updated user manual (Appendix C). The user manual includes example problems, such as how to assess the design of a BAM Vegetated Filter Strip (VFS) on a roadway shoulder.

In 2008, stormwater professionals within the State of Florida started a process to evaluate the effectiveness of stormwater best management practices (BMPs). At that time, the Florida Department of Transportation (FDOT) professionals were part of a Technical Advisory Committee that reviewed existing and new BMPs as well as methods for evaluation of nutrient mass removal on an average annual basis. The methods of evaluation became more complex as BMPs were integrated together. In 2008, there were only 2 BMPs, namely retention and wet detention ponds, with sufficient data to reasonably assess the annual removal effectiveness. Retention BMPs performance was also limited to data from infiltration dry ponds and exfiltration. All other BMPs simply did not have sufficient data to justify prediction of an average annual nutrient removal. The FDOT continued the work of the initial technical advisory committee with agency and co-sponsored research to document design and removal effectiveness of novel BMPs, in addition to the commonly-used retention and wet detention ponds.

With the evolution of removal data for other BMPs used within highways, a simple computer program in EXCEL format was developed for use in a single watershed. Responding to the need to incorporate highway right-of-way with adjacent land use BMPs, the spreadsheet program was expanded to evaluate BMPs for up to 4 watersheds. Then it was expanded to include BMPs not commonly used for highways, including: green roofs, rainwater harvesting (individual building), pervious pavements, exfiltration, depression areas (rain gardens), disconnecting impervious areas, stormwater harvesting, VFS, underground storage, and comingling. As of 2020, there are now 13 BMPs with acceptable average annual removal effectiveness, provided professionals follow acceptable design and operating guidelines.

In 2014, FDOT funded the continued development of the EXCEL-based computer tool for evaluating the annual effectiveness of BMPs in series and parallel configurations. As the number of BMP options increased as well as the number of catchment configurations, the EXCEL model became cumbersome to use, in some cases was unstable, and computation time suffered. Thus beginning in 2017, the spreadsheet model was overhauled to produce a model that could include more than 4 catchments, provide for easier user navigation (input and output), and integrate groundwater and surface discharges, all with continued support of regulatory agencies. The result of three years of upgrading the EXCEL-based model is the BMP Trains 2020 computer program, a tool for evaluating nutrient discharges in permit submissions and regulatory programs. Included in the computer program is the creativity of stormwater professionals (in terms of BMP combinations), most state-of-the-art BMP research results, integration of surface and groundwater, as well as an evaluation of BMPs in an unlimited number of series and parallel configurations. Through extensive testing with user focus groups, the current BMP Trains 2020 has been deemed acceptable by stormwater professionals and regulatory agencies.

4.2 The BMP Trains 2020 Model

The BMP Trains 2020 Model is a computer program that predicts average annual nutrient loading from stormwater systems. It is calibrated for Florida state-wide application using state rainfall and event mean concentration data. The computer program runs on the Windows 10 operating system, or Windows 7 environment with the addition of .net4.6. It is written in C# and Visual Basic. There is no charge for the program. The model and user manual are perpetually available for download on the UCF STARS data repository at: https://stars.library.ucf.edu/bmptrains/. In addition, presentations by professionals that explain the background and use of the model are available online.

When developing BMP Trains 2020, the primary goal was to produce a model that incorporated the most up-to-date research on effectiveness for stormwater BMPs, was consistent with current practice, and acceptable to all review agencies. Since there are many review agencies and great variability in potential modeling scenarios, the model was designed to be flexible, allowing user input of Event Mean Concentrations (EMCs), BAM types, and configurations and combinations of catchments/BMPs. Feedback regarding usability of the model was collected from professionals during training workshops across Florida (in Miami, Fort Myers, West Palm Beach, Okeechobee, Orlando, Tampa, Tallahassee, Pensacola, Jacksonville, Maitland, Palatka, and Clearwater). Over the course of the project, 360 professionals attended 14 workshops (2 each in Orlando and Tampa).

The BMP Trains 2020 computer program is an improvement from previous versions – most notably because of the departure from the Microsoft EXCEL platform to more robust computational programming that allows for a user-friendly Graphic User Interface (GUI). The following are features of the BMP Trains 2020 program that distinguish it from past releases of the model as well as those that make it consistent with current practice and permit applications:

1. The user may investigate an unlimited number of catchments (25 have been tested) in a variety of configurations (series, parallel, combinations).
2. All BMPs currently accepted by the WMDs and the FDEP have been included in the BMP Trains 2020 model. The BAM VFS evaluation of current FDOT research (see Chapter 3) was added to validate and improve permit acceptance. There is also an option to investigate a user-defined BMP and/or BAM BMP to allow preliminary evaluation of new BMPs.
3. Surface and groundwater nutrient mass and volume discharges have been integrated for overall assessment.
4. User experience (e.g. visuals, input/output formats, computation time, program stability) are improved considerably (See Figures below). Including ‘2020’ in the name not only references the year of release, but also underscores that this model is easier to view and print relative to the past model (e.g. BMP Trains 20/20).
5. The user manual is updated with additional example problems based on realistic roadway applications.

6. The model and user manual are perpetually maintained and available for download on the UCF STARS data repository at: https://stars.library.ucf.edu/bmptrains/.

While the user interface and much internal computational function has been completely overhauled, the essential goal of quantifying pre- and post-development average annual nutrient loadings (Nitrogen and Phosphorus) and determining the average annual effectiveness for nutrient removal of a wide variety of best management practices (BMPs) is preserved. The logic and research data from previous versions has been maintained and updated to reflect the most up-to-date research results. Stormwater research by Harvey Harper, Marty Wanielista, Mike Hardin, Ikiensinma Gogo-Abite, Eric Livingston, Ni-Bin Chang, Kelly Kibler, and others for computing nutrient loads and BMP removal effectiveness continues to provide the strong support for the program. Ron Eaglin provided the C# and visual programming skill. The logic statements and practical application are the responsibility of Marty Wanielista. The BMP Trains 2020 program is consistently one of the top 10 downloads on the UCF STARS repository and was downloaded over 3000 times in its first 15 months of availability.

4.3 The BMP Trains 2020 user manual

The BMP Trains 2020 user manual (Appendix C) includes details the model calculations of average annual effectiveness associated with nitrogen and phosphorus in surface and groundwater discharges and provides user navigation of the computer program. The manual is based on current (2020) stormwater management practice within the State of Florida. The information included in the Manual is based on significant input and review from state agencies and consulting professionals, including professionals experienced in using previous versions of the computer program. Example problems are used to illustrate features of the model. All existing examples from previous versions of the Manual were executed with the new BMP Trains 2020 program, with some examples maintained as a check on accuracy and to demonstrate the use of the model. Nevertheless, all users should visit a review agency to determine input endorsement for their project.

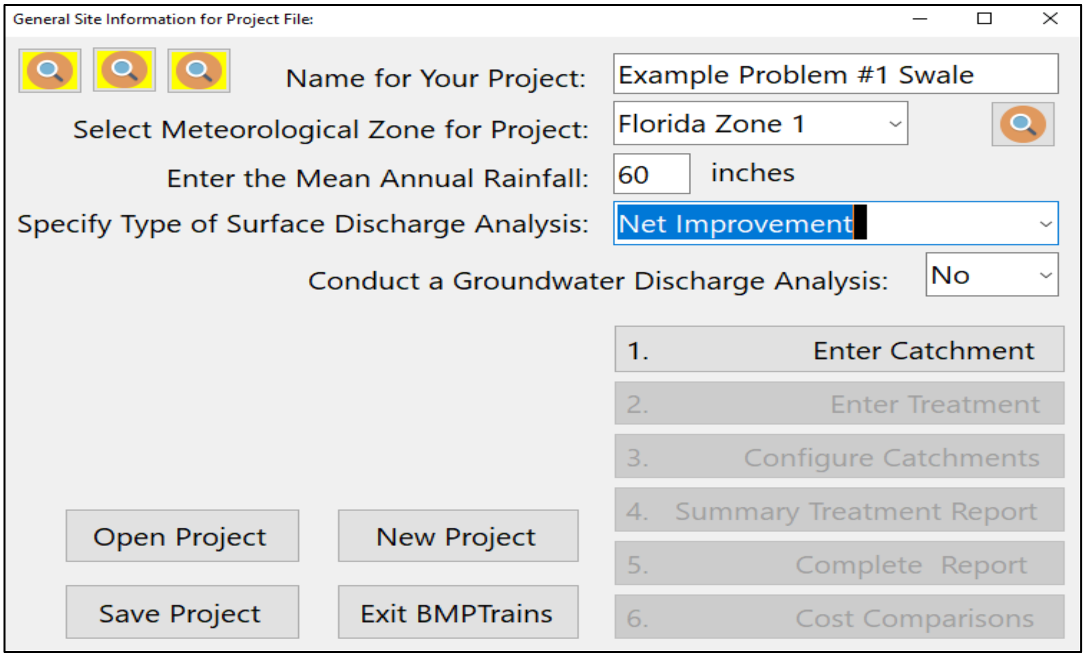
The user interface guides users through the following data input and calculation steps (“worksheets”):

1. General Site Information Worksheet,
2. Watershed Characteristics Worksheet,
3. treatment Options (selecting one or more BMPs, each with its own worksheet),
4. Catchment Configuration Worksheet,
5. Summary treatment report,
6. Complete Report (usually submitted for review purposes), and
7. Cost Comparisons (optional).

The worksheets are used to facilitate ease of use of the program. The order listed above is the general sequence of input and analysis, although users may choose to return to previous steps at any time to revise input values for a “what if” scenario or project modifications. Following are detailed example illustrations of input data and interpretation of output data.

General Site Information Worksheet

The general site information data must be entered first; an example is shown in Figure 4.1. Users cannot proceed to the treatment and other worksheets, until the catchment data are entered. Drop down menus are provided when there are specific choices.


General Site Information for Project File:

Name for Your Project: Example Problem #1 Swale

Select Meteorological Zone for Project: Florida Zone 1

Enter the Mean Annual Rainfall: 60 inches

Specify Type of Surface Discharge Analysis: Net Improvement

Conduct a Groundwater Discharge Analysis: No

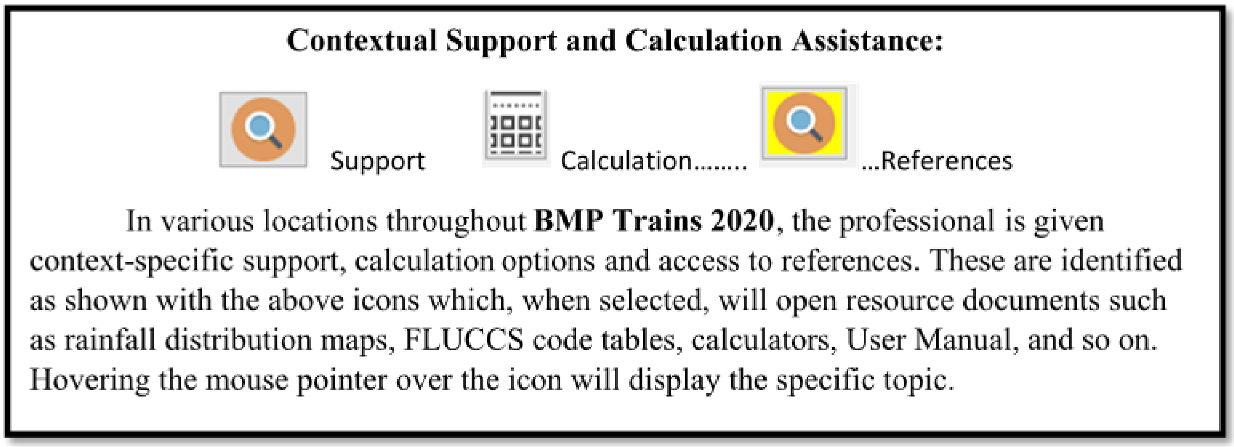
Figure 4.1. General site information worksheet.

The general site information worksheet prompts the professional to input information related to the project, including:

- Project name – any set of alphanumeric characters
- Meteorological zone – one of the five designated zones for the state of Florida
- Mean annual rainfall (inches)
- Type of analysis:
  - BMP analysis (only post-development parameters are necessary input)
  - Net improvement (compares pre- and post-development nutrient loadings)
  - 10% less than pre-development (similar to net improvement but requiring an additional 10% removal)
  - Specified removal efficiency (based upon custom entered percentages for nutrient removal efficiency rates)
  - Whether to include groundwater analysis of nutrient removal (optional)

In addition, the general site information worksheet provides typical file functions (save, open, exit, and new). You can also go to “*open pre BMP*” button when there exists a BMP in a pre-condition. The “*New Project*” button allows the professional to completely erase any values currently entered. Also, six buttons guide the professional to frequently used worksheets in proceeding with BMP analysis (plus the optional sixth step: cost analysis). Upon beginning a new project, the professional can only select button *#1 (Enter Catchment)* as the subsequent steps cannot proceed without the catchment hydrologic parameters. Upon completing step #1, the second button (*Enter Treatment*) is available.

There are user help buttons that provide information of input and analysis of data. There are three general user help information categories as shown in Figure 4.2. The complete user manual can also be accessed from the program. It is in a reference support help button on the General Site Information Worksheet.



Contextual Support and Calculation Assistance:

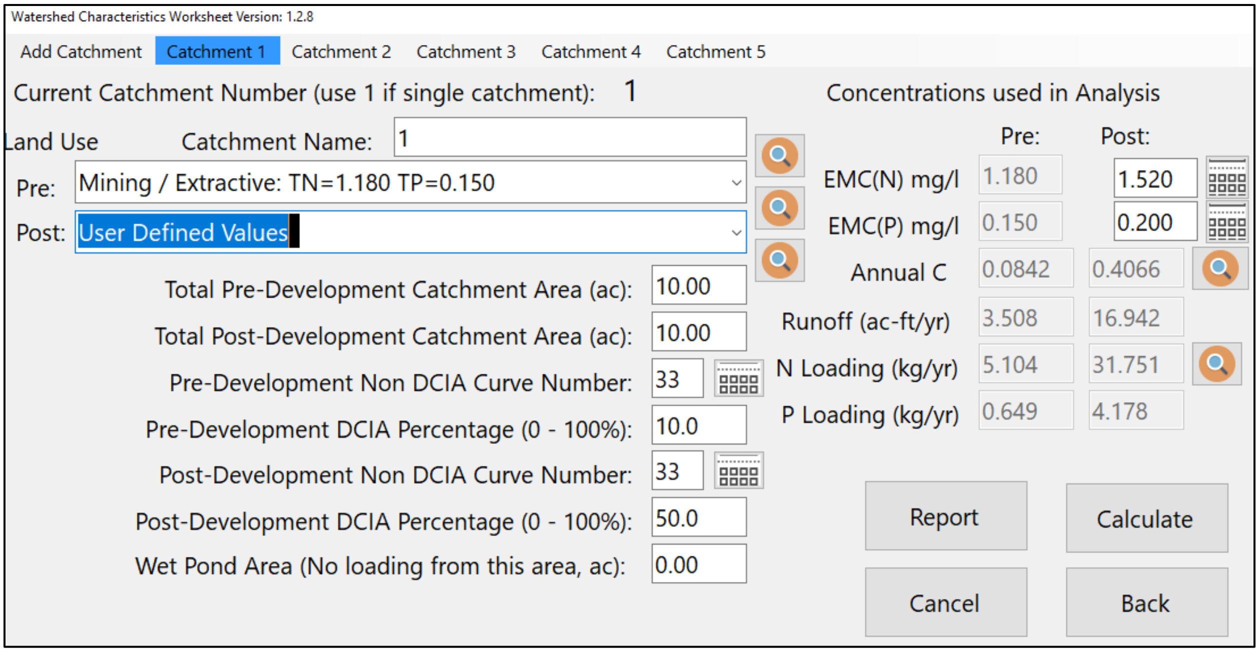
In various locations throughout **BMP Trains 2020**, the professional is given context-specific support, calculation options and access to references. These are identified as shown with the above icons which, when selected, will open resource documents such as rainfall distribution maps, FLUCCS code tables, calculators, User Manual, and so on. Hovering the mouse pointer over the icon will display the specific topic.

Figure 4.2. Contextual support and calculation assistance

Files for a project can be saved for future use of for permit submission support. Files formatted for BMP Trains 2020 are given the file extension ".bmpt". This unique file is created when the "save" button is used. Once installed on a given Windows operating system, the professional may double-click on any one of the last six saved files to open the file (typical Windows conventions).

Watershed Characteristics Worksheet

Watershed soils and impervious areas vary from site to site, thus after the professional selects the "*Enter Catchment*" button, a new window opens with the Watershed Characteristics Worksheet. An example of this Worksheet is shown in Figure 4.3 and includes the hydrologic parameters for the site's catchment(s) and support icons. Included in Figure 4.3 is the EMC calculation assist button ▦ and is available only for user-defined inputs.



Watershed Characteristics Worksheet Version: 1.2.8

Current Catchment Number (use 1 if single catchment): 1

Catchment Name: 1

Land Use Pre: Mining / Extractive: TN=1.180 TP=0.150

Post: User Defined Values

Total Pre-Development Catchment Area (ac): 10.00

Total Post-Development Catchment Area (ac): 10.00

Pre-Development Non DCIA Curve Number: 33

Pre-Development DCIA Percentage (0 - 100%): 10.0

Post-Development Non DCIA Curve Number: 33

Post-Development DCIA Percentage (0 - 100%): 50.0

Wet Pond Area (No loading from this area, ac): 0.00

Concentrations used in Analysis

	Pre:	Post:
EMC(N) mg/l	1.180	1.520
EMC(P) mg/l	0.150	0.200
Annual C	0.0842	0.4066
Runoff (ac-ft/yr)	3.508	16.942
N Loading (kg/yr)	5.104	31.751
P Loading (kg/yr)	0.649	4.178

Figure 4.3. Watershed characteristics worksheet.

The input values for the watershed characteristics worksheet are as follows:

- Catchment name – Any alphanumeric text, this typically matches the stormwater professional's designation for the project site's catchment(s). For the purpose of BMP Trains 2020, catchments (sometimes referred to as basins or sub-basins) are the smallest hydrologic designation for which one or more specific BMPs can provide treatment.
- Pre- and post-development land uses – 25 typical land use categories are available via the drop-down menu based upon current recognized values. Each has an arithmetic average EMC value (see Appendix C). A user-defined category is available for other EMCs and for composite land uses. A calculator is available for a composite EMC when there are multiple land uses based on average annual runoff for each area Curve Number (CN) value. The calculator is only visible when the "User Defined Values" is selected. For "User Defined Values", EMC values for both Nitrogen and Phosphorus must be entered. For the other 25 land uses programmed into the model, the EMC are automatically entered.
- Total pre-development catchment area – the total area in acres for the catchment in the pre-development condition.
- Total post-development catchment area – the total area in acres for the catchment in the post-development condition.
- Pre-development Non-DCIA curve number – the weighted runoff curve number for the portion of the catchment which is *not* Directly Connected Impervious Area (DCIA). A composite weighted CN can be calculated using average annual runoff. This is an option in place of simple area averages. *If this value is below 30 a warning will appear after the Calculate button is selected since the SCS/NRCS runoff curve number method is not valid for curve numbers below 30.* However, this message is

only a warning and the professional may proceed with any chosen value that is entered.

- Pre-development DCIA percentage – the percentage of the total catchment area that is directly-connected impervious area in the pre-development state.
- Post-development Non-DCIA curve number – the weighted runoff curve number for the portion of the catchment that is not directly connected impervious area in the post-development state. A composite weighted CN can be calculated using average annual runoff. This is an option in place of simple area averages. *As noted above for pre-development Non-DCIA curve numbers, if this value is below 30, the program will change the input to 29.9.*
- Post-development DCIA percentage – the percentage of the total catchment area that is directly-connected impervious area in the post-development state.
- Estimated Wet Pond area – this area will be subtracted from the overall post-development catchment area when the wet pond area is part of the total catchment area. As an alternative, the wet pond area does not have to be included in the catchment area. Thus, no contribution of nutrient loadings is included for this area. This is normally assigned to an area which remains wet all-year. For Florida sites, the average annual runoff coefficient is zero because Evapotranspiration is about equivalent to rainfall on these wet bodies of water.
- ▦ Weighted EMC and CN calculator support buttons. Copy and paste is available.

The "*Calculate"* button will provide for calculation of pre- and post-development annual runoff coefficients ("C value"), the volume of annual runoff in Acre-Feet, and the Nitrogen and Phosphorus annual mass loadings in kilograms per year.

For sites with multiple catchments, the stormwater professional may create additional catchment input by using the "*Add Catchment*" button in the top left-hand corner of this Worksheet. After selecting that button, a new dialogue box opens with several options, as shown in Figure 4.4.

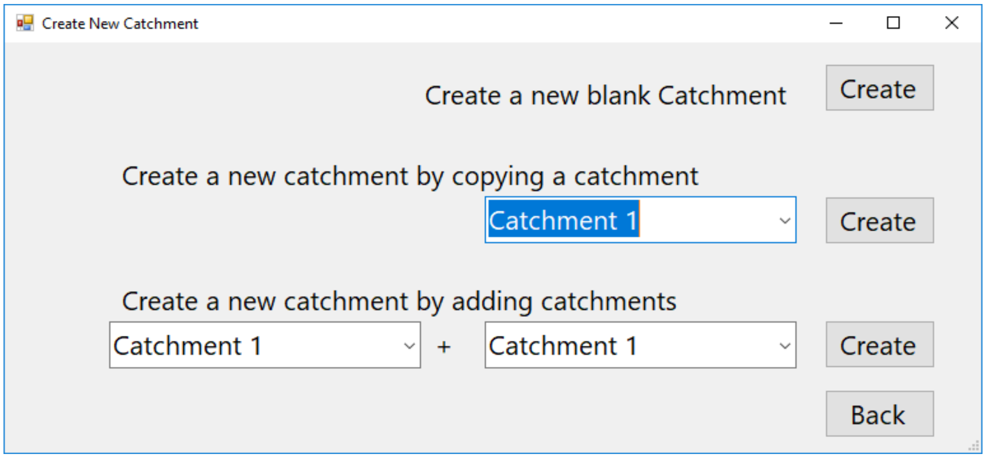
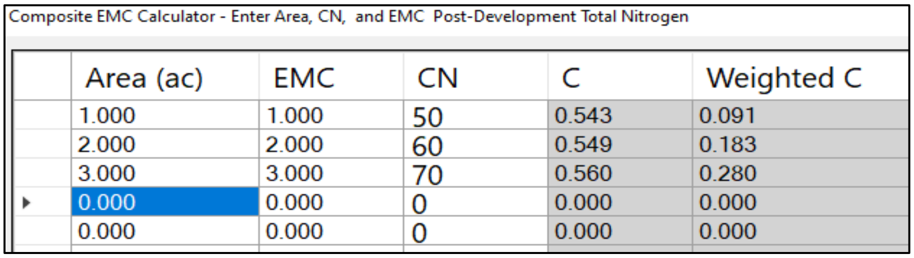


Figure 4.4. Create new catchment dialog.

There are three options for creating subsequent catchments: 1) blank catchment, 2) copy an existing catchment, and 3) create a new catchment by combining two existing catchments. The blank catchment option creates a new catchment which will need entry of all of the hydrologic parameters as described above. The professional should enter a new and unique name for each of the new catchments. The copy an existing catchment option allows the professional to duplicate any existing catchment – the copy may then be edited to make it unique and distinct from the original. The only required change is to the name of the newly created catchment; any and all other values may remain identical to the original (source) catchment or they may be modified. The create a new catchment by adding catchments option allows the professional to use the area values for any two existing catchments to be combined into a third, new catchment.

The number of catchments that may be supported is large. Twenty-Five catchments have been tested and the run speed of results could not be detected to decrease. Up to 4 BMPs can be used to treat the runoff from one catchment.

To copy and paste data (e.g. Area, CN and EMC values), the values must be in a spreadsheet format. When copying the values, make sure there are no additional data copied or if there are set (key in) the additional data equal to zero (0.000) as shown in Figure 4.5.



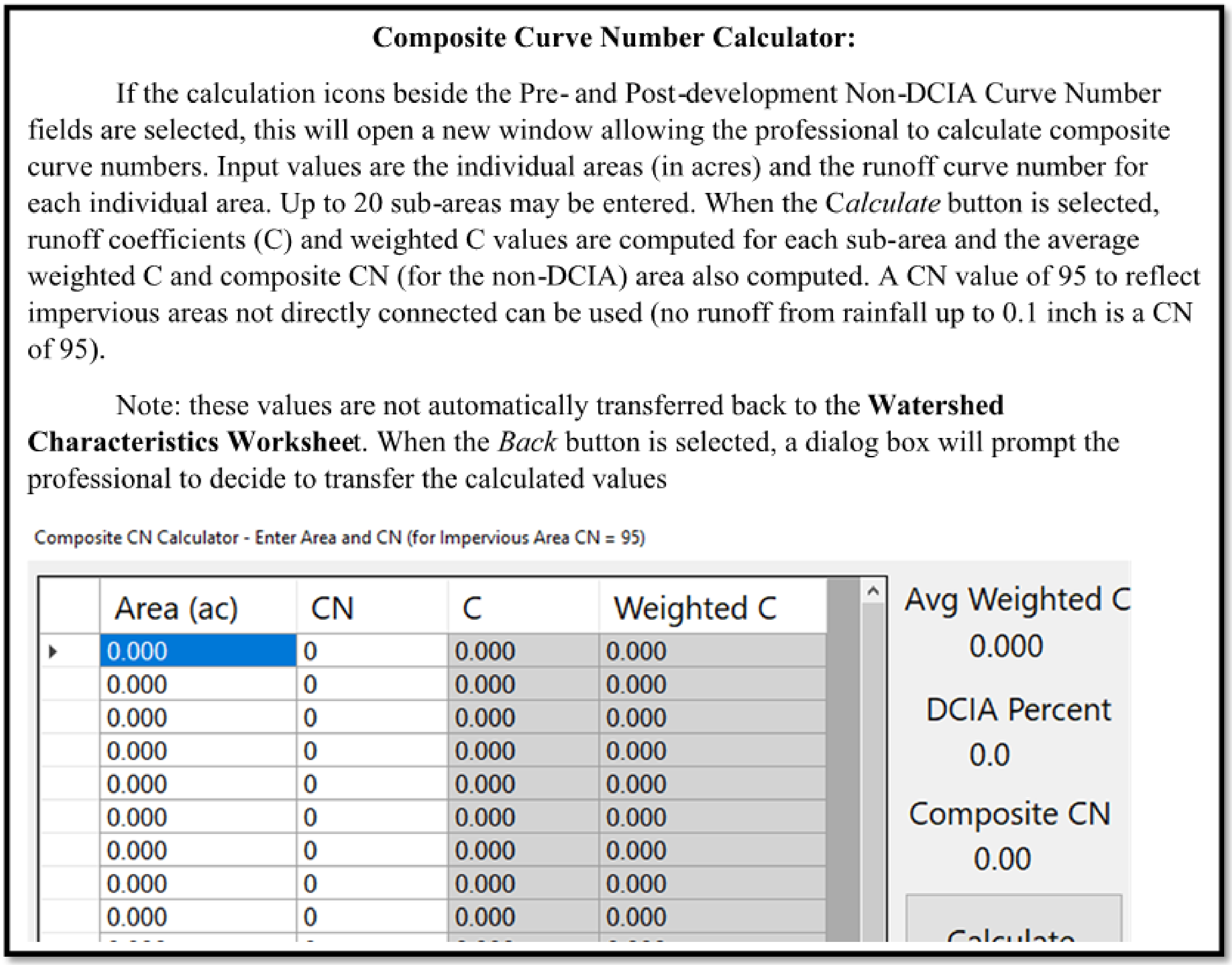
Composite EMC Calculator - Enter Area, CN, and EMC Post-Development Total Nitrogen

	Area (ac)	EMC	CN	C	Weighted C
	1.000	1.000	50	0.543	0.091
	2.000	2.000	60	0.549	0.183
	3.000	3.000	70	0.560	0.280
▸	0.000	0.000	0	0.000	0.000
	0.000	0.000	0	0.000	0.000

Figure 4.5. Example of a copy and paste option

The calculation of a composite CN is usually weighted on the area. However, the program gives the professional the option of a more accurate calculation weighted on the annual runoff for that area and CN. The same calculation procedure is also available for an annual weighted EMC value.

There are “error catches” for some of the input parameters, such as CNs and EMCs. As an example, if the CN input is 15 (not defined that low), the program will change it to the lowest curve number or 29.9. Other “error catches” are used to make the professional aware of a potential input changes with no correction, such as an entry for the name of a catchment. The name of the catchment is used in output information for ease of understanding the results. The composite curve number calculator using a weighting by annual runoff is simplified as shown in Figure 4.6.



Composite Curve Number Calculator:

If the calculation icons beside the Pre- and Post-development Non-DCIA Curve Number fields are selected, this will open a new window allowing the professional to calculate composite curve numbers. Input values are the individual areas (in acres) and the runoff curve number for each individual area. Up to 20 sub-areas may be entered. When the *Calculate* button is selected, runoff coefficients (C) and weighted C values are computed for each sub-area and the average weighted C and composite CN (for the non-DCIA) area also computed. A CN value of 95 to reflect impervious areas not directly connected can be used (no runoff from rainfall up to 0.1 inch is a CN of 95).

Note: these values are not automatically transferred back to the **Watershed Characteristics Worksheet**. When the *Back* button is selected, a dialog box will prompt the professional to decide to transfer the calculated values

Composite CN Calculator - Enter Area and CN (for Impervious Area CN = 95)

	Area (ac)	CN	C	Weighted C
▸	0.000	0	0.000	0.000
	0.000	0	0.000	0.000
	0.000	0	0.000	0.000
	0.000	0	0.000	0.000
	0.000	0	0.000	0.000
	0.000	0	0.000	0.000
	0.000	0	0.000	0.000
	0.000	0	0.000	0.000
	0.000	0	0.000	0.000

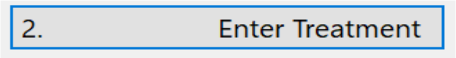
Avg Weighted C
0.000

DCIA Percent
0.0

Composite CN
0.00

Figure 4.6. The CCN calculator worksheet

Treatment Options Worksheet



Upon selecting "*Enter treatment*" from the General Site Information Worksheet, a new window opens with a selection of 13 established BMPs, a user-defined BMP, and an option for BMPs in series within a given catchment (Figure 4.7). BMP Trains 2020 will accommodate up to four BMPs in series within a single catchment; in the unlikely event that a design includes more than four then the stormwater professional may simply split the original catchment into two new catchments and assign BMPs to each. BMP descriptions are presented in detail in Appendix C of the user manual.

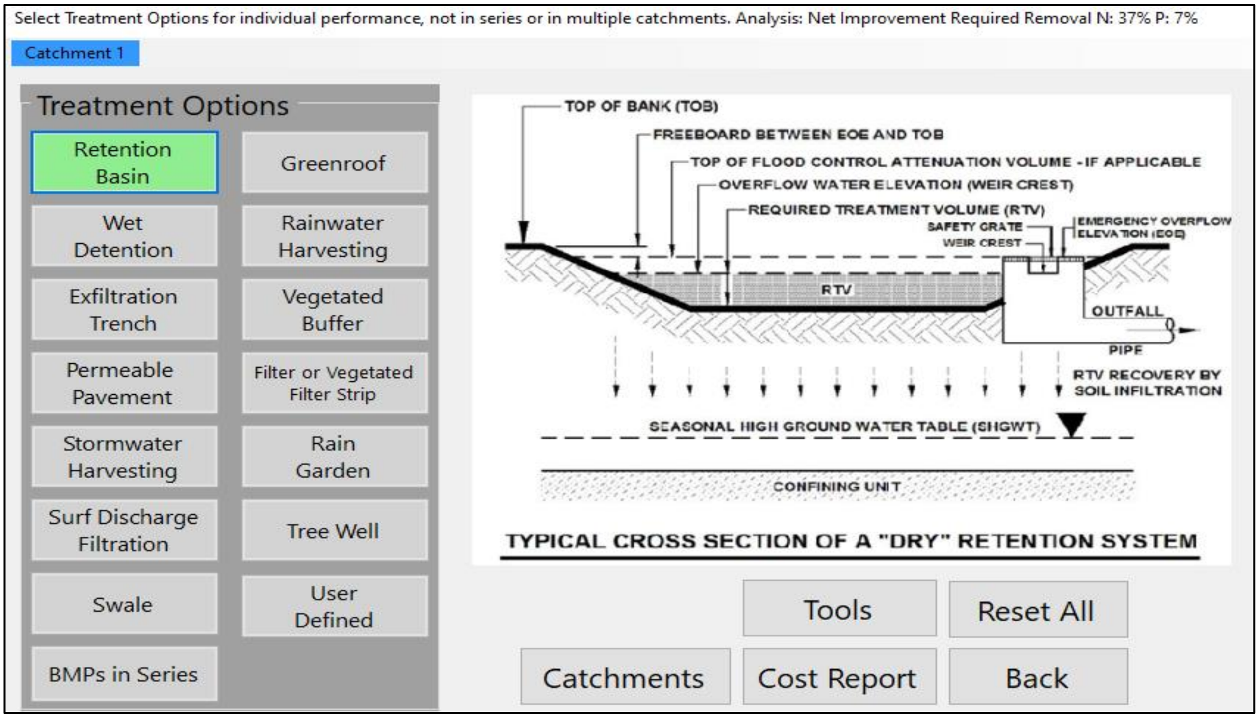

Select Treatment Options for individual performance, not in series or in multiple catchments. Analysis: Net Improvement Required Removal N: 37% P: 7%

Figure 4.7. Select treatment options worksheet.

By hovering the mouse pointer over each of the 14 BMP buttons, the professional can view a detailed schematic of that particular BMP design. Design details and assumptions are presented in Appendix C of the user manual. An example of a user defined input is the use of a pre-treatment device that has limited actual performance data or street sweeping. As in previous versions of BMP Trains, the user manual explains commonly-used BMPs in detail. However, modifications and inclusion of BMPs in series are new to this version. When the button for each BMP is selected, a new worksheet will open allowing the stormwater professional to enter the various parameters specific to that BMP's design. Common designs in the State are explained in Appendix C of the user manual. Once one or more BMPs have been configured, their gray button on the select treatment options window will turn green. After subsequent steps when a BMP is selected for routing in the configure catchment worksheet the selected BMP's button will turn to a lighter, cyan color to indicate that this is the BMP being used for the routing and summary report. All unselected BMPs will remain gray.

Once a BMP's parameters are entered for a particular catchment, that BMP will remain active. If a designer chooses to remove all BMP inputs, there is a button to reset all values. This has the effect of deleting the BMP completely from the project; thus, there is no need for the professional to delete individual numbers from the input fields.

The BMPs and changes from previous versions of the model are:

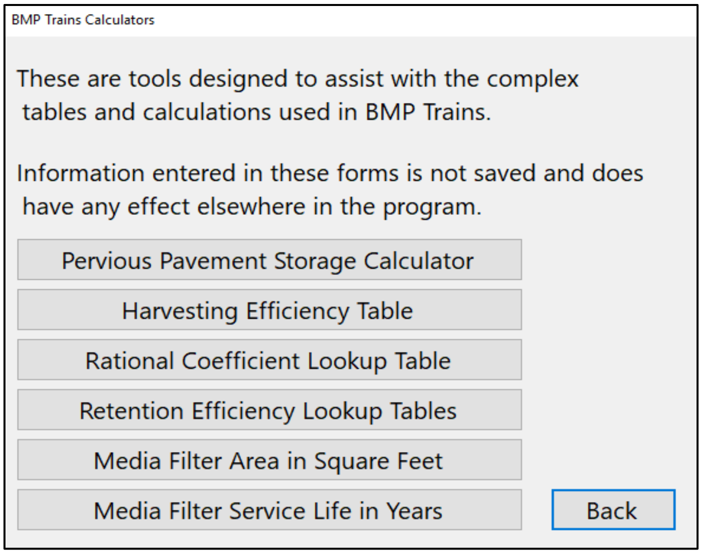
1. Retention Pond BMP – Rainfall depth as input, no other changes from previous versions.
2. Wet Detention Ponds – The professional is prompted to enter the permanent pool volume. The average annual residence time (in days) is calculated from the pond's permanent pool and the average annual runoff volume. The input was changed from

annual residence time in days to permanent pool (in acre-feet) to reduce the confusion between wet season and annual residence time.

3. Exfiltration Trench – Dimensions of trench input, no changes to input from previous versions.
4. Permeable Pavement – Input was reduced by providing internal calculations.
5. Stormwater Harvesting – In previous versions, the weighted rational runoff coefficient was manually entered by the user. This is now an unnecessary step in that the program can automatically calculate the coefficient. Also, rate of use is not a calculation but an input.
6. Surface Discharge Filtration – The professional is now prompted to input whether the filtration is associated with a wet detention pond or not (yes/no drop-down menu).
7. Swale – Input was reduced by providing internal calculations thus reducing input errors.
8. Green Roof – Input was reduced with internal calculations thus reducing input error.
9. Rainwater Harvesting – Harvest rate as output not an option.
10. Vegetated Buffer – No changes to input from previous versions.
11. Vegetated Filter Strip – Wording changes to input from previous versions.
12. Rain Garden – Rain garden dimensions as input, no changes to input from previous versions.
13. Tree Well – Tree well dimensions as input, no changes to input from previous versions.
14. User Defined BMP – No changes to input from previous versions.

Upon selecting the *Tools* button, the professional is presented with six calculation routines (Figure 4.8). To further illustrate the ease of operation, to remove all BMPs from an entire project, the professional may select *Reset All BMPs* from the Select treatment Options window. This will delete all BMPs and the professional must now proceed to select new BMPs and enter new values. *Caution: this removal process cannot be undone (unless the BMP Trains2020 file has previously been saved)!* If necessary the professional may "jump" back to the watershed characteristics worksheet by selecting the catchments button. This merely saves the step of returning to the general site information worksheet first.

For any catchment, an option to assess effectiveness of BMPs in series where each and every BMP has the same catchment area is available by selecting the *BMPs in Series* button. The professional is presented with the multiple BMP worksheet, a new dialog box from which to choose up to four already-configured BMPs in one catchment and in series (Figure 4.9).

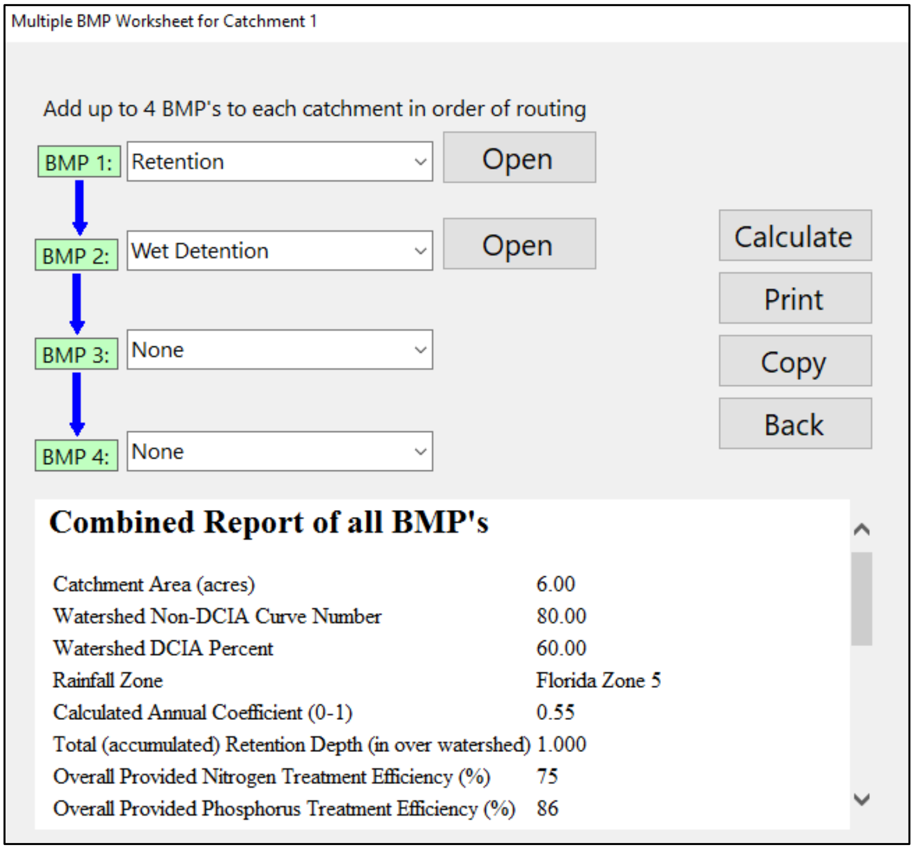


BMP Trains Calculators

These are tools designed to assist with the complex tables and calculations used in BMP Trains.

Information entered in these forms is not saved and does have any effect elsewhere in the program.

Figure 4.8. BMP Trains 2020 calculators



Multiple BMP Worksheet for Catchment 1

Add up to 4 BMP's to each catchment in order of routing

BMP 1: Retention

BMP 2: Wet Detention

BMP 3: None

BMP 4: None

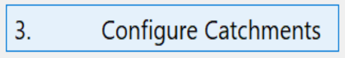
Combined Report of all BMP's

Catchment Area (acres)	6.00
Watershed Non-DCIA Curve Number	80.00
Watershed DCIA Percent	60.00
Rainfall Zone	Florida Zone 5
Calculated Annual Coefficient (0-1)	0.55
Total (accumulated) Retention Depth (in over watershed)	1.000
Overall Provided Nitrogen Treatment Efficiency (%)	75
Overall Provided Phosphorus Treatment Efficiency (%)	86

Figure 4.9. Multiple BMP worksheet.

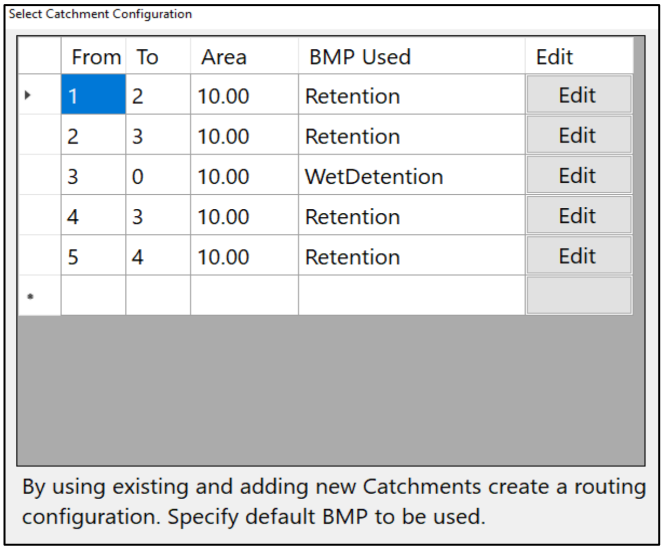
The drop-down menus beside each of the four BMPs may be chosen to select an individual BMP. Note that each of the individual BMPs must already be configured for them to appear in these drop-down menus. Upon clicking the *Calculate* button (or returning to the previous screen by clicking the *Back* button) the two or more chosen BMPs are established for the catchment and nutrient removal is calculated for the combined system. The on-screen report window shows all of the associated values, as well as a flow diagram indicating annual nutrient removal and discharge mass rates.

Catchment Configuration Worksheet



This step allows the stormwater professional to create any unique topology of an unlimited number of catchments. While previous versions were limited to a maximum of four catchments in 15 specific layouts, BMP Trains 2020 has no limit. This does require the professional to “inform” the software as to the design layout. Calculation of average annual nutrient loading removal is based upon this configuration, as nutrient removal rates are dependent upon the configuration of the catchments or the flow of stormwater from one BMP into another.

In this step, two key parameters must be set for each catchment: 1) the routing downstream to the next catchment and 2) the default BMP to be used in calculating the average annual nutrient loading removal (Figure 4.10). *For projects with only one catchment and one BMP this second parameter must still be set for subsequent calculations to be valid*. When entered initially the Worksheet defaults to all catchments discharging directly to the outfall node (i.e., in a parallel topology). In addition, no default BMP is yet selected, so if this parameter is not changed then no nutrient removal is calculated.



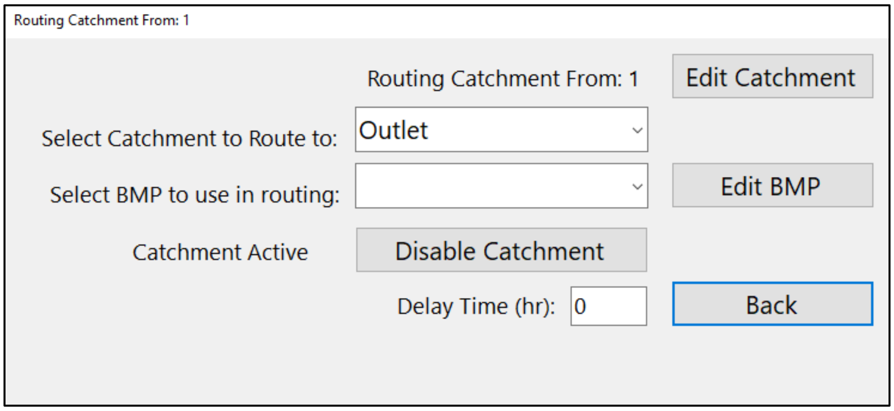
Select Catchment Configuration

From	To	Area	BMP Used	Edit
1	2	10.00	Retention	Edit
2	3	10.00	Retention	Edit
3	0	10.00	WetDetention	Edit
4	3	10.00	Retention	Edit
5	4	10.00	Retention	Edit

By using existing and adding new Catchments create a routing configuration. Specify default BMP to be used.

Figure 4.10. Select catchment configuration worksheet.

To set up the parameters for each catchment, users must click on the *Edit* button to the right end of the catchment’s row. A new dialog box will open as shown in Figure 4.11:



Routing Catchment From: 1

Select Catchment to Route to: Outlet

Select BMP to use in routing:

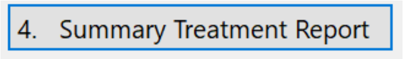
Delay Time (hr): 0

Figure 4.11. Routing catchment dialog box.

Selecting the dropdown menu to the right of *Select Catchment to Route* chooses the next downstream (receiving) catchment. For a single catchment system this should remain set as Outlet. Also, for any multiple catchment system at least one catchment (or more, if in parallel) should ultimately discharge to the outlet. Next, users select the *BMP to use in routing* by choosing the dropdown menu. All configured BMPs will appear, along with the option of "None." If BMPs in Series has been configured for any catchments, this will also appear as one of the choices along with each of the individual BMPs. Under normal circumstances, BMPs in Series should be selected for the default BMP to use in routing. However, any single BMP (or "None") may also be chosen for "what if" analysis. A catchment may be effectively ignored by selecting the *Disable Catchment* button. An offsite catchment may have a delay time before stormwater reaches an onsite BMP. A Delay Time may be entered (in hours) up to a maximum of 15 hours. For simplicity of on-the-fly editing, buttons to *Edit Catchment* and *Edit BMP* are included. Selecting either of these will jump directly to the previously configured pages for the catchment or BMP.

When the *Back* button is selected, the professional is returned to the catchment configuration worksheet and the appropriate parameters will now appear. The routing catchment configuration worksheet should be followed for each catchment until all have been properly configured. *Note that the only topology which is not allowed (and is not practically desirable) is a circular path with no discharge to an outlet.* Also, note that at least one catchment in every project should discharge to the outlet/surface waters or to the groundwater.

Summary Treatment Report



After designs for BMPs and routing are completed, a comparison to the selected BMP analysis and groundwater analysis, if selected, is available in the summary treatment report. No additional input is needed for this report and it is visible on-screen and can be sent to the user's default printer or saved to a file. If saved, the file is in a format that can be reused by the BMP Trains 2020 program and will appear the same as the on-screen report initially displayed. The summary treatment report is designed to serve as a common format between consulting designers and permit review agencies. It is anticipated that this report will be a focus of the permit submittal package. In addition, the electronic (.bmpt) file can be shared with reviewers for their own confirmation of the modeling. Figure 4.12 shows an example summary treatment report with net improvement and routing with four catchments.

Two sections of the report show essential information for the project:

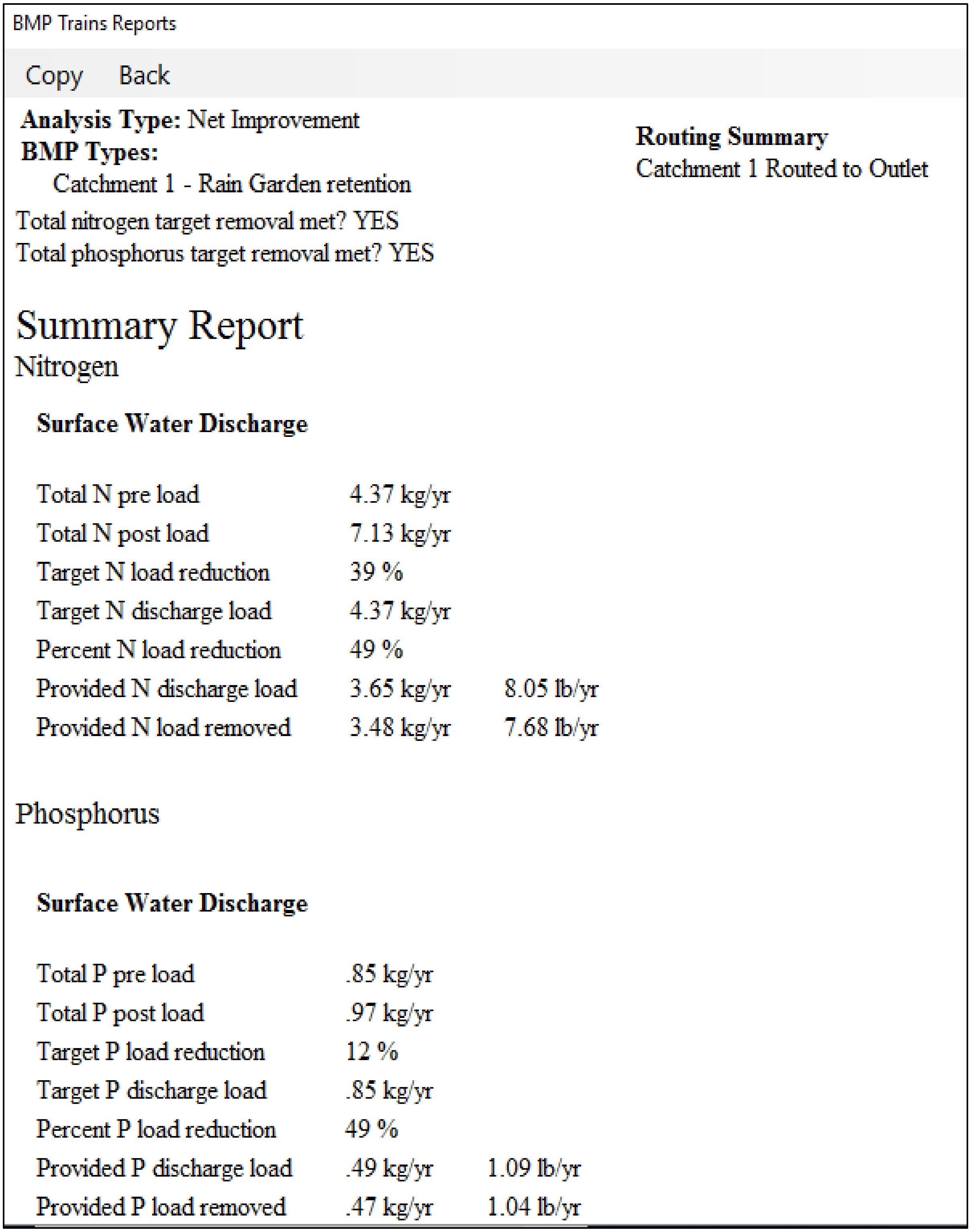
Project Summary – This section displays the name of the project and date of printing, the type of analysis, the BMP type(s), a summary of the routing among the site's catchments, and a yes/no test for whether the designed BMP(s) satisfy the surface discharge analysis requirements. This last item is omitted from the BMP Analysis, as a BMP analysis requires no pre-development nutrient loadings.

***Summary Report for Outlet* –** This section has two identical subsections for nitrogen and phosphorus. Each subsection includes the total pre- and post-development average annual loadings (kg/yr), the target load reduction (%) and target discharge load (kg/yr), the percentage of load reduction (%), and the provided discharge load and load removed. The last two values are given in both kilograms per year (kg/yr) and pounds per year (lb/yr).

If groundwater analysis is chosen, evaluation of effectiveness metrics are average recharge volume in million gallons (MG) per year, provided recharge load in kg/yr and lb/yr, and average annual concentration in the recharge water (milligrams/liter). Provided recharge, load, and concentration result from the BMP designs and reflect the sum of all BMPs having discharge to groundwater. Average concentration is the sum of all loadings to the ground divided by the sum of recharge volume.

Complete Report

The *Complete Report* button was added to produce a summary of all input and output data usually required as a hard copy report for permit review purposes. It does not include the data and results for a cost analysis because that cost is not currently part of a permit review. If cost review is needed, then the *Copy* button can be used. The complete report does include the summary report. However, it may be more advantageous to minimize the time for review by submitting the electronic file (.bmpt) for each permit.



Analysis Type: Net Improvement
BMP Types:
Catchment 1 - Rain Garden retention
Total nitrogen target removal met? YES
Total phosphorus target removal met? YES

Routing Summary
Catchment 1 Routed to Outlet

Summary Report

Nitrogen

Surface Water Discharge

Total N pre load	4.37 kg/yr	
Total N post load	7.13 kg/yr	
Target N load reduction	39 %	
Target N discharge load	4.37 kg/yr	
Percent N load reduction	49 %	
Provided N discharge load	3.65 kg/yr	8.05 lb/yr
Provided N load removed	3.48 kg/yr	7.68 lb/yr

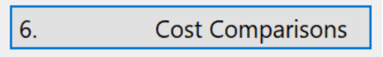
Phosphorus

Surface Water Discharge

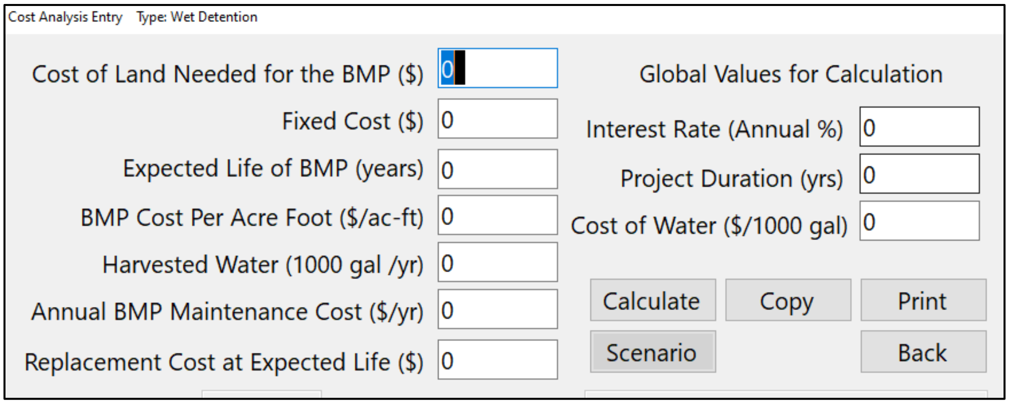
Total P pre load	.85 kg/yr	
Total P post load	.97 kg/yr	
Target P load reduction	12 %	
Target P discharge load	.85 kg/yr	
Percent P load reduction	49 %	
Provided P discharge load	.49 kg/yr	1.09 lb/yr
Provided P load removed	.47 kg/yr	1.04 lb/yr

Figure 4.12. Summary treatment report

Cost Comparisons



The *Cost Comparison* button allows the preparation of one or more cost estimate scenarios. In the user manual, helpful procedures to select cost data are outlined. The data input are relevant to the site location and thus are usually different for each site evaluation. An example of the input data are shown in Figure 4.13 and is required for each BMP. Access to this input format is through each BMP treatment method input worksheet using the *Cost* button.



Cost Analysis Entry Type: Wet Detention

Cost of Land Needed for the BMP ($): 0
Fixed Cost ($): 0
Expected Life of BMP (years): 0
BMP Cost Per Acre Foot ($/ac-ft): 0
Harvested Water (1000 gal /yr): 0
Annual BMP Maintenance Cost ($/yr): 0
Replacement Cost at Expected Life ($): 0

Global Values for Calculation
Interest Rate (Annual %): 0
Project Duration (yrs): 0
Cost of Water ($/1000 gal): 0

Figure 4.13. Cost input worksheet

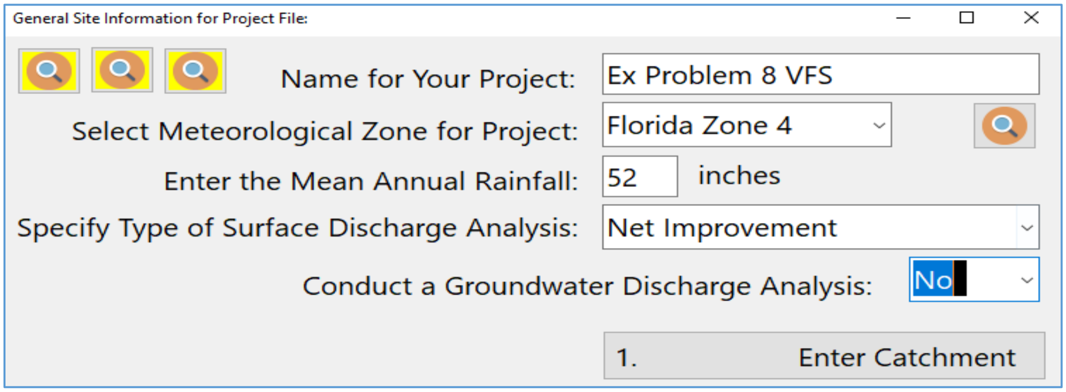
4.4 Example: Sizing a BAM VFS for roadway shoulders

This is an example assessment for the design of a BAM VFS. The example includes results from this research (Chapter 3), the new model features for VFS that better define input data, and a demonstration using the updated BMP Trains 2020 model features. Additional details for input and navigation of the BMP Trains 2020 program are explained using Example Problem 8 in the user manual.

A BAM VFS is typically placed in a highway shoulder/embankment or in an area adjacent to a parking lot and is designed to infiltrate and then percolate runoff through BAM. With the typical highway application, the groundwater table can direct the treated water to a nearby surface waterbody, most likely a roadside ditch, and usually occurs within a day after a runoff event. In these applications, the seasonal high water table is usually no deeper than 3 feet below the surface. However, for other site considerations, the percolated water may not appear in surface waters for a long period of time (usually greater than a week). The designer must know the difference in water table conditions to evaluate potential surface and ground water impacts. An estimate of nutrient removal for site soils (user defined, based on site soil characteristics) or an engineered media, usually BAM, must be an input to the BMP Trains 2020 model to calculate net improvement.

Following are input data and the output of a VFS design. The location is along the west coast of Florida near Venice, Florida. It is in meteorological zone 4. The water quality assessments needed is a net improvement for surface discharge for both total nitrogen and total phosphorus. The results of research on the performance of a BAM VFS reported within this publication (Chapter 3) are used to design the VFS, such as the VFS has a minimum of 10 feet of width adjacent to and along a highway. The VFS will be 1 foot in depth and has a slope of 16%. The length of the VFS is 1050 feet and is 26 feet wide. The watershed is 2.0 acres with a CN for the Non DCIA of 78 and 65% of the watershed is DCIA. The width of the impervious roadway discharging to the VFS is 60 feet. The BAM is CTS media and is obtained with a manufacture's certification of authenticity. All BAM mixes used in BMPs must have a certification to insure the consistency and performance of the BAM mix. The mix has a sustainable storage fraction of 0.20.

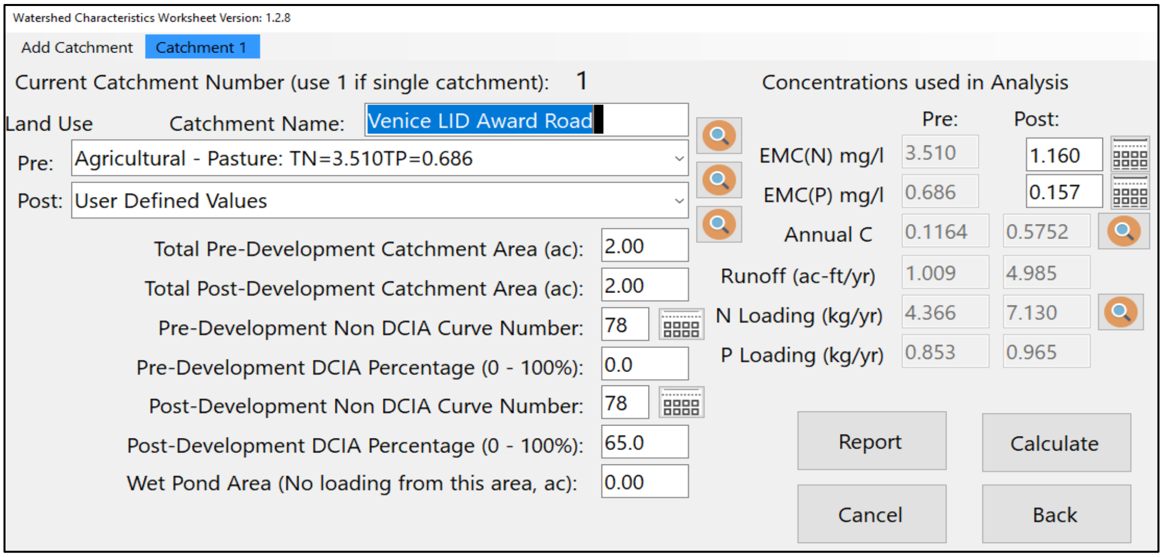
Site information and assessment choices are shown in Figure 4.14. Note at this time in the development of BMP Trains 2020, a groundwater discharge is not an option for VFS.



Name for Your Project: Ex Problem 8 VFS
Select Meteorological Zone for Project: Florida Zone 4
Enter the Mean Annual Rainfall: 52 inches
Specify Type of Surface Discharge Analysis: Net Improvement
Conduct a Groundwater Discharge Analysis: No

Figure 4.14. BAM VFS site conditions and assessment choices.

Watershed conditions are shown in Figure 4.15. The % DCIA is that area of roadway directly discharging to the shoulder where the VFS is located. There is a user defined land use condition values for EMCs because of existing pre-approved EMC data. These data are input in the "concentrations used in the analysis" section as shown in the "open" cells of Figure 4.15.


Watershed Characteristics Worksheet Version: 1.2.8

Current Catchment Number (use 1 if single catchment): 1

Land Use

Catchment Name: Venice LID Award Road

Pre: Agricultural - Pasture: TN=3.510TP=0.686

Post: User Defined Values

Total Pre-Development Catchment Area (ac): 2.00

Total Post-Development Catchment Area (ac): 2.00

Pre-Development Non DCIA Curve Number: 78

Pre-Development DCIA Percentage (0 - 100%): 0.0

Post-Development Non DCIA Curve Number: 78

Post-Development DCIA Percentage (0 - 100%): 65.0

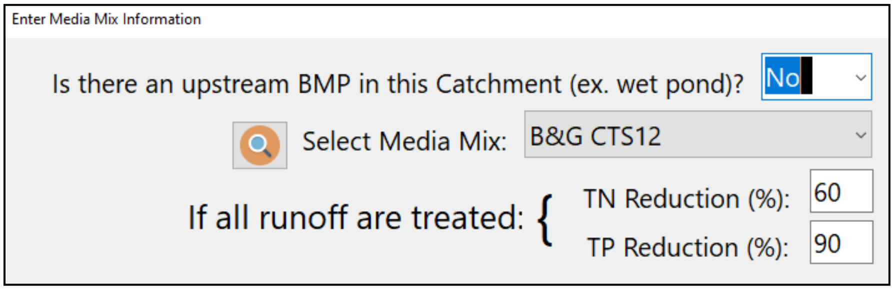
Wet Pond Area (No loading from this area, ac): 0.00

Concentrations used in Analysis

	Pre:	Post:
EMC(N) mg/l	3.510	1.160
EMC(P) mg/l	0.686	0.157
Annual C	0.1164	0.5752
Runoff (ac-ft/yr)	1.009	4.985
N Loading (kg/yr)	4.366	7.130
P Loading (kg/yr)	0.853	0.965

Figure 4.15. BAM VFS watershed conditions.

Select the media type first. A 1-ft layer of BAM (CTS12) is selected as shown in Figure 4.16. The removal effectiveness, based on a data from retention area field studies for water passing through BAM, is specified at 60% and 90% for TN and TP respectively. The removals are for state-wide applications and are in common use. Note in Chapter 3 of this work, about 80% removal for both TN and TP was obtained for a 2-ft foot BAM depth. These 80% removals may be used after consultation with the review agency. The annual volume of water that is captured by the VFS will be treated by the BAM before it enters the water table for movement to surface discharge. Not all the runoff will be treated because large rain events may flow over the filter. BMP Trains 2020 estimates the volume of these rare events.


Enter Media Mix Information

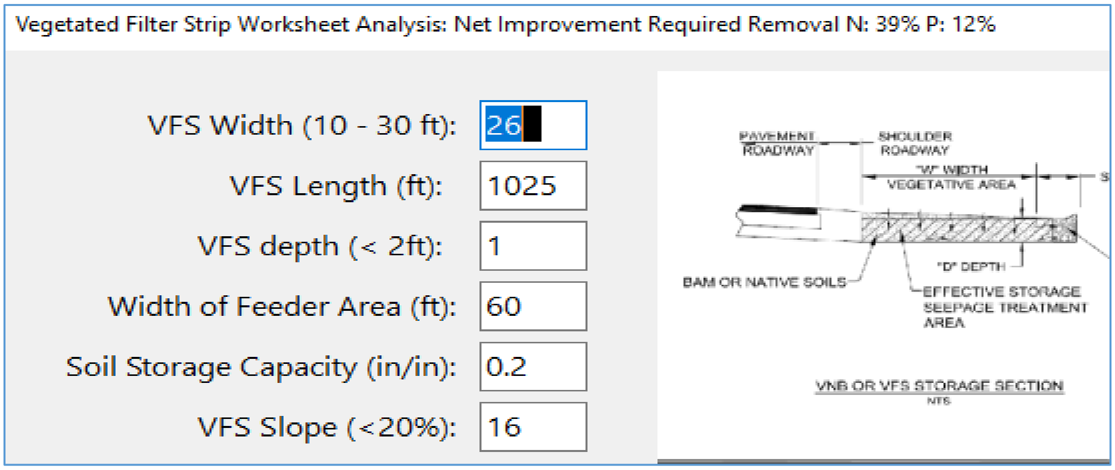
Is there an upstream BMP in this Catchment (ex. wet pond)? No

Select Media Mix: B&G CTS12

If all runoff are treated: {
TN Reduction (%): 60
TP Reduction (%): 90

Figure 4.16. BAM input information.

The design parameters for the BAM VFS are determined from the highway cross-section and include an area in which the VFS is located. The VFS area is defined by the highway length of 1025 feet, a width adjacent to the roadway of 26 feet, and a slope of 16%. The water table limits the depth of the filter to one foot. The impervious areas discharging to the VFS is 60 feet wide. The soil storage capacity is a sustainable fraction of the BAM. VFS inputs are shown in Figure 4.17.

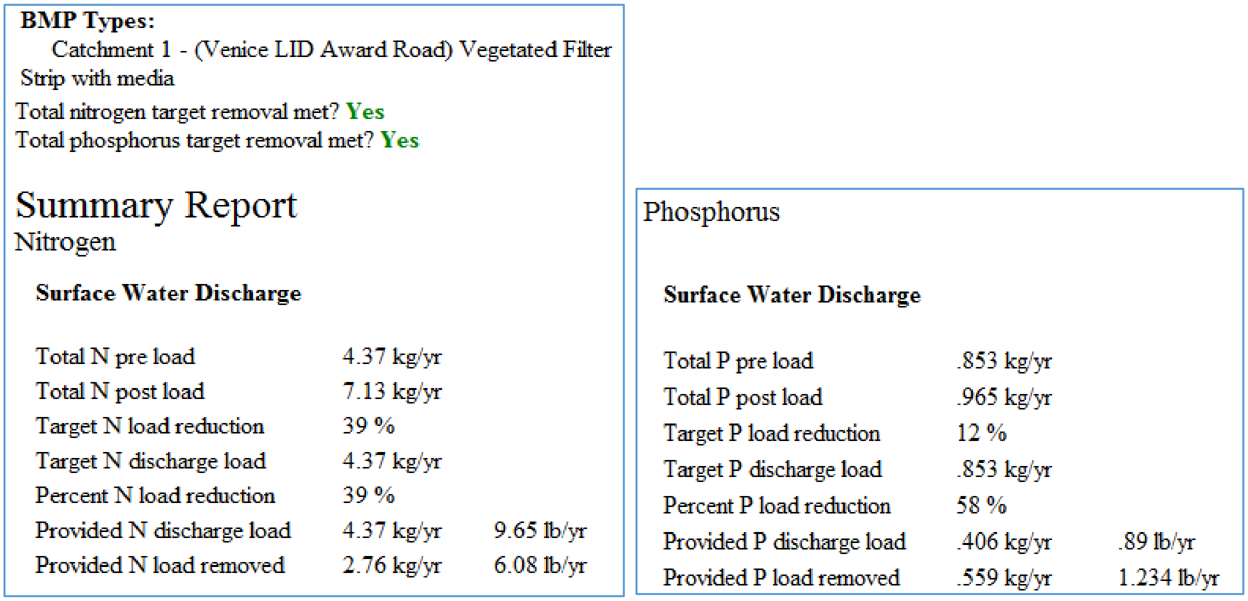


Vegetated Filter Strip Worksheet Analysis: Net Improvement Required Removal N: 39% P: 12%

VFS Width (10 - 30 ft): 26
VFS Length (ft): 1025
VFS depth (< 2ft): 1
Width of Feeder Area (ft): 60
Soil Storage Capacity (in/in): 0.2
VFS Slope (<20%): 16

Figure 4.17. VFS input data.

The assessment summary using the BAM VFS in terms of net improvement for surface discharge is shown in Figure 4.18. Net improvement for surface discharge needed is 39% TN and 12% TP. Provided are 39% for TN and 58% for TP. Without the BAM VFS, most likely removal would have been less because natural soils are not homogeneous and removal rates have not been documented for combinations of natural soil types commonly used for shoulder areas. For infiltration treatment in the State using natural local soil types, the removal is assumed to be zero, unless the soils are homogeneous, have a certified mix and removal rates documented.



BMP Types:
Catchment 1 - (Venice LID Award Road) Vegetated Filter Strip with media
Total nitrogen target removal met? **Yes**
Total phosphorus target removal met? **Yes**

Summary Report

Nitrogen

Surface Water Discharge

Total N pre load	4.37 kg/yr	
Total N post load	7.13 kg/yr	
Target N load reduction	39 %	
Target N discharge load	4.37 kg/yr	
Percent N load reduction	39 %	
Provided N discharge load	4.37 kg/yr	9.65 lb/yr
Provided N load removed	2.76 kg/yr	6.08 lb/yr

Phosphorus

Surface Water Discharge

Total P pre load	.853 kg/yr	
Total P post load	.965 kg/yr	
Target P load reduction	12 %	
Target P discharge load	.853 kg/yr	
Percent P load reduction	58 %	
Provided P discharge load	.406 kg/yr	.89 lb/yr
Provided P load removed	.559 kg/yr	1.234 lb/yr

Figure 4.18. Summary assessment for BAM VFS net improvement.

CHAPTER 5. **Development of a regional groundwater model to evaluate potential cumulative impact of BAM-based BMPs on water quality in receiving water bodies**

5.1 Research objectives

The research objective was to investigate the potential cumulative impact of implementing many individual BAM-based BMPs, including BAM blanket filters and roadway shoulder BAM Vegetated filter strips (VFS), within the Silver Springs springshed. An integrated groundwater flow and nutrient transport model was developed for the unique karst hydrogeology of the Silver Springs springshed. The model was used to compare various implementation scenarios of BAM-based BMPs based on potential effects to nitrate, TN, and TP concentrations in Silver Springs.

5.2 Design of experiments

Three monitoring wells (well-1, well-2, and well-3, Figure 5.1) were installed in the three stormwater retention basins (SRBs) for groundwater quality monitoring and to facilitate tracer tests, both of which were used to support the development of the integrated groundwater flow and nutrient transport model.

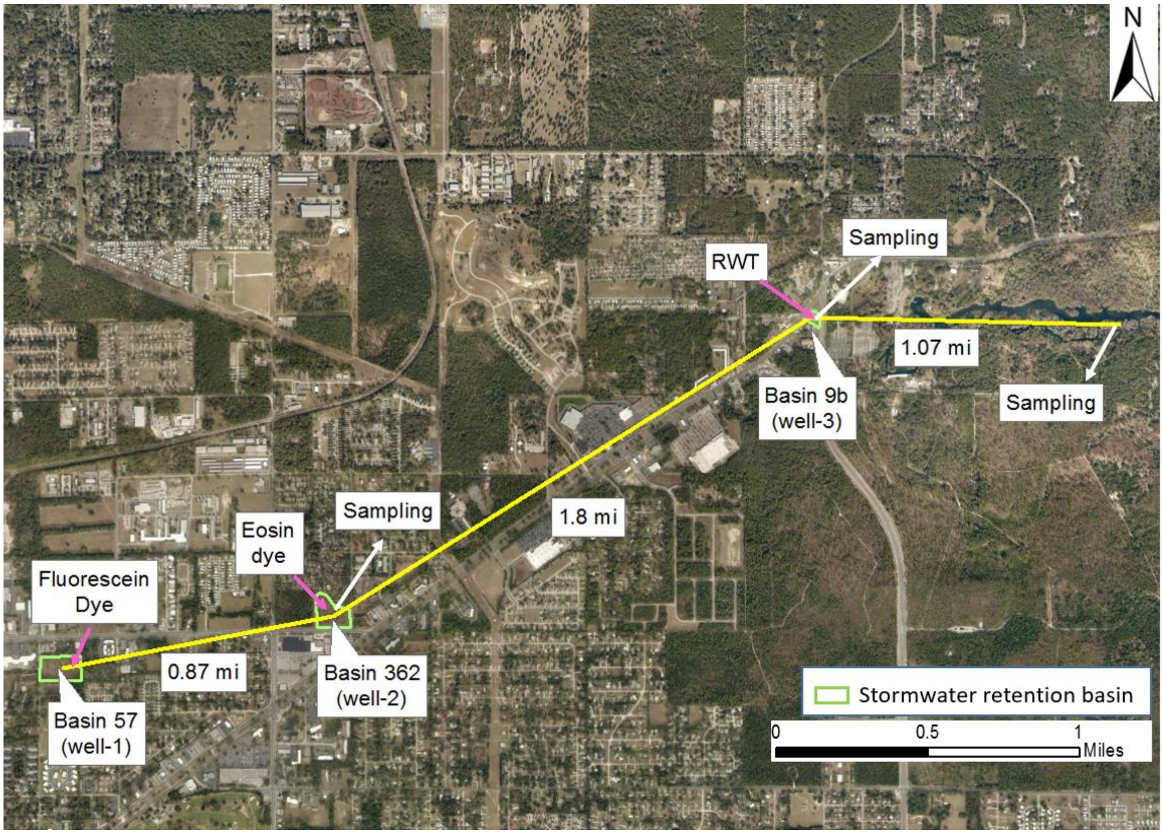


Figure 5.1. Well and spring sampling locations and dye injections to support development of the groundwater model.

Geophysical methods of ground-penetrating radar (GPR) and electromagnetic (EM) surveys were conducted in each SRB to identify the optimal locations and installation depths for groundwater monitoring wells. The well location for each basin was determined based on the detected GPR anomalies and low EM responses indicating karst features. The three monitoring wells were installed to depths of hard limestone, as an indication of the Upper Floridan Aquifer. Groundwater samples from each well and spring discharge samples from Silver Springs were collected monthly from March 2019 to March 2020 (Table 5.1 and Figure 5.2). Samples were kept cool and delivered to a certified lab (Environmental Research & Design) within 24 hours of collection. Each sample was tested in triplicate within 48 hours for concentrations of total nitrogen (TN), nitrate-nitrite (NOx), and total phosphorus (TP). Measured concentrations were used for validating the groundwater solute transport model.

A series of tracer tests were implemented to characterize the hydraulic properties of karst features near Silver Springs. Transport parameters of conduits and fractures estimated by tracer tests were incorporated into the nutrient transport model. Three types of tracer dyes with different emission wavelengths (rhodamine (RWT), fluorescein and eosin) were injected into the three wells in May 2019 (Figure 5.1). Tracer samples in each well and Silver Springs discharge were collected regularly from May 2019- March 2020 and tested for each tracer concentration using a RF 5000 spectrofluorophotometer. RWT was detected in Silver Springs almost immediately, suggesting a subsurface travel time of less than 1 hour (Figure 5.3A). This indicated the existence of subsurface karst features. The breakthrough curve from 200 to 2400 hours (8 days to 3.5 months) after dye injection captured most of the RWT tracer mass. The small peaks following the main breakthrough curve suggest the complexity of flow paths in the karst aquifer. By fitting the main breakthrough curve using a two-region non-equilibrium model (Field and Pinsky, 2000, Figure 5.3A), the dispersivity of the aquifer used in the transport model was estimated to be 6 ft. Fluorescein dye (injected upstream in well-1) was detected in well-2 after 144 hours (6 days). Fluorescein concentrations increased steadily and stabilized after 2000 hours (2.5 months) (Figure 5.2B). Fluorescein and eosin were never detected in Silver Springs or well-3, suggesting lack of an efficient karst network from well-2 to areas downstream.

Table 5.1. Measured concentrations of NO_x, total nitrogen, and total phosphorus.

Month	Site	NO_x (mg/L)	Total Nitrogen (mg/L)	Total Phosphorus (mg/L)
Mar 2019	well-1	0.002	0.44	0.28
	well-2	0.002	0.91	0.11
	well-3	0.2	0.34	0.35
	Silver Springs	1.15	1.26	0.56
Apr 2019	well-1	0.06	0.33	0.83
	well-2	0.033	0.15	0.41
	well-3	0.045	0.13	0.047
	Silver Springs	1.03	1.25	0.065
May 2019*	Silver Springs	0.47	0.87	0.057
Jun 2019*	Silver Springs	1.18	1.11	0.016
Jul 2019*	Silver Springs	1.04	1.33	0.081
Aug 2019*	Silver Springs	1.18	1.26	0.07
Sep 2019*	Well-2	0.037	0.17	0.036
	Silver Springs	1.12	1.00	0.057
Oct 2019*	Well-2	-	0.41	0.05
	Silver Springs	0.88	1.12	0.032
Nov 2019*	Well-1	-	-	0.02
	Well-2	-		0.24
	Silver Springs	1.18	1.26	0.053
Dec 2019*	Well-1	0.13	-	-
	Well-2	-	-	0.27
	Silver Springs	1.18	1.28	0.027
Jan 2020*	Well-2	-	-	0.16
	Silver Springs	1.18	1.25	0.058
Feb 2020*	Well-1	-	-	0.18
	Well-2	-	-	0.22
	Silver Springs	1.16	1.38	0.036
Mar 2020*	Well-1	0.29	-	0.29
	Well-2	-	-	0.12
	Silver Springs	1.09	1.28	0.01

* Measured nutrient concentrations in some well samples are not reasonable due to the presence of tracer dyes. Contaminated samples were not used to calibrate the model.

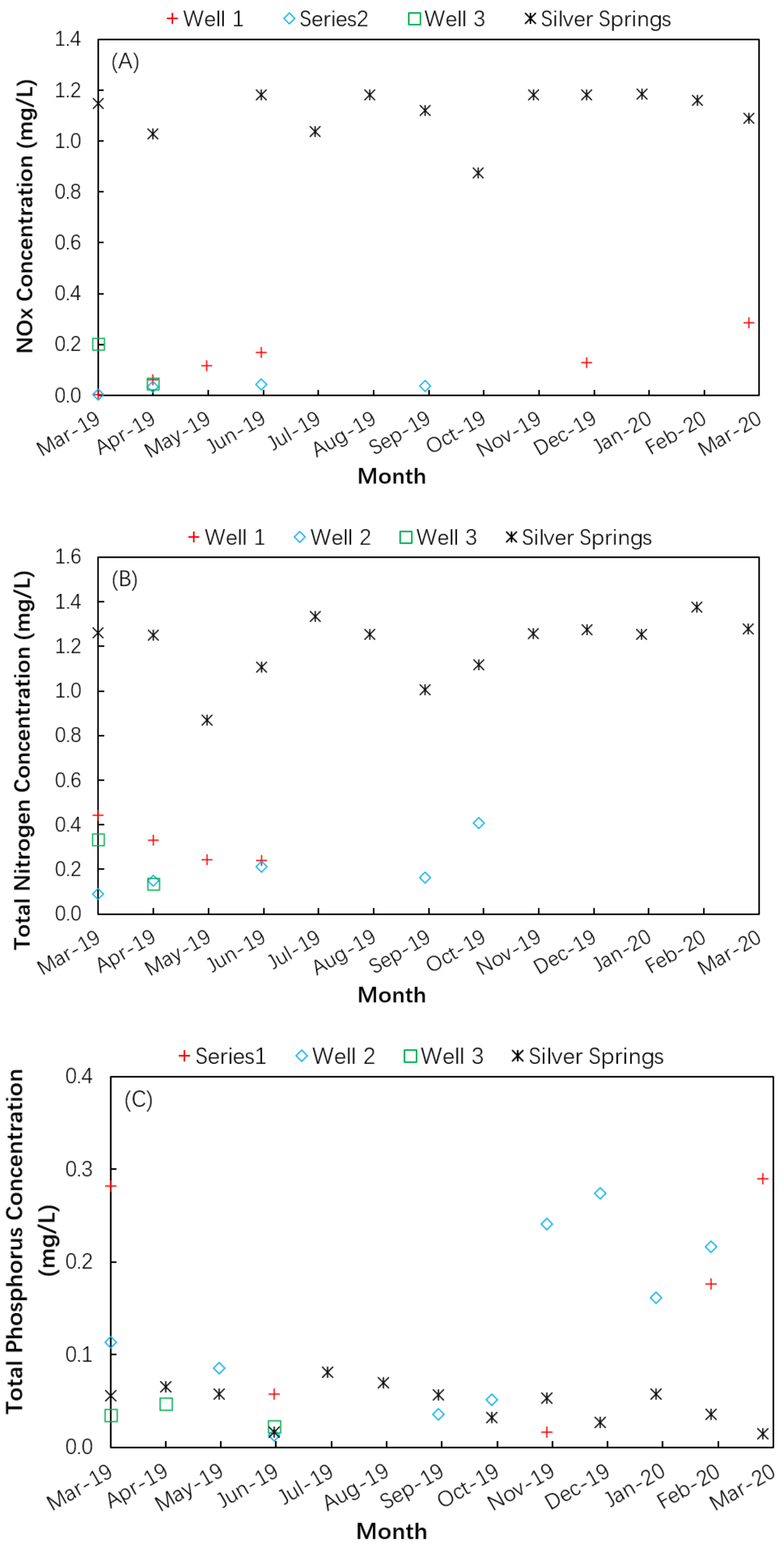


Figure 5.2. Concentrations of (a) NO_x, (b) total nitrogen, and (c) total phosphorus measured monthly in monitoring wells and Silver Springs.

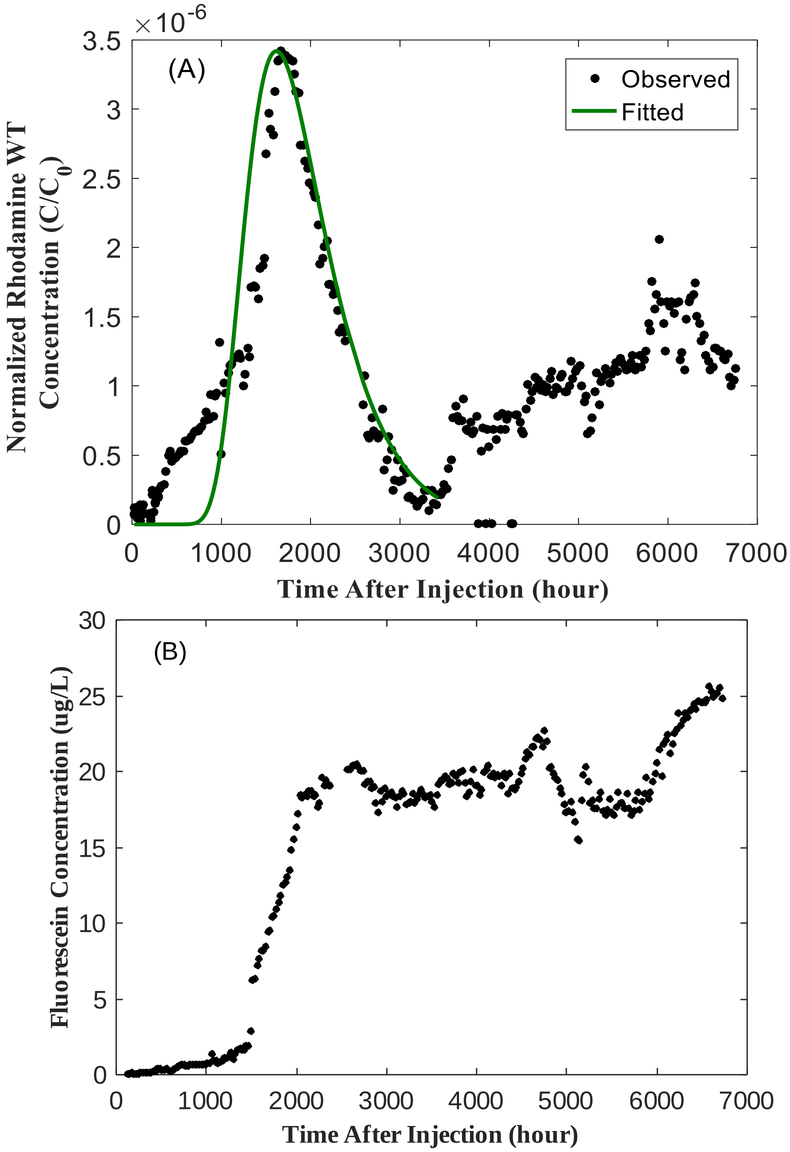


Figure 5.3. (a) Rhodamine WT concentration detected in Silver Springs with fitted curve based on the two-region non-equilibrium model; (b) Fluorescein dye concentration detected in well-2.

An integrated groundwater flow and nutrient transport model was developed to investigate the cumulative effects of BAM-based BMPs on nitrate, TN, and TP concentrations (Figure 5.4). A calibrated MODFLOW model was developed based on the North Florida Southeast Georgia (NFSEG) model (Durden et al., 2013). The MODFLOW model was discretized into 496 rows and 236 columns with the cell size of 625 ft by 625 ft (Figure 5.5A). The model includes 3 layers with variable thickness representing the surficial aquifer, the UFA, and the lower Floridan aquifer, as shown in Figure 5.5B. The springshed boundary is set as a no-flux boundary condition, and the head-dependent flux boundary is used for internal boundaries such as rivers and lakes. The top and bottom elevations of each layer, average hydraulic conductivity, boundary conditions for rivers and lakes, recharge, and evapotranspiration were obtained from the NFSEG model.

A CFPv2 model was developed to calculate flow in both karst conduits and flow in the aquifer matrix. The CFPv2 model was developed by incorporating conduits into the calibrated MODFLOW model based on the distribution of sinkhole locations (Faulkner, 1973; Ghasemizadeh et al., 2012) and results of the tracer experiment. After calibration of conduit properties in the steady-state CFPv2 model, a transient CFPv2 model was developed to transmit the calculated flow field to CMT3D for modeling nutrient transport through the aquifer matrix and heterogeneous karst conduits. Nutrient concentration in groundwater recharge, which was estimated based on land use and land cover and population density, was fed into the CMT3D model, which simulates the nutrient concentration in the discharge of Silver Springs. Results from tracer test shown (Figure 5.3A) were used to provide dispersivity of contaminant in the transport model. Groundwater monitoring data (Table 5.1 and Figure 5.2) were used for validation of nutrient concentration in the transport model. Calibration and validation statistics (Table 5.2) indicate that the performance of the flow model is acceptable. The model performance for simulating the nutrient concentrations in Silver Springs is also acceptable based on the statistics of Root Mean Square Error and Relative Error (Table 5.3).

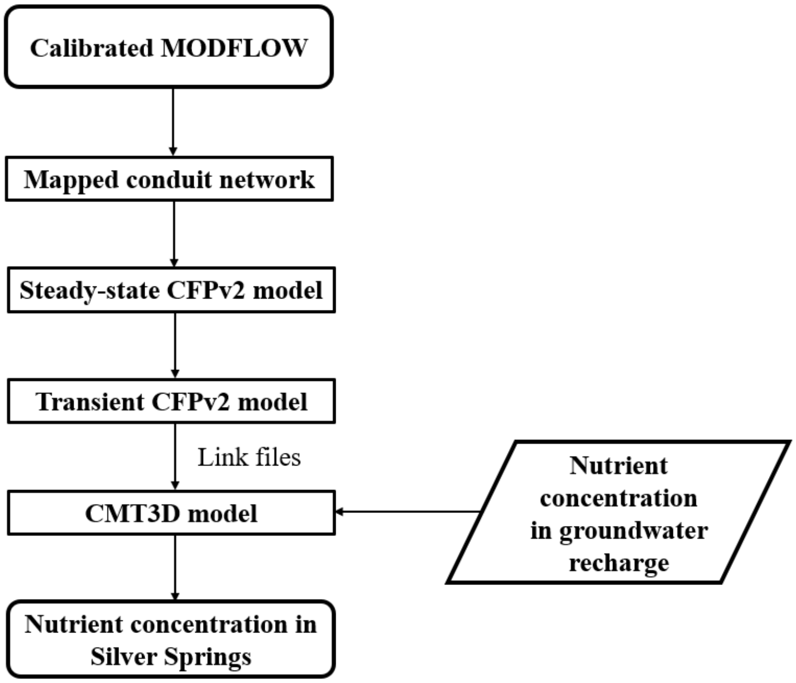


Figure 5.4: The procedures for modeling nutrient transport by coupling CFPv2 and CMT3D.

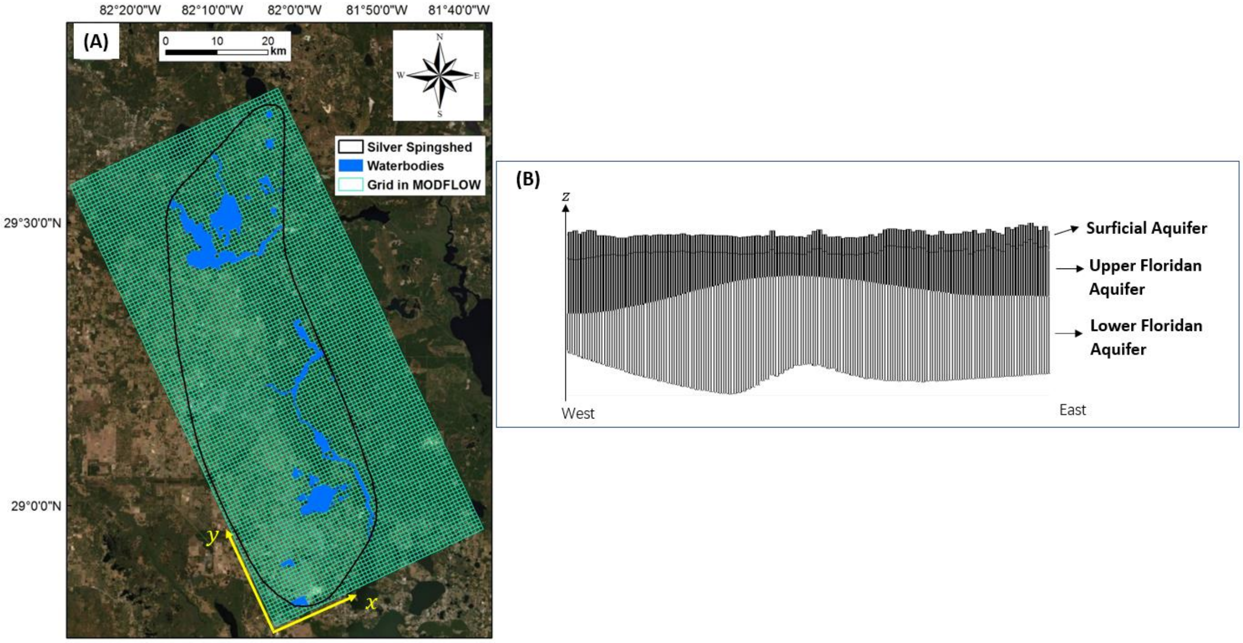


Figure 5.5: The horizontal (a) and vertical (b) discretization of the MODFLOW model.

Table 5.2: Calibration and validation statistics for the flow model.

Period		Groundwater Level		Spring Discharge	
		RMSE (ft)	Relative Error	NSE	Relative Error
Calibration	Mean annual	1.79	3%	0.86	6%
Validation	Mean annual	1.19	2%	0.70	7%
	Monthly	1.04	2%	0.84	6%

Table 5.3: Calibration and validation statistics for the nutrient transport model.

Statistics	NO_3		TN		TP	
	Calibration	Validation	Calibration	Validation	Calibration	Validation
Data range	2000-2008	2009-2016 and 2019	2001-2007	2008-2010 and 2019	2000-2007	2008-2010 and 2019
RMSE (mg/L)	0.06	0.09	0.10	0.07	0.007	0.006
Relative error (%)	4.4	5.2	7.0	5.0	11.7	11.3

The cumulative effects of BAM-based BMPs on nutrient reduction were evaluated for six implementation scenarios (Table 5.4) by the integrated transport model. Effectiveness of BAM and unaltered soils for removing nitrate, TN, and TP from stormwater was inferred based on values from previously published field and laboratory experiments and VFS experiments documented in this report (Table 5.5). When possible, soil removal efficiencies observed under field-scale testing in the blanket filter and roadway shoulder VFS configurations were adopted for modeling. However, as soils and their nutrient removal properties are spatially heterogeneous, the limited available testing indicates only a limited range of potential soil removal efficiencies. To address uncertainty due to spatial heterogeneity of soils, ranges of potential soil removal efficiencies were applied in modelling, based on ranges reported within the literature. The integrated groundwater flow and nutrient transport model was run under each of the six BMP implementation scenarios to predict nitrate, TN, and TP concentrations in Silver Springs from 2021 to 2030. Groundwater recharge rates were assumed to be similar to those observed from 2001 to 2010. Mean concentrations simulated for the period 2021-2030 were compared to mean concentrations observed from 2000 to 2020. The groundwater models and input files are available on the UCF STARS data repository at https://stars.library.ucf.edu/fdot/, and an index is provided in Appendix D.

Table 5.4: BAM BMPs implementation scenarios tested.

Scenario	Blanket filter implementation	Area (acres)	Percent of SRB area (%)	Roadway shoulder implementation	Length (miles)	Percent of roadways (%)
1	Baseline - no BAM is implemented	0	0	Baseline - no BAM is implemented	0	0
2	BAM blanket filters are implemented in 26 FDOT SRBs	3,682	13	No BAM VFS	0	0
3	BAM blanket filters are implemented in all FDOT SRBs	27,651	100	No BAM VFS	0	0
4	No BAM blanket filters	0	0	BAM VFS are implemented in 30% of roadway shoulders	2,368	30%
5	No BAM blanket filters	0	0	BAM VFS are implemented in 60% of roadway shoulders	4,735	60%
6	BAM blanket filters are implemented in all FDOT SRBs	27,651	100	BAM VFS are implemented in all roadways shoulders	7,893	100%

Table 5.5: Nutrient removal efficiencies of BAM and soils in SRBs and roadway shoulder VFS applied in modeling. Negative removal efficiency indicates nutrient generation.

	SRB Blanket Filters			Source
	NO_3	TN	TP	
BAM	62%	66%	42%	Kibler et al. 2020a and b
Soils	74%	60%	-48%	Kibler et al. 2018b
	Roadway Shoulder VFS			
	NO_3	TN	TP	
BAM	96%	81%	80%	Chapter 3
Soils	-50%	29%	80%	
Soils – potential range	-50% and 92%	29% and 78%	-177% and 80%	Hossain et al. 2010; Kibler et al. 2018b; Kibler et al. 2020b; Chapter 3

5.3 Cumulative impact of BAM BMPs to nitrate, TN, and TP concentrations

The modelling investigation provided little convincing evidence that even large-scale implementation of BAM-based stormwater BMPs will reduce nitrate or phosphorus concentrations in Silver Springs (Figures 5.6-5.8 and Tables 5.6-5.8). For instance, the largest implementation investigated (Scenario 6: BAM blanket filters are implemented in all FDOT SRBs and BAM VFS are implemented in all roadways shoulders) was associated with anywhere from a mean 22% net improvement to 18% net degradation in Silver Springs nitrate concentrations from 2021-2030 (Table 5.6). Similarly equivocal results were obtained for TP concentrations: Scenario 6 was associated with up to 8% net improvement to 4% net degradation in TP concentrations (Table 5.8). TN concentration responses were more uniformly positive, associated with anywhere from a mean 8% to 18% net improvement over 2021-2030 (Table 5.7). Net benefits associated with more realistic lower levels of implementation were similarly equivocal but offer only incremental maximum benefits.

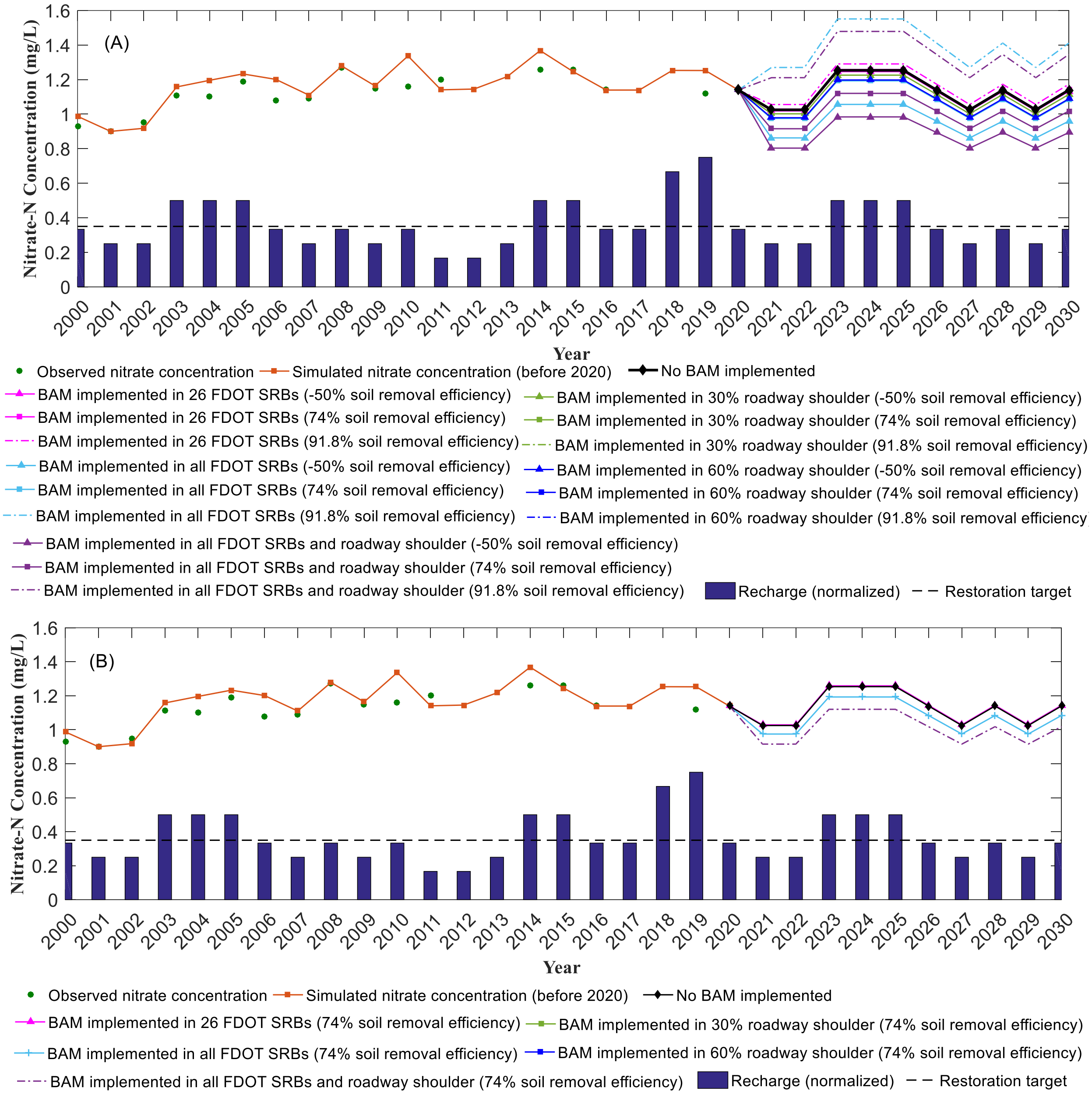


Figure 5.6: Projected cumulative effects of BAM-based BMPs on nitrate concentration in Silver Springs: (a) considering the full range of nitrate removal efficiencies observed for soil; (b) comparing to 74% soil nitrate removal efficiency.

Table 5.6: Net improvements to Silver Springs nitrate concentration expected across six BAM BMP implementation scenarios. Negative net improvement indicates poorer performance relative to the baseline (net degradation).

BMP implementation scenario	(1) No BAM	(2) 26 FDOT SRBs			(3) All FDOT SRBs			(4) 30% roadway shoulder			(5) 60% roadway shoulder			(6) All FDOT SRBs and all roadway shoulders		
Soil removal efficiency	-	-50%	74%	92%	-50%	74%	92%	-50%	74%	92%	-50%	74%	92%	-50%	74%	92%
Observed NO_3 concentration 2000-2020 (mg/L)	1.12															
Projected NO_3 concentration 2021-2030 (mg/L)	1.13	1.12	1.13	1.16	0.95	1.07	1.40	1.10	1.11	1.11	1.08	1.09	1.10	0.88	1.01	1.33
Net improvement: reduction relative to baseline (%)	-	0.6	-0.3	-2.9	15.8	4.9	-23.8	2.3	2.0	1.3	4.5	3.7	2.4	21.6	10.6	-18.1

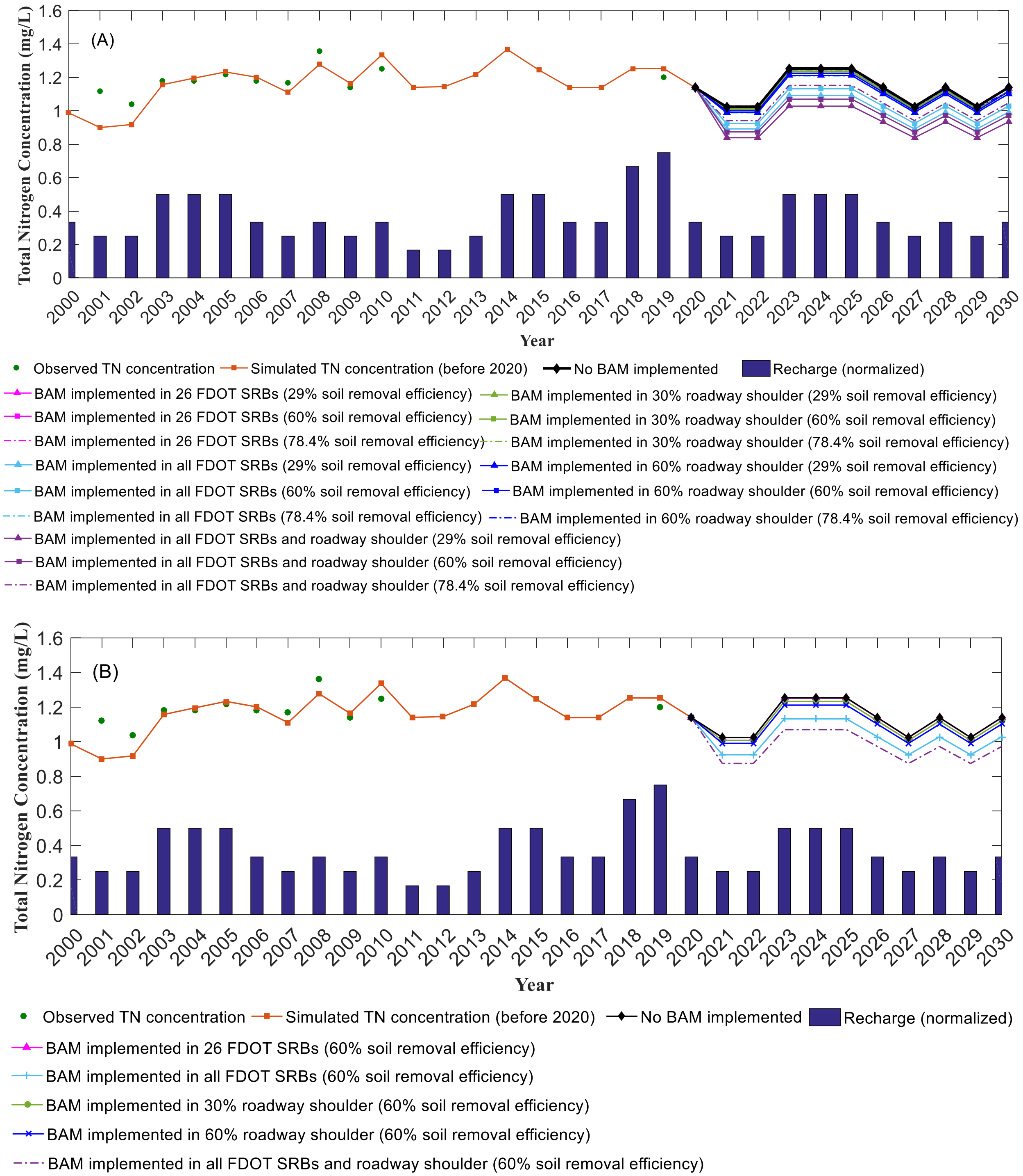


Figure 5.7: Projected cumulative effects of BAM-based BMPs on TN concentration in Silver Springs: (a) considering the full range of TN removal efficiencies observed for soil; (b) comparing to 60% soil nitrate removal efficiency.

Table 5.7: Net improvements to Silver Springs TN concentration expected across six BAM BMP implementation scenarios. Negative net improvement indicates poorer performance relative to the baseline (net degradation).

BMP implementation scenario	(1) No BAM	(2) 26 FDOT SRBs			(3) All FDOT SRBs			(4) 30% roadway shoulder			(5) 60% roadway shoulder			(6) All FDOT SRBs and all roadway shoulders		
Soil removal efficiency	-	29%	60%	78%	29%	60%	78%	29%	60%	78%	29%	60%	78%	29%	60%	78%
Observed TN concentration 2000-2020 (mg/L)	1.19															
Projected TN concentration 2021-2030 (mg/L)	1.13	1.12	1.13	1.13	0.98	1.02	1.09	1.11	1.11	1.123	1.09	1.10	1.12	0.92	0.96	1.04
Net improvement: reduction relative to baseline (%)	-	0.4	0.2	-0.4	12.9	9.8	3.5	1.7	1.3	0.4	3.4	2.4	0.7	18.1	14.7	8.2

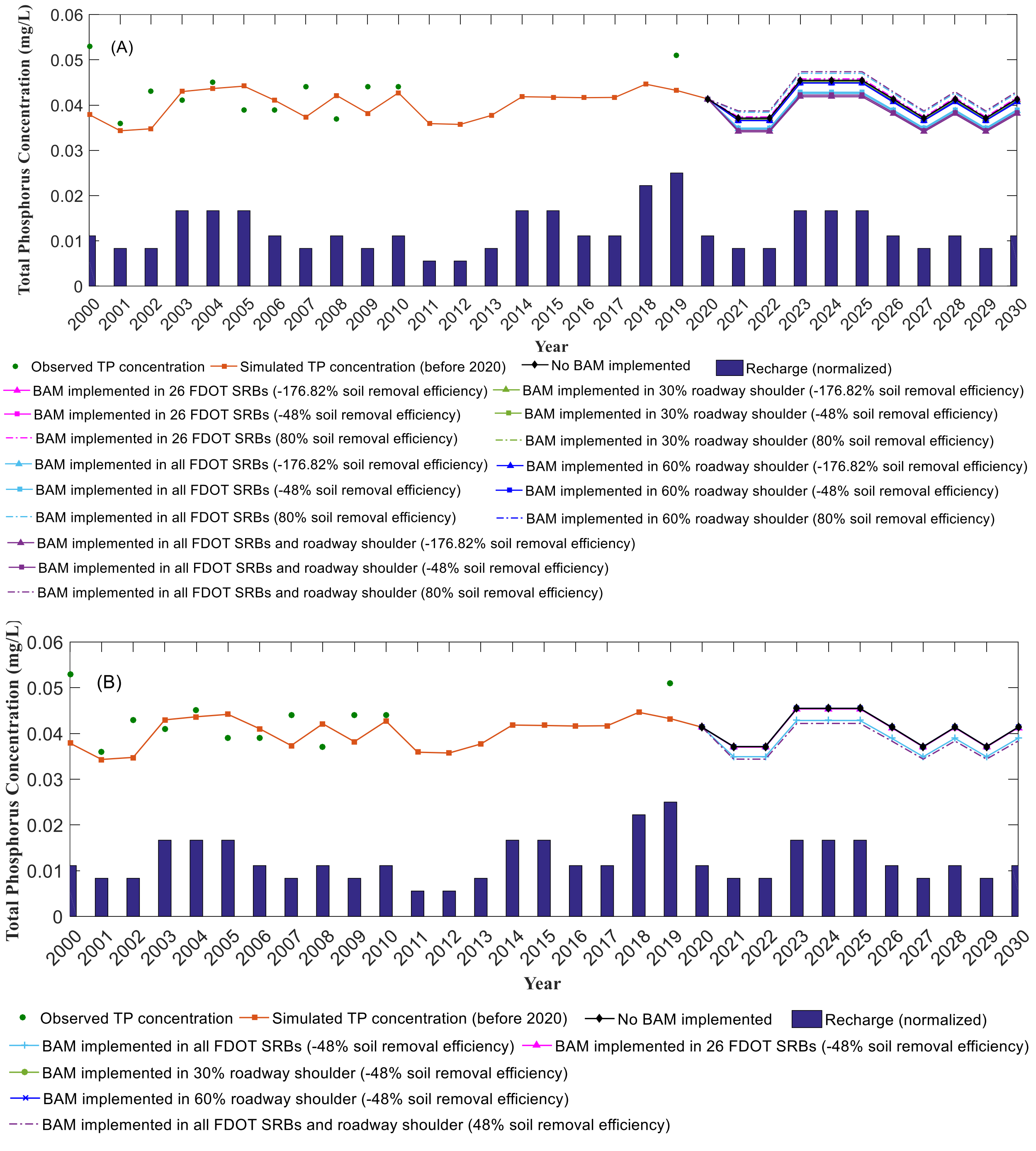


Figure 5.8: Projected cumulative effects of BAM-based BMPs on TP concentration in Silver Springs: (a) considering the full range of TP removal efficiencies observed for soil; (b) comparing to -48% soil nitrate removal efficiency.

Table 5.8: Net improvements to Silver Springs TP concentration expected across six BAM BMP implementation scenarios. Negative net improvement indicates poorer performance relative to the baseline (net degradation).

BMP implementation scenario	(1) No BAM	(2) 26 FDOT SRBs			(3) All FDOT SRBs			(4) 30% roadway shoulder			(5) 60% roadway shoulder			(6) All FDOT SRBs and all roadway shoulders		
Soil removal efficiency	-	-177%	-48%	80%	-177%	-48%	80%	-177%	-48%	80%	-177%	-48%	80%	-177%	-48%	80%
Observed TP concentration 2000-2020 (µg/L)	43.0															
Projected TP concentration 2021-2030 (µg/L)	40.9	40.8	40.8	41.2	38.3	38.5	42.3	40.6	40.6	40.9	40.3	40.4	40.9	37.6	37.9	42.6
Net improvement: reduction relative to baseline (%)	-	0.3	0.2	-0.7	6.5	5.9	3.3	0.7	0.7	0	1.5	1.3	0	8.1	7.3	-4.1

5.4 Recommendations

This modelling study indicates that the spring water quality benefits accruing from implementation of BAM-based stormwater BMPs are ambiguous. A wide range of outcomes are possible, ranging from water quality improvements to net degradation (Figures 5.6A, 5.7A, 5.8A). This equivocal result points to a critical knowledge gap that should be addressed before large-scale investments into BAM-based BMPs. Whether BAM BMPs lead to net water quality improvements or degradation depends on whether BAM removes more or less nutrients from stormwater than the unaltered soil profile. Both BMPs investigated (BAM blanket filters and BAM VFS) involve the removal and replacement of part of the soil profile with BAM media. In some places, replacing the soil profile with BAM will lead to greater transformation and removal of nutrients; in other cases the natural remediation of the unaltered soil profile will exceed that of BAM. The spatial heterogeneity of soil nutrient remediation properties introduces considerable uncertainty to the potential cumulative water quality improvements offered by BAM BMPs. The cumulative impact of large-scale BAM implementation will be on the higher end of net improvement estimated in this study (22% decrease in nitrate concentration, 18% decrease in TN concentration, 8% decrease in TP concentration) if and only if BAM replaces soils with the poorest possible nutrient remediation potential (i.e. those which generate phosphorus and nitrate and remove less than 30% of TN).

Therefore, managers' most pressing concern is: how to differentiate between soils that will benefit from BAM replacement and those which will not? This requires addressing a critical knowledge gap regarding the relative nutrient remediation potential of BAM versus soils of variable properties. This knowledge gap should be resolved before large-scale investments are made to implementing BAM BMPs. When this is accomplished, a modelling study such as this one may assess the potential cumulative effects of BAM BMPs with greater precision. The uncertainty in soil heterogeneity can be resolved, but only after achieving greater understanding of nutrient transformations within soils of variable properties and then understanding how those variable soils are distributed spatially. These two pieces of information are also critically needed to assist managers in making cost-effective decisions regarding BMP implementation.

If we assume that managers can isolate poor soils that are good candidates for replacement with BAM, the modeling study indicates that BAM BMPs benefit is likely to scale with penetration (i.e. greater water quality benefits can be expected with greater BMP implementation). However, this study suggests that even the maximum expected benefits may be nominal. The greatest possible net improvements (Scenario 6) were achieved assuming every road in the Silver Springs springshed was fitted with a roadway shoulder BAM VFS and a BAM blanket filter was installed in every FDOT SRB. This is 7,893 miles of BAM VFS and 27,651 acres of blanket filter. Scenario 6 is therefore likely an unrealistic implementation scenario associated with great cost to taxpayers.

While still representing large investments, Scenario 2 (3,682 acres of BAM blanket filters implemented in SRBs) and Scenario 4 (2,368 miles of BAM VFS are implemented in roadway shoulders) are more realistic scenarios on which to gauge possible net improvements. Removing the uncertainty from soil removals, at best, Scenarios 2 and 4 respectively would lead to maximum net spring water quality improvement of 0.3% and 0.7% for TP, 0.6% and 2.3% for nitrate, and 0.4% and 3.4% for TN. Considering the resources required for such implementation and the limited water quality benefits, the BAM-based BMPs investigated may not be a rational investment to improve Silver Springs water quality.

Given the modest improvements that can be expected with realistic BAM BMP implementation scenarios, water quality in Silver Springs would still fall quite short of restoration targets. To achieve restoration goals in Silver Springs, non-transportation sources of nutrients (such as agricultural applications and septic tanks) also need to be controlled or treated. The groundwater flow and transport models developed herein could be used to evaluate the efficiency of a larger suite of remediation measures, in conjunction with transportation-related BMPs. Additionally, similar procedures for model development, calibration and validation are applicable for other springsheds in Florida.

REFERENCES

AASHTO, M., 145-91. (2008). Standard specification of soils and soil-aggregate mixtures for Highway Construction Purposes. American Association of State Highway and Transportation Official, Washington, DC.

Barrett, M., Lantin, A. and Austrheim-Smith, S. (2004). Storm water pollutant removal in roadside vegetated buffer strips. *Transportation Research Record*, 1890(1), 129-140.

Caruso, N.T. (2014). Biofiltration enhancement for the treatment of highway stormwater runoff. [MSc Thesis], Georgia Institute of Technology, 121 p.

Chang, N. B., Wen, D., & Wanielista, M. P. (2019). Impact of changing environmental factors and species competition on iron filings‐based green environmental media for nutrient removal in stormwater treatment. *Environmental Progress & Sustainable Energy*, 38(4), 13087.

Driscoll, E.D., Shelley, P.E. and Strecker, E.W. (1990). Pollutant loadings and impacts from highway stormwater runoff. Volume I: Design Procedure (No. FHWA-RD-88-006). Federal Highway Administration, McLean, VA.

Durden, D., Cera, T., and Johnson, N. (2013). North Florida southeast Georgia (NFSEG) groundwater flow model conceptualization. St. Johns River Water Management District, Palatka, Florida, USA.

Eller, K.T., and Katz, B.G. (2017). Nitrogen Source Inventory and Loading Tool: An integrated approach toward restoration of water-quality impaired karst springs. *Journal of Environmental Management*, 196, 702-709.

Faulkner, G.L. (1973). Geohydrology of the cross-Florida barge canal area with special reference to the Ocala vicinity. United States Geological Survey, Tallahassee, Florida, USA.

Florida Department of Environmental Protection (FDEP) (2012). Nutrient TMDL for Silver Springs, Silver Springs Group, and Upper Silver River (WBIDs 2772A, 2772C, and 2772E). Florida Department of Environmental Protection, Tallahassee, Florida, USA.

Field, M.S., and Pinsky, P.F. (2000). A two-region nonequilibrium model for solute transport in solution conduits in karst aquifers. *Journal of Contaminant Hydrology*, 44, 329-351.

Florida Department of Transportation (2012). Plans Preparation Manual Volume 2: Plans Preparation and Assembly. Roadway Design Office, Tallahassee, Florida.

Gardner, K.K., and Vogel, R.M. (2005). Predicting ground water nitrate concentration from land use. *Ground Water*, 43(3), 343-352.

Ghasemizadeh, R., Hellweger, F., Butscher, C., Padilla, I., Vesper, D., Field, M., and Alshawabkeh, A. (2012). Review: groundwater flow and transport modeling of karst aquifers, with particular reference to the North Coast Limestone aquifer system of Puerto Rico. *Hydrogeology Journal*, 20, 1441-1461.

Harper, H.H., and Baker, D.M., (2007). Evaluation of current stormwater design criteria within the state of Florida. Florida Department of Environmental Protection, Tallahassee, Florida, p. 327.

Hood, A., Chopra M., and Wanielista, M. (2013). Assessment of Biosorption Activated Media under Roadside Swales for the Removal of Phosphorus from Stormwater, *Water*, 5, 53-66.

Hossain, F., Chang, N. B., & Wanielista, M. (2010). Modeling kinetics and isotherms of functionalized filter media for nutrient removal from stormwater dry ponds. *Environmental Progress & Sustainable Energy*, 29(3), 319-333.

Kayhanian, M., Suverkropp, C., Ruby, A. and Tsay, K. (2007). Characterization and prediction of highway runoff constituent event mean concentration. *Journal of environmental management*, 85(2), 279-295.

Kibler, K. M., N. B. Chang, D. B. Wang, M. P. Wanielista, Y. Gao, M. Shokri, A. Valencia, and D. Ordonez (2018a). Task 1 Report for Innovative and Integrative BMPs for Surface and Groundwater Protection. University of Central Florida, Orlando, FL. Prepared for FDOT.

Kibler, K. M., N. B. Chang, D. B. Wang, M. P. Wanielista, Y. Gao, M. Shokri, A. Valencia, and D. Ordonez (2018b). Task 2 Report for Innovative and Integrative BMPs for Surface and Groundwater Protection. University of Central Florida, Orlando, FL. Prepared for FDOT.

Kibler, K. M., N. B. Chang, D. B. Wang, M. P. Wanielista, Y. Gao, M. Shokri, and D. Ordonez (2020a). Task 3 Report for Innovative and Integrative BMPs for Surface and Groundwater Protection. University of Central Florida, Orlando, FL. Prepared for FDOT.

Kibler, K. M., N. B. Chang, M. P. Wanielista, D. Wen, M. Shokri, A. Valencia, E. Lustoso-Alves, and N. Rice (2020b). Optimal Design of Stormwater Basins with Bio-sorption activated media (BAM) in Karst Environments – Phase II: Field Testing of BMPs. FDOT Final Report BDV24-977-20. University of Central Florida, Orlando, FL.

Mallin, M.A., Johnson, V.L., and Ensign, S.H. (2009). Comparative impacts of stormwater runoff on water quality of an urban, a suburban, and a rural stream. *Environmental Monitoring and Assessment* 159(1), 475-491.

Ordonez, D., Valencia, A., Chang, N.B., & Wanielista, M. P. (2020a). Synergistic effects of aluminum/iron oxides and clay minerals. *Journal of Cleaner Production*, in review.

Ordonez, D., Valencia, A., Elhakiem, H., Chang, N.B., & Wanielista, M. P. (2020b). Adsorption Thermodynamics and Kinetics of Advanced Green Environmental Media (AGEM) for Nutrient Removal and Recovery in Agricultural Discharge and Stormwater Runoff. *Environmental Pollution*, in review.

Phelps, G.G. (2004). Chemistry of ground water in the Silver Springs basin, Florida, with an emphasis on nitrate. U.S. Geological Survey, Reston, Virginia, USA.

Sousa, A. F., Braga, T. P., Gomes, E. C. C., Valentini, A., & Longhinotti, E. (2012). Adsorption of phosphate using mesoporous spheres containing iron and aluminum oxide. *Chemical Engineering Journal*, 210, 143-149.

Suthar, S., Bishnoi, P., Singh, S., Mutiyar, P.K., Nema, A.K., Patil, N.S. (2009). Nitrate contamination in groundwater of some rural areas of Rajasthan, India. *Journal of Hazardous Materials* 171(1), 189-199.

Thomson, N.R., McBean, E.A., Snodgrass, W. and Monstrenko, I.B. (1997). Highway stormwater runoff quality: Development of surrogate parameter relationships. *Water, Air, and Soil Pollution*, 94(3-4), 307-347.

Trenouth, W.R., and Gharabaghi. B. (2016). Highway Runoff Quality Models for the Protection of Environmentally Sensitive Areas. *Journal of Hydrology* 542, 143-155.

Valencia, A., Chang, N. B., Wen, D., Ordonez, D., & Wanielista, M. P., 2019. Optimal recipe assessment of iron filing-based green environmental media for improving nutrient removal in stormwater runoff. Environmental Engineering Science, 36(10), 1323-1336.

Valencia, A., Ordonez, D., Wen, D., McKenna, A., Chang, N. B., & Wanielista, M. 2020. Dissolved Organic Nitrogen Impact on Microbial Communities in Iron-Filing Based Green Environmental Media for Nutrient Removal in Stormwater Runoff, Environmental Research, in review.

Winston, R.J. and Hunt, W.F. (2016). Characterizing runoff from roads: Particle size distributions, nutrients, and gross solids. *Journal of Environmental Engineering*, 143(1), 04016074.

Winston, R.J., Hunt, W.F., Kennedy, S.G., Wright, J.D. and Lauffer, M.S. (2011). Field evaluation of storm-water control measures for highway runoff treatment. *Journal of Environmental Engineering*, 138(1), 101-111.

Appendix A: Risk Assessment of CAM

Based on the results obtained from the batch isotherm analysis, a column bed adsorption and desorption in sequence was performed for two media. Iron based media (IFGEM-3) and the most promising aluminum-based media (AGEM-2) were selected for further investigation. To do so, a columns study with 6 columns (triplicate columns for each media) of 1-foot depth and 2 inches diameter equally assembled were filled with 500 grams of IFGEM-3 and AGEM-2 media, respectably (Figure A.1). A layer of crystal pebbles was placed at the top of each column to aid water distribution. Similarly, a layer of crystal pebbles and filter was placed at the bottom of each column to prevent clogging of the effluent. Each column was constantly fed at a flowrate of 3 mL/min with distilled (DI) water spiked with nitrate and phosphate at a concentration of 2 mg/L of NO_3^- and 2 mg/L of PO_4^{3-}, respectively. Each column was fed until media reached the breakthrough point for one of the nutrients studied (47 days). The breakthrough point refers to the point where the media has been saturated, therefore the sorption media cannot take up more nutrients. Influent and effluent water samples were collected at different time intervals during the analysis. Each water sample was analyzed in triplicates for total phosphorus, nitrate, and ammonia via Hach test 'n' tubeTM.

Subsequently, a desorption process was applied to the saturated media. After the saturation process was finalized and before the desorption process commenced the columns were left to drain for 24 hours and 30 g of samples was collected from top of the columns for media analysis. The desorption process consisted on feeding the saturated media with 1% NaOH solution at a flowrate of 3 mL/min for IFGEM-3 and 2 mL/min for AGEM-2 until all nutrients were desorbed. Samples were collected in time intervals until media reached equilibrium and no significant changes in effluent concentrations were observed. Collected effluent samples were analyzed for total phosphorus, nitrate and ammonia via Hach kits.

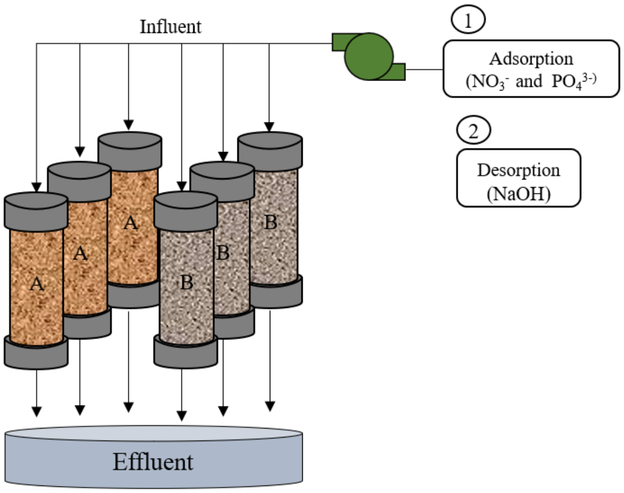


Figure A.1. Column study setup for adsorption and desorption processes.

To account for the possible health risks caused by excess leakage of aluminum and iron ions, effluent water samples were collected and analyzed initially every 24 hours for the first five days and afterwards every 72 hours until the completion of the adsorption process. In the desorption process samples were collected at different time interval and analyzed alike using Hach test 'n' tubeTM.

Two important parameters are health and environmental risk associated with the sorption media design. Iron is one of the most abundant metals found on earth, and it can be found in nature in water bodies at concentrations ranging from 0.5- 50 mg/L (WHO 1996, Oketola et al. 2013). Moreover, in water bodies with high pH a product of mining, aluminum can be found in concentrations as high as 90 mg/L (WHO 2010), thus concentration as high as 2.7 mg/L have been reported as a result of facilities using aluminum sulfate coagulation (Miller et al. 1984).

Furthermore, the U.S. Environmental Protection Agency (US EPA) has categorized aluminum and iron under the secondary drinking water standard (SDWS) signifying that they are not health threatening below secondary maximum contaminant levels (SMCL), therefore they can result in aesthetic, cosmetic and technical effects. The SMCL set by the US EPA are 0.05 to 0.2 mg/L for aluminum and 0.3 mg/L for iron (US EPA 2017). Iron concentration over 0.3 mg/L in drinking water can affect taste, plumbing and stain laundry, however, it is acceptable for human consumption in the concentrations ranging from 1-3 mg/L (WHO 1996, Oketola et al. 2013). The excess of aluminum in drinking water affect its color or its aesthetic; additionally, the excess exposure to aluminum can cause neurological disorders in humans (Fraga et al. 1990). Consequently, according to the Joint Expert Committee on Food Additives (JECFA), the acceptable aluminum concentration in water for human consumption is around 0.9 mg/L (WHO 2010).

The IFGEM-3 effluents concentration captured during the adsorption process are within the acceptable level for human ingestion (Table A.1). However, during the first 55 minutes of the desorption process the effluent iron concentrations exceed the acceptable drinking concentration but these concentrations did not surplus the concentration at which iron is found naturally in water bodies (Table A.1) (Oketola et al. 2013).

Table A.1. Mean (SD) IFGEM-3 iron effluent concentration in mg/L at different times within the adsorption and desorption process

Adsorption Process					
Day	**Iron Ion Concentration (mg/L)**	**Day**	**Iron Ion Concentration (mg/L)**	**Day**	**Iron Ion Concentration (mg/L)**
1	0.90 (1.13)	**8**	1.11 (0.35)	**38**	1.38 (0.67)
2	0.30 (0.17)	**16**	1.73 (0.90)	**44**	1.61 (1.12)
3	0.41 (0.25)	**22**	2.06 (0.85)	**47**	1.51 (1.30)
4	1.41 (0.60)	**26**	1.40 (0.37)	--	--
5	1.40 (0.99)	**32**	1.33 (0.80)	--	--
Desorption process					
Time (min)	**Iron Ion Concentration (mg/L)**	**Time (min)**	**Iron Ion Concentration (mg/L)**	**Time (min)**	**Iron Ion Concentration (mg/L)**
33	7.00 (3.68)	**135**	0.81 (0.17)	**540**	0.51 (0.14)
55	3.96 (1.56)	**255**	0.84 (0.51)	**873**	0.80 (0.59)
90	2.44 (1.89)	**260**	1.17 (0.59)	**--**	--

Likewise, iron effluent concentrations of AGEM-2 during the adsorption process did not exceed the acceptable concentration for human ingestion (Table A.2). During the desorption process iron concentrations were higher than the acceptable concentrations for human ingestion, thus similarly to IFGEM-3, the iron effluent concentrations laid within the concentration at which iron is found in natural water. The concentration of aluminum was not able to be measured due to the interference of NaOH in the collected samples.

Table A.2. Mean (SD) AGEM-2 iron and aluminum concentrations during adsorption and desorption processes.

Adsorption process					
Day	**Iron ion Concentration (mg/L)**	**Aluminum ion Concentration (mg/L)**	**Day**	**Iron ion Concentration (mg/L)**	**Aluminum ion Concentration (mg/L)**
1	1.13 (0.89)	1.11 (0.12)	**22**	1.23 (0.51)	0.40 (0.14)
2	1.81 (0.27)	1.32 (0.05)	**26**	0.97 (1.22)	0.08 (0.05)
3	0.71 (0.50)	0.96 (0.16)	**32**	0.70 (0.36)	0.45 (0.07)
4	0.50 (0.33)	0.45 (0.15)	**38**	0.75 (0.46)	0.09 (0.05)
5	0.60 (0.21)	0.33 (0.21)	**44**	1.34 (1.19)	0.01 (0.00)
8	0.57 (0.35)	0.56 (0.37)	**47**	1.26 (1.52)	0.00 (0.00)
16	1.16 (0.22)	0.11 (0.08)	--	--	--
Desorption process					
Time (min)	**Iron ion Concentration (mg/L)**	**Aluminum ion Concentration (mg/L)**	**Time (min)**	**Iron ion Concentration (mg/L)**	**Aluminum ion Concentration (mg/L)**
90	3.73 (0.24)	--	**621**	6.41 (2.74)	--
165	2.17 (0.54)	--	**960**	34.8 (8.21)	--
255	7.73 (1.12)	--	--	--	--

References

Fraga, C. G., Oteiza, P. I., Golub, M. S., Gershwin, M. E., & Keen, C. L. (1990). Effects of aluminum on brain lipid peroxidation. *Toxicology Letters, 51*(2), 213-219.

Miller, R. G., Kopfler, F. C., Kelty, K. C., Stober, J. A., & Ulmer, N. S. (1984). The occurrence of aluminum in drinking water. *Journal -American Water Works Association, 76*(1), 84-91.

Oketola, A. A., Adekolurejo, S. M., & Osibanjo, O. (2013). Water quality assessment of River Ogun using multivariate statistical techniques. *Journal of Environmental Protection, 4*(05), 466.

US EPA. (2017). *Secondary Drinking Water Standards: Guidance for Nuisance Chemicals*. Law and Regulations: U.S Environmental Protection Agency.

WHO. (1996). *Iron in Drinking-water*. Guidelines for drinking-water quality.: World Health Organization.

WHO. (2010). *Aluminium in Drinking -water*. World Health Organization.

Appendix B: Roadway runoff experimental data

Media characterization

The media used to fill treatment and control test beds were analyzed for particle size distribution and soil type according to AASHTO M 145-91, regardless of considering liquid limit and plasticity index. Dry sieve analysis conducted in triplicate (4.4 pounds (~ 2.0 kg) each sample) suggested that both media were predominantly sand and that BAM and soil had similar distributions (Figure B.1 A). However, the distribution of BAM was slightly finer than that of soils. For instance, around 30% of BAM was finer than 0.25 mm while less than 20% of soil was finer than 0.25 mm. Well over 51% of both BAM and soil passed sieve #40 (i.e. 0.425 mm) and were characterized as A-3 type according to AASHTO classification. Media in this group are characterized by mixtures of poorly-graded fine sands and a low percent of coarse sands and gravel (AASHTO, M., 145-91, 2008) (Table B.1). Media within test beds was compacted to homogenous design specifications for roadsides (80 to 100 lb/ft^3) (Figure B.1 B).

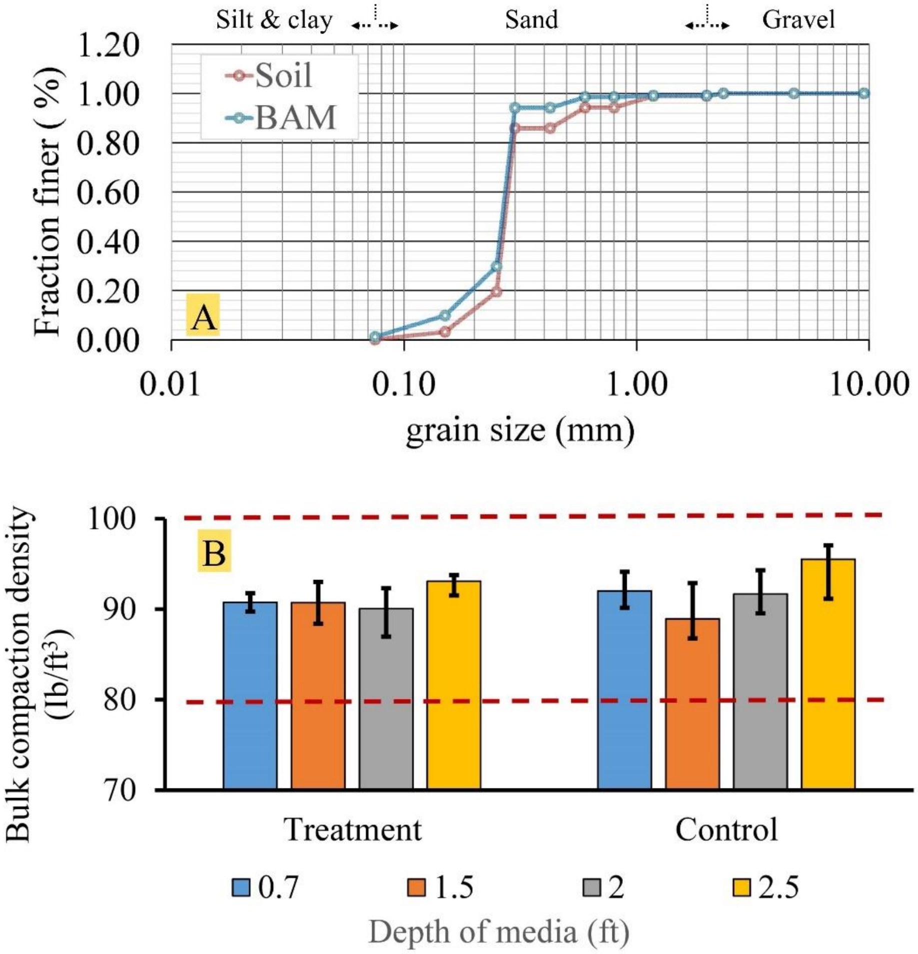


Figure B.1. (a) Particle size distributions of BAM and soil (mean of three replicate 4-kg samples) and (b) mean ± SD measured bulk density compaction treatment and control test beds.

Table B.1. Particle size fractions of BAM and soil. Note: data are mean of three replications.

Size class	BAM	Soil
Gravel	1.07%	0.84%
Sand	98.75%	97.91%
Silt & Clay	0.18%	1.26%

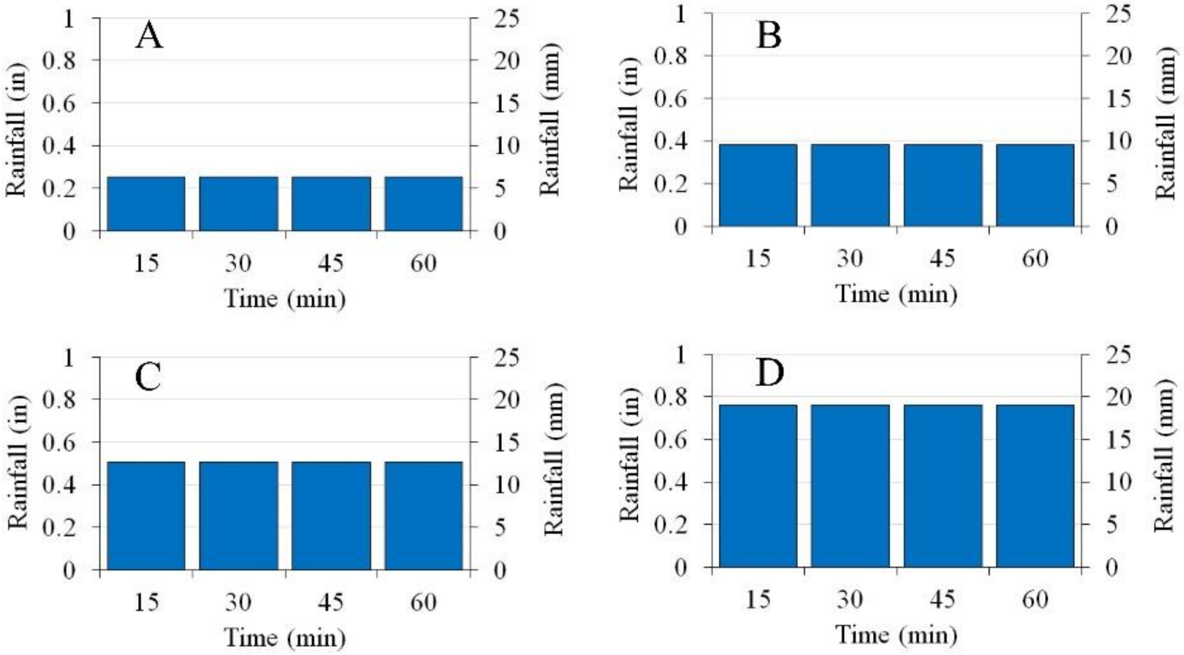


Figure B.2. Design hyetographs of high-intensity hydraulic testing: (a) 1in/h, (b) 1.5 in/h, (c) 2 in/h, and (d) 3 in/h.

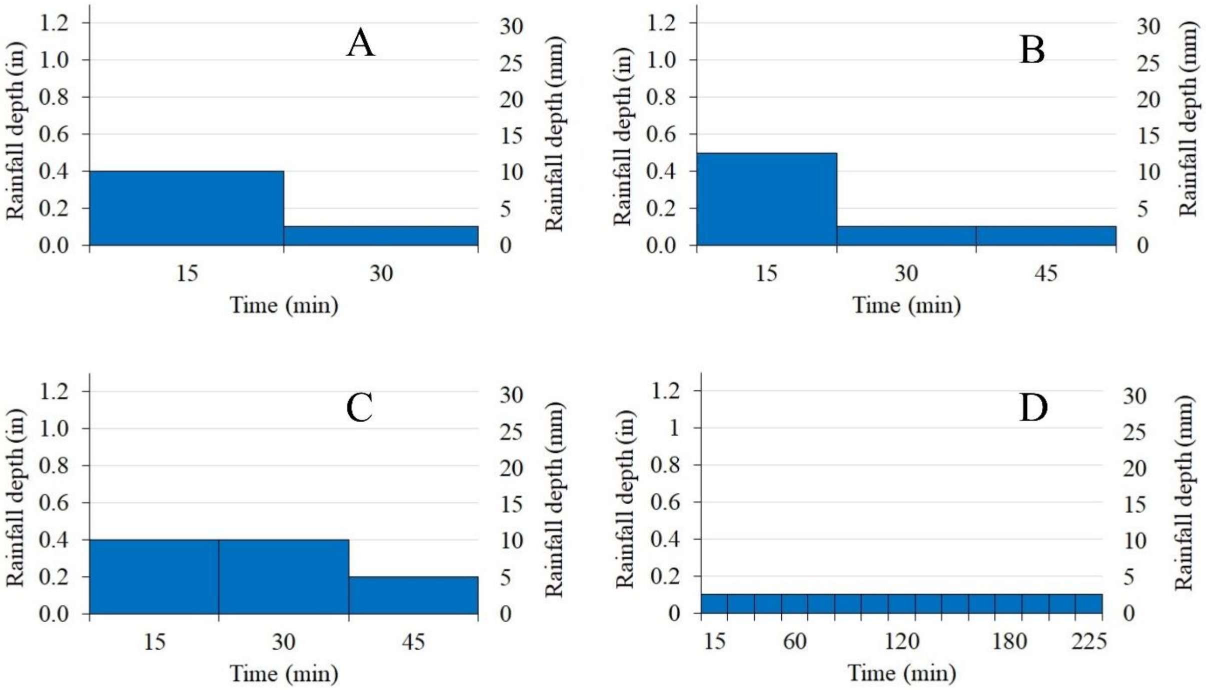


Figure B.3. Design hyetographs of lower-intensity hydraulic testing: (a) 0.5 in, (b) 0.75 in, (c) 1 in, and (d) 1.5 in storm depths.

Table B.2. Arithmetic mean, standard deviation, and percent standard deviation of triplicate background nutrient concentrations measurements in UCF tap water.

	NO_x (µg/l)	TN (µg/l)	TP (µg/l)
Mean	9	74	100
SD	1.5	4.0	1.5
RSD %	16.4	5.5	1.5

Table B.3. Volumes of water and stock solutions to create the target nutrient concentrations in the synthetic roadway runoff of 2-lane and 1-lane roadway runoff experiments.

Roadway type	Storm runoff depth in (mm)	Roadway Runoff volume (L)	Required volume NH_3 (mL)	Required volume NO_x (mL)	Required volume TN (mL)	Required volume TP (mL)
2-lane	0.5 (12.7)	226	24.92	131.39	240.13	47.57
	0.75 (19.5)	317	37.38	197.08	360.19	71.36
	1.0 (25.4)	453	49.84	262.78	480.25	95.14
	1.0 (25.4)	453	49.84	262.78	480.25	95.14
	1.0 (25.4)	453	49.84	262.78	480.25	95.14
	1.5 (38.5)	679	74.76	394.17	720.38	142.72
	3.0 (76.2)	1359	149.51	788.34	1440.76	285.43
1-lane	0.5 (12.7)	113	12.46	65.69	120.06	23.79
	0.75 (19.5)	158.6	18.69	98.54	180.09	35.68
	1.0 (25.4)	226.5	24.92	131.39	240.13	47.57
	1.0 (25.4)	226.5	24.92	131.39	240.13	47.57
	1.0 (25.4)	226.5	24.92	131.39	240.13	47.57
	1.5 (38.5)	339.8	37.38	197.08	360.19	71.36
	3.0 (76.2)	679.6	74.76	394.17	720.38	142.72

Table B.4. Conducted nutrient removal experiments of different storm depths over treatment and control test beds for a 2-lane roadway with the samplings times. Note: long-term sampling is 20 hours after the start of the experiments; time is following the experiment day.

				Influent (runoff)	Effluent (infiltrated water)			
					Sampling locations and times			
Storm depth (in)	Test bed	Date	Experiment start time	Sampling time	2 - 4 (hr)			20 (hr)
					5 ft	10 ft	20 ft	20 ft
0.5	treatment	10/14/19	14:15	14:00	17:15	18:20	18:30	10:40
	control	10/14/19	15:50	15:30	18:50	18:50	19:55	11:55
0.75	treatment	10/21/19	12:40	12:30	16:55	16:50	16:40	20:45
	control	10/21/19	14:10	14:00	16:10	18:15	18:20	10:20
1 (1st run)	treatment	10/28/19	12:23	12:15	16:23	16:23	16:23	20:45
	control	10/28/19	14:07	14:00	17:07	18:07	18:07	10:30
1 (2nd run)	treatment	11/4/19	12:55	12:45	17:10	17:10	17:30	09:10
	control	11/4/19	14:27	14:20	18:45	18:30	18:45	10:45
1 (3rd run)	treatment	11/11/19	14:00	13:55	18:15	18:10	18:30	10:00
	control	11/11/19	12:30	12:25	16:20	16:35	16:35	08:30
1.5	treatment	11/19/19	14:15	14:00	18:20	18:20	18:30	10:15
	control	11/18/19	14:40	13:45	18:45	18:45	18:45	10:45
3	treatment	1/27/20	14:20	14:00	18:40	18:30	18:30	10:30
	control	1/28/20	14:30	14:15	18:30	18:35	18:35	10:40

Table B.5. Conducted nutrient removal experiments of different storm depths over treatment and control test beds for a 1-lane roadway with the samplings times. Note: long-term sampling is 20 hours after the start of the experiments; time is following the experiment day.

				Influent (runoff)	Effluent (infiltrated water)			
					Sampling locations and times			
Storm depth (in)	Test bed	Date	Experiment start time	Sampling time	2 - 4 (hr)			20 (hr)
					5 ft	10 ft	20 ft	20 ft
0.5	treatment	2/10/20	14:15	14:00	N/A	N/A	18:20	11:40
	control	2/10/20	15:20	15:20	N/A	N/A	17:30	11:55
0.75	treatment	2/3/20	13:50	13:45	18:40	18:45	18:20	10:30
	control	2/3/20	15:05	14:45	18:55	19:40	18:40	11:45
1 (1st run)	treatment	11/25/19	12:52	12:40	17:10	17:10	18:00	8:50
	control	11/25/19	14:15	14:00	18:50	18:30	18:30	10:20
1 (2nd run)	treatment	12/16/19	12:55	12:45	17:45	17:10	17:10	08:55
	control	12/16/19	14:30	14:15	18:30	18:30	18:30	10:30
1 (3rd run)	treatment	1/6/20	14:25	14:15	18:45	18:35	18:45	10:40
	control	1/6/20	15:45	15:40	20:30	20:20	20:05	11:50
1.5	treatment	1/13/20	14:15	14:00	18:30	18:30	18:35	10:00
	control	1/14/20	13:27	13:15	17:30	17:55	17:45	09:30
3	treatment	1/21/20	14:00	13:45	18:35	18:08	18:15	10:40
	control	1/21/20	16:20	16:15	15:45	20:25	20:20	12:30

Table B.6. Mean concentrations and percent nutrient removal of collected samples over 0.5 in storm depth, 2-lane roadway. Note: percent removal is calculated based on concentration of influent water. NH_3 is not reported in this experiment.

		Mean Concentration (µg/l)				SD				% removal			
		NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP
treatment test bed	Roadway runoff	532	-	1,889	294	42	-	10	11	-	-	-	-
	Infiltrated- 5 ft (4 hr)	1,289	-	1,849	46	9	-	11	2	-142	-	2	84
	Infiltrated - 10 ft (4 hr)	1,130	-	1,631	39	6	-	5	1	-113	-	14	87
	Infiltrated - 20 ft (4 hr)	9	-	544	46	5	-	5	3	98	-	71	84
	Infiltrated - 20 ft (20 hr)	10	-	649	54	4	-	16	2	98	-	66	82
control test bed	Roadway runoff	552	-	1,931	302	4	-	30	7	-	-	-	-
	Infiltrated- 5 ft (4 hr)	1,299	-	1,794	38	16	-	20	3	-135	-	7	87
	Infiltrated - 10 ft (4 hr)	2,190	-	3,406	48	82	-	69	2	-297	-	-76	84
	Infiltrated - 20 ft (4 hr)	381	-	1,118	81	20	-	16	5	31	-	42	73
	Infiltrated - 20 ft (20 hr)	397	-	1,162	72	13	-	18	1	28	-	40	76

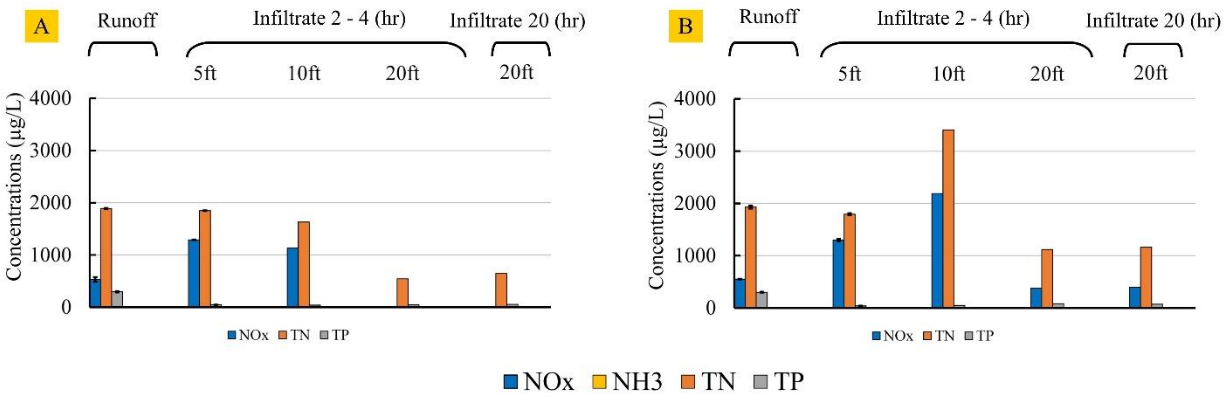


Figure B.4. Arithmetic mean of nutrient concentrations in simulated roadway runoff (influent) and infiltrated water at sampling locations of 5, 10 and 20 ft along the (a) treatment and (b) control test beds over 0.5 in storm depth for 2-lane roadway. The error bars are standard deviation across all events. Note: NH_3 was not analyzed in this experiment.

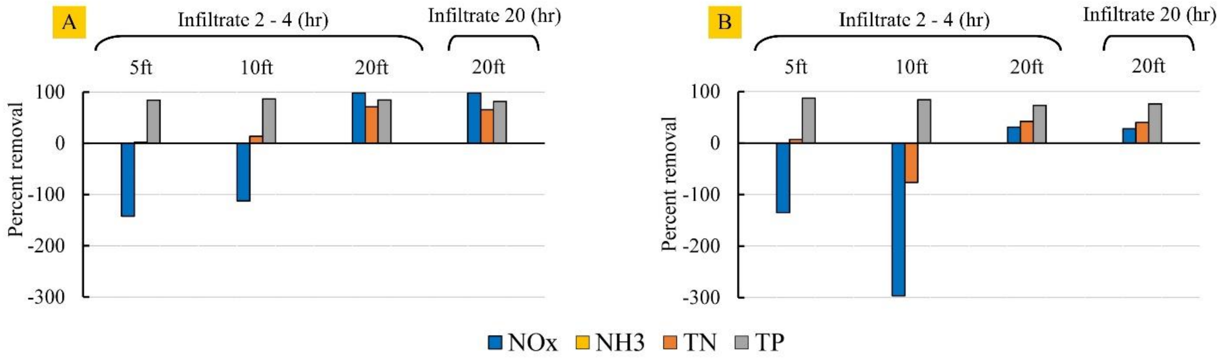


Figure B.5. Arithmetic mean of percent nutrient removal with respect to inflow nutrient load at sampling locations of 5, 10 and 20 ft along the (a) treatment and (b) control test beds over 0.5 in storm depth for 2-lane roadways. The error bars are standard deviation across all events. Note: NH_3 was not analyzed in this experiment.

Table B.7. Mean concentrations and percent nutrient removal of collected samples over 0.75 in storm depth, 2-lane roadway. Note: percent removal is calculated based on concentration of influent water.

		Mean Concentration (µg/l)				SD				% removal			
		NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP
treatment test bed	Roadway runoff	546	848	1,864	289	6	36	37	2	-	-	-	-
	Infiltrated- 5 ft (4 hr)	962	5	1,464	21	5	0	36	2	-76	99	21	93
	Infiltrated - 10 ft (4 hr)	202	5	534	22	6	0	27	2	63	99	71	92
	Infiltrated - 20 ft (4 hr)	6	5	471	46	4	0	20	8	99	99	75	84
	Infiltrated - 20 ft (20 hr)	3	5	507	41	1	0	17	2	100	99	73	86
control test bed	Roadway runoff	547	888	2,023	313	3	51	245	37	-	-	-	-
	Infiltrated- 5 ft (4 hr)	1,021	5	1,716	38	5	0	19	2	-87	99	15	88
	Infiltrated - 10 ft (4 hr)	4,816	5	7,283	62	26	0	97	3	-780	99	-260	80
	Infiltrated - 20 ft (4 hr)	403	21	1,143	70	46	2	14	3	26	98	43	78
	Infiltrated - 20 ft (20 hr)	390	11	1,169	65	2	2	6	1	29	99	42	79

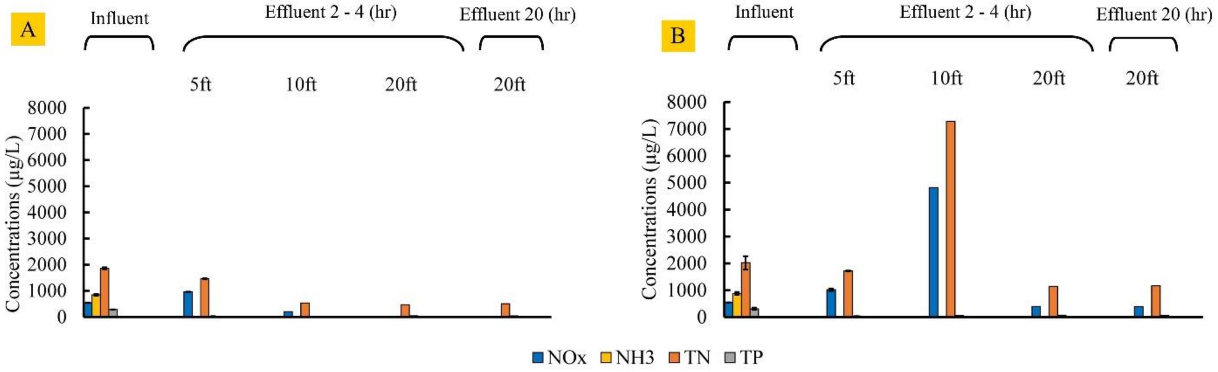


Figure B.6. Arithmetic mean of nutrient concentrations in simulated roadway runoff (influent) and infiltrated water at sampling locations of 5, 10 and 20 ft along the (a) treatment and (b) control test beds over 0.75 in storm depth for 2-lane roadways. The error bars are standard deviation across all events.

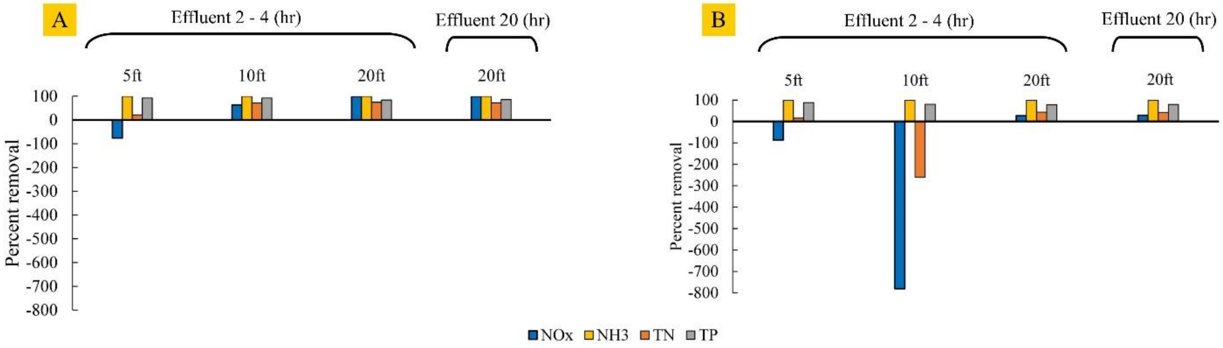


Figure B.7. Arithmetic mean of percent nutrient removal with respect to inflow nutrient load at different sampling locations along the (a) treatment and (b) control test beds over 0.75 in storm depth for 2-lane roadways. The error bars are standard deviation across all events.

Table B.8. Mean concentrations and percent nutrient removal of the collected samples over 1 in storm depth in three distinct experimental runs of 2-lane roadway. Note: percent removal is calculated based on concentration of influent nutrient of the experiment.

			Mean Concentration (µg/l)				SD				% removal			
			NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP
1st run	treatment test bed	Roadway runoff	590	106	1,791	310	5	6	30	12	-	-	-	-
		Infiltrated- 5 ft (4 hr)	4,120	27	4,635	123	64	4	110	13	-598	74	-159	60
		Infiltrated - 10 ft (4 hr)	707	11	1,164	390	7	5	166	22	-20	90	35	-26
		Infiltrated - 20 ft (4 hr)	25	11	428	257	12	10	65	34	96	90	76	17
		Infiltrated - 20 ft (20 hr)	23	11	482	277	10	9	53	16	96	89	73	11
	control test bed	Roadway runoff	595	115	1,850	529	2	22	47	263	-	-	-	-
		Infiltrated- 5 ft (4 hr)	2,136	5	2,522	264	19	0	57	14	-259	96	-36	50
		Infiltrated - 10 ft (4hr)	3,003	5	3,464	289	26	0	54	14	-404	96	-87	45
		Infiltrated - 20 ft (4 hr)	1,044	13	1,474	62	33	7	65	18	-75	89	20	88
		Infiltrated - 20 ft (20 hr)	1,383	7	1,806	43	3	3	43	5	-132	94	2	92

Table B.8 (continued). Mean concentrations and percent nutrient removal of the collected samples over 1 in storm depth in three distinct experimental runs of 2-lane roadway. Note: percent removal is calculated based on concentration of influent nutrient of the experiment.

			Mean Concentration (µg/l)				SD				%removal			
			NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP
2nd run	treatment test bed	Roadway runoff	641	128	1,240	365	25	16	39	26	-	-	-	-
		Infiltrated- 5 ft (4 hr)	6,739	18	6,556	99	45	2	11	11	-951	86	-429	73
		Infiltrated - 10 ft (4 hr)	789	13	904	93	56	1	4	1	-23	90	27	75
		Infiltrated - 20 ft (4 hr)	38	15	282	42	7	2	2	5	94	89	77	88
		Infiltrated - 20 ft (20 hr)	23	37	342	65	2	4	9	19	96	71	72	82
	control test bed	Roadway runoff	633	114	1,602	354	2	5	304	3	-	-	-	-
		Infiltrated- 5 ft (4 hr)	4,379	19	4,321	142	51	6	62	16	-591	83	-170	60
		Infiltrated - 10 ft (4 hr)	2,276	7	2,338	89	53	1	42	7	-259	94	-46	75
		Infiltrated - 20 ft (4 hr)	1,046	23	1,369	75	33	1	12	19	-65	80	15	79
		Infiltrated - 20 ft (20 hr)	1,769	17	1,932	154	9	0	31	19	-179	85	-21	57

Table B.8 (continued). Mean concentrations and percent nutrient removal of the collected samples over 1 in storm depth in three distinct experimental runs of 2-lane roadway. Note: percent removal is calculated based on concentration of influent nutrient of the experiment.

			Mean Concentration (µg/l)				SD				%removal			
			NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP
3rd run	treatment test bed	Roadway runoff	576	62	1,692	305	4	3	20	19	-	-	-	-
		Infiltrated- 5 ft (4 hr)	1,025	3	1,500	53	3	1	9	5	-78	96	11	83
		Infiltrated - 10 ft (4 hr)	601	3	765	38	3	0	6	2	-4	95	55	87
		Infiltrated - 20 ft (4 hr)	44	3	316	50	7	0	5	1	92	95	81	84
		Infiltrated - 20 ft (20 hr)	2	3	282	49	1	0	8	6	100	95	83	84
	control test bed	Roadway runoff	567	48	1,490	320	16	9	31	59	-	-	-	-
		Infiltrated- 5 ft (4 hr)	1,853	3	1,969	47	23	0	7	3	-227	94	-32	85
		Infiltrated - 10 ft (4 hr)	2,163	3	2,264	56	21	0	20	1	-281	94	-52	83
		Infiltrated - 20 ft (4 hr)	1,164	3	1,437	72	4	0	39	14	-105	94	4	78
		Infiltrated - 20 ft (20 hr)	1,358	3	1,601	53	6	0	25	3	-139	94	-7	83

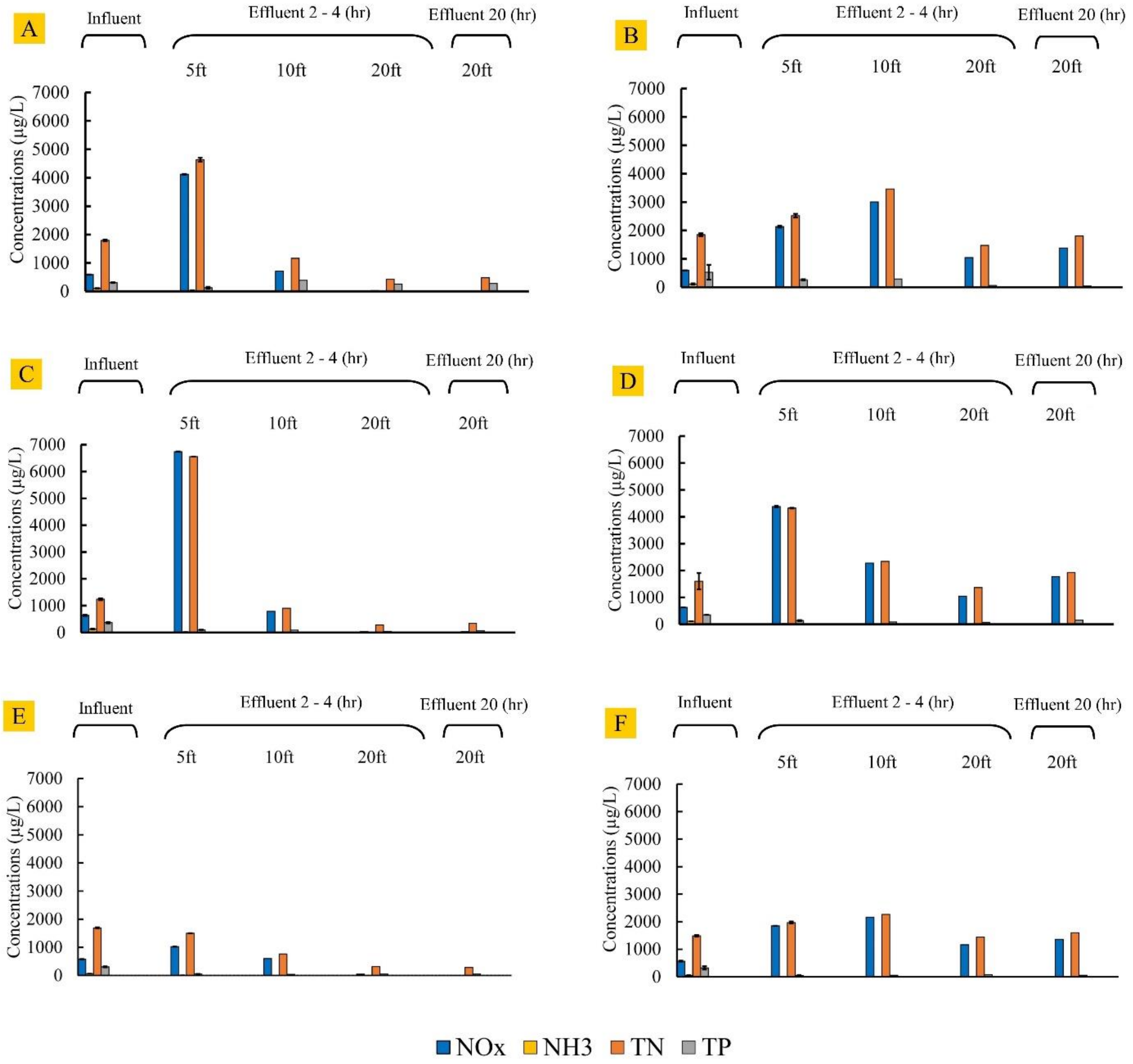


Figure B.8. Arithmetic mean nutrient concentrations in simulated roadway runoff (influent) and infiltrated water 5, 10 and 20 ft along the (a, c, e) treatment and (b, d, f) control test beds, respectively, over 3 replicates of 1 in storm depth on 2-lane roadway.

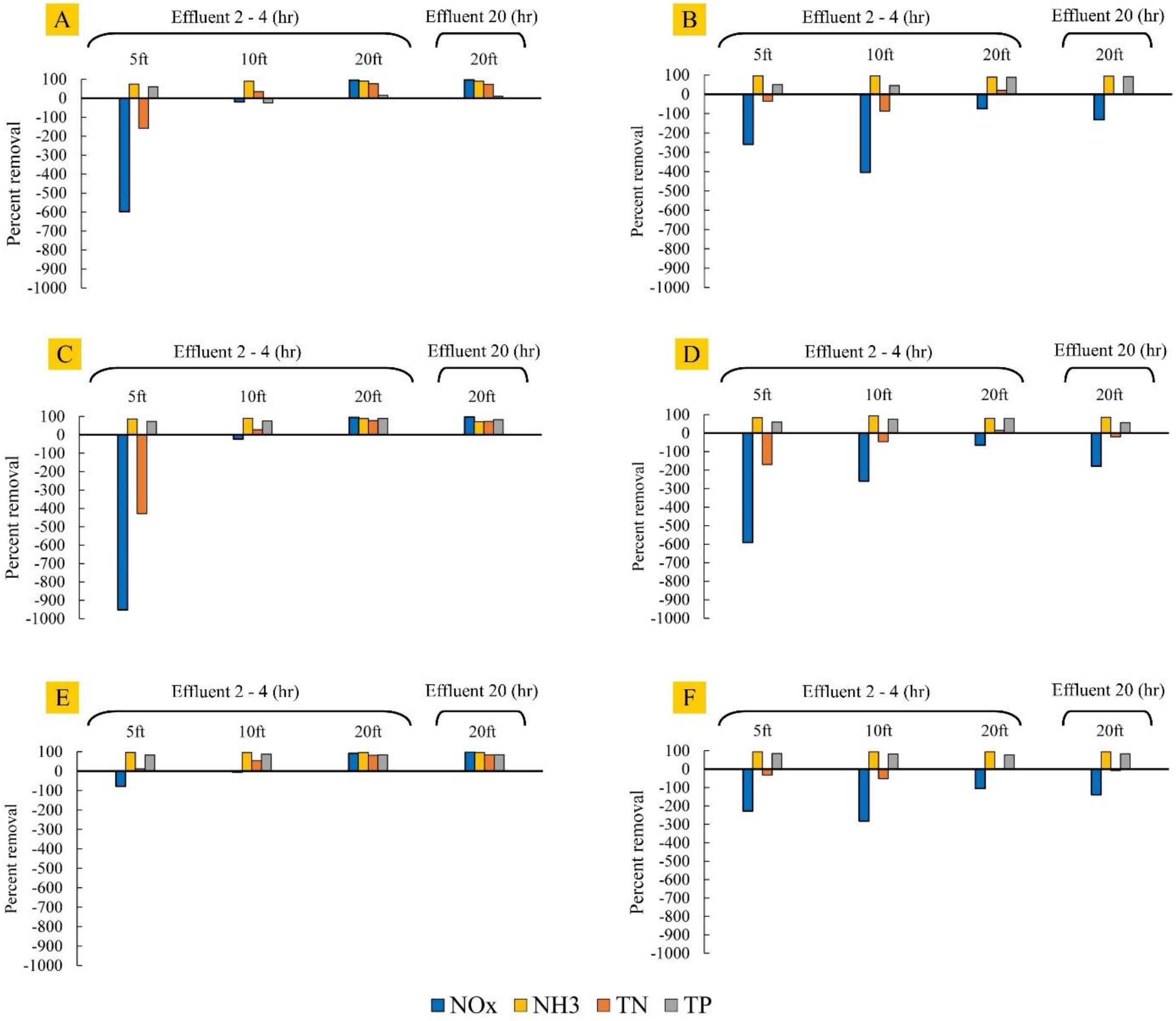


Figure B.9. Arithmetic mean percent nutrient removal in simulated roadway runoff (influent) and infiltrated water 5, 10 and 20 ft along the (a, c, e) treatment and (b, d, f) control test beds, respectively, over 3 replicates of 1 in storm depth on 2-lane roadway.

Table B.9. Mean concentrations and percent nutrient removal of collected samples over 1.5 in storm depth, 2-lane roadway. Note: percent removal is calculated based on concentration of influent water.

		Mean Concentration (µg/l)				SD				% removal			
		NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP
treatment test bed	Roadway runoff	573	62	1,768	312	5	1	43	46	0	0	0	0
	Infiltrated-5 ft (4 hr)	1,345	2	1,569	73	12	0	14	3	-135	97	11	77
	Infiltrated - 10 ft (4 hr)	1,831	2	2,008	72	6	0	14	2	-220	97	-14	77
	Infiltrated - 20 ft (4 hr)	2	2	277	95	0	0	3	2	100	97	84	70
	Infiltrated - 20 ft (20 hr)	31	2	274	81	1	0	10	6	95	97	84	74
control test bed	Roadway runoff	582	51	1,739	261	7	5	25	26	0	0	0	0
	Infiltrated-5 ft (4 hr)	1,068	2	1,516	56	11	0	46	3	-84	96	13	79
	Infiltrated - 10 ft (4 hr)	1,412	2	1,486	76	18	0	20	14	-143	96	15	71
	Infiltrated - 20 ft (4 hr)	1,652	2	1,917	66	10	0	21	12	-184	96	-10	75
	Infiltrated - 20 ft (20 hr)	1,404	2	1,741	4	11	0	76	2	-141	96	0	98

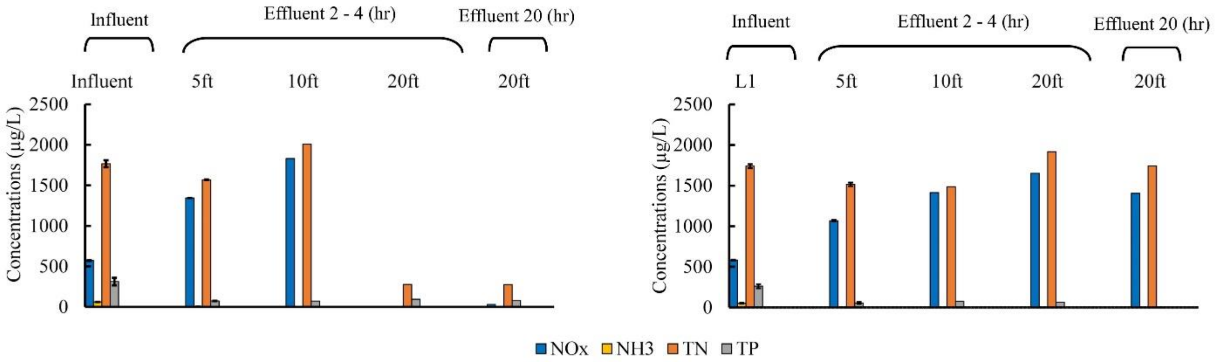


Figure B.10. Arithmetic mean of nutrient concentrations in simulated roadway runoff (influent) and infiltrated water at different sampling locations of 5, 10 and 20 ft along the (a) treatment test bed and (b) control test bed over 1.5 in storm depth for 2-lane roadway. The error bars are standard deviation across all events.

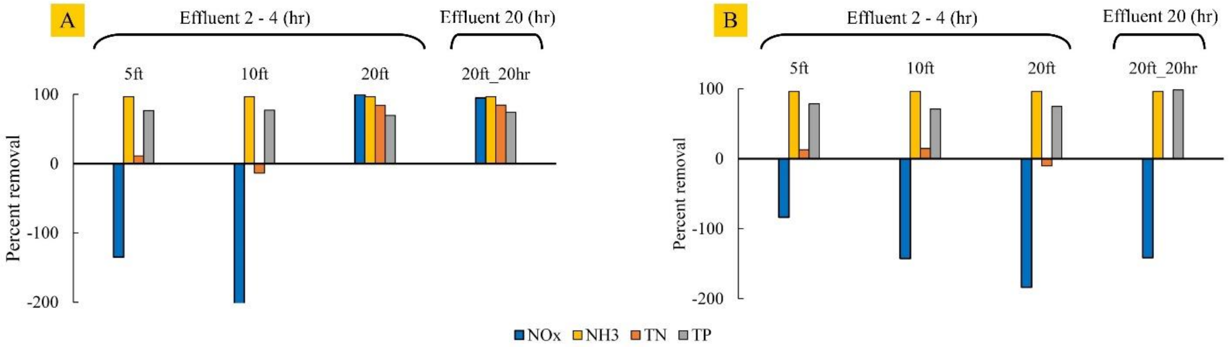


Figure B.11. Arithmetic mean of percent nutrient removal with respect to inflow nutrient load at different sampling locations along the (a) treatment test bed and (b) control test bed over 1.5 in storm depth for 2-lane roadway. The error bars are standard deviation across all events.

Table B.10. Mean concentrations and percent nutrient removal of collected samples over 1.5 in storm depth, 2-lane roadway. Note: percent removal is calculated based on concentration of influent water.

		Mean Concentration (µg/l)				SD				% removal			
		NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP
treatment test bed	Roadway runoff	571	87	1,733	282	1	1	16	2	0	0	0	0
	Infiltrated-5 ft (4 hr)	2,541	0	2,711	27	38	0	24	1	-345	100	-56	91
	Infiltrated - 10 ft (4 hr)	197	0	368	30	3	0	7	1	66	100	79	89
	Infiltrated - 20 ft (4 hr)	118	15	319	54	1	1	6	3	79	83	82	81
	Infiltrated - 20 ft (20 hr)	48	4	251	39	11	0	13	29	92	95	85	86
control test bed	Roadway runoff	567	94	1,755	285	9	2	46	12	0	0	0	0
	Infiltrated-5 ft (4 hr)	2,130	0	2,257	33	19	0	9	1	-276	100	-29	88
	Infiltrated - 10 ft (4 hr)	741	0	928	48	4	0	18	1	-31	100	47	83
	Infiltrated - 20 ft (4 hr)	580	0	822	44	2	0	36	1	-2	100	53	85
	Infiltrated - 20 ft (20 hr)	547	0	761	42	2	0	12	1	4	100	57	85

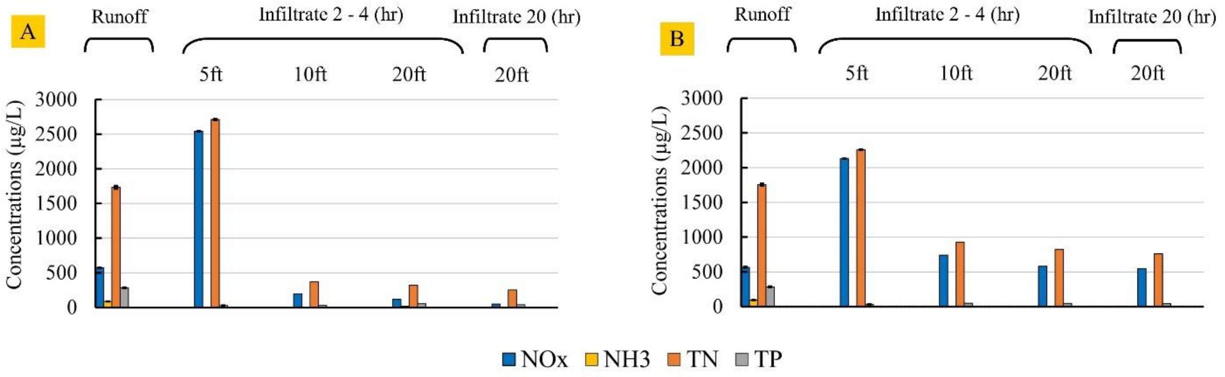


Figure B.12. Arithmetic mean of nutrient concentrations in simulated roadway runoff (influent) and infiltrated water at different sampling locations of 5, 10 and 20 ft along the (a) treatment test bed and (b) control test bed over 3 in storm depth for 2-lane roadway. The error bars are standard deviation across all events.

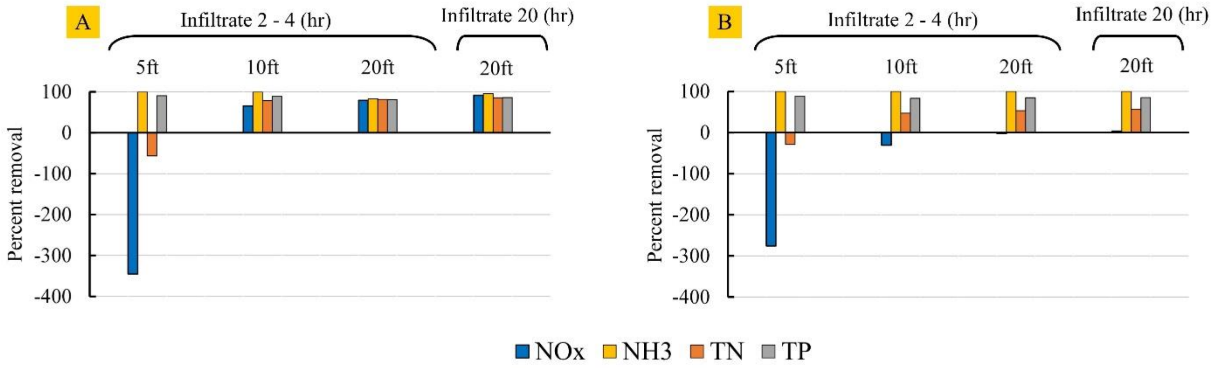


Figure B.13. Arithmetic mean of percent nutrient removal with respect to inflow nutrient load at different sampling locations along the (a) treatment test bed and (b) control test bed over 3 in storm depth for 2-lane roadway. The error bars are standard deviation across all events.

Table B.11. Mean concentrations and percent nutrient removal of collected samples over 0.5 in storm depth, 1-lane roadway. Note: percent removal is calculated based on concentration of influent water.

		Mean Concentration (µg/l)				SD				% removal			
		NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP
treatment test bed	Roadway runoff	550	72	1,730	275	4	1	57	7	0	0	0	0
	Infiltrated- 5 ft (4 hr)	-	-	-	-	-	-	-	-	-	-	-	-
	Infiltrated -10 ft (4 hr)	-	-	-	-	-	-	-	-	-	-	-	-
	Infiltrated -20 ft (4 hr)	9	2	484	48	2	0	82	2	98	97	72	82
	Infiltrated -20 ft (20 hr)	13	116	322	48	1	118	16	7	98	-61	81	83
control test bed	Roadway runoff	546	76	1,691	287	14	8	63	9	0	0	0	0
	Infiltrated- 5 ft (4 hr)	-	-	-	-	-	-	-	-	-	-	-	-
	Infiltrated -10 ft (4 hr)	-	-	-	-	-	-	-	-	-	-	-	-
	Infiltrated -20 ft (4 hr)	316	2	583	47	3	0	5	2	42	97	66	84
	Infiltrated -20 ft (20 hr)	369	2	726	63	4	0	17	1	32	97	57	78

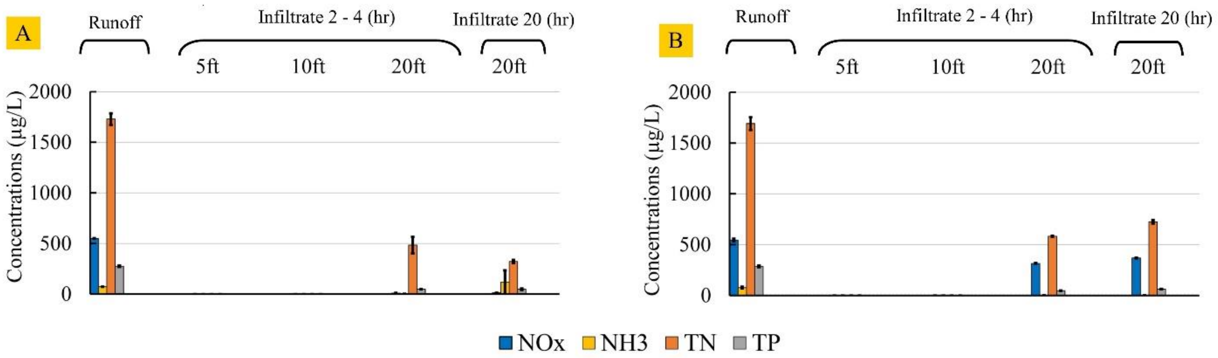


Figure B.14. Arithmetic mean of nutrient concentrations in simulated roadway runoff (influent) and infiltrated water at different sampling locations of 5, 10 and 20 ft along the (a) treatment test bed and (b) control test bed over 0.5 in storm depth for 1-lane roadway. The error bars are standard deviation across all events.

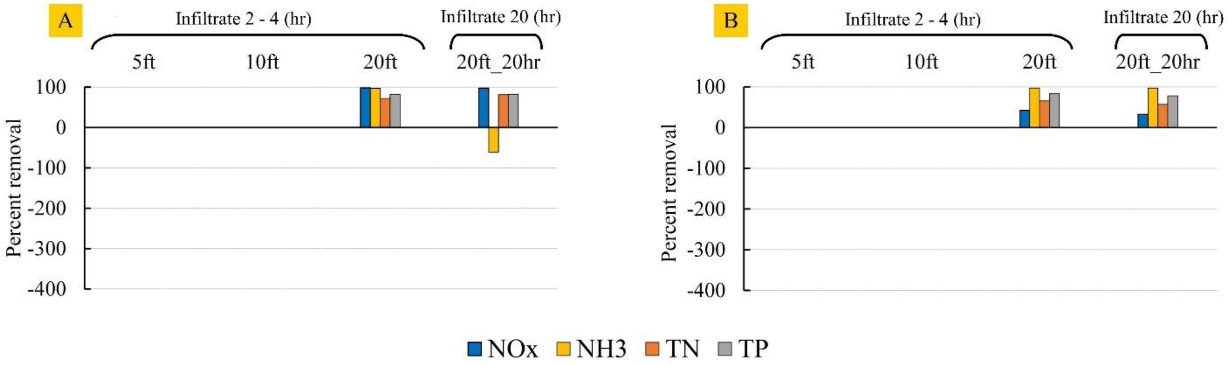


Figure B.15. Arithmetic mean of percent nutrient removal with respect to inflow nutrient load at different sampling locations along the (a) treatment test bed and (b) control test bed over 0.5 in storm depth for 1-lane roadway. The error bars are standard deviation across all events.

Table B.12. Mean concentrations and percent nutrient removal of collected samples over 0.5 in storm depth, 1-lane roadway. Note: percent removal is calculated based on concentration of influent water.

		Mean Concentration (μg/l)				SD				% removal			
		NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP
treatment test bed	Roadway runoff	566	80	1,828	260	6	1	42	4	0	0	0	0
	Infiltrated- 5 ft (4 hr)	91	2	251	35	3	0	13	2	84	98	86	87
	Infiltrated -10 ft (4 hr)	70	2	223	26	2	0	1	0	88	98	88	90
	Infiltrated -20 ft (4 hr)	17	2	220	44	1	0	4	1	97	98	88	83
	Infiltrated -20 ft (20 hr)	26	2	220	38	2	0	11	1	95	98	88	86
control test bed	Roadway runoff	590	84	1,891	269	13	4	34	2	0	0	0	0
	Infiltrated- 5 ft (4 hr)	1,476	2	1,670	33	9	0	5	1	-150	98	12	88
	Infiltrated -10 ft (4 hr)	1,026	2	1,244	33	3	0	26	1	-74	98	34	88
	Infiltrated -20 ft (4 hr)	453	2	736	43	6	0	12	2	23	98	61	84
	Infiltrated -20 ft (20 hr)	696	2	982	38	3	0	22	1	-18	98	48	86

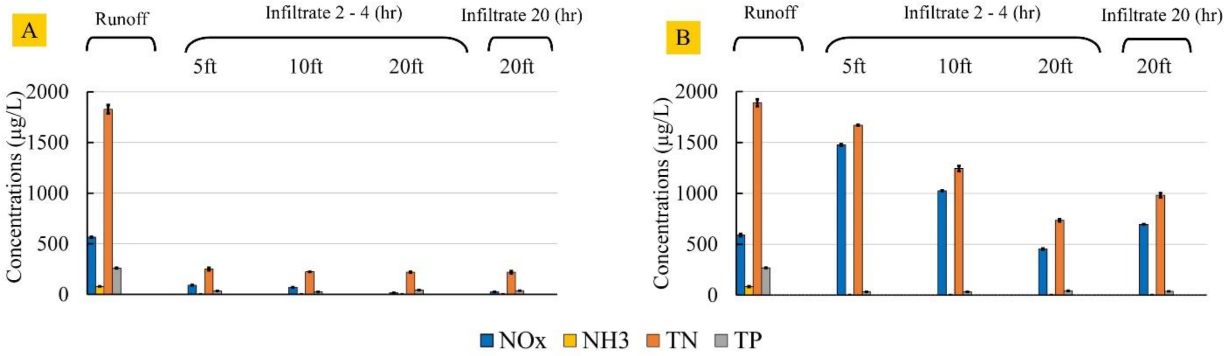


Figure B.16. Arithmetic mean of nutrient concentrations in simulated roadway runoff (influent) and infiltrated water at different sampling locations of 5, 10 and 20 ft along the (a) treatment test bed and (b) control test bed over 0.75 in storm depth for 1-lane roadway. The error bars are standard deviation across all events.

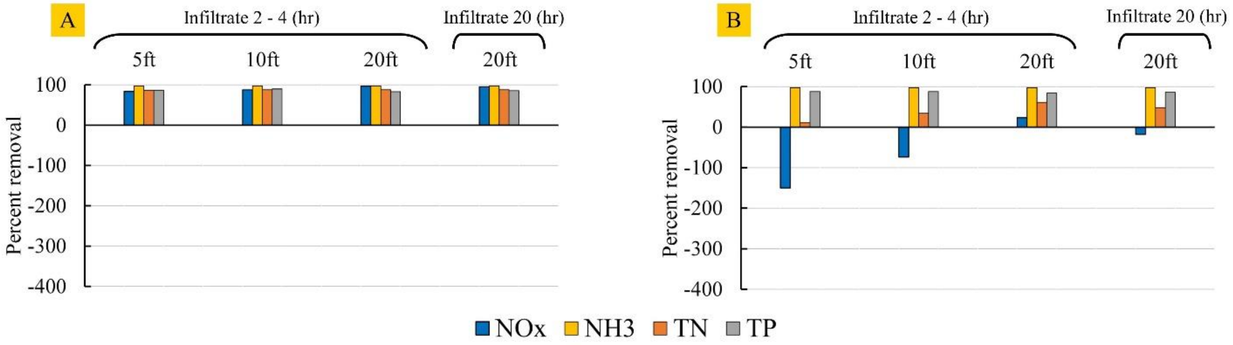


Figure B.17. Arithmetic mean of percent nutrient removal with respect to inflow nutrient load at different sampling locations along the (a) treatment test bed and (b) control test bed over 0.75 in storm depth for 1-lane roadway. The error bars are standard deviation across all events.

Table B.13. Mean concentrations and percent nutrient removal of the collected samples over 1 in storm depth in three distinct experimental runs of 1-lane roadway. Note: percent removal is calculated based on concentration of influent nutrient of the experiment.

			Mean Concentration (µg/l)				SD				% removal			
			NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP
1st run	treatment test bed	Roadway runoff	544	90	1,714	321	4	5	22	27	-	-	-	-
		Infiltrated-5 ft (4 hr)	327	2	494	51	1	0	16	7	40	98	71	84
		Infiltrated - 10 ft (4 hr)	104	2	258	86	4	0	11	51	81	98	85	73
		Infiltrated - 20 ft (4 hr)	2	4	240	76	0	2	14	19	100	96	86	76
		Infiltrated - 20 ft (20 hr)	2	2	215	53	0	0	2	25	100	98	87	83
	control test bed	Roadway runoff	540	98	1,708	302	7	10	38	45	-	-	-	-
		Infiltrated-5 ft (4 hr)	886	2	1,057	42	8	0	2	37	-64	98	38	86
		Infiltrated - 10 ft (4 hr)	1,053	2	1,221	83	20	0	29	6	-95	98	28	73
		Infiltrated - 20 ft (4 hr)	848	2	1,187	36	16	0	38	51	-57	98	31	88
		Infiltrated - 20 ft (20 hr)	1,133	2	1,434	67	23	0	16	31	-110	98	16	78

Table B.13 (continued). Mean concentrations and percent nutrient removal of the collected samples over 1 in storm depth in three distinct experimental runs of 1-lane roadway. Note: percent removal is calculated based on concentration of influent nutrient of the experiment.

			Mean Concentration (µg/l)				SD				% removal			
			NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP
2nd run	treatment test bed	Roadway runoff	522	133	1,763	292	2	5	10	3	0	0	0	0
		Infiltrated-5 ft (4 hr)	738	2	1,016	16	1	0	12	1	-41	98	42	94
		Infiltrated - 10 ft (4 hr)	326	2	592	17	16	0	7	3	38	98	66	94
		Infiltrated - 20 ft (4 hr)	2	13	315	46	0	2	1	3	100	90	82	84
		Infiltrated - 20 ft (20 hr)	2	2	281	12	0	0	13	1	100	98	84	96
	control test bed	Roadway runoff	514	91	1,758	304	3	4	44	14	0	0	0	0
		Infiltrated-5 ft (4 hr)	870	2	1,102	22	6	0	12	1	-69	98	37	93
		Infiltrated - 10 ft (4 hr)	1,435	2	1,773	23	9	0	27	3	-179	98	-1	93
		Infiltrated - 20 ft (4 hr)	549	2	976	23	1	0	11	6	-7	98	44	93
		Infiltrated - 20 ft (20 hr)	735	2	1,128	35	4	0	20	3	-43	98	36	88

Table B.13 (continued). Mean concentrations and percent nutrient removal of the collected samples over 1 in storm depth in three distinct experimental runs of 1-lane roadway. Note: percent removal is calculated based on concentration of influent nutrient of the experiment.

			Mean Concentration (µg/l)				SD				% removal			
			NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP
3rd run	treatment test bed	Roadway runoff	559	64	1,554	291	3	1	22	5	0	0	0	0
		Infiltrated- 5 ft (4 hr)	1,077	2	1,240	32	8	0	10	2	-93	97	20	89
		Infiltrated - 10 ft (4 hr)	326	2	480	31	1	0	7	1	42	97	69	89
		Infiltrated - 20 ft (4 hr)	34	2	256	44	2	0	8	3	94	97	84	85
		Infiltrated - 20 ft (20 hr)	34	2	239	37	2	0	0	1	94	97	85	87
	control test bed	Roadway runoff	555	64	1,510	279	6	1	16	8	0	0	0	0
		Infiltrated- 5 ft (4 hr)	605	2	774	38	2	0	20	1	-9	97	49	86
		Infiltrated - 10 ft (4 hr)	1,307	2	1,507	43	8	0	12	2	-135	97	0	84
		Infiltrated - 20 ft (4 hr)	611	2	906	45	2	0	4	1	-10	97	40	84
		Infiltrated - 20 ft (20 hr)	665	2	978	46	3	0	5	2	-20	97	35	84

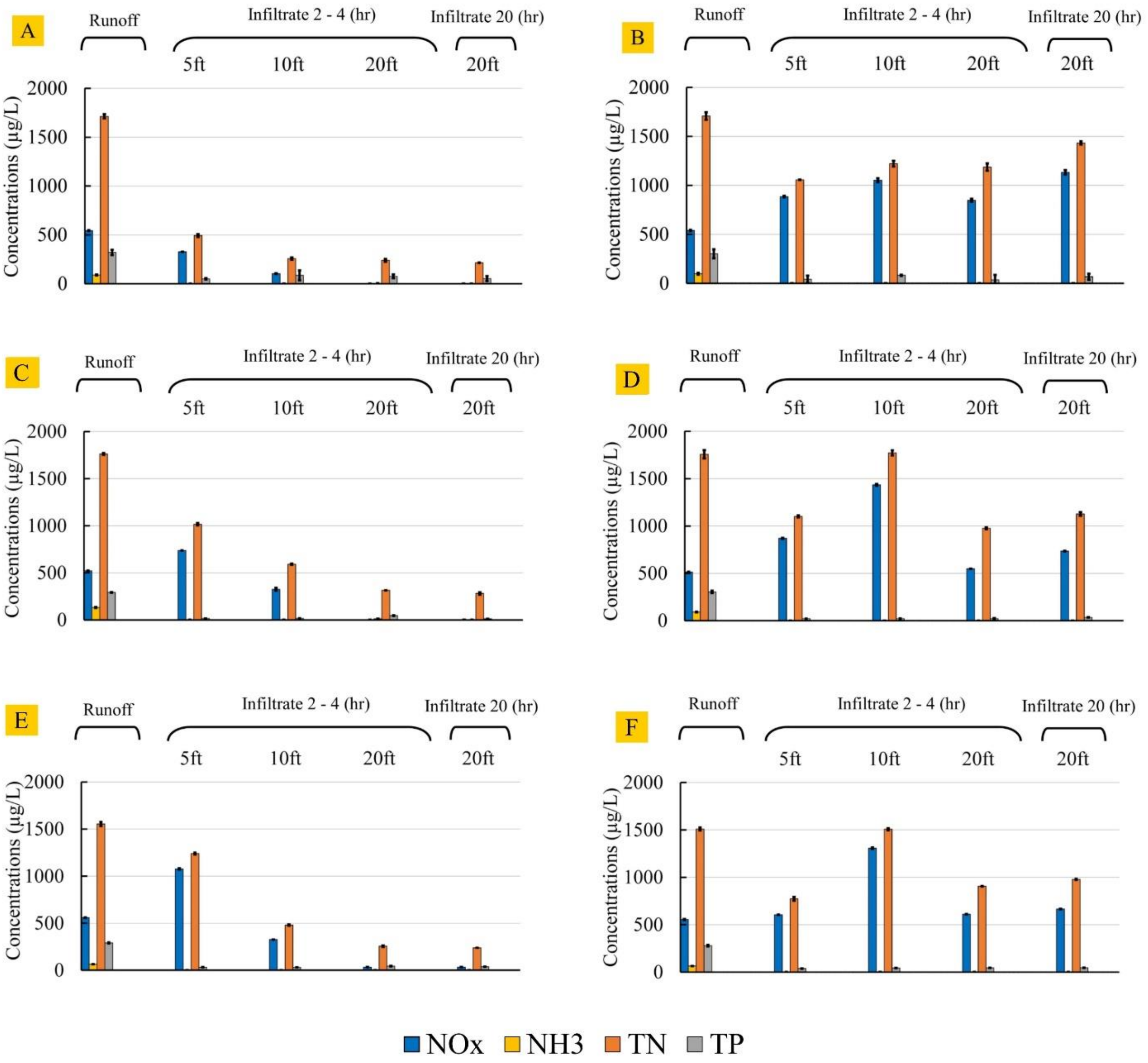


Figure B.18. Arithmetic mean nutrient concentrations in simulated roadway runoff (influent) and infiltrated water 5, 10 and 20 ft along the (a, c, e) treatment and (b, d, f) control test beds, respectively, over 3 replicates of 1 in storm depth on 1-lane roadway.

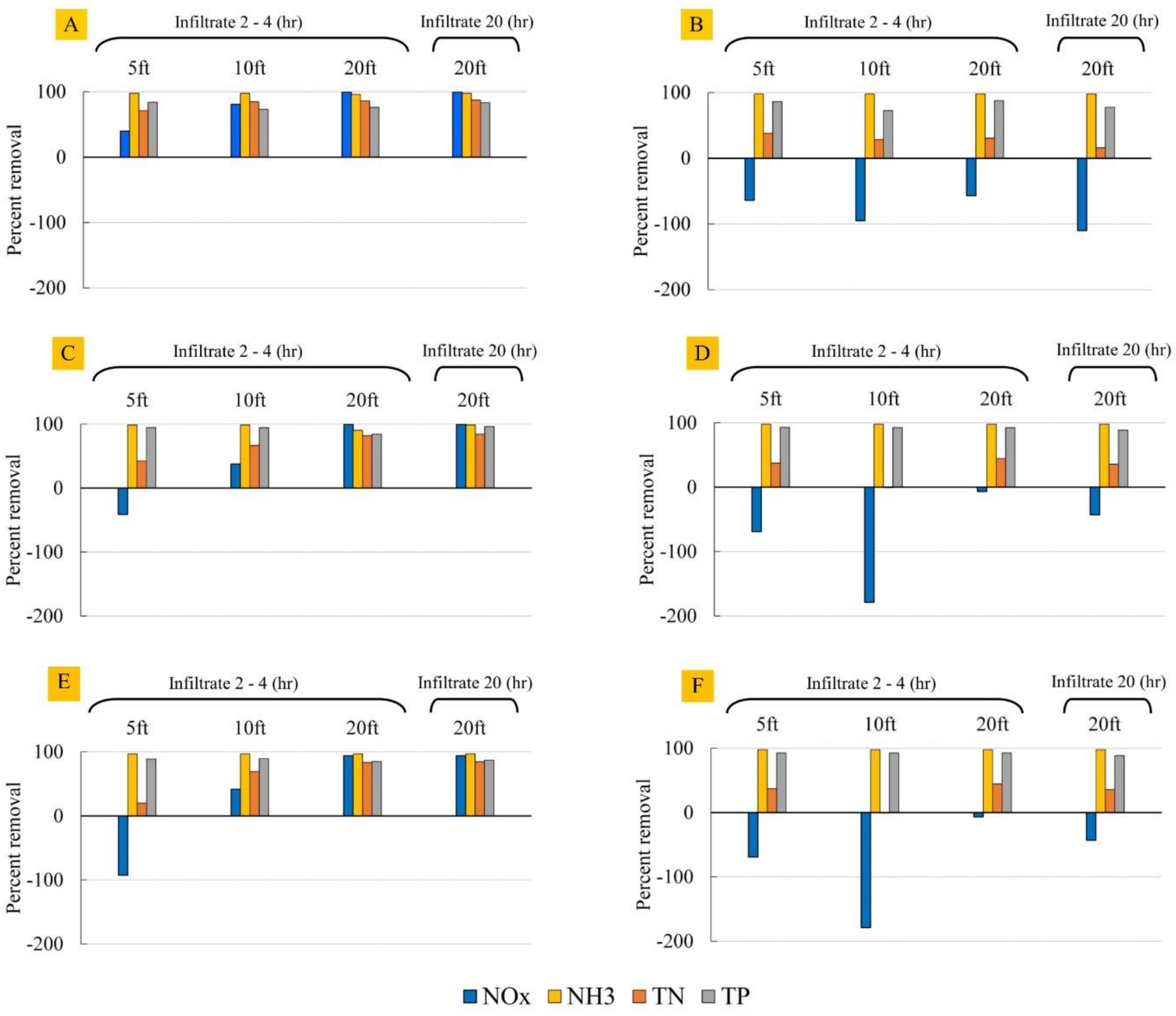


Figure B.19. Mean percent nutrient removal at 5, 10 and 20 ft along the (a, c, e) treatment and (b, d, f) control test beds, respectively, over 3 replicates of 1 in storm depth on 1-lane roadway.

Table B.14. Mean concentrations and percent nutrient removal of collected samples over 1.5 in storm depth, 1-lane roadway. Note: percent removal is calculated based on concentration of influent water.

		Mean Concentration (µg/l)				SD				% removal			
		NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP
treatment test bed	Roadway runoff	558	80	1,819	276	21	1	14	9	-	-	-	-
	Infiltrated- 5 ft (4 hr)	1,744	11	1,862	30	45	1	24	2	-212	86	-2	89
	Infiltrated - 10 ft (4 hr)	2,384	6	2,518	33	41	3	60	4	-327	93	-38	88
	Infiltrated - 20 ft (4 hr)	72	40	297	48	14	0	3	3	87	50	84	82
	Infiltrated - 20 ft (20 hr)	29	15	255	39	3	1	1	1	95	81	86	86
control test bed	Roadway runoff	586	77	1,802	278	5	2	21	7	-	-	-	-
	Infiltrated- 5 ft (4 hr)	1,120	2	1,303	40	47	0	15	2	-91	97	28	86
	Infiltrated - 10 ft (4 hr)	1,672	2	1,779	44	25	0	35	1	-186	97	1	84
	Infiltrated - 20 ft (4 hr)	301	2	662	49	23	0	7	2	49	97	63	82
	Infiltrated - 20 ft (20 hr)	819	2	1,128	43	40	0	17	1	-40	97	37	85

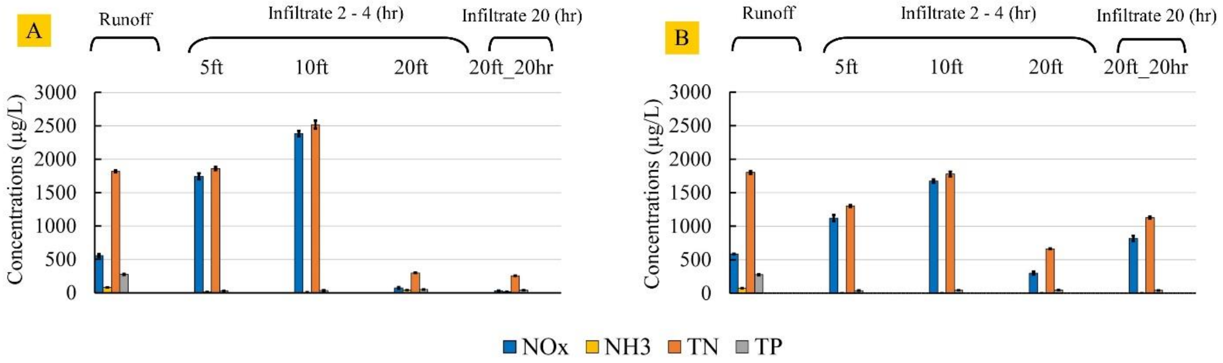


Figure B.20. Arithmetic mean of nutrient concentrations in simulated roadway runoff (influent) and infiltrated water at different sampling locations of 5, 10 and 20 ft along the (a) treatment test bed and (b) control test bed over 1.5 in storm depth for 1-lane roadway. The error bars are standard deviation across all events.

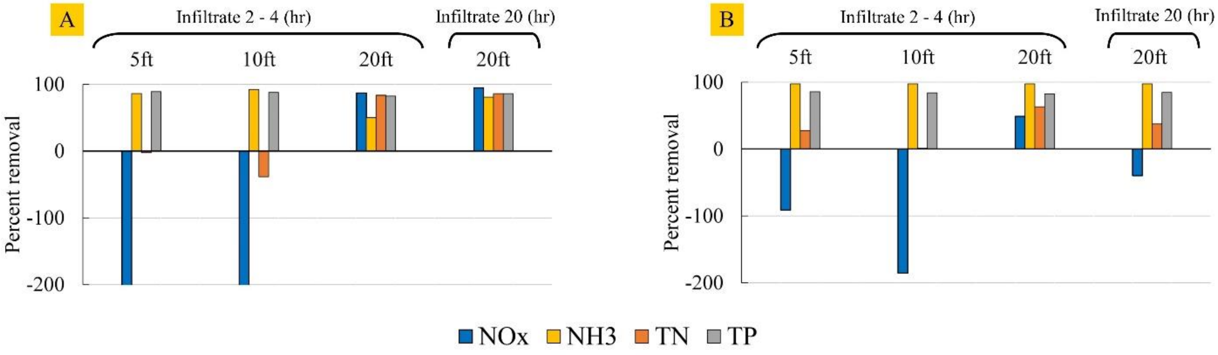


Figure B.21. Arithmetic mean of percent nutrient removal with respect to inflow nutrient load at different sampling locations along the (a) treatment test bed and (b) control test bed over 1.5 in storm depth for 1-lane roadway. The error bars are standard deviation across all events.

Table B.15. Mean concentrations and percent nutrient removal of collected samples over 3 in storm depth, 1-lane roadway. Note: percent removal is calculated based on concentration of influent water.

		Mean Concentration (µg/l)				SD				% removal			
		NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP	NO_x	NH_3	TN	TP
treatment test bed	Roadway runoff	547	120	1,824	255	13	4	11	3	0	0	0	0
	Infiltrated- 5 ft (4 hr)	1,850	0	2,219	20	18	0	53	1	-238	100	-22	92
	Infiltrated - 10 ft (4 hr)	327	4	504	22	30	6	8	1	40	97	72	91
	Infiltrated - 20 ft (4 hr)	65	18	303	25	3	1	4	0	88	85	83	90
	Infiltrated - 20 ft (20 hr)	70	6	288	20	2	6	5	1	87	95	84	92
control test bed	Roadway runoff	532	108	1,857	248	12	4	22	8	0	0	0	0
	Infiltrated- 5 ft (4 hr)	992	0	1,239	31	5	0	9	2	-87	100	33	88
	Infiltrated - 10 ft (4 hr)	520	0	772	40	11	0	6	1	2	100	58	84
	Infiltrated - 20 ft (4 hr)	450	0	709	39	4	1	5	2	15	100	62	84
	Infiltrated - 20 ft (20 hr)	356	2	621	35	7	2	12	3	33	98	67	86

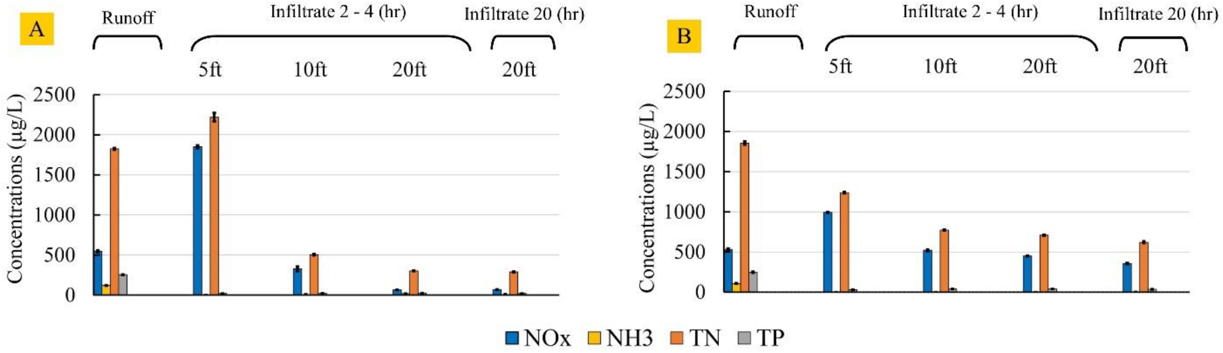


Figure B.22. Arithmetic mean of nutrient concentrations in simulated roadway runoff (influent) and infiltrated water at different sampling locations of 5, 10 and 20 ft along the (a) treatment test bed and (b) control test bed over 1.5 in storm depth for 1-lane roadway. The error bars are standard deviation across all events.

Appendix C: BMP Trains 2020 user manual

To allow for greater access and continued support, the BMP Trains 2020 user manual can be downloaded from UCF’s STARS repository. This site is maintained for wide distribution and ease of access. To download this manual, BMP Trains and support reference materials, proceed to: http://stars.library.ucf.edu/bmptrains.

Appendix D: Groundwater models for nitrate, TN, and TP

Nitrate transport models

The models used to evaluate BAM-based BMP on nitrate reduction in Silver Springs for each scenario include a ".gwv" file and two ".exe" files, which is shown in the table below. The ".gwv" file is the groundwater model. The "cfpv2.exe" is the program to run the conduit flow process in the groundwater model and the "UMT3D.exe" is the program to run the nitrate transport in conduits and rock matrix in the model. The models are included in the attachment "Nitrate_transport_model".

Table D.1. The model used for each evaluation scenario

Scenario name	Soil removal efficiency (%)	Model used
No BAM implemented	/	baseline_N.gwv cfpv2.exe UMT3D.exe
BAM implemented in 26 FDOT SRBs	-50	fdot_-50%soil.gwv cfpv2.exe UMT3D.exe
	74	fdot_74%soil.gwv cfpv2.exe UMT3D.exe
	91.8	fdot_91.8%soil.gwv cfpv2.exe UMT3D.exe
BAM implemented in all FDOT SRBs	-50	ocala_-50%soil. cfpv2.exe UMT3D.exe
	74	ocala_74%soil.gwv cfpv2.exe UMT3D.exe
	91.8	ocala_91.8%soil.gwv cfpv2.exe UMT3D.exe
BAM implemented in 30% roadway shoulder	-50	thirtyrd_NOx_-50%soil.gwv cfpv2.exe UMT3D.exe
	74	thirtyrd_NOx_74%soil.gwv cfpv2.exe UMT3D.exe
	91.8	thirtyrd_NOx_91.8%soil.gwv cfpv2.exe UMT3D.exe

Table D.1 (continued). The model used for each evaluation scenario

Scenario name	Soil removal efficiency (%)	Model used
BAM implemented in 60% roadway shoulder	-50	sixtyrd_NOx_-50%soil.gwv cfpv2.exe UMT3D.exe
	74	sixtyrd_NOx_74%soil.gwv cfpv2.exe UMT3D.exe
	91.8	sixtyrd_NOx_91.8%soil.gwv cfpv2.exe UMT3D.exe
BAM implemented in all FDOT SRBs and roadway shoulder	-50 74 91.8	SRB_rd_all.gwv cfpv2.exe UMT3D.exe

Input files to the nitrate transport models

The names of three types of files that are used to run the "cfpv2.exe" program and five specific files for each scenario to run the "UMT3D.exe" program are shown in Table D.3. The files are included in the attachment "Input_files_nitrate_tranport_model".

Table D.2. Input files to the flow and nitrate transport model.

Scenario name	Soil removal efficiency (%)	Input to the flow model	Input to the transport model
No BAM implemented	/	baseline_N_flow.nam baseline_N_flow.lmt baseline_N_flow.lct	baseline_N_transport.nam baseline_N_transport.gcg baseline_N_transport.dsp baseline_N_transport.ssc baseline_N_transport.ssm
BAM implemented in 26 FDOT SRBs	-50	fdot_flow_-50%soil.nam fdot_flow_-50%soil.lmt fdot_flow_-50%soil.lct	fdot_transport_-50%soil.nam fdot_transport_-50%soil.gcg fdot_transport_-50%soil.ssc fdot_transport_-50%soil.dsp fdot_transport_-50%soil.ssm
	74	fdot_flow_74%soil.nam fdot_flow_74%soil.lmt fdot_flow_74%soil.lct	fdot_transport_74%soil.nam fdot_transport_74%soil.gcg fdot_transport_74%soil.ssc fdot_transport_74%soil.dsp fdot_transport_74%soil.ssm
	91.8	fdot_flow_91.8%soil.nam fdot_flow_91.8%soil.lmt fdot_flow_91.8%soil.lct	fdot_transport_91.8%soil.nam fdot_transport_91.8%soil.gcg fdot_transport_91.8%soil.ssc fdot_transport_91.8%soil.dsp fdot_transport_91.8%soil.ssm
BAM implemented in all FDOT SRBs	-50	ocala_flow_-50%soil.nam ocala_flow_-50%soil.lmt ocala_flow_-50%soil.lct	ocala_transport_-50%soil.nam ocala_transport_-50%soil.gcg ocala_transport_-50%soil.ssc ocala_transport_-50%soil.dsp ocala_transport_-50%soil.ssm
	74	ocala_flow_74%soil.nam ocala_flow_74%soil.lmt ocala_flow_74%soil.lct	ocala_transport_74%soil.nam ocala_transport_74%soil.gcg ocala_transport_74%soil.ssm ocala_transport_74%soil.dsp ocala_transport_74%soil.ssc
	91.8	ocala_flow_91.8%soil.nam ocala_flow_91.8%soil.lmt ocala_flow_91.8%soil.lct	ocala_transport_91.8%soil.gcg ocala_transport_91.8%soil.nam ocala_transport_91.8%soil.dsp ocala_transport_91.8%soil.ssc ocala_transport_91.8%soil.ssm

Table D.2 (continued). Input files to the flow and nitrate transport model.

Scenario name	Soil removal efficiency (%)	Input to the flow model	Input to the transport model
BAM implemented in 30% roadway shoulder	-50	thirtyrd_NOx_flow.nam thirtyrd_NOx_flow.lmt thirtyrd_NOx_flow.lct	thirtyrd_NOx_transport.nam thirtyrd_NOx_transport.gcg thirtyrd_NOx_transport.dsp thirtyrd_NOx_transport.ssc thirtyrd_NOx_transport.ssm
	74	thirtyrd_NOx_flow_74%soil.nam thirtyrd_NOx_flow_74%soil.lmt thirtyrd_NOx_flow_74%soil.lct	thirtyrd_NOx_transport_74%soil.nam thirtyrd_NOx_transport_74%soil.gcg thirtyrd_NOx_transport_74%soil.dsp thirtyrd_NOx_transport_74%soil.ssc thirtyrd_NOx_transport_74%soil.ssm
	91.8	thirtyrd_NOx_flow_91.8%soil.nam thirtyrd_NOx_flow_91.8%soil.lmt thirtyrd_NOx_flow_91.8%soil.lct	thirtyrd_NOx_transport_91.8%soil.nam thirtyrd_NOx_transport_91.8%soil.gcg thirtyrd_NOx_transport_91.8%soil.dsp thirtyrd_NOx_transport_91.8%soil.ssc thirtyrd_NOx_transport_91.8%soil.ssm
BAM implemented in 60% roadway shoulder	-50	sixtyrd_NOx_flow.nam sixtyrd_NOx_flow.lmt sixtyrd_NOx_flow.lct	sixtyrd_NOx_transport.nam sixtyrd_NOx_transport.gcg sixtyrd_NOx_transport.dsp sixtyrd_NOx_transport.ssc sixtyrd_NOx_transport.ssm
	74	sixtyrd_NOx_flow_74%soil.nam sixtyrd_NOx_flow_74%soil.lmt sixtyrd_NOx_flow_74%soil.lct	sixtyrd_NOx_transport_74%soil.nam sixtyrd_NOx_transport_74%soil.gcg sixtyrd_NOx_transport_74%soil.dsp sixtyrd_NOx_transport_74%soil.ssc sixtyrd_NOx_transport_74%soil.ssm
	91.8	sixtyrd_NOx_flow_91.8%soil.nam sixtyrd_NOx_flow_91.8%soil.lmt sixtyrd_NOx_flow_91.8%soil.lct	sixtyrd_NOx_transport_91.8%soil.nam sixtyrd_NOx_transport_91.8%soil.gcg sixtyrd_NOx_transport_91.8%soil.dsp sixtyrd_NOx_transport_91.8%soil.ssc sixtyrd_NOx_transport_91.8%soil.ssm
BAM implemented in all FDOT SRBs and roadway shoulder	-50	SRB_rd_all_flow.nam SRB_rd_all_flow.lmt SRB_rd_all_flow.lct	SRB_rd_all_transport.gcg SRB_rd_all_transport.nam SRB_rd_all_transport.ssm SRB_rd_all_transport.dsp SRB_rd_all_transport.ssc
	74		
	91.8		

TN transport models

The models used to evaluate BAM-based BMP on TN reduction in Silver Springs for each scenario include a ".gwv" file and two ".exe" files, which is shown in the table below. The ".gwv" file is the groundwater model. The "cfpv2.exe" is the program to run the conduit flow process in the groundwater model and the "UMT3D.exe" is the program to run the TN transport in conduits and rock matrix in the model. The models are included in the attachment "TN_transport_model".

Table D.3. The model used for each evaluation scenario.

Scenario name	Soil removal efficiency (%)	Model used
No BAM implemented	/	baseline_N.gwv cfpv2.exe UMT3D.exe
BAM implemented in 26 FDOT SRBs	29	fdot_TN_29%soil.gwv cfpv2.exe UMT3D.exe
	60	fdot_TN_60%soil.gwv cfpv2.exe UMT3D.exe
	78.4	fdot_TN_78.4%soil.gwv cfpv2.exe UMT3D.exe
BAM implemented in all FDOT SRBs	29	ocala_TN_29%soil.gwv cfpv2.exe UMT3D.exe
	60	ocala_TN_60%soil.gwv cfpv2.exe UMT3D.exe
	78.4	ocala_TN_78.4%soil.gwv cfpv2.exe UMT3D.exe
BAM implemented in 30% roadway shoulder	29	thirtyrd_TN.gwv cfpv2.exe UMT3D.exe
	60	thirtyrd_TN_60%soil.gwv cfpv2.exe UMT3D.exe
	78.4	thirtyrd_TN_78.4%soil.gwv cfpv2.exe UMT3D.exe

Table D.3 (continued). The model used for each evaluation scenario.

Scenario name	Soil removal efficiency (%)	Model used
BAM implemented in 60% roadway shoulder	29	thirty_TN.gwv cfpv2.exe UMT3D.exe
	60	thirty_TN_60%soil.gwv cfpv2.exe UMT3D.exe
	78.4	thrity_TN_78.4%soil.gwv cfpv2.exe UMT3D.exe
BAM implemented in all FDOT SRBs and roadway shoulder	29 60 78.4	SRB_rd_all.gwv cfpv2.exe UMT3D.exe

Input files to the TN transport models

The names of three types of files that are used to run the “cfpv2.exe” program and five specific files for each scenario to run the “UMT3D.exe” program are shown in Table D.6. The files are included in the attachment “Input_files_TN_tranport_model”.

Table D.4. Input files to the flow and TN transport model.

Scenario name	Soil removal efficiency (%)	Input to the flow model	Input to the transport model
No BAM implemented	/	baseline_N_flow.nam baseline_N_flow.lmt baseline_N_flow.lct	baseline_N_transport.nam baseline_N_transport.gcg baseline_N_transport.dsp baseline_N_transport.ssc baseline_N_transport.ssm
BAM implemented in 26 FDOT SRBs	29	fdotTN_flow_29%soil.nam fdotTN_flow_29%soil.lmt fdotTN_flow_29%soil.lct	fdotTN_transport_29%soil.nam fdotTN_transport_29%soil.gcg fdotTN_transport_29%soil.ssc fdotTN_transport_29%soil.dsp fdotTN_transport_29%soil.ssm
	60	fdotTN_flow_60%soil.nam fdotTN_flow_60%soil.lmt fdotTN_flow_60%soil.lct	fdotTN_transport_60%soil.nam fdotTN_transport_60%soil.gcg fdotTN_transport_60%soil.ssc fdotTN_transport_60%soil.dsp fdotTN_transport_60%soil.ssm
	78.4	fdotTN_flow_78.4%soil.nam fdotTN_flow_78.4%soil.lmt fdotTN_flow_78.4%soil.lct	fdotTN_transport_78.4%soil.nam fdotTN_transport_78.4%soil.gcg fdotTN_transport_78.4%soil.ssc fdotTN_transport_78.4%soil.dsp fdotTN_transport_78.4%soil.ssm
BAM implemented in all FDOT SRBs	29	ocalaTN_flow_29%soil.nam ocalaTN_flow_29%soil.lmt ocalaTN_flow_29%soil.lct	ocalaTN_transport_29%soil.nam ocalaTN_transport_29%soil.gcg ocalaTN_transport_29%soil.ssc ocalaTN_transport_29%soil.dsp ocalaTN_transport_29%soil.ssm
	60	ocalaTN_flow_60%soil.nam ocalaTN_flow_60%soil.lmt ocalaTN_flow_60%soil.lct	ocalaTN_transport_60%soil.nam ocalaTN_transport_60%soil.gcg ocalaTN_transport_60%soil.ssm ocalaTN_transport_60%soil.dsp ocalaTN_transport_60%soil.ssc
	78.4	ocalaTN_flow_78.4%soil.nam ocalaTN_flow_78.4%soil.lmt ocalaTN_flow_78.4%soil.lct	ocalaTN_transport_78.4%soil.gcg ocalaTN_transport_78.4%soil.nam ocalaTN_transport_78.4%soil.dsp ocalaTN_transport_78.4%soil.ssc ocalaTN_transport_78.4%soil.ssm

Table D.4 (continued). Input files to the flow and TN transport model.

Scenario name	Soil removal efficiency (%)	Input to the flow model	Input to the transport model
BAM implemented in 30% roadway shoulder	29	thirtyrd_TN_flow.nam thirtyrd_TN_flow.lmt thirtyrd_TN_flow.lct	thirtyrd_TN_transport.nam thirtyrd_TN_transport.gcg thirtyrd_TN_transport.dsp thirtyrd_TN_transport.ssc thirtyrd_TN_transport.ssm
	60	thirtyrd_TN_flow_60%soil.nam thirtyrd_TN_flow_60%soil.lmt thirtyrd_TN_flow_60%soil.lct	thirtyrd_TN_transport_60%soil.nam thirtyrd_TN_transport_60%soil.gcg thirtyrd_TN_transport_60%soil.dsp thirtyrd_TN_transport_60%soil.ssc thirtyrd_TN_transport_60%soil.ssm
	78.4	thirtyrd_TN_flow_78.4%soil.nam thirtyrd_TN_flow_78.4%soil.lmt thirtyrd_TN_flow_78.4%soil.lct	thirtyrd_TN_transport_78.4%soil.nam thirtyrd_TN_transport_78.4%soil.gcg thirtyrd_TN_transport_78.4%soil.dsp thirtyrd_TN_transport_78.4%soil.ssc thirtyrd_TN_transport_78.4%soil.ssm
BAM implemented in 60% roadway shoulder	29	sixtyrd_TN_flow.nam sixtyrd_TN_flow.lmt sixtyrd_TN_flow.lct	sixtyrd_TN_transport.nam sixtyrd_TN_transport.gcg sixtyrd_TN_transport.dsp sixtyrd_TN_transport.ssc sixtyrd_TN_transport.ssm
	60	sixtyrd_TN_flow_60%soil.nam sixtyrd_TN_flow_60%soil.lmt sixtyrd_TN_flow_60%soil.lct	sixtyrd_TN_transport_60%soil.gcg sixtyrd_TN_transport_60%soil.dsp sixtyrd_TN_transport_60%soil.ssc sixtyrd_TN_transport_60%soil.ssm
	78.4	sixtyrd_TN_flow_78.4%soil.nam sixtyrd_TN_flow_78.4%soil.lmt sixtyrd_TN_flow_78.4%soil.lct	sixtyrd_TN_transport_78.4%soil.nam sixtyrd_TN_transport_78.4%soil.gcg sixtyrd_TN_transport_78.4%soil.dsp sixtyrd_TN_transport_78.4%soil.ssc sixtyrd_TN_transport_78.4%soil.ssm
BAM implemented in all FDOT SRBs and roadway shoulder	29	SRB_rd_all_flow.nam SRB_rd_all_flow.lmt SRB_rd_all_flow.lct	SRB_rd_all_transport.gcg SRB_rd_all_transport.nam SRB_rd_all_transport.ssm SRB_rd_all_transport.dsp SRB_rd_all_transport.ssc
	60		
	78.4		

TP transport models

The models used to evaluate BAM-based BMP on TP reduction in Silver Springs for each scenario include a ".gwv" file and two ".exe" files, which is shown in the table below. The ".gwv" file is the groundwater model. The "cfpv2.exe" is the program to run the conduit flow process in the groundwater model and the "UMT3D.exe" is the program to run the TP transport in conduits and rock matrix in the model. The models are included in the attachment "TP_transport_model".

Table D.5. The model used for each evaluation scenario.

Scenario name	Soil removal efficiency (%)	Model used
No BAM implemented	/	baseline_TP.gwv cfpv2.exe UMT3D.exe
BAM implemented in 26 FDOT SRBs	-176.82	FDOT_TP_-176.82%soil.gwv cfpv2.exe UMT3D.exe
	-48	FDOT_TP_-48%soil.gwv cfpv2.exe UMT3D.exe
	80	FDOT_TP_80%soil.gwv cfpv2.exe UMT3D.exe
BAM implemented in all FDOT SRBs	-176.82	ocala_TP_-176.82%soil.gwv cfpv2.exe UMT3D.exe
	-48	ocala_TP_-48%soil.gwv cfpv2.exe UMT3D.exe
	80	ocala_TP_80%soil.gwv cfpv2.exe UMT3D.exe
BAM implemented in 30% roadway shoulder	-176.82	thirtyrd_TP_-176.82soil.gwv cfpv2.exe UMT3D.exe
	-48	thirtyrd_TP_-48%soil.gwv cfpv2.exe UMT3D.exe
	80	thirtyrd_TP.gwv cfpv2.exe UMT3D.exe

Table D.5 (continued). The model used for each evaluation scenario.

Scenario name	Soil removal efficiency (%)	Model used
BAM implemented in 60% roadway shoulder	-176.82	sixtyrd_TP_-176.82soil.gwv cfpv2.exe UMT3D.exe
	-48	sixtyrd_TP_-48%soil.gwv cfpv2.exe UMT3D.exe
	80	sixtyrd_TP.gwv cfpv2.exe UMT3D.exe
BAM implemented in all FDOT SRBs and roadway shoulder	-176.82	SRB_rd_all.gwv [i]cfpv2.exe UMT3D.exe
	-48	
	80	

Input files to the TP transport models

The names of three types of files that are used to run the “cfpv2.exe” program and five specific files for each scenario to run the “UMT3D.exe” program are shown in Table D.9. The files are included in the attachment “Input_files_TP_tranport_model”.

Table D.6. Input files to the flow and TP transport model.

Scenario name	Soil removal efficiency (%)	Input to the flow model	Input to the transport model
No BAM implemented	/	baseline_N_flow.nam baseline_N_flow.lmt baseline_N_flow.lct	baseline_N_transport.nam baseline_N_transport.gcg baseline_N_transport.dsp baseline_N_transport.ssc baseline_N_transport.ssm
BAM implemented in 26 FDOT SRBs	-176.82	fdotTP_flow_-176.82%soil.nam fdotTP_flow_-176.82%soil.lmt fdotTP_flow_-176.82%soil.lct	fdotTP_transport_-176.82%soil.nam fdotTP_transport_-176.82%soil.gcg fdotTP_transport_-176.82%soil.ssc fdotTP_transport_-176.82%soil.dsp fdotTP_transport_-176.82%soil.ssm
	-48	fdotTP_flow_-48%soil.nam fdotTP_flow_-48%soil.lmt fdotTP_flow_-48%soil.lct	fdotTP_transport_-48%soil.nam fdotTP_transport_-48%soil.gcg fdotTP_transport_-48%soil.ssc fdotTP_transport_-48%soil.dsp fdotTP_transport_-48%soil.ssm
	80	fdotTP_flow_80%soil.nam fdotTP_flow_80%soil.lmt fdotTP_flow_80%soil.lct	fdotTP_transport_80%soil.nam fdotTP_transport_80%soil.gcg fdotTP_transport_80%soil.ssc fdotTP_transport_80%soil.dsp fdotTP_transport_80%soil.ssm
BAM implemented in all FDOT SRBs	-176.82	ocalaTP_flow_-176.82%soil.nam ocalaTP_flow_-176.82%soil.lmt ocalaTP_flow_-176.82%soil.lct	ocalaTP_transport_-176.82%soil.nam ocalaTP_transport_-176.82%soil.gcg ocalaTP_transport_-176.82%soil.ssc ocalaTP_transport_-176.82%soil.dsp ocalaTP_transport_-176.82%soil.ssm
	-48	ocalaTP_flow_-48%soil.nam ocalaTP_flow_-48%soil.lmt ocalaTP_flow_-48%soil.lct	ocalaTP_transport_-48%soil.nam ocalaTP_transport_-48%soil.gcg ocalaTP_transport_-48%soil.ssm ocalaTP_transport_-48%soil.dsp ocalaTP_transport_-48%soil.ssc
	80	ocalaTP_flow_80%soil.nam ocalaTP_flow_80%soil.lmt ocalaTP_flow_80%soil.lct	ocalaTP_transport_80%soil.gcg ocalaTP_transport_80%soil.nam ocalaTP_transport_80%soil.dsp ocalaTP_transport_80%soil.ssc ocalaTP_transport_80%soil.ssm

Table D.6 (continued). Input files to the flow and TP transport model.

Scenario name	Soil removal efficiency (%)	Input to the flow model	Input to the transport model
BAM implemented in 30% roadway shoulder	-176.82	thirtyrd_TP_flow_-176.82%soil.nam thirtyrd_TP_flow_-176.82%soil.lmt thirtyrd_TP_flow_-176.82%soil.lct	thirtyrd_TP_transport_-176.82%soil.nam thirtyrd_TP_transport_-176.82%soil.gcg thirtyrd_TP_transport_-176.82%soil.dsp thirtyrd_TP_transport_-176.82%soil.ssc thirtyrd_TP_transport_-176.82%soil.ssm
	-48	thirtyrd_TP_flow_-48%soil.nam thirtyrd_TP_flow_-48%soil.lmt thirtyrd_TP_flow_-48%soil.lct	thirtyrd_TP_transport_-48%soil.nam thirtyrd_TP_transport_-48%soil.gcg thirtyrd_TP_transport_-48%soil.dsp thirtyrd_TP_transport_-48%soil.ssc thirtyrd_TP_transport_-48%soil.ssm
	80	thirtyrd_TP_flow.nam thirtyrd_TP_flow.lmt thirtyrd_TP_flow.lct	thirtyrd_TP_transport.nam thirtyrd_TP_transport.gcg thirtyrd_TP_transport.dsp thirtyrd_TP_transport.ssc thirtyrd_TP_transport.ssm
BAM implemented in 60% roadway shoulder	-176.82	sixtyrd_TP_flow_-176.82%soil.nam sixtyrd_TP_flow_-176.82%soil.lmt sixtyrd_TP_flow_-176.82%soil.lct	sixtyrd_TP_transport_-176.82%soil.nam sixtyrd_TP_transport_-176.82%soil.gcg sixtyrd_TP_transport_-176.82%soil.dsp sixtyrd_TP_transport_-176.82%soil.ssc sixtyrd_TP_transport_-176.82%soil.ssm
	-48	sixtyrd_TP_flow_-48%soil.nam sixtyrd_TP_flow_-48%soil.lmt sixtyrd_TP_flow_-48%soil.lct	sixtyrd_TP_transport_-48%soil.nam sixtyrd_TP_transport_-48%soil.gcg sixtyrd_TP_transport_-48%soil.dsp sixtyrd_TP_transport_-48%soil.ssc sixtyrd_TP_transport_-48%soil.ssm
	80	sixtyrd_TP_flow.nam sixtyrd_TP_flow.lmt sixtyrd_TP_flow.lct	sixtyrd_TP_transport.nam sixtyrd_TP_transport.gcg sixtyrd_TP_transport.dsp sixtyrd_TP_transport.ssc sixtyrd_TP_transport.ssm
BAM implemented in all FDOT SRBs and roadway shoulder	-176.82	SRB_rd_all_flow.nam SRB_rd_all_flow.lmt SRB_rd_all_flow.lct	SRB_rd_all_transport.gcg SRB_rd_all_transport.nam SRB_rd_all_transport.ssm SRB_rd_all_transport.dsp SRB_rd_all_transport.ssc

---