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2 **Author**

First Name (or initial)	Middle Name (or initial)	Surname	Role (ASABE member, etc.)	E-mail	Contact author? yes or no
Jaison		Renkenberger	Student member	jaisonrenkenber ger@gmail.com	yes

3 **Affiliation**

Organization	Address	Country	Phone for contact author
Civil and Environmental Engineering Department	University of Maryland at College Park, College Park, MD, 20742	USA	

4 **Author**

First Name (or initial)	Middle Name (or initial)	Surname	Role (ASABE member, etc.)	E-mail	Contact author? yes or no
Hubert		Montas	ASABE member	montas@umd.e du	yes

5 **Affiliation**

Organization	Address	Country	Phone for contact author
Fischell Department of Bioengineering	University of Maryland at College Park, College Park, MD, 20742	USA	301-405-1196

6 **Author**

First Name (or initial)	Middle Name (or initial)	Surname	Role (ASABE member, etc.)	E-mail	Contact author? yes or no
Paul		Leisnham	non-member	leisnham@umd.edu	no

7 **Affiliation**

Organization	Address	Country	Phone for contact author
Environmental Science and Technology Department	University of Maryland at College Park, College Park, MD, 20742	USA	

8

9

Author

First Name (or initial)	Middle Name (or initial)	Surname	Role (ASABE member, etc.)	E-mail	Contact author? yes or no
Victoria		Chanse	non-member	vchanse@umd.edu	no

10

Affiliation

Organization	Address	Country	Phone for contact author
Department of Plant Science and Landscape Architecture	University of Maryland at College Park, College Park, MD, 20742	USA	

11

12

Author

First Name (or initial)	Middle Name (or initial)	Surname	Role (ASABE member, etc.)	E-mail	Contact author? yes or no
Adel		Shirmohammadi	ASABE member	ashirmo@umd.edu	no

13

Affiliation

Organization	Address	Country	Phone for contact author
College of Agriculture and Natural Resources	1201 Symons Hall, University of Maryland at College Park, College Park, MD, 20742	USA	

14

Author

First Name (or initial)	Middle Name (or initial)	Surname	Role (ASABE member, etc.)	E-mail	Contact author? yes or no
Ali		Sadeghi	ASABE member	Ali.Sadeghi@ARS.USDA.GOV	no

15

Affiliation

Organization	Address	Country	Phone for contact author
USDA-ARS Hydrology and Remote Sensing Laboratory	BARC-West, Beltsville, MD, 20705	USA	

16

Author

First Name	Middle	Surname	Role	E-mail	Contact
------------	--------	---------	------	--------	---------

(or initial)	Name (or initial)		(ASABE member, etc.)		author? yes or no
Kaye		Brubaker	non-member	kbru@umd.edu	no

17 **Affiliation**

Organization	Address	Country	Phone for contact author
Civil and Environmental Engineering Department	University of Maryland at College Park, College Park, MD, 20742	USA	

18 **Author**

First Name (or initial)	Middle Name (or initial)	Surname	Role (ASABE member, etc.)	E-mail	Contact author? yes or no
Amanda		Rockler	non-member	arockler@umd.edu	no

19 **Affiliation**

Organization	Address	Country	Phone for contact author
Sea Grant Extension	University of Maryland, Derwood, MD, 20855	USA	

20

21 **Author**

First Name (or initial)	Middle Name (or initial)	Surname	Role (ASABE member, etc.)	E-mail	Contact author? yes or no
Thomas		Hutson	non-member	thutson@umd.edu	no

22 **Affiliation**

Organization	Address	Country	Phone for contact author
University of Maryland Extension – Talbot County	University of Maryland Extension, Talbot County 28577 Mary's Court, Suite 1 Easton MD 21601	USA	

23 **Author**

First Name (or initial)	Middle Name (or initial)	Surname	Role (ASABE member, etc.)	E-mail	Contact author? yes or no
David		Lansing	non-member	dlansing@umbc.edu	no

24

Affiliation

Organization	Address	Country	Phone for contact author
Department of Geography and Environmental Systems	University of Maryland Baltimore County, Baltimore, MD, 21250	USA	

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Paper Number; pages <u>1-</u>

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EFFECTIVENESS OF BEST MANAGEMENT PRACTICES WITH CHANGING CLIMATE IN A MARYLAND WATERSHED

Renkenberger, Jaison¹; Montas, Hubert¹; Leisnham, Paul¹; Chanse, Victoria¹; Shirmohammadi, Adel¹; Sadeghi, Ali⁴; Brubaker, Kaye¹; Rockler, Amanda²; Hutson, Thomas³; Lansing, David⁵

1. University of Maryland, College Park, MD, United States. 2. University of Maryland Extension, Derwood, MD, United States. 3. University of Maryland Extension, Easton, MD, United States. 4. USDA-ARS, Beltsville, MD, United States. 5. University of Maryland Baltimore County, Baltimore, MD, United States.

ABSTRACT.

The potential impacts of climate change on BMP effectiveness were investigated using SWAT simulations for an agricultural watershed that drains into the Chesapeake Bay, in the US Northeast climate region. Critical Source Areas (CSAs) for sediments, nitrogen and phosphorus, identified for current and future climate (SRES A1B and A2), were classified by density to support BMP prioritization schemes. BMPs were designed for these CSAs and tested against current and future climate using SWAT simulations, to evaluate their robustness. A second set of BMPs was designed by optimization for all agricultural and urban lands in the study watershed, and was tested similarly for robustness. In both cases, the design goal was for the watershed's water quality response to meet the Bay TMDLs once BMPs were implemented. Results indicated that density 2 and 3 CSAs (hotspots exporting excess amounts of 2 or 3 constituents) may be good prioritization targets but reaching the Bay TMDLs would still require targeting all CSAs. BMPs designed for CSAs under current climate were effective to reach Bay TMDLs under current climate but not under scenarios A1B and A2. BMPs designed for CSAs under future scenario A2 were effective to reach the Bay TMDLs under all climates, except for nitrogen under A2. Similarly, BMPs optimized for agricultural and urban lands, when designed for current climate, were effective in meeting the TMDLs for current climate only. Optimizing these BMPs for future climate produced a design that met TMDLs under both current and future climates, except for nitrogen with future climate. However, in this case, the nitrogen TMDL was exceeded by a smaller amount than in the CSA design. It was concluded that, in the US Northeast, BMPs designed to remediate water quality problems under current climate will be insufficient to maintain water quality with climate change. Increased annual rainfall and storm intensity will cause the proportion of watershed area needing BMPs to increase and current hotspots will generate excess amounts of new constituents that will require re-design of existing BMPs. Community-based participatory strategies will likely be required to foster BMP adoption and sustain water quality gains in the Chesapeake Bay region.

Keywords.

Climate change, Best Management Practices, BMPs, NPS pollution, SWAT model, water quality, watershed hydrology

INTRODUCTION

Non-point source pollution (NPS) from urban and agricultural areas has been identified as a major contributing factor to water quality degradation of the Chesapeake Bay (Garvin and Enck, 2010). To help improve Bay water quality, the federal government's Environmental Protection Agency (EPA) issued a set of Bay wide Total Maximum Daily Loads (TMDLs) for Total Suspended Sediments (TSS), Total Nitrogen (TN), and Total Phosphorus (TP). These TMDLs define yield limits that Chesapeake Bay sub-watersheds should meet to produce sustainable improvements in Bay water quality. Jurisdictional governments were then tasked with developing Watershed Implementation Plans (WIPs) that described the strategies that watersheds in their jurisdictions would use to meet the Bay TMDLs. Upon completion of the WIPs, resources could be secured from federal programs to assist with the implementation of the identified remediation measures.

WIP development typically entails, as a first step, the identification of Critical Source Areas (CSAs) within a target watershed. This activity, as applied to NPS pollutants in agricultural and mixed land-use watersheds, has been the subject of substantial research (Chen et al., 2014; Chu et al., 2004; Huaifeng et al., 2010; Huang et al., 2015; Sexton et al., 2010; Shang et al., 2012; White et al., 2009; Winchell et al., 2014). The preferred method is to use a calibrated, spatially distributed, and physically-based hydrologic and water quality model, such as the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1993). Models of this type adapt well to varying soils, topographies, land uses, management practices and weather conditions, and are commonly considered to represent the state-of-the-art in the field. This flexibility enables them to also be used in the second step of WIP development: the design of Best Management Practices (BMPs) for remediation of the water quality problems caused by each CSA. In this step, the models are used to simulate the potential water quality impacts that BMPs implemented on CSAs, are expected to have, prior to their biophysical realization in a target watershed (Arabi et al., 2006, 2008; Chiang et al., 2012; Giri et al., 2014). The models make it possible to evaluate the effectiveness of a range of potential BMP designs, and to select that which is most appropriate for the target watershed, before the more costly step of BMP implementation is undertaken.

In the US Northeast climate region, where the Chesapeake Bay watershed is located, climate change is expected to produce the largest increases in annual rainfall and storm intensity of the country (Melillo et al., 2014). The potential impacts of this climatic non-stationarity on the effectiveness of WIPs developed to meet the Bay TMDLs under current climate conditions is largely unknown. In the central Great Plains climatic region, two studies have reported that, with moderate increases in annual rainfall, BMPs would remain essentially as effective under climate change as they are today (Woznicki et al., 2011; Van Liew et al., 2012). In the Midwest, a slightly larger annual increase in rainfall under climate change was predicted to produce a decrease in the effectiveness of BMPs designed for current climate (Bosch et al., 2014). In Ontario (Canada) it was suggested that, with climate change, it would be necessary to take some agricultural land out of production,

in an agricultural watershed, as BMPs would become insufficient to meet water quality standards (Parker et al., 2008). Meanwhile, much farther away, in South Korea, the effectiveness of specific BMPs was found to either increase or decrease with climate change, due to changes in rainfall distribution throughout the year, with not net increase in annual rainfall (Park et al., 2014). From these prior studies, it is clear that the increases in annual rainfall and storm intensity predicted to occur in the Northeast under climate change could have a variety of impacts on the effectiveness of BMPs, targeted in WIPs, to meet the Bay TMDLs. Improving our understanding of how these BMPs will fare under climate change will help us to better allocate resources for their design and implementation, in a way that remains effective in the long term.

The objective of this study is to quantify the impact of climate change on BMP effectiveness for Chesapeake Bay watersheds within the Atlantic Coastal Plain physiographic region and US Northeast climate region. The goals are to assess the robustness, against climate change, of BMPs designed to meet TMDL requirements under current climate, and to evaluate the potential benefits of designing BMPs directly for future climate conditions. The analysis is performed for a representative watershed in the study region and considers, separately, BMPs targeted to CSAs and to non-CSA areas. The next 3 sections of this article describe the study watershed and target TMDL, the materials and methods used for the investigation, and the results obtained.

STUDY AREA AND TMDLS

The study area is the Greensboro watershed (figure 1). It is an agricultural sub-watershed of the Choptank River (USGS HUC 0206005) on the Eastern Shore of Maryland and extends over part of Caroline County, MD, and Kent County, DE. The Greensboro watershed has an area of 298 Km² and a flat topography with most slopes below 1%. Its land use consists of 49% agricultural, 34% natural and 6% urban areas and its soils are predominantly of Hydrologic Soil Group C (50%), B (26%) and D (20%). The area receives 1070 mm of rainfall annually.

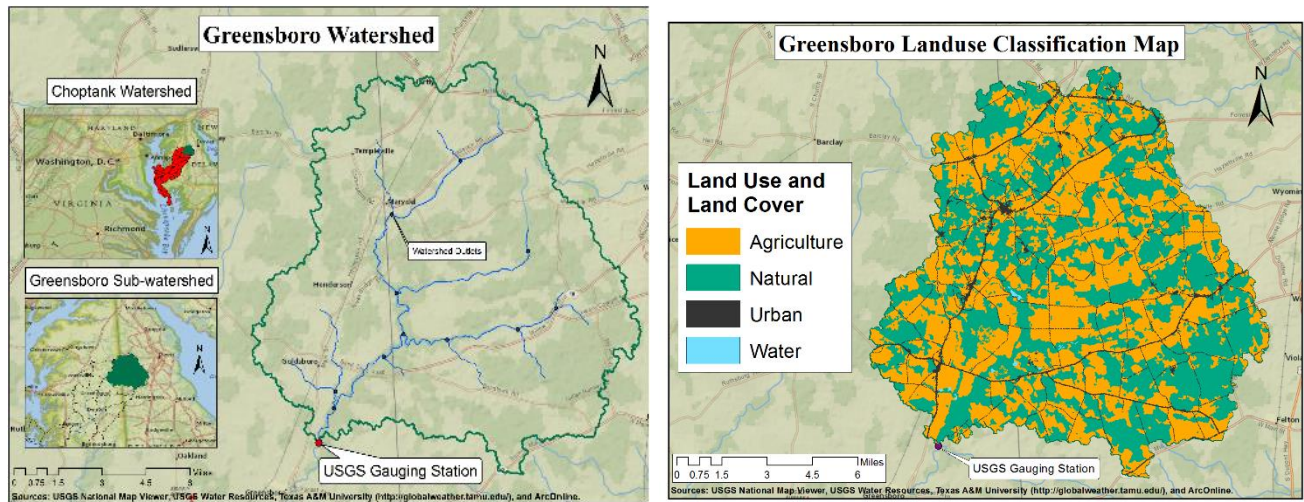


Figure 1. Location and Land Use Map for the Study Watershed

The hydrologic and water quality responses of the Greensboro watershed to current climate and IPCC SRES future climate scenarios B1, A1B and A2 were simulated by Renkenberger et al. (2015) using the SWAT model (Arnold et al., 1993). The time period for the current conditions baseline was selected as the 15 years between 1990 and 2004 based on data availability from USGS gage 01491000 located at the watershed outlet, and climate change predictions were targeted at the mid-century horizon (2046-2064) and end-century time frame (2081-2100). Table 1 summarizes these results for the baseline and end-century in terms of predicted annual rainfall, streamflow (SurQ), sediment yield (TSS), nitrogen yield (TN) and phosphorus yield (TP) at the watershed outlet. Annual rainfall is expected to increase by 25% to 30% under climate change and, due to the nonlinearity of hydrologic and water quality processes, this produces larger increases in streamflow and constituent yields. Climate change scenario A2 is predicted to produce the largest amounts of streamflow, sediments and phosphorus while A1B produces the largest nitrogen yield due to differences in rainfall intensity patterns between the two future scenarios. Additional details on model parametrization and simulation results are in Renkenberger et al. (2015).

Table 1. Hydrologic and Water Quality Response of the Greensboro Watershed under Current and Changing Climates, in Relation to Target TMDL (adapted from Renkenberger et al. (2015))

Scenario	Constituent							
	Rainfall (mm/yr)	SurQ (mm/yr)	TSS		TN		TP	
			Yield (Kg/ha/yr)	Reduction Needed	Yield (Kg/ha/yr)	Reduction Needed	Yield (Kg/ha/yr)	Reduction Needed
Baseline	1070	434	432	33%	10.9	45%	0.78	23%
B1	1340	681	773	63%	17.0	64%	1.18	49%
A1B	1390	789	936	69%	20.5	70%	1.28	53%
A2	1380	826	1004	71%	18.4	67%	1.39	57%
Water Quality TMDL (Target):			289		6.04		0.60	

125 The EPA developed TMDLs (Total Maximum Daily Loads) for the Chesapeake Bay and its sub-watersheds, for sediment,
126 nitrogen and phosphorus (Garvin and Enck, 2010). The Chesapeake Bay Program (CBP) makes these TMDLs available via
127 an interactive interface on dedicated websites through its Chesapeake Bay TMDL Tracking and Accounting System
128 (BayTAS) (www.chesapeakebay.net and https://stat.chesapeakebay.net/?q=node/130&quicktabs_10=1). BayTAS offers
129 simulated loadings in pounds per year for historical, present day and the future 2025 TMDL target. The 2025 target is ideally
130 when Bay jurisdictions will have met the Bay's TMDL for TSS, TN and TP. TMDLs for the Greensboro watershed were
131 derived from TMDL data for the Upper Choptank River sub-watershed (CHOTF), which contains the study watershed, and
132 is 1061 Km² in area, with 60% agricultural, 34% natural and 6% urban land uses. A two-step process was used: first, relative
133 reductions in TSS, TN and TP needed to attain the reported 2025 TMDL based on the 1985 baseline were computed; then,
134 these relative reductions were applied to the baseline yields calculated for the Greensboro watershed by Renkenberger et al.
135 (2015). The resulting Greensboro TMDLs are presented in the bottom row of table 1: 289 Kg/ha/yr for sediments, 6.04
136 Kg/ha/yr for nitrogen and 0.60 Kg/ha/yr for phosphorus. The table also lists the reductions in watershed yields that are
137 needed to attain the TMDLs under current climate and future climate scenarios. The required reductions range from 23% to
138 71% and are uniformly lower with current climate than with climate change scenarios, owing to the predicted increase in
139 yields with future climate in this study.

140 The Critical Source Areas (CSAs) on which BMPs should be placed to meet TMDL requirements in the Greensboro
141 watershed, were identified, on a per-constituent basis, by Renkenberger et al. (2015) and are presented in table 2. The values
142 presented here were obtained at the 20% targeting level and correspond to those Hydrologic Response Units (HRUs) in the
143 SWAT model that generate over 730 Kg/ha/yr of sediments, 16 Kg/ha/yr of nitrogen and 1.3 Kg/ha/yr of phosphorus. Under
144 current climate (baseline) each of these group contains 1541 HRUs which is 20% of the total number of HRUs in the SWAT
145 model for the study watershed. The size of the groups, and their area and export contributions, increase with climate change
146 due to the predicted increase in watershed yields. Overall, the CSAs occupy between 11% and 45% of the watershed area
147 and contribute between 31% and 81% of the constituents it generates. A comparison with table 1 shows that in nearly all
148 cases these CSAs generate more constituents than the reduction needed to meet the TMDL and therefore that targeting highly
149 efficient BMPs to them should be sufficient to achieve the related water quality goals. The two exceptions are for total
150 nitrogen under current climate and under scenario B1 where the required reductions of 45% and 64%, respectively, exceed
151 the 31% and 56% contributions of CSAs, respectively. In these two cases, in-stream attenuation processes are expected to
152 further reduce nitrogen yield, and if insufficient, then a larger set of CSAs would need to be targeted.

153

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Table 2. Critical Source Area (CSA) Characteristics in the Greensboro

Watershed (adapted from Renkenberger et al. (2015))

Scenario	CSA Contribution (%)					
	TSS		TN		TP	
	Area	Export	Area	Export	Area	Export
Baseline	18	46	11	31	13	39
B1	37	75	28	56	25	60
A1B	45	78	41	72	28	63
A2	45	81	29	57	32	66
CSA Threshold (Kg/ha/yr)	730		16		1.3	

MATERIALS AND METHODS

The principal material used in this study was the hydrologic and water quality SWAT model of the Greensboro watershed developed and calibrated by Renkenberger et al. (2015). The ArcGIS (ESRI Inc.) Geographic Information System (GIS) software, ArcSWAT interface software and the SWAT-CUP optimization program (Abbaspour, 2013) were also used in various parts of the study. Weather time series for current conditions and for climate change scenarios were obtained from the SWAT data web servers at Texas A&M University (<http://globalweather.tamu.edu/> and <http://globalweather.tamu.edu/cmip/>). The investigation was separated into three major steps: 1) identification of density CSAs for BMP implementation; 2) evaluation of climate change effects on CSA-targeted BMPs, and; 3) assessment of climate change impacts on non-CSA targeted BMPs. CSA Density is a measure of the criticality of hotspots defined, for each HRU, as the number of pollutants for which the HRU is a hotspot. It was used here to simplify the analysis by applying a single generic BMP to all hotspots and to assess the extent to which CSAs were remediated by this BMP, with climate change. Both CSA-targeted and non-CSA targeted approaches to BMP implementation were used to assess the potential advantages of each approach in relation to its robustness against climate change. In both cases, BMP efficiencies needed under current climate to meet TMDLs were applied to future climate to evaluate their long-term effectiveness and BMP efficiencies needed to meet TMDLs under future climate conditions were applied to current conditions to assess their present-day effects. The analyses were performed for the current climate baseline and for the SRES climate change scenarios A1B and A2 that were predicted to produce the largest change in watershed behavior.

IDENTIFICATION OF DENSITY CSAS

Density CSAs were identified by processing the per-constituent CSAs obtained by Renkenberger et al. (2015) at the 10% and 20% threshold levels. Logic functions available in common spreadsheet software were used to count and register the number of constituents (TSS, N and P) for which each CSA was a hotspot, at each threshold level, for current climate and for the A1B and A2 scenarios. The logic processing formulas used for this purpose are illustrated by equations 1 and 2.

$$CSA \text{ Density at 10\% Break} = IF(TSS > "CBV_TSS_10", 1, 0) + IF(TN > "CBV_TN_10", 1, 0) + IF(TP > "CBV_TP_10", 1, 0) \quad (1)$$

$$CSA \text{ Density at 20\% Break} = IF(TSS > CBV_TSS_20, 1, 0) + IF(TN > CBV_TN_20, 1, 0) + IF(TP > "CBV_TP_20", 1, 0) \quad (2)$$

Where:

TSS = Total Suspended Sediment

TN = Total Nitrogen

TP = Total Phosphorus

CBV_CC_LV = Critical Break Value for Constituent CC at CSA level LV

Note: As set up in MS Excel, if a logic statement is true then the value of that statement is 1. If false then the value of an individual statement is 0. Note that this method does not allow for overlapping or recounting hotspot areas.

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181 With three constituents considered in this analysis, the resulting density CSA classification represents HRUs that are hotspots
182 for all three constituents (density 3) for 2 constituents (density 2) or for a single constituent (density 1). A BMP prioritization
183 scheme may consider density 3 CSAs as having the highest priority for implementation as they contribute excessive amounts
184 of TSS, TN and TP. The contribution of these critical hotspots to constituent generation within the watershed were calculated
185 to determine whether targeting them would be sufficient to reach the established TMDLs. These calculations were repeated
186 with hotspots of both density 2 and 3 (i.e. density 2+3 hotspots) and for density 1+2+3 CSAs (all hotspots) to identify the
187 level of criticality required to attain the target TMDLs under the three investigated climate scenarios. Hotspot density was
188 mapped using ArcGIS to visually appraise hotspot criticality in the study watershed, as a function of climate.

189 **BMP IMPLEMENTATION ON DENSITY CSAS**

190 A generic BMP was targeted to the density CSAs at the level (1+2+3, 2+3 or 3) needed to attain the target TMDLs. The
191 BMP was designed to remove a fixed fraction of the HRU export of each constituent, calculated as the ratio between the
192 reduction required to meet the TMDL (listed in table 1) and the export contribution of density CSAs (relative to the total
193 contribution of watershed HRUs). These removal fractions, expressed as percentages, correspond to the efficiency that a
194 BMP targeted to density CSAs needs to have to meet the TMDL for a particular constituent:

$$BMP_{TSS}^{ \% ef} = 100 \ TSS^{R \%} / \sum_{D=d}^3 TSS_D^{TEx \%} \quad (3)$$

$$BMP_{TN}^{ \% ef} = 100 \ TN^{R \%} / \sum_{D=d}^3 TN_D^{TEx \%} \quad (4)$$

$$BMP_{TP}^{ \% ef} = 100 \ TP^{R \%} / \sum_{D=d}^3 TP_D^{TEx \%} \quad (5)$$

Where

BMP_{XX}^{eff} = BMP removal efficiency for TSS, TN, or TP

$XX^{R\%}$ = TSS, TN or TP removal percentage per TMDL (table 1)

$XX_D^{Tex\%}$ = TSS, TN or TP percentage of total export by CSAs at density rating d

d = bottom of the target CSA density range (1, 2 or 3)

As an example of these calculations, consider the TSS component of a BMP designed for current climate, where a 33% reduction in sediments is needed to meet the TMDL (table 1), this BMP would need to be designed with a sediment reduction efficiency of 72% if density CSAs contribute 46% of the total amount of sediments generated by watershed HRUs (i.e. $0.72 = 33\% / 46\%$). In other words, in this example, if sediment yield over the watershed, without BMPs, is denoted Y, then the amount of sediments that the BMP has to remove is: $33\% Y = 0.72 \times 46\% Y$, or 72% of the sediments contributed by CSAs. This approach is expected to result in a slight over-design of BMPs as it does not account for potential in-stream attenuation processes. BMP efficiencies were calculated similarly for other constituents (TN and TP). These calculations were performed to produce three BMP designs for TMDL attainment: a design based on current climate conditions (baseline), and an additional design for each of SRES scenarios A1B and A2. The density CSAs used in these designs were at the same levels (either 3, 2+3 or 1+2+3) to ease comparisons.

The SWAT model of the Greensboro watershed was used to simulate the study area's hydrologic and water quality response with the designed generic BMPs placed on target density CSAs (BMP option 10 in SWAT). The designed reductions for nitrogen were used for both organic and soluble nitrogen in those BMPs while those for phosphorus were used for both particulate and soluble phosphorus. Two sets of three simulations were performed. In the first set, the BMPs designed for current climate were implemented on the density CSAs identified for the current climate and the watershed's response was simulated with each of the three climate scenarios (current, A1B and A2). This was done to evaluate the robustness against climate change of BMPs designed only to address current water quality challenges. In the second set, three simulations were also performed (one for each climate scenario) but this time, the BMPs designed to reach the TMDL under scenario A2 were implemented on the density CSAs identified for the A2 scenario. This was done to determine whether a design based on future conditions would be effective under current climate and whether a design based on scenario A2 is also effective under climate predicted for the A1B scenario. This second set of simulations will be referred to as non-stationary in the following, as it presumes that climate is changing and is hence not stationary.

Simulation results were processed to locate those CSAs that remain after BMPs are implemented. The CSA thresholds used for this step were the same ones used previously (table 2) and these CSAs were classified into the density groups defined earlier. These residual post-BMP density CSAs were mapped to appraise visually the effectiveness of each design,

221 with climate change, and their areas were computed and tabulated. Averages of the annual yields of TSS, TN and TP,
 222 predicted at the watershed outlet, were also computed from simulation outputs and compared to the target TMDLs using the
 223 relative error formula:

$$ERROR_{XX} = 100 \frac{Y_{XX}^{annual} - TMDL_{XX}}{TMDL_{XX}} \quad (6)$$

Where:

$ERROR_{XX}$ = Relative TMDL attainment error for constituent XX (TSS, TN, TP)

Y_{XX}^{annual} = Average of simulated annual yields, with BMPs, for constituent XX

$TMDL_{XX}$ = TMDL for constituent XX

224

225 **BMP PARAMETERIZATION ON NON-CSA TARGETS**

226 Implementation of BMPs on non-CSA targets may be required for watersheds where an appropriate hydrologic and water
 227 quality model is unavailable or where uncalibrated model predictions are in doubt and the lack of gaging data precludes
 228 calibration. The present study simulated such a situation by targeting all agricultural and urban land, in the Greensboro
 229 watershed, for BMP implementation. In similarity to the CSA-targeted approach described earlier, generalized BMPs were
 230 designed for implementation over non-CSA targets. However, in contrast to that prior approach, a pair of BMPs were
 231 designed in each study scenario: one for agricultural land and another for urban land. In addition, instead of the forward
 232 approach used for BMP design in the prior analysis, an inverse approach (optimization) was applied for the non-CSA
 233 designs. For this purpose, synthetic time series, representing the desired levels of TSS, TN and TP at the watershed outlet,
 234 were derived from the results of prior watershed response simulations with no BMPs. These synthetic series were constructed
 235 by subtracting the required TMDL reduction levels from (table 1) from annual predictions obtained from BMP-less
 236 simulations. Generalized BMPs were then positioned over all agricultural and urban lands in the SWAT model of the
 237 Greensboro watershed, and the SWAT-CUP software was used to parameterize these generalized BMPs, separately for
 238 agricultural and urban land, such that their combined addition to the model would reproduce the synthetic outlet time series.
 239 This parametrization was performed to produce three pairs of BMP designs, one pair each for current climate, SRES A1B
 240 and SRES A2. The SUFI-2 optimization algorithm (Abbaspour et al., 2004) was selected for this purpose as it is the most
 241 widely used in conjunction with SWAT-CUP. The parameter set for optimization was defined to include all TMDL related
 242 parameters for the generalized BMPs: sediment reduction, organic nitrogen reduction, soluble nitrogen reduction, particulate
 243 phosphorus reduction and soluble phosphorus reduction. The selected SWAT land use codes over which to perform the
 244 optimization were HAY and AGRR for agricultural land and URLD, URMD, URHD and UIDU for urban land. The range
 245 of parameter values to optimize over (reduction levels) was set as 0% to 100% for all parameters. The results of this
 246 optimization-oriented approach to BMP design were evaluated using diagnostic statistics commonly used for model

247 calibration: Pearson's correlation coefficient (r) and the Nash-Sutcliffe Efficiency (NSE; referred to as coefficient of
 248 determination, R^2 , in statistics, cf. equation 3 in Nash and Sutcliffe (1970)):

$$r = \frac{\sum_{i=1}^n (Y_i^{obs} - \bar{Y}^{obs}) (Y_i^{sim} - \bar{Y}^{sim})}{\sqrt{\sum_{i=1}^n (Y_i^{obs} - \bar{Y}^{obs})^2 \sum_{i=1}^n (Y_i^{sim} - \bar{Y}^{sim})^2}} \quad (7)$$

$$NSE = 1 - \frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^n (Y_i^{obs} - \bar{Y}^{obs})^2} \quad (8)$$

Where for all equations:

Y_i^{obs} = Observed values at given time step

Y_i^{sim} = Simulated values at given time step

\bar{Y}^{obs} = Observed mean

\bar{Y}^{sim} = Simulated mean

249

250 The BMPs designed for non-CSA targets were further evaluated in the same way as those designed earlier for density
 251 CSAs. They were implemented in SWAT models of the Greensboro watershed and subjected to baseline and SRES A2
 252 scenarios to evaluate their robustness over stationary and non-stationary climate. Residual density CSAs that remained after
 253 BMP implementation were identified and mapped. The TMDL attainment error produced by each design (equation 6) was
 254 computed and compared across designs and climate scenarios.

255 RESULTS AND DISCUSSION

256 IDENTIFICATION OF DENSITY CSAs

257 Constituent density maps of Critical Source Areas (CSAs) in the Greensboro watershed are presented in figure 2 for the
 258 10% and 20% CSA threshold levels, with current and future climate. At the 10% threshold, CSAs correspond to HRUs that
 259 generate more than 1030 Kg/ha/yr of sediments, 24 Kg/ha/yr of nitrogen or 1.9 Kg/ha/yr of phosphorus. These CSAs are
 260 mostly single-constituent hotspots (density 1) and, as discussed in Renkenberger et al. (2015) the proportion of the watershed
 261 that they occupy increases substantially under future climate. The predominance of density 1 CSAs at the 10% level indicates
 262 that the most sensitive areas of the watershed are each quite specific in the type of potential pollutant that they generate. If
 263 targeting these areas was sufficient to reach the desired TMDLs, then implementing constituent-specific BMPs there would
 264 likely be the most economical option. In the baseline case (current climate) the sum of density 1, 2 and 3 CSAs (10% level)
 265 occupy 13.6% of total watershed area, but, unfortunately contribute only 31% to TSS, 30% to TN and 30% to TP, which is
 266 insufficient to reach the TSS and TN TMDLs listed in table 1. Accordingly, as far as baseline conditions are concerned (at
 267 least) BMP implementation should target the broader set of CSAs identified at the 20% level.

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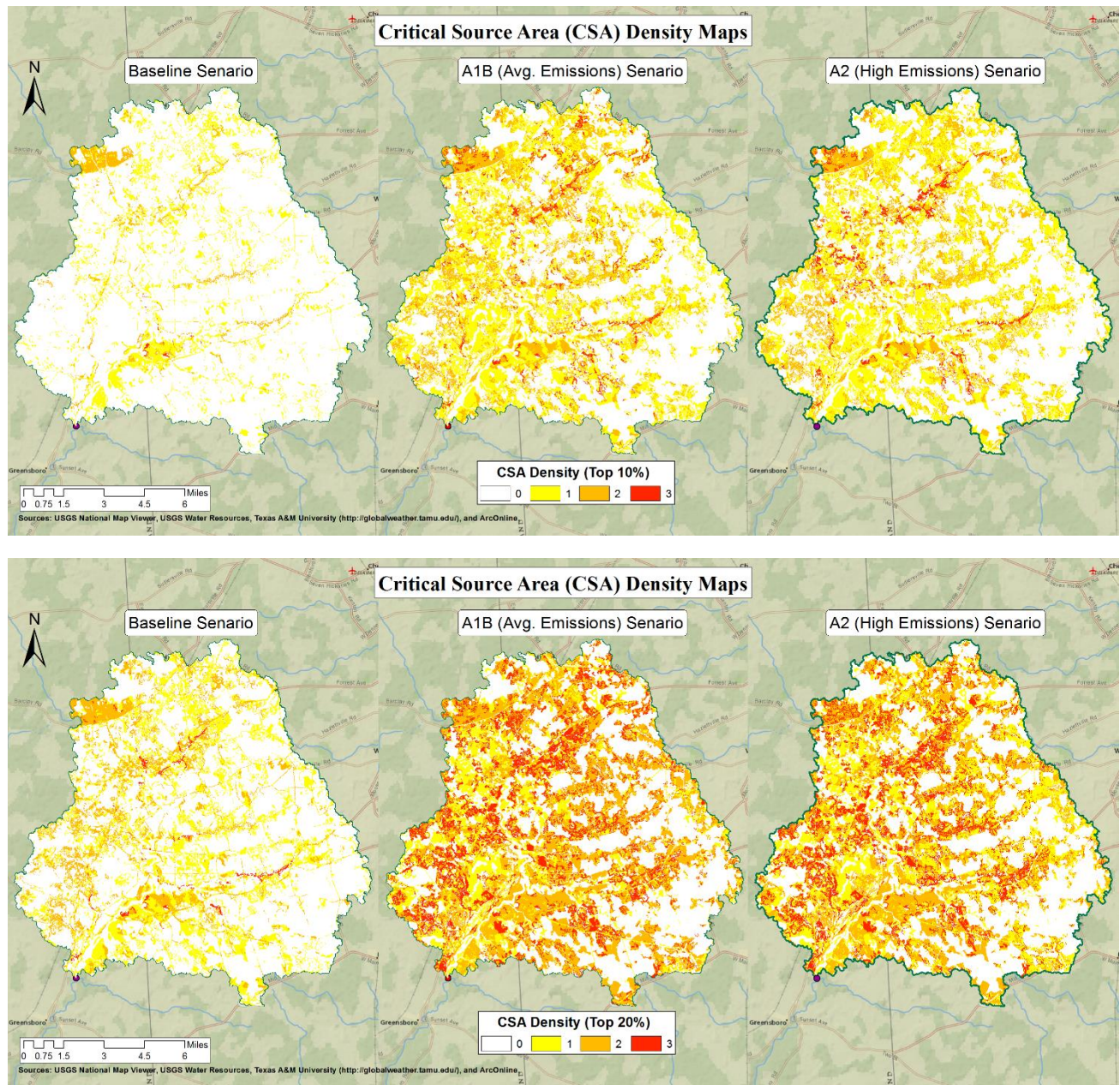


Figure 2: CSA Density Maps at Thresholds of 10% (Top) and 20% (Bottom) for the Baseline and Scenarios A1B and A2

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270 At the 20% threshold level, CSAs consist of those HRUs that generate constituents in excess of the levels listed in table
 271 2 (bottom row) and, in similarity with the 10% CSAs, the fraction of the watershed that they occupy increases substantially
 272 with climate change. In contrast to the 10% CSAs, the 20% CSAs are mostly of density 1 only under current climate (64%
 273 of CSA area), and it is the density 2 CSAs that dominate under A1B (46% of CSA area) and A2 (38% of CSA area) scenarios
 274 (table 3). The manner in which density CSAs expand, from the 10% to the 20% level, differs between the baseline and the
 275 two future scenarios. Under current climate, CSA expansion occurs primarily via the addition of new areas and secondarily
 276 by conversion of single-constituent CSAs to multi-constituent CSAs (density increase). Conversely, under future climate,

density increases dominates CSA expansion and the total area occupied by CSAs remains nearly constant between the 10% and 20% level. The density CSAs are furthermore quite similar between the A1B and A2 scenario, covering essentially all agricultural and urban land in the watershed, in addition to some non-forested natural areas. As discussed by Renkenberger et al. (2015) this suggests that the increased annual rainfall, predicted under future climate scenarios, will be sufficient to overwhelm the buffering capacity of agricultural lands, turning them mostly into hotspots. It further suggests that, whether the future occurs along scenario A1B or A2, nearly all agricultural and urban lands may require some form of BMP to meet established TMDLs.

Table 3. Contribution of Density CSAs (20% level) to Watershed Area and Constituent Generation

Scenario	CSA Density	Density CSA Contribution (%)			
		Area	Export		
			TSS	TN	TP
Baseline	3	1	4	2	3
	2+3	11	24	28	25
	1+2+3	31	54	57	53
A1B	3	14	36	26	28
	2+3	41	69	70	69
	1+2+3	58	85	87	78
A2	3	13	34	26	25
	2+3	35	66	61	62
	1+2+3	58	86	86	79

Under the baseline scenario, hotspots for 2 and 3 constituents (density 2+3) generate almost half of the total produced by all CSAs, while occupying just 1/3 of the total hotspot area. The density 2+3 CSAs further generate most of the constituents produced with climate change scenarios A1B and A2. Taken together, these results suggest that for both current and future conditions, prioritizing BMP implementation on multi-constituent hotspots (density 2 and density 3) may be a useful strategy to obtain significant water quality improvements at a lesser cost than if all CSAs are targeted. For the Greensboro watershed, a comparison of results in table 3 with TMDL requirements in table 2 shows that, for scenario A1B, the TMDLs may indeed be reached by targeting only density 2 and 3 CSAs. Unfortunately, this does not hold for either current conditions or for scenario A2, where the density 1 CSAs also need to be targeted. For this reason, the total of all CSAs (density 1+2+3) will be used as BMP targets in the remainder of this study. In a policy context, where BMP implementation may be effected over a sequence of years or decades, targeting the higher density hotspots first would however remain the preferred approach based on the above results. This approach may provide both, an initial improvement in water quality, and, simultaneously, the time needed to develop and implement the social programs needed to enhance BMP adoption by the remaining watershed stakeholders, and prolong water quality improvements into a sustainable future.

BMP IMPLEMENTATION ON DENSITY CSAS

Table 4 presents results of BMP efficiency calculations, and implementation area, for designs based on current climate and on scenarios A1B and A2 (non-stationary designs) when BMPs are aimed at density 1+2+3 CSAs. With today's climate, the BMPs need to achieve from 43% to 79% reductions in constituent generation and be sited over 31% of the watershed area to meet the Chesapeake Bay TMDLs. When designed to meet the TMDLs with future climate (non-stationary), the BMPs need to effect reductions in potential pollutants ranging from 68% to 82% and be implemented over 58% of the study watershed. In other words, designing BMPs that will remain effective for sediment and phosphorus under the selected climate change scenarios, will require them to be from 33% to 67% more efficient at preventing the loss of these constituents than today, and they will need to be placed over nearly twice as much of the watershed's surface. For nitrogen, approximately the same BMP efficiency of nearly 80% will be needed in all scenarios, but, again, they will need to be implemented on twice as much area in the future as compared to today.

**Table 4: BMP Removal Efficiencies and Area Fractions to Meet
Relative TMDL Reductions at the Land Surface by Climate Scenario**

Design Scenario	BMP-Targeted Area	Required BMP Efficiency		
		TSS	TN	TP
Baseline	31%	61%	79%	43%
A1B	58%	81%	78%	68%
A2	58%	82%	74%	72%

The effects of BMPs designed for current climate conditions on the watershed's response, under both current and future climates, is presented graphically in figure 3. These effects are displayed in terms of the residual density CSAs (20% level) that are predicted to remain after BMP implementation, as identified from SWAT simulations with BMPs in place. As expected, the BMPs are found to be effective in reducing the amount of CSAs under current weather, resulting in just 5% of the watershed area that can still be classified as a hotspot. Eighty percent of these are phosphorus CSAs, owing most probably to the relatively low BMP efficiency designed for CSA control in this case (43%). Despite this small amount of residual CSAs, the watershed is predicted to meet the TMDLs for both sediment and phosphorus, with an error of the order of just 1% (table 5). The case of nitrogen is slightly different however as, after BMP implementation, less than 0.5% of the watershed area is occupied by residual CSAs for nitrogen under current climate and yet the nitrogen TMDL is predicted to be exceeded by 24%. The reduction of nitrogen yield produced by BMPs (32%) is substantial, but comes short of the 45% needed to reach the TMDL (table 1). Since the BMP efficiencies were designed specifically to reach the TMDLs, there must be a nitrogen contribution at the watershed outlet that is not controlled by SWAT's generic BMP (for example baseflow) and its contribution can be estimated as 29% of the total nitrogen yield of the watershed (before BMP implementation).

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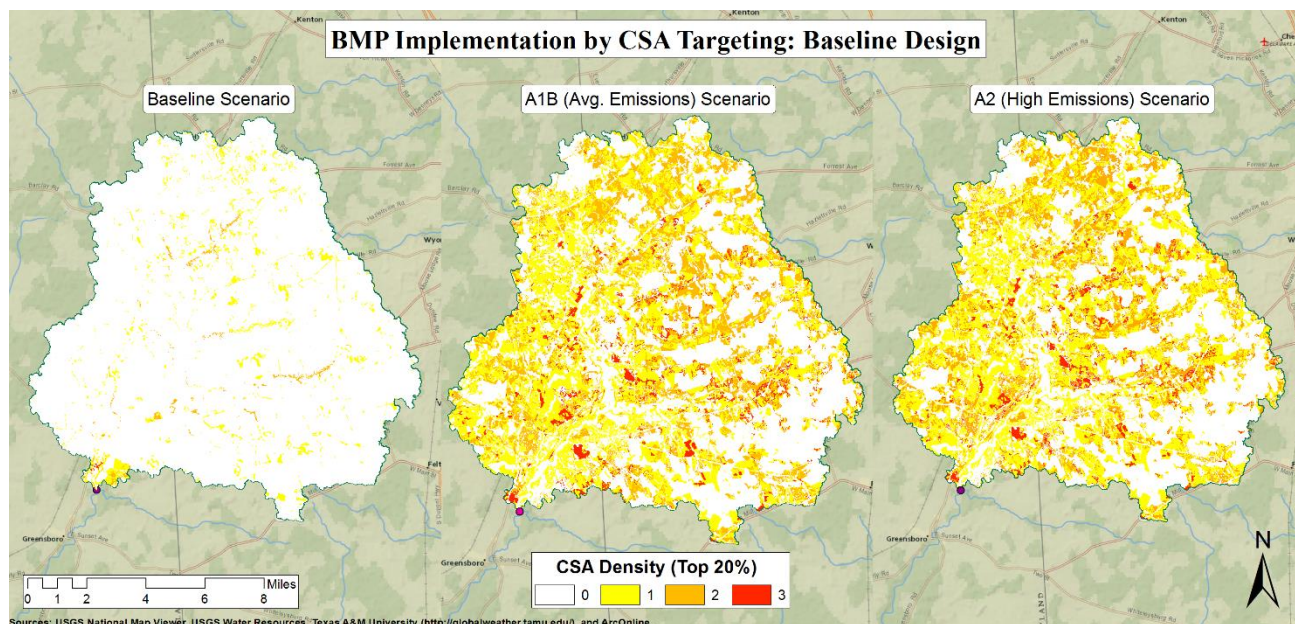


Figure 3: Residual CSA Density with Baseline BMP Design Subjected to Current, A1B and A2 Climate Conditions

331 BMPs designed for the current climate are not effective at controlling constituent exports under climate change in the
 332 Greensboro watershed. The residual CSAs that remain after such BMPs are subjected to the A1B scenario occupy 49% of
 333 the watershed area, and they grow to 51% of the area under scenario A2 (figure 3). Approximately 80% of these residual
 334 hotspots produce excessive amounts of sediments while 40% or fewer generate too much nutrients. Accordingly, all TMDLs
 335 are exceeded by this design which is not robust against climate change. The watershed's yield of sediment and phosphorus
 336 are more than twice their respective TMDLs and phosphorus yield is of the order of 70% above the TMDL for both A1B
 337 and A2 scenarios (table 5). In this watershed, climate change effectively negates the investments in BMP implementation
 338 that were performed to meet TMDLs under current climate. The lack of future effectiveness of BMPs designed based on
 339 today's conditions results from the expansion of hotspot areas under climate change, and the larger amount of constituents
 340 generated by HRUs with future climate, both of which are consequences of increased annual rainfall and increase frequency
 341 of severe storms, as discussed by Renkenberger et al. (2015). Bosch et al. (2014) found a similar decrease in BMP
 342 effectiveness for watersheds in the Lake Erie region while Woznicki et al. (2011) and Van Liew et al. (2012) found no change
 343 for watersheds in Nebraska. This trend is as expected given that, of the three US climatic regions in these studies (including
 344 the present study) the Northeast is expected to see the largest changes in annual rainfall and precipitation intensity under
 345 climate change, followed by the Midwest and the central part of the Great Plains regions, respectively (Melillo et al., 2014).
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Table 5: BMP Removal Efficiency Performance (Targeting by CSA Density)

Design Scenario	Evaluation Scenario TMDL Attainment Error (%)								
	Baseline			A1B			A2		
	TSS	TN	TP	TSS	TN	TP	TSS	TN	TP
Baseline	1.4	23.6	0.5	114.3	141.0	63.6	126.4	143.4	79.1
A2	-51.9	0.8	-35.4	-2.3	96.0	-7.9	1.2	100.8	0.2

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351 Figure 4 presents the effects of BMPs designed for climate scenario A2, on the watershed's response to current and future
 352 climates. In this case, where non-stationary climate is considered in the design, the residual CSAs remaining after BMP
 353 implementation occupy 5% or less of the watershed area, for all climate scenarios. The majority of these residual CSAs
 354 (60% to 75%) generate only excessive phosphorus, because of the lower required efficiency required of BMPs for this
 355 constituent. This non-stationary BMP design is effective at meeting the Chesapeake Bay TMDLs for the 3 constituents under
 356 today's conditions and also meets TMDLs for both sediment and phosphorus under both future climate scenarios (table 5).
 357 The only shortcoming of the design is nitrogen control in future scenarios where the TMDL is exceeded by 100%. Here
 358 again, as BMPs were designed to attain the TMDL, it appears that a fraction of the watershed's nitrogen yield (of the order
 359 of 42%) is not reachable by SWAT's generic BMP (possibly a baseflow contribution).

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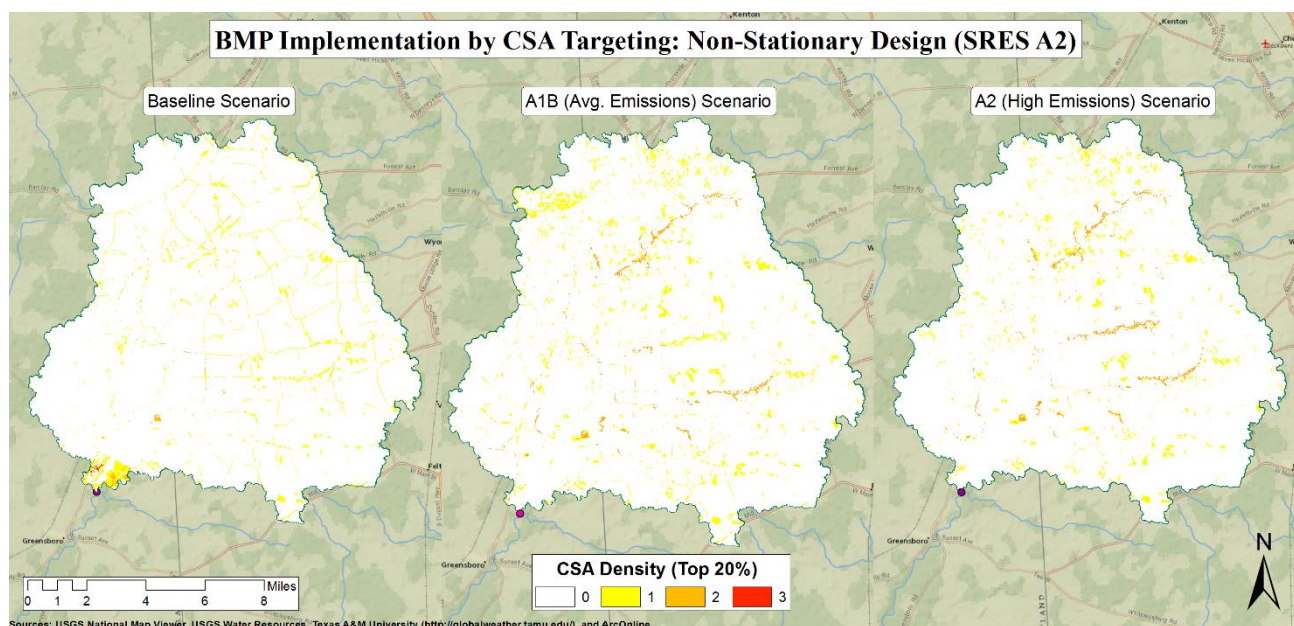


Figure 4: Residual CSA Density with A2 BMP Design Subjected to Current, A1B and A2 Climate Conditions.

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362 The present results suggest that, for long-term efficiency, BMPs should be designed by considering climate non-
 363 stationarity and implemented on the corresponding CSAs. Such BMPs will be effective today and will not need to be

redesigned or reimplemented, which can often be more costly than building them initially. Design and implementation by the A2 climate scenario (20% fixed threshold) will require targeting 58% of the land area with BMP efficiencies of 82%, 74% and 72% for TSS, TN and TP respectively. The large target area suggests a time-stepped approach for implementation which, as proposed earlier, may focus first on density 2 and 3 CSAs, and would be accompanied with social programs aimed at increasing BMP adoption, over time, by the majority of watershed stakeholders. Such an approach would be expected to provide sustainable improvements in water quality with minimal loss of invested resources.

BMP PARAMETERIZATION ON NON-CSA TARGETS

BMP designs for the alternative targeting scenario where, rather than CSAs, BMPs are to be implemented on all agricultural and urban land, are presented in table 6. For the design based on current climate conditions, the optimization of BMP efficiencies (inverse approach) was successful for all constituents, with diagnostic statistics very near 1.0 (table 7). In this case, to meet the Chesapeake Bay TMDLs, the designed BMPs need from 30% to 60% efficiency in urban areas and from 30% to 90% efficiency in agricultural areas. BMP design was also successful under the assumption of non-stationary climate, except for total nitrogen. BMP designs for the A1B and A2 scenarios resulted in negative Nash-Sutcliffe coefficients for TN, indicating that the target levels of nitrogen yield (adjusted to meet the TMDL) could not be reached (table 7). As a result, the BMP efficiencies for nitrogen removal reached their upper limit of 100%. BMP efficiencies for other constituents ranged from 55% to 90% on urban land and 60% to 95% on agricultural land. In similarity with BMPs targeted to density CSAs, those targeted directly to urban and agricultural land need higher efficiencies when designed for future climate than for current climate. However, those designed here, under current climate, occupy more of the watershed area (55%) than in the CSA approach (31%) and hence their required efficiencies are lower than in the CSA case.

Table 6: BMP Parameterization to meet 2025 TMDL Targets (% Removal)

Design Scenario	Land Use	Sediment	Organic Nitrogen	Soluble Nitrogen	Particulate Phosphorus	Soluble Phosphorus
Baseline	Urban	55%	40%	35%	60%	30%
	Agricultural	50%	60%	90%	50%	30%
A1B	Urban	85%	>100%	>100%	75%	55%
	Agricultural	95%	>100%	>100%	85%	60%
A2	Urban	90%	>100%	>100%	75%	55%
	Agricultural	95%	>100%	>100%	85%	60%

Table 7: BMP Parameterization Diagnostic Statistics By Design Scenario

Statistic	Baseline			A1B			A2		
	TSS	TN	TP	TSS	TN	TP	TSS	TN	TP
r	1.00	0.96	1.00	0.91	0.82	0.99	0.88	0.90	0.98
NSE	0.99	0.94	0.97	0.87	-3.17	0.93	0.87	-4.17	0.98

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The effects of BMPs designed for agricultural and urban land, under current climate, on the watershed’s response for current and future climates, are mapped in figure 5. The design is quite effective when exposed to current climate, with residual density CSAs that occupy just 8% of the watershed area after BMP implementation. Some of the residual CSAs are non-forested natural land that was not targeted for BMP implementation here, and hence continues to generate sediments above the CSA thresholds. The design is found to meet the Chesapeake Bay TMDLs to within 1%, at worst, for all constituents (table 8). This design is however not robust against climate change scenarios A1B and A2, which is similar to what was observed in the density-CSA targeted case. Here, residual CSAs occupy from 36% (A1B) to 39% (A2) of the watershed surface, and are mostly of density 1 (single constituent). The degree to which the TMDLs are exceeded under future climate is approximately 50% for TP and 100% for TSS and TN (table 8), with relatively minor differences between scenarios A1B and A2.

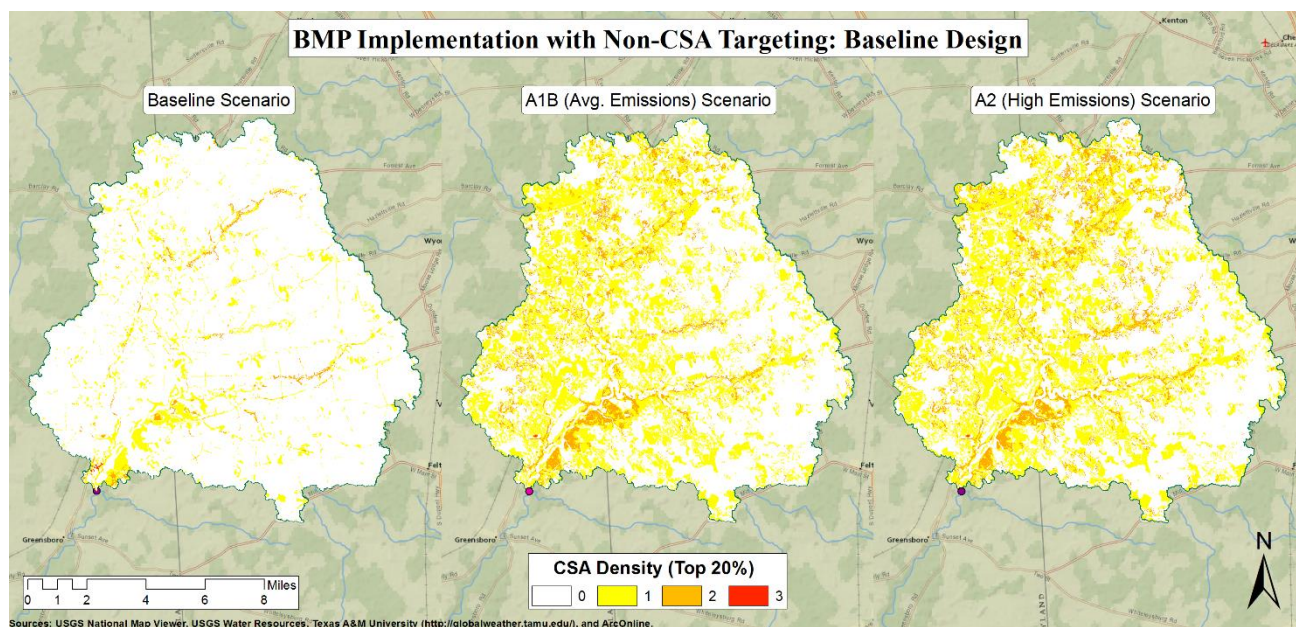


Figure 5: Residual CSA Density with Baseline BMP Design for Agricultural and Urban Land, Subjected to Current, A1B and A2 Climate Conditions.

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The predominance of density 1 residual CSAs under climate change (figure 5) is interesting given that density 2 CSAs were the most frequent in the watershed before BMP implementation (figure 2). This indicates that the BMP design performed under current climate for agricultural and urban lands will remain effective at controlling at least one potential pollutant in the future. Climate change will however cause one other potential pollutant to be produced at excessive levels on each of the locations where BMPs were implemented, generating a need for redesign of the BMPs. The constituents that

are newly generated vary by CSA, for example excessive phosphorus may be produced in an area where nitrogen remains under control, and excessive sediments may be generated in another area where phosphorus remains controlled. A false sense of security may have resulted from implementing BMPs on all agricultural and urban lands in the watershed (an over-design relative to a CSA-targeted approach), and stakeholder frustrations may emerge as water quality remains unimproved, or worsens, with the changing climate.

Table 8: BMP Removal Efficiency Performance (Non-CSA Targeting)

Design Scenario	Evaluation Scenario TMDL Attainment Error (%)								
	Baseline			A1B			A2		
	TSS	TN	TP	TSS	TN	TP	TSS	TN	TP
Baseline	-3.3	1.0	-5.5	114.3	106.1	59.7	102.8	96.5	47.7
A2	-49.2	-27.7	-35.0	-1.9	57.4	0.2	-2.3	48.8	-6.4

The response of the Greensboro watershed to current and future climate when implemented BMPs designed to meet the Chesapeake Bay TMDLs under scenario A2 are presented in figure 6. The resulting BMPs, designed considering climate non-stationarity, are clearly more robust against climate change than when designed for current conditions. The residual CSAs occupy 12% of the watershed area under scenarios A1B and A2, and just 5% under current climate. TMDLs for all constituents are met under current condition (table 8) and those for sediment and phosphorus are also attained under climate change. The only non-attainment is for nitrogen under scenarios A1B and A2 where the TMDL is exceeded by approximately 50%. This level of exceedance is half of that obtained earlier for BMP designs targeted at density CSAs (forward design) and results from the higher BMP design efficiencies obtained with the optimization approach (inverse method) used here. The inverse approach tacitly incorporates the effects of nitrogen sources that may not be controllable by SWAT's generic BMPs as it automatically updates the BMP efficiencies needed (up to 100%) to attain the TMDLs at the watershed outlet. The approach is substantially more computationally demanding than setting BMP design efficiencies from the required TMDL reductions and export contributions of CSAs (forward design) but has the demonstrated advantage that it will adjust design efficiencies to minimize TMDL attainment errors, even in the presence of extraneous sources of a constituent that may not be directly controllable by BMPs (eg. a possible contribution from baseflow). Ideally, such extraneous contributions would be controlled at their sources, but they may be located in distant watersheds, and have travelled over decades to reach the study area's outlet, such that the results of their treatment (while important and needed) would be expected to undergo a similar lag before actual effects are observed near the Bay.

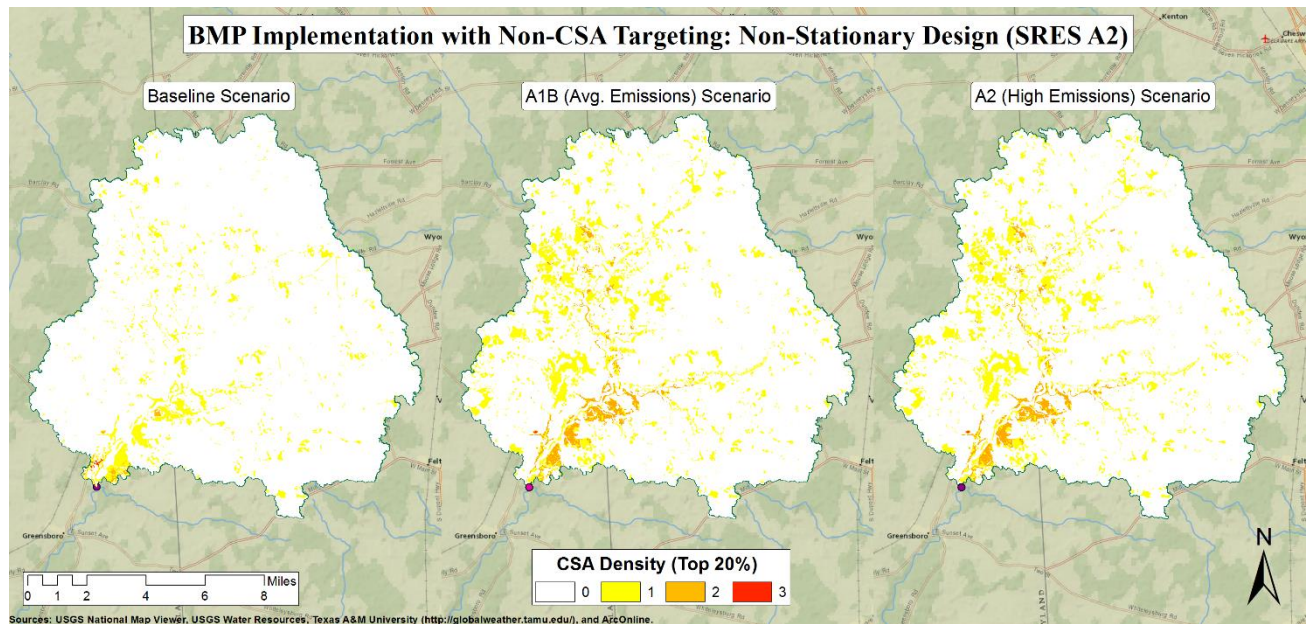


Figure 6: Residual CSA Density with A2 BMP Design for Agricultural and Urban Land, Subjected to Current, A1B and A2 Climate Conditions.

SUMMARY AND CONCLUSIONS

This study investigated the potential impacts of climate change on BMP effectiveness in an agricultural watershed located within the Chesapeake Bay basin, in the US Northeast climate region, Atlantic Coastal Plains physiographic region. The region is expected to undergo the largest increases in annual rainfall and storm intensity as a result of climate change. Prior results of Renkenberger et al. (2015), based on SWAT simulations, were used to identify Critical Source Areas (CSAs) of sediment, nitrogen and phosphorus in the watershed, at two threshold levels (10% and 20%), under current climate and SRES scenarios A1B and A2. The threshold levels correspond to the proportion of HRUs, ranked from highest to lowest generators of constituents, that are considered hotspots under current climate. A set of target TMDLs for sediments, nitrogen and phosphorus were established based on EPA Chesapeake Bay TMDLs for the Choptank River and on the predicted response of the watershed.

A method for prioritizing CSAs for BMP implementation was developed and analyzed. The method classifies CSAs based on the number of potential pollutants that are generated in excess by each hotspot. A density 2 CSA, for example, is one that generates excessive amounts of 2 constituents, under a given climate scenario. Results indicated that targeting BMPs to CSAs identified at the 10% level would be insufficient to attain the TMDLs under all possible future climates (current, A1B and A2). At the 20% level, density 2 and 3 CSAs were found to generate most potential pollutants under climate change, and almost half of the total (while occupying 1/3 of the watershed area) under current climate. This suggested that a prioritization scheme for BMP implementation may favorably focus first on the higher density CSAs in this watershed.

451 However, it was also found that CSAs of all densities eventually need to be targeted to reach the Bay TMDLs and therefore,
452 while a density-based prioritization may be effective to optimize resource use during the initial phase of implementation, it
453 will need to be expanded to the remaining CSAs in the longer term. Climate change scenarios A1B and A2 caused a
454 substantial increase in the BMP target area required to meet Bay TMDLs, from 31% of the watershed surface under current
455 climate, to 58% with climate change, which includes all agricultural and urban lands, plus some non-forested natural areas.
456 This result suggested that achieving sustainable water quality improvements in the watershed will require the involvement
457 of most of its stakeholders, and consequently, that social programs aimed at increasing BMP adoption will be key to reaching
458 water quality goals in the study area, with a changing climate.

459 BMPs were designed for the watershed's CSAs, with the efficiencies needed to attain the target TMDLs under current
460 climate and under climate change. These BMPs were then tested against all climate scenarios, using SWAT, to evaluate their
461 robustness. BMPs with removal efficiencies of 61% for TSS, 79% for TN and 43% for TP were effective in reaching the
462 sediment and phosphorus TMDLs under current climate (target area of 31% of the watershed surface), and slightly less
463 effective for nitrogen due to extraneous sources (23% exceedance of TMDL). These BMPs were, however, not effective
464 under climate change scenarios A1B and A2, and led to exceedance of TMDLs by 64% to 141%. BMPs designed for future
465 climate (scenario A2; target area of 58% of the watershed surface) with removal efficiencies of 82% for TSS, 74% for TN
466 and 72% for TP were effective at reaching the TMDLs under current climate and effective at reaching sediment and
467 phosphorus TMDLs under future climate. These BMPs could not reach the target nitrogen TMDL due to extraneous sources
468 that are not controlled by BMPs (eg. baseflow contribution).

469 An optimization technique was developed and used to design BMPs for all agricultural and urban lands in the watershed
470 (55% of the watershed surface area), as an alternative to CSA-based targeting. Their robustness was assessed by testing
471 them against all climate scenarios using SWAT simulations. Under current climate, BMPs with removal efficiencies of 30%
472 to 90% (on a per-constituent basis) were able to meet the Bay TMDLs. However, when subjected to climate change, these
473 BMPs lost their effectiveness, and the watershed exceeded the TMDLs by 48% to 114%. Optimizing BMP efficiencies to
474 meet the Bay TMDLs under climate change scenario A2 was successful for sediments and phosphorus, with BMP
475 efficiencies of 55% to 95%, but not for nitrogen where design efficiencies maxed out at 100%. With these BMPs, the
476 watershed attained all current climate TMDLs, as well as TMDLs for sediment and phosphorus under the A1B and A2
477 scenarios. As with prior cases, non-attainment of the nitrogen TMDLs under climate change was attributed to extraneous
478 sources that are not controlled by BMPs. The attainment error was however less than for CSA-targeted BMPs where design
479 efficiencies were computed using a forward (rather than optimization) approach.

480 Results of this study indicate that, in agricultural areas of the US Northeast climate region, where the Chesapeake Bay

481 watershed is located, BMPs designed to reach the Bay TMDLs under current climate conditions will become insufficient
482 with climate change. In the study watershed for example, the increase in annual precipitation and storm intensity resulting
483 from climate change was predicted to cause CSAs to nearly double in area, to a point where they cover the majority of
484 agricultural and urban lands, and even some non-forested natural zones. Accordingly, it is anticipated that new BMPs will
485 need to be implemented in large portions of agricultural watersheds in the US Northeast that are not currently identified as
486 hotspots, just to uphold the water quality improvements resulting from current BMPs. In addition, the present results
487 indicated that while current climate CSAs may have been hotspots for a single constituent, climate change is predicted to
488 cause them to produce excessive amounts of multiple constituents. Accordingly, if existing BMPs were designed to address
489 single-constituent problems, they will need to be re-designed or retrofitted to mitigate their expanded production of potential
490 pollutants, caused by the changing climate. Addressing these impacts of climate change on sustainable water quality
491 improvements and BMP adoption in the region is likely to be both expensive and frustrating. Wherever possible, in the US
492 Northeast, BMP design and implementation plans should focus on expected conditions resulting from climate change, rather
493 than current conditions, to reduce the need for costly future redesigns of BMPs. In addition, as the surface area occupied by
494 hotspots is expected to expand to, essentially, all zones productively used by humans, the participation of all community
495 stakeholders will become crucial to achieving sustainable water quality. The development of effective strategies for
496 enhancing such participation is therefore likely to become as important as technical skill, in this region, to ensure a healthy
497 and productive future that is robust against climate change (Chanse et al., 2014; Leisnham et al., 2013).

498 **ACKNOWLEDGEMENTS**

499 This project was supported by Competitive Grant no. 2012-51130-20209 from the USDA National Institute of Food and
500 Agriculture.

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