A Cost Effective Modeling Approach for Targeting the Location of Best Management Practices within a Rapidly Growing Urban Watershed to Achieve Regional Water Quality Standards

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Abstract

Water runoff from residential developments is the third leading source of water pollution in the United States. A linear programming model is developed using nutrient runoff loadings for nitrogen and phosphorous generated by the Reedy River Model Simulation Program to estimate the potential cost savings of using a basin wide targeted approach for the location of best management control practices relative to a uniform control practice that requires each sub-basin within a rapidly grown urban watershed to decrease nitrogen and phosphorous runoff by the same percentage to achieve a downstream water quality target. In one policy scenario the targeted approach reduced control cost at the basin outlet by 42% relative to instituting a uniform control standard in each sub-basin within the watershed.

Introduction

Due to increased demands for water resources associated with population growth and ever-changing water quality regulation, understanding the impact of urban development on riverine systems is critical for water quality policy. The local protection of water resources is complex, largely due to stormwater runoff which is a classic form of non-point source pollution. Residential development and land deforestation increased stormwater runoff volume that once infiltrated into the soil, but now flows over impervious surfaces into nearby streams and lakes. Residential runoff washes pollutants from the land surface into receiving water bodies. Non-point pollution runoff is the leading source of surface water contamination in the United States (Meixler and Bain, 2010). Billow (2002) noted that suburban residential development, a specific source of non-point pollution is an important source of water pollution. Residential streets and driveways commonly contribute oils and metals from cars and trucks, while lawns and gardens release fertilizers (Billow, 2002). An EPA (1994) determined that urban runoff is the third most common source of pollution for rivers.

Like many states, South Carolina's population is rapidly growing and a primary cause of residential urban sprawl. Rapid urbanization contributes to the diffuse runoff that degrades many waterways and catchments within the state, and will continue to adversely affect water quality at an accelerated rate as additional urban and suburban growth occurs without the introduction of pollution mitigation strategies. Because much of this urban built environment has yet to be constructed, policy makers have an opportunity to substantially mitigate the effects of anticipated the new residential construction. This study estimates the basin wide cost of mitigating expected nitrogen and phosphorous loadings into a downstream receptor lake for a rapidly growing South Carolina urban basin. Two broad policies are examined. The first policy is a uniform control policy that imposes a uniform control standard for the percentage reduction in total nitrogen and/or total phosphorous runoff for each sub-basin in the basin from their expected uncontrolled levels to achieve the downstream control standard. The second policy is a targeted policy that achieves the downstream percentage reduction in total nitrogen and/or total phosphorous loadings without requiring each sub-basin within the basin decrease their uncontrolled baseline loading by the same percentage. The basin wide cost of each policy to achieve a specific level of control at the downstream receptor site is subsequently compared.

Study Area

The study site is the Reedy River basin (RRB) which originates north of the rapidly growing Greenville, South Carolina metropolitan area, flows southward through Greenville and then continues southward for 40 additional miles before emptying into Lake Greenwood. The Reedy River basin contains 36 sub-basins and has a total acreage 166,112 acres, or 260 square miles. Over the last few decades, rapid residential and industrial development has caused numerous algal blooms in Lake Greenwood from nutrients entering the lake through the Reedy

River. Several segments of the river are currently in violation of the South Carolina Water Quality Standards (SCWQS) due to excessive total nitrogen and total phosphorus. South Carolina requires that the nutrient concentration within the Piedmont and Southeastern Plains ecoregions not exceed 0.06 mg/L and 1.5 mg/L for total phosphorus and total nitrogen, respectively (Harden, 2011).

In 2007, the Clemson University Strom Thurman Institute (STI) conducted an urban growth study to estimate expected urban growth for an eight county region in the South Carolina Upstate. These eight counties are Greenville, Spartanburg, Pickens, Anderson, Laurens, Newberry, Abbeville, and Greenwood. Using historical population trends, a GIS-based statistical model was constructed to predict future urban population growth within these eight counties in five year increments for the years 2000 to 2030 (Allen et al., 2007). The amount of land developed in these eight counties was projected to increase by 1,576,336 acres over the thirty year period under the sprawling 5 to 1 low density residential development scenario, where a 5 to 1 development density requires 5% more land in residential and commercial use for every 1% growth in population. Under the 5 to 1 development ratio, the amount of developed acreage in the Ready River watershed increased from an initial level of 47,622 acres in 2000 (28.7% of the basin) to 100,378 acres in 2030 (60.4% of the basin), an increase of 52,756 acres with most of the increase located in the northern sub-basins. This large increase in developed residential and commercial acreage will significantly decrease pervious surface area and result in increased chemical runoff which will negatively impact basin water quality if future total nitrogen and total phosphorous loadings are not controlled.

Hydrologic Simulation Model

The Reedy River Model (RRM) developed by ENSR, now AECOM is a comprehensive model that incorporates EPA's Loading Simulation Program in C++ (LSPC) to generate pollutant loads from a watershed and then uses EPA's Water Quality Analysis Simulation Program (WASP) to transport the simulated loads through a riverine system (Harden, 2011). EPA's LSPC Program simulates stormwater runoff as a function of time-varying rainfall and hydrologic abstraction established by land use attributes, soil type/characteristics, and topographic conditions. EPA's WASP program is a robust water quality model, capable of running three-dimensional analysis, and includes a post processor for reviewing input data and results. Because the WASP model is capable of handling multiple pollutant types over multiple years with varying meteorological and environmental conditions it has been widely applied in the development of Total Maximum Daily Loads (TMDL). The WASP7 model was selected for this analysis due to its ability to link with several fully dynamic hydrodynamic models, such as LSPC, and its capability to predict nutrient cycling. WASP7 incorporates a Windows® interface to simplify model setup and to make it easier to evaluate the results of the model (Heim and McGovern, 2007). In summary, the Reedy River Model is a comprehensive model of the Reedy River Basin and uses LSPC to generate pollutant loads from each sub-basin based on the level of sub-basin development and then uses WASP to transport the loads through the Reedy River Sub-basin. The RRM was used to simulate the total daily nitrogen and phosphorous loads from the 36 sub-basins areas that enter Lake Greenwood at the bottom of the basin.

The land development data needed to drive the Reedy River Model was taken from the STI 30 year growth study. The STI data was carefully disaggregated to determine how much of the RRB geographical area was predicted to be developed between the years of 2000 and 2030 within each of the 36 sub-basins of the RRB. This was achieved using ArcGIS to overlay individual sub-basin layers and the predicted development maps for the 5:1 growth ratio. The GIS analysis allowed for the amount of land predicted to be developed in each of the 36-sub-basins to be calculated. Once the total developed acres in each sub-basin was estimated, the acres in land use categories representing low intensity residential (LIR), high intensity residential (HIR), and high intensity commercial (HIC) was determined for the initial development level (2000) and the ending development level in the year 2030.

The developed land use data was subsequently input into the Reedy River Model and model simulations were run for seven years of weather data, consisting of dry, average and wet years for the 2000 and 2030 development levels. The 2000 development level is representative of the development level in each sub-basin in 2000. The 2030 development level corresponds to the 2030 estimated development under the 5 to 1 land development scenario. For both development scenarios, the average annual nutrient loads (total nitrogen and total phosphorus) for the seven simulations in each sub-basin were calculated for each sub-basin based on the seven years of simulated model output.

The difference in the average loading levels for total nitrogen and total phosphorous between the 2000 versus the 2030 development level was calculated for each sub-basin. This difference between the total nitrogen level and total phosphorous level that drain into Lake Greenwood in the two time periods, from each sub-basin, estimates the expected increase in the uncontrolled load for each sub-basin. Dividing the increases in the total nitrogen and total phosphorous loads from each sub-basin by the additional land developed in each sub-basin during the 30 year period provides the per acre estimate of the additional total nitrogen and total phosphorous loads per acre developed. The average per acre loadings for new development, are

0.929 kg/acre for total nitrogen and 0.112 kg/acre for total phosphorous. However, due to difference in sub-basin average slope, crop cover, percent impervious cover, soil types, and water table elevation considerable differences exist between sub-basin averages. For total nitrogen, individual sub-basin per acre averages range from 0.098 kg/ac to 3.276 kg/ac, and for total phosphorous the individual sub-basin averages range from 0.010 kg/ac to 0.370 kg/ac. This variation in per acre loading suggest there may be "hot spots" in the basin and the nutrient level entering the Lake Greenwood could be controlled at a lower cost by targeting the high runoff sub-basins for control instead of imposing a uniform control standard across each sub-basin.

BMP Practices

BMPs are any type of practical/effective method that can be used to prevent or reduce the potential adverse effects of land development. BMPs can either be non-structural or structural. Non-structural BMPs can be either institutional and pollution-prevention type practices designed to either prevent pollutants from being transported by stormwater runoff or practices designed to decrease the volume of storm water that must be treated (US EPA, 1999). Non-structural BMPs achieve this by reducing the generation of pollution at its source. In contrast, structural BMPs are engineered and constructed systems designed to provide for water quantity and/or water quality control of stormwater runoff (EPA, 1999). Structural BMPs are designed to receive, detain or retain, surface pollution runoff to reduce pollutant levels through one of the following mechanisms: sedimentation, flotation, filtration, infiltration, adsorption, biological uptake, biological conversion, and degradation. Given the dominant physical characteristics for slope, soil type, and cover within the RRB five structural BMP control practices were identified as suitable control technologies. These five BMP control technologies are: (1) vegetated swale (VS); (2) dry detention pond (DP); (3) wet detention pond (WP); (4) bioretention areas (BR); and

(5) infiltration trenches (INF). Appendix Table 1 briefly describes each of the five structural BMP practices used in this study.

Trapping Efficiency**:** Trapping efficiency, or pollution removal efficiency, for a specific BMP is measured as the percentage reduction in the level of a specific stormwater runoff nutrient removed by the BMP. For example a 50 percent trapping efficiency for total nitrogen removal for the vegetated swale BMP is interpreted as 50 percent of the total nitrogen load entering the BMP is removed. A review of the literature found a wide range of trapping efficiencies for the various BMPs considered. This is because BMP trapping efficiency is a function soil type, rainfall intensity, slope, and groundcover. Given the wide range of reported trapping efficiencies this study used the trapping efficiencies reported in the South Carolina BMP Handbook (January, 2013) published by the South Carolina Department of Health and Environmental Control (SCDHEC). The trapping efficiencies for the five BMPs used in this study are reported in table 1. For each BMP used in our empirical analysis we used the median trapping efficiency for both total nitrogen and total phosphorus removal. It is important to note that the higher the trapping efficiency, for a given BMP cost, the lower the BMP per unit cost of pollution removal.

Table1. Trapping Efficiency for total Nitrogen and Total Phosphorous Removal for Selected BMPs

	Total Nitrogen			Total Phosphorous		
BMP Practice	Low	Median	High	Low	Median	High
Vegetated Swale	.400	.500	.600	.350	.425	.500
Wet Detention Pond	.300	.375	.450	.500	.600	.700
Dry Detention Pond	.190	.240	.290	.140	.195	.250
Bioretention	.350	.450	.550	.550	.625	.700
Infiltration Trench	.350	.450	.550	.500	.550	.600
None	.000	.000	.000	.000	.000	.000

Source: South Carolina Department of Health and Environmental Control. BMP Handbook (January, 2013)

BMP Per acre control Cost**:** The annualized BMP costs per acre treated by each BMP are reported in Table 2. The annualized BMP costs were derived over a 20 year useful life and include construction cost, annual maintenance cost, and the land cost to establish the BMP.

Table 2. Annualized BMP Cost per Acre Controlled

BMP Practice	Cost ($s)
Vegetated Swale	3,254
Wet Detention Pond	2,149
Dry Detention Pond	3,566
Bioretention	4,183
Infiltration Trench	5,600
None	0

Source: King and Hagan 2011. Per acre treatment cost converted to 2016 dollars using the US CPI.

Economic Control Cost Model

A linear programming model was constructed to minimize basin wide BMP control cost to achieve a given percentage reduction in annual total nitrogen and/or total phosphorous loadings emptying into Lake Greenwood given existing BMP costs and trapping efficiencies from new residential and commercial development. The analytic approach examines cost-effectiveness for two alternative policy approaches. The first policy approach is a uniform control policy that requires each of the 36 sub-basins to reduce their total nitrogen and/or total phosphorous loads by an identical percentage to achieve the overall basin wide percentage reduction for these two nutrients flowing into Lake Greenwood. The second approach is a targeted approach that does not require all sub-basins to reduce the nutrient loadings by the basin-wide percentage as long as the total basin-wide loading reduction into Lake Greenwood is achieved. Equation 1 is the objective function which minimizes total basin-wide BMP control cost using five available control technologies in each sub-basin across all 36 sub-basins.

$$(1) \quad Min\ BasinCost = \sum_{j=1}^{36} SubBasinCost_j$$

Policy cost is minimized subject to a set of ten constraints that control for BMP trapping efficiency, BMP cost, the policy dictated percentage reduction in Lake Greenwood nutrient loadings, and the policy type, either uniform or targeted. The first constraint (equation 2) is an accounting equation that requires all developed residential and commercial acres in each of the j sub-basins (j = 1, …, 36) to be allocated to among the five available BMP_i control practices plus a sixth option of no control (i = 1, …, 6).

ST:

$$(2) \quad DevSubBasinAcres_j = \sum_{i=1}^{6} BMP_{ij} \quad j = 1, \ldots, 36$$

Equation 3 calculates BMP cost for each of the j sub-basins over all six BMPs (including the sixth option of no BMP use on some acreage) and C_i is the cost for each BMP_i per treated acre.

$$(3) \quad SubBasinCost_j = \sum_{i=1}^{6} C_i * BMP_{ij} \quad j = 1, \ldots, 36$$

Equations 4 and 5 respectively assure that the required percentage reduction in total nitrogen and total phosphorous from the uncontrolled baseline level is satisfied in each sub-basin. $SBNL_j$ and $SBPL_j$ are the respective uncontrolled annual baseline loading levels for total nitrogen and total phosphorus, measured in kilograms, from each sub-basin j that flow into Lake Greenwood. SR%N and SR%P are the respective parameters for the required percentage reductions in total nitrogen and total phosphorous in each sub-basin. $TEFFN_i$ and $TEFFP_i$ are the respective parameters for total nitrogen and total phosphorous trapping efficiency for each of the BMP_i practices. Finally, the parameters $BPerAcN_j$ and $BPerAcP_j$ are the respective measures for uncontrolled baseline per acre total nitrogen and total phosphorus loadings in each region measured in kg/acre. Whenever the parameters for SR%N and/or SR%P in equations 4 and 5 are greater than zero the model estimates the cost of a uniform policy that requires the same percentage reduction for total nitrogen and/or total phosphorous runoff in each of the j sub-basins. To relax the uniform pollutant control policy the parameters SR%N and SR%P are set equal to zero. Doing implies that pollution loadings for total nitrogen and total phosphorous cannot exceed their respective baseline level in each sub-basin. Constraints 4 and 5 are relaxed (SR%N and SR%P are set to zero) when estimating the basin wide cost of a targeting policy.

$$(4)\quad SBNL_j - \sum_{i=1}^{6} BPerAcN_j * TEffN_i * BMP_{ij} \leq (1 - SR\%N) * SBNL_j \qquad j = 1, \dots, 36$$

$$(5)\quad SBPL_j - \sum_{i=1}^{6} BPerAcP_j * TEffP_i * BMP_{ij} \leq (1 - SR\%P) * SBPL_j \qquad j = 1, \dots, 36$$

Equations 6 and 7 are utilized to estimate the basin-wide control cost of a targeting policy that seeks the lowest basin wide cost of meeting a specific percentage reduction in total nitrogen and/or total phosphorous deposits into Lake Greenwood. Construction of equations 6 and 7 is similar to the design of equations 4 and 5, except instead of having 36 sub-basin equations for total nitrogen and total phosphorous control, the 36 sub-basin control equations are collapsed into one basin-wide control equation for each pollutant. Parameters BBNL and BBPL are the sum of the annual respective baseline loads for total nitrogen and total phosphorous deposited into Lake Greenwood from all 36 sub-basins. For a specific targeted percentage decrease in total nitrogen and/or total phosphorous deposits into Lake Greenwood the parameters BR%N and BR%P are set to their basin wide policy targets. All other parameters and variables in equations 6 and 7 are as previously defined. When minimizing basin wide control cost for a targeting policy the sub-basin percentage reduction parameters (SR%N and SR%P) in equations 4 and 5 must be set equal to zero. Thus, under the targeting approach, sub-basin regions with high per unit control cost may not be required to install any BMPs if the basin-wide control reduction can be achieved by controlling runoff to a greater degree in those sub-basins with lower per unit control cost. The targeted optimization procedure seeks the lowest basin wide control cost by targeting sub-basins with the lowest per kg control cost for each pollutant. To estimate the basin wide cost of a uniform control strategy that requires each sub-basin reduce their baseline load by the same percentage the values for parameters BR%N and BR%P must be set to zero. When the values of BR%N and BR%P are respectively set to zero in equations 6 and 7, the constraints become non-binding in the uniform policy analysis because the constraints would then require that basin wide total nitrogen and total phosphorous loadings to be no greater than they were in the uncontrolled baseline.

$$(6)\quad BBNL - \sum_{j=1}^{36}\sum_{i=1}^{6} BPerAcN_j * TEffN_i * BMP_{ij} \leq (1 - BR\%N) * BBNL$$

$$(7)\quad BBPL - \sum_{j=1}^{36}\sum_{i=1}^{6} BPerAcP_j * TEffP_i * BMP_{ij} \leq (1 - BR\%P) * BBPL$$

Equations 8 to 11 are accounting equations that calculate the reduction in total nitrogen and total phosphorous loads at the sub-basin and basin wide level under either a uniform or targeting policy for a given percentage reduction in each pollutant. Equations 8 and 9, respectively, calculate the annual reduction in total nitrogen and total phosphorous loads from each sub-basin, and equations 10 and 11 calculate the respective overall basin wide reduction for each pollutant.

$$(8)\quad SubBasinRedN_j = \sum_{i=1}^{6} BPerAcN_j * TEffN_i * BMP_{ij} \qquad j = 1, \ldots, 36$$

$$(9)\quad SubBasinRedP_j = \sum_{i=1}^{6} BPerAcP_j * TEffP_i * BMP_{ij} \qquad j = 1, \ldots, 36$$

$$(10)\quad BasinRedN = \sum_{j=1}^{36}\sum_{i=1}^{6} BPerAcN_j * TEffN_i * BMP_{ij}$$

$$(11)\quad BasinRedP = \sum_{j=1}^{36}\sum_{i=1}^{6} BPerAcP_j * TEffP_i * BMP_{ij}$$

Empirical Results

The linear programming model minimizes basin wide BMP cost subject to a restriction on the level of total nitrogen and/or total phosphorous that empties into Lake Greenwood at the bottom of the basin. Optimized solutions are presented for 13 scenarios, the uncontrolled baseline condition, and twelve control policy scenarios. The twelve policy scenarios consist of six uniform policies where the reduction in the uncontrolled baseline load entering into Lake Greenwood is achieved by reducing total nitrogen and/or total phosphorous runoff in each of the 36 sub-basins by the same percentage. The targeted solutions replicate the uniform scenarios with one significant difference. Instead of requiring each sub-basin to reduce their baseline total nitrogen and/or total phosphorous runoff by the same percentage, the percentage decrease between sub-basins is allowed to vary as long as the nutrient loads entering Lake Greenwood achieve the required overall percentage decrease.

The six nutrient reduction scenarios considered are: (1) a 20% reduction in total nitrogen and total phosphorous; (2) a 40% reduction in total nitrogen and total phosphorous; (3) a 20% reduction in total nitrogen only; (4) a 40% reduction in total nitrogen only; (5) a 20% reduction in total phosphorous only; and (6) a 40% reduction in total phosphorous only. Because each of the five BMPs are effective to some degree, in reducing both total nitrogen and total phosphorous runoff, a policy that has the exclusive objective of decreasing total nitrogen runoff by a given percentage, will also reduce total phosphorous runoff. Conversely, a policy that is exclusively focused on reducing baseline total phosphorous runoff by a given percentage will also reduce baseline total nitrogen runoff.

The basin wide BMP control cost to achieve each of the six nutrient reduction scenarios under a uniform versus target control policy are reported in table 3. For a given control scenario, as expected, the targeted control policy always has the lower basin wide control cost. What is surprising is the degree of cost savings between the two policy approaches. For a given control scenario, the reduction in basin wide cost for the targeted policy is 25.88% to 42.07% less than for the uniform policy. For example, if the control objective is to reduce baseline total phosphorous loadings into Lake Greenwood by 40%, the basin wide cost of the uniform policy is $75,581,619 versus $47,366,597 for the targeting policy. The targeting policy achieved the 37.33% cost reduction relative to the uniform policy by reducing total phosphorus levels above the control reduction standard of 40% in those sub-basins that had low per unit control cost and not abating the total phosphorous level in sub-basins with high per unit control cost.

Close examination of the control scenarios presented in table 3 reveal that for a given policy, decreasing both total nitrogen and total phosphorous runoff by the same given percentage has a basin wide cost identical to the cost incurred when the control focus is exclusively on decreasing total nitrogen runoff by the same percentage. This empirical result is a function of the BMPs selected and their trapping efficiencies. Wet pond (WP) is the exclusive BMP used when the objective is to decrease both total nitrogen and total phosphorous runoff by 20% or when the focus is exclusively on decreasing total nitrogen by 20%. At median trapping efficiency, wet pond reduces total nitrogen runoff by 37.5 percent per treated acre but also simultaneously decreases total phosphorous runoff by 60% per treated acre (table 1). Thus both of these control scenarios can be satisfied with the exclusive use of wet pond at the same number of treated acres within each policy. When the control objective is to decrease both total nitrogen and total phosphorous runoff by 40% two BMPs must be employed to achieve the control goal. A blend of wet pond and vegetated swale BMPs must be used under both policies because exclusive use of the wet pond BMP will not achieve the 40% total nitrogen reduction, but within a policy, control cost is again identical for both control scenarios.

Table 3: Annualized Basin BMP Cost: Uniform Versus Targeted Policy by Scenario

Policy	Control Scenario	Basin Cost
Uniform	20% Reduction N & P	$ 60,465,296
Uniform	40% Reduction N & P	$ 125,031,483
Uniform	20% Reduction N	$ 60,465,296
Uniform	40% Reduction N	$ 125,031,483
Uniform	20% Reduction P	$ 37,790,810
Uniform	40% Reduction P	$ 75,581,619
Targeted	20% Reduction N & P	$ 36,862,357
Targeted	40% Reduction N & P	$ 92,669,993
Targeted	20% Reduction N	$ 36,862,357
Targeted	40% Reduction N	$ 92,669,993
Targeted	20% Reduction P	$ 21,893,017
Targeted	40% Reduction P	$ 47,366,597
		Percent Savings
% Targeted Savings	20% Reduction N & P	39.04%
% Targeted Savings	40% Reduction N & P	25.88%
% Targeted Savings	20% Reduction N	39.04%
% Targeted Savings	40% Reduction N	25.88%
% Targeted Savings	20% Reduction P	42.07%
% Targeted Savings	40% Reduction P	37.33%

Within a policy, when the control goal is exclusively focused on achieving a given percentage reduction in total phosphorous runoff, the basin wide control cost for total phosphorous reduction is approximately half of the cost incurred to achieve the same percentage reduction in total nitrogen. Two considerations explain the outcome. First, the trapping efficiency of wet pond for total phosphorous control is 60%, much greater than the trapping efficiency of wet pond for total nitrogen, and thus fewer acres of wet pond are needed to achieve either the 20% or 40% reduction in total phosphorous. Moreover, it is not necessary to blend wet pond with another BMP that has a larger per unit total phosphorous control cost to achieve a 40% reduction in total phosphorous runoff.

Under the 30-year 5 to 1 grow-out scenario an additional 52,756 acres within the Reedy River basin goes into residential and commercial development. Table 4 reports the BMP acreage for each control practice for the two policies and six control scenarios. Under the no control scenario no BMPs are implemented.   To decrease the level of total nitrogen and/or total phosphorous runoff into Lake Greenwood, below the baseline level, various BMPs must be utilized at various intensities to achieve each control scenario. Given BMP cost per acre treated, in combination with each BMP's median trapping efficiency, only two BMPs were selected in the various control scenarios. Limited BMP selection is not an uncommon result as individual BMPs tend to be cost effective over a range of control levels (Giuffria et al.). More expensive per acre BMPs when utilized are often selected for their amenity attributes rather than per acre control cost. In two scenarios the cost effective solution is to put all developed acreage into one of two BMPs. The two scenarios are the 40% reduction in total nitrogen and total phosphorous scenario, and the 40% reduction in total nitrogen scenario under the uniform policy. The use of two BMPs is required because wet pond is incapable of meeting the 40% reduction in total nitrogen and must be blended with the slightly more expensive vegetated swale BMP in each sub-basin. However, under the targeted policy only 31,892 BMP acres are required to achieve the 40% reduction for the same two control scenarios because the BMPs are located in the sub-basins with the smallest per unit control cost. Even though the same two BMPs are used under both the uniform and target policy, the ratio of vegetated swale to wet pond changes from 1 to 4 under the uniform policy to a 2 to 1 ratio under the target policy and acreage in a BMP decreases from 100% under the uniform policy to 60.5% for the target policy.

Table 4: Basin Wide Acres Treated by each BMP by Policy and Scenario

Policy	Control Scenario	VS	WP	DP	BR	INF	NONE
Baseline	No Control	-	-	-	-	-	52,756
Uniform	20% Reduction N & P	-	28,136	-	-	-	24,619
Uniform	40% Reduction N & P	10,551	42,205	-	-	-	-
Uniform	20% Reduction N	-	28,136	-	-	-	24,619
Uniform	40% Reduction N	10,551	42,205	-	-	-	-
Uniform	20% Reduction P	-	17,585	-	-	-	35,171
Uniform	40% Reduction P	-	35,171	-	-	-	17,585
Targeted	20% Reduction N & P	518	16,369	-	-	-	35,869
Targeted	40% Reduction N & P	21,841	10,051	-	-	-	20,864
Targeted	20% Reduction N	518	16,369	-	-	-	35,869
Targeted	40% Reduction N	21,841	10,051	-	-	-	20,864
Targeted	20% Reduction P	-	10,188	-	-	-	42,568
Targeted	40% Reduction P	-	22,041	-	-	-	30,715

Table 5 reports the percentage reduction in total nitrogen and total phosphorous entering Lake Greenwood for each policy and control scenario. For all control scenarios requiring a reduction in total nitrogen runoff, the nitrogen control level is satisfied at exactly the stated scenario level. This is due to two considerations. The first is the nature of the cost minimization model which minimizes BMP control cost subject to the specified minimum level of required control. Secondly when the total nitrogen control constraint is satisfied by the selected BMPs, the total phosphorous control level is also satisfied given the higher trapping efficiency for total phosphorous by the selected BMPs. Because the BMP trapping efficiency for total phosphorous is higher than for total nitrogen, for both vegetated swale and wet ponds, the reduction in total phosphorous is greater than the minimum scenario requirement as reported in table 5. In contrast, when the focus is exclusively on a total phosphorous reduction, the minimum required reduction in total phosphorous is exactly satisfied in each scenario regardless of policy. Moreover, even though, a pure phosphorous reduction policy does not require a reduction in nitrogen some total nitrogen reduction is still achieved.

Table 5: Basin Wide Percentage Reduction for Total Nitrogen and Total Phosphorous by Policy and Scenario

Policy	Control Scenario	N % Reduction	P % Reduction
Baseline	No Control	0.0%	0.0%
Uniform	20% Reduction N & P	20.0%	32.0%
Uniform	40% Reduction N & P	40.0%	56.5%
Uniform	20% Reduction N	20.0%	32.0%
Uniform	40% Reduction N	40.0%	56.5%
Uniform	20% Reduction P	13.0%	20.0%
Uniform	40% Reduction P	25.0%	40.0%
Targeted	20% Reduction N & P	20.0%	31.0%
Targeted	40% Reduction N & P	40.0%	41.0%
Targeted	20% Reduction N	20.0%	31.0%
Targeted	40% Reduction N	40.0%	41.0%
Targeted	20% Reduction P	12.2%	20.0%
Targeted	40% Reduction P	24.0%	40.0%

Summary and Conclusions

This analysis clearly shows that policy makes should strongly consider using targeted control policies instead of uniform control policies when the policy focus is on the level of discharge entering a specific downstream water body. For a given control scenario, total control cost is as much as 42% less for the targeted policy than the uniform policy. Water quality managers in rapidly growing urban basins need to recognize that uniform basin-wide control policies are likely to incur greater public resistance that target control policies because of their higher cost. However, implementing a target control policy requires a solid technical understanding of the basin's hydrology, soils types, varying slopes, weather patterns, and land cover. But such technical investments are likely to provide large reductions in basin wide water quality control cost. While these findings are empirically robust additional research is needed regarding more precise estimates for trapping efficiency and per acre BMP control cost.

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Appendix Table 1. Selected Best Management Practices (BMPS) used in Residential Development

Practice	Description
Vegetated Swale	Vegetated conveyances are designed and installed as an alternative to curb and gutter and hard piping storm water conveyance systems. Open vegetated conveyances improve water quality by providing partial pollutant removal as water is filtered by the vegetation and provide pollutant an opportunity to infiltrate into the soil. Open vegetated conveyances are designed to reduce flow velocities when compared to hard piping systems that just track water from a source to a receptor site.
Dry Detention Pond	Dry detention ponds provide temporary storage of storm water runoff. Dry ponds have an outlet structure that detains runoff inflows and promotes the settlement of pollutants. Unlike wet ponds, dry detention ponds do not have a permanent pool. Dry ponds are most effective for trapping sediment but have limited effectiveness in removing both particulate and soluble pollutants.
Wet Detention Pond	A wet or permanent pool detention pond is a commonly used to meet water quality protection requirements. The primary advantage of permanent pool ponds to other more sophisticated BMPs are they durable and require less maintenance than other applicable water quality controls. Wet ponds are much more effective than dry ponds in removing stormwater nutrients to for water quality control.
Bioretention Areas	Bioretention areas are designed to mimic natural forest ecosystems with a combination of soil filtration and plant uptake by utilizing a planting soil layer, mulch, plantings, and an underdrain system. Bioretention areas appear as landscaped or natural areas giving this BMP an appealing image. Storm water runoff enters the Bioretention area and is temporarily stored in a shallow pond on top of the mulch layer. The ponded water then slowly filters down through the planting soil mix and is absorbed by the plantings. As the excess water filters through the system it is temporarily stored and collected by an underdrain system that eventually discharges to a designed storm conveyance system.
Infiltration Trench	Infiltration trenches are excavations typically filled with stone to create an underground reservoir for storm water runoff. The runoff volume gradually exfiltrates through the bottom and sides of the trench into the subsoil over a maximum period of three days, and eventually reaches the water table. By diverting storm water runoff into the soil, an infiltration trench not only treats the water quality volume, but it also preserves the natural water balance by recharging groundwater and preserving channel baseflow. Using natural filtering properties, infiltration trenches remove a wide variety of pollutants from the runoff through adsorption, precipitation, filtering, and bacterial and chemical degradation.
None	No control practice on acreage to control for sediment and water soluble chemical pollutants.

Source: South Carolina Department of Health and Environmental Control. BMP Handbook (July 31, 2015)