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EVALUATING RIPARIAN BUFFERS FOR NONPOINT SOURCE POLLUTION CONTROL IN AN URBAN SETTING USING THE RIPARIAN ECOSYSTEM MANAGEMENT MODEL, REMM

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ABSTRACT

Environmental planners recognize the importance of maintaining the integrity of a riparian buffer when land is developed for urban purposes. The state of Delaware requires that 60 percent of the P and 40 percent of the N loadings from new urban land developments be reduced before flowing to surface water. Riparian buffers are effective for treatment of urban storm water runoff, but they are frequently designed using non-specific site criteria for agricultural riparian buffers. The objective of this research was to evaluate the Riparian Ecosystem Management Model (REMM) as a tool for designing urban riparian buffers based on site-specific data. REMM inputs were obtained from published literature and REMM databases. N, P and sediment loadings at the buffer edge were input from SWAT model simulations. A three-zone 15 m and a 30 m riparian buffer were simulated. Results were summarized using five rainfall years (minimum, below average, average, above average and maximum) from the 25-year simulation. Total P was reduced by nearly 60 percent for the 15 m buffer except the low rainfall year. Even though the desired minimum was not reached, the total influx was small and the overall outflow was 0.3 kg P ha^{-1}. Based on these simulation results, the Delaware guidelines for buffer size appear to be too large. Currently, Delaware requires a 30 m forested or vegetation zone for developed areas. Results of this study will be beneficial to individuals who are responsible for nonpoint source permitting and for the control of urban storm water runoff.

KEYWORDS. SWAT model, Riparian Ecosystem Management Model, simulation, buffer design, Delaware

INTRODUCTION

The use of riparian buffers to reduce nonpoint source (NPS) pollutant loading to environmentally sensitive areas like wetlands, lakes, streams, or rivers is well documented (Allison 2000; Dillaha et al. 1987; and Lowrance 1997). Riparian buffers are transition zones between an upland area or pollutant source and a water body. Their importance in any landscape setting cannot be over stated, and a review of the literature illustrates their effectiveness in filtering sediment, nitrate and phosphates from agricultural runoff (Vellidis et al. 1995; and Lowrance et al. 1995). Jacobs and Gilliam (1985) reported that buffer strips <16 m were effective in reducing significant quantities of nitrate before agricultural drainage reached surface waters. Allison and Dhakal (2000) stated that 9 m (30 ft.) vegetative filter strips reduced soil loss upwards to 85 percent. Sediment adsorbed P transported from areas with grass buffers was 20-36 percent less than from areas with no grass buffers (Norman 1996). Dosskey et al. (2002) reported that potentially riparian buffers could remove up to 99 percent of sediment from upland agricultural land, however when concentrated flow dominated, the effective filtering area was reduced and the trapping effectiveness was reduced to a maximum of 43 percent. The effectiveness of buffers is dependent on a critical size, condition of the vegetation and quantity of runoff.

Environmental planners recognize the importance of maintaining the integrity of existing riparian buffers or of newly constructed riparian buffers when land is developed for urban purposes (McKague et al. 1996; and Norman 1996). Schueler (1987) found that buffers were effective in controlling urban NPS pollutants. Palone and Todd (1997) concluded that riparian buffers were effective for treatment of urban storm water runoff, but often they were not designed properly. This can be explained in part by the fact that urban buffers are frequently designed using criteria for agricultural riparian buffers. Given the difference in level of disturbance in urban and agricultural land, separate guidelines need to be developed based on the urban setting.

A riparian buffer is designed and maintained to reduce the impact of adjacent land use on water quality. Even though there is agreement among scientists about the need to maintain the environmental integrity of existing riparian buffers, there is continued debate about the riparian buffer design criteria to meet specific environmental and land use planning objectives. Regardless of the end function of a riparian buffer (for example sediment, N, or P removal), a critical design criterion is buffer width. Published guidelines for determining buffer width are commonly not based on site specific conditions and do not reflect the long-term dynamics of a riparian buffer. Land use planners, city engineers, and environmental scientists are left to choose a buffer width that can range from 7-50 m. Shisler et al., 1987 recommended a forested riparian buffer >19m to control P and nitrogen. Dilllaha et al. (1989) recommended a vegetated filter strip > 9m to remove 84 percent of the suspended solids, 79 percent of P, and 73 percent of N, while Horner and May (1999) suggested that riparian buffers be defined by buffer width, riparian continuity and riparian quality for storm water control. Regulatory and planning agencies often state a minimum set-back from an environmentally sensitive area. This can result in over or under designing the buffer.

A systems analysis of landscape and riparian buffer dynamics can often be facilitated by the use of computer models. Models are often necessary simply because of the many variables present, which make even the smallest environmental system very complex. Computer models make it possible to sort out the different components of a system and rearrange the spatial or temporal scale into a form that is within our physical or mental grasp. This simplification of nature can then be used to determine how a system works and to explore and to analyze the interrelationships of its components

The objective of this research was to develop a modeling methodology using the SWAT model and REMM for designing urban riparian buffers based on site-specific landscape and buffer characteristics, long-term weather, and sediment, nitrogen (N), and phosphorus (P) loadings to a riparian buffer.

METHODS AND MATERIALS

Model Selection

The Soil and Water Assessment Tool (SWAT) (Arnold et al. 1995) and Riparian Ecosystem Management Model (REMM) (Altier et al. 2002) were selected. A two step modeling procedure was adopted because there are no field or watershed scale models capable of simulating riparian ecosystems. The SWAT model was used to generate sediment, N and P loadings at the edge of the riparian buffer. The SWAT model was developed to simulate the effects of land use practices on water, sediment, nutrient and pesticide yields for ungaged watersheds or river basins. SWAT also has the capability of simulating impervious surfaces for urban landscapes (residential housing, commercial, transportation, industrial and institutional). REMM was developed specifically for simulating plant nutrient and soil dynamics in riparian buffers. Both models have weather generators that can be accessed to simulate 100-year weather files.

SWAT and REMM Overview

SWAT

SWAT is a continuous grid-based model with a daily time step. Watersheds are divided into subbasins based on differences in topography, soil, weather and land use. Water, sediments, nitrogen, phosphorus and pesticides are routed among subbasins to a common drainage outlet. Soil series, US-wide weather, land management, plant and urban databases are available as part of the model. A detailed model description with simulation theory is available on the Internet at http://www.brc.tamus.edu/swat/

Plant, soil and urban databases are integrated into the SWAT model. When a specific plant or crop is selected, the crop growth parameters are loaded. Appropriate land management practices are then selected in the management database (tillage, chemical or fertilizer application and irrigation scheduling) and are identified by date of operation. The soils database consists of over 16000 soil series profile descriptions. If more current data is available for a soil, that data can be loaded into the SWAT model. Eight different urban land use types can be selected in the SWAT urban database.

REMM

REMM is simulation model for riparian ecosystems. A three-zone buffer design was used in REMM. The three-zones are described in Table 1. Topography, soil and vegetation are defined in the input file for each zone. If a zone is actively managed, a management database is accessed and the operation selected (i.e. tree harvest, fertilizer application, tillage, mowing and managed fire). Soil files are defined using a three-layer soil profile and vegetation is selected using the REMM database.

Table 1: An overview of a typical 3-zone buffer – location, function, and type vegetation.

Zone	Location	Function	Vegetation
1	Adjacent to the stream bank	Streambank stabilization, shade, and final zone for sediment and nutrient removal	Permanent native trees and shrubs with understory growth
2	Upslope from zone 1	Sediment and nutrient removal from surface and ground water, animal habitat and aesthetics	Managed riparian forest.
3	Upslope from zone 2	Initial filtering of NPS pollutants	Grass and herbaceous species

Weather inputs include maximum and minimum air temperature, rainfall amount and duration, solar radiation and dew point temperatures. Similar to the SWAT model, an internal weather generator is available to generate a long-term weather file. REMM simulates variables for each buffer zone and soil horizon and the output includes over 225 variables. Major simulation categories are erosion and sediment transport, vegetation dynamics, hydrology and soil nutrient dynamics in each of the three buffer zones. REMM output is extensive and many variables are not needed for urban buffer design. A listing of the pertinent variables is given in Table 2. A detailed description of REMM theory, documentation, inputs and outputs can be found at http://sacs.cpes.peachnet.edu/remmwww.

Table 2: Pertinent REMM output variables.

Nutrient Dynamics	• Nitrogen cycling and flux • Phosphorus cycling and flux • Net retention /trapping over annual/monthly scales of N and P in the riparian buffer
Vegetation Dynamics	• Riparian vegetation N and P pools over time for leaves, branches, stem, and fine & coarse roots • Annual estimates of photosynthesis, respiration, NPP and carbon allocation, mortality • Annual biomass increment
Sediment	• Sediment entering and exiting a buffer zone and buffer/riparian interface • Sediment transport/deposition for individual storm event
Hydrology	• Annual /monthly hydrology budget for the riparian buffer - e.g., runoff, ET and drainage • Daily values for – buffer runoff, ET and drainage

REMM inputs were obtained from published literature, REMM databases and SWAT results. The 25-year weather file from the SWAT simulation was used. A three-zone 15 m and a three-zone 30 m riparian buffer were simulated based on the Natural Resources and Conservation Service's three vegetation zones of grass, shrubs and forest. In order to have similarity in soil data, the soil profile input data for REMM were created using SWAT database values. Vegetation inputs were selected from REMM databases**.**

Simulation Assumptions

- A Downer (Coarse-loamy, siliceous, semiactive, mesic Typic Hapludults) soil with a three percent slope was selected
- A medium density residential land use was simulated
- Buffer design was based on a mature riparian buffer
- Buffer design did not include habitat evaluation
- The same weather generator was used to create weather files for SWAT and REMM
- Buffer length is identical to adjacent upland land length
- When possible, internal databases were used in SWAT and REMM
- Constant water table height at each location – no seasonal variation
- Buffer slope was identical to the adjacent land for slopes of 1 percent and 3 percent
- For the coastal plain soils, the water table was set at one meter
- Rainfall nutrient inputs were obtained from the Chesapeake Bay Model
- SWAT and REMM simulations assumed a homogenous topography, geology, soils and vegetation within a defined subbasin (SWAT) or buffer zone (REMM)
- The Priestly-Taylor method was selected to calculate potential evapotranspiration
- Each zone in the riparian buffer was of equal width. For example, a 15 m buffer would have three-zones with each zone having a 5 m width.
- Long-term average soil N and P values were input into SWAT and REMM

RESULTS AND DISCUSSION

A modeling approach to urban riparian buffer design was investigated. Currently, the state of Delaware stipulates a 30 m buffer zone on new land development. The SWAT model was used to generate sediment, N and P loadings at the edge of the buffer. REMM was then used to simulate buffer dynamics for a 25-year period. For data summary, five simulated rainfall years were selected that corresponded to minimum, below average, average, above average and maximum rainfall (Table 3). These five rainfall years captured a range of surface hydrology conditions sufficient to adequately describe P and sediment behavior. The results that are reported in this research focus on the percent total P reduction and the percent sediment yield reduction at the outflow of zone 1 for a 15 m riparian buffer. This corresponds to the interface between the riparian buffer and a water body. Delaware currently requires a 60 percent reduction in total P and 80 percent reduction in sediment yield at the outflow of zone 1.

The CLIGEN weather generator simulated the rainfall data used in SWAT and REMM. Since SWAT and REMM are weather driven models, simulated rainfall must be representative of the test region. The maximum simulated rainfall was 1497 mm, the minimum simulated rainfall was 739 mm and the average simulated rainfall was 1162 mm (Table 3). These data compare favorably to long-term rainfall measured at the state weather station at Georgetown, Delaware.

Table 3. Five rainfall periods used from the simulated 25-year data set.

Rainfall Category	Rainfall mm	Corresponding Simulation Year
Minimum	739	23
Below Average	950	4
Average	1162	11
Above Average	1330	22
maximum	1497	24

The percent total P reduction in the 15 m buffer is summarized in Figure 1. A 60 percent reduction was nearly achieved in all years except the minimum rainfall year. Even though the desired minimum outflow was not reached for the minimum rainfall year, the total influx was small and the overall outflow in zone 1 was 0.26 kg ha^{-1}. For the average rainfall year, the percent total P reduction was only 3 percent below the level of reduction set by Delaware. These levels of reduction agree well with those of Sharpley et al. (2002), Dillaha et al. (1989) and Chaubey et al. (1995). Sharpley et al. (2002) showed that 40-65 percent of the total P could be reduced with filter strips and riparian buffers. Dillaha et al. (1989) found when a 9.1 m vegetative filter strip was used on cropland with slopes of 11-16 percent that total P was reduced 79 percent when compared to cropland without filter strips. Chaubey et al. (1995) stated that vegetated buffers could reduce total P in runoff by as much as 90 percent. Even with these potential reductions in total P, the results were dependent on buffer length, runoff rate, concentrated flow and soil physical factors.

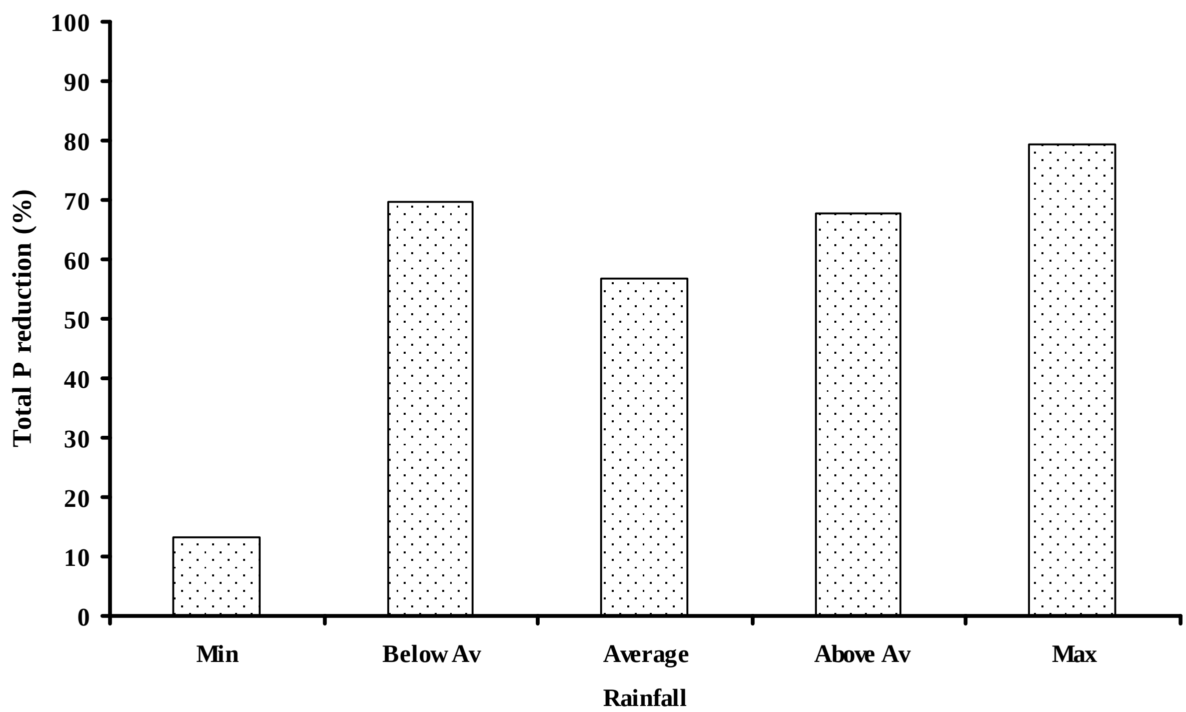

Figure 1. Percent total P reduction for a 15 m buffer for five rainfall periods.

The reduction in total P can be explained in part by the reduction in through flow of organic P and of sediment. Total organic P was reduced by greater than 80 percent except for minimum rainfall, which was 44 percent or 0.11 kg ha^{-1} (Table 4). However, total inorganic P increased by an average of 229 percent across the five rainfall years. The average increase in inorganic P was 0.31 kg ha^{-1}. This increase in inorganic P was most likely from mineralization in the buffer and the application of inorganic lawn fertilizer that possibly was transported in runoff to the buffer in the solid form.

Table 4. Total organic and inorganic P input at zone 3 and the percent reduction in total organic and inorganic P at the zone 1 outflow.

Rainfall Period	Total Organic P Input kg ha^{-1}	Total Organic P Reduction percent	Total Inorganic P Input kg ha^{-1}	Total Inorganic P Reduction percent
Minimum	0.24	44	0.02	-330
Below Average	0.70	85	0.05	-177
Average	1.60	80	0.09	-342
Above Average	1.70	87	0.12	-200
Maximum	3.62	94	0.22	-155

The sediment yield at the buffer edge (zone 3) reflected topographic features, yearly rainfall and soil and vegetation conditions. A reduction of greater than 83 percent in sediment yield outflow in zone 1 was simulated except for above average rain (Figure 2). Majority of the reduction occurred in zone 1 (Table 5). There was a relatively constant reduction in sediment yield in zone 1 and zone 3 regardless of rainfall amount. The three-zone riparian buffer simulated in this study used grass in zone 3. These results were consistent with those of Allison and Dhakal (2000). They reported that a 3 m grass buffer removed 75 percent of the soil sediment for coarse textured soils on slopes of less that seven percent. However, McKague et al. (1996) reported that a 6.1 m buffer reduced sediment by 65 percent, but a buffer of 27.4 m was required to reduce loadings to an acceptable level. They further concluded that for some of their watersheds grass riparian buffers had no effect on reducing sediment load. Grass is effective in trapping sediments; however the effectiveness is dependent on grass species, the condition of the grass, soil texture and slope.

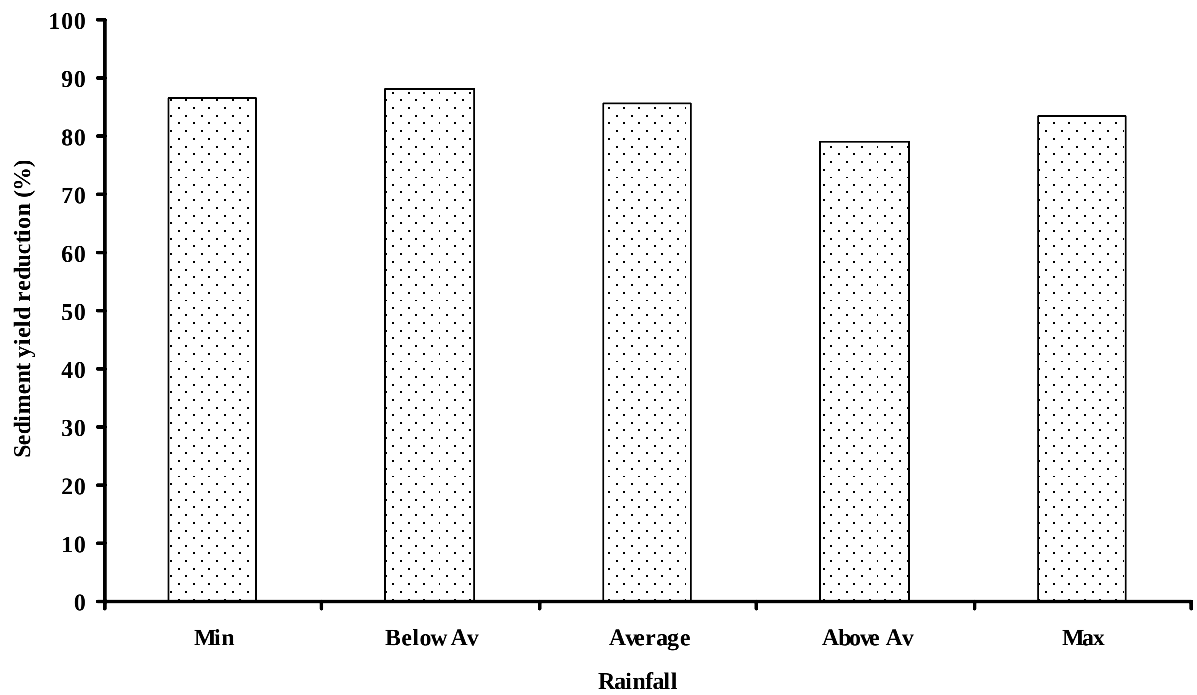

Figure 2. Percent sediment yield reduction for a 15 m buffer for five rainfall periods.

The 15 m buffer appeared to be effective in reducing sediment and P outflow in zone 1. The Downer soil has a sandy loam to loamy sand texture throughout the profile and based on official soil series descriptions there are no subsurface compaction layers. Internal drainage class is well drained, infiltration rate is moderate to moderately rapid and slope was three percent. This soil setting with a three-zone buffer is ideal for trapping and removing sediments and P. These results should not be transferred to other locations in Delaware without additional simulations using different soils and rainfall data. Changes in soil hydraulic properties, slope, buffer configuration or vegetation would affect surface hydrology, which subsequently would influence sediment delivery and nutrient behavior.

Table 5. Sediment yield input at zone 3 and the percent reduction in sediment yield at the zone 1 outflow.

Rainfall Period	Sediment Yield Reduction in Zone 3 (%)	Total Sediment Yield Reduction (%)
Minimum	73	87
Below Average	80	88
Average	77	86
Above Average	73	79
Maximum	76	85

CONCLUSIONS

This simulation study does not provide a total explanation of the complexity of the P biogeochemical cycle or sediment dynamics in urban and riparian buffer landscapes, but the modeling approach used in this research was effective and provided realistic criteria for designing urban riparian buffers. Based on Delaware riparian standards, buffers on Downer soils are over designed at 30 m. Simulation results indicated that a 15 m buffer would meet requirements for removing 80 percent of the sediment (except for above average rainfall) and 60 percent of the P loadings (except for minimum rainfall). An average of 76 percent of the sediment was removed in zone 3 and 85 percent of the sediment was removed at the outflow of zone 1 for the five rainfall amounts. The average total P removal was 68 percent, excluding the minimum rainfall year. Majority of the total P removed was in the organic form.

Before recommendations on buffer size are modified in Delaware based on this research, a wide variety of Delaware soils need to be simulated. For example, the Piedmont soils in northern Delaware have higher clay contents than the Downer soil and are located on slopes upwards to 12 percent. These two factors alone are sufficient to modify surface hydrology conditions. Subsequently, buffer width would need to be adjusted to account for increased runoff volume and sediment transport. Additional research also needs to focus on the long-term sustainability of urban buffers and the effects of urban encroachment on their ecological resiliency and resistance.

While the use of the modeling approach for designing urban buffers summarized in the paper has broad applications, the ease of the simulation process needs to be streamlined for users across a variety of disciplines. Currently, separate simulations must be completed to create loadings data for REMM and then those data must be input to REMM. The entire simulation needs to be seamless.

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