CENTER FOR WATERSHED PROTECTION

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SWMM Modeling for Biochar in Bioretention

Center for Watershed Protection

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Introduction

The purpose of this modeling exercise using PCSWMM was to evaluate the increase in runoff reduction due to the addition of biochar in the media layer of a bioretention system. Biochar is known to improve soil moisture retention and hydraulic properties, potentially enhancing the performance of bioretention systems in managing urban stormwater (Chowdhury et al., 2024). By simulating different design scenarios, this study aims to quantify the hydrologic benefits of biochar amendments and assess their impact on bioretention runoff reduction.

The results of this modeling effort will be used to inform adjustments to the retrofit removal adjuster curve (Bahr et al., 2012), which is a key tool for estimating pollutant removal efficiencies of stormwater Best Management Practices (BMPs). The anchor points of the retrofit removal adjuster curve provide critical information on how much Total Phosphorus (TP), Total Nitrogen (TN), and Total Suspended Solids (TSS) are removed by a BMP that is designed to treat 1-inch of runoff from its contributing impervious drainage area. By determining how biochar influences runoff reduction, this study will help refine the rightward shift of the curve, ensuring more accurate pollutant removal crediting for biochar-enhanced bioretention systems.

Methods

The bioretention system simulated in PCSWMM was sized following the Maryland SWM Volume 1 criteria (MDE, 2000), ensuring compliance with standard stormwater management design. The bioretention facility was designed to treat runoff from a 0.5-acre parking lot with 100% imperviousness, a drainage area size that is representative of the study sites used to develop the retrofit removal adjuster curve. The bioretention was 800 square feet, with 1’ of ponding, 3’ of bioretention media, and 8” of stone. Once the bioretention sizing was determined using the Maryland SWM Manual, it was incorporated into the SWMM modeling framework.

The soil properties of the bioretention media layer were required as inputs in SWMM, including porosity, field capacity, wilting point, and hydraulic conductivity. The porosity and hydraulic conductivity of the bioretention media before biochar addition were obtained directly from the Maryland SWM Manual. However, the manual does not provide specific guidance on field capacity and wilting point for the bioretention media layer. Therefore, these values were extracted from monitoring studies done by University of Delaware (Akpinar, 2023; Akpinar et al., 2023; Chowdhury et al., 2024).

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Once the baseline bioretention system (without biochar) was incorporated in SWMM, a second set of bioretention systems was simulated with the same physical dimensions, but with modified soil properties in the media and storage layers to represent the effect of biochar addition. The porosity, hydraulic conductivity, and available water content of the biochar-amended soil were increased based on a scaling factor, where the median values reported monitoring studies done by University of Delaware were used. The monitoring study conducted by the University of Delaware examined the impact of biochar amendments on soil properties, where biochar was incorporated into the soil media at rates of 9% and 18% by volume (Akpinar et al., 2023; Chowdhury et al., 2024).

A total of five primary scenarios were simulated in SWMM (Table 1), with each scenario having two versions of the bioretention system—one without biochar and one with biochar. The scenarios reflected different underlying soil types and the presence or absence of an underdrain. Additionally, Scenario 3 was included to evaluate a bioretention system sized to capture only 0.5 inches of runoff instead of the full 1-inch design storm.

Once the SWMM model reflecting these scenarios was set up, the model was run using a 1-inch design storm with an SCS Type II rainfall distribution (United States Department of Agriculture, 1986).

After running the model, results were evaluated based on the reduction in total runoff due to biochar addition. Here, runoff reduction was defined as the difference between the total inflow into the bioretention system and the combined outflow through the underdrain and surface overflow.

Table 1. Description of scenarios simulated in SWMM and their respective runoff reduction amount

	Runoff Reduction Amount (ft^3)		Increase in Runoff Reduction (%)
	A - without biochar	B - with biochar	
Scenario 1: C type soil, underdrain	566	582	2.87
Scenario 2: B type soil, no underdrain	1024	1262	23.24
Scenario 3: C type soil, underdrain, sized for 0.5” storm	289	299	3.32
Scenario 4: Lined Bottom, underdrain	281	531	89
Scenario 5: D type soil, underdrain	405	553	36
Average Increase			**31**

While the model was able to incorporate different soil parameters that are altered by biochar, there are some limitations to the model.

- SWMM does not model water exiting the sides of the bioretention
- Plants and plant-water interactions, including transpiration, are not included
- The model used is a 1D model, where once the water reaches the underdrain, it will immediately exit the system
- Only a 1” storm was modeled. It is expected that for a continuous simulation, the bioretention with biochar would be able to reduce more runoff. Without the plant

interaction in the model, the full runoff reduction potential of biochar will not be accounted for in SWMM

- The underdrain is modeled as slots within a pipe, where once the water level reaches the invert of the underdrain, water leaves the system. In reality, water enters the underdrain at variable rates, depending on the water level at the underdrain. If the underdrain is large relative to the size of the bioretention, this error will impact the drainage significantly, as show in Scenario 1There were only 6 bioretention design scenarios modeled in SWMM. The underlying bioretention design can impact the overall performance

All of these limitations will decrease the amount of runoff reduced, so the estimates are all conservative.

Results

The results of the SWMM simulations demonstrate that the increase in runoff reduction due to biochar addition varies significantly across the different scenarios. Table 1 presents the runoff reduction amounts for bioretention systems in all five scenarios, both with and without biochar, along with the increase in runoff reduction due to biochar addition.

The increase in runoff reduction due to biochar addition spans a wide range. In Scenario 1, the increase is only 2%, indicating that biochar has a minimal effect on runoff reduction in this case. However, in Scenario 4, where the bioretention system is lined and includes an underdrain, the increase in runoff reduction is much greater, reaching nearly 89%. Table 2 presents the mass balance of the BMP for Scenario 1 and 4, illustrating the redistribution of water between infiltration losses and underdrain outflow. Figure 1 shows the time series plot of soil percolation rate, storage layer exfiltration, underdrain outflow, and soil moisture content for Scenario 1 and 4. Figure 2, adapted from the SWMM manual, illustrates the general relationship among soil moisture parameters. In Scenario 1A, where the bioretention system does not contain biochar, percolation from the soil layer to the storage layer occurs over an extended period because the Field Capacity (FC) is lower. With a lower FC, the soil reaches saturation more quickly and allows continuous downward movement of water into the storage layer for a longer duration. Since percolation occurs gradually, a significant portion of the water that reaches the storage layer is lost through infiltration into the underlying soil rather than exiting through the underdrain. In SWMM, infiltration into the native soil is prioritized before excess water is discharged through the underdrain, which results in similar amount of infiltration losses and underdrain outflow in Scenario 1A.

In Scenario 1B, where biochar has been added to the media layer, Field Capacity (FC) is higher, meaning that the soil retains more water before allowing percolation to occur. As a result, percolation from the soil layer to the storage layer happens for only a short duration before stopping once the soil moisture content reaches FC. Because percolation stops quickly, there is less opportunity for infiltration into the native soil, and most of the water that reaches the storage layer exits through the underdrain instead. The C-type soil beneath the bioretention has low hydraulic conductivity, so infiltration is already limited, and with percolation ceasing sooner, the stored water

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is redirected toward the underdrain rather than percolating downward. This explains why Scenario 1B shows only a 2% increase in runoff reduction due to biochar—most of the excess water bypasses infiltration and leaves through the underdrain.

In Scenario 4, where the bioretention system is lined, infiltration into the underlying soil is completely eliminated, meaning that all water that reaches the storage layer must either be stored or discharged through the underdrain. In Scenario 4A (without biochar), this results in higher underdrain outflow compared to Scenario 1A, as there are no infiltration losses. However, in Scenario 4B (with biochar), the increased Field Capacity (FC) results in greater water retention within the BMP, but since infiltration is not an option, all excess water must exit through the underdrain. The removal of infiltration losses amplifies the effect of biochar on water retention, leading to a much higher increase in runoff reduction in Scenario 4B compared to Scenario 1B.

Table 2 presents the mass balance of the BMP for Scenario 1 and 4, further illustrating the redistribution of water between infiltration losses and underdrain outflow. Figure 2 shows the time series plot of soil percolation rate, storage layer exfiltration, underdrain outflow, and soil moisture content for Scenario 1 and 4, which highlights how percolation in Scenario 1A continues for a longer duration compared to Scenario 1B due to differences in FC. Figure 3, adapted from the SWMM manual, illustrates the importance of Field Capacity, Wilting Point, and Porosity in controlling soil percolation. This figure confirms that soil percolation occurs only when the soil moisture content exceeds FC, explaining why percolation is cut off earlier in biochar-amended scenarios.

In Scenario 2, where the underlying soil is Hydrologic Soil Group B, the increase in runoff reduction is 23%. Interestingly, in this scenario, the entire incoming runoff is stored or reduced due to biochar addition, meaning that biochar-enhanced bioretention is capable of fully retaining the inflow under these conditions.

These findings indicate that the effectiveness of biochar in reducing runoff is highly dependent on the bioretention design, the presence of a liner, and the infiltration characteristics of the underlying soil. The scenarios with lined systems and higher native soil infiltration tend to show higher percentage increases in runoff reduction due to biochar, while systems with lower native soil infiltration exhibit more moderate improvements.

Table 2. The total inflow, evaporation loss, infiltration loss (storage exfiltration), surface overflow, and drain outflow for each scenario.

Scenario	Total Inflow	Evaporation Loss	Infiltration Loss (Storage Exfiltration)	Surface Overflow	Drain Outflow
	(in)	(in)	(in)	(in)	(in)
4A	19.97	1.73	0	3.58	11.14
4B	19.97	1.69	0	0	10.97
1A	19.97	1.73	4.84	3.58	6.86

1B	19.97	1.69	1.41	0	10.19

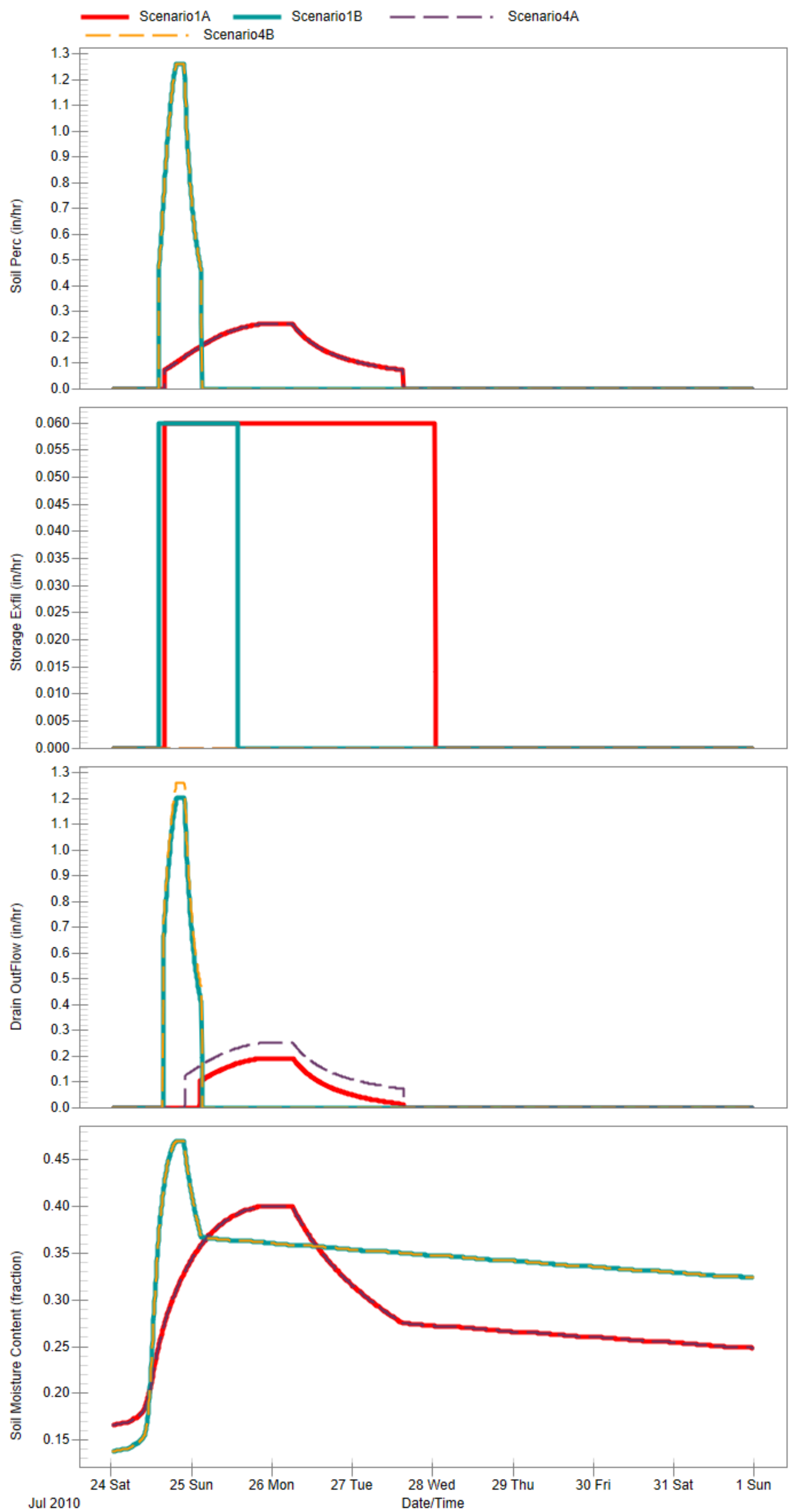

Figure 1. Time-series plots of bioretention processes for Scenario 1 and Scenario 4. The (a) soil percolation rate, (b) storage layer exfiltration, (c) drain outflow, and (d) soil moisture content over time.

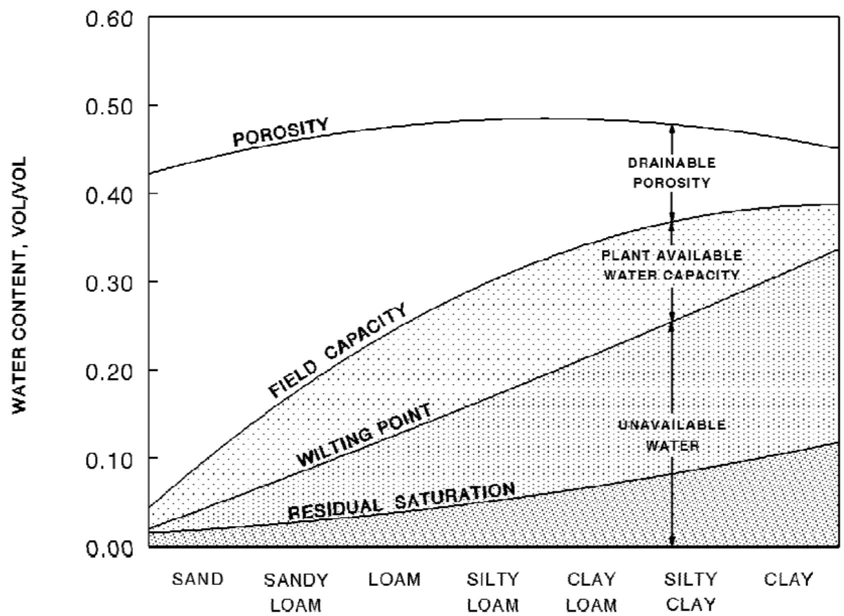

Figure 2. General relationship among soil moisture retention properties and soil texture class (adapted from SWMM Manual).

Conclusion

The results of this modeling exercise indicate that biochar amendments in bioretention systems can lead to significant increases in runoff reduction, with an average increase of approximately 30% across the five simulated scenarios. The magnitude of runoff reduction enhancement varied depending on the underlying soil type and the presence of an underdrain or liner, with the highest increases observed in systems where infiltration was restricted. When translated to the retrofit removal adjuster curve, a 30% increase in runoff reduction for a bioretention system designed to treat 1-inch of runoff corresponds to an increase in Total Phosphorus (TP) removal efficiency from 70% to 75%. This suggests that biochar-enhanced bioretention systems could provide improved pollutant removal benefits, making them a valuable consideration for stormwater retrofits and nutrient reduction strategies.

Further validation with field data would help refine these findings and improve confidence in how biochar influences long-term hydrologic performance in bioretention systems.

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