- multiplying the number of measurable benefits (3), by their benefit scoring value (0.667),
- multiplying the number of potential benefits (10), by their benefit scoring value (0.333),
- multiplying the number of not applicable benefits (0), by their benefit scoring value (0),
- Adding the subtotals together results in a total score of (2 + 2 + 3.3 + 0 = 7.3).

Table 2: Point Values and Symbols for Benefit Levels

Symbol	Level of Impact	Point Value
●	Monetizable	1
◉	Measurable	0.67
○	Potential	0.33
⊗	Not Applicable	0

Table 3: Overview of Green Infrastructure Strategies Potential Relative Benefit Scores

Ref.	Description of Strategy Group	Category	Strategy Outcome	Monetizable	Measurable	Potential	Not Applicable	Total Point Value	Number of Applicable Benefits
19	Green Infrastructure	Structural	Green Infrastructure	2	3	10	0	7.33	15
20	Green Streets	Structural	Green Infrastructure	2	3	10	0	7.33	15
21	Multiuse Treatment Areas - Infiltration and Detention Basins	Structural	Multiuse Treatment Areas	2	1	6	6	4.67	9
22	Multiuse Treatment Areas - Stream, Channel and Habitat Rehabilitation Projects	Structural	Multiuse Treatment Areas	0	2	8	5	4.00	10

In Table 4, a detailed summary of the potential benefit level for each strategy and benefit category is presented. Note that, in some cases, the strategy group includes individual strategies that are classified by different types of strategy outcomes.

RESULTS OF ASSESSMENT

Overall, the approach presented provides a rational basis for evaluating, comparing, and prioritizing options for storm water management within a community that is grounded in economic principles.

The next step is be to assign monetary values to those benefits that are monetizable and develop monetary values for the quantifiable benefits. This will provide a community insight into the total economic value they may obtain from an investment in storm water controls that would allow them to evaluate how to fund storm water projects to obtain the greatest community benefits from each dollar spent.

This technique is applicable to all investments of public funds. Communities throughout the U.S. have been adopting these techniques for decision making regarding their transportation, power, wastewater, and storm water systems.

Table 4: Overview of Potential Other Benefits of Water Quality Improvement Plan Jurisdictional Strategies

		Financial		Environmental						Social								
Ref	**Strategy Group**	**Water Cost Savings**	**Energy Cost Savings**	**Flood Risk Reduction**	**Air Particulate Entrainment**	**Climate Impacts**	**Habitat Related Benefits**	**Air Quality Emission Reduction**	**GHG Emission Reduction**	**Property Value Enhancement**	**Recreational Benefits**	**Business Development & Jobs**	**Crime Reduction**	**Public Education/ Environmental Stewardship**	**Noise Reduction**	**Heat Island Effect**	**Total Point Value**	**Number of Applicable Benefits**
19	Green Infrastructure	○ 0.33	○ 0.33	⊙ 0.67	● 1	● 1	○ 0.33	○ 0.33	○ 0.33	⊙ 0.67	○ 0.33	⊙ 0.67	○ 0.33	○ 0.33	○ 0.33	○ 0.33	**7.3**	**15**
20	Green Streets	○ 0.33	○ 0.33	⊙ 0.67	● 1	● 1	○ 0.33	○ 0.33	○ 0.33	⊙ 0.67	○ 0.33	⊙ 0.67	○ 0.33	○ 0.33	○ 0.33	○ 0.33	**7.3**	**15**
21	Multiuse Treatment Areas - Infiltration and Detention Basins	○ 0.33	○ 0.33	○ 0.33	● 1	● 1	○ 0.33	○ 0.33	○ 0.33	⊗ 0	⊗ 0	⊗ 0	⊗ 0	⊙ 0.67	⊗ 0	⊗ 0	**4.7**	**9**
22	Multiuse Treatment Areas - Stream, Channel and Habitat Rehabilitation Projects	○ 0.33	○ 0.33	⊙ 0.67	○ 0.33	○ 0.33	○ 0.33	○ 0.33	○ 0.33	⊙ 0.67	⊗ 0	⊗ 0	⊗ 0	○ 0.33	⊗ 0	⊗ 0	**4.0**	**10**

A New Method for Sizing Flow-Based Treatment Systems to Meet Volume-Based Standards

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ABSTRACT

As BMP sizing standards have evolved towards a focus on volume-based approaches (e.g., capture of the first 1 inch of runoff), sizing methods are typically absent or lacking for flow-based BMPs. Yet, flow-based BMPs that are certified with high pollutant removal performance can serve an important role in stormwater management in space constrained areas or as part of treatment trains in combination with volume-based systems. In response to these factors, Modular Wetland Systems, Inc. commissioned the development of a new sizing methodology for forty-five regions within fifteen states on the eastern seaboard of the United States for the flow-based MWS Linear treatment system. This methodology is based on providing equivalent long term capture efficiency of stormwater runoff volumes as compared to volume-based regulatory standards. The sizing methodology developed first involves establishing a target capture efficiency for each region, obtained directly from state guidance, or developed via continuous simulation modeling using long-term, high-resolution precipitation data. Facility flow rates needed to achieve the target long term capture efficiency for different drainage area conditions were then calculated via continuous simulation modeling. Findings were normalized and used to develop sizing tables to allow for application to flow-based facility sizing for user-specific drainage area types.

INTRODUCTION

Flow-based BMPs are designed to treat a given flow rate of stormwater runoff at the time the runoff occurs (i.e., “flow-based” sizing). This sizing basis is different from typical best management practices (BMPs), which are often sized to hold a given volume of stormwater runoff and treat it during and after a storm event (e.g., “volume-based” sizing).

This paper describes the technical basis for a flow-based sizing approach that is formulated to provide treatment for an equivalent amount of long term runoff volume in comparison to traditional BMP sizing standards that are based on a specified design storm depth or long term capture efficiency. The approach includes continuous simulation modeling for catchments with varying time of concentrations, as it is important to account for short-interval, high intensity precipitation in flow-based BMP sizing for small urban catchments. The approach described tends to result in more efficient sizes than sizing for the absolute peak of a design storm hydrograph, which is currently the typical regulatory flow-based sizing method.

METHODOLOGY FOR DEVELOPING SIZING CRITERIA

Overview of Methodology

The flow-based sizing approach was formulated to provide treatment of runoff in flow-based BMPs for an equivalent amount of long term runoff volume in comparison to traditional volume-based BMP sizing standards. Long term capture efficiency is the underlying metric used in this methodology. The methodology used to develop the flow-based sizing approach consisted of four primary steps:

1. **Determine applicable sizing criteria for stormwater quality BMPs:** Regulatory sizing criteria in a given location are typically expressed as either a design storm volume (e.g., capture and treat the runoff from a 1-inch storm event), or a long term capture efficiency approach (e.g., capture and treat the 90 percent of long term runoff volume). In some cases, both options are available.
2. **Establish target long term capture efficiency for flow-based BMP sizing:** If long term capture efficiency was expressed in the applicable regulations, then this was set as the target long term capture efficiency. If only a design storm-based sizing criterion was provided, then continuous simulation was conducted for a representative BMP that was sized based on the design storm criterion to determine the level of long term capture efficiency provided by that BMP.
3. **Determine flow-based sizing required to achieve target capture efficiency:** Continuous simulation modeling was conducted for a range of BMP design flow rates (in this case, specific to MWS Linear®), in various project locations (i.e., rainfall and evapotranspiration records), for a range of drainage area time of concentration (Tc) values to determine the required BMP design flow rates needed to achieve the target capture efficiency in each combination of conditions.
4. **Develop sizing worksheets and supporting tables:** The results of step 3 were normalized by drainage area and runoff coefficients, so that these results can be applied to the drainage area characteristics that are most appropriate for each project. This was facilitated by converting each required size from step 3 to an equivalent required "treatment intensity." This required treatment intensity can then be applied to a given drainage area using the Rational Method to calculate the required treatment flow rate. Additionally, for the case of the MWS Linear® facility, the equalization and detention within the forebay of the facility was used to calculate a "detention time" that could be added to the Tc value for the watershed.

Continuous Simulation Modeling

Continuous simulation modeling was conducted for steps 2 and 3 of the methodology. The USEPA Stormwater Management Model (SWMM) version 5.1.010 was used to model each scenario, including runoff generation and routing, to estimate the long term capture efficiency provided by the BMP.

Batch continuous simulation modeling is a method of running many models quickly by using code to change a few variables in each input file and run model iterations automatically rather than manually rerunning each new model file. For flow-based sizing, this process was used to model seven different Tc values (5, 7.5, 10, 12.5, 15, 20, 25, and 30 minutes) each draining to a facility with a range of 25 different treatment flowrates. As a result, a total of 175 models were run per precipitation gage.

A long term rainfall record consisting of 10 to 15 years of data at 5-minute temporal resolution and 0.01-inch depth resolution served as the primary meteorological input, supplemented with temperature-based estimates of evapotranspiration.

Precipitation

Continuous 5-minute precipitation data were obtained from the Automated Surface Observation System (http://www.nws.noaa.gov/asos/). ASOS gages are heated tipping bucket gages, typically located at airports. Forty-five precipitation gages located in fifteen states were identified for use in this analysis. Gage selection was based on the length of record, quality (i.e. percent missing data), and location. The gage locations were selected based on (1) proximity to urbanized areas where use of the sizing results will be most concentrated, and (2) ability to reflect the climatic variability across a state. The precipitation gages used in the analysis are shown in Table 1.

Table 1: ASOS Precipitation Gages Included in Analyses

State	Location and Gage ID	State	Location and Gage ID
Connecticut	Bridgeport - KBDR	New York	Albany - KALB
	Windsor Locks- KBDL		Buffalo - KBUF
Delaware	Wilmington - KILG		JFK Airport- KJFK
Florida	Jacksonville - KJAX		Syracuse - KSYR
	Miami - KMIA	North Carolina	Asheville - KAVL
	Orlando - KMCO		RDU Airport - KRDU
	Tallahassee - KTLH		Wilmington - KILM
	Tampa - KTPA	Pennsylvania	Avoca - KAVP
Georgia	Atlanta - KATL		Erie - KERI
	Augusta/Bush - KAGS		Philadelphia - KPHL
	Savannah - KSAV		Pittsburgh - KPIT
Maine	Bangor - KBGR	Rhode Island	Providence - KPVD
	Millinocket - KMLT	South Carolina	Charleston - KCHS
	Portland - KPWM		Columbia- KCAE
Maryland	BWI Airport - KBWI		Greer - KGSP
	Hagerstown - KHGR	Vermont	Bennington - KDDH
	Ocean City - KOXB		Burlington - KBTV
Massachusetts	Boston - KBOS		Springfield - KVSF
	Plymouth - KPYM	Virginia	Norfolk - KORF
	Worcester - KORH		Roanoke - KROA
New Hampshire	Concord - KCON		Richmond - KRIC
	Lebanon - KLEB		Dulles Airport - KIAD
	Rochester - KDAW		

Precipitation records were checked for anomalous data by screening the ASOS records against the 5 minute, 50 year precipitation intensity from the NOAA ATLAS 14 point Precipitation Frequency estimates (NOAA, 2014). In addition to the individual data point checks, total monthly precipitation from these processed ASOS precipitation records were checked against monthly precipitation from climate division averages (NCDC 2016a) for each regions. A subset of the corrected ASOS precipitation records were also compared to records from nearby National Climatic Data Center (NCDC) hourly precipitation gages, which have longer periods of records and are more thoroughly quality controlled (NCDC 2016b). This comparison was based on two metrics that are meaning for stormwater BMPs that could be computed from both gages: the 90th percentile, hourly precipitation depth and the 90th percentile, 24-hour precipitation volume.

Evaporation

Evaporation was applied to the subcatchments modeled in SWMM using Hargreaves Method by inputting a climate file of daily temperature. Daily temperature was also obtained from the ASOS weather stations at the same locations as the corresponding precipitation record. This is an approximate method, but has relatively low sensitivity in urban catchments.

Time of Concentration

Catchment time of concentration was represented in the model by altering the catchment flow path length to provide the desired Tc corresponding to each model scenario. The time of concentration equation used is based on kinematic wave routing, and is provided below (FHWA, 2009):

$$Tc = \frac{0.93 \times L^{0.6} \times n^{0.6}}{I^{0.4} \times S^{0.3}}$$

Where,

Tc = time of concentration (minutes)
L = length (feet)
n = Manning’s n (0.12, corresponding to impervious surface Manning’s n)
S = Slope (ft/ft) (0.03)
I = intensity (in/hr)

The intensity used in this analysis was equivalent to the 90th percentile, five minute intensity, which varied by gage modeled.

Development of Target Long Term Capture Efficiency

A review of state-based standards for all fifteen states identified those standards that were based on an average annual percentage of total runoff and those standards which had a volume-based standard only. State sizing standards were obtained from stormwater BMP sizing manuals, state code, and other technical reports promulgated by the respective regulatory agency which were available at the time of the analyses. A summary of state requirements is provided in Table 2. Maximum BMP drawdown requirements are also provided.

For states where long term capture efficiency was not included in regulatory BMP sizing requirements, continuous simulation modeling was conducted to estimate the target long term capture efficiency that would result from the applicable volume-based sizing criterion. For each of the regions analyzed in these states, the applicable design storm event sizing criterion (e.g., 1 inch storm) and applicable BMP drawdown time (e.g., drain within 48 hours) were applied to a hypothetical one acre, 100 percent impervious catchment to determine the storage volume and discharge rates associated with the traditional volume-based BMP design. This configuration was modeled using the precipitation and climate inputs described above to estimate the target long term capture efficiency.

Table 2: Summary of Water Quality Volume Sizing Requirements by State

State	**Summary of Standard Analyzed to Establish Target Capture Efficiency**	**Drawdown Requirement**
Connecticut	90% Capture of Average Annual Runoff Volume	
Delaware	90% Capture of Average Annual Runoff Volume	
Florida (see note)	90% Capture of Average Annual Runoff Volume	
Georgia	Volume of runoff generated by 1.2 inches of precipitation over the site.	48 hours
Maine	90% Capture of Average Annual Runoff Volume	
Maryland	90% Capture of Average Annual Runoff Volume	
Massachusetts	Volume of runoff equivalent to 1.0 inch of runoff from impervious surfaces on the site.	72 hours
New Hampshire	Volume of runoff generated by 1.0 inch of precipitation over the site.	72 hours
New York	90% Capture of Average Annual Runoff Volume	
North Carolina	Volume of runoff generated by 1.0 inch of precipitation over the site for non-coastal areas and 1.5 inches for coastal areas.	48 hours
Pennsylvania	95% Capture of Average Annual Runoff Volume	
Rhode Island	90% Capture of Average Annual Runoff Volume	
South Carolina	Volume of runoff generated by 1.0 inch of precipitation over the site.	48 hours
Vermont	90% Capture of Average Annual Runoff Volume	
Virginia	90% Capture of Average Annual Runoff Volume	

Note: Florida's Water Management Districts have varying requirements which range from capture of the first one half inch of runoff to capture of the total runoff of 2.5 inches times the imperviousness, and drawdown variations of 24 to 72 hours. Based on preliminary runs it was estimated that the most stringent requirements equate to approximately 90% capture; for the sake of consistency Florida sizing was conducted assuming a 90% capture requirement.

Volume-based BMPs are not sensitive to time of concentration within the range typically found in urban catchments (5 to 30 minutes) because they include substantial equalization storage volume typically greater than runoff volume that occurs in 30 minutes. A single representative Tc value of 10 minutes was selected for the purpose of modeling volume-based BMPs. In contrast, multiple catchment configurations represent different Tc values were analyzed for the flow-based systems, as described below.

Flow-based BMP Sizing to Achieve Target Long Term Capture Efficiency

A range of treatment flow rates were modeled for combinations of Tc and each region analyzed, which were converted to an equivalent required "treatment intensity." The resulting treatment intensity that achieves the target long term capture efficiency for a given region and catchment Tc can be used as the sizing basis for a flow-based BMP.

A one acre, 100 percent impervious catchment was used as the standard drainage area for consistency with the volume-based BMP sizing analyses and to allow for normalization of the treatment flow rate to treatment intensity. Continuous simulation was used to model seven different drainage area Tc values draining to a flow-based BMP with a range of treatment flow rates. The flow-based BMP was assumed to capture all runoff flows up to the identified treatment flow rate. Flows in excess of the identified treatment flow rate were bypassed.

The flow rates modeled in each simulation were converted to an equivalent treatment intensity using an inverse form of the Rational Method, where the design treatment intensity corresponding to a given model run was calculated as:

$$I_{treatment} = Q/(A * R_v)$$

Where,

$I_{treatment}$ = design treatment intensity, in/hr (approximately 0.1 to 1 in/hr)
Q = modeled flow rate, cfs (ranged from approximately 0.09 to 0.95 cfs)
A = tributary area, ac (set to 1)
R_v = runoff coefficient of a 100 percent catchment (set to 0.95 for modeling purposes based on model estimates and regulatory references)

An example summary result of these continuous simulations is provided in Figure 1. Each symbol on this plot represents a different continuous simulation model run (10 to 15 years of rainfall-runoff-routing simulation in each run). As can be seen in this figure, the required treatment intensity to achieve a given capture efficiency (dashed line) is a function of the drainage area Tc. A longer Tc tends to result in more attenuation of the hydrograph on the catchment surface and a lower required treatment flow rate, and vice versa.

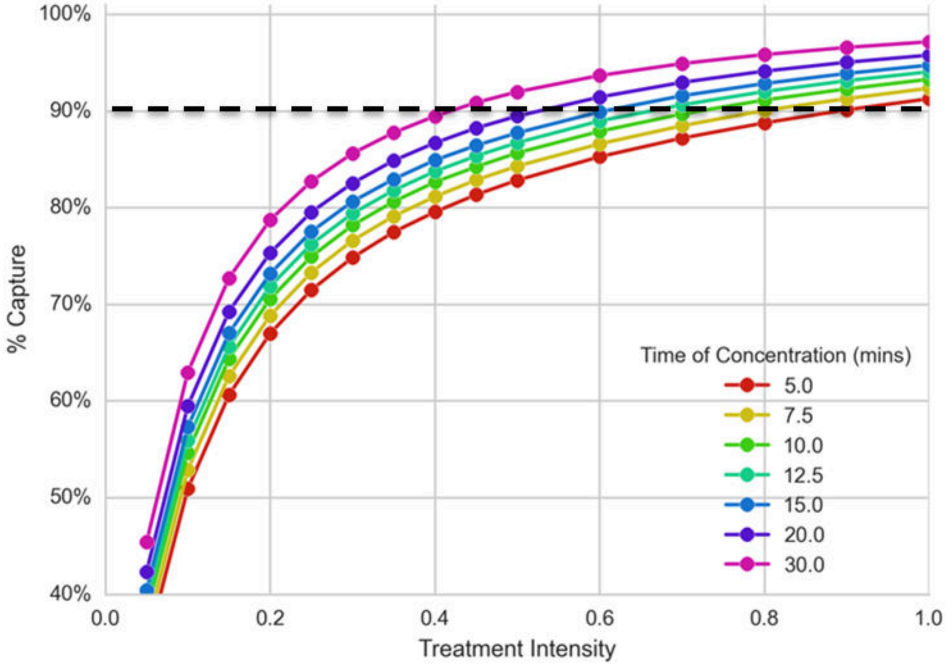

Figure 1: Example Nomograph of Capture Efficiencies for Various Treatment Intensities. (*For Example Purposes Only*)

Using the results from the batch continuous simulation modeling described, coupled with the target long term capture efficiency, the required treatment intensities were summarized for each region (i.e. precipitation gage) and Tc (see Table 3).

Flow-based System Detention Time

If the flow-based system includes components that allow for detention within the facility, this detention time can be added to the catchment Tc to adjust the Tc used to estimate the required treatment intensity needed for flow-based facility. This is because the flow-based BMP sizing analysis model does not account for any detention within the facility.

For instance, the MWS Linear® consists of a two-part treatment chamber, including a pre-treatment chamber and a second chamber which provides horizontal flow through biofiltration media and vegetation. The outlet from the second chamber includes flow control to provide the appropriate residence time within the system. The detention time for each MWS Linear® model was estimated based on the volume in the pre-treatment chamber divided by the design flowrate.

SUMMARY OF FLOW-BASED BMP SIZING APPROACH

The results of the analyses described were distilled into a simple sizing approach to determine the required size of flow-based BMPs (in this case, MWS Linear® systems) to achieve the target long term capture efficiency.

Overview of Sizing Approach

The sizing approach includes four primary steps, as described below.

Step 1: Determine applicable requirements

A. Determine project location.
B. Select the most representative rainfall gage based on the available regions.
C. Look up the design treatment intensities associated with the selected gage (see example provided in Table 3).

Step 2: Determine drainage area properties

A. Determine the drainage area to the flow-based BMP (in acres).
B. Estimate the runoff coefficient for the drainage area under the range of design treatment intensity that applies to the project location; utilize methods that are locally acceptable and represent site conditions.
C. Estimate the Tc of the drainage area under the range of design treatment intensity that applies to the project location.

Optional Step 2a: Determine time of concentration adjustment for detention storage provided in flow-based BMP

A. Identify the detention time associated with the flow-based BMP anticipated to be used for your drainage area. This step may require some iteration if the detention time varies between flow-based BMP sizes.
B. Add the identified detention time adjustment to the estimated Tc to obtain the adjusted Tc for use in flow-based sizing.

Step 3: Conduct rational method calculations to determine required design flowrate

A. Based on the original or adjusted Tc, determine the required treatment intensity associated with the selected gage (see example provided in Table 3Table 3). If the estimated Tc value is in between Tc values provided, linear interpolation between increments is acceptable.
B. Calculate the required treatment flow rate using the following equation (no unit conversion is needed):

$$Q_{treatment} = I_{treatment} * R_v * A$$

Where:

$Q_{treatment}$ = Required flow-based BMP treatment flow rate (cfs)
$I_{treatment}$ = Flow-based BMP treatment intensity (inches per hour)
Rv = Drainage area runoff coefficient (unitless)
A = Drainage area (acres)

Step 4: Select a flow-based BMP which will provide required treatment flowrate

A. Select a flow-based BMP with a treatment flow rate that is equal to or greater than the required treatment flow rate.
B. Confirm that the detention time adjustment to Tc used in Step 2A is met or exceeded by the selected flow-based BMP.

Supporting Sizing Resources Developed for MWS Linear®

Required treatment intensities for MWS Linear® sizing conducted were developed for each region analyzed (summarized in Table 1) to enable users to utilize the sizing methodology described. Table 3 shows an example of how these tables are organized. This table is for example purposes and is based on the example model results presented in Figure 1.

Table 3: Example MWS Linear® Sizing Table

Time of Concentration (minutes)	Required Treatment Intensity (inches per hour)
5	0.85 (example)
7.5	0.76 (example)
10	0.67 (example)
12.5	0.61 (example)
15	0.56 (example
20	0.48 (example)
30	0.38 (example)

For Example Purposes Only – Not Applicable for Sizing in Any Specific Jurisdiction

CONCLUSIONS

The sizing approach described in this paper has been formulated to result in treatment of an equivalent level of long term runoff volume in flow-based BMPs compared to the traditional volume-based sizing criteria and methods that apply in a given location. The use of long term capture efficiency as an equivalency metric is appropriate and robust, as this metric has a direct