Nutrient Accounting for Bioretention Design Variants

This document addresses the nutrient credit assignments for applications of bioretention design variants used for compliance with Nutrient Management Strategies Stormwater Rules. This credit information supplements the statewide practice design guidance for bioretention found in Chapter 12 of NCDENR's Stormwater BMP Manual found here: http://portal.ncdenr.org/web/lr/bmp-manual

In order to receive this credit, bioretention practices **must be designed and maintained** as specified by NCDEQ:

- Pursuant to Minimum Design Criteria and related requirements of rules 15A NCAC 2H .1000. (http://portal.ncdenr.org/c/document_library/get_file?uuid=0212634d-9aa9-4301-a481-1d6c57930c44&groupId=38334), and
- Guided by Chapter 12 of the NC BMP Design Manual.
- Assume a factor of safety of 10 percent in the HyPer Tool.

Nutrient Credit Overview

Bioretention practices are stormwater control measures that achieve nutrient reductions by biological and physical treatment processes and infiltrating the volume of stormwater runoff associated with a design storm of a particular size. Pollutant removal is enhanced by modifying key design elements. Bioretention design variants that are installed to meet the nutrient reduction requirements of Nutrient Management Strategy stormwater rules shall be credited using a two-step calculation process that begins with the HyPer Tool followed by the Jordan Falls Stormwater Accounting Tool (JFSAT) Version 3.0 or a subsequent Division-approved tool. To account for uncertainty associated with this modeling based approach, a factor of safety of 10 percent must be assumed when applying the HyPer Tool.

The estimates for total nitrogen (TN) and total phosphorus (TP) reductions will be based on the following design variants: inclusion of internal water storage (IWS), soil media depth, average surface ponding, surface storage ratio (relative to water quality volume), and the ratio of the bioretention cell area to the drainage area (over- or –under design). The potential load reductions for commonly applied design variants may range from 45-90% for TN and 29-88% for TP, but will vary given site specific design variants and soil conditions applied.

Relative Confidence in Credit Assignments

Credit estimates for bioretention with design variants are considered to have high confidence based on the well understood methods and conservative assumptions used to account for the degree of practice variability with respect to design variants.

Nutrient Credit Estimation and Relative Confidence

A. Summary of Nutrient Load Reduction Credit Method

For this practice, the nutrient credit varies based on key design parameters and the Hydrologic Soil Group (HSG) entered into the HyPer (Hydrologic Performance) Tool developed for bioretention by the NCSU Stormwater Engineering Group under the direction of Dr. Bill Hunt. The design variants entered into the HyPer Tool include the following (Figure 1):

- Soil media depth
- Depth to internal water storage (IWS): depth from surface of soil media to IWS
- Average surface ponding depth
- Surface storage ratio: the ratio of bioretention surface storage capacity (bowl volume above mulch surface area and below outlet structure) to design water quality volume
- Drainage coefficient: the overall maximum drainage rate of outlet pipe network (underdrains, outlet structure, and storm sewer); default 2 ft/d
- Ratio of bioretention cell area to drainage area: ratio of bioretention cell surface area to drainage area (calculated by HyPer Tool)
- Water quality characterization inputs are not necessary in HyPer Tool: they are accounted for in JFSAT
- An assumed factor of 10 percent (required for crediting design variants)

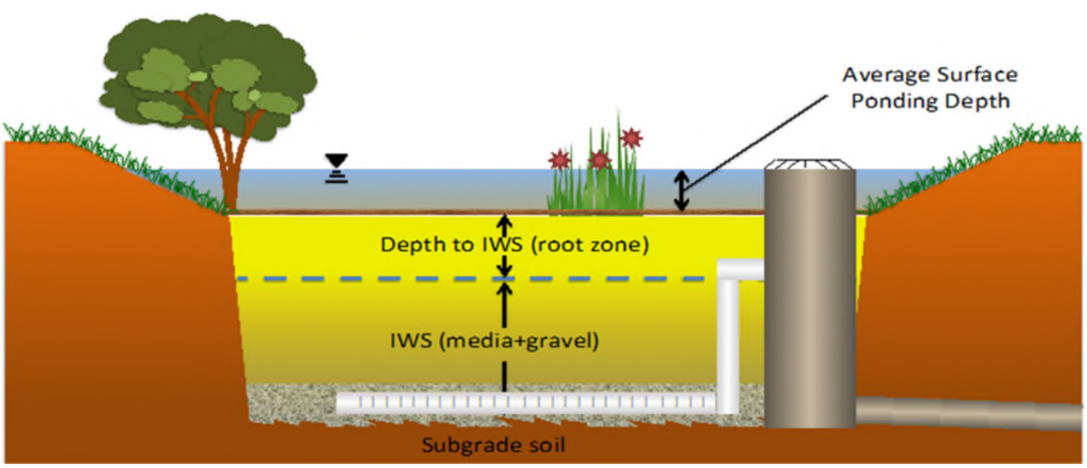

Figure 1. Bioretention Cell Design Variants (from HyPer Tool)

The hydrology output provided by the HyPer Tool is then entered into the latest approved version of the Jordan/Falls Stormwater Accounting Tool (JFSAT) or subsequent Division-approved tool or calculation method as follows:

After the *Project Information* and *Watershed Characteristic* tabs have been populated for the project in JFSAT, the user will simulate a bioretention cell with design variants by entering the following parameters on the *BMP Characteristics* tab:

- For *Type of BMP*, select either "*Custom Bioretention with IWS*" or "*Custom Bioretention without IWS*" from the drop-down menu depending on whether or not the cell includes internal water storage.
- Select the underlying HSG.
- Enter the *Description of the Custom BMP* (e.g., Bioretention with IWS) for record keeping purposes.
- Leave the Under- or Over-sized Percentage blank as this is already accounted for in the HyPer Tool output.
- Enter the Hydrologic Values:
  - Enter the 'Overflow' value from the HyPer Tool into the *Overflow %* in JFSAT
  - Enter the 'Drainage' value from the HyPer Tool into the *% Treated* in JFSAT
  - Note that the values entered into the JFSAT for *% Treated* and *Overflow %* will not sum to zero; the balance is equivalent to the % Volume Reduction due to Exfiltration and evapotranspiration (ET)
- Leave the default nutrient effluent EMCs for bioretention with or without IWS that are automatically populated by JFSAT (0.81 mg-N/L and 0.1 mg-P/L for bioretention with IWS and 1.08 mg-N/L and 0.13 mg-P/L for bioretention without IWS).
- Enter the amount of drainage area that is routed to the bioretention next to the appropriate land use in the cells below the BMP input data.
- Enter the amount of area taken up by the bioretention in the cells below the BMP input data.

B. Reductions Obtained with Practice

Bioretention practices that are properly designed and sited can provide cost effective treatment of stormwater; practices that include internal water storage (IWS) consistently provide higher rates of pollutant removal (Hunt et al 2006, Line and Hunt 2009, Liu et al 2014). The pollutant removal effectiveness of a bioretention cell depends on several design factors as well as the project site characteristics. Researchers at NCSU have developed the HyPer Tool (based on the DRAINMOD model) to account for the various design factors associated with bioretention cells.

Table 1 summarizes the potential nutrient reductions estimated using the HyPer Tool. These example ranges are for illustrative purposes, and the load reductions estimated for specific practices may differ as described below. The HyPer Tool assumes generalized influent concentrations from developed areas, and these reductions are example ranges only. **More specific reductions will be estimated by JFSAT which accounts for the specific land uses draining to the bioretention practice rather than assuming a general urban land use composition.** The table provides an example range of potential volume reductions based on changing certain design specifications for a given soil hydrologic group. The minimum value is generated assuming the lower end of the range for soil media depth, no IWS, and the higher end of the range for average surface ponding. The maximum value assumes the higher end of the range for soil media depth, with IWS, and the lower end of the range for average surface ponding. These examples assume a 100% surface storage ratio relative to the water quality volume, but the tool allows the user to vary this ration from 50 percent to 200 percent, and this design variant will significantly affect the credits for a project. These examples also assume the recommended default value for the drainage coefficient of 2 ft/d, and a factor of safety of ten percent.

Table 1. Example Mass Load Reductions and Percent Reductions Achieved with Bioretention Cells (Ranges reflect different design configurations using the HyPer Tool)[1]

Hydrologic Soil Group Under Bioretention Cell	Range of TN Load Reduction (lb/ac/yr)	Range of TN Percent Load Reduction	Range of TP Load Reduction (lb/ac/yr)	Range of TP Percent Load Reduction
A	11.5 - 15.5	67 - 90	1.2 - 1.8	58 - 88
B	8.7 - 14.5	50 - 84	0.7 - 1.6	36 - 80
C	7.9 - 11.4	46 - 66	0.6 - 1.1	31 - 57
D	7.8 - 8.8	45 - 51	0.6 - 0.7	29 - 37

[1] These example ranges are for illustrative purposes only, and the load reductions estimated for specific practices may differ based on watershed characteristics.

Bioretention Example

The following is an example of how to calculate the nutrient load reductions for a bioretention cell treating runoff from an existing commercial parking lot using the HyPer Tool and JFSAT. The site has the following characteristics:

- *Parking lot* = **21,225** s.f. commercial parking lot that drains to a bioretention that takes up **1,775** s.f. (total developed area is **23,000** s.f.)
- The example bioretention with IWS is located in Butner, NC on HSG B soils, has a soil media depth of 3 ft, a 1-ft depth to the underdrain, 9" average surface ponding, 75% surface storage ratio, 2 ft/d drainage coefficient and a 10% factor of safety.

To estimate the nutrient load reductions for this example, take the following steps:

<u>Data Entry for the HyPer Tool</u>

1. Enter all the *Design Input Parameters.* Note that some cells include prescribed values for the user to select from a cell drop down menu.
    a) Units: English
    b) Hydrologic Soil Group: B
    c) Soil Media Depth: 3 ft
    d) Depth to IWS: 1 ft
    e) Average Surface Ponding: 9"
    f) Surface Storage Ratio: 75%
    g) Drainage Coefficient: 2 ft/d (default)
    h) BRC Area: Drainage area ratio: 8.3% (calculated by HyPer Tool)
    i) Factor of Safety: 10%

2. Ignore the cells under Water Quality Characterization: these values do not affect the hydrology of the bioretention cell.
3. Record the 'Overflow and 'Drainage' values calculated by the HyPer Tool and reported in the Design Output Parameters/Hydrology section of the Tool. These values will be input to the JFSAT tool as Overflow % and % Treated, respectively. For this example, the Overflow is 9 percent and the Drainage is 31 percent.

Data Entry for the JFSAT Tool

1. Enter all the relevant information on the *Project Info* and *Watershed Characteristics* pages. On the *Watershed Characteristics*:
   a) In the *Pre-Development* column, enter 23,000 s.f. of *Commercial parking lot*
   b) In the *Post-Development* column, enter 21,225 s.f. of *Commercial parking lot* and 1,775 s.f. as land taken up by BMPs.

2. On the *BMP Characteristics* page, select the *Custom Bioretention with IWS* as the type of BMP.
3. Select the predominant hydrologic soil group (HSG) for the location of the BMP. For the example, HSG B is entered.
4. Enter a brief description of the practice and the design variants next to Description of Custom BMPs
5. Enter the *Overflow %* and *% Treated* for the bioretention based on the HyPer Tool output.
   - The *Overflow %* should be entered as 9% (Overflow from HyPer Tool).
   - The *% Treated* is 31% (Drainage from HyPer Tool).
6. Leave the default nutrient $EMC_{effluent}$ values for Bioretention with IWS (Note: the default values will change if a bioretention without IWS is used):
   a) TN $EMC_{effluent}$ (mg/L) =0.81.
   b) TP $EMC_{effluent}$ (mg/L) = 0.1.
7. In the rows under the *Area Treated by BMP*, enter in the *Parking Lot* area that is being treated (**21,225** s.f.) and the *Land Taken up by BMP* (**1,775** s.f.).

Interpreting Results

On the *Overall Summary* page, the *Total Nitrogen* & *Phosphorus Loading* (lbs/yr) should show the following values:

a) *Pre-Development Conditions*
   - *Total Nitrogen Loading (lbs/yr)* = 7.69
   - *Total Phosphorus Loading (lbs/yr)* = 0.85

b) Post-Development Conditions w/BMPs
   - *Total Nitrogen Loading (lbs/yr)* = 2.02
   - *Total Phosphorus Loading (lbs/yr)* = 0.24

The above are the tool outputs in pounds per year. The user completes the remaining steps by hand to calculate the credits (reductions in loading):

8. Compute the nutrient reductions in pounds per year, which would be used towards compliance with *Existing* Development Rule requirements:
    a) Compute the reduction in loading rates
        - Nitrogen -> 7.69-2.02=5.67 lbs/yr
        - Phosphorus -> 0.85-0.24= 0.61 lbs/yr

D. Tier Assignment and Basis

Bioretention with design variants has been designated Tier II based on the fact that bioretention practices have applicable, published research data and the methodology used to simulate the effects of design variants is based on a rigorous, well- studied models (DRAINMOD and HyPer Tool). Tier II measures receive the currently established credit at the time of installation for their functioning lifetime. Any credit refinements based on additional research would apply only to installations done subsequent to those refinements.

To evaluate relative confidence in the measure's estimated reduction, Division staff considered a range of factors outlined in the document "*DWR Approval Framework For Nutrient Load-Reducing Measures.*"

1. Supporting Research

Based on the following factors and the well-studied use and performance of bioretention in North Carolina, there is high confidence in the crediting methods for these practices.

Data Scope

To achieve the flexibility to vary multiple design parameters for varying credit, HyPer Tool was used as it allows for custom analysis and design of bioretention cells. (Brown et al 2011). DRAINMOD is the underlying hydrologic model in HyPer Tool and its application for bioretention cells are fully described in Brown et al 2011a, Winston 2016). Over 400 simulations of DRAINMOD were used to develop the HyPer Tool. Field monitoring studies of bioretention design variants conducted in NC indicate that HyPer Tool predicts the total water budget to within 10 percent of observed values.

A critical assumption of this crediting method is that the bioretention practice is properly installed as designed for the selected design storm. In order to receive this credit, infiltration devices must be designed and maintained as specified by NCDEQ pursuant to Minimum Design Criteria and related requirements of rules 15A NCAC 2H .1000. (http://portal.ncdenr.org/c/document_library/get_file?uuid=0212634d-9aa9-4301-a481-1d6c57930c44&groupId=38334), and guided by Chapter 12 of the NC BMP Design Manual. The exception to this requirement is the allowance for over or undersizing practices, which is represented by the Surface Storage Ratio that is input to the HyPer Tool.

Applicability

Existing bioretention specifications at study sites in NC were altered to analyze the overall impact of different design specifications on the model and the implications for design recommendations. Long-term simulations were also conducted based on 60 years of historical hourly rainfall and daily temperature records. The key design factors are accounted for in the HyPer Tool, making this credit method fully applicable, and thus uncertainty based on applicability is negligible

Data Quality

The quality of the data and the methods and assumptions used in the analysis result in a high degree of confidence in the nutrient reductions associated with bioretention devices. The data and methods used for this assessment were primarily collected and developed by researchers at NC State University and are considered high quality.

2. Measure Design & Operation Specification

Confidence in sustained load reductions is reasonably good given that the practice is relatively simple in design, and design variants have been well studied and modeled. A longer record of use will further improve this confidence.

3. Load Reduction Estimation Methods

Bioretention is a relatively simple practice, and the nutrient removal assumptions used in the HyPer Tool and the Jordan/Falls Tool are known and straightforward, so the practice and the credit method are well matched and don't introduce significant uncertainties.

Co-Benefits

In the case of bioretention, additional benefits may include further reducing other pollutants including Total Suspended Solids (TSS), metals, and bacteria. Because of the reductions of runoff volume associated with bioretention, the practice may also help to alleviate drainage issues and reduce flooding.

References & Resources

Brown, R.A., Hunt, W.F., and Skaggs, R.W. 2011a. *Long-term Modeling of Bioretention Hydrology with DRAINMOD. Project #70255*. Water Resources Research Institute of the University of North Carolina, N.C. State University, Raleigh, N.C., 1-113. Documentation of field studies and datasets used to develop bioretention application of DRAINMOD.

Brown, R.A., Hunt, W.F., 2011b. *Underdrain Configuration to Enhance Bioretention Exfiltration to Reduce Pollutant Loads.* J. Environ. Eng. 137, 1082–1091. Two bioretention cells in Rocky Mount, North Carolina, were monitored for two year-long periods to measure the impact of varying IWS zone depths over sandier underlying soils. This research builds on previous findings of underdrain configuration at Piedmont sites in North Carolina. The increased hydraulic retention time in the sandy clay loam media resulted in lower outflow concentrations. For events monitored with drainage from the SCL cell, efficiency ratios of all the nitrogen species and TSS exceeded 0.5.

Brown, R.A., Hunt, W.F., 2011c. *Impacts of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells.* J. Irrig. Drain. Eng. 137, 132–143. Two sets of loamy-sand-filled bioretention cells of two media depths (0.6 m and 0.9 m), located in Nashville, North Carolina, were monitored from March 2008 to March 2009 to examine the impact of media depth on their performance with respect to hydrology and water quality. Estimated annual pollutant load reduction for total nitrogen, total phosphorus, and total suspended solids were 21, 10, and 71% for the 0.6-m media cells and 19, 44, and 82% for the 0.9-m media cells, respectively. Design specifications and local nutrient sources attributed to the results of this study.

Brown, R. a., Skaggs, R.W., Hunt, W.F., 2013. *Calibration and validation of DRAINMOD to model bioretention hydrology*. J. Hydrol. 486, 430–442. Peer-review publication of Brown et al 2011. Description of DRAINMOD application for bioretention practices.

Hunt, W.F, A. R. Jarrett, J. T. Smith, and L. J. Sharkey. 2006. *Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina.* Journal of Irrigation and Drainage Engineering, 132:600-608. Three bioretention cells with varying media types and drainage configurations were evaluated for pollutant removal capabilities. Total nitrogen reductions averaged 40 percent by mass. Selection of media with a low phosphorus index improved phosphorus reductions relative to cells with a higher phosphorus index.

Line, D.E. and W.F. Hunt. 2009. *Performance of a Bioretention Area and a Level Spreader-Grass Filter Strip at Two Highway Sites in North Carolina*. Journal of Irrigation and Drainage Engineering, 135(2): 217-224. One LS-VFS and a bioretention area along the North Carolina highway system were evaluated for pollutant and volume reduction. The LS-VFS was found to have 49 percent total volume reduction over the 13 storm events monitored.

Liu, J., Sample, D.J., Bell, C., Guan, Y. (2014). *Review and research needs of bioretention used for the treatment of urban stormwater.* Water 2014, 6, 1069-1099. This review paper summarizes data from 11 bioretention field studies for water quality performance. It includes discussion of Total Nitrogen (TN) and Total Phosphorus (TP) for systems with and without IWS. The studied BMPs varied in location, media composition and depth, surface area and ponding depth.

Winston, R. J. 2016. *Resilience of Green Infrastructure under Extreme Conditions*. PhD dissertation, North Carolina State University. Department of Biological and Agricultural Engineering. Raleigh, NC. This study validated the application of DRAINMOD as a tool to predict bioretention water balance to low-conductivity, clayey underlying soils.

Supporting Technical Information

This supporting technical information is provided for the bioretention with design variants nutrient crediting document and includes a description of the development of the HyPer Tool based on DRAINMOD simulations.

Development of the nutrient credit document for this practice was a collaborative effort that included representatives from the following organizations:

- North Carolina Department of Environmental Quality Division of Water Resources: Rich Gannon, MEM, CPM; John Huisman; Trish D'Arconte; and Amin Davis, PWD
- North Carolina Department of Environmental Quality Division of Energy, Mineral and Land Resources: Annette Lucas, PE
- North Carolina State University Biological & Agricultural Engineering Stormwater Engineering Group: Andrew Anderson, PE; Erin Carey, MS; and Bill Hunt, Ph D, PE
- Upper Neuse River Basin Association: Forrest Westall, PE
- Cardno: Alix Matos, PE
- The Center for Watershed Protection, Inc: Neely Law, Ph D

The credit approach for bioretention with design variants is based on a two-step approach that begins with the HyPer Tool which provides a method to provide a flexible crediting approach that allows for various combinations of design factors, rather than a "one size fits all" approach. To achieve this flexibility, HyPer Tool was used as a basis for the credit estimation approach that allows for custom analysis and design of bioretention cells. HyPer Tool is a macro-embedded Microsoft Excel spreadsheet model that references a database of 432 DRAINMOD simulations to allow for custom analysis and design of bioretention cells using predicted long-term hydrology and water quality data (Brown et al 2011). DRAINMOD is the underlying hydrologic model in HyPer Tool, and its application for bioretention cells are fully described in Brown et al 2011a, Winston 2016). DRAINMOD is a long-term, continuous simulation agricultural drainage model that is readily adaptable to simulate water movement through bioretention practices. That is, many of the DRAINMOD inputs correspond directly to bioretention cell design specifications, while its output can be directly applied to assess the hydrologic performance of bioretention practices (see Tables 2 and 3 in Brown et al 2011).

The DRAINMOD application for bioretention was based on detailed field-based monitoring of bioretention facilities in Rocky Mount and Nashville, North Carolina. Long-term simulations using DRAINMOD were conducted to calibrate model input parameters with a specific focus on bioretention design specifications currently presented in the NCDENR Stormwater BMP Manual (NCDENR 2009). Each of the 432 DRAINMOD simulations are based on sixty years of historical, hourly rainfall and daily temperature records from the Raleigh-Durham International and Wilmington airports. The factors that varied between the simulations were surface storage depth, surface storage volume relative to the design event, underlying soil type, media depth, and drainage configuration. The effects of over-sizing and under-sizing the bioretention surface storage volume was also evaluated based on five additional variations of surface storage volume relative to the design capacity.

Detailed hydrologic data were collected from two bioretention field sites over a two year-long monitoring calibration period. The eight bioretention cells were located in Nashville, NC representing a Piedmont/Coastal site and Rocky Mount, NC (Upper Coastal Plain) and were monitored for 24 months to calibrate and test the DRAINMOD model. Each field site had two bioretention cells that varied key design parameters. The Nashville site was conventionally drained, while the Rocky Mount bioretention cells had IWS. Variable media depths, media types, drainage configurations, underlying soils, and surface storage volumes were also manipulated (see Brown 2011a et al, Brown et al. 2011b, Brown et al. 2011c, and Brown et al 2013 for details) but differed between the two sites. The results of the field studies were used to calibrate and validate DRAINMOD. For both the calibration and validation time periods, the modeled stormwater volume of exfiltration and evapotranspiration was within 1% and 5% of the predicted volume for the underlying soil type sand and sandy clay loam cells, respectively.

Existing bioretention specifications at Rocky Mount and Nashville were altered to analyze the overall impact of different design specifications on the model and the implications for design recommendations. Long-term simulations were also conducted based on 60 years of historical hourly rainfall and daily temperature records as described above. These studies provide data that extend the applicability of this practice across the NC Piedmont and Upper Coastal Plain. The application of the drainage results can also reasonably be extended to Coastal Plain systems which may lie above predominately sandy soils as the underlying soil types studied in the Upper Coastal Plain cells in the Rocky Mount study were sandy clay loam and sand. Three underdrain configurations associated with these cells were assessed, adding more robust calibration data to the DRAINMOD simulations. The two cells studied in Nashville, NC contained soil cores classified as sandy-loam, loamy-sand, sandy-clay-loam, and clay-loam. The presence of clay in these underlying soils suggested extrapolation of DRAINMOD and HyPerTool to the Piedmont and Mountain regions could be possible, where more clay is typically found than in the Coastal Plain.

DRAINMOD as a model for bioretention hydrology was successfully validated with field-collected data atop associated with heavier clay soils by Winston (2016). Measured saturated conductivity of soils in that study were low and representative of HSG D soils, which is more common in the Piedmont and Mountains than in the Coastal Plain.

The results of the field data were used to calibrate and validate DRAINMOD. Model statistics demonstrate the strong agreement between simulated and observed data, (i.e., the predictive capabilities of the model (see Figures 1 and 2, taken from Brown et al 2011)). Overall, the maximum error between predicted and measured volumes from each set of cells during the validation period was less than 10 percent of the total water budget. For this reason, the HyPer Tool incorporates an option for the user to apply a Factor of Safety of 10 percent. Consistent with the data, nutrient credits that are calculated using the procedures established in this document require that the Factor of Safety of 10 percent be assumed when running the HyPer Tool.

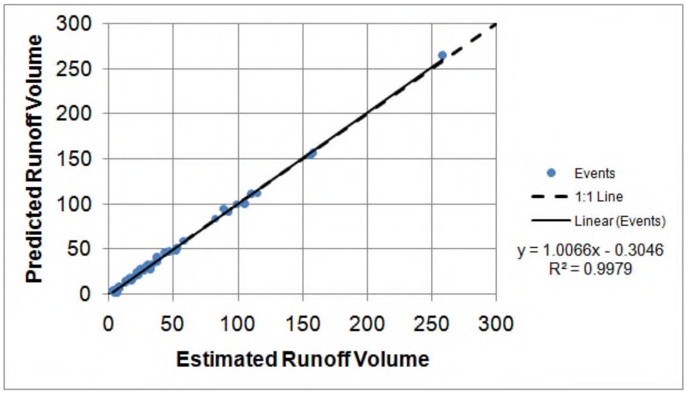

Figure 1 Predicted (modeled) versus estimated runoff volume data for validation period of the 0.6-m (2 ft) media depth bioretention cells at Nashville. Also presented are the linear trend of these data and coefficient of determination (r2). (All units are runoff in cm per bioretention surface area).

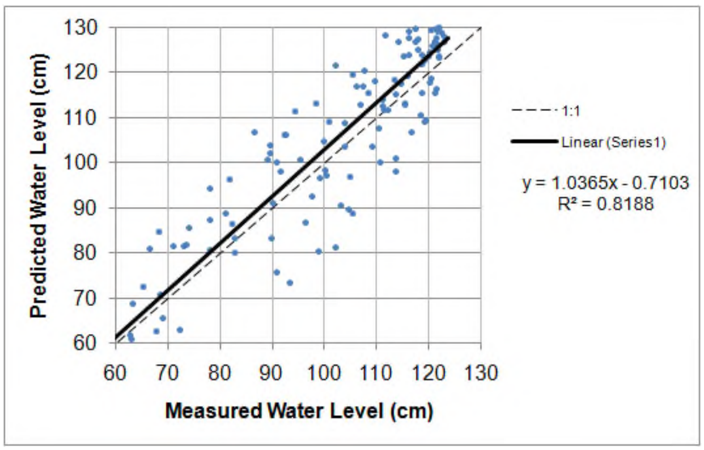

Figure 2. Calibration results from Rocky Mount bioretention cell comparing predicted versus measured water table depths (shallow IWS zone monitoring period).