Development of a Total Phosphorus Removal Model for Bioretention Systems

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Bioretention is a relatively new stormwater management practice that relies on physical, chemical and biological processes within a terrestrial ecosystem to provide stormwater retention and treatment. Bioretention systems, also referred to as rain gardens, include a layer of high permeability soil filtration media, covered by an optional thin layer of mulch, and planted with woody and herbaceous plants. In areas with low permeability native soils, an underdrain structure is installed below the soil filtration media to prevent water from standing for excessive periods of time. An overflow structure is also incorporated into the system to drain excess water when the ponding capacity of the system is exceeded.

Field monitoring and laboratory testing performed to date have demonstrated the ability of bioretention systems to significantly decrease runoff flows and to efficiently reduce a number of pollutant loads. However, large discrepancies in phosphorus removal efficiencies have been reported from the field monitoring of bioretention systems. Two bioretention cells on the University of Maryland campus, monitored by Davis (2007), achieved 79% and 77% total phosphorus mean mass removals, respectively, over 12 storm events. Conversely, Hunt et al. (2006) noted an increase of 240% in total phosphorus, on a mass basis, in the outflow of a bioretention cell in North Carolina over a 12-month monitoring period.

Some theories have been put forward to explain the wide range of phosphorus loadings at the outflow of field-scale bioretention systems. Dietz and Clausen (2005) noted that outflow phosphorus concentrations were consistently above inflow phosphorus concentrations for two similar rain gardens monitored over a period of 12 months. After observing an exponentially decreasing trend over time in phosphorus concentrations from both the rain garden inlets and outlets, they suggested that the increased outflow phosphorus concentrations may have been caused by a disturbance in the soil. Alternatively, Hunt et al. (2006) and Hunt et al. (2008) suggested that phosphorus sorption to bioretention soils, which is maximized in low phosphorus content soils, greatly influences cycling in bioretention systems.

Current bioretention design guidelines focus mainly on peak flow reduction, which may not provide adequate treatment in areas sensitive to pollutant loading. In particular, most freshwater environments are sensitive to high phosphorus loadings, which can lead to the eutrophication of receiving water bodies. This chapter presents the preliminary conceptual and mathematical modeling framework that will be incorporated in a user-friendly tool for designers to predict phosphorus removal in a bioretention system. This tool will also assist researchers in identifying the main factors that influence phosphorus removal in bioretention systems and in understanding the high variability in phosphorus removal observed in the field.

A comprehensive review of the current literature on bioretention indicates that bioretention system modeling is still in its infancy. Only a few models have been developed to simulate hydrologic processes inside bioretention systems. The most comprehensive of these are the RECHARGE and RECARGA models, developed by researchers at the University of Wisconsin–Madison (Dussaillant et al. 2003, Dussaillant et al. 2004), which use the Richard’s and the Green–Ampt infiltration equations to model groundwater recharge through bioretention systems. Moreover, the bioretention water quality model developed by Li and Davis (2008) simulates one-dimensional suspended solids filtration through bioretention media.

Building on previous research, the authors are currently developing the bioretention phosphorus removal model (BPRM), an event-based one-dimensional finite difference model to simulate total phosphorus removal in a bioretention system. The model comprises four layers which act as completely-mixed reactors: the ponding layer, the mulch layer (optional in bioretention systems), the soil root zone, and the deep soil zone. Model subcomponents estimate water volumes and phosphorus mass within the model layers. Total phosphorus is divided into particulate and soluble phosphorus. The model requires input time series for rainfall and runoff inflows, as well as soluble and
particulate phosphorus inflow concentrations. Processes modeled inside the bioretention system include: evapotranspiration and overflow from the ponding layer of water; sedimentation of particulate phosphorus; infiltration of water and soluble phosphorus across model layers; vegetative uptake of soluble phosphorus; mulch and soil sorption and desorption of soluble phosphorus; exfiltration of water and soluble phosphorus from the system to the surrounding native soils; as well as underdrain discharge of water and soluble phosphorus.

Preliminary model processes, input parameter requirements and model limitations will be discussed in detail in this chapter. The first section of this chapter describes the structure of the model being developed, along with the modeling assumptions made in developing BPRM. Then, the equations selected to represent each process in BPRM and the reasons behind these choices are detailed in Section 20.2. Section 20.3 includes a list of the input parameters required by BPRM for a simulation, including unit requirements and a range of recommended values for each input parameter. In the final section, the capabilities and the limitations associated to the model being developed are discussed. The work presented in this chapter is in progress and future work will focus on improving the mathematical framework presented and addressing some of the limitations described. The model developed will also be evaluated against field data and the sensitivity of modeling predictions to input parameter selection will be assessed.

20.1 Model Development

The objective of the bioretention model being developed is to estimate the concentration and mass of total phosphorus in the outflow of a bioretention system over the duration of a storm event.

The decision to build BPRM as an event simulation model was motivated by the fact that current design guidelines (PGC 2002) require engineers to design bioretention systems based on a design storm, rather than based on long term system performance. Continuous models typically require large amounts of input data for simulation and their calibration and evaluation may require multiple field observations over long time periods. Also, because continuous models tend to use coarser time steps than single-event models, they are susceptible to produce good agreement with specific data sets without accurately capturing the short term behaviour of the systems modeled.

BPRM is being developed as a one-dimensional model with four distinct model layers. Each layer is assumed to be a completely mixed reservoir with vertical water flow and phosphorus mass transfer across adjacent layers.
Bioretention systems are designed to enhance downwards infiltration and design guidelines specify a maximum water ponding time of 4 hours after the storm event (PGC 2002). It is thus reasonable to ignore the influence of two-dimensional horizontal flow on phosphorus removal inside bioretention systems.

Figure 20.1 shows a conceptual bioretention system diagram with the four model layers and the main processes considered in BPRM.

![Conceptual bioretention system diagram for BPRM](image)

The model being developed includes two main components: a hydrologic component and a phosphorus transport component. The hydrologic component determines the volume of water ponding at the surface of the system, the volume of water infiltrating into each layer, and the total outflow volume from the bioretention system. The bioretention outflow volume is defined as the sum of underdrain discharge and overflow volumes. The phosphorus transport component is divided into soluble and particulate phosphorus subcomponents. It simulates phosphorus mass transport through the system and determines the concentration and total mass of phosphorus in the bioretention outflow.

Each model layer incorporates different bioretention system processes. The first layer, the ponding layer, is used to simulate the volume of water that ponds above the surface of the bioretention system when the infiltration capacity of the system is exceeded. Processes that are specific to this layer include overflow, which occurs once the ponding capacity of the system is exceeded, evapotranspiration and particulate phosphorus sedimentation. An optional
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mulch layer was added to BPRM to represent the transport of phosphorus through the layer of mulch that is often placed at the surface of bioretention systems to capture pollutants. The mulch layer provides additional water storage capacity in the system, as well as a media for phosphorus sorption. Exfiltration from the mulch layer into surrounding native soils is not included in BPRM, as it is expected to be negligible due to the thinness of the layer.

The bioretention soil filtration media was divided into two model layers; the soil root zone and the deep soil zone. Processes considered inside the soil root zone include soluble phosphorus sorption to soil, vegetation uptake of soluble phosphorus and exfiltration of water and soluble phosphorus to surrounding native soils. Soluble phosphorus sorption, exfiltration of water and soluble phosphorus and underdrain discharge of water and soluble phosphorus occur in the deep soil zone.

Laboratory column studies performed by Hsieh and Davis (2005) have shown that bioretention media have the potential to capture over 90% suspended solids from stormwater. For this reason, BPRM does not allow particulate phosphorus to infiltrate within the soil layers. Sedimentation allows particulate phosphorus to deposit on the surface of the mulch layer, where it is captured and remains stable. For this reason, particulate phosphorus is only found in system outflow when overflow events occur.

Movement of phosphorus between particulate and soluble phosphorus forms is not included in BPRM. Phosphorus precipitation and dissolution reactions are greatly influenced by stormwater pH and by the presence of minerals in water with which phosphorus forms complexes, namely calcium, aluminum and iron (vanLoon and Duffy 2005). Under average stormwater pH—between 7.1 and 7.7 (Pitt et al. 2004)—calcium ion concentrations dictate the aqueous solubility of phosphorus (vanLoon and Duffy 2005). However, because calcium is not considered as a stormwater pollutant, very little data on the concentration of calcium ions in stormwater is available in the literature. For modeling purposes, the rates of phosphorus dissolution and precipitation are assumed to be equal in BPRM, such that no net change in soluble and particulate phosphorus mass occurs.

Microbial phosphorus mineralization and immobilization in bioretention soils are not included in BPRM. Both processes occur simultaneously in soils and the net rate of phosphorus immobilization or mineralization is generally low over the duration of a storm event (Stevenson 1999).

Figure 20.2 shows detailed model diagrams for the hydrologic model component and both the particulate and soluble phosphorus transport model subcomponents. The direction of the arrows indicates whether flows enter or leave the system. Double-headed arrows in the case of sorption indicate that
soluble phosphorus can be transported either from water into the soil or from the soil into water.

Based on the model diagram shown in Figure 20.2, balances on water volume, soluble phosphorus mass, and particulate phosphorus mass can be expressed for each model layer. Equations 20.1 to 20.4 represent the hydrologic processes for the ponding layer, the mulch layer, the soil root zone and the deep soil zone, respectively.

\[
\frac{dW_1}{dt} = q_W + r_W - n_W - o_W - i_{W_1} \tag{20.1}
\]

\[
\frac{dW_2}{dt} = i_{W_1} - i_{W_2} \tag{20.2}
\]

\[
\frac{dW_3}{dt} = i_{W_2} - i_{W_3} - e_{W_3} \tag{20.3}
\]

\[
\frac{dW_4}{dt} = i_{W_3} - u_W - e_{W_4} \tag{20.4}
\]

where:

- \( W_1 \) = volume of water in the ponding layer (m³),
- \( W_2 \) = volume of water in the mulch layer (m³),
- \( W_3 \) = volume of water in the soil root zone (m³),
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\[ W_4 = \text{volume of water in the deep soil zone (m}^3) \]
\[ q_w = \text{rainfall inflow rate (m}^3/\text{min}) \]
\[ r_w = \text{runoff inflow rate (m}^3/\text{min}) \]
\[ n_w = \text{rate of evapotranspiration (m}^3/\text{min}) \]
\[ o_w = \text{ponding layer overflow rate (m}^3/\text{min}) \]
\[ i_{w1} = \text{rate of infiltration to the mulch layer (m}^3/\text{min}) \]
\[ i_{w2} = \text{rate of infiltration to the soil root zone (m}^3/\text{min}) \]
\[ i_{w3} = \text{rate of infiltration to the deep soil zone (m}^3/\text{min}) \]
\[ e_{w3} = \text{rate of exfiltration from the soil root zone to surrounding native soils (m}^3/\text{min}) \]
\[ e_{w4} = \text{rate of exfiltration from the deep soil zone to surrounding native soils (m}^3/\text{min}) \]
\[ u_w = \text{underdrain discharge rate (m}^3/\text{min}) \]
\[ t = \text{time (min)} \]

Equations 20.5 to 20.8 describe the movement of soluble phosphorus through the model layers:

\[
\frac{dSP_1}{dt} = r_{SP} - o_{SP} - i_{SP1}
\]

\[
\frac{dSP_2}{dt} = i_{SP1} - b_{SP2} - i_{SP2}
\]

\[
\frac{dSP_3}{dt} = i_{SP2} - b_{SP3} - i_{SP3} - v_{SP} - e_{SP3}
\]

\[
\frac{dSP_4}{dt} = i_{SP3} - b_{SP4} - u_{SP} - e_{SP4}
\]

where:

\[ SP_1 = \text{soluble phosphorus mass in the ponding layer (mg as P)} \]
\[ SP_2 = \text{soluble phosphorus mass in the mulch layer (mg as P)} \]
\[ SP_3 = \text{soluble phosphorus mass in the soil root zone (mg as P)} \]
\[ SP_4 = \text{soluble phosphorus mass in the deep soil zone (mg as P)} \]
\[ r_{SP} = \text{inflow rate of soluble phosphorus in runoff (mg as P/min)} \]
\[ o_{SP} = \text{soluble phosphorus overflow rate (mg as P/min)} \]
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\[ i_{SP1} = \text{soluble phosphorus infiltration rate to the mulch layer (mg as P/min),} \]

\[ i_{SP2} = \text{soluble phosphorus infiltration rate to the soil root zone (mg as P/min),} \]

\[ i_{SP3} = \text{soluble phosphorus infiltration rate to the deep soil zone (mg as P/min),} \]

\[ b_{SP2} = \text{soluble phosphorus sorption rate to mulch (mg as P/min),} \]

\[ b_{SP3} = \text{soluble phosphorus sorption rate to soil in the root zone (mg as P/min),} \]

\[ b_{SP4} = \text{soluble phosphorus sorption rate to soil in the deep zone (mg as P/min),} \]

\[ v_{SP} = \text{soluble phosphorus vegetation uptake rate (mg as P/min),} \]

\[ e_{SP3} = \text{soluble phosphorus exfiltration rate from the soil root zone (mg as P/min),} \]

\[ e_{SP4} = \text{soluble phosphorus exfiltration rate from the deep soil zone (mg as P/min),} \]

\[ u_{SP} = \text{soluble phosphorus underdrain discharge rate (mg as P/min).} \]

Lastly, Equation 20.9 describes particulate phosphorus movement within the ponding layer. As particulate phosphorus infiltration is assumed to be negligible, the only model layer to receive particulate phosphorus inflow is the ponding layer.

\[
\frac{dPP_1}{dt} = r_{PP} - z_{PP} - o_{PP} \quad (20.9)
\]

where:

\[ PP_1 = \text{particulate phosphorus mass in the ponding layer (mg as P),} \]

\[ r_{PP} = \text{particulate phosphorus inflow rate in runoff (mg as P/min),} \]

\[ z_{PP} = \text{particulate phosphorus sedimentation rate (mg as P/min), and} \]

\[ o_{PP} = \text{particulate phosphorus overflow rate (mg as P/min).} \]
Total bioretention system outflow volumes are computed in BPRM as the sum of underdrain and overflow volumes. The concentration of phosphorus in the outflow is determined as the sum of the mass of soluble and particulate phosphorus leaving the system, through both overflow and underdrain discharge, divided by the total outflow volume calculated. The model will also provide separate information on the water volumes, soluble phosphorus mass and particulate phosphorus mass in the underdrain and overflow. Model outputs will include tabulated values of the rate of all modeling processes within the bioretention system at each time step throughout the simulation, which allows the user to compare the relative importance of different processes during the storm event modeled.

To solve the model equations listed above, a fourth-order explicit Runge–Kutta finite difference scheme is being considered (Chapra and Canale 2002). The complexity of the proposed model does not likely permit the use of an implicit Runge–Kutta method due to its computationally intensive nature. The model will be coded into the Visual Basic programming language to facilitate the creation of a user-friendly interface for designers. The following section discusses in detail the preliminary equations selected to represent each process within the model.

### 20.2 Model Processes

#### 20.2.1 Rainfall and Runoff

Total inflow to the bioretention system includes surface runoff which drains to the system for treatment, as well as precipitation into the system area. The model requires input time series for rainfall intensities \(Q_w, \text{mm/min}\) and surface runoff inflow rates \(r_W, \text{m}^3/\text{min}\) over the duration of the storm event. The model converts rainfall intensities to rainfall inflow rates based on the bioretention system area \(A_b, \text{m}^2\), as per Equation 20.10.

\[
q_w = Q_w \cdot A_b \quad (20.10)
\]

To simulate phosphorus transport in the system, the model also requires input time series of both soluble and particulate phosphorus inflow concentrations in surface runoff \(R_{SP}\) and \(R_{PP}\) mg as P/m³). These are used to derive soluble and particulate phosphorus mass inflow rates, as described by Equations 20.11 and 20.12.

\[
r_{SP} = r_w \cdot R_{SP} \quad (20.11)
\]
Precipitation into the bioretention system area is assumed to contribute no phosphorus to the system. Measurements of total phosphorus wet atmospheric deposition fluxes reported by Koelliker et al. (2004) suggest that this assumption is reasonable, as significantly greater phosphorus loadings can be expected to enter the system from urban runoff. For Jersey City, in an area qualified as urban-industrial, an annual wet deposition flux of 5.2 mg/m²/y was measured. Data reported by Shaver et al. (2007) on stormwater pollutants shows total phosphorus loadings of 1.3 lb/acre/y (150 mg/m²/y) in industrial areas and 1.5 lb/acre/y (170 mg/m²/y) in commercial areas.

### 20.2.2 Evapotranspiration

Evapotranspiration rates vary with the type of vegetation planted in a bioretention system and the weather conditions during a storm event. Evapotranspiration is calculated in the model based on a constant user-specified evapotranspiration rate ($N_w$, mm/min) selected to describe the conditions of the storm event being simulated:

$$n_w = N_w \cdot A_p$$

(20.13)

It is recognized here that the duration of a storm event does not allow for large quantities of water to undergo evapotranspiration, which is a slow process, and that, under high humidity levels, evapotranspiration rates are generally minimal, but the process was included in the model for the sake of completeness. When modeling large storm events that require longer infiltration periods, evapotranspiration may become significant.

Mass of both soluble and particulate phosphorus forms are assumed to be unaffected by evapotranspiration. However, soluble phosphorus is taken up by vegetation within the soil root zone, as described in section 20.2.8.

### 20.2.3 Overflow from the Ponding Layer

Overflows from the ponding layer occur when the ponding capacity of the system is exceeded. Design guidelines (PGC 2002) require that bioretention systems be constructed with either a safe overflow path or an appropriate outlet structure. Because safe overflow paths can be of a non-structural nature,
predicting overflows from bioretention systems that are not equipped with a fixed outlet structure can be difficult. In this model, equations describing the flow rate over two different weir types; rectangular and triangular, are available to simulate bioretention system overflow. The user should choose the weir type most similar to the overflow structure to be modeled.

For a rectangular weir, the flow rate of water leaving the system through overflow can be defined by Equation 20.14.

\[
o_w = \frac{2}{3} C_d \cdot \sqrt{2g} \cdot L_o \cdot \left(\frac{W}{A_b} - D_p\right)^{\frac{3}{2}}
\]  

(20.14)

where:

- \( C_d \) = overflow weir discharge coefficient,
- \( g \) = gravitational acceleration (m/min²),
- \( L_o \) = width of the overflow weir (m), and
- \( D_p \) = ponding capacity of the system, that is weir height above the bioretention system surface (m).

For a triangular weir, the overflow rate is defined by Equation 20.15:

\[
o_w = \frac{8}{15} C_d \cdot \sqrt{2g} \cdot \tan\left(\frac{\theta}{2}\right) \cdot \left(\frac{W}{A_b} - D_p\right)^{\frac{5}{2}}
\]  

(20.15)

where:

- \( \theta \) = weir notch angle (°).

From the assumption of completely mixed model layers, it follows that the mass of soluble and particulate phosphorus that leave the system through overflow are proportional to the volume of water that leaves the system, as represented by Equations 20.16 and 20.17:

\[
o_{SP} = o_w \cdot \frac{SP}{W_i}
\]  

(20.16)

\[
o_{PP} = o_w \cdot \frac{PP}{W_i}
\]  

(20.17)

20.2.4 Particulate Phosphorus Sedimentation

Particulate phosphorus infiltration is ignored in BPRM, such that settled particulate phosphorus is assumed to remain trapped within the mulch and the
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top portion of the soil layers. No resuspension of settled phosphorus is assumed to occur in BPRM.

Sedimentation rates in the ponding layer are modeled based on an average settling velocity for particulate phosphorus:

\[
z_{PP} = \frac{PP_1 \cdot v_{PP} \cdot A_b}{W_l}
\]  

(20.18)

where:

- \( v_{PP} \) = particulate phosphorus average settling velocity in still water (m/min).

Braskerud (2002) suggested that the average settling velocity of sediments to which phosphorus agglomerates (sizes 2 µm to 6 µm), calculated using Stokes’s law, could be used to estimate the average settling velocity of particulate phosphorus. The use of Stokes’s law implies that no turbulence is produced by particle settling and quiescent flow conditions apply, which are reasonable assumptions for most particle sizes of interest under significant ponding depths.

20.2.5 Infiltration

Infiltration is the main stormwater volume retention process in bioretention systems. Dussaillant et al. (2003) compared the performance of two rain garden infiltration models, RECHARGE and RECARGA, which are based on Richard’s and the Green–Ampt infiltration equations, respectively, and confirmed that both models provided good agreement. For this reason, infiltration is represented in BPRM by the Green–Ampt equation, which is less complex than Richard’s infiltration equation.

To account for the effects of variable runoff inflows and rainfall intensities on surface ponding, a modified version of the Green–Ampt equation for unsteady rainfall conditions developed by Chu (1978) was selected to represent infiltration in BPRM.

The mulch layer in a bioretention system is usually thin and easily infiltrated, as mulch tends to float on ponded water. For simplification, BPRM assumes that infiltration in the mulch layer occurs as soon as water is available and continues until the porosity of the mulch layer is completely filled with water, after which point water accumulates in the ponding layer. In this way, the mulch layer offers no resistance to downward flows. The rate of infiltration to the mulch layer is given by Equation 20.19.
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\[
i_{W_1} = \begin{cases} 
\frac{\left( \alpha_2 \cdot D_2 \cdot A_b \right) - W_2}{\alpha_2 \cdot D_2 \cdot A_b} \frac{dt}{dt}, & \text{for } W_1 \geq \left( \alpha_2 \cdot D_2 \cdot A_b \right) - W_2 \\
W_1 \frac{dt}{dt}, & \text{for } W_1 < \left( \alpha_2 \cdot D_2 \cdot A_b \right) - W_2 
\end{cases}
\]

(20.19)

where:
\(\alpha_2\) = effective porosity of the mulch layer (unitless), and
\(D_2\) = depth of the mulch layer (m).

Infiltration into the soil root zone is modeled based on the Green–Ampt equation by Chu (1978), as described by Equation 20.20.

\[
i_{W_2} = \begin{cases} 
f_{p_1}, & \text{for } W_2 \geq f_{p_1} \ dt \text{ and } f_{p_1} \ dt \leq \left[ \alpha_3 \cdot D_3 \cdot A_b - W_3 \right] \\
\frac{\alpha_3 \cdot D_3 \cdot A_b - W_2}{\alpha_3 \cdot D_3 \cdot A_b - W_3} \frac{dt}{dt}, & \text{for } W_2 \geq f_{p_1} \ dt \text{ and } f_{p_1} \ dt > \left[ \alpha_3 \cdot D_3 \cdot A_b - W_3 \right] \\
W_2 \frac{dt}{dt}, & \text{for } W_2 < f_{p_1} \ dt 
\end{cases}
\]

(20.20)

where:
\(f_{p_1}\) = infiltration capacity of the soil root zone (m³/min),
\(\alpha_3\) = effective porosity of the soil root zone (unitless),
\(K_3\) = saturated hydraulic conductivity of the soil root zone (m/min), and
\(\psi_3\) = capillary tension parameter of the soil root zone (m).

For deep soil zone infiltration, the hydraulic conductivity and storage parameters of the soil are modified according to the Green–Ampt equation proposed by Chu (1985) for crusted soils. Water is allowed to infiltrate above the storage capacity of the deep soil zone:

\[
f_{p_3} = K_3 \cdot A_b \left[ 1 + \frac{\alpha_3 \cdot (A_b \cdot \psi_3 + W_1 + W_2)}{W_3} \right]
\]

(20.20a)

and where:
\(f_{p_3}\) = infiltration capacity of the soil root zone (m³/min),
\(\alpha_3\) = effective porosity of the soil root zone (unitless),
\(K_3\) = saturated hydraulic conductivity of the soil root zone (m/min), and
\(\psi_3\) = capillary tension parameter of the soil root zone (m).
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\[
i_{W_3} = \begin{cases} 
  f_{p_4} & , \quad \text{for } W_3 \geq f_{p_4} \, dt \\
  \frac{W_3}{dt} & , \quad \text{for } W_3 < f_{p_4} \, dt 
\end{cases} \tag{20.21}
\]

where:

\[
f_{p_4} = \left[ D_3 + \left( \frac{W_4}{A_b \cdot \alpha_4} \right) \frac{D_3}{K_3} \right] \left[ A_b \left( \frac{1}{D_3} + \left( \frac{W_4}{A_b \cdot \alpha_4 \cdot K_4} \right) \right) \right] \left( A_b \cdot \psi_4 \right)
\tag{20.21a}
\]

and where:

- \( f_{p_4} \) = infiltration capacity of the deep soil zone (m³/min),
- \( \alpha_4 \) = effective porosity of the deep soil zone (unitless),
- \( D_4 \) = depth of the soil root zone (m),
- \( K_4 \) = hydraulic conductivity of the deep soil zone (m/min), and
- \( \psi_4 \) = capillary tension parameter of the deep soil zone (m).

Since all model layers are completely mixed, the mass of soluble phosphorus that infiltrates from one layer to the next can be defined by the volume of water that infiltrates to that same layer and the concentration of phosphorus in the initial layer (Equations 20.22 to 20.24).

\[
i_{SP_1} = i_{W_1} \cdot \frac{SP_1}{W_1} \tag{20.22}
\]

\[
i_{SP_2} = i_{W_2} \cdot \frac{SP_2}{W_2} \tag{20.23}
\]

\[
i_{SP_3} = i_{W_3} \cdot \frac{SP_3}{W_3} \tag{20.24}
\]

20.2.6 Phosphorus Sorption and Desorption

Soluble phosphorus desorption from bioretention soils is suspected to be responsible for the low phosphorus removals observed in some bioretention
systems in the field (Hunt et al. 2006, Hunt et al. 2008). Therefore, a reversible sorption function was included in the model being developed. This means that phosphorus transport in BPRM can occur both from water to soil and from soil to water. In reality, sorption is a complex process that occurs in two phases: an initial fast reversible reaction followed by a slow nearly irreversible reaction (McGechan and Lewis 2002). Phosphorus desorption over short time periods is generally considered to correspond closely to the inverse of the short term phosphorus sorption reaction stage (McGechan and Lewis 2002). For practical reasons, net phosphorus desorption is assumed to proceed at the same rate as net phosphorus sorption, only in the opposite direction.

Hsieh et al. (2007) measured the short term phosphorus sorption capacity of a mulch sample, two different types of sand and three different types of soil. The Langmuir isotherm equation, which provided a good fit for most data, was selected to represent the phosphorus sorption capacity of the samples. At the time BPRM was being developed, results published by Hsieh et al. (2007) were the only sorption parameters available for bioretention media. Therefore, a kinetic version of the Langmuir isotherm equation (McGechan and Lewis 2002) was selected to model soluble phosphorus sorption to mulch and soil in BPRM:


g_{SP} = \beta \left( D_2 \cdot A_b \cdot \rho_2 \right) \left( k_{L2} \frac{SP_2}{W_2} - \frac{Q_2}{Q_{max}} \left( 1 + k_{L2} \frac{SP_2}{W_2} \right) \right) \quad (20.25)

g_{SP} = \beta \left( D_3 \cdot A_b \cdot \rho_3 \right) \left( k_{L3} \frac{SP_3}{W_3} - \frac{Q_3}{Q_{max}} \left( 1 + k_{L3} \frac{SP_3}{W_3} \right) \right) \quad (20.26)

g_{SP} = \beta \left( D_4 \cdot A_b \cdot \rho_4 \right) \left( k_{L4} \frac{SP_4}{W_4} - \frac{Q_4}{Q_{max}} \left( 1 + k_{L4} \frac{SP_4}{W_4} \right) \right) \quad (20.27)

where:

\begin{align*}
\beta & = \text{kinetic sorption rate constant (/min),} \\
k_{L2} & = \text{Langmuir constant for sorption to mulch (m}^3/\text{mg as P),} \\
k_{L3} & = \text{Langmuir constant for sorption to soil in the root zone (m}^3/\text{mg as P),} \\
k_{L4} & = \text{Langmuir constant for sorption to soil in the deep zone (m}^3/\text{mg as P),} \\
Q_2 & = \text{mass of phosphorus sorbed in mulch (mg as P/kg soil),} \\
Q_3 & = \text{mass of phosphorus sorbed in soil of the root zone (mg as P/kg soil),}
\end{align*}
\( Q_4 \) = mass of phosphorus sorbed in soil of the deep zone (mg as P/kg soil),
\( Q_{\text{max}2} \) = maximum sorption capacity of mulch (mg as P/kg soil),
\( Q_{\text{max}3} \) = maximum sorption capacity of soil in the root zone (mg as P/kg soil),
\( Q_{\text{max}4} \) = maximum sorption capacity of soil in the deep zone (mg as P/kg soil),
\( D_4 \) = deep soil zone depth (m),
\( \rho_2 \) = mulch density (kg/m\(^3\)),
\( \rho_3 \) = soil root zone density (kg/m\(^3\)), and
\( \rho_4 \) = deep soil zone density (kg/m\(^3\)).

To calculate phosphorus sorption rates based on the kinetic Langmuir equations above, the quantity of phosphorus sorbed in mulch and in soil of the root zone and of the deep zone need to be known. The change in mass of phosphorus sorbed per mass of soil over the duration of the simulation can be described by Equations 20.28 to 20.30:

\[
\frac{dQ_2}{dt} = \frac{s_{sp2}}{(D_2 \cdot A_b \cdot \rho_2)} \tag{20.28}
\]

\[
\frac{dQ_3}{dt} = \frac{s_{sp3}}{(D_3 \cdot A_b \cdot \rho_3)} \tag{20.29}
\]

\[
\frac{dQ_4}{dt} = \frac{s_{sp4}}{(D_4 \cdot A_b \cdot \rho_4)} \tag{20.30}
\]

20.2.7 Exfiltration to Native Soils

Exfiltration of water to native soils is represented in BPRM by extending the modified version of the Green–Ampt equation developed Chen and Young (2006) for infiltration into sloping soils to a case of infiltration into a vertical soil surface, as follows:
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\[
e_{w_3} = \begin{cases} 
K_N \frac{\psi_N}{y_{N_3}} (P_b \cdot D_3), & \text{for } W_3 \geq \left[ K_N \frac{\psi_N}{y_{N_3}} (P_b \cdot D_3) \right] dt \\
\frac{W_3}{dt}, & \text{for } W_3 < \left[ K_N \frac{\psi_N}{y_{N_3}} (P_b \cdot D_3) \right] dt 
\end{cases}
\]

(20.31)

\[
e_{w_4} = \begin{cases} 
K_N \frac{\psi_N}{y_{N_4}} (P_b \cdot D_4), & \text{for } W_4 \geq \left[ K_N \frac{\psi_N}{y_{N_4}} (P_b \cdot D_4) \right] dt \\
\frac{W_4}{dt}, & \text{for } W_4 < \left[ K_N \frac{\psi_N}{y_{N_4}} (P_b \cdot D_4) \right] dt 
\end{cases}
\]

(20.32)

where:

- \( K_N \) = permeability of surrounding native soils (m/min),
- \( \psi_N \) = wetting front soil suction head in native soils (m),
- \( y_{N_3} \) = wetting front depth inside native soils at soil root zone (m),
- \( y_{N_4} \) = wetting front depth inside native soils at deep soil zone (m), and
- \( P_b \) = bioretention system perimeter (m).

The wetting front depths inside native soils change with time as total exfiltration increases. Equations 20.33 and 20.34 keep track of the wetting front depths throughout the simulation:

\[
\frac{dy_{N_3}}{dt} = \frac{e_{w_3}}{P_b \cdot D_3 \cdot \alpha_N}
\]

(20.33)

\[
\frac{dy_{N_4}}{dt} = \frac{e_{w_4}}{P_b \cdot D_4 \cdot \alpha_N}
\]

(20.34)

The mass rate of soluble phosphorus leaving the system becomes:

\[
e_{SP_3} = e_{w_3} \cdot \frac{SP_3}{W_3}
\]

(20.35)
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\[ e_{sp} = e_w \cdot \frac{SP}{W} \]  

(20.36)

where:

\[ \alpha_N = \text{effective porosity of native soils (unitless).} \]

20.2.8 Vegetative Uptake of Soluble Phosphorus

Vegetative uptake is a slow process that occurs as plant roots come into contact with plant-available phosphorus forms. For this reason, research has focused primarily on long term phosphorus uptake and limited data is available on short term vegetative uptake kinetics.

The soluble phosphorus net uptake rate by vegetation is estimated in BPRM using a relationship of the Michaelis–Menten type (Barber 1984), as given by Equation 20.37.

\[ v_{SP} = I_n \cdot A_r = \left\{ \frac{I_{max} \left( \frac{SP}{W} - C_{min} \right)}{K_m + \frac{SP}{W} - C_{min}} \right\} \cdot A_r \]  

(20.37)

where:

\[ I_n = \text{phosphorus ion influx per unit area of plant root (mg as P/m}^2/\text{min),} \]
\[ A_r = \text{total root surface area (m}^2), \]
\[ I_{max} = \text{maximum phosphorus uptake rate (mg as P/m}^2/\text{min),} \]
\[ C_{min} = \text{minimum soil water phosphorus concentration for vegetative uptake (mg as P/m}^3), \] and
\[ K_m = \text{Michaelis constant for phosphorus uptake (mg as P/m}^3). \]

Phosphorus uptake rates depend on a number of factors including the vegetative species planted in a bioretention system and the maturity of the vegetation. Barber (1984) provided phosphorus uptake parameters for different vegetative species which can be used to model vegetative uptake.

The only form of phosphorus considered to be directly available for vegetative uptake is soluble inorganic phosphorus (Ritter and Shirmohammadi 2001). Since BPRM does not differentiate between organic and inorganic soluble phosphorus forms, the parameters used in the uptake rate equation may
need to be adjusted if large concentrations of soluble organic phosphorus are known to be present in the stormwater to be treated. For instance, the total root surface area parameter may be multiplied by the percentage of soluble phosphorus that is available to plants.

20.2.9 Underdrain Discharge

Underdrain structures are used in bioretention systems surrounded by native soils of low permeability. Their purpose is to ensure that the system is drained rapidly; they do not provide water quality treatment. The PGC design guidelines require underdrain structures to be installed where the infiltration rate of native soils is below 3.8 cm/h (1.5 in./h) (PGC 2002).

The underdrain structure is represented in BPRM as a layer of high permeability soil (which corresponds to the granular material that is generally packed around underdrain pipes). Underdrain discharge occurs in the model when water and soluble phosphorus reach the depth of the high permeability layer surrounding the underdrain structure. This assumes instantaneous particle travel in the horizontal direction, which should be a reasonable assumption inside a layer of granular material in the absence of capillary action and under weak surface tension.

Since infiltration in BPRM is defined by the Green–Ampt infiltration equation, which assumes a horizontal wetting front, underdrain discharge occurs once the wetting front reaches the underdrain layer depth, or when the capacity of the deep soil zone is reached:

\[
\frac{dW}{dt} = Ku \cdot A_b, \text{ for } (W_4 - D_4 \cdot \alpha_4 \cdot A_b) > Ku \cdot A_b
\]

\[
W_4 - \left[D_4 \cdot \alpha_4 \cdot A_b\right] dt, \text{ for } 0 < (W_4 - D_4 \cdot \alpha_4 \cdot A_b) \leq Ku \cdot A_b
\]

(20.38)

where:

\[K_u = \text{underdrain layer permeability (m/min)}.\]

If no underdrain structure is present in the bioretention system being modeled, the hydraulic conductivity of the native soil below the system can be used as input parameter to represent exfiltration to the native soil below the bioretention system.

The concentration of soluble phosphorus in the underdrain is assumed to equal the soluble phosphorus concentration in the deep soil layer, as follows from the assumption of mixed layers:


\[ u_{sp} = u_w \cdot \frac{SP}{W_4} \]  

(20.39)

## 20.3 Input Parameter Requirements

### 20.3.1 Bioretention System Characteristics

A list of the bioretention system characteristics required by BPRM as input parameters for simulation is provided in Table 20.1. The table includes the equation symbol corresponding to each input parameter, the units of the input parameter, and a recommended range of input values, based on values reported in the literature.

It should be noted that some unit requirements listed in the table do not correspond to the units required by the process equations. Unit conversions will be built into the model in these cases.

<table>
<thead>
<tr>
<th>Required BPRM Input</th>
<th>Symbol in Equation</th>
<th>Units Required</th>
<th>Recommended Range</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioretention system area</td>
<td>( A_b )</td>
<td>m²</td>
<td>55–250</td>
<td>USEPA 1999</td>
</tr>
<tr>
<td>System ponding capacity</td>
<td>( D_p )</td>
<td>mm</td>
<td>75–150</td>
<td>PGC 2002</td>
</tr>
<tr>
<td>Mulch layer depth</td>
<td>( D_3 )</td>
<td>mm</td>
<td>0–75</td>
<td>PGC 2002</td>
</tr>
<tr>
<td>Soil root zone depth</td>
<td>( D_4 )</td>
<td>m</td>
<td>varies</td>
<td></td>
</tr>
<tr>
<td>Deep soil zone depth</td>
<td>( D_5 )</td>
<td>m</td>
<td>varies</td>
<td></td>
</tr>
<tr>
<td>Evapotranspiration rate</td>
<td>( N_W )</td>
<td>mm/d</td>
<td>0–5</td>
<td>Nourbaeva et al. 2003</td>
</tr>
<tr>
<td>Weir discharge coefficient</td>
<td>( C_d )</td>
<td>–</td>
<td>0.5–0.9</td>
<td>Osman 2006</td>
</tr>
<tr>
<td>Weir width (for rectangular weirs)</td>
<td>( L_o )</td>
<td>mm</td>
<td>varies</td>
<td></td>
</tr>
<tr>
<td>Weir notch angle (for triangular weirs)</td>
<td>( \theta )</td>
<td>°</td>
<td>20–100</td>
<td>Osman 2006</td>
</tr>
<tr>
<td>Effective porosity of the mulch layer</td>
<td>( \alpha_2 )</td>
<td>–</td>
<td>0.2–0.4</td>
<td>Maidment 1993</td>
</tr>
<tr>
<td>Effective porosity of the soil root zone</td>
<td>( \alpha_3 )</td>
<td>–</td>
<td>0.15–0.4</td>
<td>Maidment 1993</td>
</tr>
<tr>
<td>Effective porosity of the deep soil zone</td>
<td>( \alpha_4 )</td>
<td>–</td>
<td>0.15–0.4</td>
<td>Maidment 1993</td>
</tr>
<tr>
<td>Hydraulic conductivity of the soil root zone</td>
<td>( K_4 )</td>
<td>mm/h</td>
<td>25–240</td>
<td>PGC 2002 and Maidment 1993</td>
</tr>
<tr>
<td>Hydraulic conductivity of the deep soil zone</td>
<td>( K_5 )</td>
<td>mm/h</td>
<td>25–240</td>
<td>PGC 2002 and Maidment 1993</td>
</tr>
<tr>
<td>Capillary tension parameter of the soil root zone</td>
<td>( \psi_3 )</td>
<td>mm</td>
<td>50–100</td>
<td>Maidment 1993</td>
</tr>
<tr>
<td>Capillary tension parameter of the deep soil zone</td>
<td>( \psi_4 )</td>
<td>mm</td>
<td>50–100</td>
<td>Maidment 1993</td>
</tr>
<tr>
<td>Kinetic sorption rate constant</td>
<td>( \beta )</td>
<td>/h</td>
<td>0–1</td>
<td>McGechan and Lewis 2002</td>
</tr>
<tr>
<td>Langmuir constant for sorption to mulch</td>
<td>( K_{L_2} )</td>
<td>L/mg</td>
<td>≈0.2</td>
<td>Hsieh et al. 2007</td>
</tr>
<tr>
<td>Langmuir constant for sorption to soil in the root zone</td>
<td>( K_{L_3} )</td>
<td>L/mg</td>
<td>0.8–2.6</td>
<td>Hsieh et al. 2007</td>
</tr>
</tbody>
</table>

“–” denotes a unitless variable.

Table 20.1 BPRM input data—bioretention system characteristics; “–” denotes a unitless variable.
The soluble phosphorus sorption parameters should be selected carefully to accurately represent sorption under low phosphorus concentrations typical of stormwater and the presence of other stormwater pollutants which interact with phosphorus. Also, the overflow weir parameters should be calibrated for small water depths above the weir. Table 20.2 lists the bioretention system antecedent conditions required by BPRM for simulation, along with their equation symbols and required units.

**Table 20.2 BPRM Input data—bioretention system antecedent conditions.**

<table>
<thead>
<tr>
<th>Required BPRM Antecedent Condition</th>
<th>Symbol</th>
<th>Units Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial water volume in the ponding layer</td>
<td>$W_1$</td>
<td>m$^3$</td>
</tr>
<tr>
<td>Initial water volume in the mulch layer</td>
<td>$W_2$</td>
<td>m$^3$</td>
</tr>
<tr>
<td>Initial water volume in the soil root zone</td>
<td>$W_3$</td>
<td>m$^3$</td>
</tr>
<tr>
<td>Initial water volume of water in the deep soil zone</td>
<td>$W_4$</td>
<td>m$^3$</td>
</tr>
<tr>
<td>Initial soluble phosphorus mass in the ponding layer</td>
<td>$SP_1$</td>
<td>mg as P</td>
</tr>
<tr>
<td>Initial soluble phosphorus mass in the mulch layer</td>
<td>$SP_2$</td>
<td>mg as P</td>
</tr>
<tr>
<td>Initial soluble phosphorus mass in the soil root zone</td>
<td>$SP_3$</td>
<td>mg as P</td>
</tr>
<tr>
<td>Initial soluble phosphorus mass of water in the deep soil zone</td>
<td>$SP_4$</td>
<td>mg as P</td>
</tr>
<tr>
<td>Initial particulate phosphorus mass in the ponding layer</td>
<td>$PP_1$</td>
<td>mg as P</td>
</tr>
<tr>
<td>Initial concentration of phosphorus sorbed in mulch</td>
<td>$Q_1$</td>
<td>mg as P/kg</td>
</tr>
<tr>
<td>Initial concentration of phosphorus sorbed in soil root zone</td>
<td>$Q_2$</td>
<td>mg as P/kg</td>
</tr>
<tr>
<td>Initial concentration of phosphorus sorbed in deep soil zone</td>
<td>$Q_4$</td>
<td>mg as P/kg</td>
</tr>
<tr>
<td>Initial wetting front depth inside native soils at soil root zone</td>
<td>$y_{x_1}$</td>
<td>m</td>
</tr>
<tr>
<td>Initial wetting front depth inside native soils at deep soil zone</td>
<td>$y_{x_4}$</td>
<td>m</td>
</tr>
</tbody>
</table>
20.3.2 Inflow Time Series

The model requires time series of rainfall intensities and runoff inflow rates to determine the total volume of stormwater entering the bioretention system at each time step. Modeling time steps are user-defined but must remain constant throughout the storm event. Runoff inflow volumes can be measured on site, if at all possible, or can be derived either from a surface runoff generation equation, such as the SCS curve number method (Soil Conservation Service 1969), or from a rainfall-runoff simulation model, such as SWMM (USEPA 2009). If total bioretention system inflow rates can be measured (including precipitation falling directly above the system), they can be used to replace the series of runoff inflow volumes, with rainfall intensities set to zero.

The model also requires time series of soluble phosphorus and particulate phosphorus concentrations in surface runoff entering the system. Median values of total phosphorus and soluble phosphorus stormwater concentrations collected in >200 U.S. municipalities over a period of nearly 10 y for residential, commercial, industrial, freeway and open space land uses were reported in the National Stormwater Quality Database (Pitt et al. 2004) and are reproduced in Table 20.3. These values can be used as guidelines for soluble and particulate phosphorus inflow concentrations if no other information on the composition of the stormwater to be treated is available.

<table>
<thead>
<tr>
<th>Land-Use Type</th>
<th>Soluble Phosphorus (mg/L)</th>
<th>Total Phosphorus (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>0.17</td>
<td>0.30</td>
</tr>
<tr>
<td>Commercial</td>
<td>0.11</td>
<td>0.22</td>
</tr>
<tr>
<td>Industrial</td>
<td>0.11</td>
<td>0.26</td>
</tr>
<tr>
<td>Freeway</td>
<td>0.20</td>
<td>0.25</td>
</tr>
<tr>
<td>Open space</td>
<td>0.13</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Precipitation which falls directly above the bioretention system is assumed to contribute no additional phosphorus to the system. If total phosphorus concentrations in rainfall are known to be high at the location of the bioretention system, the runoff inflow phosphorus concentrations can be adjusted to compensate for this assumption.

Lastly, BPRM requires users to specify the length of the modeling time step to be used for simulation. The time step length should be selected based on the frequency of available input data points for runoff inflow rates, rainfall
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intensities and phosphorus concentrations. The modeling time step should be chosen to be compatible with the time interval between input data points for all input time series as BPRM does not have the capability to interpolate between input data points.

### 20.4 Model Limitations

BPRM represents a first step towards better predicting and understanding phosphorus movement and removal efficiencies in bioretention systems. However, the event-based model is being derived using a series of simplifying assumptions which limit its applicability.

Since BPRM is being developed as a single-event simulation model, bioretention system antecedent conditions must be approximated by the user, which can significantly impact the modeling results. The importance of antecedent conditions is reduced when using continuous models, as only short term outputs are significantly influenced by the choice of antecedent conditions. Future work will assess the effect of uncertainties in antecedent conditions on model outputs through comprehensive sensitivity analyses.

BPRM allows users to estimate phosphorus removal in a bioretention system over the duration of a single storm event. However, a continuous model would be more appropriate to estimate the long term reduction in phosphorus loading to receiving water bodies produced by the installation of a bioretention system, as BPRM does not account for some processes, such as long term sorption, which may become significant during dry periods between storm events.

BPRM does not allow users to vary bioretention system characteristics over time during a single simulation. For event simulations, this is generally a reasonable assumption, but the characteristics defining the capacity of a bioretention system to remove pollutants can be expected to change over longer time periods. Also, the rate of different bioretention processes, such as evapotranspiration and vegetative uptake, can be expected to vary significantly with time. Evapotranspiration rates can have a significant impact on the soil moisture conditions in bioretention systems between storm events. Anaerobic conditions which promote the microbial release of phosphorus from soils (Fleischer 1978) can develop in bioretention soils between storm events. Moreover, as particulate phosphorus accumulates in bioretention soils over time, the infiltration capacity of the soils tends to decrease. The accumulation of particulate phosphorus in bioretention soils should be included in the model if it is to be used for continuous modeling.
The assumption that model layers in BPRM are completely mixed may not be an accurate representation of the behaviour of the system, especially in cases where differential flow patterns are formed in the soil filtration media. Also, the model layers created for BPRM are fairly coarse, so that significant vertical gradients in water saturation levels and phosphorus concentrations may exist within the soil layers. A first step in improving the accuracy of the model would involve increasing the number of model layers or replacing the model layers used in BPRM with continuous one-dimensional downward flow modeling. Two-dimensional horizontal flow could be incorporated in the model to increase modeling accuracy further, but it may prove excessively computationally demanding.

The model assumes that no sediment is carried through the soil filtration media into the underdrain. This may be unrealistic at the beginning of the bioretention system operation period, during which time stabilization of the filtration media has been observed to lead to high quantities of solids outflow (Davis 2007). The type of soil selected as filtration media, along with the construction practices followed to build a bioretention system, may also influence its performance at retaining solids.

Previous studies have reported that the transport through soil of particulate phosphorus sorbed onto small colloidal particles can be significant (McGechan and Lewis 2002). BPRM ignores this process which has not been studied extensively.

To increase the accuracy of BPRM, a biogeochemical model which takes into account the interactions of phosphorus with other surface runoff pollutants, such as metals and suspended sediment, as well as with microorganisms present in stormwater, in soil and in symbiosis with plants (e.g. mycorrhizae) should be developed. However, there is currently limited data available on reaction rates required to incorporate these processes into the model.

20.5 Conclusion

Research on bioretention systems has shown great potential for storm flow reduction and stormwater quality improvement. However, high variability in phosphorus removal has been reported from the field monitoring of bioretention systems. Potential explanations related to a disturbance in the soil and to phosphorus desorption from the soil filtration media have been presented to explain this phenomenon, but no numerical tool currently exists to predict phosphorus removal through bioretention.
BPRM, a finite-difference numerical model, is being developed to estimate total phosphorus removal in a bioretention system over the duration of a storm event. In this chapter, the preliminary framework and development of the model was presented. BPRM is divided into hydrologic and phosphorus transport components and includes four completely-mixed model layers; the ponding layer, the mulch layer, the soil root zone and the deep soil zone. The phosphorus transport component includes subcomponents for soluble and particulate phosphorus. Processes considered in the model include: rainfall and runoff, evapotranspiration, ponding layer overflow, particulate phosphorus sedimentation, infiltration into soil layers, phosphorus mulch and soil sorption, exfiltration to surrounding native soils, vegetative uptake and underdrain discharge.

The preliminary equations selected to represent each model process were described in this chapter and model input parameter requirements were discussed. The model being developed represents a first step towards better understanding the processes and system characteristics that influence phosphorus removal in bioretention systems. However, the assumptions made in developing BPRM limit its applicability to modeling bioretention systems over short time periods. Also, BPRM does not consider horizontal two-dimensional or vertical gradients in water saturation and phosphorus concentrations inside model layers. Lastly, the assumption that particulate phosphorus does not infiltrate bioretention soil media may not be accurate, in particular during the early operation period.

The mathematical framework of BPRM presented in this chapter will be refined further in future work and additional bioretention processes will be considered. The performance of the model presented will then be evaluated using data from the field monitoring of a bioretention system. An in-depth sensitivity analysis will be performed on the input parameters required for simulation to identify areas where additional research is required.

References


PGC. (2002). "The Bioretention Manual." Prince George’s County, Department of Environmental Resources, Programs and Planning Division, Largo, MD.


