The interactions between stormwater and the groundwater beneath infiltration basins are complex and not well understood. Analytical solutions to estimate maximum groundwater mounding have been shown to suffer from many limiting assumptions. The most significant sources of error with analytical solutions involve vadose zone storage, the assumption of homogeneous conditions, and neglecting transient flow effects (NDWRC/DP, 2005). Numerical models can account for these factors but often suffer from complexity and the need for additional site-specific data. Predictions for mound height have generally been much higher with analytical methods than with numerical methods (NDWRC/DP, 2005). As over estimation of mound height can have basin siting implications, an accurate estimation of mound formation is important.

**Objectives**

The goal of this study was to increase our understanding of the causes of groundwater mounding beneath stormwater infiltration basins. By understanding the relative importance of factors affecting groundwater mounding, the potential mound formation at future sites can be evaluated with greater confidence. The main objectives of the project were: 1) To monitor groundwater levels and changes in soil moisture in the unsaturated zone in response to infiltrating stormwater from an infiltration basin, 2) To calibrate and validate a groundwater flow and contaminant transport model using data obtained under objective one, and 3) To use the model to extrapolate field data to other hydrogeologic settings.

This report presents an overview of methods to estimate groundwater mounding, followed by characterization of the study site and model design, and concludes with modeling results from the study site, as well as modeling results from hypothetical basin operation scenarios.

**Groundwater Mounding**

Groundwater mounding can occur when stormwater infiltration rates exceed the soil's capacity to carry water down to the water table and laterally away from the site via unconfined flow. The potential for mounding increases when the materials have low hydraulic conductivity, the water table is near the surface, the gradient is low, and the saturated and unsaturated zones are thin (NDWRC/DP, 2005). Evaluation for the potential for groundwater mounding can require different levels of effort depending on characteristics of the subsurface, available site information, and the consequences of system failure.

As a very simple estimate of basin separation to the groundwater table, a minimum of four feet of soil medium in the unsaturated zone is recommended for every foot of water in the basin (Guo, 2001). This conservative estimate is derived from the concept of soil storage associated with porosity, and is obtained by dividing the maximum expected ponding depth by the specific yield of the receiving soil. Bouwer (1990) suggests that because the capillary fringe in permeable materials usually is less than 0.3 meters (1.0 ft) high, the depth to groundwater should be at least 0.5 - 1.0 meters (1.6 - 3.3 ft) below any basin clogging layer that may exist. If no clogging layer exists, then the depth to groundwater should be more than twice the width of the recharge basin. A simple empirical estimate of mound height is given in the hydraulics literature (Parmley, 2001) as:

\[
H = \left( \frac{Q \log (R/r)}{1.3C} + \bar{h}^2 \right)^{1/2}
\]  

(1)
where, \( H = \) initial saturated thickness + mound height (L), \( Q = \) flow (VT\(^{-1}\)), \( R = \) distance from basin center to zero mound height (L), \( r = \) basin radius (L), \( C = \) coefficient of permeability (VT\(^{-1}\)A\(^{-1}\)), and \( h = \) initial saturated thickness (L).

The next level of effort to estimate groundwater mounding involves analytical modeling. While analytical models have the advantage of being more straight-forward and less time consuming to use, they suffer from a number of simplifying assumptions. The more commonly used analytical solutions and their simplifying assumptions are discussed in the following section.

Finally, numerical modeling can be used to estimate groundwater mounding. Numerical modeling requires more knowledge of the site conditions, as well as experience with numerical methods, soil physics, and hydrogeology. However, the power and flexibility of numerical modeling allows for this method to overcome many of the limitations associated with analytical methods. A brief description of numerical models capable of estimating groundwater mounding is presented in the following section.

**Mounding Estimation by Analytical Methods**

**Hantush Solution**

One of the best known analytical solutions for predicting groundwater mound development was presented by Hantush (1967). Hantush solved the linearized form of the saturated, radial, groundwater flow equation subject to infiltration from a rectangular or circular area. The solution is for transient groundwater mound development beneath a recharge area with a constant rate of infiltration, and requires inputs of saturated hydraulic conductivity, storativity, and initial saturated thickness. Rao and Sarma (1981) demonstrated the utility of Hantush’s mound function in representing observed groundwater mounds. Since Hantush’s solution contains an error function and is therefore not very convenient to use, an algebraic approximation for Hantush’s mound function was developed by Swamee et al. (1997).

![Conceptual Model for Hantush Solution](image)

**Figure 1. Conceptual Model for Hantush Solution Adapted for WSAS (NDWRCDP, 2005).**

Hantush’s solution for a rectangular source has been adapted for use in the wastewater soil adsorption system (WSAS) industry (Figure 1 & Equation 2) (NDWRCDP, 2005). The solution assumes a homogeneous and isotropic aquifer, bounded by a horizontal water table overlying a
horizontal impermeable base. The maximum mound height, \( z_{\text{max}} \) or \( h_{\text{max}} \), occurs at the center of the basin, and is estimated as:

\[
z_{\text{max}} = \sqrt{h_i^2 + q' h_{\text{avg}} t \left[ 4S' \left( \frac{l}{4K_h h_{\text{avg}} t}, \frac{w}{4K_h h_{\text{avg}} t} \right) \right]} - h_i 
\]

where: \( z_{\text{max}} = h_{\text{avg}} - h_i \) (L); \( q' \) = effective wastewater infiltration rate per unit area of infiltration zone (A); \( h_i \) = initial saturated thickness (L), \( h_{\text{avg}} \) = iterated head at location and time of interest: \( 0.5(h_0(t) + h(t)) \) (L); \( K_h \) = horizontal hydraulic conductivity (LT\(^{-1}\)), \( l = 1/2 \) overall infiltration area length, \( w = 1/2 \) overall infiltration area width, \( 1/2 \) W; \( S_y \) = specific yield (0.001 used for conservative, long-term solution); \( t \) = time since infiltration began (10 yrs used for conservative, long-term solution),

\[
S' = \int_0^1 \text{erf} \left( \frac{\alpha}{\sqrt{\tau}} \right) \text{erf} \left( \frac{\beta}{\sqrt{\tau}} \right) d\tau \quad \text{if } \alpha^2 + \beta^2 < 0.04, \text{ use following approximation:}
\]

\[
S' \approx \frac{4}{\pi} \alpha \beta \left[ 3 + W(\alpha^2 + \beta^2) - \left( \frac{\alpha}{\beta} \tan^{-1} \frac{\beta}{\alpha} + \frac{\beta}{\alpha} \tan^{-1} \frac{\alpha}{\beta} \right) \right].
\]

\[
D = \sqrt{\frac{4K_h h_{\text{avg}} t}{S_y}}
\]

\[
\alpha = \frac{l + x}{D} \quad (x = 0 \text{ for } z_{\text{max}}) \quad \beta = \frac{w + y}{D} \quad (y = 0 \text{ for } z_{\text{max}})
\]

A spreadsheet has been developed to solve for maximum mound height, using the approximation for \( S' \) found in Equation 3, and is available at [www.ndwrcdp.org/publications](http://www.ndwrcdp.org/publications).

**Finnemore Solution**

Finnemore and Hantzsche (1983) describe a simplification of Hantush's method by reducing the solution to the following single equation for calculating groundwater mounding:

\[
z_m = IC \left( \frac{L}{4} \right)^n \left( \frac{1}{Kh} \right)^{0.5n} \left( \frac{t}{S_y} \right)^{1-0.5n}
\]

where, \( z_m = \) maximum mound height (L), \( I = \) average volume recharge rate of wastewater entry into unit area (LT\(^{-1}\)), \( C \) and \( n = \) constants that depend on the length to width ratio of the source (see table in Finnemore and Hantzsche (1983)), \( L = \) disposal field length (L), \( K = \) hydraulic conductivity (LT\(^{-1}\)), \( h = \) initial aquifer thickness + (\( 1/2 \))\( z_m \) (L), \( t = \) time since beginning of water application (T), and \( S_y = \) specific yield (dimensionless). Equation 4 neglects unsaturated flow, and is limited to cases where there is a single permeable layer with a lower impermeable boundary. The equation has a further assumption that there is a minimum specified distance between the water table and infiltrative surface of two to five feet.
Since Equation 4 is not straightforward to solve, Finnemore (1993) developed a simplified long-term solution for a trench system (Figure 2) with limited input parameters. The method is best suited for longer application times of 10-20 years, which mimics a steady state condition. This method would be best applied to a wastewater disposal field, and not to the highly transient conditions observed under a stormwater infiltration basin. Finnemore (1993) demonstrated the impact of subdividing a single disposal field into widely separated, smaller fields on mound height. The author reported that replacing a single disposal field by two widely separated fields, each with half of the area, reduces the mound height to 55-65% of that of the single field.

Finnemore (1995) developed a software program, MOUNDHT, to estimate mound height based on Hantush’s solution. The program was written in FORTRAN-77, and was developed to rapidly perform the necessary iterations and to evaluate the exponential integrals (well functions) in the Hantush solution for longer periods. A Washington State Department of Transportation (WDOT, 2000) study describes an application of the public domain program, including model input and output parameters.

![Diagram of Finnemore 1993 & 1995 Conceptual Model](image)

**Figure 2.** Finnemore 1993 & 1995 Conceptual Model.

**Khan et al. Solution**

Khan et al. (1976) developed the following solution for mounding for large wastewater soil adsorption systems.

\[
H = W \left[ \frac{K_2}{K_1} \left( \frac{q'}{K_1} - 1 \right) \left( \frac{q'}{K_2} - \frac{x^2}{W^2} \right) \right]^{1/2}
\]  (5)

where \(H\) = mound height above impermeable layer (L), \(W\) = trench width (L), \(K_1\) = hydraulic conductivity of more permeable material (LT\(^{-1}\)), \(K_2\) = hydraulic conductivity of less permeable material (LT\(^{-1}\)), \(q'\) = infiltration rate (LT\(^{-1}\)), and \(x\) = distance from basin center (L). The solution is well-suited for mounding on relatively impermeable layers in the unsaturated zone, but does not address unsaturated flow physics. It also assumes that the width of the system is much smaller than the length, that ponding does not occur, and that the water table is deep and does not cause mounding (the impermeable layer is the sole cause of mounding).

**Other Analytical Solutions**

Morel-Seytoux (1990) developed a solution for groundwater mounding that addressed the issues of specific yield, vertical flows, anisotropy, and transient basin operations associated with the Hantush equation. This was done by including both saturated and unsaturated flow...
modeling, and by including a tailing distribution on the uniform infiltration rate (NDWRCDP, 2005). However, the solution suffered from several limitations, including lack of mound definition, a priori knowledge of temporal patterns of recharge, restrictions of basin size, and linearizations related to a simplified flow-path delineation (Sumner et al., 1999). Further improvements to the model relaxed these limitations, but suffered from the one-dimensionality of the simulation within the unsaturated zone, which did not allow for lateral spreading of infiltrating water.

Guo (1998) presented a two-dimensional surface-subsurface model to estimate the required subsurface geometry for an infiltration trench. However, applications of this two-dimensional model to a circular basin resulted in as much as twice the overestimation of the hydraulic conductivity in order to match predicted to observed mound heights.

**Analytical Solutions for Mounding on Perched Layers**

In addition to the water table, layers of less permeable material in the unsaturated zone can also cause mounding. The Khan et al. (1976) solution is well-suited for determining mound heights on impermeable perched layers, and Bouwer et al. (1999) presented the following equation for determining mound height on an impermeable layer:

\[
L_p = L_r \frac{i}{K_r (i - 1)}
\]

where \( L_p \) = height of perched mound above restricting layer (L), \( L_r \) = thickness of restricting layer (L), \( i \) = infiltration rate (LT^-1), \( K_r \) = hydraulic conductivity of restricting layer (LT^-1), and \( K_s \) = hydraulic conductivity of soil above restricting layer (LT^-1). This solution assumes that the pressure head is zero for water at the bottom of the restricting layer, which is valid if the material below the restricting layer is relatively coarse.

**Analytical Model Assumptions and Limitations**

The Hantush solution is based on the following assumptions: 1) a priori known infiltration rate, 2) a priori known transit time for infiltration to reach the water table, 3) infiltration reaching the water table with no storage losses, 4) no delayed drainage from the unsaturated zone upon end of basin loading, 5) a circular or rectangular basin area that is identical to the area of recharge at the water table, 6) less than 50% rise in the water table relative to the initial saturated thickness, 7) one-dimensional radial flow below the water table, 8) and no leakage from the surficial aquifer to the underlying strata (Sumner et al., 1999). All but the last three assumptions are liabilities of estimating groundwater mounding based on solutions of the saturated groundwater flow equation (Sumner et al., 1999).

Morel-Seytoux (2000) also discusses the short-comings of the mound solution by Hantush: 1) as a result of infiltration, the fillable pore space above the rising water table is lower than the specific yield, and it varies with time and space, 2) the Dupuit-forchheimer assumption (flow lines are horizontal and horizontal hydraulic gradient is equal to the slope of the free surface and is invariant with depth) is not valid due to vertical gradients under the spreading basin, 3) the infiltration hydrograph is delayed and attenuated to become the recharge hydrograph, 4) as the infiltration rate is discontinued at the surface, water in the unsaturated zone will not instantaneously drain, and the recession curve of the mound will be slower than under the Hantush assumptions, 5) most aquifers are anisotropic, with the vertical hydraulic conductivity being an order of magnitude smaller than the horizontal, 6) the recharge process is transient, 7)
infiltration rates within a recharge event are not constant, and 8) soil conditions are not homogeneous, and less permeable layers will affect recharge and mound heights.

Although these simplifying assumptions show the limitations of analytical models, their expediency warrants their use before numerical modeling is considered (NDWRCDP, 2005).

**Mounding Estimation by Numerical Methods**

When there is the potential for problematic mounding determined from either a preliminary site assessment or from analytical modeling, the use of numerical modeling is required. Using numerical methods to solve the variably saturated flow equation can allow for the evaluation of complex conditions including variable infiltration rates, dynamic water tables, anisotropic and heterogeneous conditions, and unsaturated flow (NDWRCDP, 2005). Because the unsaturated zone offers storage capacity that is not considered by analytical models, an analytical model is a worst-case predictor for modeling, generally producing a higher mound than with numerical modeling (NDWRCDP, 2005). Sumner et al. (1999) showed that differences between the analytical and numerical solution of the variably saturated flow equation increased for shorter loading times, greater depth to groundwater, larger heterogeneity, and inclusion of fine-grained layers.

The reliability of model predictions depends on how well the model approximates the field situation (Anderson et al., 1982). Fewer simplifying assumptions need to be made when solving the variably saturated flow equations numerically than analytically, allowing for a more accurate representation of field conditions. Due to the greater need for site-specific input parameters, however, the most important task in using numerical models is the ability to accurately characterize the aquifer beneath and adjacent to the infiltration area (NDWRCDP, 2005). Numerical modeling involves identifying three aspects: a governing equation, boundary conditions, and initial conditions. These items are discussed briefly below; a more thorough discussion is found in the Materials and Methods section of this report.

Water movement through variably saturated conditions is commonly analyzed by solving Richard's equation (Equation 7, Materials & Methods) (Richards, 1931). Modeling unsaturated flow is more complex than modeling saturated flow due to the need to specify the relationship between moisture content and tension, between hydraulic conductivity and tension, and because the governing equation is highly nonlinear (Anderson et al, 1992). The instability caused by the nonlinearity of the flow equation can cause the model to calculate unrealistic oscillating values of pressure head. The instability must be minimized when solving the mathematical model using a number of numerical techniques.

Two common numerical techniques used to solve Richard's equation are finite element and finite difference models (Anderson et al., 1982). In both cases, a system of nodal points is superimposed over the problem domain. The numerical solution yields values for only this finite number of predetermined points. The smaller the distance between the nodal points, the closer the approximation comes to the analytical solution (Anderson et al., 1982). Determining nodal point spacing is a compromise between representing site detail and computational efficiency, and strongly influences numerical results (Anderson et al., 1992). Using a small node spacing is one way to minimize instability inherent in the nonlinear flow equation.

The finite difference method is usually implemented with rectangular cells centered around the nodal points. Aquifer properties and head are assumed to be constant within each cell, and heads are computed only for the nodes at the center of the cell. The finite element method is commonly implemented with triangular elements defined by nodes at each of the three corners. The heads are computed at each nodal point, and the head within each element is defined in
terms of the nodal values by interpolation functions (Anderson et al., 1982). The flexibility of the finite element method is useful in solving moving boundary problems such as a moving water table occurring under an infiltration basin.

Correct selection of boundary conditions is a critical step in model design (Anderson et al., 1992). Numerical models provide a solution for a finite area with a given set of input data. Unlike analytical models, numerical models cannot extend to infinity. Every boundary of the model must be assigned a flow, head, or pressure. These boundary conditions are ideally set at natural hydrologic boundaries such as water bodies or units of low hydraulic conductivity. Often, however, artificial boundaries must be selected in order to maintain the desired level of detail or to maintain a reasonable computer execution time, while not imposing unnatural effects on modeling results.

Due to the dynamic nature of recharge through infiltration basins (short, irregularly-spaced events), modeling groundwater mound formation must be done under transient conditions. Transient simulations analyze time-dependent problems, and produce a set of heads for each time step (Anderson et al., 1992), in contrast with steady-state simulations that generate only one set of heads. Transient problems require storage characteristics of the aquifer, initial conditions of head distribution, and time steps to be specified. During transient simulations, water is released from or taken into storage within the porous material. When this transfer stops, the system reaches steady state and heads stabilize. The relevant storage parameter for unconfined aquifers, typical of those receiving recharge from infiltration basins, is specific yield. Specific yield will be discussed in detail in the Factors Affecting Mound Height sub-section of this report.

Initial conditions refer to the head distributions in the system at the start of the simulation, and thus are boundary conditions in time (Anderson et al., 1992). It is common to assign hydrostatic equilibrium conditions for the initial conditions in a variably saturated flow model (Simunek, 2006). Soil above the water table is at a negative pressure head relative to atmospheric pressure. Under hydrostatic equilibrium conditions, the pressure head decreases linearly with distance above the water table, where pressure head is equal to zero. This condition occurs when a system is fully drained. Following a recharge event, pressure heads would be lower (closer to zero) than the equilibrium pressure head conditions.

Just as with node spacing, time step selection strongly influences numerical results (Anderson, et. al, 1992). Using a small time step is another method of minimizing instability inherent in the nonlinear flow equation. A balance between solution accuracy (smaller time steps) and computational efficiency (larger time steps) must be sought, with time steps on the order of seconds often required.

**Numerical Model Review**

Numerical codes for solving the variably saturated flow equation were reviewed. A summary of capable codes for determining groundwater mounds is provided below along with our rationale for model selection.

TOUGH2 is a general-purpose numerical simulation program for multi-phase fluid and heat flow in porous and fractured media (Pruess et al., 1999). It was developed in the Earth Sciences Division of Lawrence Berkeley National Laboratory for applications in vadose zone hydrology, among others. The latest version of TOUGH2, Version 2.0, was released in December 1999, and the model is available for purchase from the Department of Energy. A graphical user interface (GUI), called PETRISM, is available at www.petrasim.com. TOUGH2 is a two dimensional finite difference model that performs forward modeling only. A version of the program, iTOUGH2, solves the inverse problem by automatically calibrating a TOUGH2 model.
against observed data. TOUGH2 was not chosen for this study because other models were available of similar capability that provide for both the direct and inverse solution, as well as a GUI, all in the same software program.

FEMWATER is a three-dimensional finite element, variably saturated, density driven, flow and transport model. FEMWATER was originally written by G.T. Yeh at Penn State University (Yeh et al., 1992). The model is public domain, available from the U.S. EPA at www.epa.gov/ceampil/gwwater/femwater. Groundwater Modeling Systems (GMS) is a GUI for the model, available at www.ems-i.com. FEMWATER was not chosen for this study due to reported difficulties and program crashes within the GMS environment, as well as the high cost of the GUI. Version 6.0 of GMS, released in June 2007, has addressed the operating issues.

SUTRA is a model for variably saturated, variable density groundwater flow with solute or energy transport (Voss et al., 2002). The code includes both two and three dimensional capabilities. It is a public domain model available from the United States Geological Survey (USGS) at www.water.usgs.gov/nrp/gwsoft/sutra/sutra.html. Utility codes, called SutraGUI, are included for pre- and post-processing. Together, all of the utility codes and SUTRA are called SutraSuite. A commercially available GUI, called Argus ONE, is required to operate the pre- and post-processing codes. Argus ONE is available at www.argusint.com. SUTRA was not chosen for this study due to the complexity involved with obtaining and integrating the various codes and the GUI. Other programs of similar modeling capability were available without this drawback.

FEFLOW is a finite element, three dimensional, variably saturated flow and contaminant transport model (Diersch, 2005). The program contains a GUI and has the capability of automatic calibration using PEST (Parameter Estimation). The program is available commercially at www.feflow.com. FEFLOW was found to be fully capable of analyzing groundwater mounding, however FEFLOW was not chosen for this study due to the high cost of the program, and because the unsaturated flow component of the model was not as robust as the selected model.

VS2DT is a two dimensional, finite difference, variably saturated flow and solute transport model (Lappala et al., 1987). The model is public domain, available from the USGS at http://wwwbrr.cr.usgs.gov/projects/GW_Unsat/vs2di1.2/index.html. The model comes with an easy-to-use GUI for pre- and post-processing. VS2DT was not chosen for this study due to limited post-processing options and the lack of inverse modeling and calibration capabilities.

MODFLOW (Harbaugh et al., 2000) is used more than any other numerical groundwater code (NDWRCDP, 2005). MODFLOW is a three-dimensional finite difference, saturated flow code. The code is public domain, available from the USGS at http://water.usgs.gov/nrp/gwsoft/modflow2000/modflow2000.html. A number of GUIs are commercially available to assist with operating the code. Since MODFLOW is a saturated flow code, recharge applied at the ground surface directly enters the aquifer with no unsaturated zone effects. An unsaturated zone flow package (UZF1) was recently developed for MODFLOW-2005. The one dimensional form of Richard’s equation is approximated by a kinematic-wave equation in this module. The UZF1 package is a substitution for the recharge and evapotranspiration packages of MODFLOW-2005. The UZF1 module for MODFLOW was not chosen for this study because it only became publicly available shortly after this study began, and because of the one-dimensional limitation for unsaturated flow.

HYDRUS (Simunek, 2006) is a two dimensional, finite element, variably saturated flow and contaminant transport model. A three dimensional version was released in 2006 with major upgrades in March of 2007. A one dimensional version is available in the public domain. All
versions are available at www.pc-progress.cz. HYDRUS includes a parameter optimization algorithm for inverse estimation of a variety of soil hydraulic and solute transport parameters. The model is supported by GUI for data pre-processing, generation of the finite element mesh, and graphic presentation of results. The two dimensional version of HYDRUS was selected for this study. The three dimensional version would have been used had it been available at the time of model selection. HYDRUS was selected because: 1) it was designed specifically for infiltration and recharge simulation in the variably saturated flow regime, 2) it contains an extensive database of unsaturated soil hydraulic parameters, and 3) it utilized a robust parameter estimation technique for inverse estimation of soil hydraulic parameters.

Factors Affecting Mound Height

The shape of groundwater mounds depend on the size and shape of the infiltration basin, infiltration rate and hydraulic properties of the soil medium (Ferguson, 1990). Currently, in Wisconsin, the infiltration basins are sized according to Wisconsin Department of Natural Resources (WDNR) Conservation Practice Standard 1003 – Infiltration Basin (WDNR, 2004b). This standard allows for a maximum ponding time of 24 hours and maximum ponding depths of 0.60 meters (24 inches). Design infiltration rates are given in WDNR Conservation Practice Standard 1002 - Site Evaluation for Stormwater Infiltration (WDNR, 2004c).

Basin Design

Rastogi et al. (1998) investigated the influence of basin shape on the underlying aquifer system. Basins of square, circular, hexagonal, triangular, and rectangular shapes, having equal areas and transmitting equal recharge rates, were investigated. The investigators found that a rectangular basin shape produced a lower mound height compared with the other shapes, and that the groundwater mound increased with a decreasing basin perimeter. The circular recharge basin had the smallest perimeter (792.6 m) and the highest mound (4.24 m) compared with the rectangular basin with the largest perimeter (1,200 m) and smallest mound (3.55 m). However, a linear relationship between mound height and basin perimeter could not be established. Bouwer et al. (1999) found that mound heights can be reduced by arranging basins in long, narrow recharge strips instead of compact round or square areas, and by dispersing the basins over larger areas. Zomorodi (2005) concluded that the rate of groundwater rise is independent of the basin length as long as the length exceeds four times the basin width.

Infiltration Rate

For surface infiltration systems in uniform soils without surface clogging, infiltration rates will be approximately equal to the vertical hydraulic conductivity of the soil (Bouwer et al., 1999). Ponding will occur when the infiltration rate is less than the saturated hydraulic conductivity of the receiving soil (NDWRC, 2005).

Infiltration rates follow Darcy’s Law, which equals the product of the saturated hydraulic conductivity and the flow gradient (Hillel, 2004). Without ponding, the maximum gradient is unity, where the hydraulic head equals the elevation head. The maximum infiltration rate in this case equals the saturated hydraulic conductivity. However, ponding will occur if the saturated hydraulic conductivity is less than the infiltration rate. When ponding occurs, the low conductivity layer causing the ponding can infiltrate water at a rate higher than the saturated hydraulic conductivity because the ponding causes a gradient greater than unity. The gradient will equal the head difference between the top of the pond and the bottom of the low conductivity layer, divided by the thickness of the layer.
Infiltration rates depend on initial soil wetness and suction, as well as on the soil structure, texture, and layering (Hillel, 2004). Infiltration rate into a dry soil generally decreases with time to a minimum value equal to the saturated hydraulic conductivity, due to decreasing gradients in soil-water pressure within the zone of infiltration (Hillel, 2004). If the soil surface is initially dry and then is suddenly saturated by ponding, the difference in hydraulic potential between the saturated surface and the relatively dry soil just below it creates a steep matric suction gradient. As the wetted zone deepens, the same difference in potential acting over a greater distance results in a diminishing gradient and a reduced infiltration rate.

Under ponding conditions, infiltration generally does not remain constant as assumed in the Hantush equation (Equation 2). Infiltration varies temporally as previously described, and with ponding depth due to changes in gradient. Solution of the unsaturated/saturated flow equation allows for a pressure head to be specified at the basin floor, equal to the ponding depth. Since ponding depth is easier to design for and control than infiltration rate, using ponding depth to estimate aquifer response to basin recharge is the recommended approach (Sumner et al., 1999). This approach is also more realistic in that the infiltration rate is allowed to vary in response to changes in ponding depth. Sumner et al. (1996) states that if the ponded depth is large relative to the sum of the thickness of the surface control layer (i.e., sediment layer) and surface matric potential, the infiltration response to a change in ponded depth will approach 1:1 proportionality. If ponding depth is small in relation to this sum, the infiltration response to a change in ponded depth will be negligible.

Once the infiltrating front reaches the groundwater table and a mound develops, the infiltration rate decreases further due to a back pressure effect in the growing groundwater mound. The operation of a basin during loading has been found to be more controlled by seepage recharging to groundwater than by the infiltration rate into soil (Guo, 2001).

**Unsaturated Zone Effects**

Neglecting unsaturated zone effects produced errors in estimating groundwater mounding of up to 800% compared to methods that include vadose zone storage (Sumner et al., 1999). The error was due in large part to water being released from the vadose zone over a period of time longer than the length of basin loading (Figure 3). Water entered the pore storage during basin loading and then was released slowly during basin rest. In contrast, when the Hantush method is used, water is delivered to the water table at the full infiltration rate as at land surface until the end of basin loading. Once basin loading is complete, water delivered to the water table is stopped immediately. This discrepancy caused by the storage effects were greatest during highly transient events, such as short basin loading periods typical of infiltration basins (Sumner et al., 1999). As the time of basin loading increases, the system approaches steady state, and the storage effects become negligible. A relatively thick vadose zone would amplify the delayed drainage effects, due to the larger capacity for water storage. The soil storage effect was found to not be as significant during mound recession as during mound formation (Guo, 2001).
Specific Yield

Specific yield is a storage term that accounts for the release of water from storage. Specifically, it is the ratio of the volume of water a soil will yield by gravity drainage to the volume of the soil (Healy et al., 2002). Values of specific yield range from 0.1 to 0.4, with 0.25 – 0.30 for coarse sand and gravel (Anderson et al., 1992). Groundwater mound heights generally decrease as specific yield increases (Rai et al., 2001). Specific yield is different than the porosity term commonly used in analytical equations for mound rise.

Specific yield increases as depth to the water table decreases (Healy et al., 2002). Specific yield also increases with time due to delayed drainage from the unsaturated zone. Aquifer analyses that do not take into account unsaturated flow will predict values of specific yield that are unrealistically low (Healy et al., 2002). These limitations will cause overestimation of mound height. Conditions with a shallow water table where the capillary fringe intersects the land surface were found to be problematic using the Hantush method because of the difficulty in estimating the effective specific yield. The specific yield in this case would vary spatially and temporally and would not be simply equal to the difference of the saturated moisture content and field capacity (Sumner et al., 1999).

Aquifer Thickness and Transmissivity

Groundwater mounding decreases as the saturated thickness increases (NDWRCDP, 2005). A greater saturated thickness has a greater transmissivity (the product of hydraulic conductivity and saturated thickness), and more capacity to convey recharge water away from under the basin. Mounding decreases more rapidly with increased saturated thickness for higher hydraulic conductivity values because a given rise in head increases transmissivity more in a high hydraulic conductivity material (NDWRCDP, 2005). Zomorodi (2005) concluded that the rate of mound rise does not depend on saturated thickness of the aquifer as long as the thickness exceeds the width of the basin.

The assumption of constant transmissivity and use of transmissivity for an entire unconfined aquifer thickness can lead to error in estimating mound height. The assumption of constant transmissivity is acceptable only if the mound height is small compared with the thickness of the aquifer (Guo, 2001). A difficulty in obtaining meaningful mounding estimates from analytical solutions (where transmissivity is assumed to be constant) is getting a representative value of aquifer transmissivity (Bouwer et al., 1999). Accurate predictions of transmissivity for rising groundwater levels are difficult to make and require considerable judgment. The most reliable transmissivity data come from existing recharge systems and calibrated aquifer models, followed by Theis-type pumping tests, step-drawdown and other pumped well tests, and slug tests (Bouwer et al., 1999). In thick, unconfined aquifers, streamlines of recharge flow are concentrated in the upper portion of the aquifer, with less flow in the deeper part of the aquifer (Bouwer et al., 1999). The streamlines in the groundwater mound also tend to be more vertical.
Consequently, the use of transmissivities of the entire aquifer for mound calculations could then under-estimate the mound height. Bouwer (1962) showed that for rectangular recharge areas, the thickness of the active, upper portion of the isotropic aquifer is about equal to the width of the recharge area. In an anisotropic system, the effective thickness will be less than the width of the recharge area.

**Hydraulic Conductivity and Anisotropy**

A decrease in hydraulic conductivity increases mound height. Hydraulic conductivity is the most influential parameter on mound height (NDWRCDP, 2005). This is problematic since hydraulic conductivity is difficult to accurately measure. Freeze and Cherry (1979) indicate that the value of hydraulic conductivity can vary by two orders of magnitude for a particular soil type. Hydraulic conductivity can vary by an order of magnitude spatially due to heterogeneities within an apparently homogeneous soil. Therefore, it is recommended to evaluate moundings using a range of hydraulic conductivities above, and most importantly below, the expected value (NDWRCDP, 2005).

The assumption of an isotropic hydraulic conductivity (required in an analytical solution) can also be a source of error in predicting mound height. Typically, the vertical hydraulic conductivity ($K_v$) is less than the horizontal hydraulic conductivity ($K_h$). The assumption of isotropic hydraulic conductivity can over-predict mound height if the vertical hydraulic conductivity ($K_v$) is used, and under-predict mound height if the horizontal hydraulic conductivity ($K_h$) is used. For analytical solutions, an equivalent homogeneous hydraulic conductivity value can be found by using the square root of the product of the horizontal and vertical hydraulic conductivity values ($\sqrt{K_h \cdot K_v}$) (NDWRCDP, 2005). Numerical solutions can account for anisotropy in the hydraulic conductivity.

The degree of impact of anisotropy on moundings is site specific and depends on the saturated thickness as well as the value of hydraulic conductivity relative to basin loading and the proximity to hydraulic boundaries (NDWRCDP, 2005). An anisotropy ratio of at least 2:1 is likely in most soils (NDWRCDP, 2005). The influence of anisotropy is also more significant in thicker aquifers. Transmissivity controls the increased gradient needed to carry water away from the recharge area. However, horizontal hydraulic conductivity spans a much larger range of values than saturated thickness, making it more important to the magnitude of moundings than saturated thickness (NDWRCDP, 2005).

**Water Table Slope**

The assumption of a flat water table (required in an analytical model) can lead to errors in estimating mound height. In a thin aquifer, moundings will increase as the slope of the water table decreases. In a thick aquifer, moundings will decrease with a decrease in water table slope, since only a small gradient is required to transmit the recharged water in a larger flow field (NDWRCDP, 2005).

Rastogi et al. (1998) reported greater mound heights underneath the downgradient side of a recharge basin compared to the upgradient side, and that the bulk of the recharge contribution is stored downgradient. It was suggested that the mound slope was perpendicular to the predominant flow direction.

All infiltrated water eventually moves downgradient, essentially decreasing the flow area under a basin by a factor of two (NDWRCDP, 2005). The decrease in flow area may be offset by the increased gradient, depending on aquifer thickness, regional flow table, and increased loading. Therefore, the impact of water table slope on moundings is not intuitively obvious, and should be modeled numerically to determine the effects of the competing processes (NDWRCDP, 2005).

**Groundwater Mounding & Contaminant Transport Beneath Stormwater Infiltration Basins**

University of Wisconsin – Madison Department of Biological Systems Engineering
August 2007
Case Study

A literature review found few studies on the application of numerical modeling specific to recharge or infiltration basins. The most comprehensive study found in the literature is summarized below.

The USGS conducted field experiments at a one acre rapid infiltration basin in Orange County Florida, in 1992 (Sumner et al., 1996). The site consisted of 37 feet of unsaturated zone and 52 feet of saturated zone. Soils were a poorly graded sand with some clay, and had horizontal and vertical hydraulic conductivities of 150 and 45 feet per day, respectively. The basin was flooded in a cycle for 17 hours followed by a rest period of four to nine hours. Ponded depth in the basin was maintained at an average of four inches, and the system produced an infiltration rate of 5.5 feet per day. A network of monitoring wells in and around the basin recorded groundwater levels during and after basin loading.

The two dimensional, variably saturated flow model VS2DT (Lappala et al., 1987) was applied to describe the flow system beneath the basin under observed and hypothetical basin operations, and to estimate hydraulic properties of the soil. The model design included a spatial grid discretization of 0.5 feet vertical by 3.0 feet horizontal beneath the basin. Three model layers were used to account for various layering of fines mixed with the sand.

Boundary conditions were set to no-flow at the basin center (assuming radial symmetry), no flow at the base, and a constant head at a distance of 1,000 feet from the basin, where no change in water level was observed. A pressure head equal to the average ponding depth of four inches was set for the basin floor. Initial conditions were set with a water table at 37.5 feet below grade. Since tensiometric data indicated that the unsaturated zone had not drained to an equilibrium condition, an equilibrium head distribution was only set to a height of 1.5 feet above the water table. Above this height, matric potential was set to a constant value of 1.5 feet.

The model was calibrated by altering infiltration rate, hydraulic heads, moisture front transit time, laboratory-derived soil-moisture curves, field-observed soil/aquifer textural patterns and tensiometric data, and literature-derived estimates of subsurface hydraulic properties. A model was developed that approximately replicated the field measurements. The model was found to be most sensitive to vertical and horizontal hydraulic conductivity, and residual and saturated moisture content.

The flow model indicated that infiltration capacity is unaffected by small (less than 10 feet) increases in depth to the water table. However, water table elevation increases of 15 and 20 feet produced a reduction in the infiltration capacity of the basin by 8 and 25%, respectively. Increasing the ponded depth from 4 to 12 inches increased basin capacity by less than 6 and 11%, respectively.

About 1.5 days were required for the initial infiltration front to reach the water table, and a maximum mound height of seven feet was recorded during a two week loading period. Pore water velocity was found to be 20 feet per day, predominantly in the vertical direction. As the infiltrating front reached the water table, pore-water velocity was estimated to have changed to 10 feet per day, and predominantly in the horizontal direction. The large radial component of flow below the water table implied that infiltrated water moves preferentially in the shallow part of the saturated zone after reaching the water table.