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Madison, Wisconsin: Wisconsin Department of Natural Resources, 2007

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Groundwater Mounding and Contaminant Transport Beneath Stormwater Infiltration Basins

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Joint Solicitation Project

Wisconsin Department of Natural Resources Project #189

August 2007

Madison, WI

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Abstract

Increased impervious areas resulting from urbanization cause an increase in stormwater runoff and a decrease in infiltration to the groundwater table. Infiltration basins are often required to recharge a portion of the pre-development infiltration volume. The localized recharge by these relatively small basins can cause a groundwater mound to form below the basin. Mound formation is important as it may reduce the ability of the soil to filter pollutants, and may reduce the infiltration rate of the basin. Therefore, an accurate understanding of groundwater mound formation is important in the proper design of infiltration basins.

The goal of this study was to understand groundwater mounding and the potential for contaminant transport resulting from recharge beneath stormwater infiltration basins. The specific objectives were to monitor changes in groundwater levels and soil moisture content in response to infiltrating stormwater from an infiltration basin, and to calibrate and validate a groundwater flow and contaminant transport model.

A 0.10 hectare (0.25 acre) infiltration basin serving a 9.4 hectare (23.2 acre) residential subdivision in Oconomowoc, Wisconsin was used in this study. Subsurface conditions included sand and gravel material and a groundwater table at 2.3 meters (7.5 ft) below grade. Three storm events, 4.93 cm, 2.84 cm, and 4.28 cm, on 08/24/06, 10/04/06, and 04/03/07, respectively, were modeled using the two-dimensional numerical model HYDRUS. Inverse modeling was performed with HYDRUS to estimate soil and aquifer parameters. A good fit was achieved between modeled and observed data for the timing and magnitude of the maximum rise in the water table. Predicted soil hydraulic parameters matched well with measured and literature values. The model was found to be most sensitive to the thickness of the basin sedimentation layer and the hydraulic conductivity.

The calibrated model was then used to evaluate hypothetical basin operation scenarios for various basin sizes, soil types, ponding depths, and water table depths, with parameters obtained from WDNR post-construction stormwater standards 1002 and 1003. The groundwater mound intersected the basin floor in most scenarios with loamy sand and sandy loam soils, an unsaturated thickness of 1.52 meters (5 ft), and a ponding depth of 0.61 meters (2 ft). No groundwater table response was observed with ponding depths of 0.305 meters (12 in) and 0.152 meters (6 in) with an unsaturated zone thickness of 6.09 meters (20 ft). The mound height was most sensitive to hydraulic conductivity and unsaturated zone thickness. A 7.62 cm (3 in) sediment layer delayed the time to reach maximum mound height, but had a minimal effect on the magnitude of the mound. Mound heights increased as infiltration basin size increased.

Introduction

Background and Purpose

As urbanization continues to expand the limits of corporated areas, previous farmland, grassland, and wooded areas are converted to impervious roads, buildings, and parking lots. These land use changes cause an increase in surface runoff and a decrease in infiltration and groundwater recharge. The combined effects of reduced groundwater recharge and increased groundwater pumping to sustain a larger population has lowered groundwater levels in aquifers and reduced baseflow to lakes and streams. As an example, the Yahara River at McFarland, Wisconsin, has suffered a greater than 50% reduction in base flow due to human activities, according to the Dane County Regional Planning Commission (DCRPC, 1999). Base flows are of important environmental and economical concern for several reasons. Base flows must be capable of absorbing pollution from sewage treatment plants and non-point sources, supporting aquatic life dependent on stream flow, and replenishing water supply reservoirs for municipal use in the seasons when water levels tend to be lowest and water demands highest (USEPA, 1999).

To mitigate the effects of reduced recharge, Wisconsin regulations require that the average annual infiltration volume for new residential and non-residential areas must be 90% and 60%, respectively, of the infiltration volume under pre-developed conditions (WDNR, 2004a). Infiltration basins are a commonly used stormwater management practice to enhance groundwater recharge. Infiltration, or artificial recharge basins, have long been used to augment groundwater supplies by using surplus rainfall runoff water and treated sewage effluents (Pettyjohn, 1968).

Infiltration basins are depressions in the landscape that function by holding stormwater for durations long enough to allow the water to infiltrate into the soil. The infiltration basin area is typically small compared to the contributing area. This localized, or focused recharge from the basin has the potential to increase the groundwater table in the immediate vicinity of the basin. The height of the groundwater mound underneath an infiltration basin is important to understand and be able to predict. If the groundwater table rises near the ground surface, the infiltration rate will be reduced, causing greater water losses to the atmosphere by evapotranspiration and reducing the volume recharged to the aquifer.

The groundwater table rising close to the ground surface also has important water quality implications. In addition to causing increased runoff volume, urbanized areas also contribute various pollutants including volatile organic compounds (VOCs), pesticides, nutrients, metals, pathogens, and other oxygen-demanding substances to runoff (USEPA, 1999). These pollutants are then transported by runoff into the infiltration basin, so that the basin might in effect act as a “point source” of pollution to the groundwater. The unsaturated soil beneath the basin acts as a natural filter for many of these pollutants. As the rising groundwater mound reduces the unsaturated zone thickness, the filtering effect of the soil will be minimized, and the pollutants will have a direct pathway to the groundwater aquifer.

Therefore, the interaction between the surface and groundwater is important for the proper design, installation, and management of infiltration basins. If the effect of various soil and aquifer parameters on the height and shape of the groundwater mound formation is known, infiltration basins could be designed to minimize potential groundwater impacts and allow proper infiltration rates.

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 (NDWRCDP, 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 (NDWRCDP, 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 (NDWRCDP, 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 emperical estimate of mound height is given in the hydraulics literature (Parmley, 2001) as:

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

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).

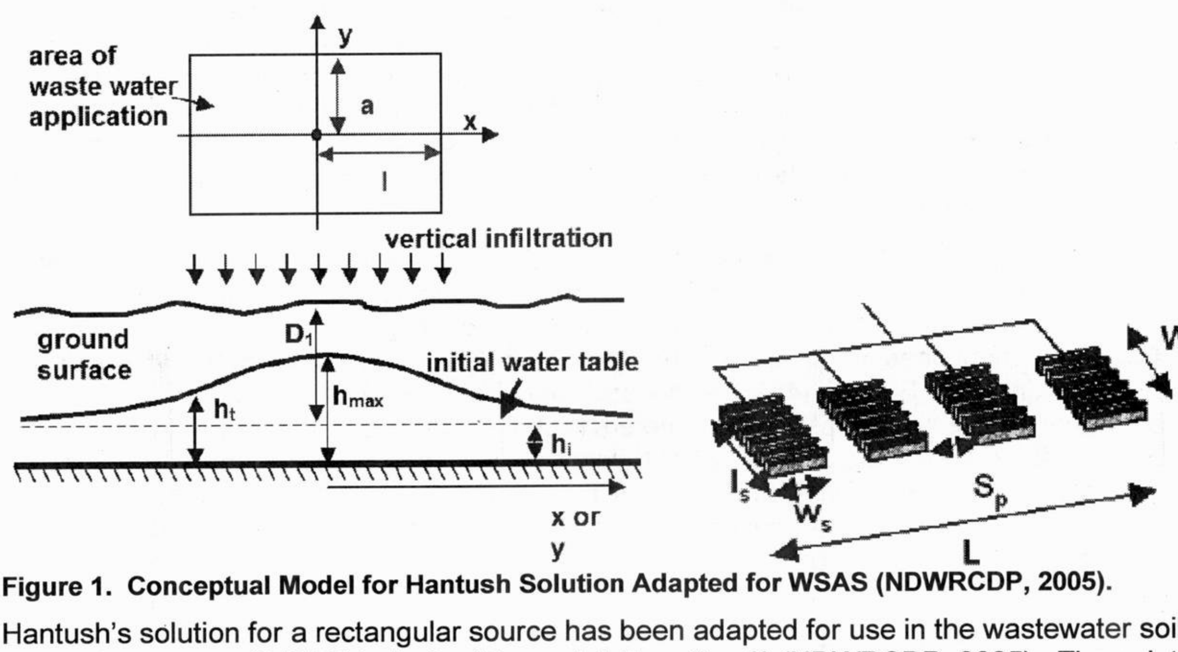

Figure 1. Conceptual Model for Hantush Solution Adapted for WSAS (NDWRCDP, 2005).

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_{max} or h_{max}, occurs at the center of the basin, and is estimated as:

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

where: $z_{max} = h_{avg} - h_i$ (L); q' = effective wastewater infiltration rate per unit area of infiltration zone (A); h_i = initial saturated thickness (L), h_{avg} = iterated head at location and time of interest: $0.5(h_i(0)+h(t))$; (L), K_h = horizontal hydraulic conductivity (LT^{-1}), l = ½ overall infiltration area length, ½ L; w = ½ overall infiltration area width, ½ 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), and

$$S^* = \int_0^1 erf\left(\frac{\alpha}{\sqrt{\tau}}\right) erf\left(\frac{\beta}{\sqrt{\tau}}\right) d\tau$$

if $\alpha^2 + \beta^2 < 0.04$, use following approximation:

$$S^* = \cong \frac{4}{\pi}\alpha\beta\left\{3 + W\left(\alpha^2 + \beta^2\right) - \left[\frac{\alpha}{\beta}\tan^{-1}\frac{\beta}{\alpha} + \frac{\beta}{\alpha}\tan^{-1}\frac{\alpha}{\beta}\right]\right\} \qquad (3)$$

$$D = \sqrt{\frac{4K_h h_{avg} t}{S_y}}$$

$\alpha = \dfrac{l+x}{D}$ (x = 0 for z_{max}) $\qquad \beta = \dfrac{w+y}{D}$ (y = 0 for z_{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.

Finnemore Solution

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

$$z_m = IC\left(\frac{L}{4}\right)^n \left(\frac{1}{K\bar{h}}\right)^{0.5n} \left(\frac{t}{S_y}\right)^{1-0.5n} \qquad (4)$$

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 + (½)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.

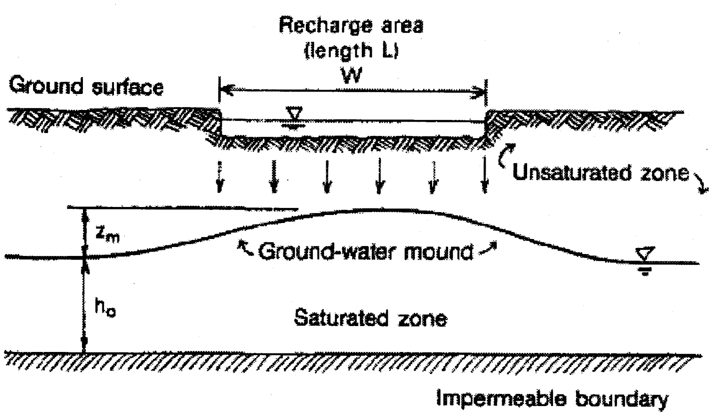

Figure 2. Finnemore 1993 & 1995 Conceptual Model.

<u>Khan et al. Solution</u>

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

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

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).

<u>Other Analytical Solutions</u>

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:

$$L_p = L_r \frac{\frac{i}{K_r} - 1}{1 - \frac{i}{K_r}} \qquad (6)$$

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.

<u>Numerical Model Review</u>

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/ceampubl/gwater/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/gwsoftware/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/gwsoftware/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 (NDWRCDP, 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).

<u>Unsaturated Zone Effects</u>

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).

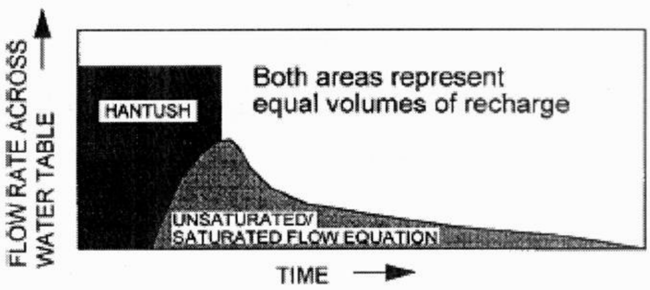

Figure 3. Recharge Volume Comparison (Sumner et al., 1999).

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.

<u>Hydraulic Conductivity and Anisotropy</u>

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 mounding 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 ($[K_h*K_v]^{-0.5}$) (NDWRCDP, 2005). Numerical solutions can account for anisotropy in the hydraulic conductivity.

The degree of impact of anisotropy on mounding 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 mounding than saturated thickness (NDWRCDP, 2005).

<u>Water Table Slope</u>

The assumption of a flat water table (required in an analytical model) can lead to errors in estimating mound height. In a thin aquifer, mounding will increase as the slope of the water table decreases. In a thick aquifer, mounding 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 mounding is not intuitively obvious, and should be modeled numerically to determine the effects of the competing processes (NDWRCDP, 2005).

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.

Methods and Materials

Study Site

The infiltration basin studied serves a residential subdivision located in Oconomowoc, Wisconsin (Figures 4 & 5). The Wood Creek subdivision is a 9.4 hectare (23.2 acre) single-family development completed in 2003 (Figure 6 & 7). A single infiltration basin receives runoff from the subdivision via storm sewer. The basin is located in the NE¼ of the SW¼ of Section 27, T8N, R17E, Waukesha County, Wisconsin.

The landscape in the area was largely formed during the Wisconsin Glaciation, and is characterized by stratified silt, sand and gravel deposited by meltwater (Clayton, 2001). The surface soils in the immediate vicinity of the infiltration basin are characterized as a silt loam (USDA, 2007). Regional hydrogeology is characterized by a shallow groundwater table and many surface water bodies. Rosenaw Creek, designated as a cold water trout stream, is located approximately 150 meters (500 feet) to the northeast of the infiltration basin.

Runoff from the subdivision is directed via storm sewer to a 0.10 hectare (0.25 acre) infiltration basin (Figure 8). The basin is rectangular in shape, with dimensions of 35 meters (115 ft) long by 30.5 meters (100 ft) wide by 1.37 meters (4.5 ft) deep. Water enters the basin through a single 0.61 meter (24 inch) diameter storm sewer. Prior to entering the infiltration basin, stormwater flows through a 0.10 hectare (0.25 acre) vegetated area to allow sediment to settle. Water enters the infiltration basin over a rock gabion. The basin outlets through a single weir outlet structure on the east side of the basin. The basin was designed such that the maximum ponding depth for the 1-year, 24-hour storm is 0.46 meters (1.5 feet).

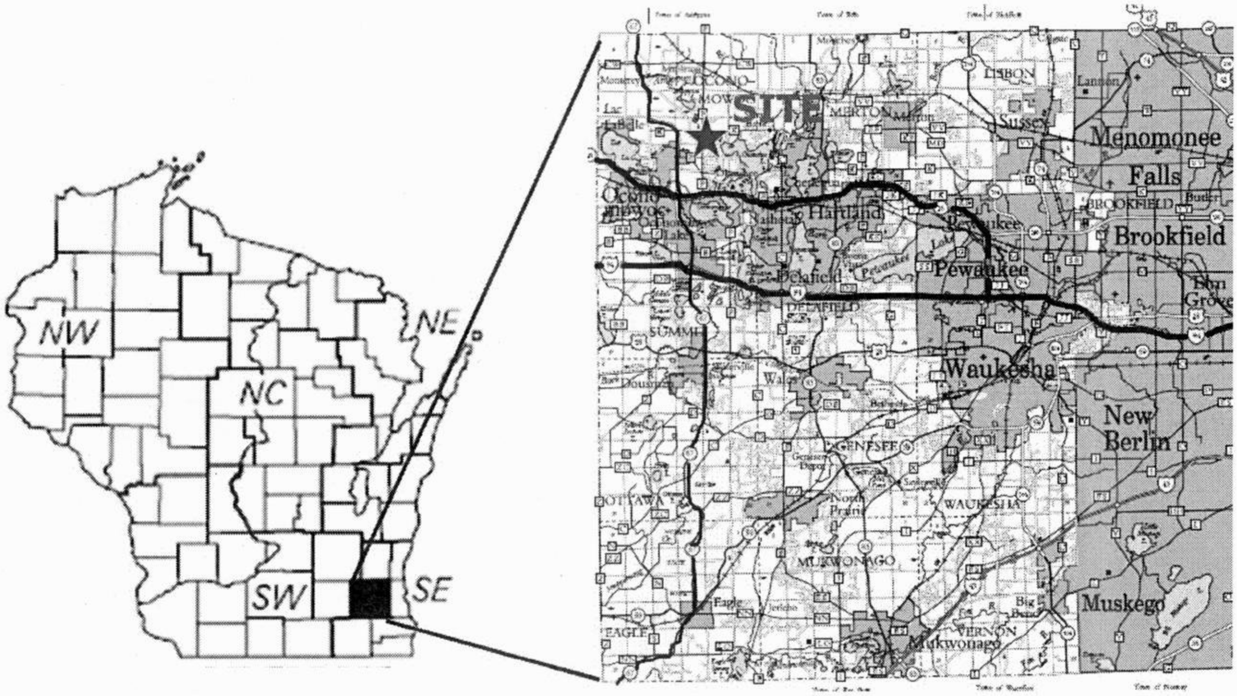

Figure 4. Study Site Location Map.

Figure 5. Study Site Regional View.

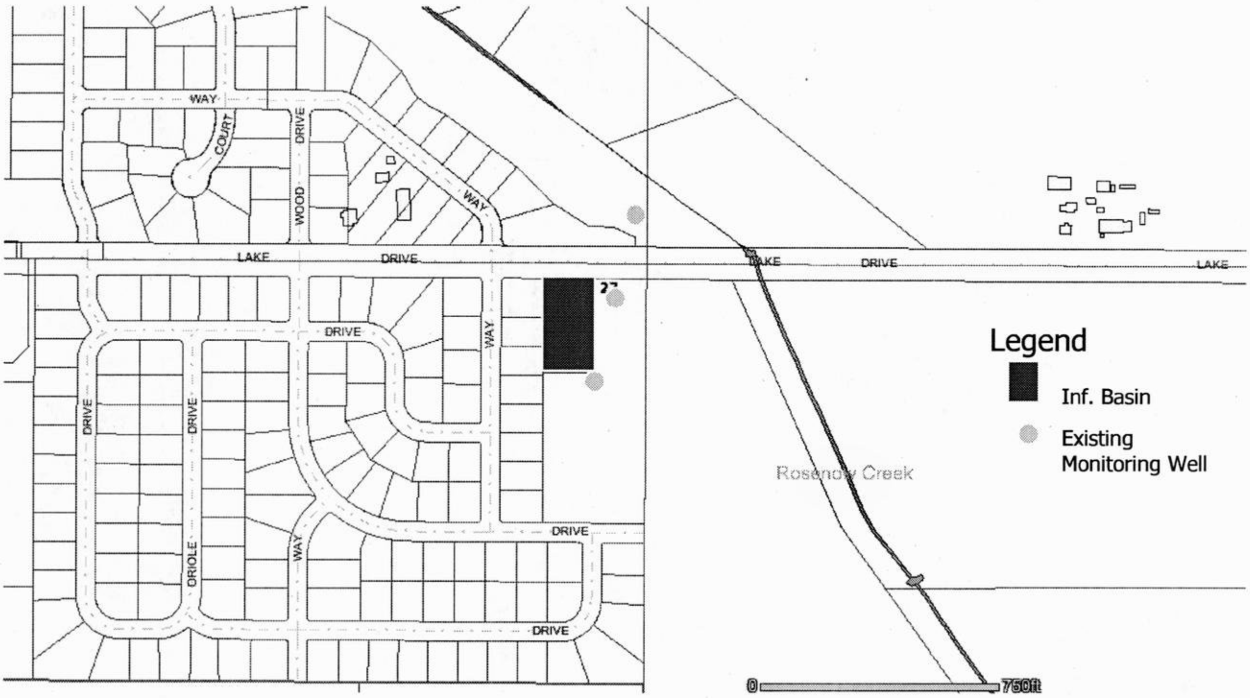

Figure 6. Wood Creek Subdivision Overview.

Figure 7. Wood Creek Subdivision Aerial Photo.

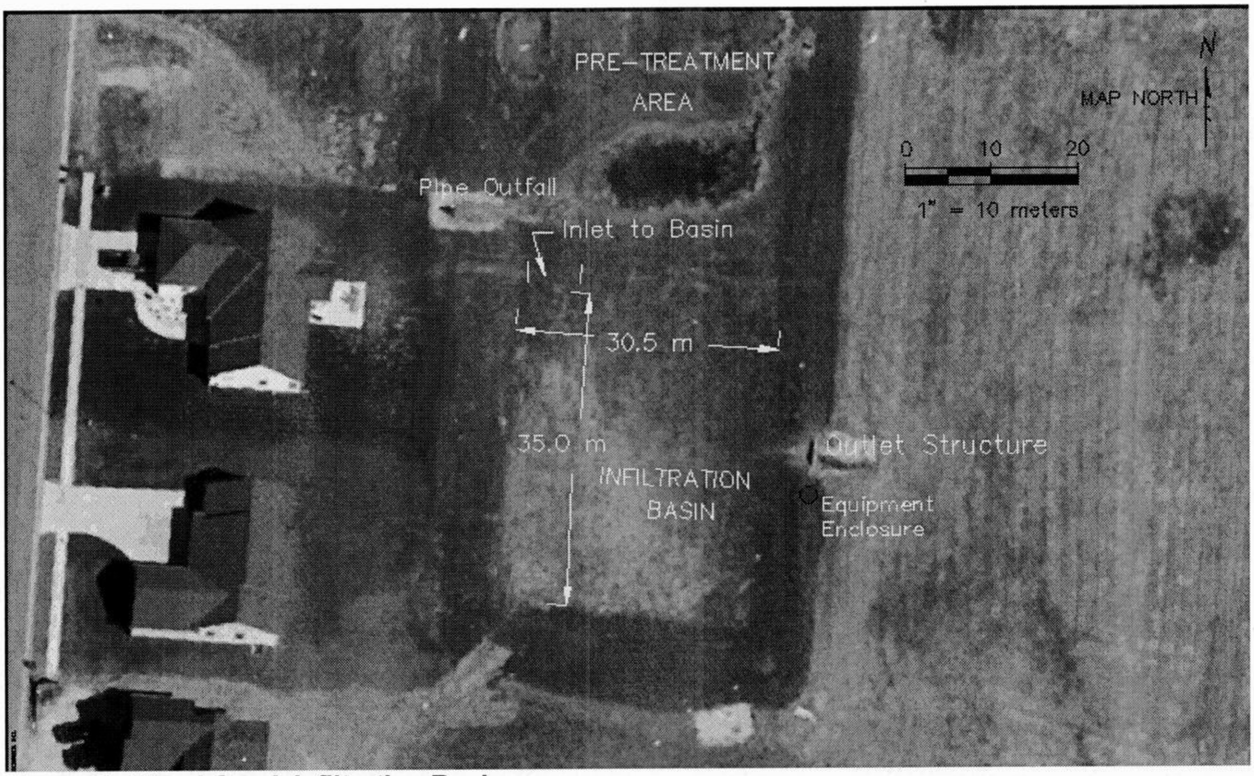

Figure 8. Wood Creek Infiltration Basin.

Monitoring wells were installed inside and adjacent to the basin to facilitate collection of groundwater level data and to characterize subsurface conditions (Figures 9 &10). Three monitoring wells (MW1 – MW3) had been installed prior to this study. These wells were required as part of the basin permit to monitor thermal impacts of infiltrating water. Three additional monitoring wells (MW4 – MW6) were installed by Midwest Engineering Services (MES) (Waukesha, WI) on March 29, 2006. Four more monitoring wells (MW6 – MW9) were installed by Soils and Engineering Services (Madison, WI) on September 9, 2006. These wells were installed in conjunction with a water quality study conducted at the basin by the Wisconsin Department of Agriculture, Trade, and Consumer Protection (WDATCP). A single well (MW10) was installed inside the basin by MES on January 4, 2007.

The wells were installed per NR 141 – Groundwater Monitoring Well Requirements. Monitoring well construction forms (Form 4400-113A) were completed for each well (Appendix A). All wells were installed with hollow stem augers with dimensions of 19.3 cm (7.6 in) outside diameter and 10.8 cm (4.3 in) inside diameter. The 5.1 centimeter (2 inch) diameter polyvinyl chloride (PVC) wells were installed to approximately 4.57 meters (15 feet) beneath the basin floor elevation. The wells were constructed with a 3.05 meter (10 foot) screened section intersecting the water table found at approximately 2.3 meters (7.5 feet) below grade (Figure 11). Monitoring well MW10 was installed to 3.5 meters (11.5 feet) below grade with a 0.91 meter (3 foot) screen. This well was installed for purposes of slug testing, where a completely submerged screen is required. Wells inside the basin were extended above grade to prevent ponded water from entering the well cap. Wells outside the basin were terminated below grade and protected with a flushmount cover. All well tops were capped (vented to atmosphere) and surveyed to the nearest 0.25 centimeter (0.10 inches) with a level. The local topography was surveyed to the nearest 0.31 centimeter (0.12 inches) with a total station. All elevations were referenced to a local datum.

Figure 9. Monitoring Well Locations.

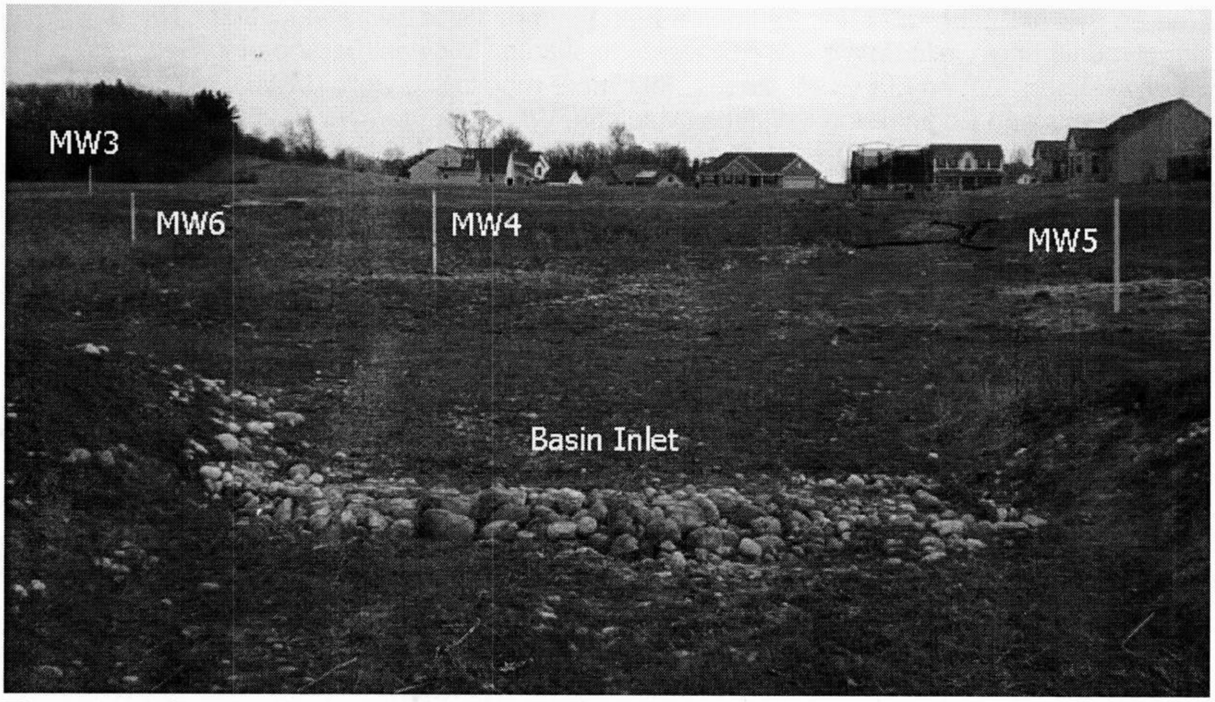

Figure 10. Infiltration Basin & Monitoring Well Photo.

Soils were characterized during the drilling process by split-spoon sampling in two foot intervals, and by observing drill cuttings. Select samples were analyzed for particle size distribution (Table 1) by the University of Wisconsin Soil and Plant Analysis Lab (Madison, WI) using the hydrometer method (Bouyoucos, 1962). A single sample from monitoring well MW10 was taken to MES (Waukesha, WI), and analyzed for particle size by the ASTM D422 method.

Table 1. Textural Properties of Materials Within and Outside Infiltration Basin.

Location	Location Description	Depth (m)	Texture [1,2]	Gravel (%)	Sand (%)	Silt (%)	Clay (%)
NW ¼	Basin floor	0 – 0.115	Loam	0	47	40	13
SW ¼	Basin floor	0 – 0.115	Silt Loam	0	21	56	23
SE ¼	Basin floor	0 – 0.115	Silt Loam	0	27	52	21
Center	Basin floor	0 – 0.115	Loam	0	29	48	23
Average	Basin floor avg.	0 – 0.115	Loam	0	31	49	20
MW 10	Beneath basin	1.5	Poorly graded sand & gravel	42.4 coarse 27.3 fine	23.6	6.7	
MW 10	Beneath basin	4.57	Silty clay loam	0	43	38	19
MW 7	Outside basin	1.0	Silty clay loam	0	7	62	31

1 - Sample with gravel analyzed with ASTM D422 by Midwest Engineering Service, Waukesha, WI.
2 – Other samples analyzed by hydrometer method (Bouyoucos, 1962) by Soil and Plant Analysis Lab, Madison, WI.

A sedimentation layer, between 0 – 0.115 meters (0 - 4.5 inches) thick, exists at the infiltration basin surface (Figure 11). This layer is likely a clogging layer formed by sedimentation of particulate matter from stormwater entering the basin. Soil from below the sedimentation layer to approximately 4.57 meters (15 feet) below grade is a poorly graded gravel with some sand and little fines. Below 4.57 meters, a much less permeable silty clay loam material exists. Drilling and well installation did not occur beyond this layer, as wells could be constructed at this depth and still straddle the shallow water table per NR 141, and because the silty clay loam was thought to be a confining layer. The boring for monitoring well MW5 was advanced deeper prior to well installation to determine the thickness of this confining layer. The silty clay loam extended to 6.1 meters (20 feet) below grade where the boring was terminated.

Immediately outside the basin, a silty clay loam extends from the surface to approximately 1.37 meters (4.5 feet) below grade before the more permeable sand and gravel layer was encountered. Further outside the basin to the northeast and east, the silty clay loam extends from the ground surface to the termination of the borings at approximately 4.57 meters (15 feet) below grade, as observed in monitoring well MW9.

All wells were developed per NR 141.21, and monitoring well development forms (Form 4400-113B) were completed for each well (Appendix A). Development was performed by surging with a bailer, and then extracting water by either bailing or pumping. A minimum of 10 well volumes of water was removed, or until sediment-free water was produced.

Groundwater beneath the basin was at approximately 2.28 meters (7.5 feet) below grade at the time of the boring installation. Periodic groundwater level measurements were manually recorded to the nearest 0.305 centimeter (0.01 foot) at all well locations with a Solinst Model 101 electronic tape (Ontario, Canada). Regionally, groundwater flows from the northeast to the southwest at a gradient of approximately 0.01 m/m (Figure 12). The gradient was higher outside the basin than underneath the basin, where the groundwater table was almost flat. Little seasonal variation was found in the flow direction. A series of regional groundwater flow maps (Appendix B) show water levels to fluctuate seasonally by approximately 0.60 meters (2.0 feet).

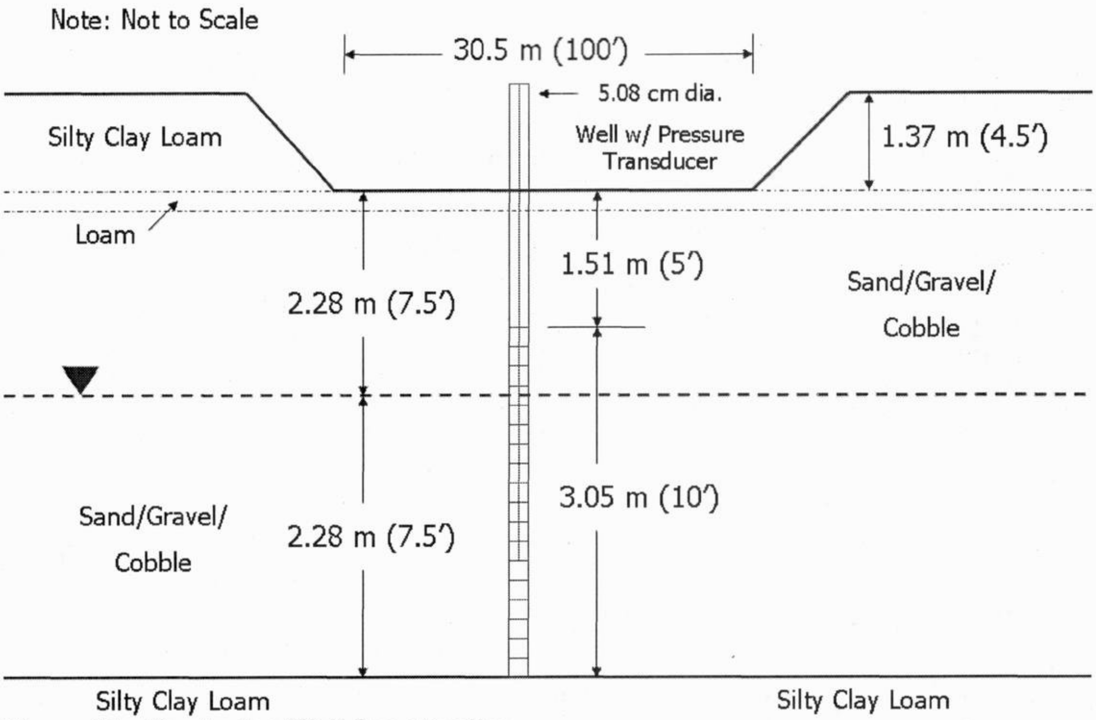

Figure 11. Monitoring Well Construction.

Figure 12. Regional Groundwater Flow Direction.

Estimates of hydraulic conductivity were obtained in both the sand and gravel material and in the surficial silty clay loam outside the basin. A Guelph permeameter was used to obtain field measurements of saturated hydraulic conductivity in the silty clay loam. The permeameter is a constant head device that uses the Mariotte siphon principle to measure the steady-state rate of water recharge into unsaturated soil from a cylindrical well hole 0.06 meters (2.38 in) in diameter and 0.20 meters (8 in) deep. Measurements were made every 15 meters (50 feet) along the eastern and southern edges of the infiltration basin. Saturated hydraulic conductivities range from 8.35×10^{-5} to 2.81×10^{-4} cm/s.

Estimates of saturated hydraulic conductivity in the sand and gravel material were obtained by the Bouwer and Rice slug test method (Schwartz et al., 2003). Slug tests were conducted at monitoring well MW10, located to the southeast of the center of the basin, as this was the only well that was installed with a completely submerged screen necessary for the test. A total of 11 tests were performed on January 9, and April 21, 2007 (Table 2). A single slug test was performed at monitoring well MW1 and MW9 on January 9, 2007, and at monitoring well MW2 on April 21, 2007, as the well screens were submerged at these times.

The slug tests were performed by inserting a solid slug into the well and observing groundwater level change. Groundwater level changes were recorded with a Solinst Levelogger (Ontario, Canada) pressure transducer/datalogger set to record in 0.5 second intervals. In monitoring well MW10, water level returned to background conditions in approximately four seconds. In monitoring wells MW1, MW2, and MW9, water levels returned to background conditions in approximately 10 minutes. Details on the slug test procedure and computations are given in Appendix C.

Hydraulic conductivities in monitoring well MW10, representative of the sand and gravel material, range from 2.14×10^{-2} to 2.87 cm/s, with an average of 3.49×10^{-1} cm/s (Table 2). In the silty clay loam to the northeast of the basin (MW1, MW2, MW9), hydraulic conductivities ranged from 1.78×10^{-3} to 6.99×10^{-4} cm/s.

Table 2. Hydraulic Conductivities from Slug Tests.

Well	Date	K (cm/s)
10	1/9/07	4.36×10^{-1}
10	1/9/07	6.99×10^{-2}
10	1/9/07	2.14×10^{-2}
10	1/9/07	2.87
10	4/21/07	6.82×10^{-2}
10	4/21/07	6.31×10^{-2}
10	4/21/07	6.64×10^{-2}
10	4/21/07	5.62×10^{-2}
10	4/21/07	6.14×10^{-2}
10	4/21/07	7.51×10^{-2}
10	4/21/07	5.60×10^{-2}
1	1/9/07	1.09×10^{-4}
2	4/21/07	6.99×10^{-5}
9	1/9/07	1.78×10^{-3}

Monitoring Equipment

A WL400 pressure transducer (Global Water; Gold River, CA) was installed near the bottom of monitoring wells MW3-MW8. A transducer was also installed at the center of the basin at the location of monitoring well MW4 to measure ponding depth. The transducers have an operating range of 0 – 4.57 meters (0-15 feet), with an accuracy of +/- 0.1%. The transducers were installed between 0.91-1.52 meters (3-5 feet) beneath the water table. The Solinst Levelogger (Ontario, Canada) used for the slug tests was installed in monitoring well MW2, and set to record in 10 minute intervals. The depth of the transducers beneath the PVC well top was recorded. This allowed the transducer elevation to be tied in to the local survey datum, as the PVC well top elevations were recorded relative to this local datum. The transducers were connected to a CR10X datalogger (Campbell Scientific; Logan, Utah) set to record water levels every 10 minutes. A TE525-L tipping bucket (Campbell Scientific; Logan, Utah) with 0.0254 millimeters (0.01 inches) per tip was installed to record precipitation.

In addition to the water level measurements, soil moisture was recorded at two locations using 616-L water content reflectometers (Campbell Scientific; Logan, Utah). The reflectometers were installed near monitoring well MW4 at the center of the basin, at depths of 0.91 meters (3 feet) and 1.52 meters (5 feet) below grade. They were installed by placing them in the center of a hollow stem auger and letting the natural formation collapse around them as the augers were removed. The reflectometers could not be calibrated to the site-specific soil prior to installation, and the large amount of gravel and cobble present would have made calibration difficult. Therefore, the reflectometers were only used to determine the timing of the wetting front movement. Soil moisture was recorded every 10 minutes and stored in the datalogger.

Model Background

HYDRUS-2D was used to simulate water movement through the unsaturated zone and groundwater system (Simunek, 2006). The governing equation for water flow through variably saturated porous media that HYDRUS solves is a modified version of Richards equation (Richards, 1931). HYDRUS solves Richards equation using a Galerkin-type linear finite element scheme. The two-dimensional Darcian flow of water in a variably saturated rigid porous medium is given by the following form of the Richards equation (HYDRUS, 2006):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}{}^{A}\frac{\partial h}{\partial x_j} + K_{iz}{}^{A}\right)\right] - S \qquad (7)$$

where θ is the volumetric soil water content (L^3L^{-3}), h is the pressure head (L), S is a sink term (e.g., root water uptake; T^{-1}), x_i are spatial coordinates (L), K_{ij}^A and K_{iz}^A are components of the dimensionless anisotropy tensor K^A, and K is the unsaturated hydraulic conductivity function [$K(h) = K_sK_r(h)$] ($L\ T^{-1}$) where K_s is the saturated hydraulic conductivity ($L\ T^{-1}$), and K_r is the relative hydraulic conductivity. In this study, K^A was assumed to be isotropic, and the sink term was set to zero since the soil in this study had little vegetation. The unsaturated soil hydraulic properties, *θ(h)* and *K(h)*, in Equation 7 are highly nonlinear functions of the pressure head (HYDRUS, 2006). Different analytical models are available to relate water content to pressure head and pressure head to hydraulic conductivity. In this study, the soil water retention curve, *θ(h)*, was described using a form of the van Genuchten (1980) equation:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + |\alpha h|^n\right]^m} \qquad \text{for } h < 0 \qquad (8)$$

$$\theta(h) = \theta_s \quad \text{for } h \geq 0$$

where θ_r is the residual soil moisture content (L^3L^{-3}), θ_s is the saturated soil moisture content (L^3L^{-3}), h is the pressure head (L), α is the inverse of air-entry pressure (L^{-1}), n is the slope of moisture characteristic curve (dimensionless), and m equals $1 - 1/n$ (dimensionless). Equation 8 uses the statistical pore-size distribution model of Mualem (1976) to describe the unsaturated soil hydraulic conductivity function, *K(h)*:

$$K(h) = K_s S_e^{\,l}\left[1-\left(1-S_e^{\,1/m}\right)^m\right]^2 \tag{9}$$

where l is the pore connectivity parameter (dimensionless), taken to be 0.5, and S_e is the relative saturation (dimensionless), which is equal to $(\theta - \theta_r) / (\theta_S - \theta_r)$.

HYDRUS is capable of inverse modeling, or estimating model parameters by matching a mathematical model to observed data points. The inverse method is based on minimizing an objective function, which expresses the difference between observed and predicted values. The objective function is minimized using the Levenberg-Marquardt nonlinear minimization method, which is a weighted least-squares approach based on Marquardt's maximum neighborhood method. Confidence intervals can be generated for the optimized parameters, and a correlation matrix of the optimized parameters is produced.

Results and Discussion

Storm Event Information

The hydrology of the watershed is such that approximately 2.54 centimeters (1.0 inch) of rainfall is required over a relatively short time period in order to produce measurable and sustained ponding in the basin. Three storm events (Table 3) caused significant ponding in the basin over the time period of this study. For storms #1 and #2, total ponding time was approximately 18 hours (Figures 13 & 14). The groundwater mound in monitoring well MW4 (basin center) also began to recede in this time period. Due to a prolonged rain event with multiple high intensity periods, storm #3 showed a prolonged ponding duration of approximately 30 hours (Figure 15 & 16).

Table 3. Storm Event Data Used for Modeling.

	Storm #1	Storm #2	Storm #3
Date	08/24/06	10/04/06	04/03/07
Total Rainfall (cm)	4.93	2.84	4.28
Maximum Ponding Depth (m)	0.410	0.386	0.472
Maximum Groundwater Rise (m)	0.384	0.397	0.616

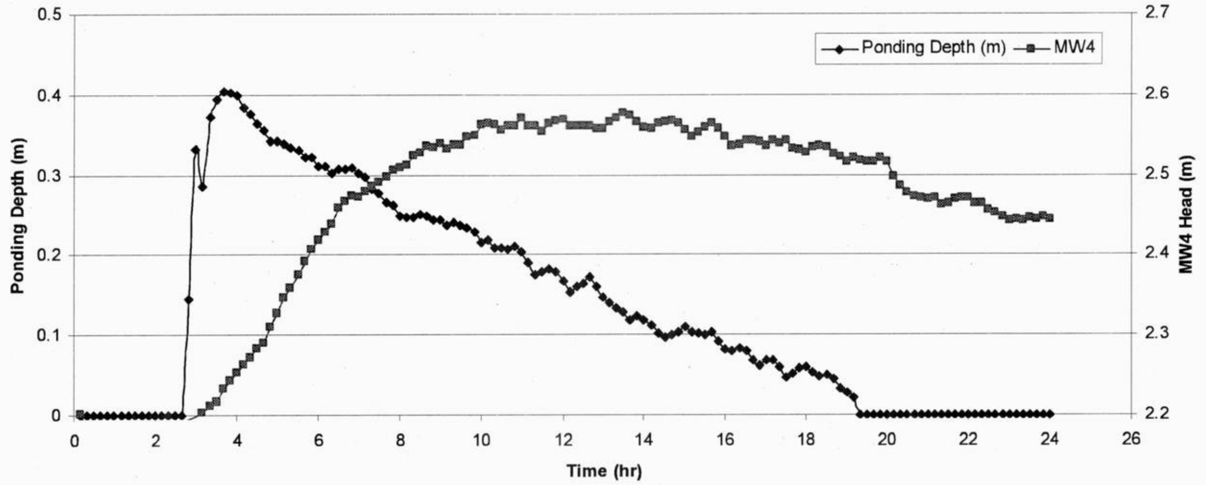

Figure 13. Ponding Depth and Water Table Response - 08/24/06 (Storm #1).

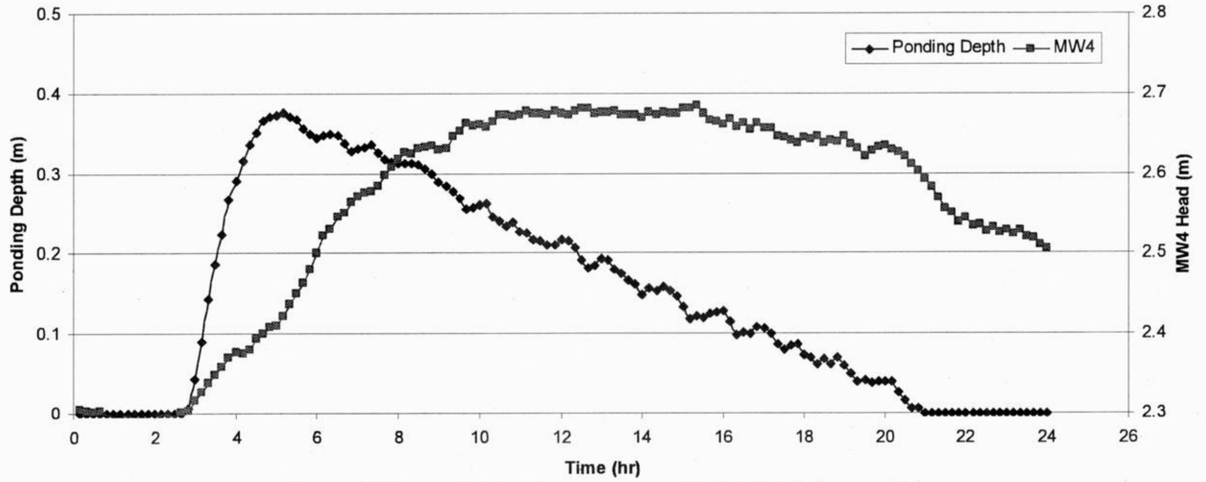

Figure 14. Ponding Depth and Water Table Response - 10/04/06 (Storm #2).

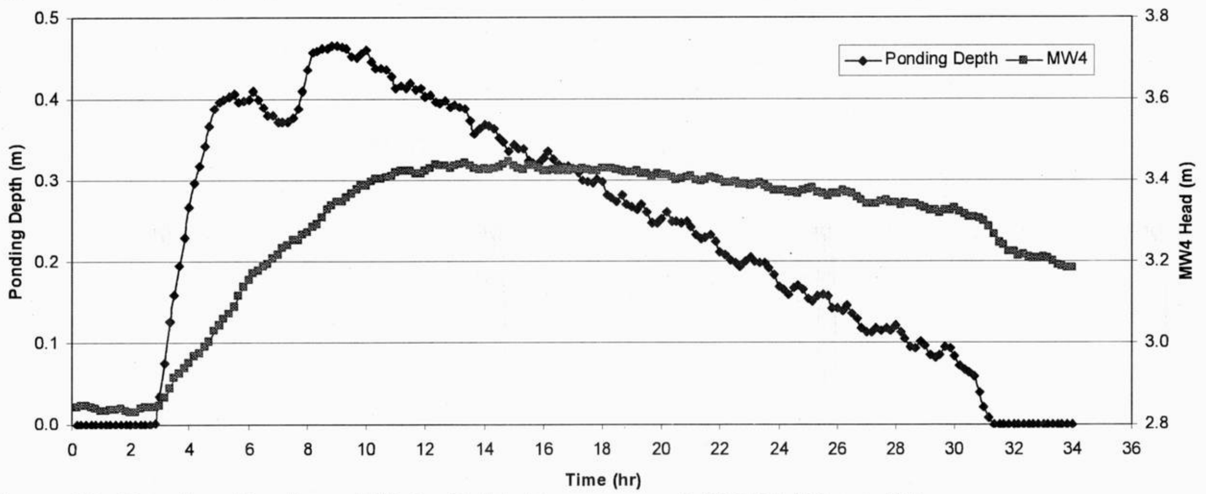

Figure 15. Ponding Depth and Water Table Response - 04/03/07 (Storm #3).

Figure 16. Ponding Following 04/03/07 Storm.

Model Design

A 100 meter (328 feet) transect was modeled, starting at the center of the basin and extending outside the basin to the southeast (Figure 17). This transect is roughly perpendicular to the regional groundwater flow direction. This transect was chosen due to the number of monitoring wells in this direction available for comparing heads.

Groundwater head data were used to set model boundary conditions, which define the flow field at the edges of the model (Figure 18). At the infiltration basin floor, a variable head boundary condition was used. The ponding depth, recorded in 10 minute intervals at the basin center, was used for this time-varying boundary. The ponding data was smoothed using a moving average with a 20 minute window that includes three data points. When no ponding was present, the boundary automatically switched to an atmospheric boundary condition, equal to either the precipitation rate, or zero during periods with no precipitation.

A no-flow boundary condition was set at the center of the basin due to assumed symmetry of the mound. The bottom was set to a no-flow boundary condition. The difference in hydraulic conductivity between the sand and gravel and silty clay loam layers was estimated to be more than two orders of magnitude. This estimate was based on slug tests in the sand and gravel, and literature values of hydraulic conductivity based on particle size analysis of the silty clay loam. A no-flow boundary may be assumed when the hydraulic conductivity difference is two orders of magnitude or greater (Anderson, 1992).

Outside the basin, at a distance of 100 meters (328 feet) from the basin center, a constant head boundary was set equal to the background water table elevation before the storm event. This boundary was set far enough outside the basin to minimize any effects the constant head may have on the flow field under the basin. The background water table over the 100 meter transect was assumed to be flat. While no monitoring well exists 100 meters from the basin center, groundwater levels were inferred based on head data in MW3, and on the observation of a flat water table underneath and adjacent to the basin in directions perpendicular to groundwater flow. A no-flow boundary condition was set in the unsaturated zone at the 100 meter boundary outside the basin. A no-flow boundary was used for the surface boundary outside the basin, rather than entering precipitation data. This was done as initial model results showed that precipitation caused a minimal infiltration depth due to the low conductivity material in this area. Combined with the extra 1.37 meters (4.5 feet) of unsaturated soil in this area, the precipitation did not impact the water table. The precipitation was therefore eliminated to allow for more efficient model operation.

Figure 17. Two Dimensional Transect Modeled with HYDRUS.

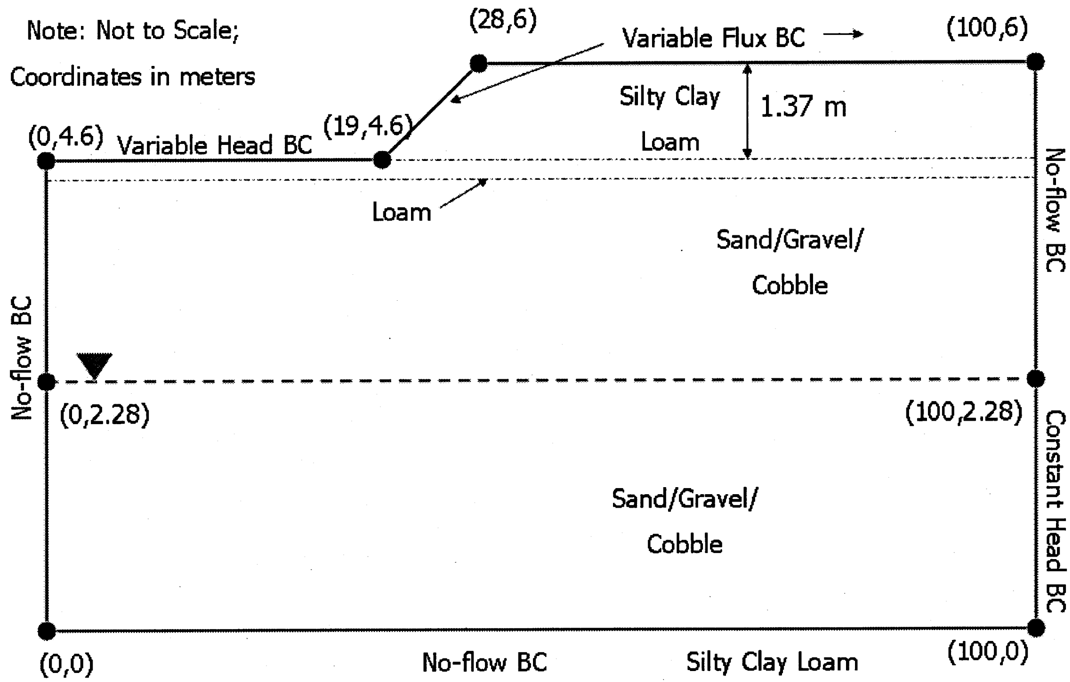

Figure 18. Model Boundary and Initial Conditions.

The initial condition for the saturated zone was set based on the water table elevation before the storm event. As previously discussed, the background water table was assumed to be flat along the modeled transect. The initial condition in the unsaturated zone was assumed hydrostatic, or the negative pressure head in the unsaturated zone was set to equal the distance above the water table. The hydrostatic assumption would be valid in a well-drained material with extended time periods between storms, as was the case for the storms modeled for this study.

The finite element mesh in HYDRUS was set to an eight centimeter resolution immediately under the basin to allow for the thin sediment layer to be added. Elsewhere in the model the resolution was set to one meter. This resulted in 3,151 element nodes and 6,300 element meshes. The initial and minimum time steps were 0.6 seconds, and the pressure head tolerance was one cm.

The HYDRUS code is coupled with Rosetta Lite Dynamically Linked Library (Rosetta) to predict hydraulic properties of soil. Rosetta implements pedotransfer functions which predict van Genuchten's water retention parameters and the saturated hydraulic conductivity in a hierarchical manner from soil textural class, particle size distributions, bulk density, and points from a water retention curve. Three different soil types were included in the model: the surficial silty clay loam outside the basin, the loam sedimentation layer on the basin floor, and the sand and gravel material beneath the basin. For the loam and silty clay loam material, particle size analysis data were entered into Rosetta and the parameters predicted by Rosetta were entered into HYDRUS as fixed values. Since the sand and gravel material fell outside the range of materials in the Rosetta database, these parameters were estimated by the inverse solution. Table 4 lists the hydraulic parameters predicted by Rosetta, as well as the initial estimates provided for the sand and gravel material used in the inverse solution.

Table 4. Hydraulic Parameters Used in HYDRUS.

Material	Θ_r (-)	Θ_s (-)	α (1/m)	n (-)	K_{sat} (cm/sec)	l (-)
Silty clay loam	0.0885	0.473	0.78	1.52	1.30×10^{-4}	0.5
Loam	0.0650	0.416	0.62	1.58	1.85×10^{-4}	0.5
Sand & gravel [1]	0.0655	0.231	25.8	3.42	8.08×10^{-1}	0.5

1 – Values given are initial estimates used in the inverse solution

For storms #1 and #2, readings at 10 minute intervals for a period of 24 hours (a total of 144 calibration points) were used for the inverse solution calculations. Twenty-four hours allowed for the full precipitation time, for ponding to completely disappear, and for the groundwater mound to reach the maximum value and begin to recede. For storm #3, a period of 36 hours was used. The groundwater elevation data from MW4 was smoothed using a moving average with the window set to three. The inverse solution was set to run for a maximum of 10 iterations. Pore connectivity (*l*) was held constant at 0.5. No constraints were placed on any other parameters.

Model Calibration

The thickness of the sediment layer at the basin floor was determined using data from storm #1. The thickness was varied until the total flux through the infiltration basin floor matched the observed flux. Observed fluxes were calculated by summing the total ponded depth, the total precipitation before ponding, and an estimate of infiltration during ponding before the maximum ponding depth was reached. This calibration process resulted in a sediment thickness of 10.5 cm (4.13 in).

Once the sediment thickness was set, the hydraulic properties of the sand and gravel material were determined. To do this, the model was calibrated against observed pressure heads from the center monitoring well (MW4). The initial hydraulic parameters for the sand and gravel material (Table 4) used for the inverse solution were first chosen based on literature values. They were then refined by running direct solutions with storm #1 data, until the general shape of the water table response was fitted. The hydraulic parameters for the sand and gravel material were then further refined by the inverse method within HYDRUS.

Using the inverse solution, modeled pressure heads at the center of the basin were in close agreement with measured values for storm #1 (RMSE = 0.021 m; Figure 19), storm #2 (RMSE = 0.016 m; Figure 20), and storm #3 (RMSE = 0.026 m; Figure 21). The magnitude and timing of maximum mound rise was predicted well for all three storms (Table 5), with ≤ 1.3% difference between observed and modeled mound heights. Maximum mound heights occurred between 9.5 and 12.0 hours after the initial water table rise. The assumption of a constant head boundary condition 100 meters away from the basin center was shown to not influence mound height; an observation well located approximately two meters from the boundary did not show an increase in head.

The modeled initial water table rise was between 20 - 40 minutes later than observed for all three storms. This discrepancy may be attributed to preferential flowpaths in the field, either natural or created during well installation.

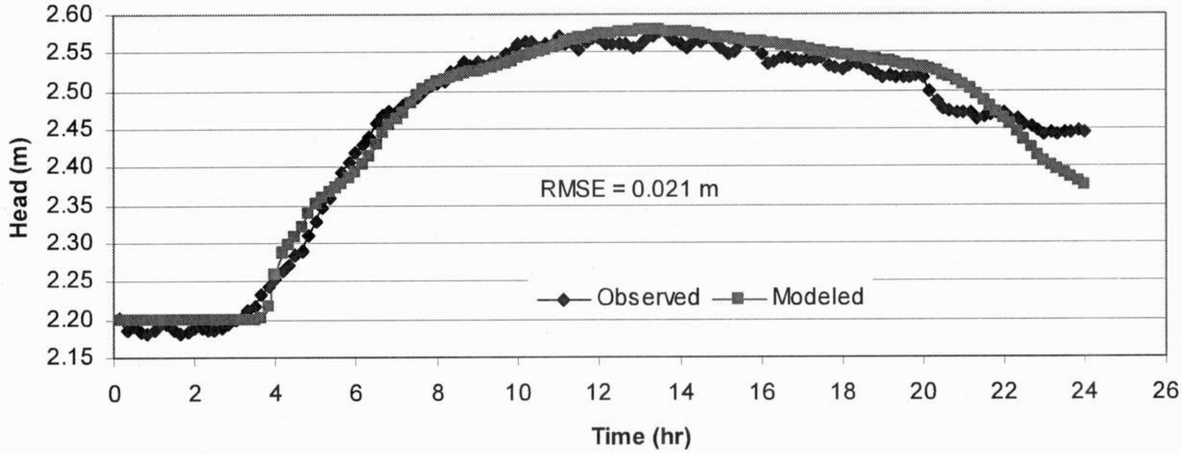

Figure 19. Observed & Modeled (Inverse Solution) Pressure Heads at Basin Center - Storm #1.

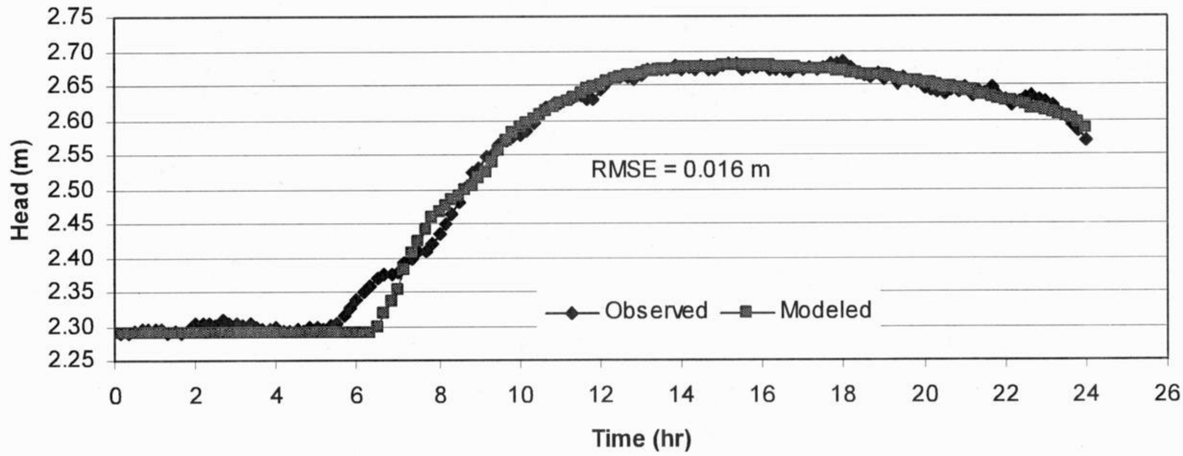

Figure 20. Observed & Modeled (Inverse Solution) Pressure Heads at Basin Center - Storm #2.

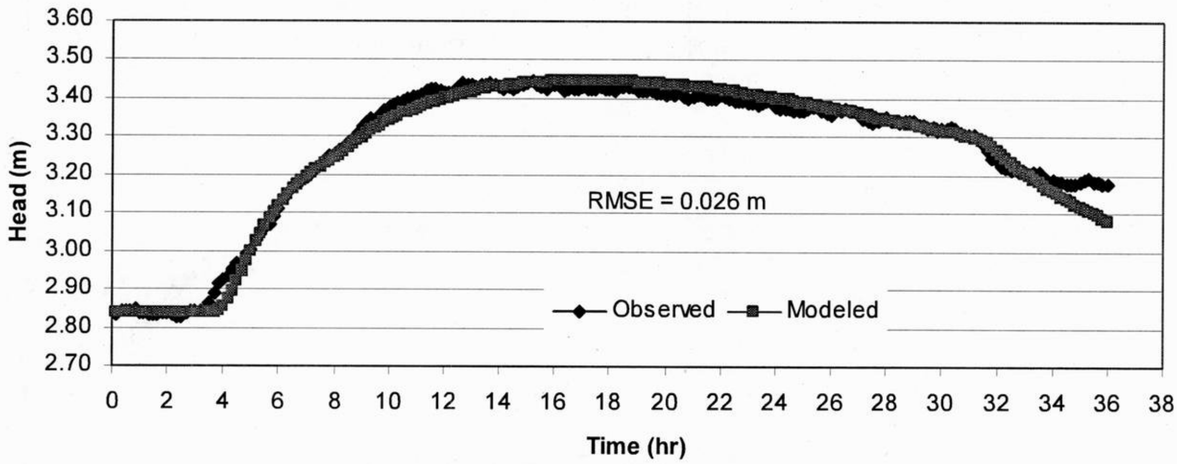

Figure 21. Observed & Modeled (Inverse Solution) Pressure Heads at Basin Center - Storm #3.

The modeled total water flux (infiltration depth) through the infiltration basin floor matched well with the observed flux for storm #1 (Table 5). The sediment thickness was calibrated using storm #1 data prior to running the inverse solution, so total fluxes from the inverse solution were expected to produce a close fit. With the calibrated sediment thickness of 10.5 cm (4.13 in), the maximum modeled infiltration rate for storm #1 was 4.19 cm/hr, and then decreased over a period of 18 hours as the ponding depth decreased. The modeled total flux through the infiltration basin floor was 11 and 26% higher than observed for storms #2 and #3, respectively. These discrepancies might be explained in part by error in estimating the actual fluxes occurring in the field. The duration between the first recorded ponding and maximum ponding was four and 11.5 times longer for storms #2 and #3, respectively, compared to storm #1. Ponding for storm #3 also lasted for approximately 10 hours longer than for storm #1 and had two peak ponding depths with a recession between. These conditions present more opportunity for error in estimating total flux into the system.

Table 5. Water Table Response, Infiltration Volume, and Model Mass Balance Error.

	Storm #1 08/24/06			Storm #2 10/04/06			Storm #3 04/03/07		
	Obs	Model	% Diff	Obs	Model	% Diff	Obs	Model	% Diff
Initial Groundwater Rise (min)	190	220	15.7	340	380	11.7	210	230	9.5
Max. Groundwater Rise (min)	810	800	-1.2	910	900	-1.1	910	910 - 1030	0.0 – 13.2
Max. Mound Height (m)	0.377	0.380	0.8	0.392	0.388	-1.0	0.605	0.597	-1.3
Total Infiltration Depth (m^3/m^2)	0.450	0.443	-1.6	0.484	0.538	11.1	0.710	0.897	26.3
Final Mass Balance Error (%)	-	0.13	-	-	0.34	-	-	0.046	-

Model Validation

The hydraulic parameters of the sand and gravel material fitted by the inverse solution are within the ranges reported in literature (Table 6). To validate model performance, the fitted hydraulic parameters for storm #1 were used to predict mound characteristics for storm #2, and visa versa. The modeled pressure heads were in close agreement with measured values for storm #1 (RMSE = 0.031 m; Figure 22) and storm #2 (RMSE = 0.026 m; Figure 23). The timing and magnitude of mound rise matched reasonably well with observed values (Table 7).

Table 6. Fitted Hydraulic Parameters (with Inverse Solution) for Storms 1-3.

	Θ_r (v/v)	Θ_s (v/v)	α (1/m)	n (unitless)	K_s (cm/sec)
Literature[1,2]	0.01 – 0.10	0.2 – 0.4	4 - 40	1 - 10	1.0×10^{-3} - 3.3
Initial	0.066	0.232	25.8	3.42	0.81
#1: 08/24/06	0.011	0.243	20.2	5.71	1.13
#2: 10/04/06	0.057	0.277	10.9	7.36	1.35
#3: 04/03/07	0.089	0.286	23.2	5.30	0.82

1 – van Genuchten Parameters from Rosetta Lite DDL Database.
2 – Hydraulic Conductivity Values from *Fundamentals of Groundwater* (Schwartz & Zhang, 2003).

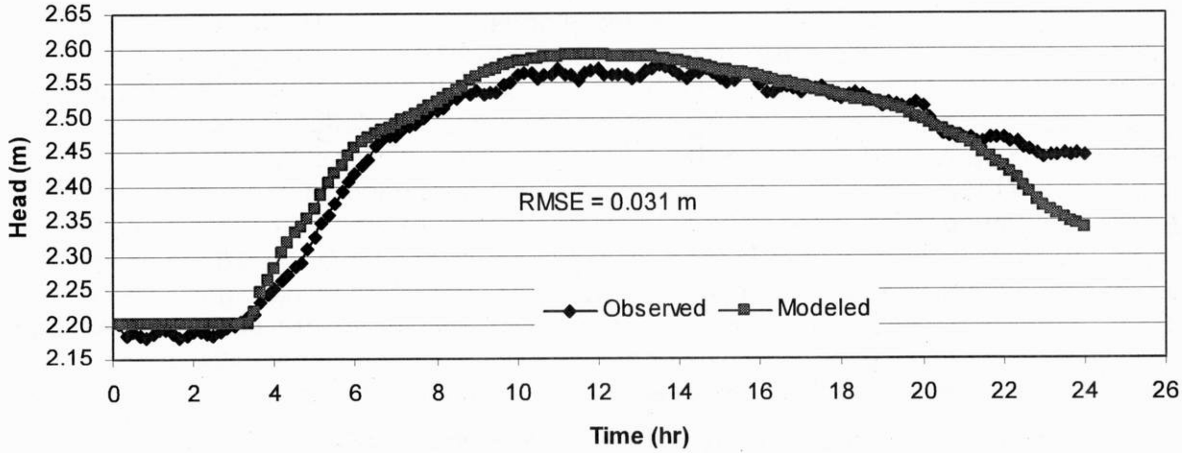

Figure 22. Water Table for Storm #1 Modeled Using Storm #2 Hydraulic Properties.

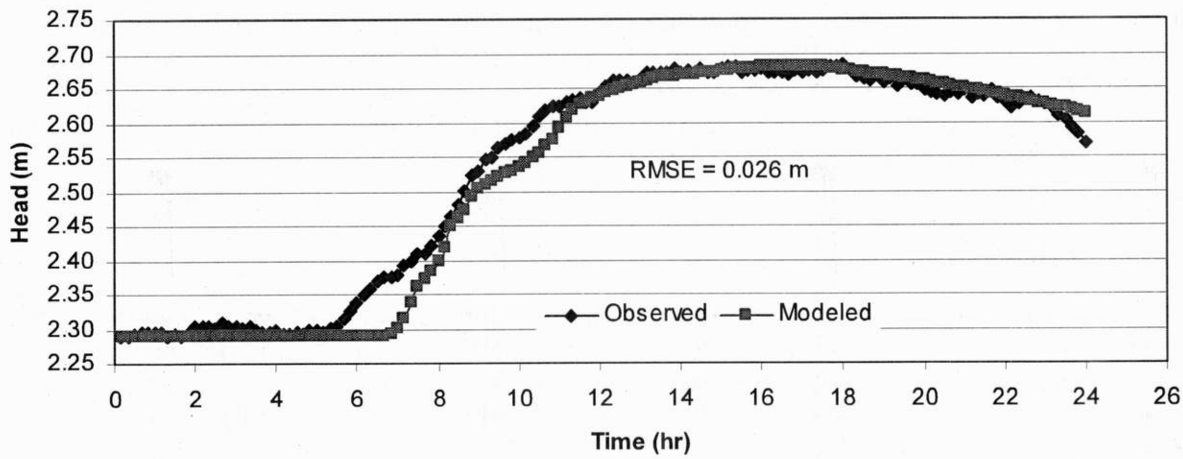

Figure 23. Water Table for Storm #2 Modeled Using Storm #1 Hydraulic Properties.

Table 7. Water Table Response, Infiltration Volume, and Model Mass Balance Error for Storm #1 & #2 with Hydraulic Parameters Interchanged.

	Storm #1 w/ Storm #2 Parameters			Storm #2 w/ Storm #1 Parameters		
	Obs	Model	% Diff	Obs	Model	% Diff
Initial Groundwater Rise (min)	190	210	10.5	340	410	20.5
Max. Groundwater Rise (min)	810	730	-9.8	910	970	6.6
Max. Mound Height (m)	0.377	0.389	3.2	0.392	0.391	-0.3
Total Infiltration Depth (m^3/m^2)	0.450	0.479	6.4	0.472	0.472	0.0
Final Mass Balance Error (%)	-	0.23	-	-	0.24	-

The hydraulic parameters of the sand and gravel material fitted by the inverse solution for storm #3 did not produce a good fit when used to model storms #1 and #2. The maximum predicted mound heights for storms #1 and #2 were approximately 20% higher when the hydraulic parameters from storm #3 were used. The hydraulic conductivity for storm #3 is lower than for the other storms, which would lead to higher mound heights. In an effort to obtain a better fit, an inverse solution was run for storm #3 with the hydraulic conductivity held constant at the fitted value for storm #1 (1.13 cm/sec). The resulting fitted hydraulic parameters for storm #3 again over-predicted mound height when used in storm #1. Differences in field conditions between storm #3 and the first two storms include the background water table being 0.64 m and 0.55 m higher than for storms #1 and #2, respectively, and the soil moisture being slightly higher. Both conditions reduce vadose zone effects on mound height by minimizing travel time and storage capacity, which lead to a higher groundwater mound. However, the higher initial saturated thickness during this storm would serve to reduce groundwater mounding.

The modeled and observed heads begin to diverge following the initial mound recession (Figures 19 – 21). The model predicts the mound to recede faster than the observed heads. This is likely caused by regional aquifer effects, and not a condition of mound hydraulics under the basin. Geology in the region surrounding the basin varies quite widely, with areas of silty clay loam present in addition to the sand and gravel observed under the basin (Clayton, 2001; NRCS, 2007). The finer grained material was evident as close as monitoring wells MW2 and MW9, where silty clay loam extended from the surface to 4.57 meters (15 feet) below grade. If this material also existed downgradient of the basin, it would restrict drainage of the groundwater mound, causing the water table to remain elevated for a longer period of time.

Sensitivity Analysis

The fitted hydraulic parameters, head, and precipitation data for storm #1 were used to perform a sensitivity analysis. Of the hydraulic properties estimated for the sand and gravel material, mound height was most influenced by hydraulic conductivity; mound heights decreased as hydraulic conductivity increased (Figure 24). Mound heights increased rapidly below a hydraulic conductivity of approximately 1.5 cm/s.

The predicted hydraulic conductivity of the sand and gravel material is approximately one order of magnitude greater than the average values determined by slug tests. It is possible that the saturated hydraulic conductivity in the vadose zone is higher than the saturated hydraulic conductivity in the saturated zone due to fines being washed from the vadose zone during infiltration events. The differences between observed and modeled hydraulic conductivity are also within the two orders of magnitude variation for a given soil type reported by Freeze and Cherry (1979). Increasing anisotropy (the ratio of horizontal to vertical hydraulic conductivity) decreased mound height (Figure 25), particularly for anisotropy less than 10. Increasing horizontal hydraulic conductivity beyond this ratio had little effect; mound height decreased from 0.072 m to 0.013 m as anisotropy increased from 10 to 100.

After hydraulic conductivity, mound height was most sensitive to saturated thickness. Mound height decreased as the initial saturated thickness increased (Figure 26). A thicker aquifer provides for a larger flow area available to transport water away from under the basin. Increasing the unsaturated zone thickness had less of an impact on mound height (Figure 27). As the unsaturated zone thickness increased, the larger storage capacity reduced the mound height, and also delayed mound formation. The relatively small difference in mound height with change in thickness is likely a result of the high conductivity of the sand and gravel material.

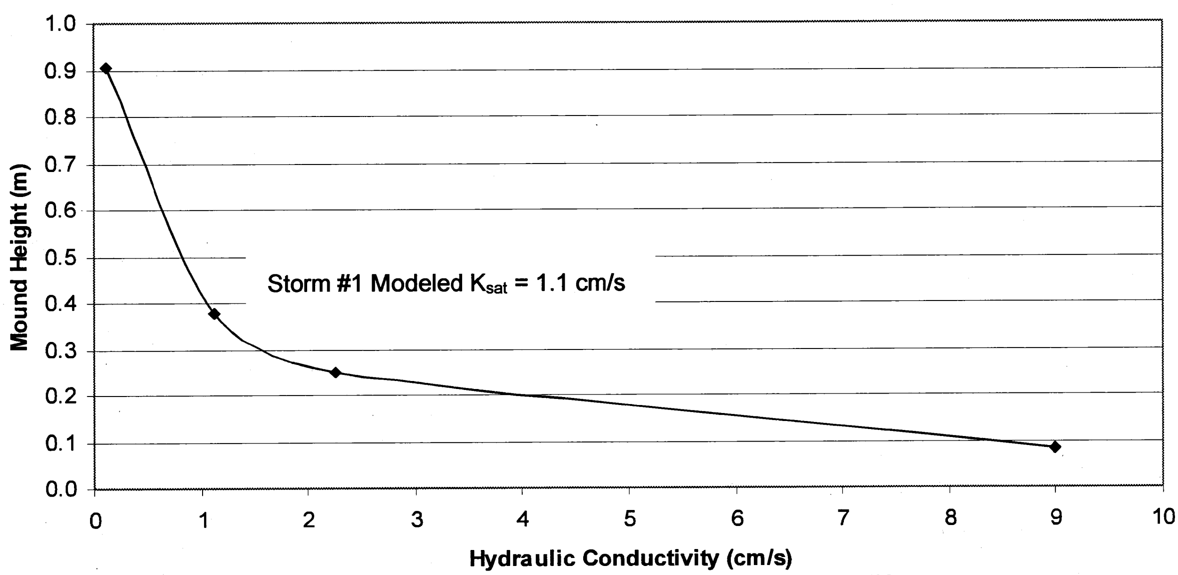

Figure 24. Effects of Hydraulic Conductivity on Mound Height - Storm #1.

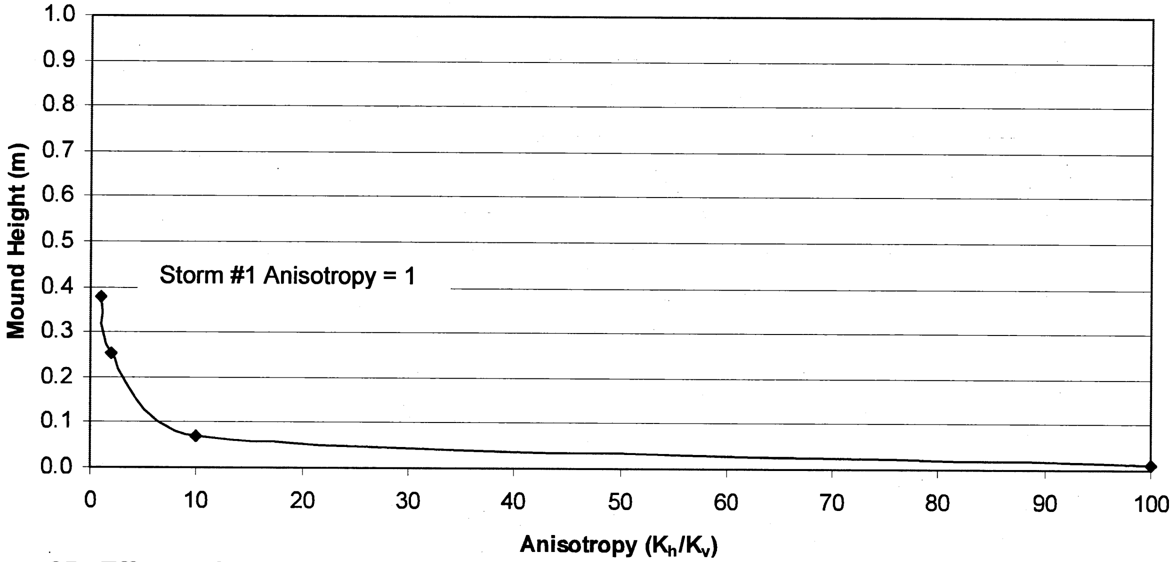

Figure 25. Effects of Anisotropy on Mound Height - Storm #1.

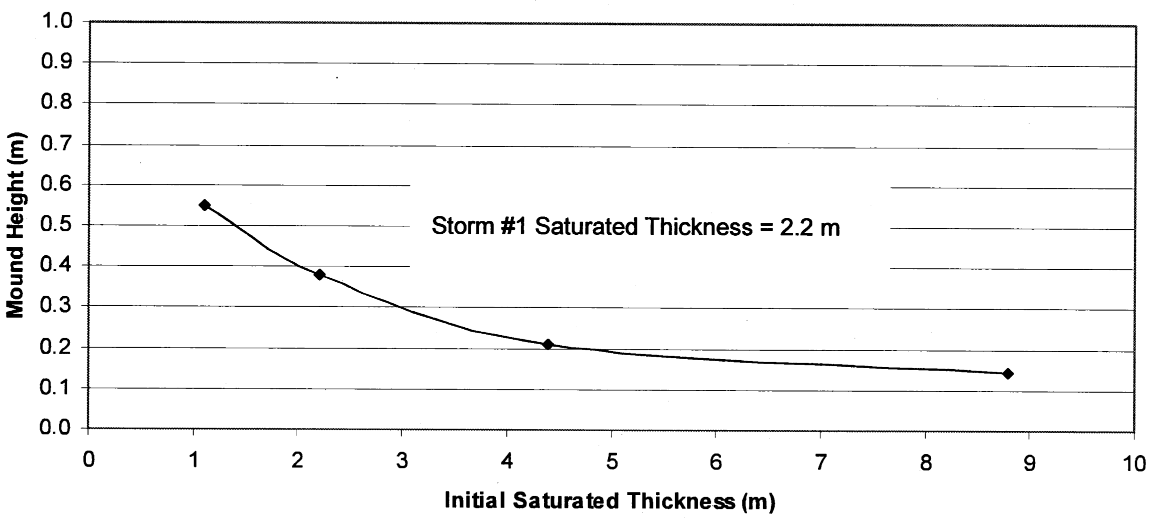

Figure 26. Effects of Initial Saturated Thickness on Mound Height - Storm #1.

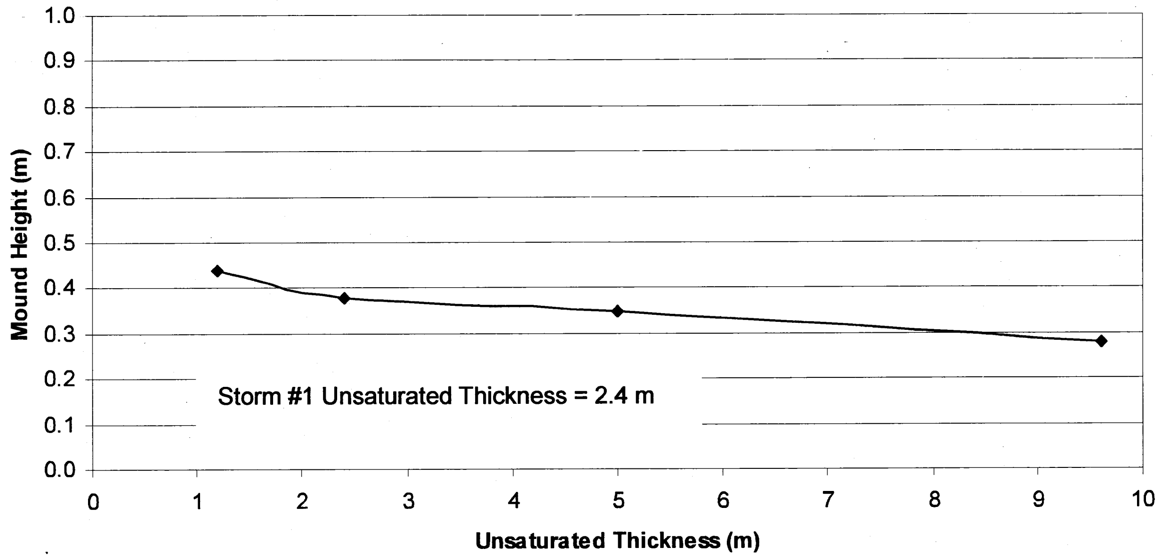

Figure 27. Effects of Unsaturated Thickness on Mound Height - Storm #1.

The initial conditions (matric potential) of the unsaturated zone had little effect on mound height (Figure 28). This is likely due to the very flat soil-moisture curve of the largely gravel and cobble material (Figure 29). Finally, the thickness of the sediment layer on the infiltration basin floor had a significant effect on the volume of water infiltrated and on the groundwater response. Reducing the sediment layer by 50% (10.5 cm to 5.25 cm) caused the water table to rise to the bottom of the basin floor, increasing from a mound height of 0.38 m to 2.4 m.

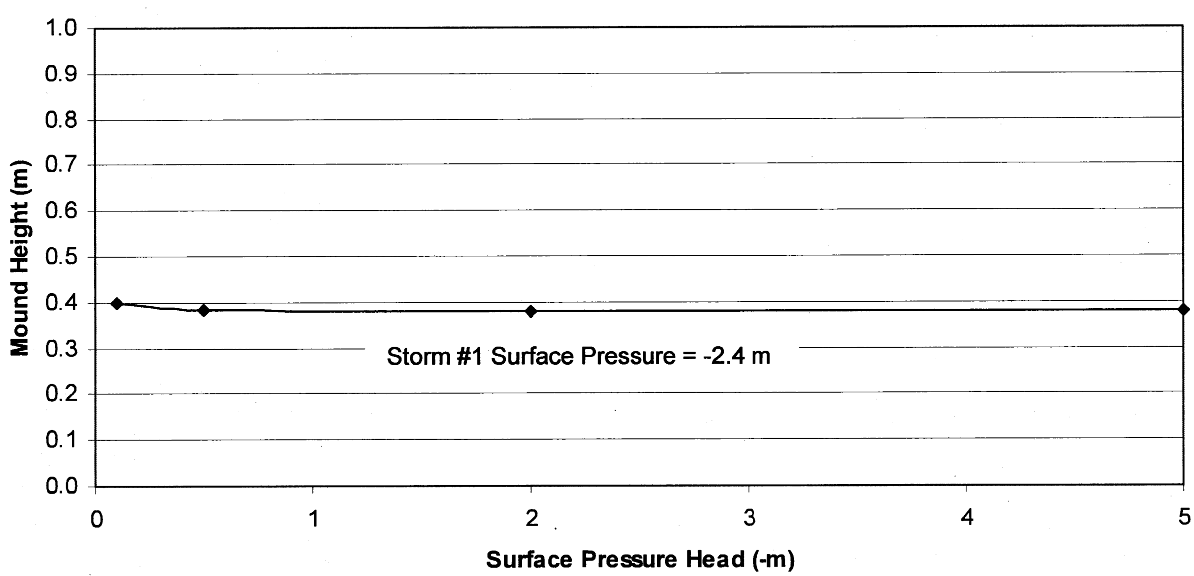

Figure 28. Effects of Matric Potential on Mound Height.

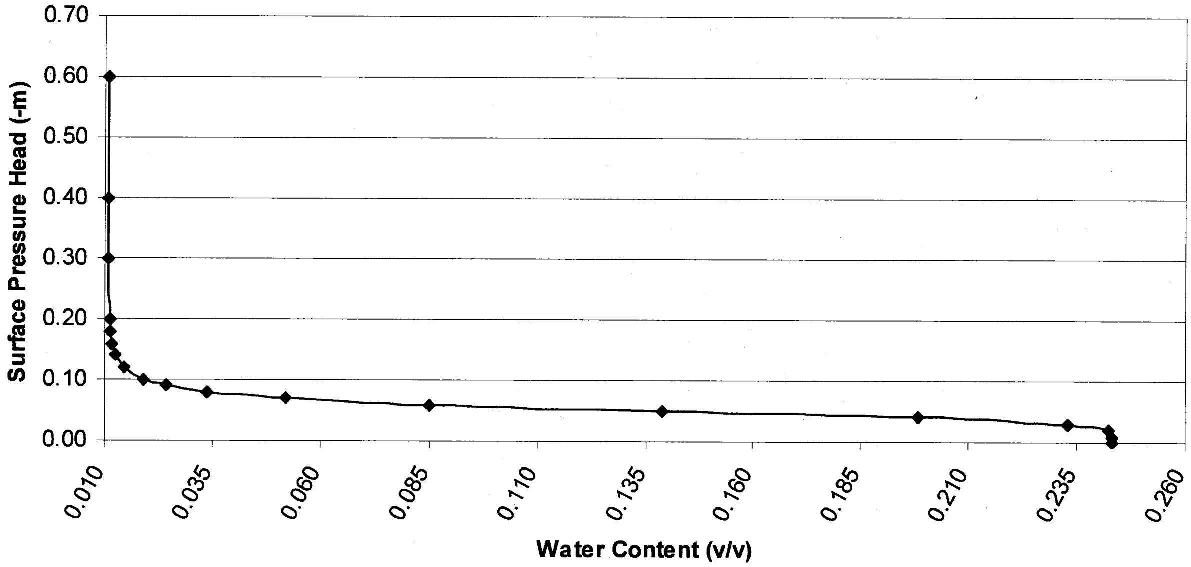

Figure 29. Soil – Water Characteristic Curve for Sand & Gravel.

Model Application

Once calibrated, the model was used to determine the effects of different basin designs, aquifer characterisitcs, and basin loading conditions on mound height (Figure 30). Guidelines for this evaluation were taken from the Wisconsin Department of Natural Resources Standards 1002 (Site Evaluation for Stormwater Infiltration) and 1003 (Infiltration Basin Standard), and in consultation with Mr. Roger Bannerman, WDNR Water Resources Management Specialist (personal communication with Mr. Roger Bannerman, 2007).

Two infiltration basin sizes were modeled. A 45.7 m (150 ft) by 45.7 m basin was chosen as a typical infiltration basin size. A 9.15 m (30 ft) by 9.15 m basin was chosen as a typical rain garden size. Three ponding depths typical of infiltration devices were used: 0.61 m (24 in), 0.305 m (12 in), and 0.15 m (6 in). The 0.61 m (24 in) depth is maximum ponding depth allowed in WDNR Standard 1003. Ponding was modeled with a constant head boundary using the average ponding depth. For example, a ponding depth of 0.305 m was used when the design depth of 0.61 m of ponding was being simulated. Ponding was applied for a duration such that the total flux into the system equaled the design ponding depth. For the example of simulating a ponding depth of 0.61 m, ponding was stopped once the total flux through the basin floor reached 0.61 m^3/m^2.

Two different soil materials, a sandy loam and a loamy sand, were used in the model. These materials are commonly used in the construction of infiltration devices. Infiltration rates given for these soils in WDNR standard 1002 were applied to the model; 1.27 cm/hr (0.5 in/hr) for sandy loam and 4.14 cm/hr (1.63 in/hr) for loamy sand. Saturated and unsaturated zone thicknesses were of 1.52 m (5 ft), 3.05 m (10 ft), and 6.09 m (20 ft) were used for both zones. Finally, two surface sedimentation layer thicknesses (0.0 cm and 7.62 cm (3 in)) were used to simulate the changes in infiltration rates that will likely occur over the life of a basin.

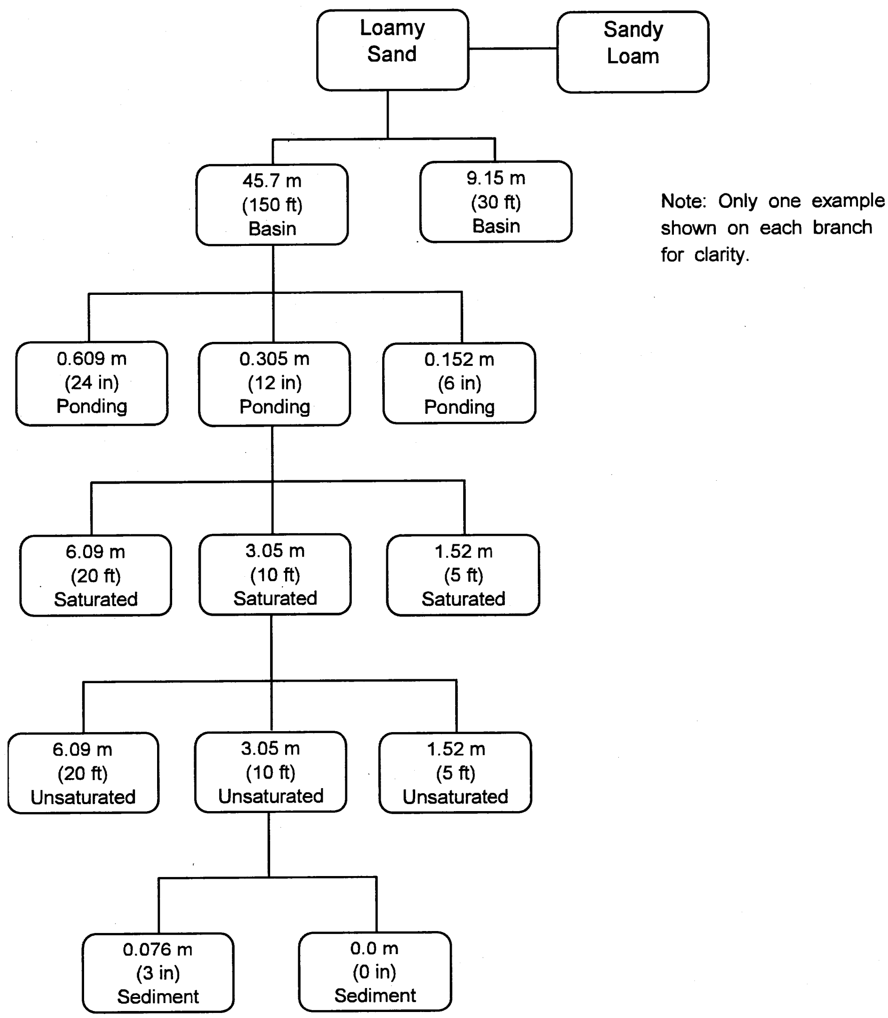

Figure 30. Model Application Parameter Combinations.

Model results from all scenarios in the flowchart in Figure 30 are summarized in Tables 8 and 9. Select results are found in Figures 31 - 36. Unlike the Wood Creek Basin site, these hypothetical model applications with loamy sand and sandy loam were more sensitive to unsaturated than saturated thickness (Figures 31 & 32). These materials have a higher specific yield and lower infiltration rate than the material at the Wood Creek site. These factors serve to attenuate the infiltrating stormwater front. This slower release of water from the unsaturated zone over a longer time period decreases mound height.

Mound height was affected by both basin size and ponding depth. Mound heights increased as both basin size and ponding depth increased (Figure 33). Increasing basin size by a factor of five (9.15 m to 45.7 m) increased mound heights by a factor of 2.6, 3.5, and 2.6 for ponding depths of 0.15 m, 0.305 m, and 0.61 m respectively.

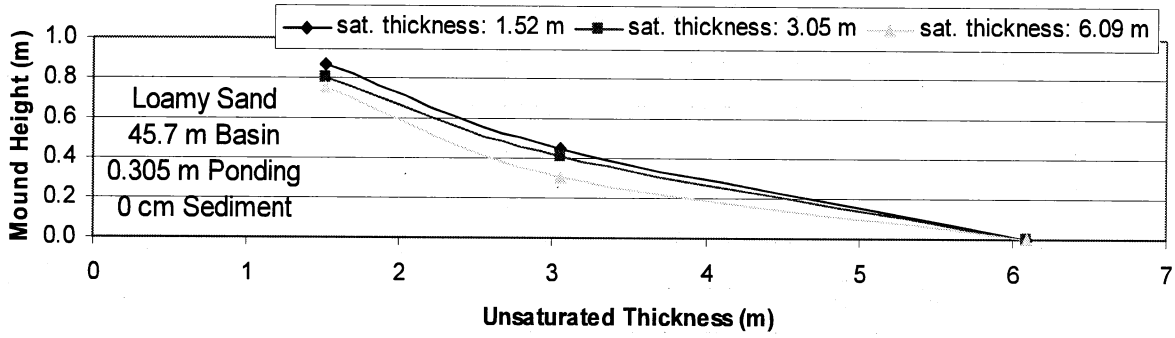

Figure 31. Model Application - Effects of Unsaturated Thickness on Mound Height.

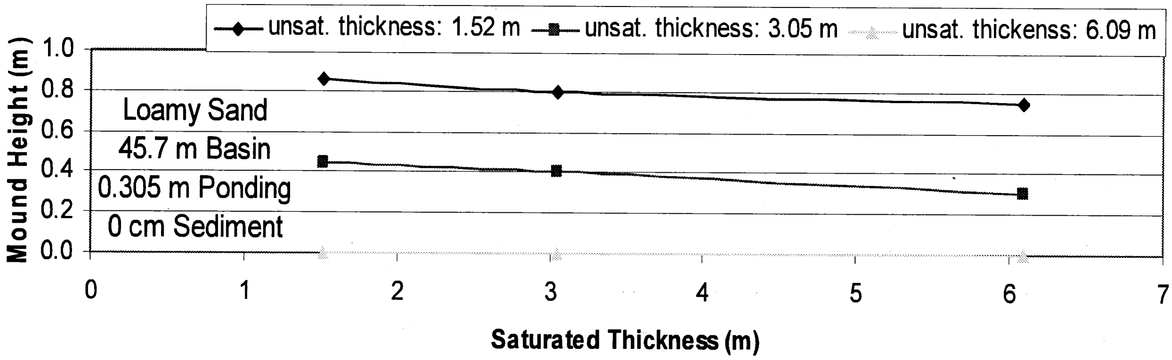

Figure 32. Model Application - Effects of Saturated Thickness on Mound Height.

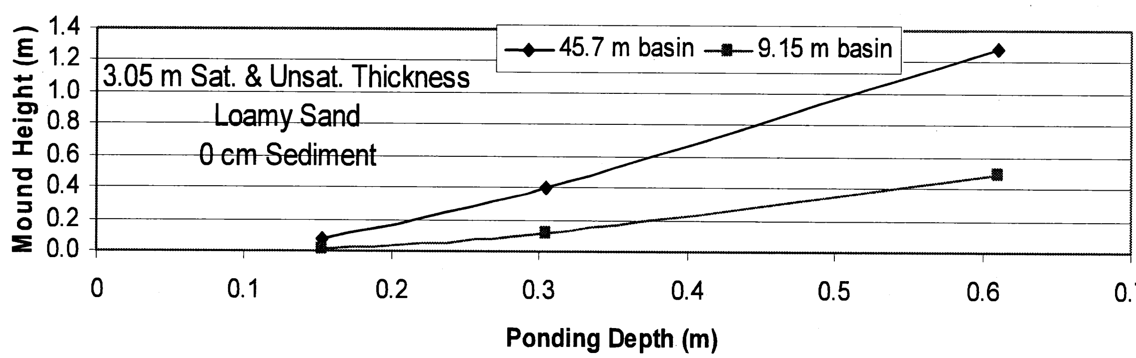

Figure 33. Model Application - Effects of Ponding Depth on Mound Height.

Mound heights were largely unaffected by a 7.62 cm (3 in) sediment layer applied to the basin floor (Figure 34). This is in stark contrast to the Wood Creek basin, where a small change in sediment thickness significantly affected mound heights. This discrepancy is likely due to the differences in saturated hydraulic conductivity used in the sediment layer and underlying soil for the different scenarios. While the same sediment material (loam) was used for all models (0.5 cm/hr), the underlying soil at the Wood Creek site had a much higher saturated hydraulic conductivity (360 cm/hr) compared to the loamy sand (4.1 cm/hr).

The sediment layer did, however, affect the timing to maximum mound height. For the site conditions corresponding to Figure 34, the maximum mound occurred 600 hours after ponding was initiated without the sediment layer, compared to 678 hours with the sediment layer. Figure 34 also shows that the differences in mound height with and without a sediment layer increase as ponding depth decreases. The effects of the lower conductivity sediment layer are more apparent as the gradient across the layer (driven by ponding depth) decreases.

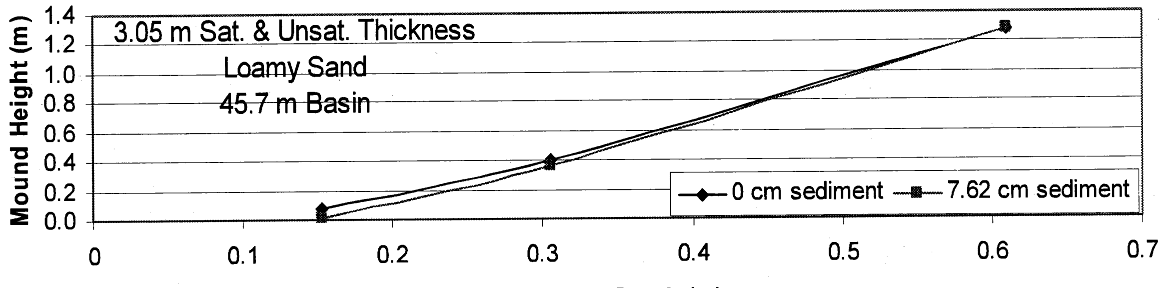

Figure 34. Model Application - Effects of Sediment Thickness on Mound Height.

The effects of anisotropy and the initial conditions were also evaluated for the scenario with a 45.7 m (150 ft) basin with loamy sand and 0.305 m (12 in) of ponding with no sediment. As seen with the Wood Creek basin, mound height decreases as anisotropy increases (Figure 35). The effects of anisotropy again are more apparent with a horizontal to vertical hydraulic conductivity ratio of 10:1 and below.

The initial soil moisture conditions of the loamy sand had an impact on mound height (Figure 36). Mound heights decreased with an increase in surface pressure head, or matric potential. Increases in matric potential correspond to decreases in soil moisture content. At low initial water contents the soil has a greater capacity to store infiltrating water. As previously discussed, attenuating the wetting front decreases mound height.

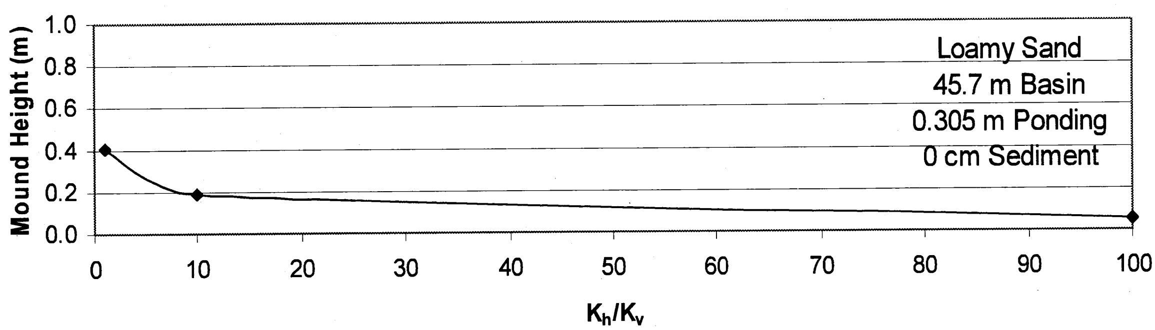

Figure 35. Model Application - Effects of Anisotropy on Mound Height.

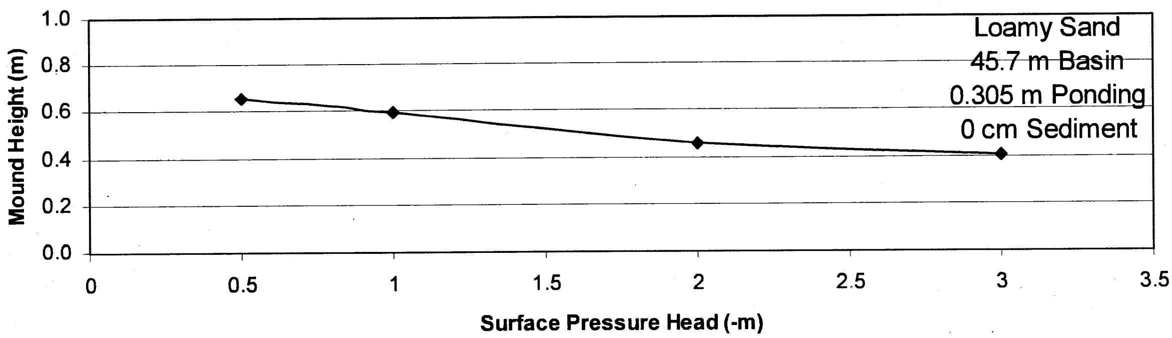

Figure 36. Model Application - Effects of Matric Potential on Mound Height.

Table 8. Model Application Results for Loamy Sand.

Loamy Sand	Max. Mound Height (m) Ponding Depth (m) 0.6097	0.3048	0.1524
Basin Size: 45.7 m x 45.7 m			
Sediment: 0 cm			
Sat. Thickness: 6.09 m			
Unsat. Thickness: 6.09 m	0.375	0	0
Unsat. Thickness: 3.05 m	1.075	0.303	0.028
Unsat. Thickness: 1.52 m	1.80 (f)	0.75	0.216
Sat. Thickness: 3.05 m			
Unsat. Thickness: 6.09 m	0.509	0	0
Unsat. Thickness: 3.05 m	1.28	0.405	0.079
Unsat. Thickness: 1.52 m	1.83 (f)	0.797	0.25
Sat. Thickness: 1.52 m			
Unsat. Thickness: 6.09 m	0.622	0	0
Unsat. Thickness: 3.05 m	1.35	0.446	0.113
Unsat. Thickness: 1.52 m	1.83 (f)	0.862	0.291
Sediment: 7.62 cm			
Sat. Thickness: 6.09 m			
Unsat. Thickness: 6.09 m	0.379	0	0
Unsat. Thickness: 3.05 m	1.1	0.282	0.029
Unsat. Thickness: 1.52 m	1.80 (f)	0.702	0.213
Sat. Thickness: 3.05 m			
Unsat. Thickness: 6.09 m	0.476	0	0
Unsat. Thickness: 3.05 m	1.28	0.364	0.01
Unsat. Thickness: 1.52 m	1.83 (f)	0.792	0.26
Sat. Thickness: 1.52 m			
Unsat. Thickness: 6.09 m	0.601	0	0
Unsat. Thickness: 3.05 m	1.37	0.425	0.062
Unsat. Thickness: 1.52 m	1.83 (f)	0.852	0.303
Basin Size: 9.15 m x 9.15 m			
Sediment: 0 cm			
Sat. Thickness: 6.09 m			
Unsat. Thickness: 6.09 m	0.072	0	0
Unsat. Thickness: 3.05 m	0.334	0.071	0.002
Unsat. Thickness: 1.52 m	1.03	0.276	0.068
Sat. Thickness: 3.05 m			
Unsat. Thickness: 6.09 m	0.098	0	0
Unsat. Thickness: 3.05 m	0.487	0.117	0.01
Unsat. Thickness: 1.52 m	1.44 (f)	0.391	0.097
Sat. Thickness: 1.52 m			
Unsat. Thickness: 6.09 m	0.156	0	0
Unsat. Thickness: 3.05 m	0.603	0.149	0.008
Unsat. Thickness: 1.52 m	1.55 (f)	0.492	0.13
Sediment: 7.62 cm			
Sat. Thickness: 6.09 m			
Unsat. Thickness: 6.09 m	0.075	0	0
Unsat. Thickness: 3.05 m	0.336	0.07	0.002
Unsat. Thickness: 1.52 m	0.976	0.27	0.06
Sat. Thickness: 3.05 m			
Unsat. Thickness: 6.09 m	0.10	0	0
Unsat. Thickness: 3.05 m	0.518	0.111	0.003
Unsat. Thickness: 1.52 m	1.37	0.395	0.091
Sat. Thickness: 1.52 m			
Unsat. Thickness: 6.09 m	0.161	0	0
Unsat. Thickness: 3.05 m	0.63	0.144	0.022
Unsat. Thickness: 1.52 m	1.63 (f)	0.497	0.13

Notes:
(f) = entire vadose zone flooded
+ = simulation ended w/ max not reached

Table 9. Model Application Results for Sandy Loam.

Sandy Loam	Max. Mound Height (m) Ponding Depth (m) 0.6097	0.3048	0.1524
Basin Size: 45.7 m x 45.7 m			
Sediment: 0 cm			
Sat. Thickness: 6.09 m			
Unsat. Thickness: 6.09 m	0	0	0
Unsat. Thickness: 3.05 m	1.32	0.29	0
Unsat. Thickness: 1.52 m	1.81 (f)	1.00	0.34
Sat. Thickness: 3.05 m			
Unsat. Thickness: 6.09 m	0	0	0
Unsat. Thickness: 3.05 m	1.51 +	0.36+	0
Unsat. Thickness: 1.52 m	1.82 (f)	1.04	0.39
Sat. Thickness: 1.52 m			
Unsat. Thickness: 6.09 m	0	0	0
Unsat. Thickness: 3.05 m	1.63	0.41+	0
Unsat. Thickness: 1.52 m	1.83 (f)	1.08	0.43
Sediment: 7.62 cm			
Sat. Thickness: 6.09 m			
Unsat. Thickness: 6.09 m	0	0	0
Unsat. Thickness: 3.05 m	1.37	0.31+	0
Unsat. Thickness: 1.52 m	1.81 (f)	1.00	0.32
Sat. Thickness: 3.05 m			
Unsat. Thickness: 6.09 m	0	0	0
Unsat. Thickness: 3.05 m	1.49	0.41+	0
Unsat. Thickness: 1.52 m	1.83 (f)	1.05	0.37
Sat. Thickness: 1.52 m			
Unsat. Thickness: 6.09 m	0	0	0
Unsat. Thickness: 3.05 m	1.60	0.48+	0
Unsat. Thickness: 1.52 m	1.83 (f)	1.09	0.41+
Basin Size: 9.15 m x 9.15 m			
Sediment: 0 cm			
Sat. Thickness: 6.09 m			
Unsat. Thickness: 6.09 m	0	0	0
Unsat. Thickness: 3.05 m	0.36	0.062+	0
Unsat. Thickness: 1.52 m	1.01	0.38	0.094
Sat. Thickness: 3.05 m			
Unsat. Thickness: 6.09 m	0	0	0
Unsat. Thickness: 3.05 m	0.52	0.12+	0
Unsat. Thickness: 1.52 m	1.42 (f)	0.53	0.13
Sat. Thickness: 1.52 m			
Unsat. Thickness: 6.09 m	0	0	0
Unsat. Thickness: 3.05 m	0.67	0.16+	0
Unsat. Thickness: 1.52 m	1.65 (f)	0.68	0.20
Sediment: 7.62 cm			
Sat. Thickness: 6.09 m			
Unsat. Thickness: 6.09 m	0	0	0
Unsat. Thickness: 3.05 m	0.37	0.069+	0
Unsat. Thickness: 1.52 m	1.0	0.41	0.10
Sat. Thickness: 3.05 m			
Unsat. Thickness: 6.09 m	0	0	0
Unsat. Thickness: 3.05 m	0.56	0.12	0.01
Unsat. Thickness: 1.52 m	1.38	0.56	0.14
Sat. Thickness: 1.52 m			
Unsat. Thickness: 6.09 m	0	0	0
Unsat. Thickness: 3.05 m	0.73	0.15+	0
Unsat. Thickness: 1.52 m	1.63 (f)	0.74	0.19

Notes:
(f) = entire vadose zone flooded
+ = simulation ended w/ max not reached

Tracer Study

Tracer experiments are generally conducted to estimate the degree of hydraulic connection between various locations, to estimate physical transport parameters used in describing solute migration, to determine a solute-matrix interaction parameter, or to calibrate and validate a flow or transport model (Seaman, et al., 2007). Tracers can be used to determine the effects of groundwater mounding on contaminant transport. A tracer applied to a groundwater mound would be expected to move away from the basin at a faster rate than without a mound, due to the increased gradient caused by the mound. Derby (2001) showed that a surface applied potassium chloride tracer moved more rapidly to shallow groundwater under depression areas after infiltration of spring snowmelt and during rainfall events.

A conservative, or non-sorbing tracer is transported advectively in the flow field and spreads by hydrodynamic dispersion, which is a combination of molecular diffusion and mechanical dispersion resulting from differences in pore water velocity and flow path (Seaman et al., 2007). Hydrodynamic dispersion (D), is given by: $D = \alpha_L v + D^*$, where α_L is the longitudinal dispersivity (L); v is the seepage velocity (LT^{-1}); and D^* is the molecular diffusion coefficient (L^2T^{-1}). Since the seepage velocity is proportional to the hydraulic gradient, the gradient directly impacts the hydrodynamic dispersion term in the solute transport equation. A non-conservative, or sorbing tracer moves slower than the conservative tracer, producing a lower breakthrough concentration due to tracer mass being lost in the soil matrix.

One of the initial project objectives was to conduct a tracer study at the selected study infiltration basin. However, due to a combination of uncertainty whether a tracer study would be applicable to site conditions, timing issues with regard to basin selection and monitoring well installation, and relatively few storms that would allow the study to be conducted, a tracer study was not performed at the Wood Creek basin. Once the Wood Creek site was found, a general understanding of basin hydraulics was first gained by observing a few storms. The relatively low mound heights observed and flat gradient under the basin observed during these storm events caused uncertainty as to whether a tracer study would produce meaningful results. A relatively dry spring and early summer of 2007 provided very limited opportunities to conduct the study.

We are currently conducting work that will serve as an alternative to a field tracer study. A literature review is being conducted of case studies involving tracer applications at sites with relatively flat groundwater gradients and with sand and gravel material. Once an appropriate case study is selected, we will model the conditions with a groundwater flow and contaminant fate and transport model (*e.g.*, MT3D). The model will be calibrated using tracer breakthrough data at observation points downgradient of the tracer application. Once calibrated, a groundwater mound will be created by adding focused recharge to the area of tracer injection. The breakthrough curves (time vs. concentration) will be compared to determine the transport effects caused by the mound. The results from this analysis will also assist with evaluating whether enough of a response is expected at the Wood Creek site to warrant a field tracer study. This study is in progress, and results will be reported in an addendum to this report.

Conclusions and Recommendations

The goal of this study was to understand groundwater mounding and the potential for contaminant transport resulting from recharge beneath stormwater infiltration basins. A study was conducted on a 0.10 hectare (0.25 acre) infiltration basin serving a 9.4 hectare (23.2 acre) residential subdivision in Oconomowoc, Wisconsin. Subsurface conditions included sand and gravel material and a groundwater table at 2.3 meters (7.5 ft) below grade. Three storm events between August 2006 and April 2007 produced mounding and were modeled. Precipitation depths were 4.93, 2.84, and 4.28 cm. The storms produced ponding depths of 0.386 m – 0.472 m (15 in – 18.5 in), causing a maximum water table rise under the basin center of 0.384 m – 0.616 m (15 in – 24 in).

The storms were modeled using the two-dimensional, finite element, variably saturated flow and contaminant transport model HYDRUS. 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.

Inverse modeling was performed with HYDRUS to estimate soil and aquifer parameters of the sand and gravel material. Predicted pressure heads at the center of the infiltration basin were in close agreement with measured values for the period encompassing basin ponding and until initial mound recession (RMSE: 0.016 m – 0.026 m). Hydraulic parameters of aquifer material predicted using the inverse solution were within ranges reported in the literature. The magnitude and timing of maximum mound rise was predicted well for all storms. Differences in modeled and observed mound heights were ≤1.3% for all storms. Maximum mound heights occurred 9.5 – 12 hours after the initial water table rise. The modeled initial water table rise was between 20 - 40 minutes later than observed in the field for all three storms. This discrepancy was attributed to preferential flowpaths in the field, either natural or created during well installation. HYDRUS predicted a faster mound recession than observed in the field. This was attributed to fine-grained material outside the basin reducing drainage away from underneath the basin.

Model performance was validated by using fitted hydraulic parameters from storm #1 to predict mound formation in storm #2. Close agreement between modeled and measured values was observed (RMSE: 0.026 m – 0.031 m). Fitted parameters from the inverse solution for storm #3 did not produce a good fit when used to model storms #1 and #2. The maximum predicted mound heights for storms #1 and #2 were approximately 20% higher when the hydraulic parameters from storm #3 were used. This discrepancy is attributed to a higher initial water table and soil moisture content for storm #3 (Spring 2007) compared with the other two storms (Summer & Fall 2006).

A sensitivity analysis of system parameters showed that mound height was most influenced by hydraulic conductivity. Mound heights increased as hydraulic conductivity decreased; mound heights increased rapidly below a hydraulic conductivity of approximately 1.5 cm/s. Increasing anisotropy decreased mound height, particularly for anisotropy less than 10. To a lesser extent, mound height was sensitive to saturated thickness; mound height decreased as the initial saturated thickness increased. Increasing the unsaturated zone thickness had less of an impact on mound height; mound height increased slightly and was delayed as the unsaturated thickness increased. Mound heights were not sensitive to the initial soil moisture content (matric potential) of the sand and gravel material. The thickness of the sediment layer on the infiltration basin floor had a significant effect on the volume of water infiltrated and on the groundwater response. Reducing the sediment layer by 50% (10.5 cm to 5.25 cm) caused the water table to rise to the bottom of the basin floor, increasing the mound height from 0.38 m to 2.4 m.

The calibrated model was then used to evaluate hypothetical basin operation scenarios with parameters found in WDNR post-construction stormwater standards 1002 and 1003. Various basin sizes, ponding depths, soil types, and aquifer dimensions were investigated. The groundwater mound intersected the basin floor in most scenarios with loamy sand and sandy loam soils, combined with an unsaturated thickness of 1.52 meters (5 ft), and a ponding depth of 0.61 meters (2 ft). No groundwater table response was observed with ponding depths of ≤0.305 meters (12 in) with an unsaturated zone thickness of 6.09 meters (20 ft). The mound height was most sensitive to hydraulic conductivity and anisotropy (≤10), followed by unsaturated zone thickness. A 7.62 cm (3 in) sediment layer delayed the time to reach maximum mound height, but had a minimal effect on the magnitude of the mound. Mound heights increased with an increase in infiltration basin size. Mound heights were more sensitive to matric potential than for the study site; mound heights increased as matric potential decreased.

Recommendations for future work include applying a three-dimensional model to the study site and collecting water table response data from a site with more fine-grained material beneath the infiltration basin for additional model calibration and validation. Field application of appropriate tracers will allow assessment of the effect of mound formation on contaminant transport.

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Appendix A

WDNR Forms

Department of Natural Resources

GROUNDWATER MONITORING INVENTORY FORM
Form 3300-67 Rev. 8-95

Wisconsin Unique Well Number: ☒ Add ☐ Change

Inventory Completed By (Last Name, First, MI): NIMMER, MIKE A
Date: 08/29/2007 (m m d d y y y y)
With: ☐ DNR ☐

Facility ID #:
Facility Name: WOOD CREEK BASIN
Local Well ID: MW4
High Cap Well #:

Primary Contact Name (Last, First, MI): STUBEN, STAN, R
Telephone Number: (262) 542-5733
Mailing Address: W233 N2080 RIDGEVIEW PARKWAY
City: WAUKESHA
State: WI
Zip Code: 53188

- ☐ Owner
- ☐ Operator
- ☐ Occupant
- ☐ Consultant
- ☒ Manager
- ☐ Contractor
- ☐ Driller
- ☐ Business
- ☐ Facility
- ☐ Sampler
- ☐ Other

Other Contact Name (Last, First, MI):
Telephone Number: ( )
Mailing Address:
City:
State:
Zip Code:

- ☐ Owner
- ☐ Operator
- ☐ Occupant
- ☐ Consultant
- ☐ Manager
- ☐ Contractor
- ☐ Driller
- ☐ Business
- ☐ Facility
- ☐ Sampler
- ☐ Other

Well Location
☒ Town ☒ City ☐ Village: OCONOMOWOC
Fire # (If avail.):
County: WAUKESHA
Grid or Street Address or Road (If avail.): COUNTY HWY Z, OCONOMOWOC, WI
Govt. Lot #:
OR NE 1/4 of SW 1/4 of Section 27
T 8 N; R 17 ☒ E ☐ W
OR Latitude: Deg. Min. Sec.
Longitude:
Subdivision Name: WOOD CREEK
Lot:
Block:

(X) 1/4 1/4 Sec.
Location
N
W E
X
S
← Mile →

Construction Type
- ☒ Drilled
- ☐ Driven Point
- ☐ Jetted
- ☐ Dug
- ☐ Spring
- ☐ Other

Land Surface Elevation: ______ ft. MSL
Number of Wells on Property: 10

Construction Date: 03/29/2005 (m m d d y y y y)
Constructor: MIDWEST ENGINEERING SERVICES

Well Use
- ☐ Private Potable
- ☐ Priv. Non-Potable
- ☒ Monitoring Well
- ☐ Community-Municipal
- ☐ Community OTM
- ☐ Non Transient Non-Com.
- ☐ Transient Non-Com.

Source of Well Data: ☒ Well Report ☐ Owner/Occupant ☐ Other*

Well Status
- ☒ Active Use
- ☐ Inactive
- ☐ Perm Filled

Depth From Land Surface To:
- Bedrock: – ft.
- Well Bottom: 15.0 ft.
- Static Water: 7.5 ft.
- Casing Bottom: 5.0 ft.

Casing Diameter: 2 in.

Water Bearing Formation
- ☒ Unconsolidated
- ☐ Limestone
- ☐ Sandstone
- ☐ Shale
- ☐ Crystalline

Comments: eg. reason for inventory, samples taken, directions to property, details of well location on property, collected before or after water softener.

*For "Other", enter a description in the comment area if needed.

Department of Natural Resources

GROUNDWATER MONITORING INVENTORY FORM
Form 3300-67 Rev. 8-95

Wisconsin Unique Well Number ☑ Add ☐ Change

Inventory Completed By: (Last Name, First, MI) Nimmer, Mike A
Date 08/29/2007 (m m d d y y y y)
With ☐ DNR ☐

Facility Name Wood Creek Basin
Facility ID #
Local Well ID MW5
High Cap Well #

Primary Contact Name (Last, First, MI) Sugden, Stan, R
Telephone Number (262) 542-5733
Mailing Address W213 N2580 Riverview Parkway
City Waukesha State WI Zip Code 53188

☐ Owner ☐ Driller ☐ Operator ☐ Business ☐ Occupant ☐ Facility ☐ Consultant ☐ Sampler ☑ Manager ☐ Other ☐ Contractor

Other Contact Name (Last, First, MI)
Telephone Number ( )
Mailing Address
City State Zip Code

☐ Owner ☐ Driller ☐ Operator ☐ Business ☐ Occupant ☐ Facility ☐ Consultant ☐ Sampler ☐ Manager ☐ Other ☐ Contractor

Well Location
☑ Town ☒ City ☐ Village Oconomowoc
Fire # (If avail.)
County: Waukesha
Grid or Street Address or Road (If avail.) County Hwy Z, Oconomowoc, WI
Govt. Lot #
OR NE 1/4 of SW 1/4 of Section 27
T 8 ; R 17 ☑ E ☐ W
OR Latitude Deg. Min. Sec.
Longitude
Subdivision Name Wood Creek Lot Block

(X) 1/4 1/4 Sec. Location (N, S, E, W, Mile)

Construction Type
☑ Drilled ☐ Dug
☐ Driven Point ☐ Spring
☐ Jetted ☐ Other

Land Surface Elevation ft. MSL
Number of Wells on Property 10

Construction Date 03/29/2006 (m m d d y y y y)
Constructor Midwest Engineering Services

Well Use
☐ Private Potable ☐ Community-Municipal
☐ Priv. Non-Potable ☐ Community OTM
☑ Monitoring Well ☐ Non Transient Non-Com.
☐ Transient Non-Com.

Source of Well Data
☑ Well Report ☐ Owner/Occupant ☐ Other*

Well Status
☑ Active Use
☐ Inactive
☐ Perm Filled

Depth From Land Surface To:		Casing Diameter	Water Bearing Formation
Bedrock	— ft.	2 in.	☑ Unconsolidated ☐ Sandstone
Well Bottom	15.0 ft.		☐ Limestone ☐ Shale
Static Water	7.5 ft.		☐ Crystalline
Casing Bottom	5.0 ft.		

Comments: eg. reason for inventory, samples taken, directions to property, details of well location on property, collected before or after water softener.

*For "Other", enter a description in the comment area if needed.

Department of Natural Resources

GROUNDWATER MONITORING INVENTORY FORM
Form 3300-67 Rev. 8-95

Wisconsin Unique Well Number: ☒ Add ☐ Change

Inventory Completed By (Last Name, First, MI): Nimmer, Mike A

Date: 08/29/2007 (mm dd yyyy)

With: ☐ DNR ☐

Facility ID #:

Facility Name: Wood Creek Basin

Local Well ID: MW6

High Cap Well #:

Primary Contact Name (Last, First, MI): Sieden, Shan R
Telephone Number: (262) 542-5733
Mailing Address: W233 N2080 Ridgeview Parkway
City: Waukesha State: WI Zip Code: 53188

☐ Owner ☐ Operator ☐ Occupant ☐ Consultant ☒ Manager ☐ Contractor ☐ Driller ☐ Business ☐ Facility ☐ Sampler ☐ Other

Other Contact Name (Last, First, MI):
Telephone Number: ( )
Mailing Address:
City: State: Zip Code:

☐ Owner ☐ Operator ☐ Occupant ☐ Consultant ☐ Manager ☐ Contractor ☐ Driller ☐ Business ☐ Facility ☐ Sampler ☐ Other

Well Location
☒ Town ☒ City ☐ Village: Oconomowoc
Fire # (If avail.):
County: Waukesha
Grid or Street Address or Road (If avail.): County Hwy Z, Oconomowoc, WI
Govt. Lot #:
OR NE 1/4 of SW 1/4 of Section 27
T 8 R 17 ☒ E ☐ W
Subdivision Name: Wood Creek Lot: Block:
OR Latitude Deg. Min. Sec.
Longitude
Land Surface Elevation ______ ft. MSL
Number of Wells on Property: 10

(X) 1/4 1/4 Sec. Location
N
W E
X
S
← Mile →

Construction Type
☒ Drilled ☐ Driven Point ☐ Jetted ☐ Dug ☐ Spring ☐ Other

Construction Date: 03/29/2006 (mm dd yyyy)
Constructor: Midwest Engineering Services

Well Use: ☐ Private Potable ☐ Priv. Non Potable ☒ Monitoring Well ☐ Community-Municipal ☐ Community OTM ☐ Non Transient Non-Com. ☐ Transient Non-Com.

Source of Well Data: ☒ Well Report ☐ Owner/Occupant ☐ Other*

Well Status: ☒ Active Use ☐ Inactive ☐ Perm Filled

Depth From Land Surface To:		Casing Diameter	Water Bearing Formation
Bedrock	— ft.	2 in.	☒ Unconsolidated ☐ Limestone ☐ Sandstone ☐ Shale ☐ Crystalline
Well Bottom	15 ft.		
Static Water	7.5 ft.		
Casing Bottom	5.0 ft.		

Comments: eg. reason for inventory, samples taken, directions to property, details of well location on property, collected before or after water softener.

*For "Other", enter a description in the comment area if needed.

Department of Natural Resources

GROUNDWATER MONITORING INVENTORY FORM
Form 3300-67 Rev. 8-95

Wisconsin Unique Well Number 2 H 9 9 3 ☒ Add ☐ Change

Inventory Completed By (Last Name, First, MI): Nimmer, Mike, A
Date: 08/29/2007 (m m d d y y y y)
With: ☐ DNR ☐

Facility Name: Wood Creek Basin
Facility ID #:
Local Well ID: MW7
High Cap Well #:

Primary Contact Name (Last, First, MI): Sugden, Stan, R
Telephone Number: (262) 542-5733
Mailing Address: W233 N2080 Ridgeview Parkway
City: Waukesha State: WI Zip Code: 53188

☐ Owner ☐ Driller
☐ Operator ☐ Business
☐ Occupant ☐ Facility
☐ Consultant ☐ Sampler
☒ Manager ☐ Other
☐ Contractor

Other Contact Name (Last, First, MI):
Telephone Number: ( )
Mailing Address:
City: State: Zip Code:

☐ Owner ☐ Driller
☐ Operator ☐ Business
☐ Occupant ☐ Facility
☐ Consultant ☐ Sampler
☐ Manager ☐ Other
☐ Contractor

Well Location
☒ Town ☒ City ☐ Village: Oconomowoc
Fire # (If avail.):
County: Waukesha
Grid or Street Address or Road (If avail.): County Hwy Z, Oconomowoc, WI
Govt. Lot #:
OR NE 1/4 of SW 1/4 of Section 27
T 8 ; R 17 ☒ E ☐ W
Subdivision Name: Wood Creek Lot: Block:

(X) 1/4 1/4 Sec. Location
N
W X E
S
← Mile →

Construction Type
☒ Drilled ☐ Dug
☐ Driven Point ☐ Spring
☐ Jetted ☐ Other

OR Latitude Deg. Min. Sec.
Longitude
Land Surface Elevation ______ ft. MSL
Number of Wells on Property: 10

Construction Date: 08/25/2005 (m m d d y y y y)
Constructor: ~~[illegible]~~ Sand/Earth Engineering Services

Well Use
☐ Private Potable ☐ Community-Municipal
☐ Priv. Non-Potable ☐ Community OTM
☒ Monitoring Well ☐ Non Transient Non-Com.
☐ Transient Non-Com.

Source of Well Data
☒ Well Report ☐ Owner/Occupant ☐ Other*

Well Status
☒ Active Use
☐ Inactive
☐ Perm Filled

Depth From Land Surface To:		Casing Diameter	Water Bearing Formation	
Bedrock	— ft.	2 in.	☒ Unconsolidated	☐ Sandstone
Well Bottom	16 ft.		☐ Limestone	☐ Shale
Static Water	10 ft.			☐ Crystalline
Casing Bottom	6 ft.			

Comments: eg. reason for inventory, samples taken, directions to property, details of well location on property, collected before or after water softener.

*For "Other", enter a description in the comment area if needed.

Department of Natural Resources

GROUNDWATER MONITORING INVENTORY FORM
Form 3300-67 Rev. 8-95

Wisconsin Unique Well Number: DJH 9 1 4 1 4 ☒ Add ☐ Change

Inventory Completed By (Last Name, First, MI): Nimmer, Mike A

Date: 08/29/2007 (m m d d y y y y)

With: ☐ DNR ☐ ______

Facility ID # ______

Facility Name: Wood Creek Basin

Local Well ID: MWB

High Cap Well # ______

Primary Contact Name (Last, First, MI): Sugden, Stan R

Telephone Number: (262) 542-5733

Mailing Address: W233 N2080 Ridgeview Parkway

City: Waukesha State: WI Zip Code: 53188

☐ Owner ☐ Driller
☐ Operator ☐ Business
☐ Occupant ☐ Facility
☐ Consultant ☐ Sampler
☒ Manager ☐ Other
☐ Contractor

Other Contact Name (Last, First, MI)

Telephone Number ( )

Mailing Address

City State Zip Code

☐ Owner ☐ Driller
☐ Operator ☐ Business
☐ Occupant ☐ Facility
☐ Consultant ☐ Sampler
☐ Manager ☐ Other
☐ Contractor

Well Location

☒ Town ☐ City ☐ Village: Oconomowoc

Fire # (If avail.)

County: Waukesha

Grid or Street Address or Road (If avail.): County Hwy Z

Govt. Lot # ______

OR NE 1/4 of SW 1/4 of Section 27

T 8 ; R 17 ☒ E ☐ W

OR Latitude Deg. Min. Sec.

Longitude

Subdivision Name: Wood Creek Lot Block

(X) 1/4 1/4 Sec. Location

N

W E

S

← Mile →

Construction Type
☒ Drilled ☐ Dug
☐ Driven Point ☐ Spring
☐ Jetted ☐ Other

Land Surface Elevation ______ ft. MSL

Number of Wells on Property: 10

Construction Date: 09/25/2006 (m m d d y y y y)

Constructor: Sears & Assoc. Engineering Services

Well Use
☐ Private Potable
☐ Priv. Non-Potable
☒ Monitoring Well
☐ Community-Municipal
☐ Community OTM
☐ Non Transient Non-Com.
☐ Transient Non-Com.

Source of Well Data
☐ Well Report ☐ Owner/Occupant ☐ Other*

Well Status
☒ Active Use
☐ Inactive
☐ Perm Filled

Depth From Land Surface To:
Bedrock — ft.
Well Bottom 18 ft.
Static Water 13 ft.
Casing Bottom 8 ft.

Casing Diameter: 2 in.

Water Bearing Formation
☒ Unconsolidated ☐ Sandstone
☐ Limestone ☐ Shale
☐ Crystalline

Comments: eg. reason for inventory, samples taken, directions to property, details of well location on property, collected before or after water softener.

*For "Other", enter a description in the comment area if needed.

Department of Natural Resources

GROUNDWATER MONITORING INVENTORY FORM
Form 3300-67 Rev. 8-95

Wisconsin Unique Well Number JH 192 ☒ Add ☐ Change

Inventory Completed By (Last Name, First, MI): Nammer, Mike, A
Date: 08/29/2007 (m m d d y y y y)
With: ☐ DNR ☐

Facility Name: Wood Creek Basin
Facility ID #:
Local Well ID: MW9
High Cap Well #:

Primary Contact Name (Last, First, MI): Judson, Stan, R
Telephone Number: (262) 542-5733
Mailing Address: W233 N2080 Ridgeview Parkway
City: Waukesha State: WI Zip Code: 53188

☐ Owner ☐ Driller
☐ Operator ☐ Business
☐ Occupant ☐ Facility
☐ Consultant ☐ Sampler
☒ Manager ☐ Other
☐ Contractor

Other Contact Name (Last, First, MI):
Telephone Number: ( )
Mailing Address:
City: State: Zip Code:

☐ Owner ☐ Driller
☐ Operator ☐ Business
☐ Occupant ☐ Facility
☐ Consultant ☐ Sampler
☐ Manager ☐ Other
☐ Contractor

Well Location
☐ Town ☒ City ☐ Village: Oconomowoc
Fire # (If avail.):
County: Waukesha
Grid or Street Address or Road (If avail.): County Hwy Z
Govt. Lot #:
OR NE 1/4 of SW 1/4 of Section 27
T 8 N R 17 ☒ E ☐ W
Subdivision Name: Wood Creek Lot: Block:
OR Latitude Deg. Min. Sec.
Longitude
(X) 1/4 1/4 Sec. Location: N, S, E, W — Mile

Construction Type
☒ Drilled ☐ Dug
☐ Driven Point ☐ Spring
☐ Jetted ☐ Other

Land Surface Elevation ____ ft. MSL
Number of Wells on Property: 10

Construction Date: 09/25/2006 (m m d d y y y y)
Constructor: Soils & Engineering Services

Well Use
☐ Private Potable ☐ Community-Municipal
☐ Priv. Non-Potable ☐ Community OTM
☒ Monitoring Well ☐ Non Transient Non-Com.
☐ Transient Non-Com.

Source of Well Data
☒ Well Report ☐ Owner/Occupant ☐ Other*

Well Status
☒ Active Use
☐ Inactive
☐ Perm Filled

Depth From Land Surface To:		Casing Diameter	Water Bearing Formation	
Bedrock	— ft.	2 in.	☒ Unconsolidated	☐ Sandstone
Well Bottom	16 ft.		☐ Limestone	☐ Shale
Static Water	11.5 ft.			☐ Crystalline
Casing Bottom	6 ft.			

Comments: eg. reason for Inventory, samples taken, directions to property, details of well location on property, collected before or after water softener.

*For "Other", enter a description in the comment area if needed.

Department of Natural Resources

GROUNDWATER MONITORING INVENTORY FORM
Form 3300-67 Rev. 8-95

Wisconsin Unique Well Number [| | | |] ☒ Add ☐ Change

Inventory Completed By (Last Name, First, MI): Nimmer, Mike, A
Date: 01 / 04 / 2007 (m m d d y y y y)
With: ☐ DNR ☐

Facility Name: Wood Creek Basin
Facility ID #:
Local Well ID: MW10
High Cap Well #:

Primary Contact Name (Last, First, MI): Suden, Stan, K.
Telephone Number: (262) 542-5733
Mailing Address: W233 N2080 Ridgeview Parkway
City: Waukesha State: WI Zip Code: 53188

☐ Owner ☐ Driller ☐ Operator ☐ Business ☐ Occupant ☐ Facility ☐ Consultant ☐ Sampler ☒ Manager ☐ Other ☐ Contractor

Other Contact Name (Last, First, MI):
Telephone Number: ( )
Mailing Address:
City: State: Zip Code:

☐ Owner ☐ Driller ☐ Operator ☐ Business ☐ Occupant ☐ Facility ☐ Consultant ☐ Sampler ☐ Manager ☐ Other ☐ Contractor

Well Location
☐ Town ☒ City ☐ Village: Oconomowoc
Fire # (If avail.):
County: Waukesha
Grid or Street Address or Road (If avail.): County Hwy Z
Govt. Lot #:
OR NE 1/4 of SW 1/4 of Section 27
T 8 R 17 ☒ E ☐ W
Subdivision Name: Wood Creek Lot: Block:
OR Latitude Deg. Min. Sec.
Longitude

(X) 1/4 1/4 Sec. Location — N, S, E, W — Mile

Construction Type
☒ Drilled ☐ Driven Point ☐ Jetted ☐ Dug ☐ Spring ☐ Other

Land Surface Elevation ____ ft. MSL
Number of Wells on Property: 10

Construction Date: 01 / 04 / 2007 (m m d d y y y y)
Constructor: Midwest Engineering Services

Well Use:
☐ Private Potable ☐ Priv. Non-Potable ☒ Monitoring Well ☐ Community-Municipal ☐ Community OTM ☐ Non Transient Non-Com. ☐ Transient Non-Com.

Source of Well Data: ☒ Well Report ☐ Owner/Occupant ☐ Other*

Well Status: ☒ Active Use ☐ Inactive ☐ Perm Filled

Depth From Land Surface To:
Bedrock — ft.
Well Bottom 11.5 ft.
Static Water 7.5 ft.
Casing Bottom 8.5 ft.

Casing Diameter: 2 in.

Water Bearing Formation: ☒ Unconsolidated ☐ Limestone ☐ Sandstone ☐ Shale ☐ Crystalline

Comments: eg. reason for inventory, samples taken, directions to property, details of well location on property, collected before or after water softener.

*For "Other", enter a description in the comment area if needed.

State of Wisconsin
Department of Natural Resources

Route to: Watershed/Wastewater ☐ Waste Management ☐ Remediation/Redevelopment ☐ Other ☐

MONITORING WELL CONSTRUCTION
Form 4400-113A Rev. 7-98

Facility/Project Name: Wood Creek Basin	Local Grid Location of Well: ____ ft. ☐N ☐S ____ ft. ☐E ☐W	Well Name: MWA
Facility License, Permit or Monitoring No.	Local Grid Origin ☐ (estimated: ☐) or Well Location ☐ Lat. ____ Long. ____ or	Wis. Unique Well No. / DNR Well ID No.
Facility ID	St. Plane ____ ft. N, ____ ft. E. S/C/N	Date Well Installed: 02/24/2006 (m m d d y y y y)
Type of Well: Well Code 11 / MW	Section Location of Waste/Source: NE 1/4 of SW 1/4 of Sec. 27, T. 6 N, R. 17 ☑E ☐W	Well Installed By: Name (first, last) and Firm: Steve Gonyer, Midwest Groundwater Services
Distance from Waste/Source ____ ft. Enf. Stds. Apply ☐	Location of Well Relative to Waste/Source: u ☐ Upgradient s ☐ Sidegradient d ☐ Downgradient n ☐ Not Known	Gov. Lot Number

A. Protective pipe, top elevation ____ ft. MSL
B. Well casing, top elevation ____ ft. MSL
C. Land surface elevation ____ ft. MSL
D. Surface seal, bottom ____ ft. MSL or ____ ft.

12. USCS classification of soil near screen:
GP ☐ GM ☐ GC ☐ GW ☐ SW ☐ SP ☐
SM ☐ SC ☐ ML ☐ MH ☐ CL ☐ CH ☐
Bedrock ☐

13. Sieve analysis performed? ☐ Yes ☐ No

14. Drilling method used: Rotary ☐ 5 0; Hollow Stem Auger ☐ 4 1; Other ☐

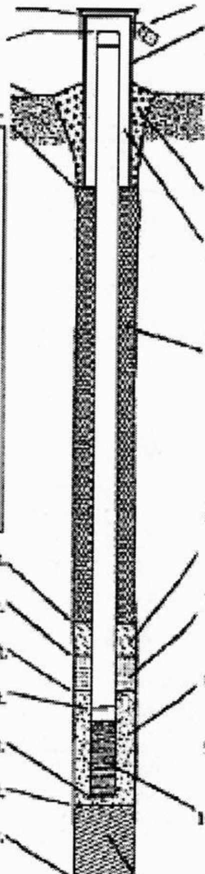
15. Drilling fluid used: Water ☐ 0 2; Air ☐ 0 1; Drilling Mud ☐ 0 3; None ☐ 9 9

16. Drilling additives used? ☐ Yes ☐ No

Describe ____

17. Source of water (attach analysis, if required):

E. Bentonite seal, top ____ ft. MSL or 0.0 ft.
F. Fine sand, top ____ ft. MSL or 4.0 ft.
G. Filter pack, top ____ ft. MSL or 4.0 ft.
H. Screen joint, top ____ ft. MSL or 5.0 ft.
I. Well bottom ____ ft. MSL or 15.0 ft.
J. Filter pack, bottom ____ ft. MSL or 15.0 ft.
K. Borehole, bottom ____ ft. MSL or 15.5 ft.
L. Borehole, diameter 7.125 in.
M. O.D. well casing 2.4 in.
N. I.D. well casing 2.05 in.



1. Cap and lock? ☑ Yes ☐ No
2. Protective cover pipe:
   a. Inside diameter: ____ in.
   b. Length: ____ ft.
   c. Material: Steel ☐ 0 4; Other ☐
   d. Additional protection? ☐ Yes ☐ No. If yes, describe: ____
3. Surface seal: Bentonite ☑ 3 0; Concrete ☐ 0 1; Other ☐
4. Material between well casing and protective pipe: Bentonite ☐ 3 0; Other ☐
5. Annular space seal: a. Granular/Chipped Bentonite ☑ 3 3
   b. ____ Lbs/gal mud weight . . . Bentonite-sand slurry ☐ 3 5
   c. ____ Lbs/gal mud weight . . . . . Bentonite slurry ☐ 3 1
   d. ____ % Bentonite . . . . . . Bentonite-cement grout ☐ 5 0
   e. ____ Ft^3 volume added for any of the above
   f. How installed: Tremie ☐ 0 1; Tremie pumped ☐ 0 2; Gravity ☑ 0 8
6. Bentonite seal: a. Bentonite granules ☐ 3 3
   b. ☐1/4 in. ☑3/8 in. ☐1/2 in. Bentonite chips ☑ 3 2
   c. 2 bags Other ☐
7. Fine sand material: Manufacturer, product name & mesh size
   a. red flint Coarse 40-60 1 bag
   b. Volume added ____ ft^3
8. Filter pack material: Manufacturer, product name & mesh size
   a. red flint coarse sand 2 bags
   b. Volume added ____ ft^3
9. Well casing: Flush threaded PVC schedule 40 ☑ 2 3; Flush threaded PVC schedule 80 ☐ 2 4; Other ☐
10. Screen material: Sch 40 PVC
    a. Screen type: Factory cut ☑ 1 1; Continuous slot ☐ 0 1; Other ☐
    b. Manufacturer ____
    c. Slot size: 0.010 in.
    d. Slotted length: 10.0 ft.
11. Backfill material (below filter pack): None ☑ 1 4; Other ☐

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature	Firm
[signature]	UW - Madison

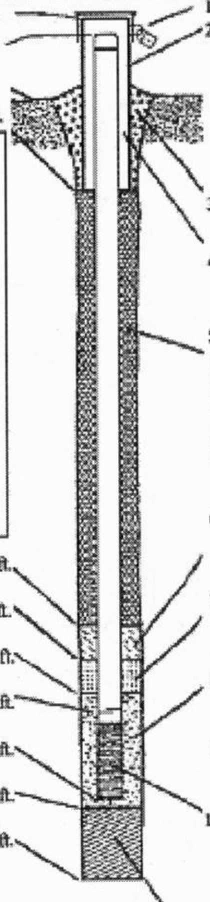
Please complete both Forms 4400-113A and 4400-113B and return them to the appropriate DNR office and bureau. Completion of these reports is required by chs. 160, 281, 283, 289, 291, 292, 293, 295, and 299, Wis. Stats., and ch. NR 141, Wis. Adm. Code. In accordance with chs. 281, 289, 291, 292, 293, 295, and 299, Wis. Stats., failure to file these forms may result in a forfeiture of between $10 and $25,000, or imprisonment for up to one year, depending on the program and conduct involved. Personally identifiable information on these forms is not intended to be used for any other purpose. NOTE: See the instructions for more information, including where the completed forms should be sent.

State of Wisconsin
Department of Natural Resources

Route to: Watershed/Wastewater ☐ Waste Management ☐ Remediation/Redevelopment ☐ Other ☐

MONITORING WELL CONSTRUCTION
Form 4400-113A Rev. 7-98

Facility/Project Name: Wood Creek Basin	Local Grid Location of Well: ____ ft. ☐N. ☐S. ____ ft. ☐E. ☐W.	Well Name: MW5
Facility License, Permit or Monitoring No.	Local Grid Origin ☐ (estimated: ☐) or Well Location ☐ Lat. ____ Long. ____ or	Wis. Unique Well No. / DNR Well ID No.
Facility ID	St. Plane ____ ft. N, ____ ft. E. S/C/N	Date Well Installed 03/29/2007 (mm dd yyyy)
Type of Well: Well Code 11 / MW	Section Location of Waste/Source: NE 1/4 of SW 1/4 of Sec. 27, T. 7 N, R. 17 ☑E ☐W	Well Installed By: Name (first, last) and Firm: Steve Gonyer, Midwest Engineering Services
Distance from Waste/Source ____ ft. Enf. Stds. Apply ☐	Location of Well Relative to Waste/Source: u ☐ Upgradient s ☐ Sidegradient d ☐ Downgradient n ☐ Not Known	Gov. Lot Number



A. Protective pipe, top elevation ______ ft. MSL
B. Well casing, top elevation ______ ft. MSL
C. Land surface elevation ______ ft. MSL
D. Surface seal, bottom ______ ft. MSL or ____ ft.

12. USCS classification of soil near screen: GP ☐ GM ☐ GC ☐ GW ☐ SW ☐ SP ☐ SM ☐ SC ☐ ML ☐ MH ☐ CL ☐ CH ☐ Bedrock ☐
13. Sieve analysis performed? ☐ Yes ☐ No
14. Drilling method used: Rotary ☐ 5 0; Hollow Stem Auger ☐ 4 1; Other ☐
15. Drilling fluid used: Water ☐ 0 2; Air ☐ 0 1; Drilling Mud ☐ 0 3; None ☐ 9 9
16. Drilling additives used? ☐ Yes ☐ No
Describe ______
17. Source of water (attach analysis, if required):

E. Bentonite seal, top ______ ft. MSL or 0.0 ft.
F. Fine sand, top ______ ft. MSL or 4.0 ft.
G. Filter pack, top ______ ft. MSL or 4.0 ft.
H. Screen joint, top ______ ft. MSL or 5.0 ft.
I. Well bottom ______ ft. MSL or 15.0 ft.
J. Filter pack, bottom ______ ft. MSL or 15.0 ft.
K. Borehole, bottom ______ ft. MSL or 15.5 ft.
L. Borehole, diameter 7.625 in.
M. O.D. well casing 2.4 in.
N. I.D. well casing 2.05 in.

1. Cap and lock? ☑ Yes ☐ No
2. Protective cover pipe:
a. Inside diameter: __ in.
b. Length: __ ft.
c. Material: Steel ☐ 0 4; Other ☐
d. Additional protection? ☐ Yes ☐ No
If yes, describe: ______
3. Surface seal: Bentonite ☑ 3 0; Concrete ☐ 0 1; Other ☐
4. Material between well casing and protective pipe: Bentonite ☐ 3 0; Other ☐
5. Annular space seal: a. Granular/Chipped Bentonite ☑ 3 3
b. ____ Lbs/gal mud weight . . . Bentonite-sand slurry ☐ 3 5
c. ____ Lbs/gal mud weight . . . . . Bentonite slurry ☐ 3 1
d. ____ % Bentonite . . . . . . Bentonite-cement grout ☐ 5 0
e. ____ Ft^3 volume added for any of the above
f. How installed: Tremie ☐ 0 1; Tremie pumped ☐ 0 2; Gravity ☑ 0 8
6. Bentonite seal: a. Bentonite granules ☐ 3 3
b. ☐1/4 in. ☑3/8 in. ☐1/2 in. Bentonite chips ☑ 3 2
c. 2 bags Other ☐
7. Fine sand material: Manufacturer, product name & mesh size
a. Red Flint Coarse 40-60 1bag
b. Volume added ______ ft^3
8. Filter pack material: Manufacturer, product name & mesh size
a. Red Flint Coarse 2 bags
b. Volume added ______ ft^3
9. Well casing: Flush threaded PVC schedule 40 ☑ 2 3; Flush threaded PVC schedule 80 ☐ 2 4; Other ☐
10. Screen material: Sch 40 PVC
a. Screen type: Factory cut ☑ 1 1; Continuous slot ☐ 0 1; Other ☐
b. Manufacturer ______
c. Slot size: 0.010 in.
d. Slotted length: 10.0 ft.
11. Backfill material (below filter pack): None ☑ 1 4; Other ☐

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature: [signature] Firm: UW-Madison

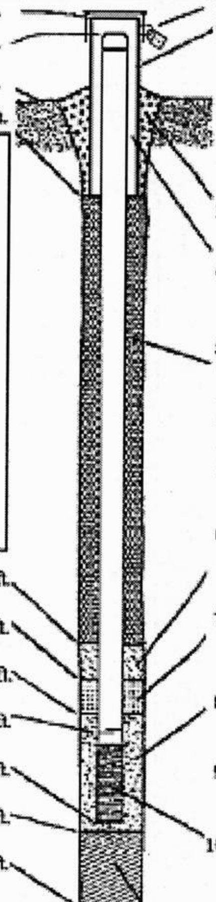
Please complete both Forms 4400-113A and 4400-113B and return them to the appropriate DNR office and bureau. Completion of these reports is required by chs. 160, 281, 283, 289, 291, 292, 293, 295, and 299, Wis. Stats., and ch. NR 141, Wis. Adm. Code. In accordance with chs. 281, 289, 291, 292, 293, 295, and 299, Wis. Stats., failure to file these forms may result in a forfeiture of between \$10 and \$25,000, or imprisonment for up to one year, depending on the program and conduct involved. Personally identifiable information on these forms is not intended to be used for any other purpose. NOTE: See the instructions for more information, including where the completed forms should be sent.

State of Wisconsin
Department of Natural Resources

Route to: Watershed/Wastewater ☐ Waste Management ☐
Remediation/Redevelopment ☐ Other ☐

MONITORING WELL CONSTRUCTION
Form 4400-113A Rev. 7-98

Facility/Project Name: Wood Creek Basin	Local Grid Location of Well: ____ ft. ☐N. ☐S. ____ ft. ☐E. ☐W.	Well Name: MW6
Facility License, Permit or Monitoring No.	Local Grid Origin ☐ (estimated: ☐) or Well Location ☐ Lat. __ ° __ ' __ " Long. __ ° __ ' __ " or	Wis. Unique Well No. / DNR Well ID No.
Facility ID	St. Plane ____ ft. N, ____ ft. E. S/C/N	Date Well Installed: 03/29/2006 (m m d d y y y y)
Type of Well: Well Code U / MW	Section Location of Waste/Source: NE 1/4 of SW 1/4 of Sec. 27, T. 8 N, R. 8 ☐E ☐W	Well Installed By: Name (first, last) and Firm: Steve Gunther, Midwest Engineering Services
Distance from Waste/Source ____ ft. Enf. Stds. Apply ☐	Location of Well Relative to Waste/Source: u ☐ Upgradient s ☐ Sidegradient d ☐ Downgradient n ☐ Not Known	Gov. Lot Number



A. Protective pipe, top elevation _______ ft. MSL
B. Well casing, top elevation _______ ft. MSL
C. Land surface elevation _______ ft. MSL
D. Surface seal, bottom _______ ft. MSL or ____ ft.

12. USCS classification of soil near screen:
GP ☐ GM ☐ GC ☐ GW ☐ SW ☐ SP ☐
SM ☐ SC ☐ ML ☐ MH ☐ CL ☐ CH ☐
Bedrock ☐

13. Sieve analysis performed? ☐ Yes ☐ No

14. Drilling method used: Rotary ☐ 5 0; Hollow Stem Auger ☐ 4 1; Other ☐

15. Drilling fluid used: Water ☐ 0 2; Air ☐ 0 1; Drilling Mud ☐ 0 3; None ☐ 9 9

16. Drilling additives used? ☐ Yes ☐ No

Describe ____________

17. Source of water (attach analysis, if required):

E. Bentonite seal, top _______ ft. MSL or 0.0 ft.
F. Fine sand, top _______ ft. MSL or 4.0 ft.
G. Filter pack, top _______ ft. MSL or 4.0 ft.
H. Screen joint, top _______ ft. MSL or 5.0 ft.
I. Well bottom _______ ft. MSL or 15.0 ft.
J. Filter pack, bottom _______ ft. MSL or 15.5 ft.
K. Borehole, bottom _______ ft. MSL or 15.5 ft.
L. Borehole, diameter 7.625 in.
M. O.D. well casing 2.4 in.
N. I.D. well casing 2.05 in.

1. Cap and lock? ☑ Yes ☐ No
2. Protective cover pipe:
a. Inside diameter: ___ in.
b. Length: ___ ft.
c. Material: Steel ☐ 0 4; Other ☐
d. Additional protection? ☐ Yes ☐ No
If yes, describe: ____________
3. Surface seal: Bentonite ☑ 3 0; Concrete ☐ 0 1; Other ☐
4. Material between well casing and protective pipe: Bentonite ☐ 3 0; Other ☐
5. Annular space seal: a. Granular/Chipped Bentonite ☑ 3 3
b. ____ Lbs/gal mud weight . . . Bentonite-sand slurry ☐ 3 5
c. ____ Lbs/gal mud weight . . . . . Bentonite slurry ☐ 3 1
d. ____ % Bentonite . . . . . . Bentonite-cement grout ☐ 5 0
e. ____ Ft^3 volume added for any of the above
f. How installed: Tremie ☐ 0 1; Tremie pumped ☐ 0 2; Gravity ☑ 0 8
6. Bentonite seal: a. Bentonite granules ☐ 3 3
b. ☐1/4 in. ☑3/8 in. ☐1/2 in. Bentonite chips ☑ 3 2
c. 2 bags Other ☐
7. Fine sand material: Manufacturer, product name & mesh size
a. red flint Grade 40-60 1 bag
b. Volume added ____ ft^3
8. Filter pack material: Manufacturer, product name & mesh size
a. red flint Coarse
b. Volume added 2 bags ft^3
9. Well casing: Flush threaded PVC schedule 40 ☑ 2 3; Flush threaded PVC schedule 80 ☐ 2 4; Other ☐
10. Screen material: Sch 40 PVC
a. Screen type: Factory cut ☑ 1 1; Continuous slot ☐ 0 1; Other ☐
b. Manufacturer ____________
c. Slot size: 0.010 in.
d. Slotted length: 10.0 ft.
11. Backfill material (below filter pack): None ☑ 1 4; Other ☐

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature	Firm
[signature]	UW-Madison

Please complete both Forms 4400-113A and 4400-113B and return them to the appropriate DNR office and bureau. Completion of these reports is required by chs. 160, 281, 283, 289, 291, 292, 293, 295, and 299, Wis. Stats., and ch. NR 141, Wis. Adm. Code. In accordance with chs. 281, 289, 291, 292, 293, 295, and 299, Wis. Stats., failure to file these forms may result in a forfeiture of between $10 and $25,000, or imprisonment for up to one year, depending on the program and conduct involved. Personally identifiable information on these forms is not intended to be used for any other purpose. NOTE: See the instructions for more information, including where the completed forms should be sent.

State of Wisconsin
Department of Natural Resources

Route to: Watershed/Wastewater ☐ Waste Management ☐ Remediation/Redevelopment ☐ Other ☐

MONITORING WELL CONSTRUCTION
Form 4400-113A Rev. 7-98

Facility/Project Name: Wood Creek Basin	Local Grid Location of Well: ____ ft. ☐ N. ☐ S. ____ ft. ☐ E. ☐ W.	Well Name: MW7
Facility License, Permit or Monitoring No.	Local Grid Origin ☐ (estimated: ☐) or Well Location ☐ Lat. ____ Long. ____ or	Wis. Unique Well No.: JH993 — DNR Well ID No.
Facility ID	St. Plane ____ ft. N. ____ ft. E. S/C/N	Date Well Installed: 2 / 12 / 5 / 12 2006 (m m d d y y y y)
Type of Well — Well Code 11 / MW	Section Location of Waste/Source: NE 1/4 of SW 1/4 of Sec. 27, T. 8 N, R. 17 ☑E ☐W	Well Installed By: Name (first, last) and Firm
Distance from Waste/Source ____ ft. — Enf. Stds. Apply ☐	Location of Well Relative to Waste/Source: u ☐ Upgradient s ☐ Sidegradient d ☐ Downgradient n ☐ Not Known — Gov. Lot Number	Soil & Engineering Services

A. Protective pipe, top elevation ____ ft. MSL

B. Well casing, top elevation ____ ft. MSL

C. Land surface elevation ____ ft. MSL

D. Surface seal, bottom ____ ft. MSL or ____ ft.

12. USCS classification of soil near screen:
GP ☐ GM ☐ GC ☐ GW ☐ SW ☐ SP ☐
SM ☐ SC ☐ ML ☐ MH ☐ CL ☐ CH ☐
Bedrock ☐

13. Sieve analysis performed? ☐ Yes ☐ No

14. Drilling method used: Rotary ☐ 5 0; Hollow Stem Auger ☐ 4 1; Other ☐

15. Drilling fluid used: Water ☐ 0 2; Air ☐ 0 1; Drilling Mud ☐ 0 3; None ☐ 9 9

16. Drilling additives used? ☐ Yes ☐ No

Describe ____

17. Source of water (attach analysis, if required):

E. Bentonite seal, top ____ ft. MSL or 1.0 ft.

F. Fine sand, top ____ ft. MSL or 4.0 ft.

G. Filter pack, top ____ ft. MSL or 5.0 ft.

H. Screen joint, top ____ ft. MSL or 6.0 ft.

I. Well bottom ____ ft. MSL or 16.0 ft.

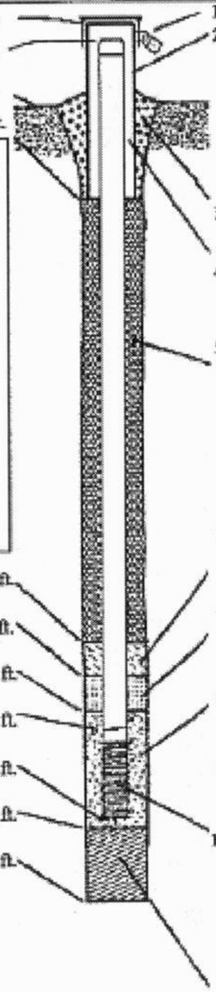
J. Filter pack, bottom ____ ft. MSL or 17.0 ft.

K. Borehole, bottom ____ ft. MSL or 17.0 ft.

L. Borehole, diameter 7.625 in.

M. O.D. well casing 2.4 in.

N. I.D. well casing 2.05 in.



1. Cap and lock? ☑ Yes ☐ No

2. Protective cover pipe:
a. Inside diameter: ____ in.
b. Length: ____ ft.
c. Material: Steel ☐ 0 4; Other ☐
d. Additional protection? ☐ Yes ☐ No
If yes, describe: ____

3. Surface seal: Bentonite ☑ 3 0; Concrete ☐ 0 1; Other ☐

4. Material between well casing and protective pipe: Bentonite ☐ 3 0; Other ☐

5. Annular space seal: a. Granular/Chipped Bentonite ☑ 3 3
b. ____ Lbs/gal mud weight . . . Bentonite-sand slurry ☐ 3 5
c. ____ Lbs/gal mud weight . . . . . Bentonite slurry ☐ 3 1
d. ____ % Bentonite . . . . . . Bentonite-cement grout ☐ 5 0
e. ____ Ft^3 volume added for any of the above
f. How installed: Tremie ☐ 0 1; Tremie pumped ☐ 0 2; Gravity ☑ 0 8

6. Bentonite seal: a. Bentonite granules ☑ 3 3
b. ☐1/4 in. ☑3/8 in. ☐1/2 in. Bentonite chips ☑ 3 2
c. ____ Other ☐

7. Fine sand material: Manufacturer, product name & mesh size
a. #15 Red Flint
b. Volume added 1 bag ft^3

8. Filter pack material: Manufacturer, product name & mesh size
a. #40 Red Flint
b. Volume added 2 bags ft^3

9. Well casing: Flush threaded PVC schedule 40 ☑ 2 3; Flush threaded PVC schedule 80 ☐ 2 4; Other ☐

10. Screen material: Sch 40 PVC
a. Screen type: Factory cut ☑ 1 1; Continuous slot ☐ 0 1; Other ☐
b. Manufacturer ____
c. Slot size: 0.010 in.
d. Slotted length: 10.0 ft.

11. Backfill material (below filter pack): None ☐ 1 4; Other ☐

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature	Firm
[signature]	Lin-Manson

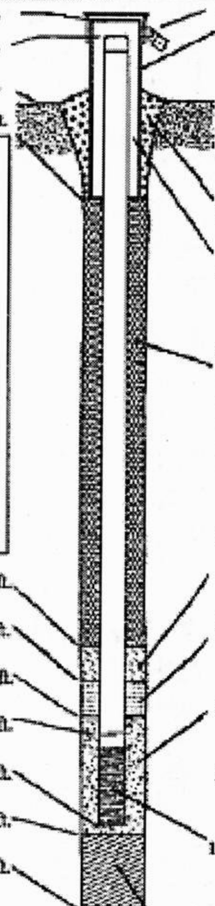
Please complete both Forms 4400-113A and 4400-113B and return them to the appropriate DNR office and bureau. Completion of these reports is required by chs. 160, 281, 283, 289, 291, 292, 293, 295, and 299, Wis. Stats., and ch. NR 141, Wis. Adm. Code. In accordance with chs. 281, 289, 291, 292, 293, 295, and 299, Wis. Stats., failure to file these forms may result in a forfeiture of between $10 and $25,000, or imprisonment for up to one year, depending on the program and conduct involved. Personally identifiable information on these forms is not intended to be used for any other purpose. NOTE: See the instructions for more information, including where the completed forms should be sent.

State of Wisconsin
Department of Natural Resources

Route to: Watershed/Wastewater ☐ Waste Management ☐ Remediation/Redevelopment ☐ Other ☐

MONITORING WELL CONSTRUCTION
Form 4400-113A Rev. 7-98

Facility/Project Name: Wood Grass Basin	Local Grid Location of Well: ___ ft. ☐N. ☐S. ___ ft. ☐E. ☐W.	Well Name: MWB
Facility License, Permit or Monitoring No.	Local Grid Origin ☐ (estimated: ☐) or Well Location ☐ Lat. ___ Long. ___	Wis. Unique Well No.: JH 994 / DNR Well ID No.
Facility ID	St. Plane ___ ft. N, ___ ft. E. S/C/N	Date Well Installed: 04/25/2006 (m m d d y y y y)
Type of Well — Well Code 11 / MW	Section Location of Waste/Source: NE 1/4 of SW 1/4 of Sec. 27, T. 8 N, R. 17 ☐E ☐W	Well Installed By: Name (first, last) and Firm
Distance from Waste/Source ___ ft. / Enf. Stds. Apply ☐	Location of Well Relative to Waste/Source: u ☐ Upgradient; s ☐ Sidegradient; d ☐ Downgradient; n ☐ Not Known / Gov. Lot Number	Soils & Engineering Services



A. Protective pipe, top elevation ___ ft. MSL
B. Well casing, top elevation ___ ft. MSL
C. Land surface elevation ___ ft. MSL
D. Surface seal, bottom ___ ft. MSL or ___ ft.

12. USCS classification of soil near screen:
GP ☐ GM ☐ GC ☐ GW ☐ SW ☐ SP ☐
SM ☐ SC ☐ ML ☐ MH ☐ CL ☐ CH ☐
Bedrock ☐
13. Sieve analysis performed? ☐ Yes ☐ No
14. Drilling method used: Rotary ☐ 5 0; Hollow Stem Auger ☐ 4 1; Other ☐
15. Drilling fluid used: Water ☐ 0 2; Air ☐ 0 1; Drilling Mud ☐ 0 3; None ☐ 9 9
16. Drilling additives used? ☐ Yes ☐ No
Describe ___
17. Source of water (attach analysis, if required): ___

E. Bentonite seal, top ___ ft. MSL or 1.0 ft.
F. Fine sand, top ___ ft. MSL or 4.0 ft.
G. Filter pack, top ___ ft. MSL or 6.0 ft.
H. Screen joint, top ___ ft. MSL or 8.0 ft.
I. Well bottom ___ ft. MSL or 18.0 ft.
J. Filter pack, bottom ___ ft. MSL or 19.0 ft.
K. Borehole, bottom ___ ft. MSL or 19.0 ft.
L. Borehole, diameter 7.625 in.
M. O.D. well casing 2.4 in.
N. I.D. well casing 2.05 in.

1. Cap and lock? ☑ Yes ☐ No
2. Protective cover pipe:
a. Inside diameter: ___ in.
b. Length: ___ ft.
c. Material: Steel ☐ 0 4; Other ☐
d. Additional protection? ☐ Yes ☐ No
If yes, describe: ___
3. Surface seal: Bentonite ☑ 3 0; Concrete ☐ 0 1; Other ☐
4. Material between well casing and protective pipe: Bentonite ☑ 3 0; Other ☐
5. Annular space seal: a. Granular/Chipped Bentonite ☑ 3 3
b. ___ Lbs/gal mud weight ... Bentonite-sand slurry ☐ 3 5
c. ___ Lbs/gal mud weight ..... Bentonite slurry ☐ 3 1
d. ___ % Bentonite ...... Bentonite-cement grout ☐ 5 0
e. ___ Ft^3 volume added for any of the above
f. How installed: Tremie ☐ 0 1; Tremie pumped ☐ 0 2; Gravity ☑ 0 8
6. Bentonite seal: a. Bentonite granules ☑ 3 3
b. ☐1/4 in. ☑3/8 in. ☐1/2 in. Bentonite chips ☑ 3 2
c. ___ Other ☐
7. Fine sand material: Manufacturer, product name & mesh size
a. #15 Red Flint
b. Volume added 1 bag ft^3
8. Filter pack material: Manufacturer, product name & mesh size
a. #40 Red Flint
b. Volume added 2 bags ft^3
9. Well casing: Flush threaded PVC schedule 40 ☑ 2 3; Flush threaded PVC schedule 80 ☐ 2 4; Other ☐
10. Screen material: Sch-40 PVC
a. Screen type: Factory cut ☑ 1 1; Continuous slot ☐ 0 1; Other ☐
b. Manufacturer ___
c. Slot size: 0.010 in.
d. Slotted length: 10.0 ft.
11. Backfill material (below filter pack): None ☑ 1 4; Other ☐

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature	Firm
[signature]	UW-Madison

Please complete both Forms 4400-113A and 4400-113B and return them to the appropriate DNR office and bureau. Completion of these reports is required by chs. 160, 281, 283, 289, 291, 292, 293, 295, and 299, Wis. Stats., and ch. NR 141, Wis. Adm. Code. In accordance with chs. 281, 289, 291, 292, 293, 295, and 299, Wis. Stats., failure to file these forms may result in a forfeiture of between $10 and $25,000, or imprisonment for up to one year, depending on the program and conduct involved. Personally identifiable information on these forms is not intended to be used for any other purpose. NOTE: See the instructions for more information, including where the completed forms should be sent.

State of Wisconsin
Department of Natural Resources

Route to: Watershed/Wastewater ☐ Waste Management ☐ Remediation/Redevelopment ☐ Other ☐ ________

MONITORING WELL CONSTRUCTION
Form 4400-113A Rev. 7-98

Facility/Project Name: Wood Creek Basin

Local Grid Location of Well: ______ ft. ☐ N. ☐ S. ______ ft. ☐ E. ☐ W.

Well Name: MW9

Facility License, Permit or Monitoring No.

Local Grid Origin ☐ (estimated: ☐) or Well Location ☐
Lat. ___ ° ___ ' ___ " Long. ___ ° ___ ' ___ " or

Wis. Unique Well No.: JH 992
DNR Well ID No.: ____

Facility ID

St. Plane ______ ft. N, ______ ft. E. S/C/N

Date Well Installed: 09/25/2006 (m m d d y y y y)

Section Location of Waste/Source: NE 1/4 of SW 1/4 of Sec. 27, T. 8 N, R. 17 ☐ E ☐ W

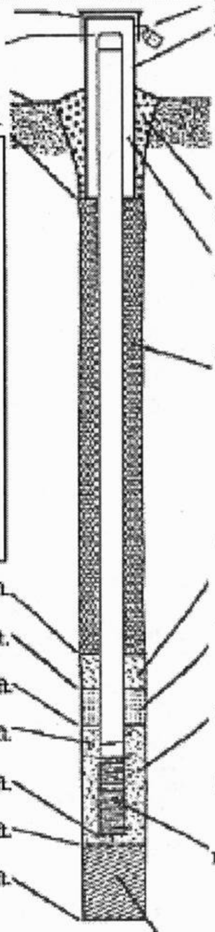
Well Installed By: Name (first, last) and Firm: Soils & Engineering Services

Type of Well
Well Code 11 / MW

Location of Well Relative to Waste/Source
u ☐ Upgradient s ☐ Sidegradient
d ☐ Downgradient n ☐ Not Known

Gov. Lot Number

Distance from Waste/Source ______ ft.
Enf. Stds. Apply ☐



A. Protective pipe, top elevation ______ ft. MSL

B. Well casing, top elevation ______ ft. MSL

C. Land surface elevation ______ ft. MSL

D. Surface seal, bottom ______ ft. MSL or ____ ft.

12. USCS classification of soil near screen:
GP ☐ GM ☐ GC ☐ GW ☐ SW ☐ SP ☐
SM ☐ SC ☐ ML ☐ MH ☐ CL ☐ CH ☐
Bedrock ☐

13. Sieve analysis performed? ☐ Yes ☐ No

14. Drilling method used: Rotary ☐ 5 0
Hollow Stem Auger ☐ 4 1
Other ☐

15. Drilling fluid used: Water ☐ 0 2 Air ☐ 0 1
Drilling Mud ☐ 0 3 None ☐ 9 9

16. Drilling additives used? ☐ Yes ☐ No

Describe ________

17. Source of water (attach analysis, if required):

E. Bentonite seal, top ______ ft. MSL or 1.0 ft.

F. Fine sand, top ______ ft. MSL or 4.0 ft.

G. Filter pack, top ______ ft. MSL or 5.0 ft.

H. Screen joint, top ______ ft. MSL or 6.0 ft.

I. Well bottom ______ ft. MSL or 16.0 ft.

J. Filter pack, bottom ______ ft. MSL or 17.0 ft.

K. Borehole, bottom ______ ft. MSL or 17.0 ft.

L. Borehole, diameter 7.625 in.

M. O.D. well casing 2.4 in.

N. I.D. well casing 2.15 in.

1. Cap and lock? ☑ Yes ☐ No

2. Protective cover pipe:
a. Inside diameter: ____ in.
b. Length: ____ ft.
c. Material: Steel ☐ 0 4
Other ☐
d. Additional protection? ☐ Yes ☐ No
If yes, describe: ________

3. Surface seal: Bentonite ☑ 3 0
Concrete ☐ 0 1
Other ☐

4. Material between well casing and protective pipe:
Bentonite ☑ 3 0
Other ☐

5. Annular space seal: a. Granular/Chipped Bentonite ☑ 3 3
b. ____ Lbs/gal mud weight . . . Bentonite-sand slurry ☐ 3 5
c. ____ Lbs/gal mud weight . . . . . Bentonite slurry ☐ 3 1
d. ____ % Bentonite . . . . . . Bentonite-cement grout ☐ 5 0
e. ____ Ft^3 volume added for any of the above
f. How installed: Tremie ☐ 0 1
Tremie pumped ☐ 0 2
Gravity ☑ 0 8

6. Bentonite seal: a. Bentonite granules ☐ 3 3
b. ☐ 1/4 in. ☑ 3/8 in. ☐ 1/2 in. Bentonite chips ☑ 3 2
c. ________ Other ☐

7. Fine sand material: Manufacturer, product name & mesh size
a. #15 Red Flint
b. Volume added 1 bag ft^3

8. Filter pack material: Manufacturer, product name & mesh size
a. #40 Red Flint
b. Volume added 2 bags ft^3

9. Well casing: Flush threaded PVC schedule 40 ☑ 2 3
Flush threaded PVC schedule 80 ☐ 2 4
Other ☐

10. Screen material: Sch 40 PVC
a. Screen type: Factory cut ☑ 1 1
Continuous slot ☐ 0 1
Other ☐
b. Manufacturer ________
c. Slot size: 0.010 in.
d. Slotted length: 10.0 ft.

11. Backfill material (below filter pack): None ☑ 1 4
Other ☐

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature: [signature]
Firm: UW - Madison

Please complete both Forms 4400-113A and 4400-113B and return them to the appropriate DNR office and bureau. Completion of these reports is required by chs. 160, 281, 283, 289, 291, 292, 293, 295, and 299, Wis. Stats., and ch. NR 141, Wis. Adm. Code. In accordance with chs. 281, 289, 291, 292, 293, 295, and 299, Wis. Stats., failure to file these forms may result in a forfeiture of between $10 and $25,000, or imprisonment for up to one year, depending on the program and conduct involved. Personally identifiable information on these forms is not intended to be used for any other purpose. NOTE: See the instructions for more information, including where the completed forms should be sent.

State of Wisconsin
Department of Natural Resources

Route to: Watershed/Wastewater ☐ Waste Management ☐ Remediation/Redevelopment ☐ Other ☐

MONITORING WELL CONSTRUCTION
Form 4400-113A Rev. 7-98

Facility/Project Name Wood Creek Basin	Local Grid Location of Well ___ ft. ☐N ☐S. ___ ft. ☐E. ☐W.	Well Name MW10
Facility License, Permit or Monitoring No.	Local Grid Origin ☐ (estimated: ☐) or Well Location ☐ Lat. ___ ° ___ ' ___ " Long. ___ ° ___ ' ___ " or	Wis. Unique Well No. / DNR Well ID No.
Facility ID	St. Plane ___ ft. N, ___ ft. E. S/C/N	Date Well Installed 01/04/2007 (m m d d y y y y)
Type of Well Well Code 11 / MW	Section Location of Waste/Source NE 1/4 of SW 1/4 of Sec. 27, T. 8 N, R. 17 ☐E ☐W	Well Installed By: Name (first, last) and Firm
Distance from Waste/Source ___ ft. / Enf. Stds. Apply ☐	Location of Well Relative to Waste/Source u ☐ Upgradient s ☐ Sidegradient d ☐ Downgradient n ☐ Not Known / Gov. Lot Number	Midwest Engineering Services

A. Protective pipe, top elevation ___ ft. MSL
B. Well casing, top elevation ___ ft. MSL
C. Land surface elevation ___ ft. MSL
D. Surface seal, bottom ___ ft. MSL or ___ ft.

12. USCS classification of soil near screen:
GP ☐ GM ☐ GC ☐ GW ☐ SW ☐ SP ☐
SM ☐ SC ☐ ML ☐ MH ☐ CL ☐ CH ☐
Bedrock ☐

13. Sieve analysis performed? ☐ Yes ☐ No

14. Drilling method used: Rotary ☐ 5 0
Hollow Stem Auger ☐ 4 1
Other ☐

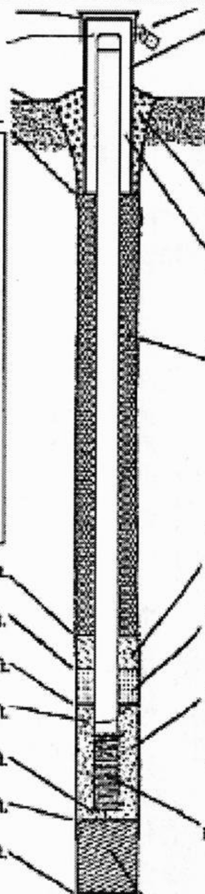
15. Drilling fluid used: Water ☐ 0 2 Air ☐ 0 1
Drilling Mud ☐ 0 3 None ☐ 9 9

16. Drilling additives used? ☐ Yes ☐ No

Describe ___

17. Source of water (attach analysis, if required):

E. Bentonite seal, top ___ ft. MSL or 1.0 ft.
F. Fine sand, top ___ ft. MSL or ___ ft.
G. Filter pack, top ___ ft. MSL or ___ ft.
H. Screen joint, top ___ ft. MSL or 8.5 ft.
I. Well bottom ___ ft. MSL or 11.5 ft.
J. Filter pack, bottom ___ ft. MSL or 11.5 ft.
K. Borehole, bottom ___ ft. MSL or 12.5 ft.
L. Borehole, diameter ___ in.
M. O.D. well casing ___ in.
N. I.D. well casing ___ in.



1. Cap and lock? ☑ Yes ☐ No
2. Protective cover pipe:
a. Inside diameter: ___ in.
b. Length: ___ ft.
c. Material: Steel ☐ 0 4
Other ☐
d. Additional protection? ☐ Yes ☐ No
If yes, describe: ___

3. Surface seal: Bentonite ☑ 3 0
Concrete ☐ 0 1
Other ☐

4. Material between well casing and protective pipe:
Bentonite ☐ 3 0
Other ☐

5. Annular space seal: a. Granular/Chipped Bentonite ☑ 3 3
b. ___ Lbs/gal mud weight . . . Bentonite-sand slurry ☐ 3 5
c. ___ Lbs/gal mud weight . . . . . Bentonite slurry ☐ 3 1
d. ___ % Bentonite . . . . . . Bentonite-cement grout ☐ 5 0
e. ___ Ft^3 volume added for any of the above
f. How installed: Tremie ☐ 0 1
Tremie pumped ☐ 0 2
Gravity ☑ 0 8

6. Bentonite seal: a. Bentonite granules ☑ 3 3
b. ☐1/4 in. ☑3/8 in. ☐1/2 in. Bentonite chips ☐ 3 2
c. ___ Other ☐

7. Fine sand material: Manufacturer, product name & mesh size
a. Red Flint Coarse 40-60
b. Volume added 1 bag ft^3

8. Filter pack material: Manufacturer, product name & mesh size
a. Red Flint Coarse sand
b. Volume added 2 bags ft^3

9. Well casing: Flush threaded PVC schedule 40 ☑ 2 3
Flush threaded PVC schedule 80 ☐ 2 4
Other ☐

10. Screen material: Sch 40 PVC
a. Screen type: Factory cut ☑ 1 1
Continuous slot ☐ 0 1
Other ☐
b. Manufacturer ___
c. Slot size: 0.010 in.
d. Slotted length: 3.0 ft.

11. Backfill material (below filter pack): None ☑ 1 4
Other ☐

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature	Firm
[signature]	UW - Madison

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State of Wisconsin
Department of Natural Resources

MONITORING WELL DEVELOPMENT
Form 4400-113B Rev. 7-98

Route to: Watershed/Wastewater ☐ Waste Management ☐
Remediation/Redevelopment ☐ Other ☐

Facility/Project Name	County Name	Well Name	
Wood Creek Basin	Waukesha	MW4	
Facility License, Permit or Monitoring Number	**County Code**	**Wis. Unique Well Number**	**DNR Well ID Number**
	—	—	—

1. Can this well be purged dry? ☐ Yes ☑ No

2. Well development method
   - surged with bailer and bailed ☑ 41
   - surged with bailer and pumped ☐ 61
   - surged with block and bailed ☐ 42
   - surged with block and pumped ☐ 62
   - surged with block, bailed and pumped ☐ 70
   - compressed air ☐ 20
   - bailed only ☐ 10
   - pumped only ☐ 51
   - pumped slowly ☐ 50
   - Other ______ ☐

3. Time spent developing well 120 min.

4. Depth of well (from top of well casing) 19.5 ft.

5. Inside diameter of well 2.05 in.

6. Volume of water in filter pack and well casing 11.4 gal.

7. Volume of water removed from well 35.0 gal.

8. Volume of water added (if any) — gal.

9. Source of water added —

10. Analysis performed on water added? ☐ Yes ☑ No
(If yes, attach results)

		Before Development	After Development
11. Depth to Water (from top of well casing)	a.	13.28 ft.	13.25 ft.
Date	b.	04/01/2006	04/01/2006
Time	c.	1:20 ☐ a.m. ☑ p.m.	3:20 ☐ a.m. ☑ p.m.
12. Sediment in well bottom		— inches	— inches
13. Water clarity		Clear ☐ 10 / Turbid ☑ 15 (Describe)	Clear ☑ 20 / Turbid ☐ 25 (Describe)

Fill in if drilling fluids were used and well is at solid waste facility:

	Before Development	After Development
14. Total suspended solids	____ mg/l	____ mg/l
15. COD	____ mg/l	____ mg/l

16. Well developed by: Name (first, last) and Firm
First Name: Mike Last Name: Nimmer
Firm: UW Madison

17. Additional comments on development:

Name and Address of Facility Contact/Owner/Responsible Party	I hereby certify that the above information is true and correct to the best of my knowledge.
First Name: Stan Last Name: Sobden	Signature: [signature]
Facility/Firm: City of Oconomowoc	Print Name: Mike Nimmer
Street: W233 N2080 Ridgeview Parkway	Firm: UW-Madison
City/State/Zip: Waukesha, WI 53188	

NOTE: See instructions for more information including a list of county codes and well type codes.

State of Wisconsin
Department of Natural Resources

MONITORING WELL DEVELOPMENT
Form 4400-113B Rev. 7-98

Route to: Watershed/Wastewater ☐ Waste Management ☐
Remediation/Redevelopment ☐ Other ☐ ______

Facility/Project Name	County Name	Well Name
WOOD CREEK BASIN	WAUKESHA	MW6

Facility License, Permit or Monitoring Number	County Code	Wis. Unique Well Number	DNR Well ID Number
	__ __	______	___

1. Can this well be purged dry? ☐ Yes ☑ No

2. Well development method
   - surged with bailer and bailed ☑ 41
   - surged with bailer and pumped ☐ 61
   - surged with block and bailed ☐ 42
   - surged with block and pumped ☐ 62
   - surged with block, bailed and pumped ☐ 70
   - compressed air ☐ 20
   - bailed only ☐ 10
   - pumped only ☐ 51
   - pumped slowly ☐ 50
   - Other ______ ☐

3. Time spent developing well __90__ min.

4. Depth of well (from top of well casing) __70.3__ ft.

5. Inside diameter of well __2.05__ in.

6. Volume of water in filter pack and well casing __1.4__ gal.

7. Volume of water removed from well __35.0__ gal.

8. Volume of water added (if any) __–__ gal.

9. Source of water added __–__

10. Analysis performed on water added? ☐ Yes ☑ No
(If yes, attach results)

		Before Development	After Development
11. Depth to Water (from top of well casing)	a.	12.76 ft.	12.85 ft.
Date	b.	04/05/2006 (mm dd yyyy)	04/05/2006 (mm dd yyyy)
Time	c.	14:25 ☐ a.m. ☑ p.m.	15:55 ☐ a.m. ☑ p.m.
12. Sediment in well bottom		– inches	– inches
13. Water clarity		Clear ☐ 10 Turbid ☑ 15 (Describe)	Clear ☑ 20 Turbid ☐ 25 (Describe)

Fill in if drilling fluids were used and well is at solid waste facility:

	Before	After
14. Total suspended solids	– mg/l	– mg/l
15. COD	– mg/l	– mg/l

16. Well developed by: Name (first, last) and Firm
First Name: MIKE B? Last Name: NOWAEK
Firm: UW-MADISON

17. Additional comments on development:

Name and Address of Facility Contact/Owner/Responsible Party	
First Name: STAN	Last Name: SIGDEN
Facility/Firm: CITY OF BROOKFIELD	
Street: W233 N2080 RIDGEVIEW PARKWAY	
City/State/Zip: WAUKESHA, WI 53188	

I hereby certify that the above information is true and correct to the best of my knowledge.

Signature: [signature]
Print Name: MIKE NOWAEK
Firm: UW-MADISON

NOTE: See instructions for more information including a list of county codes and well type codes.

State of Wisconsin
Department of Natural Resources

MONITORING WELL DEVELOPMENT
Form 4400-113B Rev. 7-98

Route to: Watershed/Wastewater ☐ Waste Management ☐
Remediation/Redevelopment ☐ Other ☐ ____________

Facility/Project Name	County Name	Well Name	
WOOD CREEK BASIN	WAUKESHA	MW 7	
Facility License, Permit or Monitoring Number	County Code	Wis. Unique Well Number	DNR Well ID Number
	__ __	__ __ __ __ __	__ __ __

1. Can this well be purged dry? ☐ Yes ☑ No

2. Well development method
   - surged with bailer and bailed ☑ 41
   - surged with bailer and pumped ☐ 61
   - surged with block and bailed ☐ 42
   - surged with block and pumped ☐ 62
   - surged with block, bailed and pumped ☐ 70
   - compressed air ☐ 20
   - bailed only ☐ 10
   - pumped only ☐ 51
   - pumped slowly ☐ 50
   - Other ____________ ☐

3. Time spent developing well __ 90 min.

4. Depth of well (from top of well casisng) __ 15.0 ft.

5. Inside diameter of well __ 2.05 in.

6. Volume of water in filter pack and well casing __ __ 1.4 gal.

7. Volume of water removed from well __ 35.0 gal.

8. Volume of water added (if any) __ __ __ . __ gal.

9. Source of water added ____________

10. Analysis performed on water added? ☐ Yes ☑ No
(If yes, attach results)

	Before Development	After Development
11. Depth to Water (from top of well casing)	a. __ 9.0 ft.	__ 9.05 ft.
Date	b. 09/30/2006 (mm dd yyyy)	09/30/2006 (mm dd yyyy)
Time	c. 10:14 ☑ a.m. ☐ p.m.	11:44 ☑ a.m. ☐ p.m.
12. Sediment in well bottom	__ . __ inches	__ . __ inches
13. Water clarity	Clear ☐ 10 Turbid ☑ 15 (Describe)	Clear ☑ 20 Turbid ☐ 25 (Describe)

Fill in if drilling fluids were used and well is at solid waste facility:

14. Total suspended solids	__ __ __ . __ mg/l	__ __ __ . __ mg/l
15. COD	__ __ __ . __ mg/l	__ __ __ . __ mg/l

16. Well developed by: Name (first, last) and Firm
First Name: Last Name:
Firm:

17. Additional comments on development:

Name and Address of Facility Contact /Owner/Responsible Party
First Name: STAN Last Name: SUSDEN
Facility/Firm: CITY OF OCONOMOWOC
Street: W233 N2080 ROBERSON PARKWAY
City/State/Zip: WAUKESHA, WI 53188

I hereby certify that the above information is true and correct to the best of my knowledge.
Signature:
Print Name: Mike Nimmer
Firm: UW-Madison

NOTE: See instructions for more information including a list of county codes and well type codes.

State of Wisconsin
Department of Natural Resources

MONITORING WELL DEVELOPMENT
Form 4400-113B Rev. 7-98

Route to: Watershed/Wastewater ☐ Waste Management ☐
Remediation/Redevelopment ☐ Other ☐ ________

Facility/Project Name	County Name	Well Name
Wood Creek Basin	Waukesha	MW 8

Facility License, Permit or Monitoring Number	County Code	Wis. Unique Well Number	DNR Well ID Number
	__	_______	___

1. Can this well be purged dry? ☐ Yes ☑ No

2. Well development method
- surged with bailer and bailed ☑ 41
- surged with bailer and pumped ☐ 61
- surged with block and bailed ☐ 42
- surged with block and pumped ☐ 62
- surged with block, bailed and pumped ☐ 70
- compressed air ☐ 20
- bailed only ☐ 10
- pumped only ☐ 51
- pumped slowly ☐ 50
- Other ________ ☐

3. Time spent developing well 90 min.

4. Depth of well (from top of well casing) 18.0 ft.

5. Inside diameter of well 2.05 in.

6. Volume of water in filter pack and well casing 1.4 gal.

7. Volume of water removed from well 35.5 gal.

8. Volume of water added (if any) —.— gal.

9. Source of water added ________

10. Analysis performed on water added? ☐ Yes ☑ No
(If yes, attach results)

	Before Development	After Development
11. Depth to Water (from top of well casing)	a. 12.29 ft.	12.31 ft.
Date	b. 09/30/2006 (mm dd yyyy)	09/30/2006 (mm dd yyyy)
Time	c. 12:22 ☐ a.m. ☑ p.m.	2:00 ☐ a.m. ☑ p.m.
12. Sediment in well bottom	—.— inches	—.— inches
13. Water clarity	Clear ☐ 10 Turbid ☑ 15 (Describe)	Clear ☑ 20 Turbid ☐ 25 (Describe)

Fill in if drilling fluids were used and well is at solid waste facility:

14. Total suspended solids	—— mg/l	—— mg/l
15. COD	—— mg/l	—— mg/l

16. Well developed by: Name (first, last) and Firm
First Name: Mike Last Name: Nimmer
Firm: UW-Madison

17. Additional comments on development:

Name and Address of Facility Contact/Owner/Responsible Party
First Name: Stan Last Name: Siebert
Facility/Firm: City of Oconomowoc
Street: W233 N2080 Ridgeview Pkwy
City/State/Zip: Waukesha, WI 53188

I hereby certify that the above information is true and correct to the best of my knowledge.
Signature: [signature]
Print Name: Mike Nimmer
Firm: UW-Madison

NOTE: See instructions for more information including a list of county codes and well type codes.

State of Wisconsin
Department of Natural Resources

MONITORING WELL DEVELOPMENT
Form 4400-113B Rev. 7-98

Route to: Watershed/Wastewater ☐ Waste Management ☐
Remediation/Redevelopment ☐ Other ☐ ____________

Facility/Project Name	County Name	Well Name
Wood Creek Basin	Waukesha	MW9
Facility License, Permit or Monitoring Number	County Code	Wis. Unique Well Number / DNR Well ID Number

1. Can this well be purged dry? ☐ Yes ☑ No

2. Well development method
- surged with bailer and bailed ☑ 41
- surged with bailer and pumped ☐ 61
- surged with block and bailed ☐ 42
- surged with block and pumped ☐ 62
- surged with block, bailed and pumped ☐ 70
- compressed air ☐ 20
- bailed only ☐ 10
- pumped only ☐ 51
- pumped slowly ☐ 50
- Other ________ ☐

3. Time spent developing well 100 min.

4. Depth of well (from top of well casing) 16.0 ft.

5. Inside diameter of well 2.05 in.

6. Volume of water in filter pack and well casing 1.4 gal.

7. Volume of water removed from well 5.0 gal.

8. Volume of water added (if any) __.__ gal.

9. Source of water added ________

10. Analysis performed on water added? ☐ Yes ☑ No (If yes, attach results)

	Before Development	After Development
11. Depth to Water (from top of well casing) a.	3.12 ft.	3.43 ft.
Date b. (mm/dd/yyyy)	09/30/2006	09/30/2006
Time c.	2:30 ☐ a.m. ☑ p.m.	4:00 ☐ a.m. ☑ p.m.
12. Sediment in well bottom	__.__ inches	__.__ inches
13. Water clarity	Clear ☐ 10 Turbid ☑ 15 (Describe)	Clear ☑ 20 Turbid ☐ 25 (Describe)

Fill in if drilling fluids were used and well is at solid waste facility:

14. Total suspended solids	__.__ mg/l	__.__ mg/l
15. COD	__.__ mg/l	__.__ mg/l

16. Well developed by: Name (first, last) and Firm
First Name: Mike Last Name: Nimmer
Firm: UW-Madison

17. Additional comments on development:

Name and Address of Facility Contact/Owner/Responsible Party
First Name: Stan Last Name: Sugden
Facility/Firm: City of Oconomowoc
Street: W233 N2080 Ridgeview Parkway
City/State/Zip: Waukesha WI 53188

I hereby certify that the above information is true and correct to the best of my knowledge.
Signature:
Print Name: Mike Nimmer
Firm: UW-Madison

NOTE: See instructions for more information including a list of county codes and well type codes.

State of Wisconsin
Department of Natural Resources

MONITORING WELL DEVELOPMENT
Form 4400-113B Rev. 7-98

Route to: Watershed/Wastewater ☐ Waste Management ☐
Remediation/Redevelopment ☐ Other ☐ ______

Facility/Project Name	County Name	Well Name	
Wood Creek Basin	Waukesha	MW10	
Facility License, Permit or Monitoring Number	County Code	Wis. Unique Well Number	DNR Well ID Number
	__	____	__

1. Can this well be purged dry? ☐ Yes ☐ No

2. Well development method
- surged with bailer and bailed ☐ 41
- surged with bailer and pumped ☐ 61
- surged with block and bailed ☐ 42
- surged with block and pumped ☐ 62
- surged with block, bailed and pumped ☐ 70
- compressed air ☐ 20
- bailed only ☐ 10
- pumped only ☐ 51
- pumped slowly ☐ 50
- Other ______ ☐

3. Time spent developing well __90 min.

4. Depth of well (from top of well casing) _15.2 ft.

5. Inside diameter of well _2.05 in.

6. Volume of water in filter pack and well casing __1.6 gal.

7. Volume of water removed from well _35.0 gal.

8. Volume of water added (if any) ___.__ gal.

9. Source of water added ______

10. Analysis performed on water added? ☐ Yes ☑ No
(If yes, attach results)

	Before Development	After Development
11. Depth to Water (from top of well casing)	a. _10.20 ft.	_10.23 ft.
Date	b. 01/10/2007 (mm dd yyyy)	01/10/2007 (mm dd yyyy)
Time	c. __:__ ☐ a.m. ☐ p.m.	__:__ ☐ a.m. ☐ p.m.
12. Sediment in well bottom	__.__ inches	__.__ inches
13. Water clarity	Clear ☐ 10 Turbid ☐ 15 (Describe)	Clear ☑ 20 Turbid ☐ 25 (Describe)

Fill in if drilling fluids were used and well is at solid waste facility:

14. Total suspended solids	____.__ mg/l	____.__ mg/l
15. COD	____.__ mg/l	____.__ mg/l

16. Well developed by: Name (first, last) and Firm
First Name: Mike Last Name: Nimmer
Firm: UW - Madison

17. Additional comments on development:

Name and Address of Facility Contact/Owner/Responsible Party
First Name: Stan Last Name: Suboren
Facility/Firm: City of Oconomowoc
Street: W233 N2080 Ridgeview Parkway
City/State/Zip: Waukesha, WI 53188

I hereby certify that the above information is true and correct to the best of my knowledge.
Signature: [signature]
Print Name: Mike Nimmer
Firm: UW-Madison

NOTE: See instructions for more information including a list of county codes and well type codes.

Appendix B

Regional Groundwater Flow Maps

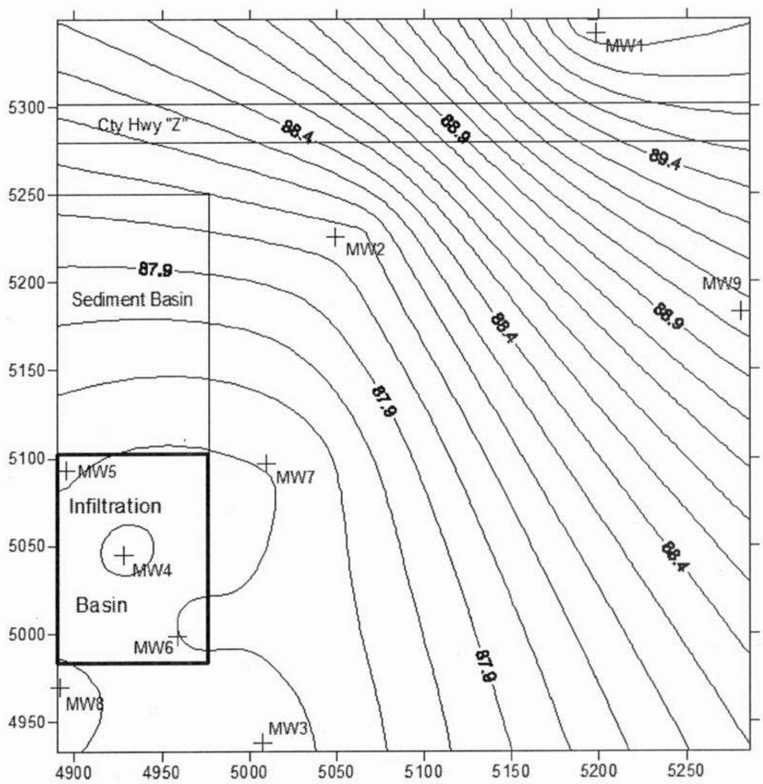

Figure 1. Groundwater Flow Direction Map – 10/19/06.

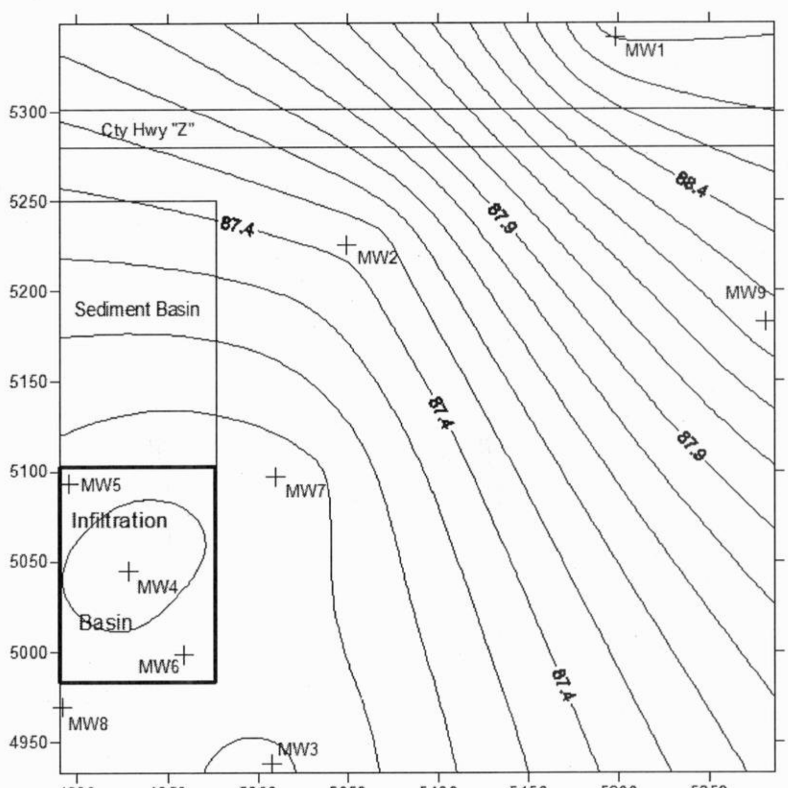

Figure 2. Groundwater Flow Direction Map – 02/21/07.

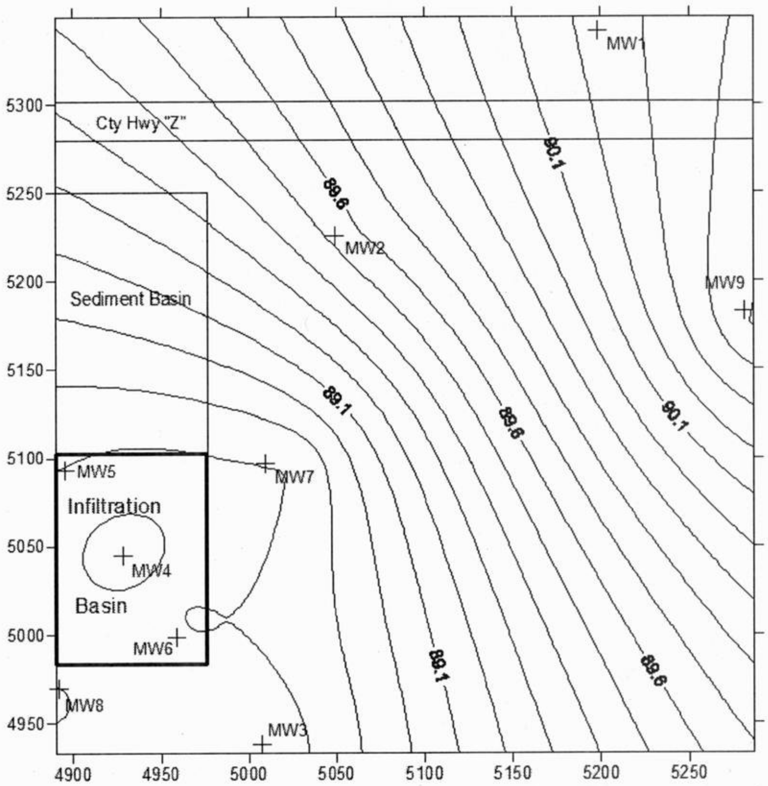

Figure 3. Groundwater Flow Direction Map – 03/30/07.

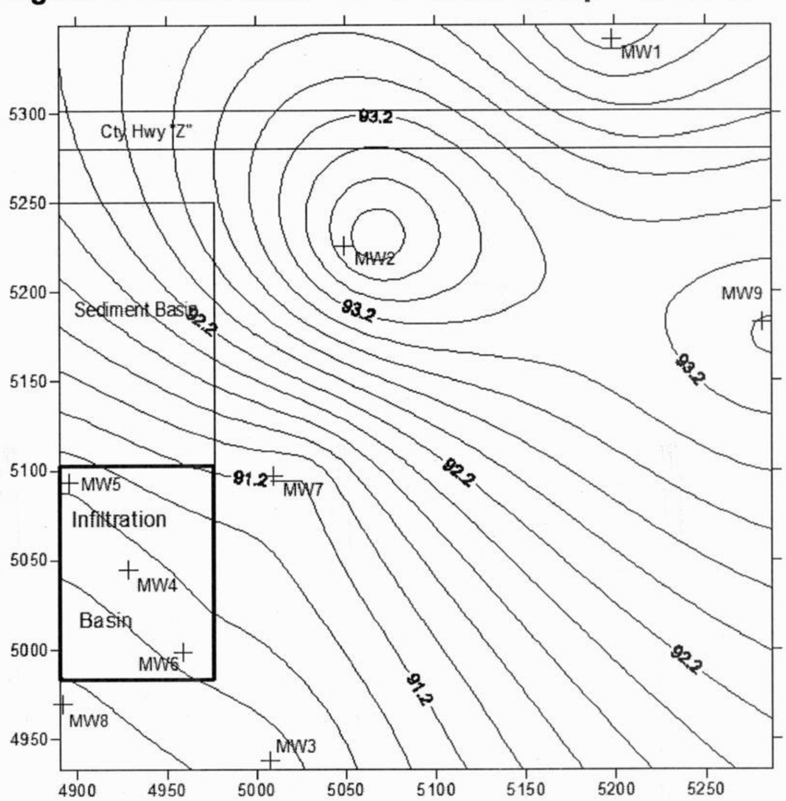

Figure 4. Groundwater Flow Direction Map – 04/03/07.

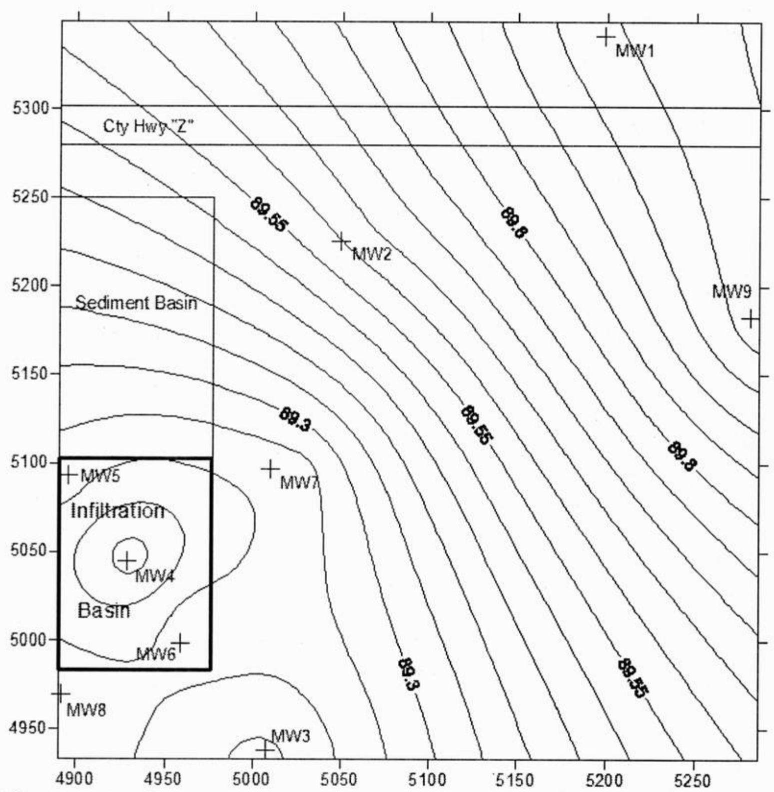

Figure 5. Groundwater Flow Direction Map – 04/21/07.

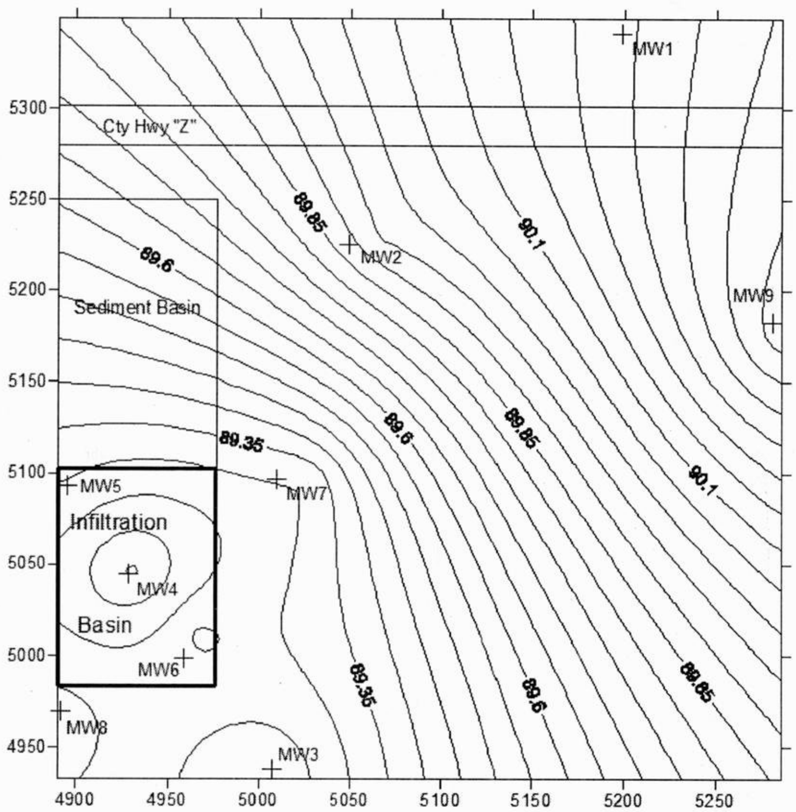

Figure 6. Groundwater Flow Direction Map – 05/04/07.

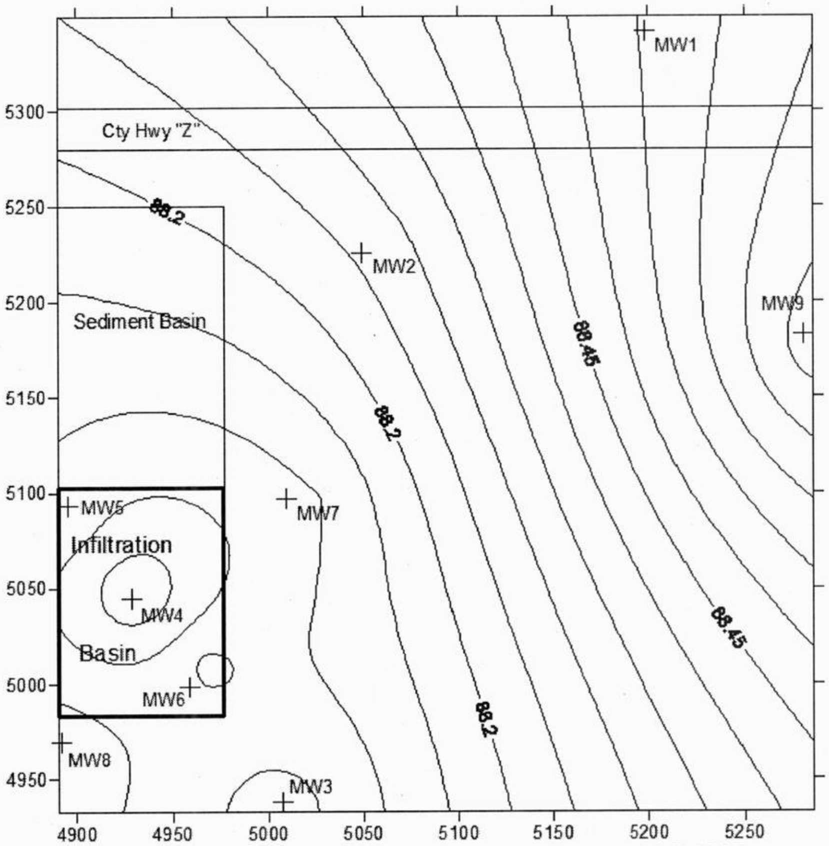

Figure 7. Groundwater Flow Direction Map – 06/16/07.

Appendix C

Equations

Bouwer & Rice Slug Test Equations and Procedures

$$\ln\frac{R_e}{r_w} = \left[\frac{1.1}{\ln(L_w / r_w)} + \frac{A + B\ln(H - L_w)/r_w}{L_e / r_w}\right]^{-1} \quad (1)$$

where R_e = radius of influence (L), r_w = radius of well (L), L_w = well length in aquifer (L), A & B are dimensionless constants as function of L_e/r_w, H = thickness of saturate material (L), and L_e = screen length (L). Hydraulic conductivity is found by Equation 2.

$$K = \frac{r_c^2 \ln(R_e / r_w)}{2L_e}\frac{1}{t}\ln\frac{s_0}{s} \quad (2)$$

where the terms not previously listed are: K = hydraulic conductivity (LT^{-1}), t = time (T), s_0 = initial water level change (L), and s = water level change (L) at time t.

The following steps were followed to determine hydraulic conductivity with the Bouwer and Rice method:

1) Plot water level change on a log scale versus time on a linear scale (Figure 13).
2) Approximate the straight line portion of the plotted curve by a straight line method and extend the line to time t = 0.
3) Calculate $\ln(H - L_w)/r_w$ for $L_w \neq H$.
4) Find dimensionless parameters A and B as a function of L_e/R_w from the Bouwer and Rice plot (Figure 12.8, pg. 281, Schwartz, et. al., 2003).
5) Calculate $\ln(R_e/r_w)$.
6) Record initial water level change (s_o), and drawdown and time for one other point on line from step 2. Calculate hydraulic conductivity.

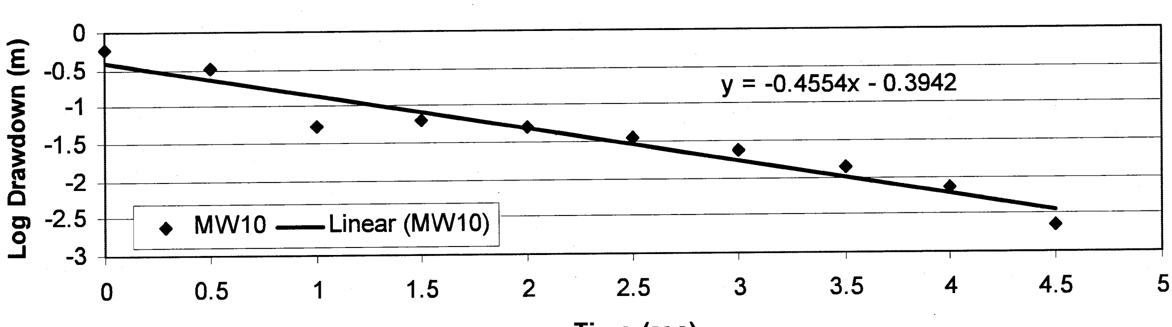

Figure 1. Bouwer and Rice Slug Test on MW10.