Stormwater Retention Pond Recovery Analysis

Forward

To design a stormwater retention pond, one of the analyses that engineers have to perform is the retention and recovery of polluted runoff water. The initial portion of stormwater runoff is typically directed to a retention pond and which contains the most polluted runoff water (the first flush). The polluted water must be fully retained within the retention pond for treatment and infiltration. This course will be limited to recovery analysis for dry retention ponds where the entire polluted water volume must be stored within the pond and then recovered by infiltration within a specified period of time.

The regulatory agencies generally establish the minimum criteria for recovery of the first flush volume, which is sometimes referred to as the pollution abatement volume. For a dry pond the designer must verify the pond's capacity to infiltrate the volume within a specified period of time. This course will present the analytical approach and the methodology to calculate the infiltration losses from a dry retention pond.

Objective

The objective of this course is to provide the pond designer with the tools needed to conduct an infiltration analysis that calculates the time of recovery of the polluted water from a dry retention pond system. This analysis was originally developed by Nicolas E. Andreyev, P.E. and Lee P. Wiseman, P.E. in 1989, as part of the research and development project for the Southwest Florida Water Management District ("Stormwater Retention Pond Infiltration Analyses in Unconfirmed Aquifers", Permitting Guidelines for Southwest Florida Water Management District, 1989) and later field tested for verification of the analytical approach by the St. Johns River Water Management District. This method is applicable to stormwater retention ponds built in sandy aquifer systems anywhere in the world.

Background

A stormwater retention pond is usually designed to receive a minimum of the first ½-inch of runoff generated by the contributing area, which must be fully retained and then infiltrated within a prescribed period of time (typically 3 days).

The main purpose of a retention pond is to collect and treat "the first flush" of polluted stormwater. In many instances, a single pond incorporates both retention of the polluted water and detention of the entire design storm event, such as a 25 year 24 hour storm. For this course, only the stormwater retention and recovery analysis will be presented.

Retention Ponds

Stormwater runoff has been recognized as a source of surface water pollution. Local regulatory agencies have responded to this concern by developing criteria for better design and construction of retention ponds. The current design strategy of stormwater retention ponds is based on the premise that the most highly polluted stormwater will occur at the beginning of the storm. It is assumed that after the first ½-inch of runoff or after 1-inch of rain has fallen, the contributing polluted surfaces and stormwater sewers have been sufficiently washed and subsequent runoff will be relatively clean. Runoff exceeding the first flush retention volume is generally not retained and is discharged to a detention pond or is directed off-site.

Several types of retention ponds are used, including combined retention and detention ponds, off-line retention ponds, closed basin (100% capture) ponds and existing natural depressions. The most effective pollution control systems are off-line retention ponds. These ponds are provided with a diversion structure that directs the first flush volume to enter the retention pond and all additional runoff is then directed to a detention pond or discharged off-site. A closed basin retention system is also efficient for pollution control, as all runoff is retained within the pond system. It is presumed that the most polluted water will be treated through biological, chemical and filtration processes, as it infiltrates into the natural soil. In most areas of the world approximately 90% of storms have less than 1-inch of rainfall. As a result, a retention pond will retain and treat a high percentage of the yearly rainfall. In addition to the water quality benefits, this process reduces the total volume of runoff from a catchment and increases the amount of local aquifer recharge.

The retention pond will generally work effectively if it recovers quickly after a storm event. However, if at the beginning of the storm a retention pond contains runoff from the preceding storm, then its effectiveness will be reduced. During periods when the antecedent storm was so recent that the pond has not yet recovered, and assuming that the "first flush" theory is correct, then there should not be much upstream pollution to accumulate in the runoff from the second storm. Therefore, it is important to determine how soon after the storm the retention pond will again be empty and be capable of operating at the intended design capacity.

Simplified Infiltration Analysis

In general, the water initially infiltrates vertically through the pond bottom until the water table or the confining layer is reached. Once the water table or the confining layer is reached, lateral seepage and mounding begins. The goal of this course is to develop a simplified technique to analyze the infiltration capacity of retention ponds and to calculate the time of recovery of a specific volume of polluted stormwater.

For this analysis, it is assumed that the subsurface soil conditions, the groundwater level, hydraulic conductivity of the aquifer and the polluted water volume are known. The characterization of the shallow aquifer system, measurement of the average hydraulic conductivity of the aquifer and the calculation of the polluted water volume (pollution abatement volume) are not presented in this course.

The presentation of the analytical approach for this simplified technique begins with the description of the problem to be analyzed. Next, the relevant analytical methods are presented. These techniques incorporate the unsaturated and the saturated infiltration as it normally occurs in retention ponds in shallow groundwater conditions and sandy unconfined aquifer systems. The detailed technical presentation of the analytical approach and derivation of the applicable equations are included in the referenced document, Andreyev & Wiseman (1989) and will not be presented herein.

This analysis is suitable for retention ponds where the majority of the infiltration occurs through horizontal flow in the shallow aquifer. This is typical for areas where the depth to groundwater level is between 2 and 8 feet within an unconfined shallow aquifer system. This analysis may not be applicable where the soil conditions consist of thick surficial deposits of clayey sands and clays and/or groundwater levels that occur at more than 10 feet below pond bottom.

For the purposes of this analytical approach, it can be assumed that the subsurface conditions as presented in **Figure 1** exist, where the soil is homogeneous and isotropic. When water enters the pond, the standing water begins to infiltrate through unsaturated vertical flow. Unsaturated flow follows Darcy's law just as saturated flow does, but both the coefficient of permeability and the gradients are variable. Permeability (also referred to as hydraulic conductivity) depends on the degree of saturation, because the decrease in moisture content will produce a decrease in the cross sectional area of flow between the soil particles. The gradient changes because the head at the soil surface is constant and the head at the wetting front is constant (in homogeneous soil) but the distance between the two increases. A graphic depiction of the wetting front is presented on **Figure 2**.

Figure 1: Idealized Pond-Aquifer System

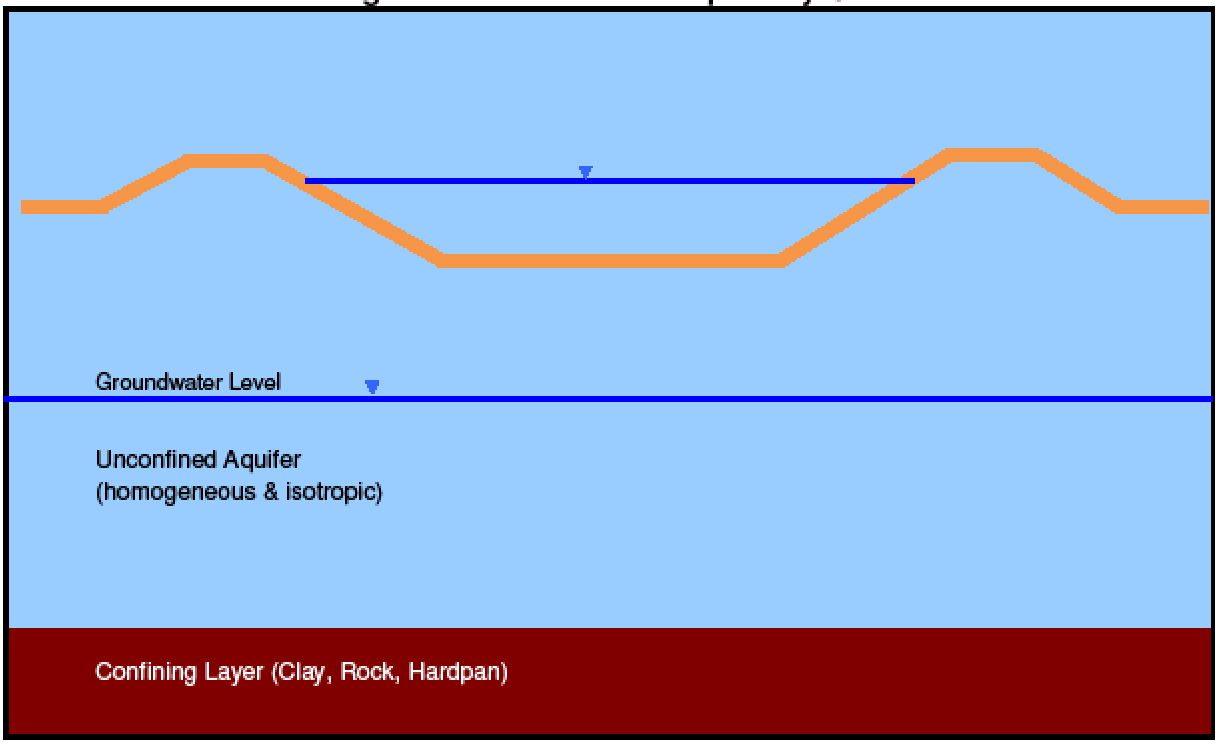
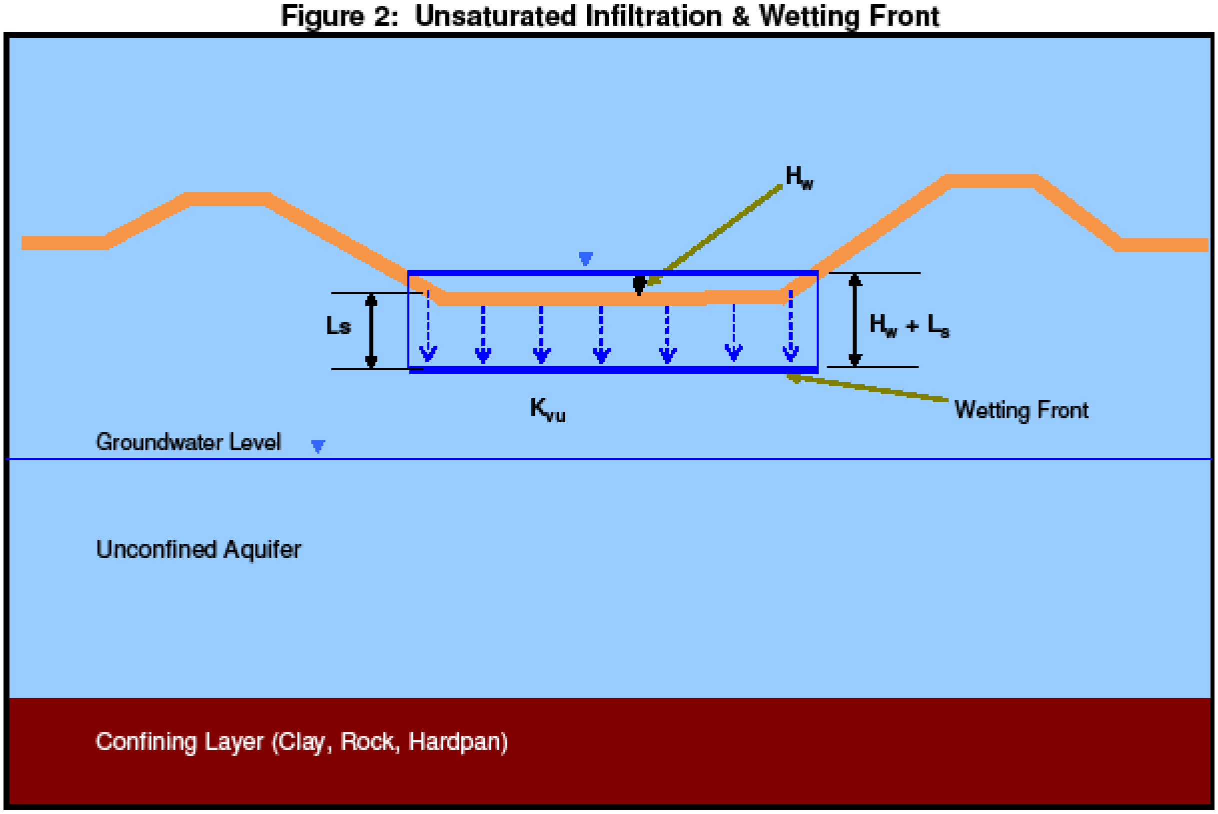
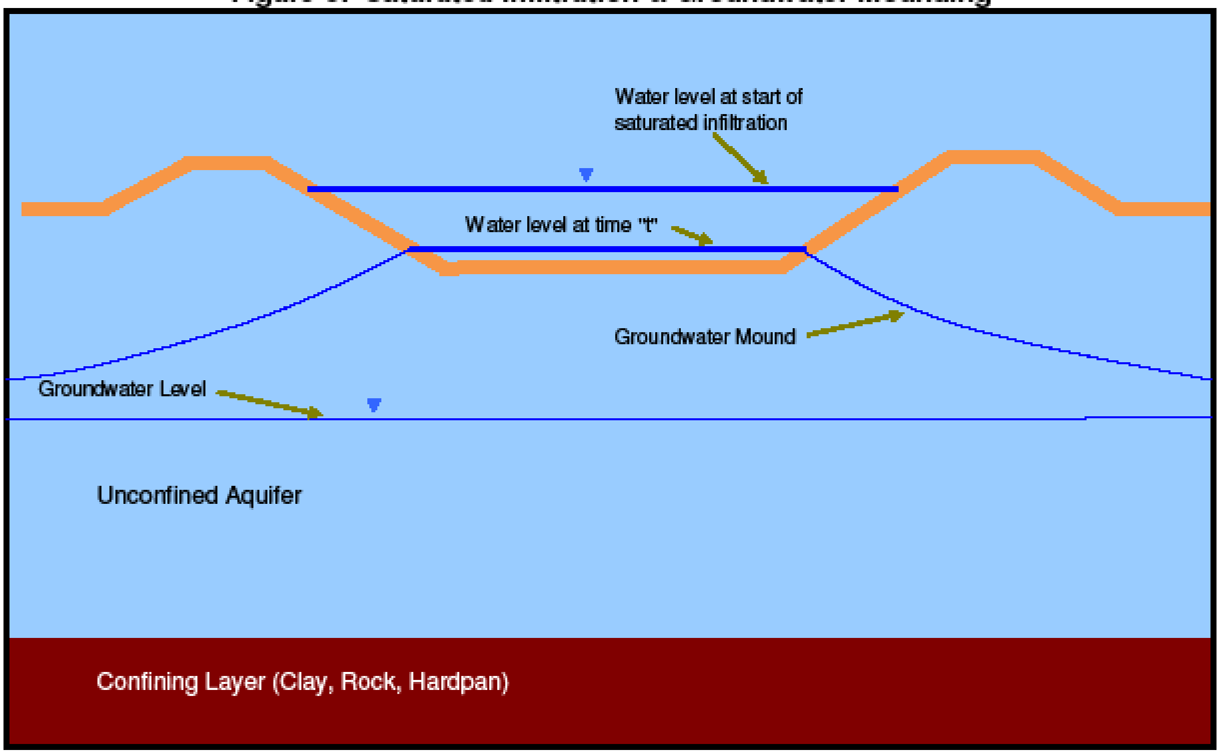


Figure 2: Unsaturated Infiltration & Wetting Front



The second stage of seepage starts when the wetting front reaches the water table or a confining layer. The effective capillary suction potential at the wetting front disappears and vertical infiltration takes place under a constant gradient of 1.0 where the pressure head is approximately equal to the seepage path length. The vertical infiltration begins to add water to the water table aquifer. From this time on, horizontal groundwater seepage in the saturated aquifer occurs and simultaneously the storage in the unsaturated portion above the water table begins, resulting in groundwater mounding as shown on **Figure 3**.

Figure 3: Saturated Infiltration & Groundwater Mounding



Unsaturated Infiltration Analysis

The equation of motion for infiltration is Darcy's law which has been found to apply to unsaturated flow even though the hydraulic conductivity is not constant with changing moisture content. Rigorous theoretical treatment of the infiltration phenomenon requires the determination of the variation in the hydraulic conductivity as the wetting front advances and other functional relationships by extensive laboratory testing of the particular soil. Infiltration into the soil for which these relationships have been found can then be described by numerical solutions of the diffusivity form of the unsaturated flow equation (Philips 1957).

For practical design of stormwater retention ponds a simpler analysis is needed without expensive instrumentation and testing procedures. For such purposes, the infiltration equation developed by Green and Ampt (1911), is sufficient. This equation was presented in1911 as an empirical description of infiltration. Later investigators modified the original Green and Ampt equation by theoretical determination of the original empirical constants (Bouwer, 1969). In its modified form, the equation has been compared to more rigorous solutions and found to give almost identical results (Whisler and Bouwer, 1970). Hydraulic conductivity and water content in the transmissive zone are considered constant as is the capillary suction potential acting on the advancing wetting front. Applying Darcy's law to the transmissive zone, the infiltration (I) is described as:

$$I = Kvu \frac{Hw + Ls - hcr}{Ls} \qquad (1)$$

Where:

I = infiltration rate
Kvu = unsaturated vertical hydraulic conductivity
Hw = depth of ponded water
hcr = capillary suction potential at the wetting front
Ls = depth of penetration of the wetting front

The rate of advance for the wetting front is:

$$\frac{dLs}{dt} = \frac{I}{f} \qquad (2)$$

Where:

I = infiltration rate
t = time
f = effective storage coefficient (fillable porosity)

Combining equations 1 and 2 and integrating gives the relationship of depth of wetting to time:

$$t = \frac{f}{Kvu}(Ls - (Hw - hcr) In\left(\frac{Hw + Ls - hcr}{Hw - hcr}\right) \qquad (3)$$

Where:

t = time since start of infiltration

Equations 1 and 3 can be further simplified and used to calculate the approximate infiltration rate and the movement of the wetting front. The values of

f and Kvu to be used in these equations are important enough to warrant some discussion. The void space in which water is stored after the passing of the wetting front (effective storage coefficient or fillable porosity, f) is the difference between the initial moisture content and the moisture content in the transmissive zone. Experiments by Bodman & Coleman (1943) indicate that the transmissive zone for sand is about 90% of full saturation. Therefore, a reasonable engineering approach for infiltration analysis is to let the moisture content be the actual field measured parameter. The effective storage coefficient is the fractional difference between these two values. In terms of soil mechanics, the effective storage coefficient can be approximated as:

$$f = 0.9n - \left(\frac{\omega \gamma_d}{\gamma_w} \right) \qquad (4)$$

Where:

f = effective storage coefficient
n = total soil porosity
ω = moisture content (fraction, based on a dry weight)
γ_d = dry unit weight of soil
γ_w = unit weight of water

The unsaturated hydraulic conductivity of the transmissive zone, Kvu, can be determined by field testing with an air entry permeameter (Bouwer, 1966) or approximated by the results of a double-ring infiltrometer test (ASTM D-3385). The unsaturated hydraulic conductivity, Kvu, is normally less than the saturated hydraulic conductivity, Kvs. Based on Bouwer's research of Kvu versus Kvs, the Kvu for sand varies from 1/2 to 2/3 of Kvs (Bouwer 1978). For typical natural fine sand deposits a correlation factor of 2/3 is applicable and will be used in this analysis.

The other two parameters in the Green & Ampt equation is the depth of water in the pond, Hw and the capillary suction potential, hcr. For simplification and due to the fact that these parameters are minor influences on the equation when considering retention ponds with 2 to 10 feet of depth to water table, both parameters can be ignored with minimal effect on the final results of this analysis. The removal of Hw and hcr leaves the final simplified equation more conservative, resulting in a slight reduction of the calculated infiltration rate. Therefore, equation 1 can be rewritten as:

$$I = Kvu \qquad (5)$$

Where:

I = infiltration rate
Kvu = unsaturated vertical hydraulic conductivity

And equation 3 can be rewritten as:

$$t = \frac{f\ Ls}{Kvu}$$

And the time necessary for the wetting front to reach water table is

$$dt = \frac{f\ h_b}{Kvu} \qquad (6)$$

Where:

dt = time to saturate soil between pond bottom and water table
f = effective storage coefficient between pond bottom and water table
h_b = height of pond bottom above water table
Kvu = unsaturated vertical hydraulic conductivity (average)

$$Kvu = \frac{2}{3} Kvs \qquad (7)$$

The total volume of water required to saturate the soil below the pond can be calculated as follows:

$$Vu = A_p\ h_b\ f \qquad (8)$$

Where:

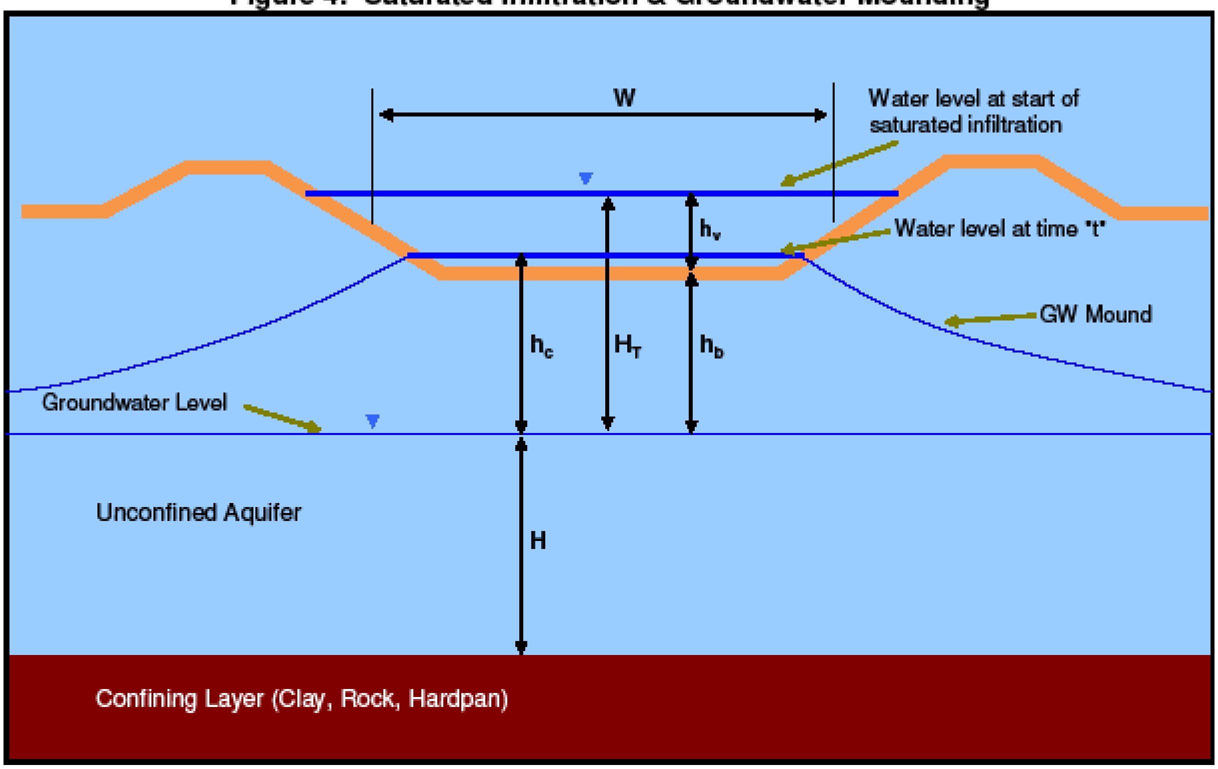
Vu = total volume of water to saturate soil below pond
A_p = average pond area (between bottom and design water level)
h_b = height of pond bottom above water table
f = average effective storage coefficient

Therefore, equations 6 and 8 can be used to calculate the approximate time and volume to saturate the soil below the pond bottom. This part of the analysis is relatively simple and straight forward. However, it is only a small portion of the infiltration losses from retention ponds where groundwater levels occur at relatively shallow depths below pond bottom. The remaining infiltration losses will occur under saturated infiltration and mounding conditions and the analysis becomes considerably more complicated.

Saturated Groundwater Flow

Saturated flow beneath a typical stormwater retention pond is governed by the transmissive characteristics of the shallow aquifer, available lateral seepage gradients, pond geometry and other factors affecting the general form of Darcy's law for saturated seepage. Recharge into the groundwater aquifer creates a groundwater mound beneath the pond and its vicinity as presented on **Figure 4**.

Figure 4: Saturated Infiltration & Groundwater Mounding



Once the groundwater mound intersects the pond bottom or if groundwater is at pond bottom, the infiltration to the soil will be governed by the saturated seepage in the groundwater aquifer with lateral gradients equal to the slope of the free surface, instead of the downward seepage with a gradient of 1.0. The rate of water level decline in the pond is directly proportional to the rate of groundwater mound recession in the saturated aquifer. Therefore, for stormwater retention ponds constructed in areas of high groundwater conditions, it is important to predict the rate of growth and decay of the groundwater mound. Numerous analytical methods are available to evaluate the growth and decay of the groundwater mounds. For successful design of stormwater retention ponds, both the unsaturated and saturated seepage must be accounted for and incorporated into the analysis.

The majority of numerical solutions for groundwater mound growth and decay are a function of a uniform rate of recharge and spatially uniform storage coefficient. In the Andreyev & Wiseman (1989) research a series of dimensionless curves were developed to solve the effects of water level recovery in stormwater retention ponds. The method selected to generate the dimensionless curves was “Three-Dimensional Finite Difference Groundwater Flow Computer Model" developed by the U.S. Geological Survey (McDonald & Harbaugh, 1984). The 3D model is widely used and is generally know as MODFLOW. This three-dimensional transient simulation model allows for a spatially variable storage coefficient. This is significant since the storage coefficient in the pond area is 1.0 and in the surrounding aquifer is less than 1.0.

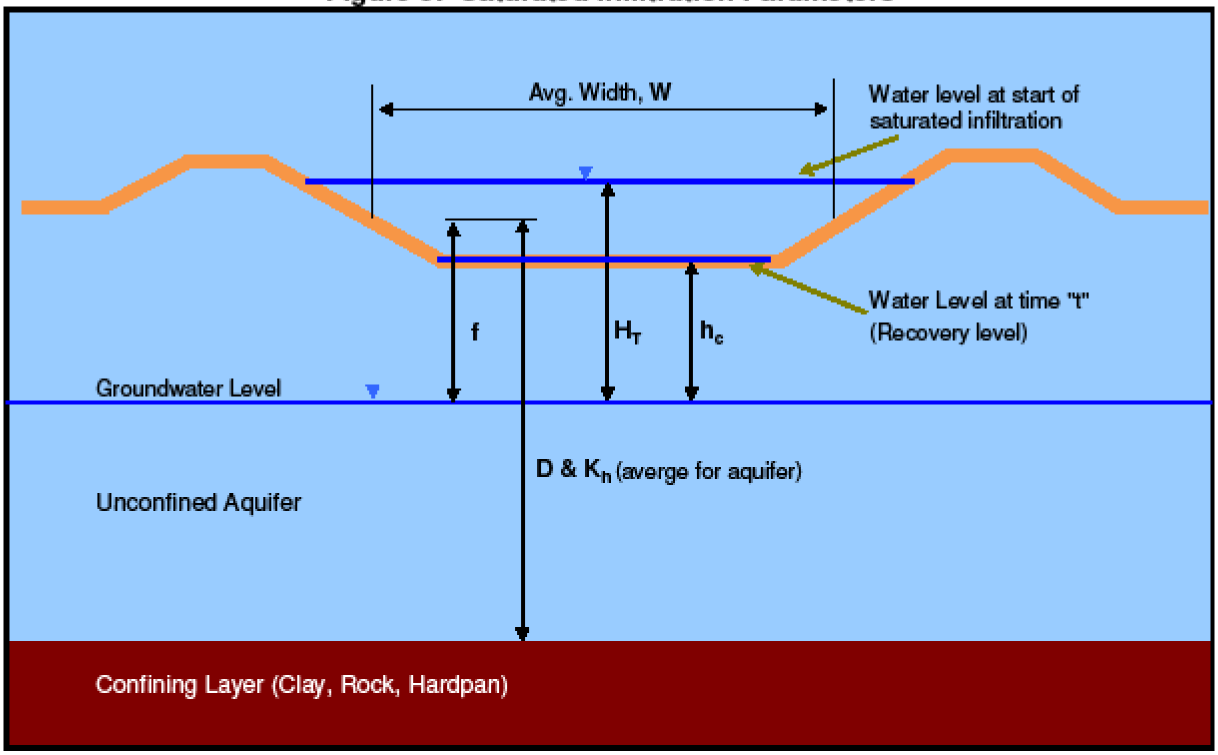
To simplify the analytical method for stormwater retention ponds, Andreyev & Wiseman (1989) modified the dimensionless parameters developed by Ortiz, Zachmann, McWhorter and Sunada (1979). To generate the modified dimensionless curves, Andreyev & Wiseman (1989) conducted hundreds of MODFLOW model runs for a variety of pond sizes, aquifer thicknesses, depths to groundwater level and horizontal hydraulic conductivities. The model simulations were conducted for rectangular ponds with the following five length to width ratios (L/W) and four specific values of storage coefficients (f):

L/W = 1.0, 2.0, 4.0, 10.0 and 100.0
f = 0.10, 0.20, 0.30, 0.40

For all practical purposes, the modeling results indicated that for $L/W > 100.0$ the infiltration characteristics are the same as for $L/W = 100.0$. The four sets of dimensionless curves, for each value of storage coefficient, are presented on **Figures 6 through 9**.

The modified dimensionless parameters are presented on **Figure 5** below:

Figure 5: Saturated Infiltration Parameters



The dimensionless parameters can be expressed as follows:

$$Fx = \left(\frac{W^2}{4 K_h D t} \right)^{1/2}$$

$$Fy = \frac{hc}{H_T}$$

The dimensionless curves of **Figures 6 through 9** can be used to calculate the water level in the pond, hc, for a given set of pond and aquifer parameters and a specified time period of recovery; or to calculate the time of recovery, t, for a given set of pond and aquifer parameters and a level of recovery, such as the pond bottom. The following are equations to solve for "t" and "hc", which were derived from the dimensionless parameter equations above:

$$t = \frac{W^2}{4 K_h D {F_x}^2}$$

$$h_c = F_y \, H_T$$

The MODRET model was developed by Nicolas Andreyev in 1990 based on the results of the Andreyev & Wiseman (1989) research to allow estimated of infiltration analysis using the MODFLOW model directly without applying the dimensionless curves method. The MODRET model has been improved and modified multiple times over the years and the version 7.0 is the latest model improvements made in 2018. The changes made this version of the model simplify the utilization of the model and expand the various applications that allow design and permitting of stormwater retention/detention ponds.

Summary

An analysis of the infiltration losses from a stormwater retention pond has been presented in two phases. The first phase is concerned with the rate at which water flows out of a pond by vertical infiltration through its bottom. The equation developed by Green and Ampt (1911) is used to describe the vertical infiltration for the retention pond. The second phase of the analysis deals with the response of the water table to recharge from the retention pond. From a pond designer's point of view, this is important because when the groundwater mound intersects the pond bottom, the infiltration rate analysis becomes a function of lateral dissipation through the saturated aquifer and storage in the unsaturated zone instead of vertical infiltration. It is important to note that the hydraulic conductivity referred to in the two phases of the analysis is not the same. Unsaturated infiltration is concerned with vertical flow while the groundwater mounding is mainly influenced by horizontal flow. The difference between the hydraulic conductivities in the two directions is usually associated with horizontal layering of the soil. Hydraulic conductivity tests can be conducted in the field or in the laboratory. Numerous methods of hydraulic conductivity (permeability) tests are available in various text books and publications and will not be presented in this course.

This course is offered through SunCam.com for 4 PDH (hours) of continuing education credits for engineers.

References

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Figure 6

Dimensionless Curves Relating Pond and Aquifer Design Parameters to Pond Water Level for a Rectangular Pond in an Unconfined Aquifer System (Soil Storage Coefficient f=0.10)

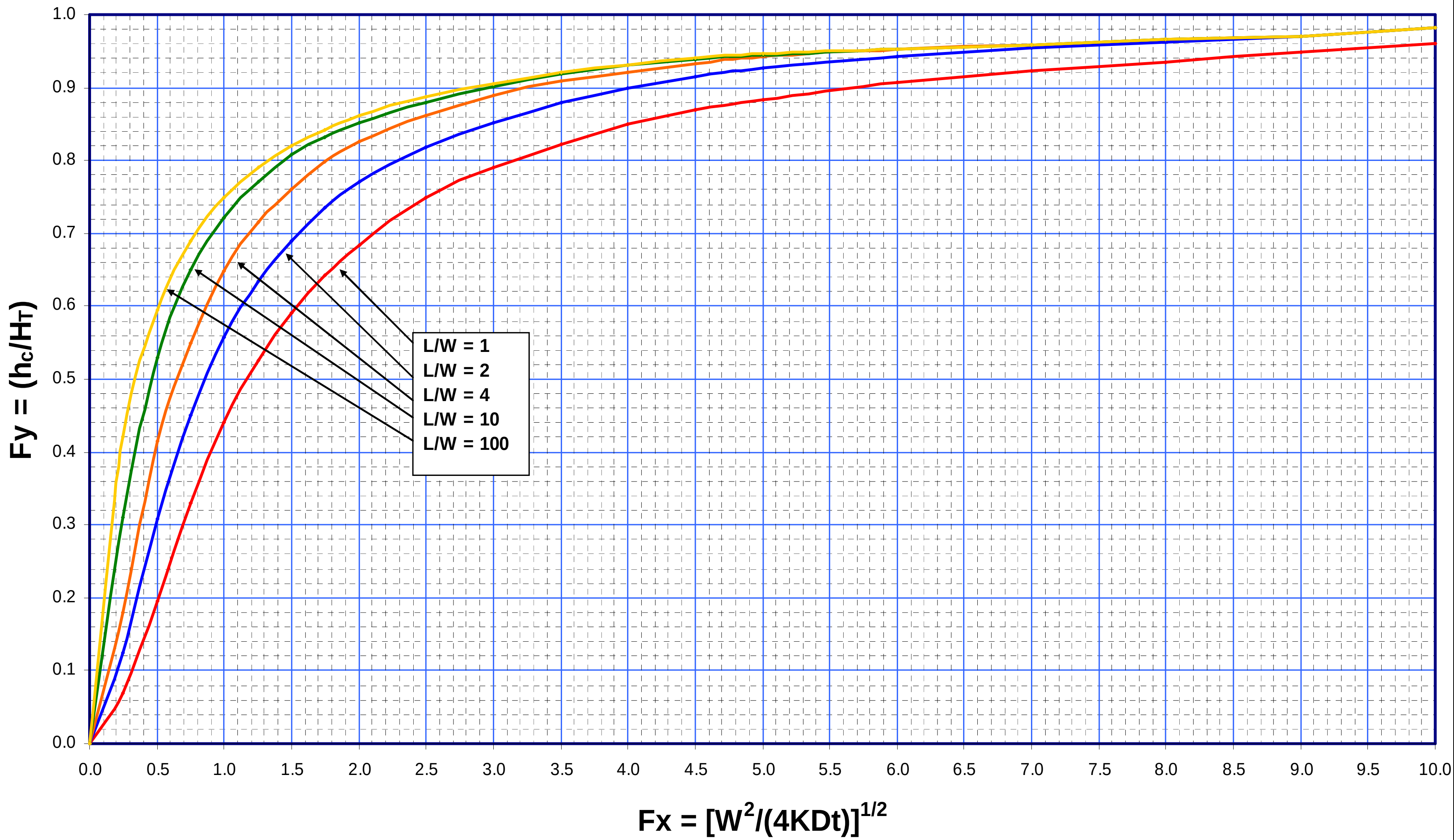


Figure 7

Dimensionless Curves Relating Pond and Aquifer Design Parameters to Pond Water Level for a Rectangular Pond in an Unconfined Aquifer System (Soil Storage Coefficient f=0.20)

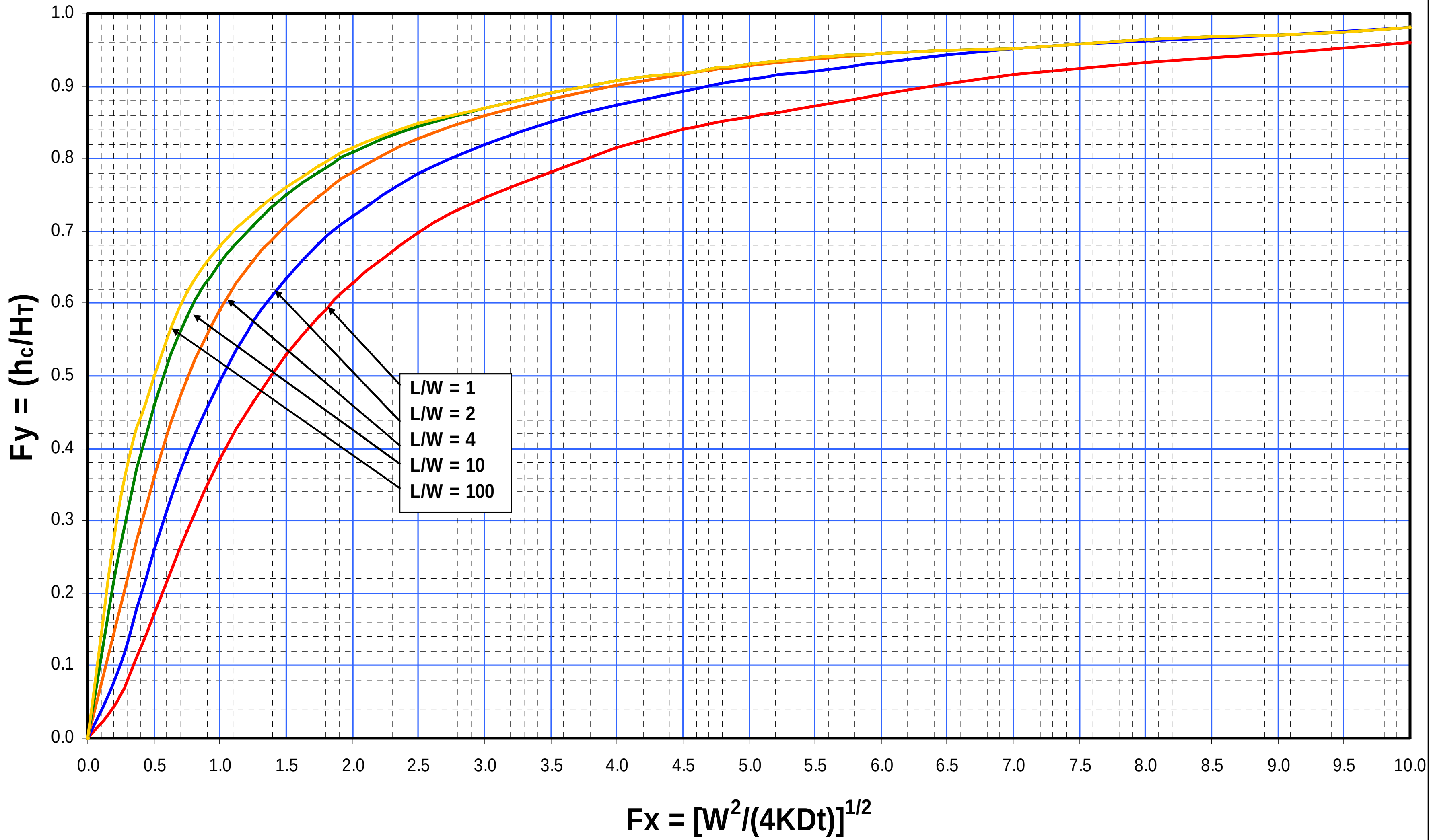
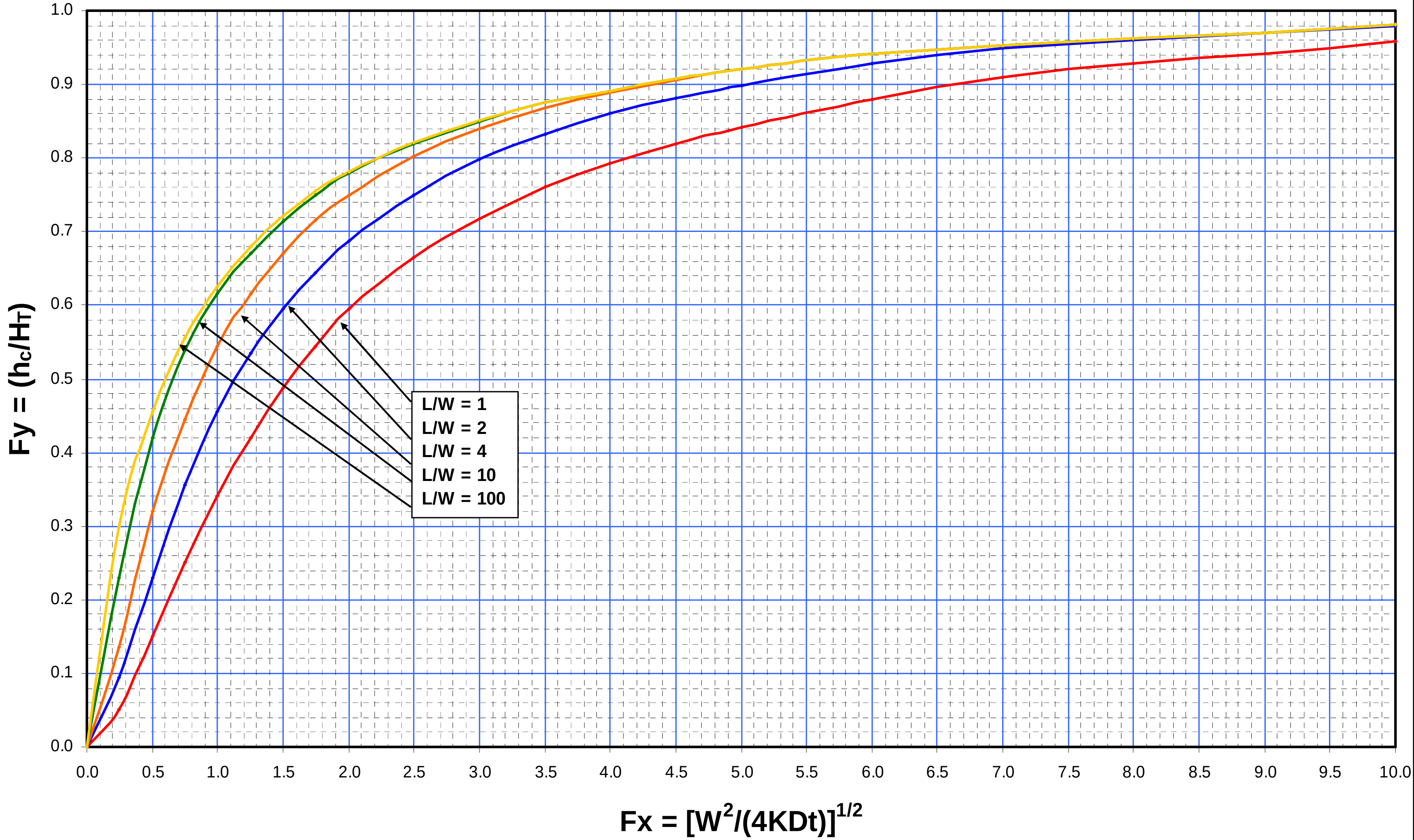


Figure 8

Dimensionless Curves Relating Pond and Aquifer Design Parameters to Pond Water Level for a Rectangular Pond in an Unconfined Aquifer System (Soil Storage Coefficient f=0.30)



$F_y = (h_c/H_T)$

$F_x = [W^2/(4KDt)]^{1/2}$

Figure 9

Dimensionless Curves Relating Pond and Aquifer Design Parameters to Pond Water Level for a Rectangular Pond in an Unconfined Aquifer System (Soil Storage Coefficient f=0.40)