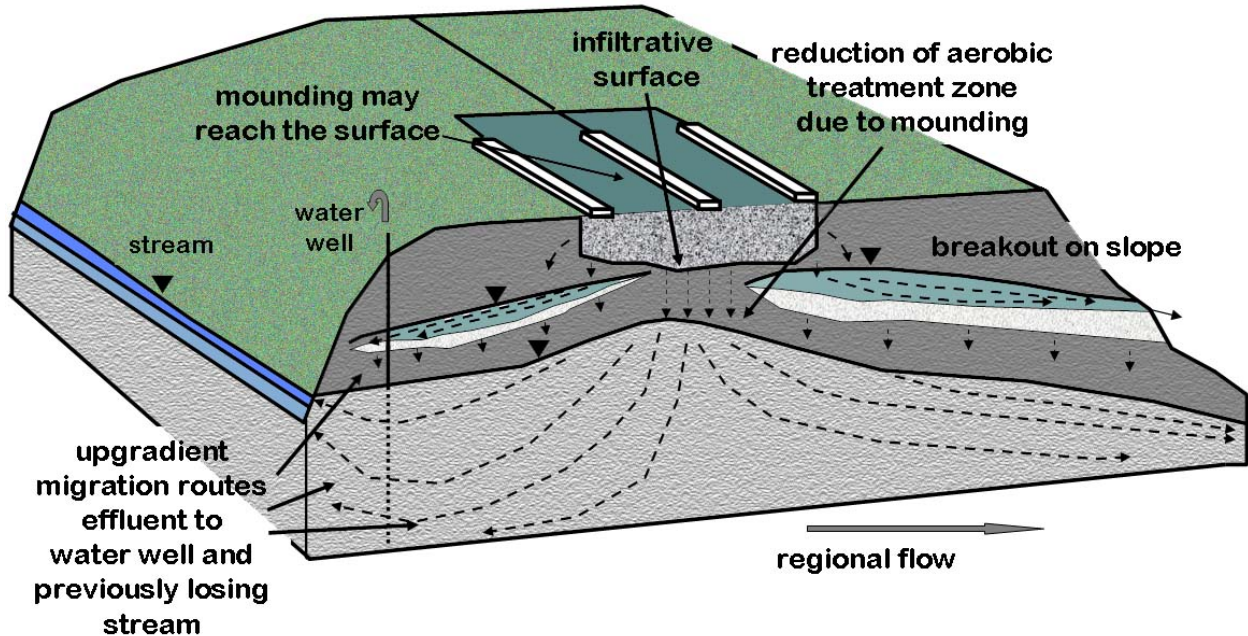


**This report by Poeter et al. (2005) contains an error in the section on vadose-zone mounding. In the report, the figure and equations mistakenly use the full width (W) in place of the half-width, w, which should have been used. The vadose-zone layer examples in the report that demonstrate calculation and use of a maximum infiltration-area width, actually represent a maximum half width for a given  $H_{\max}$ . The methodology example in the report is still correct, however. The full width W was and should be used for design calculations. The terminology and equations for the saturated zone mounding in the report are not affected by this correction.**



## Guidance for Evaluation of Potential Groundwater Mounding Associated with Cluster and High-Density Wastewater Soil Absorption Systems

Colorado School of Mines  
Golden, Colorado

January 2005

# **Guidance for Evaluation of Potential Groundwater Mounding Associated with Cluster and High-Density Wastewater Soil Absorption Systems**

**Submitted by International Groundwater  
Modeling Center of Colorado School of  
Mines, Golden, Colorado**

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## ABSTRACT

Hydrologic evaluation of cluster and high-density wastewater soil absorption systems (WSAS) is important because it can help ensure that a site has sufficient capacity to assimilate water in excess of natural infiltration. Insufficient capacity may result in significant groundwater mounding on low hydraulic conductivity lenses or elevate the water table, which may alter saturated flow direction or reach the surface. Insufficient capacity can also cause lateral movement of water, which may affect nearby water supplies or water bodies or cause effluent breakout on slopes in the vicinity. Practitioners and stakeholders must be informed of the issues so they will be able to complete the proper investigations and evaluations. Most critical is evaluation of the potential for reduction of the vadose zone thickness, which could result in inadequate retention times and conditions for treatment of wastewater pollutants. This report presents a methodology for:

- Evaluation of site-conditions and system-design influences on the potential for groundwater mounding and lateral spreading
- Selection of investigation techniques and modeling approaches based on site conditions, system parameters, and the severity of the consequences of excessive mounding

A flow chart and decision-support tool are provided to determine the strategy-level for site investigation and model evaluation depending on the potential for groundwater mounding and the consequences should it occur. Characterization activities and modeling approaches, appropriate for each level of assessment are delineated.



## EXECUTIVE SUMMARY

Cluster and high-density wastewater soil-absorption systems (WSAS) (those receiving more than 2,000 gallons of water per day or GPD) are increasingly required to serve development. In the past, system designers and regulators focused on vertical movement of water from WSAS because most systems are small and isolated. However, insufficient capacity may result in (see Figure ES-1):

- Significant groundwater mounding on low hydraulic conductivity lenses or elevation of the water table (which may alter saturated flow direction or reach the surface)
- Lateral movement of water, which may affect nearby water supplies or water bodies, or may cause effluent breakout on slopes in the vicinity

### Rationale and Purpose

For the purpose of this report, failure is considered to be excessive mounding. Some mounding will not cause hydraulic breakout at the surface or side slopes or insufficient treatment of the wastewater, but may impact performance efficiency of the WSAS, or cause the system to be out of compliance with local regulations. This report focuses on the methodology for determining the magnitude of mounding, vertically and laterally. Once that magnitude is known, the designer must determine whether the WSAS function will be acceptable based on treatment requirements and local regulations.

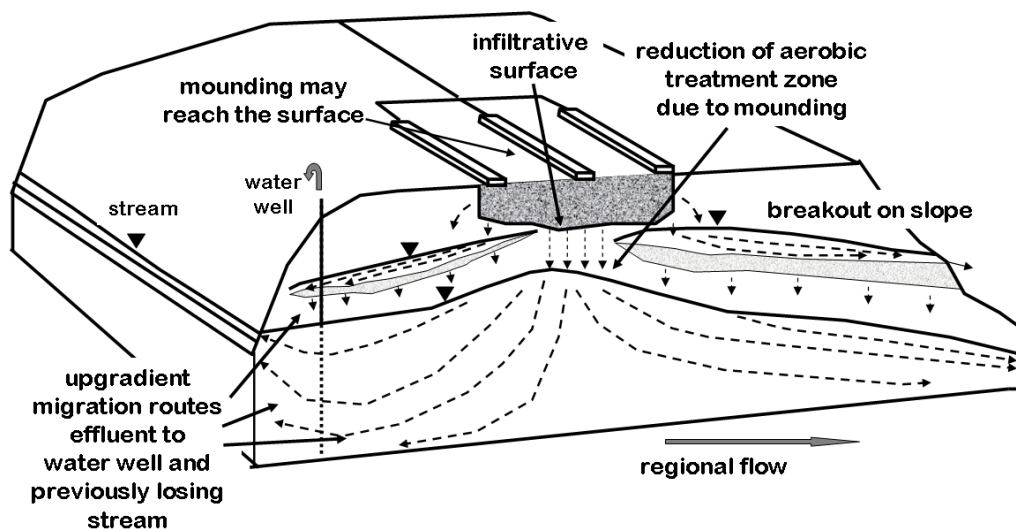


Figure ES-1  
Potential Groundwater Mounding Below WSAS



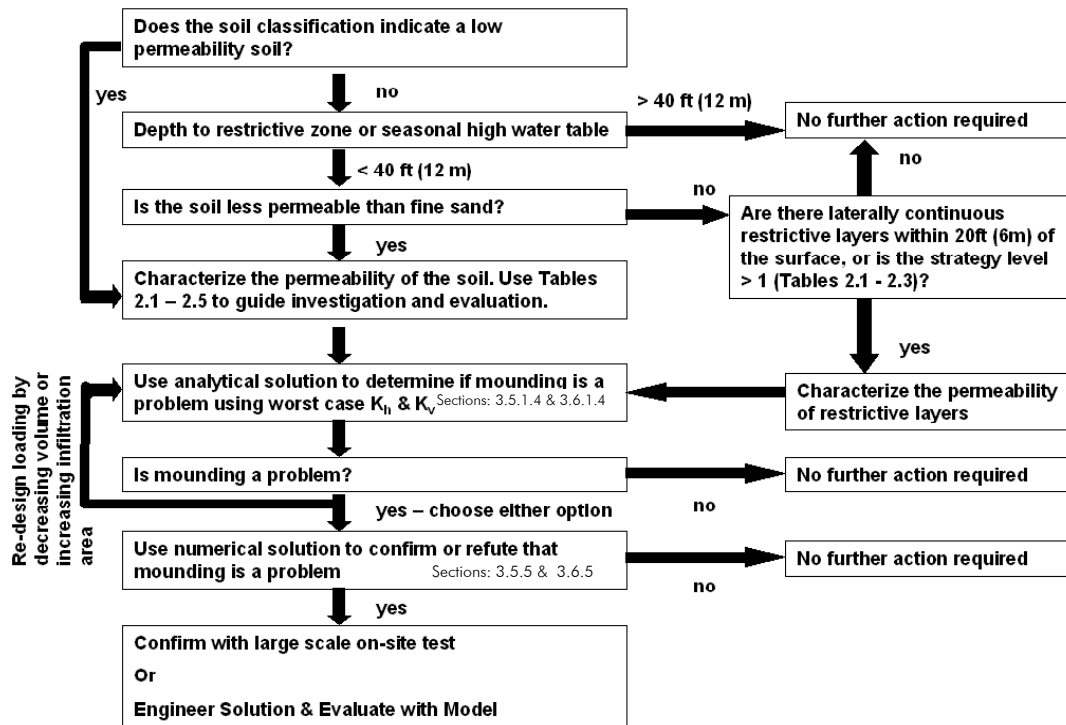
Hydrologic evaluation is important because it ensures a site has sufficient hydraulic capacity to assimilate water in excess of natural infiltration. Practitioners and stakeholders must be informed of the issues so they will be able to complete the proper investigations and evaluations. Most critical is evaluation of the potential for reduction of the vadose (unsaturated) zone thickness, which could result in inadequate retention times and conditions for treatment of wastewater pollutants.

This report presents a methodology for:

- Evaluation of site-conditions and system-design influences on the potential for groundwater mounding and lateral spreading
- Selection of investigation techniques and modeling approaches based on site conditions, system parameters, and the severity of the consequences of excessive mounding

## Methodology

Evaluation of the potential for groundwater mounding and break-out on the surface or side slopes requires different levels of effort depending on the characteristics of the subsurface and the consequences of system failure. The phased approach indicates more investigation as the risk of mounding increases and the consequences of failure due to mounding become more severe. A flowchart guides preliminary assessment and indicates subsequent steps, based on preliminary site investigation to determine depth to groundwater and soil types (Figure ES-2). Specific sections of the report elaborate on these steps.



**Figure ES-2**  
**Flowchart for Preliminary Assessment of the Potential for Groundwater Mounding Guides**  
**Subsequent Steps of the Assessment Process**

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## ***Decision-Support Tool***

A decision-support tool quantifies a subjective strategy level that defines the intensity of site characterization and modeling appropriate for a given site, following the philosophy that the degree of characterization and associated cost should be considered in light of the potential for mounding and the consequences should mounding occur. The decision-support tool utilizes additional qualitative information relative to the flowchart as well as site-specific quantitative data from field investigations to determine the strategy level for site assessment. The strategy level provides a guide to the magnitude and intensity of field investigation and the sophistication of modeling. Guidance on site investigation is provided in Chapter 2, while guidance on modeling is presented in Chapter 3 of this report. Associated costs of field investigations and model assessment are discussed at the end of Chapters 2 and 3.

## ***Levels of Site Investigation***

Sites with hydraulic conditions that indicate low risk of mounding, and have minimal consequences in the case of mounding, can be assessed using minimal site investigation (Chapter 2, sections 2.2 through 2.4) and using analytical solutions to estimate mound height (Chapter 3, sections 3.5.1 through 3.5.4 for evaluation of vadose zone mounding; and sections 3.6.1 through 3.6.4 for saturated zone modeling). Spreadsheets for evaluating mounding of the water table ([WaterTableMounding\\_EnglishUnits.xls](#) or [WaterTableMounding\\_SIUnits.xls](#)) are available electronically with this report on the CD and online at [www.ndwrcdp.org](http://www.ndwrcdp.org). In these low-risk cases, the estimated height of mounding is added to the high water table to determine if the design will be acceptable.

Sites with hydraulic conditions that indicate risk of mounding, and where the consequences of mounding are severe, require more intense field investigations (Chapter 2, sections 2.5 and 2.6) and sophisticated numerical models to estimate mound height (Chapter 3, section 3.5.5 for evaluation of vadose zone mounding of water on low hydraulic conductivity layers; and section 3.6.5 for mounding of the water table based on flow in the saturated zone). Advanced assessment is particularly important for sites where mounding has serious consequences, and sites that exhibit strong heterogeneity and/or anisotropy, sites with complicated boundary conditions, and those with significant time-varying hydraulic conditions.

## ***Hydraulic Conductivity of the Soil And Aquifer***

For evaluation of mounding, the most significant factor is the hydraulic conductivity of the soil and aquifer, as indicated by example calculations presented in this report. Accurate measurement of hydraulic conductivity (K) is difficult because its value varies substantially over short distances due to heterogeneity. Therefore, careful attention must be given to this important parameter.

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Hydraulic conductivity cannot be accurately estimated from simply knowing the soil type because  $K$  of a given soil type may vary by orders of magnitude. Therefore, obtaining reliable measurements of  $K$  when performing engineering analysis for cluster systems is important. Suggested methods for measurement of  $K$  in unsaturated and saturated soil are outlined in Chapter 2, section 2.6. Errors on the order of a factor of 10 would not be unusual; even when site-specific measurements are collected.

Analyzing the statistics on several measurements provides insight on the error associated with  $K$  measurements. If the designer has not collected detailed measurements of  $K$ , but has obtained a reasonable estimate based on soil classification or a few measurements, then the site should be evaluated using a range of  $K$ , including the expected value and a factor of 10 above and, most importantly, below the expected value for estimating mound height.

### ***Analytical and Numerical Modeling***

Whether the assessment requires analytical or numerical modeling, the designer must consider two possibilities:

- Wastewater may mound on low hydraulic conductivity layers in the vadose zone
- Wastewater may cause mounding of the water table beneath the infiltration area or the perched mound

Analytical models provide estimates of both types of mounding with little investment of the designer's time. If the analyses use conservative parameter values and the results indicate mounding is not excessive, then more expensive and time-consuming analyses are not required.

Limitations of analytical models should be recognized so that conservative parameter values can be selected. These limitations are summarized in the following section. Guidance on coping with the limitation is provided in this report. The limitations include:

- The analytical solutions provided for estimating mounding on a low hydraulic conductivity layer in the vadose zone do not consider unsaturated-flow physics due to the computational complications such consideration would generate. Consideration of these processes would delay the time of mound development, but decrease its magnitude; thus their omission is reasonable.
- The analytical solutions do not account for anisotropic hydraulic conductivity. Hydraulic conductivity,  $K$ , is a soil property describing how easily water flows through the soil. Anisotropy is the situation where  $K$  varies with direction. Generally the vertical hydraulic conductivity is less than the horizontal; however, the reverse is sometimes found in soil deposited by wind.

- 
- The analytical solutions do not account for heterogeneity. Heterogeneity is the variation of K in space. If heterogeneities are randomly distributed, then the best value to use for K is the geometric mean of the various K values. However, collecting sufficient data for a reasonable assessment of the geometric mean is unfeasible. Thus, a conservative (low) value for K must be chosen, probably based on the results of several spatially variable estimates or measurements of K. If a discontinuous layer exists, then assuming the layer is continuous would provide a conservative estimate (over prediction) of the mound height and extent because some of the wastewater would travel between the discontinuous low-K zones and would not mound in these areas. For severely heterogeneous systems, several pilot-scale infiltration tests should be conducted.
  - The analytical solutions do not consider the possibility of heavy rainfall causing short-term increased mounding. To address this issue, one needs to use a numerical model that can simulate transient, unsaturated flow. However, as a conservative assumption, the designer could assume that the mound height would increase by the total rainfall accumulated during the storm divided by porosity of the soil. A more reasonable estimate could be obtained by subtracting an estimated amount for runoff.

Although simplifying assumptions are made when using analytical models, expediency warrants their use before numerical modeling is considered. When there is potential for problematic mounding as judged by preliminary assessment and design changes cannot sufficiently reduce that potential, then use of a numerical model is appropriate. Setting up numerical models for a specific site is time consuming and requires a significant level of expertise in hydrology, soil physics, numerical methods, and computer operation, and is therefore quite expensive. However, if the risks associated with excessive mounding are serious, the expense may be worth the effort.

## Getting Started

Practitioners seeking to utilize the methods presented in this report can best accomplish this by working through the recommendations of Chapter 2, *Site Evaluation for Groundwater Mounding Potential* and moving on to sections of Chapter 3, *Evaluating Groundwater Mounding With Models* as needed.

The first consideration in design of a large system is to specify an overall size of the infiltration area that, when coupled with the anticipated volumetric loading rate, results in an infiltration rate that is less than the vertical hydraulic conductivity of the soil to prevent the development of ponding of wastewater over the infiltration area. That is:

$$\frac{Q}{A} < K_v$$

for consistent dimensional units of volume, length, and time. Next, recognizing spatial constraints of the site and reasonable dimensions for construction, strive to elongate the infiltration area in the direction perpendicular to groundwater flow beneath the site. Preliminary data acquisition as outlined in Chapter 2, *Site Evaluation for Groundwater Mounding Potential*, will provide approximate values for  $K_v$  and flow direction.

---

After establishing this reasonable design, the designer must consider the potential for perching and mounding of water on low hydraulic conductivity layers in the vadose zone and ultimately the rise of the water table required to carry the wastewater away from the site. Site-scale hydraulic conductivities are extremely important to performance of the WSAS, but are difficult to determine with certainty. Chapter 2, *Site Evaluation for Groundwater Mounding Potential*, guides the designer in evaluating the amount and type of field investigation appropriate for a site and refers the designer to Chapter 3, *Evaluating Groundwater Mounding With Models* for analytical, and if necessary, numerical modeling.

The analytical modeling recommended in this report is readily accomplished using a calculator in the case of estimating mounding on low hydraulic conductivity layers in the vadose zone, and the spreadsheets that accompany the report ([WaterTableMounding\\_EnglishUnits.xls](#) or [WaterTableMounding\\_SIUnits.xls](#)) in the case of water table mounding of the saturated zone.

Unless the designer is knowledgeable in the area of numerical modeling, he or she will likely enlist a modeler to assist with the work. In spite of this, the sections on numerical modeling (Chapter 3, sections 3.5.5 and 3.6.5) are recommended reading because they are not directions on how to conduct numerical modeling, but rather illustrations of how mounding is likely to vary for conditions that cannot be evaluated with analytical models. The insight they provide is useful to all phases of investigation and design. Hypothetical site dimensions and conditions are evaluated to illustrate generic system responses. Actual values of mound height and extent can only be determined for site-specific properties, dimensions, and boundary conditions.



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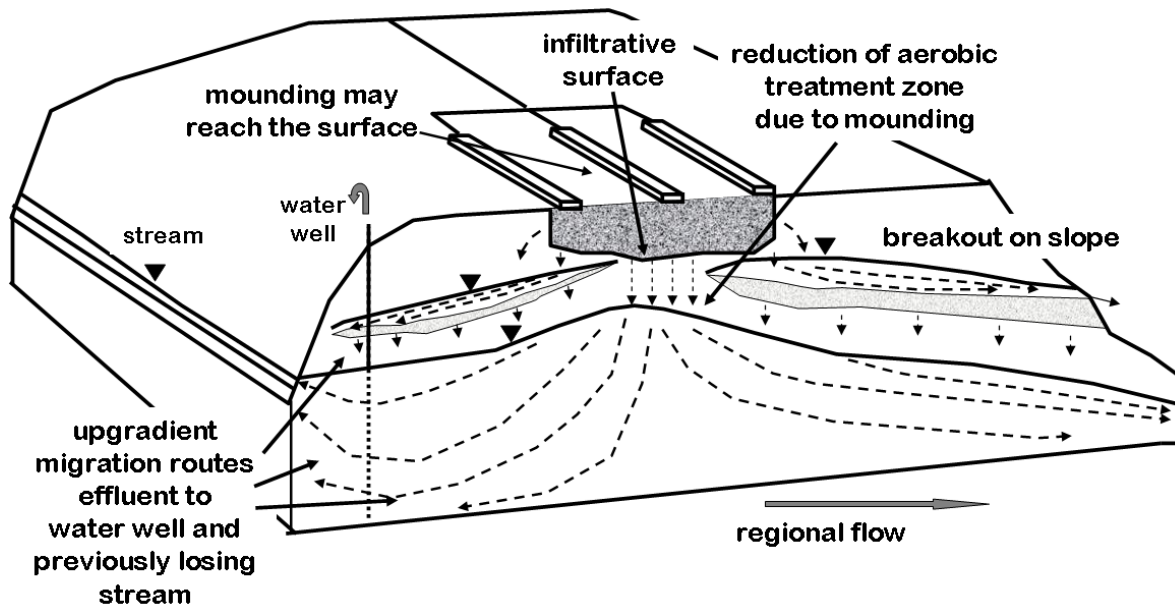
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# 1 INTRODUCTION

Cluster and high-density wastewater soil-absorption systems (WSAS) (those receiving more than 2,000 gallons per day, GPD) are increasingly required to serve development. In the past, system designers and regulators focused on vertical movement of water from WSAS because most systems are small and isolated. However, increased use of high-density or cluster WSAS requires hydrogeologic evaluation to help ensure the site has sufficient capacity to accept the design flow in addition to the natural infiltration without:

- Resulting in groundwater mounding on low hydraulic conductivity (K) lenses or by elevating the water table (which may alter flow directions or cause groundwater to reach the surface)
- Lateral movement of water, which may affect nearby water supplies or water bodies, or may cause effluent breakout on slopes in the vicinity (Figure 1-1)



**Figure 1-1**  
**Issues of Concern That Can Be Addressed With a Hydrogeologic Evaluation.**

## 1.1 Rationale

Hydrologic evaluation is important because it ensures that a site has sufficient capacity to assimilate water in excess of natural infiltration. Practitioners and stakeholders must be informed of the issues so they will be able to complete the proper investigations and evaluations. Most critical is the evaluation of the potential for reduction of vadose zone thickness, which could result in inadequate conditions for treatment of wastewater pollutants.

## 1.2 Purpose

The purpose of this document is to provide guidance on evaluation of the magnitude of mounding, which may cause breakout of groundwater above or adjacent to large cluster and high-density WSAS such as those that may serve clusters of homes, resorts, small communities, apartment and condominium complexes, and have daily flow volumes 10 or more times greater than individual systems. This document specifically does not address the long-term acceptance rate (LTAR) of the WSAS trenches. For discussion of LTAR, refer to Siegrist (1987) and Siegrist *et al.* (2001).

This report presents methodology for determining the magnitude of mounding, vertically and laterally. Once that magnitude is known, the designer must determine whether the WSAS function will be acceptable based on treatment requirements and local regulations.

## 1.3 Methodology

This report presents a methodology for:

- Evaluation of site-conditions and system-design influences on the potential for groundwater mounding and lateral spreading
- Selection of investigation techniques and modeling approaches based on site conditions, system parameters, and the severity of the consequences of excessive mounding

Methodology for site investigation and evaluation of the potential for groundwater mounding as perched zones or as a rise in the water table is presented in Chapter 2, *Site Evaluation for Groundwater Mounding Potential*. The phased approach indicates more investigation as the risk of mounding increases and the consequences associated with excessive mounding become more severe. A flowchart guides preliminary assessment and indicates subsequent steps, based on preliminary site investigation to determine depth to groundwater and soil types. A decision-support tool extends the method, following the philosophy that the degree of characterization and associated cost should be considered in light of the potential for mounding and the consequences of failure. The decision-support tool utilizes additional qualitative information as well as site-specific quantitative data from field investigations to determine the strategy-level for site assessment. The strategy level provides a guide to the magnitude and intensity of field investigation and the sophistication of modeling.

Modeling approaches are presented in Chapter 3, *Evaluating Groundwater Mounding With Models*. Findings are summarized in section 3.6.5.1.

References, definitions, and a summary of software for numerical simulation of the vadose zone are presented in Chapter 5, *References*, Appendix A, *Definitions*, and Appendix B, *Numerical Unsaturated Flow Codes*, respectively.

To begin design work immediately, read Chapter 4, *Summary*; then proceed to Chapter 2, *Site Evaluation for Groundwater Mounding Potential* and begin work as you read.

## 1.4 Background

While this document is focused on methods to evaluate the potential for groundwater mounding, the overall design criteria are briefly reviewed to provide a framework for the detailed discussion of mounding. WSAS are required to dispose and treat large quantities of sewage without degrading groundwater quality. This requirement drives the primary design criteria.

### 1.4.1 Wastewater Treatment by WSAS

As presented by US EPA (2002) and Siegrist *et al.* (2001), treatment of raw wastewater may occur by a variety of methods (such as septic tank or sand filter). Then effluent is dispersed to the infiltrative surface, which is usually a series of trenches, or in some cases, a single bed, where the effluent is allowed to infiltrate into the soil. During infiltration, treatment occurs, involving physical, chemical, and biological processes that remove and transform most pollutants. Finally, the treated water percolates downward through the vadose (unsaturated) zone until it reaches the water table as recharge.

If low hydraulic conductivity units are encountered during percolation, perched water tables may form and, in some cases, mound to the surface or breakout on nearby slopes. Ultimately the water infiltrates to the water table (recharge), causing a rise of the water table (a mound), and flows away from the site. The rate of application and the magnitude of the mound are related, depending on the properties of the soil and the hydraulic boundaries of the groundwater system. Hydraulic failure occurs if the mound reaches the surface; however, the system may be categorized as failing if mounding causes the vadose zone thickness to be less than regulation specifications.

Treatment processes occur in the vadose zone, which includes mineral grains (sand and silt), clays, organic particles, and organic grain coatings. Important processes include:

- Retention caused by the range of pore throat sizes in soil where pathogens such as bacteria are trapped by small soil pores
- Sorption, which causes the solutes to adhere to organic soil particles and grain coatings
- Reaction of iron- and aluminum-bearing phases in the fine-grained portion of the soil facilitates phosphorus removal that can occur in the unsaturated (aerated, oxygenated) zone
- Conversion of solutes by native microorganisms to more desirable chemical species (this process is more efficient in the unsaturated zone)
- Denitrification (conversion of nitrate to nitrogen gas), which requires anaerobic (oxygen depleted) conditions and a suitable organic carbon source
- Aeration enhances aerobic degradation of organic matter and allows gas phase transport of volatile components
- Nitrification, the conversion of reduced (organic and inorganic) nitrogen to nitrate allows denitrifying bacteria to convert to the nitrate nitrogen gas

- Virus removal is facilitated by sorption onto surfaces, which retards transport rates and promotes viral death
- Pathogen die-off after sufficient time of exposure to adverse conditions

Thus, the ideal WSAS would remove pollutants from the wastewater effluent while allowing the water to reach the water table where it can dissipate without forming a large mound.

To function at maximum efficiency, a portion of the soil zone must be unsaturated because many key treatment processes are more rapid in an aerated environment. Thus, the soil profile under an infiltrative surface should have a sufficiently thick unsaturated zone to enable advanced treatment. Although local regulations vary, requirements often stipulate about three feet (one meter) of permeable, unsaturated, aerobic soil with a low percolation rate (to allow time for treatment) below the infiltrative surfaces (Tyler and Converse 1994). Some permitting entities allow for a thinner vadose zone if wastewater is pretreated.

### **1.4.2 WSAS Failure**

Unsuitable soil conditions and high water tables can cause hydraulic dysfunction and even failure. The most common cause of hydraulic failure is the inability to handle the excessive recharge to the soil due to the application rate being greater than the hydraulic conductivity of the soil as modified by biomat formation.

Three main shortcomings of characterization that lead to hydraulic failure are:

- Underestimating K of the water-table aquifer
- Overlooking a low-K layer below the infiltrative surface
- Failing to recognize that a seasonal water table rise reduces the thickness of the unsaturated zone

Finnemore and Hantzche (1983) identified high water tables as one of the major causes of failure in WSAS. Typically such failures were associated with:

- Larger-scale treatment systems in clay and clay loam (low hydraulic conductivity soils)
- Shallow depth to groundwater (less than two feet or 0.6 meter)
- Low effluent quality

Failures can be minimized by proper site evaluation and system design. Design solutions to problems that are recognized during evaluation include increasing trench length or area, alignment of the long axes of trenches perpendicular to the direction of regional groundwater flow, and relocation of infiltrative surfaces to more favorable areas.

### 1.4.3 WSAS Case Studies

Numerous case studies from the literature and from submissions to a web site specifically designed for this project were reviewed (see Table 1-1) to identify studies of WSAS to provide examples to illustrate the importance of evaluating the potential for groundwater mounding. The intention was to locate a few case studies with sufficient information to test that the procedure specified in this report identifies mounding problems prior to installation and operation. None of the studies provided sufficiently detailed site information on WSAS to enable rigorous testing of the recommended procedure. Some studies, however, are related to the preliminary assessment process in Chapter 2, section 2.8 (Characterization Costs) of this report.

**Table 1-1**  
**List of Case Studies Reviewed to Identify Useful Examples for This Report**

Author(s)	Year
Bianachi and Haskell	1968
Bouma	1971
Chan and Sykes	1984
Cheschair and others	1988
Corbett and Iverson	1999
Converse and Tyler	1985
Daniels and Fritton	1994
Dewalle	1981
Fielding	1982
Finnemore and Hantzsche	1983
Goff and others	2001
Guo	2001
Jones and Taylor	1964
Kahn and others	1976
Marino	1974
Ortiz and others	1979

Author(s)	Year
Plews and Dewalle	1985
Rao and Sarma	1980
Rea and Upchurch	1980
Sherlock and others	2002
Sherman and others	1998
Sumner and Bradner	1996
Sumner and others	1999
Tsay and Hoopes	1998
Tyler and Converse	1994
Tyler and Converse	1985
Tyler	2001
Uebler and others	1985
Uebler and others	1991
USEPA	2002
Weymann and others	1998
Wilson and others	1987



#### 1.4.3.1 WSAS Case Studies Indicate the Need to Evaluate Potential Groundwater Mounding

A number of these studies illustrate the need for assessment as discussed in this section. For instance, Goff *et al.* (2001) reported on a case in Jefferson County, Arkansas where seasonal high water tables rise within two inches (5 cm) of the surface causing WSAS installations to fail, with failure defined by fecal coliform levels remaining above regulatory requirements. In this case, drains were installed on either side of a trench in fine silty Aquic-Dystric-Eutrochrept soil to lower the water table and enable sufficient treatment.

Water levels and fecal coliform levels were monitored in adjacent wells to determine if water levels were lower and treatment was sufficient. Water levels were lowered at least 50 cm, but fecal coliform levels remained above regulatory requirements. The report presented information on the soil structure including detailed soil type descriptions to a depth of 1.3 m, loading rates, and water table elevations for a four-month period. The report did not include measurements of soil properties or clear definitions of boundary conditions, making accurate calculations problematic. If these data were available, mounding could have been predicted at the initial design stage, and drains could have been included in the initial design. In this case, however, failure in terms of water quality may still have occurred due to the limited thickness of the infiltrative zone.

Another study by Uebler *et al.* (1985) also used a series of drains to lower seasonal high water levels. In this study, the soil was described carefully and measurements of the water table, monitoring wells and application rates are available. Low hydraulic conductivity layers were present in the form of cemented zones. The study concluded that the drains were able to lower water levels near application trenches where the cemented layers were not continuous or cementing was poor, while the water table remained high in areas with laterally extensive, well-cemented layers. Direct measurements of flow properties were not provided for either the dominant soil or the low hydraulic conductivity layers. In addition, the degree of cementation and lateral continuity were not quantitatively defined. These missing data would be instrumental in predicting the mounding problem.

The studies of Bianchi and Haskell (1968), Guo (2001), and Sumner *et al.* (1999) all compared various mathematical techniques for estimating mounding beneath large recharge ponds, not failing WSAS. In these studies, the properties of the soil zone and underlying aquifer were either based on well tests that produced an average value for the entire saturated zone (Bianchi and Haskell 1968) or assumed values for the purposes of calculations. The studies all mention the limitations of the assumption of homogeneous soil properties. In fact, Bianchi and Haskell (1968) report that the presence of a low hydraulic conductivity layer under the pond only became evident during development of the main central well on the site. This indicates the necessity for careful site characterization if prediction of mounding is to be reliable.

The most interesting published study was presented by Chan and Sykes (1984) who describe a period of failure during operation of a large experimental leaching area. During initial loading of the infiltration area at 122,700 liters per day (LPD), the system failed as evidenced by surface ponding. Reducing the load to 40,900 LPD allowed the system to function properly. Estimations for most of the required parameter values were based on soil types and approximate values for hydraulic conductivity were obtained from several slug tests. A model of the system was then calibrated to obtain final parameter values that would yield water levels that matched observed water levels for two model solutions. Estimated values were applied to the entire soil column even though there were soil surveys showing layering, including sediments ranging from silty-sand to clayey-silt underlying the leach area. Several deviations between field and simulated mounds were noted. While the study is interesting, the soil data were only summarized, which did not provide sufficient detail to carry the recommended procedure through rigorous numerical modeling.

#### 1.4.3.2 Large WSAS and Cluster Systems

Although large WSAS and cluster systems have been designed and implemented across the US for more than 20 years, they have rarely been implemented through design practices based on thorough site evaluation, soil and groundwater testing, and modeling, and they seldom are monitored for hydrologic performance over long time frames (such as decades). As a result, case studies of large WSAS or cluster WSAS have not been located in the literature for evaluation of the utility and appropriateness of the methodologies developed in this project.

After concluding that sufficiently detailed case studies were not available in the literature, the project team identified several large WSAS and cluster WSAS that were installed in Washington County, Minnesota during the 1980s that included system designs employing

- Shallow serial trench networks for soil treatment and disposal of septic tank effluent (STE)
- Narrow geotextile-lined trenches for infiltration of community STE
- Shallow trench networks for high rate infiltration of sand filter effluent

These large WSAS were designed and implemented by R. L. Siegrist, R. J. Otis, and others affiliated with Ayres Associates in Madison, Wisconsin. The system designs were based on thorough site evaluations, site-specific testing, and analytical modeling. Implementation included process operation and performance monitoring during startup and early operation. Whether process and performance monitoring has continued during the past 15 years is unknown. Case studies of these Washington County systems were not published in the literature, and the acquisition and evaluation of data from these sites is beyond the scope of this project. However, given the absence of other large WSAS to use as case studies, these systems in Minnesota represent prime candidates for a future project employing case studies to evaluate and refine the methodologies developed in this project.

## 1.5 Methods for Evaluating Potential Groundwater Mounding

Many studies have addressed estimation of groundwater mounds beneath a recharge source and generally fall into one of two categories. The first category involves mounding under WSAS that have relatively small amounts of recharge to the water table. The second category includes studies of artificial recharge systems that deliver large amounts of water from sources such as storm runoff to the groundwater table. The basic parameters used in these quantitative studies are compiled in Table 1-2.

**Table 1-2**  
**Basic Parameter Values Used in Quantitative Case Studies**

Author	Method	Horizontal Hydraulic Conductivity	Specific Yield	Application Rate	Dimensions	Saturated Thickness	Initial Depth to Water	Soil Medium
Sumner <i>et al.</i> 1999	VS2D Finite Difference model	$K_{sat} = 2.1$ m/d		0.3 m/d 1.05 m/d	25 m radius	25 m	12 m	Isotropic sand
Chan and Sykes 1984	Hantush 1967 Finite Element	$5.1 \times 10^{-4}$ m/d	0.2	0.0228 m/d 0.0076 m/d	84 × 64 m	12 m	3 m	Silty-sand, sandy-silt layering
Bianchi and Haskell 1968	Analytical	32 m/d 8 m/d	0.26 0.17	0.1 m/d 0.11 m/d	50.7 m radius	23 m 24 m	6.4 m 7.6 m	
Guo 1998	Flow model	0.75m/d (unsat) 2.1 m/d (sat)	0.284	1.05 m/d	25m radius	12 m	12 m	Sand

One of the best known studies is by Hantush (1967) who presented analytical solutions for transient groundwater mound development beneath rectangular and circular recharge sources with a constant rate of infiltration. The solutions require values for saturated K, storativity, and initial saturated thickness of the saturated zone. The technique is described as applicable to increases in water table elevations that do not exceed 50 percent of the initial depth of saturation.

Khan *et al* (1976) formulated solutions for the steady-state shape of groundwater mounds under rectangular or circular recharge basins and compared the predictions between their calculated flow and the Dupuit-Forchheimer (DF) theory. They conclude that two-dimensional mound heights calculated by either method were similar, but the DF theory underestimates three-dimensional mound heights.

Bianchi and Haskell (1968) tested predictions of the DF theory for mound heights under recharge basins in Fresno County, California. Two-acre square ponds were located on gently sloping alluvial fans with clay loam soils. The predictions were tested against measured mound growth and the analytical solutions produced good agreement with the field data for most conditions. The volume of recharge in storage in the vadose zone was calculated to compensate for the theory, which does not include such storage. The results showed that if mound volume is small relative to vadose storage, the analytical solutions are useful. However, larger vadose storage can influence the falling hydrograph.

The conclusion of this report is that vadose storage and aquifer depth are the most significant sources of error in the calculations. Fielding (1982) presented a comparison of predictions from the Hantush (1967) solution with data collected for three years under a large leaching area operated with variable infiltration rates. The results showed good agreement between the average of the field data and the predictions.

Finnemore and Hantzche (1983) describe another procedure for calculation of mounding. Their method uses a simplification of Hantush's (1967) method for calculation by reducing the prior method to a single equation. The methodology is particularly good for longer term (10–20 years), and they found that, for most situations, the maximum rise is between two and four feet after 20 years.

A simplified methodology is presented by Uebler *et al.* (1991), which provides an equation developed for initial design studies that does not require extensive calculations. All of these techniques used the same basic formulation.

The solutions of Hantush (1967) and Khan *et al.* (1976) are described in detail in Chapter 3, *Evaluating Groundwater Mounding With Models*. The simplified solution of Finnemore and Hantzche (1983) is described here to illustrate the basic technique. The formulation neglects unsaturated flow and is limited to cases where there is a single permeable layer with a lower horizontal impermeable boundary. Finnemore and Hantzche assumed a minimum specified distance between water table and infiltrative surface of two to five feet. Using this value, the authors calculated the water table mound height,  $z_m$ , for a wastewater discharge rate of 2,500 gallons per day (GPD) over a 10,000 ft<sup>2</sup> (929 m<sup>2</sup>) infiltration area. The  $K$  values ranged from 1 to 10 feet per day (0.3 to 3 meters per day). The saturated thickness was 50 feet (4.6 m), and the solutions used the condition of  $W=L=100$  ft (30 m). Specific yield values ranged between 0.1 and 0.25, but had little effect. The solution is most sensitive to  $K$ ,  $t$ , and  $h_o$  (the thickness of the underlying aquifer). The fundamental equation is:

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

Equation 1-1

This equation is accurate provided that

- $t > t_{lim} = 40L^2Sy/(K h_o)$
- $I$  = average recharge rate of wastewater

Terms include:

- $t$  = time since beginning of infiltration
- $S_y$  = specific yield of aquifer
- $L$  is the length of the disposal trench
- $K$  is horizontal hydraulic conductivity
- $\bar{h}$  is  $h_o + z_m/2$ ,  $h_o$  is the initial saturated thickness
- $C$  and  $n$  are constants that depend on the length to width ratio of the source (taken from a table—see Finnemore and Hantzche 1983)

Note that the method requires an estimation of  $h_o$  in order to begin the calculation.

Rao and Sarma (1980) tested the Hantush (1967) and Baumann's (1952) methods for calculating the height of a mound due to surface recharge. The model results were compared to sand-tank data. The Hantush procedure provided a better match to the data, and was shown to be valid over a wider range of mound heights (up to three times the initial water table height). As noted, many of the earlier formulations ignored unsaturated flow and solved linearized versions of the Boussinesq equation for two-dimensional flow under uniform infiltration (Hantush 1967 and Finnemore and Hantzche 1983).

Suggestions for improvements include a tailing distribution on the uniform infiltration rate and inclusion of unsaturated and saturated flow modeling to overcome these limitations (Morel-Seytoux and Miracapillo 1988 and Morel-Seytoux *et al.* 1990).

Numerical models can be used to simulate mounding under an infiltration source (Radcliffe and West 1998). Numerical models can evaluate complex conditions including variable infiltration rates, dynamic water tables, and unsaturated flow. Predictions for mound height can be as much as 25% higher using analytical solutions such as the Hantush method compared to VS2D numerical model simulations that incorporate unsaturated flow and storage. The difference in approaches is small relative to the accuracy with which  $K$  values (saturated vs. unsaturated) are measured, but the inaccuracy may be critical in cases where the unsaturated zone is thin. Sumner *et al.* (1999) showed that the difference between predicted values (analytical versus numerical solution of the unsaturated-saturated flow equation) increased for shorter loading times, greater depth to the water table, larger subsurface heterogeneity, and particularly with the inclusion of fine-grained layers.

Guo (2001) used the data from Sumner *et al.* (1999) to calculate mounding below a circular recharge basin where the infiltrating water is inflow seepage to groundwater outflow and the mound is storage using an axially symmetrical flow model to describe flow through the unsaturated zone. He states that anisotropic conditions can be converted to an isotropic equivalent by coordinate transformation with an equivalent hydraulic conductivity equal to the geometric mean of radial and vertical hydraulic conductivity. He showed that soil storage effects are most significant during short loading periods.

The predictions from the potential model, numerical simulations using the VS2D finite-difference code (Lappala *et al.* 1987), and Hantush's method were compared with field data from a storm infiltration basin in North Carolina. The results showed Guo's formulation and the Hantush method produced similar calculated mound heights during loading, while the VS2D simulations were different due to explicit consideration of soil storage effects. During mound recession, the flow model and the VS2D predictions matched more closely. Overall, all three methods produced good results. The study concluded that the ratio of shallow-soil infiltration rate to subsurface hydraulic conductivity was a critical parameter in calculating mound heights.



## 2 SITE EVALUATION FOR GROUNDWATER MOUNDING POTENTIAL

Site evaluation is the most important aspect of wastewater soil-absorption systems (WSAS) design (Hantzsche *et al.* 1982; Tyler *et al.* 1985; Persyn *et al.* 1999; and US EPA 2002). This chapter provides a methodology to guide users in gathering the correct information to perform a sufficiently rigorous hydrogeologic evaluation to minimize potential mounding problems. The recommended procedure involves using a flowchart and a decision-support tool. A full site investigation to evaluate the potential for groundwater mounding typically consists of:

- Gathering existing data
- Visiting the site
- Preliminary field observation
- Conducting soil and groundwater investigations
- Estimating perching and mounding
- Determining the required level of investigation and evaluation
- Conducting further field investigations and modeling (as necessary)
- Iterating between field investigation, modeling, and design of the WSAS

Sites with low potential for mounding and minimal consequences in the event mounding occurs require less investigative effort than sites with high potential for mounding and serious consequences associated with mounding.

### 2.1 Getting Started

Practitioners seeking to utilize the methods presented in this report can best accomplish this by working through the recommendations in this chapter and moving on to sections of Chapter 3, *Evaluating Groundwater Mounding With Models* as needed.

The first consideration in design of a large system is to specify an overall size of the infiltration area that, when coupled with the anticipated volumetric loading rate, results in an infiltration rate that is less than the vertical hydraulic conductivity,  $K_v$ , of the soil to prevent the development of ponding of wastewater over the infiltration area. That is:

$$\frac{Q}{A} < K_v$$

for consistent dimensional units of volume, length, and time.

Next, recognizing spatial constraints of the site and reasonable dimensions for construction, strive to elongate the infiltration area in the direction perpendicular to groundwater flow beneath the site. Preliminary data acquisition as outlined in this chapter will provide approximate values for  $K_v$  and flow direction.

After establishing this reasonable design, the designer must consider the potential for perching and mounding of water on low hydraulic conductivity layers in the vadose (unsaturated) zone, and ultimately the rise of the water table required to carry the treated wastewater away from the site. Site-scale hydraulic conductivities are extremely important to performance of the WSAS, but are difficult to determine with certainty. This chapter guides the designer in evaluating the amount and type of field investigation appropriate for a site and refers the designer to Chapter 3, *Evaluating Groundwater Mounding With Models* for analytical, and if necessary, numerical modeling.

After establishing this reasonable design, the designer must consider the potential for perching and mounding of water on low hydraulic conductivity layers in the vadose zone and ultimately the rise of the water table required to carry the wastewater laterally away from the site. Site-scale hydraulic conductivities are extremely important to performance of the WSAS, but are difficult to determine with certainty.

The level of required evaluation depends on site conditions, system parameters, and the severity of the consequences of excessive mounding. A general description of the methodology for this determination is presented in the section 2.2, while some specific examples of the procedure are presented in section 2.9.

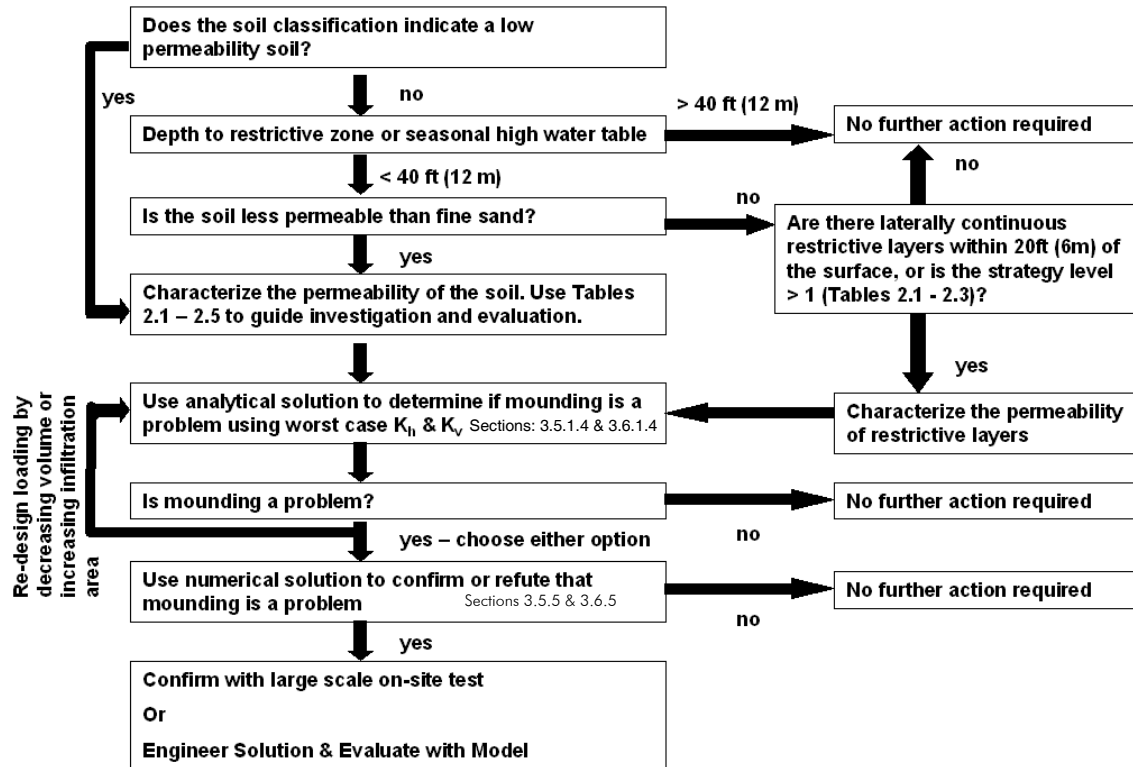
The analytical modeling recommended in this report is readily accomplished using a calculator in the case of estimating mounding on low hydraulic conductivity layers in the vadose zone, and the spreadsheets that accompany the report ([WaterTableMounding\\_EnglishUnits.xls](#) or [WaterTableMounding\\_SIUnits.xls](#)) in the case of water table mounding of the saturated zone.

Unless the designer is knowledgeable in the area of numerical modeling, he or she will likely enlist a modeler to assist with the work. In spite of this, the sections on numerical modeling (Chapter 3, sections 3.5.5 and 3.6.5) are recommended reading because they are not directions on how to conduct numerical modeling, but rather illustrations of how mounding is likely to vary for conditions that cannot be evaluated with analytical models. The insight they provide is useful to all phases of investigation and design. Hypothetical site dimensions and conditions are evaluated to illustrate generic system responses. Actual values of mound height and extent can only be determined for site-specific properties, dimensions, and boundary conditions.



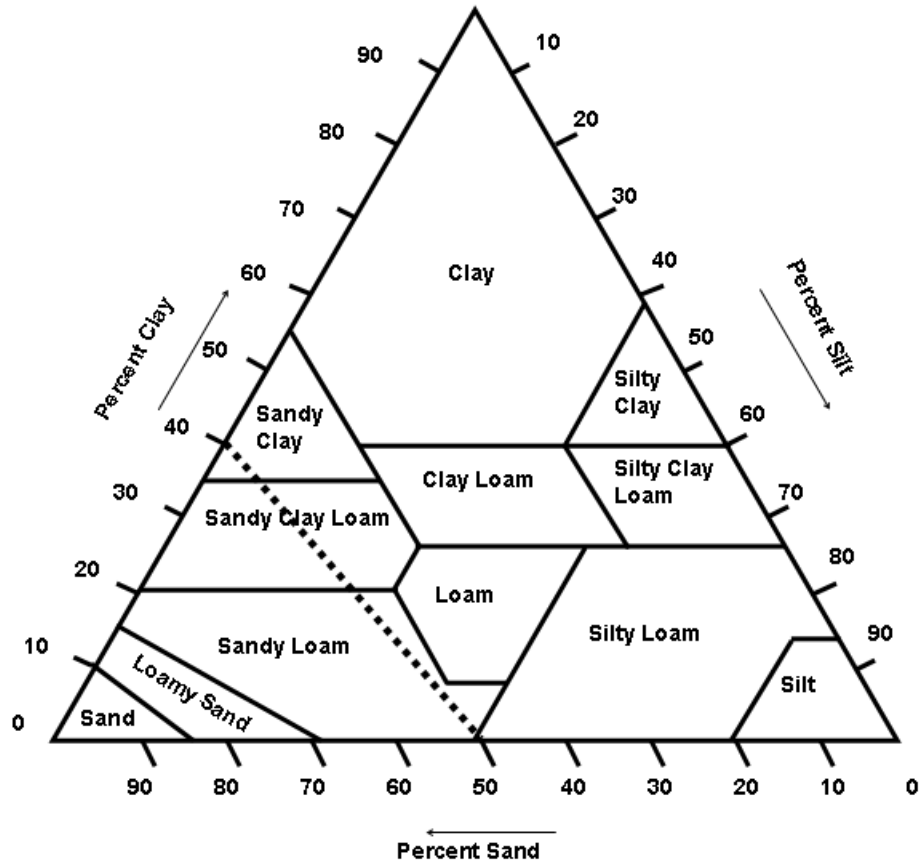
## 2.2 Determination of the Level of Required Evaluation

A flowchart (Figure 2-1) is used to make a preliminary assessment and provide an overview of the steps required to evaluate mounding potential based on depth to groundwater and soil types.



**Figure 2-1**  
**Flowchart for Preliminary Evaluation of Site Characterization Requirements**

Preliminary site investigations as delineated in the sections 2.2 through 2.4 are necessary to initiate use of the flowchart. The flowchart is a technical aid and does not include local regulatory requirements. The flowchart indicates the basic evaluation requirements and may establish that no further action is required. For example, a coarse-grained soil (see the lower-left section delineated by a dashed line in Figure 2-2) with relatively high hydraulic conductivity, with no low permeability layers, and an unsaturated zone of more than 40 feet thickness would not require rigorous evaluation. Alternatively, a fine-grained soil with a shallow water table and potential for low hydraulic conductivity layers may require an extensive investigation as guided through the use of tables (discussed in this section) depending on the design specifications (such as loading rate and infiltrations area). For economic reasons, re-design should be considered in an attempt to reach a clearly acceptable situation prior to undertaking numerical modeling.



**Figure 2-2**  
**USDA Soil Classification by Grain Size**

The decision-support tool (Table 2-1 through Table 2-5) is based on the philosophy that the degree of characterization and associated cost should be considered in light of the potential for mounding and the consequences should mounding occur. The decision-support tool utilizes additional qualitative information gathered from existing information, a site visit, and possibly soil investigations (see sections 2.2 through 2.5), to determine the strategy level for site assessment.

First, the potential for water perching, mounding of the water table, and/or breakout on slopes is estimated by quantified, subjective site ratings entered in Table 2-1. Weighting factors based on experience with similar sites can be considered when making these qualitative judgments. The weights must total one and are site-specific.

For example, if the bedrock is far below the ground surface, then its hydraulic conductivity is not important. Hydraulic conductivity of the material directly below the infiltration area is generally the most important factor. However, if the water table is exceedingly shallow, then its hydraulic conductivity becomes most important. This procedure is intended as a guide. If this guide hints at a problem, then the final design decision should be based on a more rigorous analysis.

Next, the severity of consequences associated with failure of the WSAS is evaluated by considering quantified, subjective evaluation of consequences based on common sense (Table 2-2). Using the combined estimate of mounding potential (Table 2-1) on the vertical axis of Table 2-3 and consequence of failure rankings (Table 2-2) on the horizontal axis of Table 2-3, the investigation strategy level is read from their intersection in the body of Table 2-3. The strategy level read from Table 2-3 provides a guide to the magnitude and intensity of field investigation and modeling by viewing the column associated with that strategy level in Table 2-4 and Table 2-5. If sophisticated evaluation is required, then the site investigations discussed in the sections 2.3 through 2.5 may be undertaken in a more extensive manner and evaluations discussed in the section 2.6 may be utilized.

The term investigation is used in the general sense and the user should recognize that it occurs at two levels. The first level relies on estimates of the high and low-K values of materials based on their soil type as input to models that evaluate the mounding potential. If the risk of mounding is high, site-specific measurements are required to ensure greater confidence in the model results.

**Table 2-1  
Methodology for Subjective Evaluation of the Potential for Perching, Water Table Mounding, or Breakout on Slopes**

Parameter	Low 1	High 10	Weight 0-1 (WT)	Site Rating (Value * Wt)
Loading Rate	Low (for example, <1 cm/day)	High (for example, >6 cm/day)		
Soil Type	Sands/clay-loams	Fine-sand, heavy-clay		
Soil Sorting	Poor	Well		
Soil Structure	Granular/blocky	Platy/prismatic/massive		
Soil Heterogeneity	Uniform	Variable		
Drainage	Moderate to well	Poor		
Depth to Water Table/Low-K Layer	Large	Small		
Proximity to Slopes	Far	Near		
Bedrock character	Homo, high K	Hetero, Low-K		
Characteristic curve for $K_{unsat}$	Flat	Steep		

**Table 2-1  
Methodology for Subjective Evaluation of the Potential for Perching, Water Table Mounding, or Breakout on Slopes (cont.)**

Parameter	Low 1	High 10	Weight 0-1 (WT)	Site Rating (Value * Wt)
Horizontal Hydraulic Conductivity	High	Low		
Proximity to Wetlands	Far	Near		
Prone to intense storms	No	Yes		
			<b>Wts Sum=1</b>	<b>Sum of Weighted Ratings</b>

**Table 2-2  
Methodology for Subjective Evaluation of the Consequences Should the System Fail**

Condition	Mild 1	Serious 5	Site Rating
Alternative infiltration area locations	Numerous	None	
Timing relative to full construction	Early	Late	
Proximity to shallow water supply	Far	Close	
Proximity to surface water & sensitive habitats	Far	Close	
Local population density	Low	High	
		<b>Average</b>	

**Table 2-3  
Methodology for Subjective Evaluation of the Strategy Level for Site Investigation and Modeling**

Mounding Potential	Consequence of Failure				
	1	2	3	4	5
1	0	0	1	1	2
2	0	1	1	2	2
3	1	1	2	2	3
4	1	2	2	3	3
5	2	2	3	3	4
6	2	3	3	4	5
7	3	3	4	5	5
8	3	4	5	5	5
9	4	5	5	5	5
10	5	5	5	5	5

**Table 2-4  
Intensity of Field Investigation for Each Strategy Level**

Parameter	Strategy Level				
	Least Expense 1	Less Expense 2	Increasing Expense 3	More Expense 4	Most Expense 5
Soil Type	Hand sample description from pits	Plasticity bulk-density	Moderate number of samples	Increase number of samples	Large number of samples
Soil Sorting	Hand sample description from pits	Sieve analysis	Sieve analysis plus hydrometer	Increase number of samples	Large number of samples
Soil Structure	Hand sample description from pits	Increase number of samples	Microscopic evaluation	Auger drill deeper samples	Increase number of drill holes

**Table 2-4  
Intensity of Field Investigation for Each Strategy Level (cont.)**

Parameter	Strategy Level				
	Least Expense 1	Less Expense 2	Increasing Expense 3	More Expense 4	Most Expense 5
Soil Heterogeneity	Hand sample description from pits	Increase number of samples	Numerous K tests across site	Geophysical surveys	Increase number of K tests; correlate with geophysics
Drainage	Percolation test	Core analysis	Infiltrometer tests	Pilot field scale flooding	Full scale flooding
Depth to Water Table	Estimate from local well data or shallow pits	Auger drill to 20 ft (7 m)	Auger drill to water table	Geophysical surveys	Increase number of monitor locations and correlate with geophysics
Fluctuation of Water Table	Estimate from local data	Install piezometers, monitor water levels	Predict for wet years from modeling	Geophysical surveys	Long-term water level monitoring
Topography	Topographic assessment, field visit				
Proximity to Slopes	Topographic assessment, field visit				
Bedrock character	Assessment of available local data	Drilling to evaluate geology	Geophysical surveys	Slug tests	Pump tests
Unsaturated K	Estimate from soil character (Rosetta)	Laboratory test $K_{sat}$	Increase number of samples	Laboratory test $P_{cap}$ curve	Large number of samples
Vertical Hydraulic Conductivity	Estimate from soil description	Percolation test	Infiltrometer tests	Laboratory K on cores	Large number of samples
Horizontal Hydraulic Conductivity	Estimate from soil description	Laboratory test sat K on horizontal cores	Slug tests	Pump tests	Large number of tests

**Table 2-4**  
Intensity of Field Investigation for Each Strategy Level (cont.)

Parameter	Strategy Level				
	Least Expense 1	Less Expense 2	Increasing Expense 3	More Expense 4	Most Expense 5
Proximity to Wetlands	Topographic assessment, field visit				
Prone to Intense Storms	Nearby historic weather records				Monitor weather on site

**Table 2-5**  
Sophistication of Model Evaluation for Each Strategy Level

Modeling Approach by Strategy Level				
Least Expense 1	Less Expense 2	Increasing Expense 3	More Expense 4	Most Expense 5
Analytical Hand Calculations	Analytical Spreadsheet Solutions	Numerical Modeling	More Complex Numerical Modeling	Sophisticated Numerical Modeling
Darcy's Law	Hantush 1967	MODFLOW	MODFLOW	MODFLOW
Khan <i>et al.</i> 1976		HYDRUS	HYDRUS	HYDRUS
				VS2DI
				TOUGH2/T2VOC
				STOMP
Uncertainty Evaluation				
Worst/Mean/Best	Worst/Mean/Best	Worst/Mean/Best	Worst/Mean/Best	Worst/Mean/Best
		Confidence intervals if field data available for calibration	Confidence intervals if field data available for calibration	Confidence intervals if field data available for calibration
			Stochastic sampling of parameter values	Stochastic sampling of parameter values

## **2.3 Existing Data and Site Visit**

Acquire the proposed development plans including site layout and waste loading and the existing data on the site. Current construction plans including location of structures, open areas, and timing of the WSAS construction relative to the entire facility development should be obtained. Site-specific data are preferable, but when site-specific data are not available, seek data from nearby sites, including:

- Topographic, geologic, and soil maps
- Aerial photos
- Water supply wells in the vicinity
- Hydrographs from wells
- Values for hydraulic conductivity, or data from tests designed to determine hydraulic conductivity (see section 2.6)
- Climate information from nearby weather stations to estimate recharge rate and water table fluctuation
- Storm drainage plan that includes location of roads, parking, and other hard surfaces (including how runoff from these is handled)

Visit the site to make observations of site conditions (see section 2.6). Identify potential areas for the WSAS on the site, and select the most likely specific site based on factors such as:

- Topography
- Soil type
- Depth to bedrock
- Character of bedrock
- Proximity to wells
- Water supply
- Location of wetlands
- Proximity to breaks in slope

During the evaluation, consider if there is a better location for the WSAS than is suggested in the site plans. Developers and architects generally are not as knowledgeable about groundwater mounding as those who work on WSAS design so they may overlook the best site even though it may be easily accommodated in the site plans.

## **2.4 Preliminary Evaluation**

The fundamental aim of the preliminary evaluation is to estimate the volume of water the soil is capable of transmitting without raising the water table substantially (hydraulic capacity) while treating the projected volume of wastewater. The depth of the water table is important in determining the maximum allowable rise of the water table due to mounding. The size of the infiltration area is based on the design volume (a function of the development to be served) and the design infiltration rate (a function of the soil hydraulic conductivity and effluent characteristics).



Existing data should be used to make a preliminary evaluation. For some situations a preliminary evaluation may be sufficient; however, evaluation of the suitability of sites for large WSAS can be complex. Large systems require more data because the infiltrative surface is larger. Tyler and Converse (1994) state that site information should be adequate to establish:

- Surface water conditions
- Infiltration rate (determine if water is pre-treated as rates can be higher in that case)
- Vertical and horizontal conductivities
- Unsaturated hydraulic conductivity and capillarity characteristics of layers that may perch water
- Zones of permanent and perched water tables
- Groundwater conditions for each of the soil horizons present
- System boundaries

System boundaries are the locations where wastewater is assimilated in, or sequestered from, the environment and is not detectable or will not influence system operation. Examples are:

- Surface-water discharge points (such as lakes, ponds, or streams)
- Changes in slope
- Clay layers
- Perched zones
- Regional water tables
- Points of convergent flow such as wells

Both horizontal and vertical boundaries should be identified and used to establish the physical extent of the investigation.

## **2.5 Site Observations**

Landscape conditions should be described including vegetation, surface waters, slopes and landforms. Locations underlain by highly fractured rock, such as fractured limestone, are less likely to have mounding problems in contrast to locations underlain by sound rock or low hydraulic conductivity sediments, such as clay lenses. Careful site observations are required for locations likely to have mounding problems, such as areas with:

- Steep slopes
- Soils with poor natural drainage as indicated by ponding during rain
- Shallow water table
- Nearby wetlands
- Perched water tables
- Areas subject to high precipitation

Such areas may only be suitable with specialized installations (Hantzsche and Fishman 1982; Converse and Tyler 1985, Uebler *et al.* 1985, Goff *et al.* 2001). Installations with high loading rates that exceed site assimilative capacity are clearly situations that require additional measures to ensure proper operation.

Areas with high seasonal infiltration may result in seasonal fluctuation of the water table, which may exacerbate mounding. An example of this situation was reported for the Norwood Sewage Treatment Plant in Peterborough, Ontario, which receives 31.5 inches per year (80 cm/yr) of precipitation (Chan and Sykes 1984). Water levels can rise dramatically during spring recharge events and cause the system to overload temporarily.

Areas with shallow groundwater or shallow low hydraulic conductivity layers are prone to failure due to mounding. Uebler *et al.* (1985) found a failure rate of 20.5 percent for WSAS installed on Leon hardpan soils compared to 7.5 percent for systems in other types of soils. The presence of low hydraulic conductivity layers can markedly alter the ability of the soil layer to transmit wastewater downward. The degree of restriction is a function of the hydraulic conductivity of the layer and its lateral continuity (see Chapter 3, section 3.5).

Uebler *et al.* (1985) installed drains to lower the high seasonal water tables at sites in North Carolina. These sites all had the same generalized soil profile and descriptions, with low hydraulic conductivity layers of cemented soil. The overall soil would be classified as moderate to moderately-high hydraulic conductivity; however, the degree of cementation and the lateral continuity controlled the ability of the drains to lower the water table. Water tables declined at sites with discontinuous, poorly cemented layers after drain installation, but water tables remained high at sites with more continuous, better cemented layers. These small, but critical differences would not be revealed by soil type determined from maps, nor soil profiles based on limited core data.

## 2.6 Subsurface Investigation

Characterization of the soils at and below the infiltrative surface, in the vadose zone, and below the water table is necessary to evaluate groundwater mounding and lateral flow. A principle component of soil analysis is hydraulic conductivity determination. In particular, the location and properties of low hydraulic conductivity layers should be identified. The important factors controlling soil hydraulic conductivity are texture, structure, bulk-density (degree of compaction), percent coarse fragments, clay mineralogy, and organic content.

The percolation test is the most widely used evaluation technique to determine soil hydraulic conductivity and hence, infiltration capacity. There are major problems with this test including:

- High degree of variability in results
- Lack of measurement of a fundamental soil property
- Regulatory requirements to perform testing during wet-weather season (Hantzsche *et al.* 1982)

Percolation test procedures vary as to pre-treatment of the soil (including saturating for specified time or dry) and use of clean water, which can overestimate the infiltration rate (Jenssen and Siegrist 1991). For instance, summer percolation-test values used to calculate the size of the infiltration area overestimate the ability of the soil to transit water, about half the time, due to seasonal changes in the water table (Gross *et al.* 1998). Alternative techniques for field measurement of hydraulic conductivity are more likely to measure hydraulic conductivity in the horizontal direction, which is important to dissipation of the mound, but they do not indicate the vertical hydraulic conductivity of low hydraulic conductivity layers (Siegrist *et al.* 1985).

A widely accepted alternative method for hydraulic conductivity determination is use of soil characterization information. This information may be derived from United States Department of Agriculture (USDA) soil survey maps, which are based on relative amounts of sand, silt, and clay; or a site-specific survey of soil conditions that characterizes the likely hydraulic conductivity of the soil (Hantzsche *et al.* 1982 and Plews and DeWalle 1985) and helps predict the necessary type of installation (Engebretson and Tyler 1998). Design infiltration rates based on soil types were developed from the work of Bouma (1975). The infiltration rates are based on the four major soil types (Anderson *et al.* 1982):

- I—Sands
- II—Sandy-loams and loams
- III—Silt loams and some silty-clay loams
- IV—Clays

Percentages of sand, silt, and clay define soil types as shown in Figure 2-2. In general, hydraulic conductivity decreases as the distribution of sizes increases (poorly-sorted or well-graded sediments) and with a larger percentage of finer grains (more silt and clay). However, the shape, arrangement, and packing of grains also influence hydraulic conductivity, so it cannot be determined solely from grain-size information.

Soil observations should be made for each distinct layer and include:

- Texture
- Color
- Mottling (gray colors) and salts associated with seasonal water tables
- Structure, including the location of clays and banding (even thin horizons may be important in controlling flow and should be sampled for testing)

Site maps should be constructed including:

- Soil conditions (including bulk-density/compaction, plasticity)
- Depth to bedrock
- Slopes of the ground surface
- Subsurface horizons
- Piezometric surface maps

To obtain a conservative evaluation, the lowest values for estimated or measured parameters should be used when making calculations or constructing groundwater models.

The soil characterization approach can be employed on soil cores, backhoe pits, or trenches at specific sites, and the information used to calculate infiltrative surface size (Rutledge *et al.* 1992).

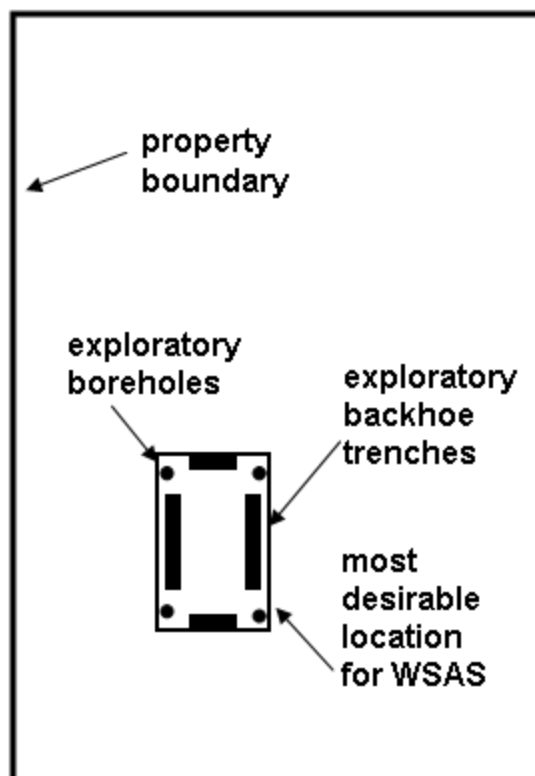
The three most important factors in estimating hydraulic conductivity from soil characteristics are:

- Soil texture
- Bulk-density (degree of compaction)
- Coarse fragment content

However, soil survey maps provide general information on a coarse scale. Studies have found that the homogeneity of soil units ranges from less than 30 percent to greater than 80 percent (Engebretson and Tyler 1998). Of particular interest are the hydraulic parameters for the low hydraulic conductivity soil layers below the bottom of the trenches that may not be related to surface soils. Low hydraulic conductivity soil layers are those with the lowest hydraulic conductivity (often the highest clay content). If thickness and coloring of soil layers and depth to bedrock, hardpan, or an impermeable layer are determined, a general classification of the soil properties can be made using diagrams from the Soil Conservation Service of the USDA.

Tyler (2001) presented a table that enables estimation of infiltration capacity based on soil characteristics for soil with very firm or weak consistency. In conclusion, the soil survey method is comparable with percolation test results, can be conducted in any season (Hantzsche *et al.* 1982), and, coupled with knowledge of the plasticity of the fine-grained material, is more reproducible than the percolation test (Gross *et al.* 1998). However, even if soil survey data are used in conjunction with percolation tests, they are not sufficient to describe the natural variability at most sites (Siegrist *et al.* 1985).

Large cluster and high-density WSAS generally require a large area, and heterogeneity is often substantial, thus an effort should be made to capture the variability of the site. To evaluate the potential for heterogeneity at a site, identify the area most conducive to infiltration and away from planned structures. Drill a borehole at each corner to the base of the unconfined aquifer, or at least to a depth that provides an acceptable minimal aquifer thickness, if an aquifer base is not encountered (50 feet or approximately 15 meters is suggested). Evaluation of the boreholes determines the saturated thickness (or if the aquifer base is not detected, a minimum thickness of water-table elevation minus maximum borehole depth, as well as soil character and depth to water. Dig about one test pit per 10,000 square feet (1,000 square meters) (one along each side of the infiltration area to investigate lateral heterogeneity and continuity of units as shown in Figure 2-3). Document materials in the boreholes and trench walls; in particular, document layering with descriptions of soil types and lateral extent of layers, as well as seeps and water tables. If the strategy level for the site warrants testing, the low hydraulic conductivity (tight, fine-grained, poorly sorted materials) layers will be the targets of future testing.



**Figure 2-3**  
**A Broad Distribution of Boreholes and Trenches Provides an Overview of the Magnitude of Heterogeneity at the Site**

Full-year groundwater level monitoring data is also important. This type of information may be available from local water districts or private wells. Some areas of the country can experience significant seasonal changes in water table elevation. In such situations, depth to groundwater may be sufficient during drier months, but may rise causing the top of the mound to approach or even breach the surface during periods of increased precipitation.

For instance, Chan and Sykes (1984) describe a system in Ontario, Canada where seasonal changes in the local water table of approximately three meters caused a period of failure during operation of a large experimental leaching bed. This failure required reduction of the initial loading (122,700 liters per day (LPD)) by a factor of about three (40,900 LPD) for the system to operate normally. Goff *et al.* (2001) reported a case in Arkansas where seasonal high water tables are within two inches (5 cm) of the ground surface causing WSAS installations to fail. Installation of drains lowered the water table, but the fecal coliform levels did not decline below required regulatory levels. Uebler *et al.* (1985) also used a series of drains to lower seasonal high water levels in North Carolina. In this area, drains were able to lower water levels for application trenches near discontinuous cemented-layers, but areas with laterally extensive, well-cemented layers were not affected. Such areas may require specialized installations (Hantzsche and Fishman 1982; Converse and Tyler 1985, Uebler *et al.* 1985, Goff *et al.* 2001) or lower application rates during wet periods.

## 2.7 Advanced Hydrologic Testing

Beyond the widely used percolation and soil characterization approaches to determining hydraulic conductivity for WSAS design, are a range of other field and laboratory tests that are rarely used in this arena. Generally, field tests are preferable to laboratory tests because they encompass the scale of interest and determine properties of undisturbed soils.

Field tests, in order of decreasing scale of assessment, include a flood plot, single- or double-ring infiltrometer, and an air entry permeameter. These and field test procedures are described in hydrology texts such as Domenico and Schwartz (1990), Fetter (2001), Tindal and Kunkel (1999), Weight and Sonderegger (2000), as well as Black (1965), US EPA (1981, 1984; and 2002), and ASTM (1997). Laboratory tests include the concentric ring permeameter (Hill and King 1982) and the cube method (Bouma and Dekker 1981). These classic tests are strongly oriented toward assessing vertical hydraulic conductivity, which is important for determining mounding and lateral movement. The lateral continuity of low hydraulic conductivity layers is important to determining whether they will impede downward migration and perch significant amounts of water. Shallow geophysical techniques coupled with control data from trenches and/or cores that describe the soil features can assess this continuity, and large scale flooding can be used to generate saturated conditions and monitor lateral movement.

Unsaturated hydraulic conductivity is a function of soil moisture content, and soil properties may be altered by wastewater composition (Amoozgar and Niewoehner 1998 and Jenssen and Siegrist 1991). To evaluate the correlation of hydraulic conductivity, moisture content, and capillary pressure, characteristic curves can be measured on cores in the lab, or via moisture (neutron probe, time domain reflectometry, resistance) and pressure (tensiometer) sensors (Weight and Sonderegger 2000 and Tindal and Kunkel 1999) in the field. Measurement of moisture content as a function of capillary pressure in the laboratory can be expensive (see section 2.8), with lower costs if the soil is sand.

Capillary curves can be related to hydraulic conductivity via a theoretical expression (such as Mualem 1976). Measuring unsaturated hydraulic conductivity as a function of moisture content depends on the character of the soil but is likely to be an order of magnitude more expensive (see section 2.8). A more complex approach involves inverse modeling to estimate parameters defining characteristic curves (Simunek *et al.* 1998) given pressure or moisture content data. Modeling costs are discussed in Chapter 3, section 3.7. A less expensive, albeit less accurate, approach is estimation of the characteristic curve parameters using pedotransfer functions. Schaap and van Genuchten (2001) present software that estimates the capillary pressure-saturation relationship and the unsaturated hydraulic conductivity function from soil texture and bulk density.

Estimation of unsaturated hydraulic conductivity ( $K_{\text{unsat}}$ ) is expensive and time consuming. Alternatively, estimations can be made using a closed form equation developed by van Genuchten (1980) for different soil moisture values. Formulations that employ computer calculations have been developed that use physical soil properties as input (Schaap and van Genuchten 2001).

Jaynes and Tyler (1985) evaluated two simple methods for estimating unsaturated hydraulic conductivity. The first is based on grouping soils into classes of similar hydraulic properties and using detailed soil maps to predict  $K_{\text{unsat}}$  values for a site. The second involves estimating a value from more easily measured soil properties such as bulk density, sand and silt fractions, and porosity. They concluded that the first method (soil classes) was useful, but the range of  $K_{\text{unsat}}$  for any single soil type was two orders of magnitude. Therefore, this method is useful for determining minimum and maximum values, but cannot provide specific values.

The second method, using easily measured soil properties, showed that specific physical properties such as percent sand had good correlations with measured  $K_{\text{unsat}}$ , but that the controls on  $K_{\text{unsat}}$  vary in different soil types and this method would require calibration for each site.

Characterization of the saturated zone includes determination of:

- Depth to the water table
- Water table seasonal variation, magnitude, and direction of the prevailing hydraulic gradient
- Thickness of the unconfined aquifer
- Distribution of the saturated hydraulic conductivity within the aquifer

Only unusually shallow, thin aquifers can be evaluated using test pits. Borings, piezometers, and monitor wells are needed to characterize deep, thick aquifers. Heads are measured to determine gradient and seasonal variation and high water table. Jenssen and Siegrist (1991) suggest that a soil classification involving effective and mean grain size and sorting can be used to pre-screen soils and determine the need for direct measurements of hydraulic properties.

If wells, or piezometers, are installed, slug and/or pump tests are typically used to characterize hydraulic conductivity (Theis 1935, Hvorslev 1951, Bouwer 1978, Bouwer and Rice 1976, Freeze and Cherry 1979, and Fetter 2001). Saturated hydraulic conductivity also can be measured with a permeameter using the constant or falling-head methods (Hill and King 1982, Reynolds *et al.* 1983, Reynolds and Elrick 1985, and Klute 1986). For appropriate conditions, the constant-head well method of Amoozegar (1996) can be used.

Material characterization (such as description and grain size distribution) may be used to estimate hydraulic conductivity where hydraulic tests are not conducted. In addition, pump tests can be used to estimate specific yield, which controls the rate of mound development and fluctuations. Large systems may require more data since the infiltrative surface may be much larger. Tyler and Converse (1994) suggest up to 100 measurements may be required to characterize a large site, which may be cost prohibitive. Finnemore and Hantzche (1983) suggest that local observations of mounding may be sufficient to constrain calculations of  $K$  by inverse means.

## **2.8 Characterization Costs**

The costs associated with characterization are often an important consideration and are variable depending on the level of investigation, conditions of the site, and geographic area due to economic differences in labor and professional rates. For discussing cost, a typical high-density/cluster system site is assumed to be in unconsolidated material and have a 50 by 100 feet (approximately 15 by 30 m) infiltration area with underlying bedrock at least 50 feet (15 m) below a relatively flat surface.

The preliminary level of characterization involves drilling four soil cores, one in each corner, with logging observations made by trained geotechnical personnel. The results would include water level, soil core description, and grain size observations, summarized in a report with an approximate cost of \$15 per foot or \$3,000 for four, 50-foot (15-m) holes.

The information in such reports can be used to estimate a range of soil property values, but this cost does not include testing of soil properties in the lab or field. Trenching with a backhoe is roughly \$50 per hour. The time required to dig four test pits will vary with the character and compaction of the soil, but eight hours should be sufficient. While excavation cost is low, the cost of soil descriptions along trench walls are high because of the additional time required; thus a reasonable cost for trenching and an associated report is approximately \$2,000. These costs will vary depending on the degree of characterization.

The most important aspect is the identification of continuous, low hydraulic conductivity features, which may be thin and difficult to recognize by visual inspection. The cost of investigation will increase if soil property tests (such as Atterberg-limits) are performed (approximately \$50 to \$100 per test). Often percolation tests are performed at this level of characterization, for periods up to 10 hours, which may add \$500 to \$750 to the investigative cost.

If obvious, significant features, such as low hydraulic conductivity layers are noted in preliminary investigations, then determination of their lateral continuity is important. In this case, the next level of characterization involves more cores and/or trenches. This activity may double or triple the original costs.

Laboratory tests measuring saturated hydraulic conductivity increases cost per sample by approximately \$300 to \$400. Laboratory tests can provide valuable data, but disturbance of the soil during sampling may produce values that are not applicable to field conditions. Measurement of moisture content as a function of capillary pressure in the laboratory will likely cost around \$2,000 for the first sample and \$1,000 for additional samples. Lower costs may be found if the soil is sand. These capillary curves can be related to hydraulic conductivity via a theoretical expression (such as Mualem 1976).

The cost of measuring unsaturated hydraulic conductivity as a function of moisture content depends on the character of the soil but is likely to be \$10,000 or more per sample. Thus, the costs for complete characterization of a large site could easily range from thousands to tens-of-thousands of dollars.



An alternative methodology is to conduct a long-term large-scale infiltration test by trucking water to the site. Briefly, such a test is essentially a pilot study of the actual system, applying clean water at a design rate to an area or trench and monitoring mound development. While it may take too long to achieve steady-state conditions, the mounding behavior under various rates may provide insight to infiltration rates that are likely to be acceptable. These tests are designed based on site conditions, by a hydrologist with training in infiltration processes. The test could be expensive if a long period of time is required to achieve steady mounding levels, but may be less expensive than a detailed site characterization. The relative costs are highly site specific.

## 2.9 Application to Case Studies

While the available case studies discussed in Chapter 1, section 1.4.3 do not provide sufficient information to demonstrate performance of the approach to evaluating the potential for mounding presented in this report, two examples illustrate the applicability of the flowchart (Figure 2-1).

First, consider the study by Uebler *et al.* (1985). In this case, the soil type for the area is highly permeable, which means it is not a low-K class of soil. Consequently, the user would proceed to the next level and evaluate depth to low hydraulic conductivity layers or seasonal high water tables greater or less than 40 feet. In this case, the seasonal high for the water table was known to be near the surface (less than one foot). Based on the soil descriptions, the presence of shallow (less than three feet) cemented layers had been noted. Therefore, the user would be guided to the following questions:

- Is the soil less permeable than fine sand? No
- Is there more than 20 feet of unsaturated zone? No
- Are there continuous low hydraulic conductivity layers? Yes

Then, the user would proceed to characterize the hydraulic conductivity of the low hydraulic conductivity layers and use the analytical model to calculate the likelihood of mounding. Such an evaluation would show that the critical parameters at the site are hydraulic conductivity and lateral extent of the low hydraulic conductivity layers. This procedure guides the user to

- Focus characterization efforts on obtaining the most useful information
- Perform initial calculations to test the sensitivity of mounding across the likely range of values even before actual characterization

Although the required data are not available from the papers, the designer would use Table 2-1 through Table 2-3 to quantify the qualitative assessment. Unless there is clear reason, the designer would weight the parameters of Table 2-1 equally and choose a value for each qualitative evaluation. From the minimal available data one may obtain a seven for mounding potential and a three for consequence of failure indicating a level-four characterization strategy. Consequently, the site evaluation would advance to the iterative process of analyzing and redesigning until an acceptable condition is achieved.

The flowchart can also be applied to the work of Chan and Sykes (1984) that was described in Chapter 1, section 1.5. At that site, the infiltration area experienced failure as defined by surface ponding of effluent. The situation was improved by lowering the application rate. At this site, the chart would lead the user to the question: Do you have a low-K class of soil? In this case, the soil is described as sandy-silt, not a particularly low-K soil. Next, depth to low hydraulic conductivity layers or water tables would put the user on the path of less than 40 feet (the site survey noted that depth to water was about 10 feet (3 m) and there was a dense layer of silt with sands noted about 12 to 15 feet (4 to 5 m) below the surface).

In both cases, the flowchart leads the user to the less than 40 feet category, and thus to the question: “Is the soil less permeable than fine sand?” In this case the answer is yes, which leads the user to characterize the hydraulic conductivity of the soil.

At this site, hydraulic conductivity values determined by two methods, “falling head” and in-situ “infiltration” on samples of the sandy-silt. Chan and Sykes used these values to calculate the mounding and showed that there was good agreement between predicted and actual data for several of the piezometers, but the water table near the northern and southern edges of the site was much higher than predicted. Chan and Sykes suggested that the difference could be due to variations in soil properties or inaccurate K values. They did not discuss the effects of the silty low-hydraulic conductivity layer explicitly. Their study demonstrated that, for the most part, the predicted and actual water table elevation were similar using both the Hantush (1967) method and a finite-element model. The effect of a later seasonal spring thaw and the subsequent rise in the water table were also noted, but not modeled, nor were they considered as the datum from which mounding should be evaluated.

Using the tables and the flowchart *prior* to applying the effluent would have correctly predicted the failure of the higher application rate even with the use of one homogeneous K value. Further refinement of the analysis would include the effects of the low-K low hydraulic conductivity layer and consideration of seasonal changes in water levels when considering application rates.



# 3 EVALUATING GROUNDWATER MOUNDING WITH MODELS

Groundwater perching, mounding, and lateral flow can occur when the effluent application rate to an infiltration area exceeds 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 ( $K$ ), the water table is near the surface, the gradient is low, and the saturated zone is thin. Modeling of the system facilitates assessment of the maximum site capacity, but the choice of modeling method needs to be appropriate for the site, system, and the severity of the consequences associated with excessive mounding.

## 3.1 Challenges of Quantitative Estimating

Although a qualitative evaluation of the potential for mounding is useful for early site assessment, a quantitative estimate may be necessary to design the system. At first consideration, this seems a relatively simple task, but a number of confounding issues make it a challenge.

The first challenge is obtaining accurate parameter values (see Chapter 2, *Site Evaluation for Groundwater Mounding Potential*). Depending on the required level of assessment, this may be as quick and inexpensive as looking up representative values in a book or may involve elaborate, expensive field and laboratory tests. Generally, the accuracy of the values improves as the effort and expense of field investigation increase.

Most wastewater soil-absorption systems (WSAS) investigations involve low-cost characterization, so the uncertainty associated with parameter values is likely large relative to the errors resulting from approximations made in model development. Nevertheless, it is important for the designer to understand the errors that can arise from model selection and setup.

## 3.2 Analytical Models

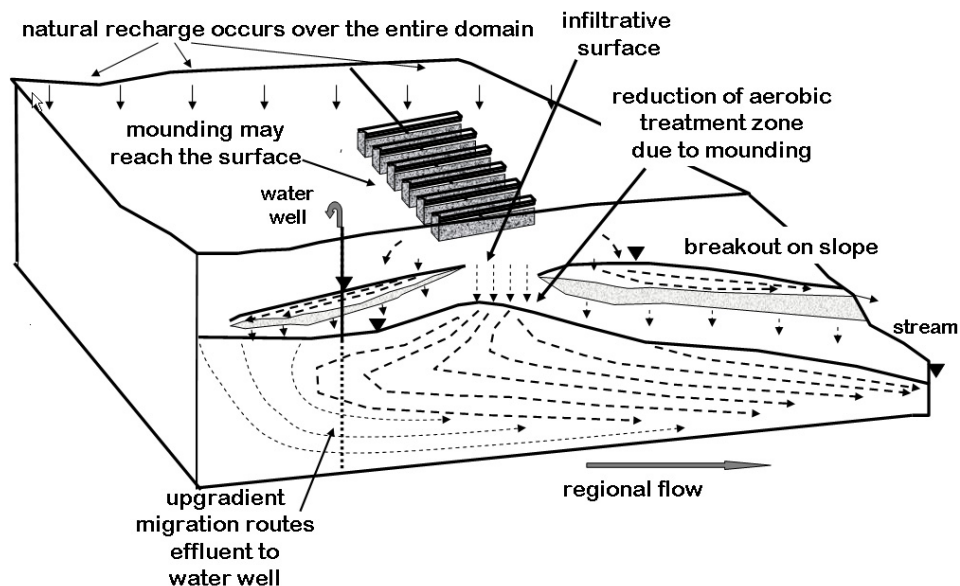
Analytical models generally assume hydraulic properties are homogeneous and isotropic, while geometry and boundary conditions are simple and constant. Some analytical solutions assume the aquifer is infinite, which has both benefits and disadvantages in evaluating mounding. Relative to an assumed infinite aquifer, a no-flow boundary in the field will cause the mound to be higher than predicted by the model as will the presence of a nearby high constant head boundary. On the other hand, a nearby, low constant head boundary will result in less mounding in the field than predicted by the model. Often analytical models for mounding consider only two dimensions. Generally, limiting dimensionality yields conservative results. That is, higher mounding will be predicted than will occur in the field.

### 3.3 Numerical Models

Complex problems can be tackled using numerical models. These are useful when site-specific data are available and the designer is familiar with numerical modeling. Unlike analytical models, numerical models cannot extend to infinity. Every boundary of the model must be assigned a flow, head, or pressure. Terminating models at natural geohydrologic boundaries such as water bodies or units of low hydraulic conductivity is desirable, but sometimes the locations of boundaries are not known. In other cases, limiting the extent of the model is necessary in order to maintain the desired level of detail while maintaining reasonable computer execution time. Consequently, models may have artificial boundaries. For example, heads may be fixed at known water table elevations at a county line. A flow-line, or groundwater divide, may be set as a no-flow boundary. Use of artificial boundaries is acceptable as long as the boundary has an insignificant effect on the result.

Consider the generic conceptual model for groundwater mounding beneath a WSAS as shown in Figure 3-1. In this model an infiltration area is introduced to a groundwater domain with an impermeable boundary at the base, a groundwater divide on the left, a stream on the right, and natural infiltration reaching the water table at the average annual rate on the top. The combination of these boundary conditions and hydraulic properties of the subsurface yields a natural flow-field.

Addition of the WSAS application rate to the natural recharge over the area of the infiltration area represents its presence. In the simplest case, the WSAS infiltration migrates vertically through the vadose zone and to the water table. The gradient increases beneath the infiltration area to accommodate the additional flow, thus creating a mound. The accumulation of water in perched zones and/or the difference in elevation of the water table, before and after increasing recharge on the infiltration area, indicates the magnitude of mounding. These conditions can be evaluated with analytical and numerical flow models.



**Figure 3-1**  
**Conceptual Diagram of Mounding Below WSAS**

Cluster and high-density WSAS require more landscape area than individual WSAS. Avoid the use of one large infiltration area due to construction problems, distribution problems, and potential for anaerobic conditions to develop in the vadose zone (Siegrist *et al.* 1985).

In this work, infiltration areas comprised of  $n$  subunits of dimensions  $l_s$  and  $w_s$ , with a given fractional area of trenches, where effluent is introduced, and a separation between subunits of  $S_p$  is envisioned (see Figure 3-2). The solutions are presented such that any size subunit or groups of units can be considered. One option is used for demonstration purposes.

**Application rate pertains to the bottom of the trench**  
**Trenches comprise a fraction,  $f$ , of the drain field area**  
 **$q$  is the infiltration rate on the trench bottoms**  
 **$q'$  is the infiltration rate averaged over the entire area**  
**of**

the field including all subunits

**$Q$  is the volumetric loading of the drain field**

**$l_s$  = length of subunit**

**$w_s$  = width of subunit**

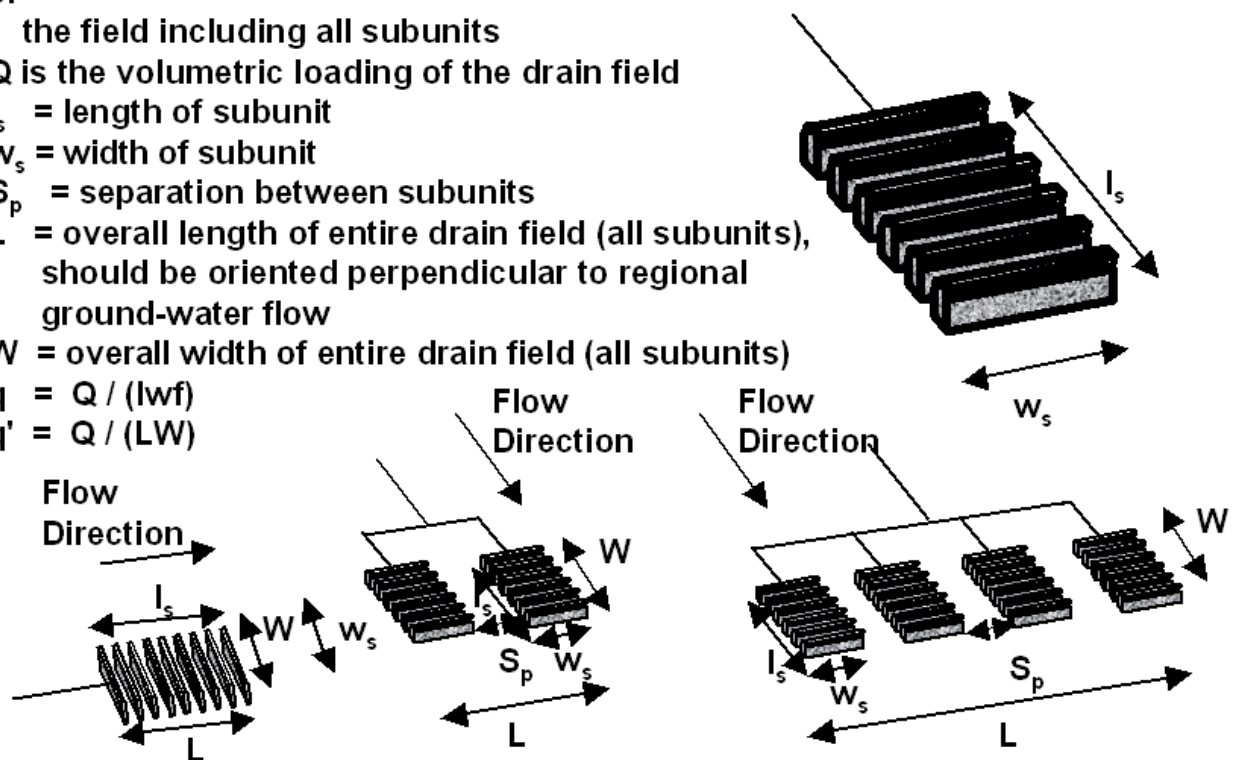
**$S_p$  = separation between subunits**

**$L$  = overall length of entire drain field (all subunits), should be oriented perpendicular to regional ground-water flow**

**$W$  = overall width of entire drain field (all subunits)**

**$q = Q / (lwf)$**

**$q' = Q / (LW)$**



**Figure 3-2**  
**Infiltration Area Subunit Layout Concept**

Optimal wastewater distribution is generally achieved by designing a long narrow infiltration area with its long axis perpendicular to regional groundwater flow. In cases where vadose zone flow dominates a sloped setting, the long axis is designed perpendicular to the landscape fall-line, maximizing the flow area, thereby decreasing the gradient required to carry water from the site, and resulting in less mounding.

When predicting groundwater mounding from WSAS the mode of potential failure needs to be considered. Water may mound on a low-K layer in the vadose zone and rise to the overlying ground surface or move laterally on that layer to breakout on a slope. Alternatively, water may move uninhibited to the water table and flow away from the site with the regional flow of groundwater. Some combination of these scenarios may occur (see Figure 3-1). If the infiltrating water perches, but does not break out at the surface, it will spread to an extent where the head of the perched zone drives water through the low-K layer at the same rate that water is introduced to the WSAS, albeit spread over a larger area. As long as the perching allows sufficient exposure of the wastewater to the vadose zone, either above or below the perching layer, then this case may be advantageous because it prolongs treatment time and decreases the recharge rate per unit area to the water table, and is therefore equivalent to a larger infiltration area.

Two potential mounding scenarios should be considered:

- Perching on a low-K layer in the vadose zone (See section 3.5. This evaluation can be bypassed if field data give no indication of layering in the vadose zone.)
- Mounding of the regional water table (See section 3.5. This evaluation needs to be conducted even if water perches in the vadose zone because, at steady state, the seepage will continue to the water table, although it may be spread over a larger area.)

These analyses are focused on mounding in the natural system below the infiltration area and do not consider conditions in the infiltration trenches. Therefore, both cases assume the infiltration water enters the system uniformly over the entire infiltration area at the long-term acceptance rate specified in the design. The details of the distribution of effluent within the infiltration trenches are not considered. Considering the long-term consistent infiltration from a WSAS, evaluating groundwater mounding for steady-state conditions is sufficient. Transient solutions can be used if they are evaluated for substantial time (10 years is considered a reasonable time to reflect steady-state hydraulic conditions associated with a WSAS).

Approaches to modeling groundwater mounding can range from simple to complex. In some situations, the use of numerical models may be advantageous even when field data are sparse because they enable assessment of processes that cannot be represented with simple models and can facilitate determination of, for example, limiting values of properties for which mounding will not be a problem. Chapter 1, section 1.5 provides information on previous evaluations of modeling groundwater mounding resulting from infiltration.

### 3.4 Preliminary Modeling Considerations

The infiltration rate  $q'$ , where  $q'$  is the total volumetric loading of the system divided by the total system area (the area of the infiltration trenches and the area between the trenches), must be less than the saturated  $K$  of the receiving soil to avoid breakout of wastewater at land surface and ponding at steady state. The rate of percolation equals the product of the gradient and  $K$ . In the direction of flow, the gradient is the difference in hydraulic head divided by the distance between the points where head is measured. Without ponding, the maximum gradient is one, as controlled by free drainage conditions (that is, the hydraulic head equals the elevation, so the difference in head equals the difference in elevation, and their quotient is one), thus the maximum velocity of infiltration is the saturated vertical  $K$ . Consequently, the infiltration area design needs to be adjusted to yield:

$$q' < \text{saturated } K_v$$

**Equation 3-1**

Once this is achieved, the saturated  $K_v$  of low- $K$  lenses in the unsaturated zone must be considered. If the  $K_v$  of these lenses is less than  $q'$ , then mounding will occur as perched water areas in the unsaturated zone, which should be considered the more pressing design problem. In this case, the low- $K$  layer can pass infiltration at a rate higher than its saturated  $K$  because the perched water above the layer causes a gradient greater than one through the low- $K$  layer. The gradient will equal the difference between the top of the mound and the bottom of the low- $K$  layer divided by the thickness of the layer.

As noted previously, the percolation rate is the product of the gradient and  $K$ . Consequently, the maximum infiltration will be controlled by the difference between the elevation of the highest acceptable mound and the bottom of the low- $K$  layer, its thickness, and its  $K$ . This warrants evaluation using the analytical solution presented in section 3.5. If the designer is familiar with Darcy's Law, he or she may find it useful to become familiar with the system by making some rough estimates.

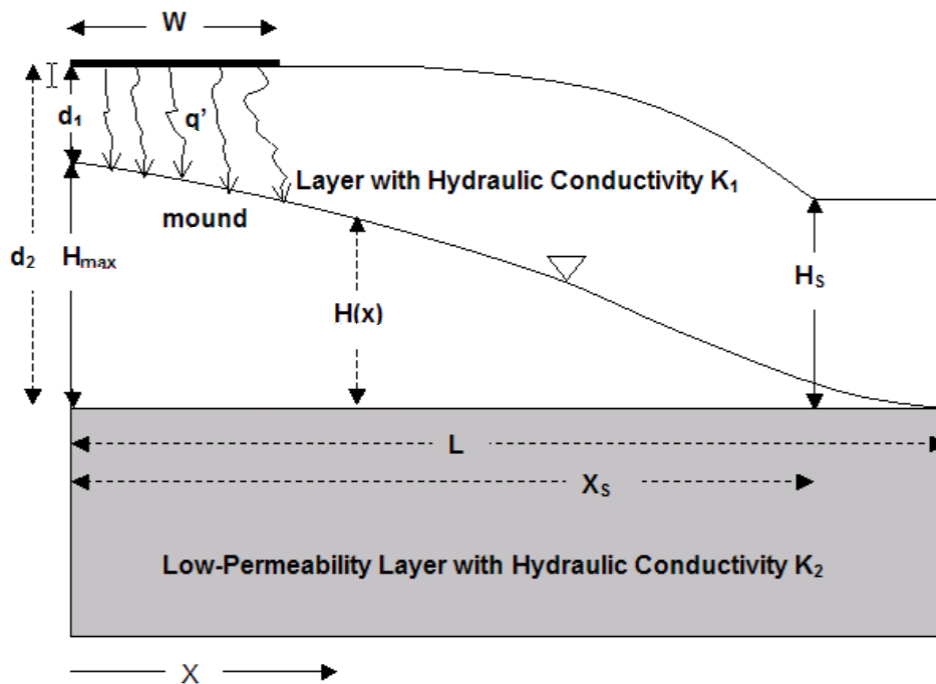
Also, if the designer is familiar with Darcy's Law, he or she may find it useful to approximate the potential carrying capacity of a site for lateral flow away from the site. Depending on the designer's conceptual model and choice of parameter values, either a conservative or liberal estimate of the site capacity may be obtained. There are complications that should be considered and there is not a simple condition that can be guaranteed to bound the problem, so that option is not presented in this methodology.

### 3.5 Estimating Mounding on a Low Hydraulic Conductivity Layer in the Vadose Zone Below a Wastewater Infiltration Area

This section provides design tools to prevent or mitigate breakout of wastewater at the ground surface due to formation of a wastewater mound on a low- $K$  layer in the unsaturated zone below the infiltration area.

Several solutions (see Chapter 1, section 1.5) are applicable to mounding on the water table from large WSAS. However, these solutions are not appropriate for mounding on a relatively impermeable layer in the vadose zone. One analytical solution in the literature is well-suited to this purpose (Khan *et al.* 1976). While this solution does not specifically address unsaturated-flow physics, it is a good tool for engineering applications. Numerical examples investigating the validity of the most important assumptions associated with this solution are provided in the next section.

Figure 3-3 illustrates the physical conceptual model that the solution is based upon. The rectangular source is most relevant to WSAS cluster system analysis, so only that solution is presented. This solution applies for a two-dimensional vertical cross-section of an infiltration area with width  $W$ . The width is assumed much smaller than the length of the area so that the two-dimensional approximation is valid. However, if the assumption does not hold, then the solution provides a conservative estimate for design, because the height of the mound, as well as the vertical extent of the mound, would be less than those values given by the solution. Finally, this solution does not account for mounding that might occur due to a high water table. The solution presented here assumes that the water table is deep, thus the affect of the low-K layer in the vadose zone is the sole cause of mounding.



Note: symbols are defined in the text

**Figure 3-3**  
**Conceptual Model for the Khan Analytical Solution (Khan *et al.* 1976)**

The solution is based on two layers (the soil below the infiltration area and the low-K layer) that are homogeneous and isotropic, but can have different values of saturated  $K$ . The  $K$  for the layer below the infiltration area is annotated as  $K_1$ , while the  $K$  for the low-K layer is given by  $K_2$ , and is the vertical  $K$  of layer two, because only the vertical  $K$  is relevant for the low-K layer.



Before describing the solution, it is important to point out some fundamental concepts related to infiltration in the unsaturated zone. First, if the infiltration rate,  $q'$ , is greater than the saturated  $K$  of the soil or infiltrative surface, then ponding will eventually develop. Ponding is normal in infiltration systems, but the analytical solution does not consider this case. The solution simply assumes a constant infiltration rate. Fortunately, WSAS infiltration rates are relatively constant. In addition, note that mounding will not occur on a layer if the infiltration rate is less than the vertical  $K$  of layer two ( $q' < K_2$ ).

### 3.5.1 Khan et al. (1976) Analytical Solution

Figure 3-3, which is relevant for designing a system to prevent or minimize the possibility of wastewater breakout on nearby side slopes, is given by the simple expression:

$$L = W \frac{q'}{K_2} \quad \text{Equation 3-2}$$

where  $q'$  is the effective wastewater infiltration rate per unit width of infiltration area. For example, if the design infiltration rate is 2 in./day (5 cm/day), and a system of equally spaced, one-meter trenches are to be used (with one-meter spacing between trenches), then the effective infiltration rate would be 1 in./day (2.5 cm/day) over design width,  $W$ . The general solution for the height of the mound ( $H$ ) above the interface of the high- and low- $K$  regions and below the infiltration area, is given by:

$$H = W \left[ \frac{K_2}{K_1} \left( \frac{q'}{K_2} - 1 \right) \left( \frac{q'}{K_2} - \frac{x^2}{W^2} \right) \right]^{1/2} \quad 0 \leq x \leq W \quad \text{Equation 3-3}$$

Note that  $x = 0$  is the center of the wastewater infiltration area, and that the mound below the area is symmetric about  $x = 0$  is assumed.

Beyond the infiltration area, the mound height is given by:

$$H = \left( \frac{K_2}{K_1} \right)^{1/2} (L - x) \quad W \leq x \leq L \quad \text{Equation 3-4}$$

The maximum height of the mound,  $H_{\max}$ , occurs when  $x = 0$  in Equation 3-3.

$$H_{\max} = W \left[ \frac{q'}{K_1} \left( \frac{q'}{K_2} - 1 \right) \right]^{1/2} \quad \text{Equation 3-5}$$

Of course, for design purposes, it is useful to rearrange Equation 3-2 and Equation 3-3 to solve for the maximum acceptable width of an infiltration basin for a desired design wastewater infiltration rate,  $q'$ .

**Equation 3-6**

$$W_{\max} \leq H_{\max} \left[ \frac{q'}{K_1} \left( \frac{q'}{K_2} - 1 \right) \right]^{-1/2}$$

The first case to examine is the one for surface breakout. In Equation 3-6,  $H_{\max}$  would be the maximum mound height above the top of the low-K layer that would still allow the desired depth of unsaturated soil for treatment of wastewater. This equation assumes that the worst case occurs in the center of the infiltration area, which is true for a nearly level surface. However, if the land slope is significantly steep, it is possible that breakout could occur at some distance away from the infiltration area (in the direction toward declining land elevations). Under these circumstances, Equation 3-3 or Equation 3-4 must be evaluated. For most cases, the center of the infiltration area is the most likely place for breakout, and Equation 3-6 is appropriate.

The next case to consider is the one where side-slope breakout is of concern. The simplest case, where the land slope extends down to the same elevation as the top of the low-K layer, is given by:

**Equation 3-7**

$$W_{\max} \leq L_s \frac{K_2}{q'}$$

For the application of Equation 3-7,  $L_s$  is the distance to the slope where breakout is anticipated. Note that Equation 3-7 does not depend on the conductivity of the top layer. Rather, it only depends on the length to the side slope, and on the ratio of the value of K to the wastewater infiltration rate. Also note that Equation 3-7 is not valid for  $q' < K_2$ . This is not a concern because, as stated earlier, mounding will not occur due to the layer effect under this condition. However, mounding of the water table may occur (discussed in section 3.6).

There is an important limitation to Equation 3-7. This simple equation is only valid for the case where the land slope extends down to the same elevation as the top of the low-K layer. In most cases, it is likely that the slope of concern will not extend this deep. Then, a rearranged form of Equation 3-3 must be evaluated for the case where the land slope does not extend down to the same elevation as the top of the low-K layer,

**Equation 3-8**

$$W_{\max} \leq \frac{K_2}{q'} \left( H_s \left( \frac{K_1}{K_2} \right)^{1/2} + X_s \right)$$

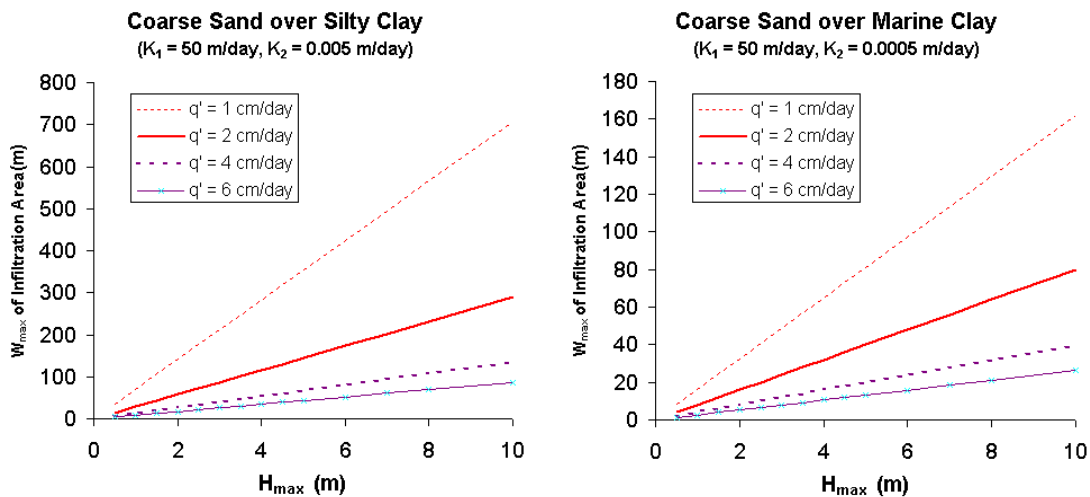
where  $X_s$  is the horizontal distance to the side slope, and  $H_s$  is the depth below the surface to the top of the low-K layer at  $X_s$ . Of course, it is possible that the most limiting condition would not occur at the base of the slope. This condition is most likely to occur in locations where the slope is close to the infiltration area and is steep (compared to the slope of the mound). Under such circumstances, it is prudent to compute the maximum area width for several values of  $H_s$  and  $X_s$ .

One cannot assume that any one of Equation 3-6, Equation 3-7, and Equation 3-8 is always the limiting condition; thus, all relevant criteria must be evaluated.

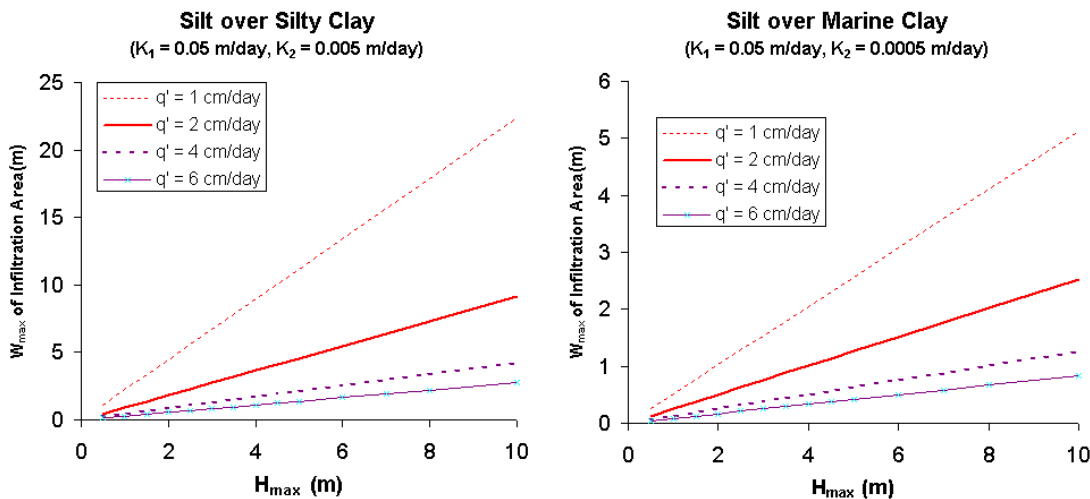
### 3.5.2 Discussion of Analytical-Solution Results

Figure 3-4 and Figure 3-5 illustrate two end-member cases for application of the analytical solution to surface breakout of wastewater at the land surface due to mounding under the trench. The top-layer soil is coarse sand for one, and the top-layer is silt for the other.

The figures were constructed using spreadsheet software and Equation 3-5. Several important characteristics of the solution are evident. First, both the value of  $K_1$  and  $K_2$  significantly influence the maximum infiltration area width,  $W_{max}$ , because one controls lateral and the other vertical flow. Lower values of  $K$  in either the top soil zone or the low- $K$  layer, will cause higher mounding. Of course, this is also evident from inspection of Equation 3-5, because  $W$  is directly proportional to a square root function that includes the product of the  $K$  values.



**Figure 3-4**  
Maximum Infiltration Area Width ( $W_{max}$ ) Versus Maximum Mound Height ( $H_{max}$ ) for Coarse Sand ( $K_1 = 164$  ft/day, 50 m/day) Over Two Different Types of Low- $K$  Soil (Silty-Clay and Marine Clay)



**Figure 3-5**  
Maximum Infiltration Area Width ( $W_{max}$ ) Versus Maximum Mound Height ( $H_{max}$ ) for Silt ( $K_1 = 0.164$  ft/day, 0.05 m/day) Over Two Different Types of Low- $K$  Soil (Silty-Clay and Marine Clay)

A second important issue is that the values of  $K$  impart the largest influence on the final estimation of  $W$ . That is, while there is uncertainty in all the design parameters, the uncertainty in  $K$  has the greatest influence on the value of  $W$ , primarily because of the large inherent uncertainty in  $K$ . If  $K_2$  varies by just an order of magnitude, then the final values of  $W$  are influenced by a factor of three to four (see Figure 3-4). A factor of three to four difference in the design width is a substantial error since there is generally a limited amount of space to construct the infiltration areas. However, estimating  $K$  within an order of magnitude cannot be achieved using simple estimation methods. As pointed out by Freeze and Cherry (1979), the value of  $K$  can vary by two orders of magnitude for a particular soil type. Therefore, obtaining accurate measurements for  $K$  is critically important. Measurement of  $K$  is discussed in Chapter 2, *Site Evaluation for Groundwater Mounding Potential*.

On the other hand,  $q'$  and  $h'$  have a more direct influence on  $W$ . A factor of two or three uncertainty will result in the same factor of potential error in  $W$ . However,  $q'$  is a design parameter, and  $H$  would be known to within 10 percent or less provided sufficient characterization is completed to know the depth of the low- $K$  layer. While these two factors have a greater influence on the value of  $W$ , the uncertainty in these parameters is generally small. Thus, while soil types are provided on the plots for practical reference, obtaining measurements or reliable estimates of  $K$  values is important.

A third item to notice about Figure 3-4 is that the curves are linear, and the relative differences between  $W$  values for various values of  $q'$  are the same for the different soil types. This factor suggests that a more general relationship might be developed so that plots of many different soil types would not be necessary, which is true for special cases.

For the general case where  $q' \gg K_2$  then  $W_{\max}$  of Equation 3-6 is approximated by the relationship:

**Equation 3-9**

$$W_{\max} \cong \frac{H_{\max}}{q'} (K_1 K_2)^{1/2} \quad \text{for } q' \gg K_2$$

In general, use of numerical analysis to evaluate the accuracy of Equation 3-9 demonstrates that this equation exhibits less than six percent error in the calculated  $W_{\max}$  provided that  $q'$  is at least 10 times greater than  $K_2$ . For cases where  $q'$  is 100 times greater than  $K_2$ , negligible error is introduced (less than one percent error) by use of Equation 3-9. Note that, unless pretreatment is implemented,  $q'$  is generally between 0.8 and 2.4 in./day (2 and 6 cm/day). Thus, for practical purposes, Equation 3-9 can be utilized if  $K_2$  is at least 10 times smaller than 0.08 in./day or 2 cm/day, or:

**Equation 3-10**

$$K_2 < 0.1 q' \quad \text{or} \quad K_2 < 0.08 \text{ in./day or } 0.2 \text{ cm/day}$$

Note that this criterion also requires  $K_1 \gg K_2$  because  $K_1$  must be greater than  $q'$  to avoid back-up of wastewater in the trench. Equation 3-9 allows a general nomograph to be constructed that is potentially useful (see Figure 3-6). For this nomograph, the user determines the subsurface properties that are relevant, including the:

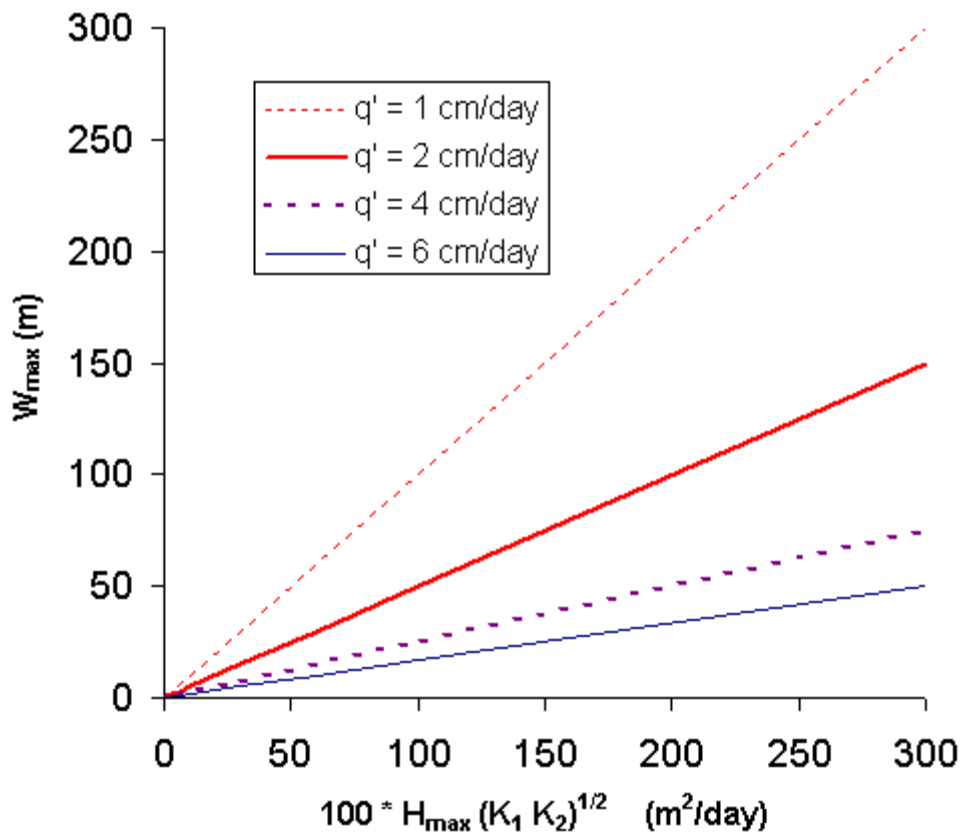
- $K$  of the soil below the infiltration area ( $K_1$ )
- $K$  of the low- $K$  layer ( $K_2$ )
- Maximum allowable mound height,  $H_{\max}$  (distance between the bottom of the infiltration trenches and the low- $K$  layer minus the thickness of vadose zone required for treatment)

Then, depending on the design infiltration rate  $q'$ , the maximum infiltration area width to prevent unacceptable mounding can be read from the chart. Figure 3-6 is relevant for the following conditions:

$$\begin{array}{rclclcl} 0.164 \text{ ft/day} & (0.05 \text{ m/day}) & < & K_1 & < & 164 \text{ ft/day} & (50 \text{ m/day}) \\ >0 \text{ ft/day} & (>0 \text{ m/day}) & < & K_2 & < & 0.02 \text{ ft/day} & (0.006 \text{ m/day}) \\ 3.28 \text{ ft} & (1 \text{ m}) & < & H_{\max} & < & 164 \text{ ft} & (50 \text{ m}) \end{array}$$

However, many of the extreme values, when combined, produce values for  $W_{\max}$  that are not reasonable. Thus, a reasonable range of  $W$  is presented in Figure 3-6 ( $1.64 \text{ ft} (0.5 \text{ m}) < W_{\max} < 656 \text{ ft} (200\text{m})$ ).

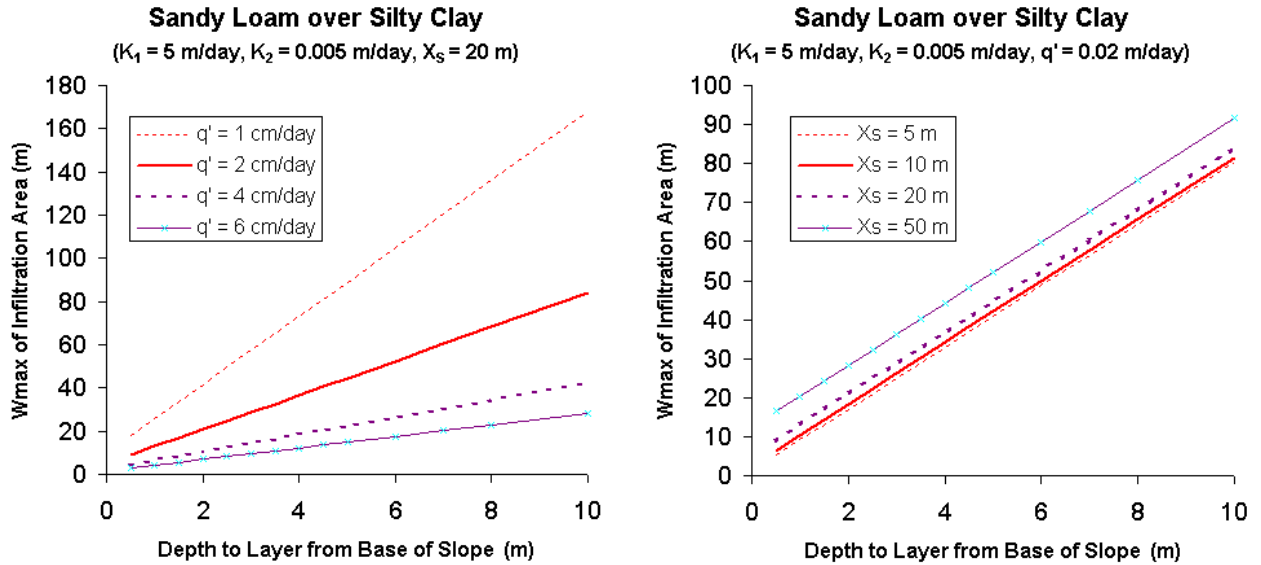
The last case is breakout of wastewater on a nearby side slope due to excessive mounding on a low-K layer. Equation 3-8 is applicable to this case.



**Figure 3-6**  
General Nomograph for Estimating Maximum Infiltration Area Width From Subsurface Properties

Figure 3-7 illustrates two types of nomographs that can easily be developed using a spreadsheet to implement Equation 3-8. The first nomograph in the figure might be useful if the infiltration area size has already been designed and the designer wishes to limit the infiltration rate to prevent side slope breakout. The second nomograph might be useful if the infiltration area and infiltration rate have been determined, and the designer wishes to estimate how close to the side slope the infiltration area can be installed. In this latter case, a few meters of additional distance between the side slope and infiltration area edge can allow a much larger width.

In Figure 3-7, the left figure uses infiltration rate ( $q'$ ) as a design variable, and the right figure uses distance to side slope ( $X_s$ ) as a design variable.



**Figure 3-7**  
 Maximum Infiltration Area Width ( $W_{max}$ ) Versus Depth to the Low-K Layer at the Slope Location for Sandy-Loam ( $K_1$ ) Over Silty-Clay ( $K_2$ )

### 3.5.3 Designing Wastewater Infiltration Areas for Cluster Systems with Respect to Groundwater Mounding in the Vadose Zone Using Analytical Modeling

The Khan solution assumes a uniform width for infiltration. However, typical cluster systems utilize trenches. Thus, wastewater infiltration does not occur over the entire width,  $W$ , of the infiltration area. For spaced trenches,  $q'$  in the Khan solution is the design infiltration rate per unit of total drain field area. The parameter  $q'$  is given by:

**Equation 3-11**

$$q' = q f_A = Q/A_T$$

where,  $q$  is the traditional design infiltration rate (the infiltration rate per unit area of trench),  $f_A$  is the fraction of infiltrative-surface area ( $A_w$ , the area of the trenches) divided by the total infiltration area of the system ( $A_T$ , the area of the trenches and the area between them), and  $Q$  is the total volumetric loading rate for the system.

For design purposes, use of this methodology requires estimation of  $q'$ , which may be different from the traditional design infiltration rate,  $q$ . In general, assuming  $N$  equally spaced trenches where the space between trenches is the same width as the trench,  $f_A$  is equal to  $N$  divided by  $(2N-1)$ . In large systems,  $f_A$  is approximately equal to 0.5. For example, for 20 trenches ( $N = 20$ ), where the trenches are 3.28 ft (1 m) wide with a 3.28 ft (1 m) spacing, then  $f_A = 20$  divided by 39 or 0.513. Then  $q'$  would be equal to about half the designed wastewater infiltration rate ( $q$ ). The relationship of  $q'$  to  $q$  would be different for other geometries. For example, if 10 trenches are used that are 6.56 ft (2 m) wide with a 3.28 ft (1 m) spacing, the total (effective) width of the infiltration area is 95.14 ft (29 m) while the actual width for wastewater application is 65.62 ft (20 m). Then,  $q'$  equals 65.62 (or 20) divided by 95.14 (or 29)  $q$ .

The nomographs are presented as examples. For nomographs to be generally useful to the practicing community, many nomographs for a variety of soil layer combinations, each presented using several different scales for  $W_{\max}$ , would be required. Such a task is beyond the scope of this document. Rather, this study provides a methodology that can be used to develop nomographs. These example nomographs are presented so potential users can easily see how a final product would look. Local professionals can better prepare appropriate monographs for a variety of locally relevant conditions based on geology, soil characteristics, and probable locations for installment of cluster systems.

The discussion here is based on using the parameter,  $W$ , as the primary design parameter for infiltration areas, as suggested by Converse and Tyler (1985). The procedure outlined in Table 3-1 is recommended.

The use of Equation 3-8 for preventing side-slope breakout as required by step 7 of Table 3-1 warrants further discussion. The conservative approach would be to choose the base of the slope where breakout is of concern because the base would be the most likely place for breakout of wastewater due to mounding. The horizontal distance ( $X_s$ ) from the center of the infiltration area to this location must be measured. Next, the height of this location above the interface of the high hydraulic conductivity layer and the low-K layer is needed. This height is also the maximum mound height ( $H$ ) allowable at distance  $X$  to avoid breakout. Simple soil borings are the best method to obtain this information. However, the location could be inferred from geologic information, but with considerably more error.

For infiltration areas that are built on a slope, the worst-case condition for mounding may not be at the center of the area, even though the maximum head is still at the center. If this condition exists, then Equation 3-3 and Equation 3-4 should be used to plot mound height ( $H$ ) versus distance from the center of the infiltration area for various values of  $W$ . This condition can be checked by plotting the mound height above the low-K layer versus distance from the center of the infiltration zone (using Equation 3-3), and comparing this to a plot of the height of the ground surface above the layer. Where mound height is larger than the ground-surface height, breakout of wastewater along the slope will occur.

For the case of side-slope breakout, the Khan method will yield a conservative solution because it assumes a flat, continuous impermeable layer and does not account for spreading along the axis of the trench as required for the analytical solution. A sloped layer would effectively allow more subsurface room for the mound.

Discontinuities in the impermeable layer would allow water to penetrate below the layer and thus mitigate the mound height; some spreading may occur along the axis of the trench, which would mitigate the mound height at the edges of the field, but not in the center. The effect of discontinuities is addressed in section 3.5.5.

Developing nomographs such as those discussed in the previous section as preliminary design tools for different soil types and design infiltration rates is often useful. Figure 3-4, Figure 3-5, Figure 3-6, and Figure 3-7 illustrate the usefulness of this approach for several soil types. The figures allow estimation of  $W_{\max}$  based on maximum allowable mound heights ( $H$ ).

An example of a design application is given in Table 3-2. This example follows the design steps outlined in Table 3-1.

**Table 3-1**  
**Design Procedure Considering Mounding on Low-Conductivity Layers in the Vadose Zone**

Step	Task
1	Estimate design volumetric flow rate (gallons/day or m <sup>3</sup> /day) ( $Q_w$ ).
2	Determine the design infiltration rate, $q$ , based on a long-term acceptable rate determined by effluent composition and soil properties (see Siegrist 1987). This value may also be determined based on known performance of other WSAS systems in a similar soil type.
3	Calculate the effective wastewater infiltration rate ( $q'$ ) from $q' = f_A q$ . Assume an initial value for $f_A$ of 0.5, which is generally true for large cluster systems. NOTE: For mature systems, unless pretreatment is employed, $q'$ must be less than about 6 cm/day because biomat formation on the infiltrative surface generally limits infiltration to this value for typical systems with a biomat formed on the infiltrative surface (Beach and McCray 2003).
4	Calculate the required area for wastewater infiltration from $A_T = Q_w/q'$ .
5	Determine depth to low-K layer ( $D_1$ ).
6	Subtract the desired or required thickness of unsaturated soil below the infiltration area ( $D_2$ ).
7	Calculate maximum mound height allowed as $H_{\max} = D_1 - D_2$ . A factor of safety may be applied to decrease the mound height if desired.
8	Measure the distance from the center of the infiltration area to the base of the side slope ( $X_s$ ), if applicable. Determine the depth of the low-K layer below the base of the slope ( $H_s$ ).
9	Measure or estimate the saturated K of the soil below the infiltration area ( $K_1$ ) and the low-K layer ( $K_2$ ). Methods for doing this are presented in Chapter 2, section 2.5.
10	Estimate the infiltration area maximum width ( $W_{\max}$ ) to prevent breakout at the surface by applying the appropriate design equation (Equation 3-6 or Equation 3-9) or chart (Figure 3-4, Figure 3-5, and Figure 3-6).
11	Estimate $W_{\max}$ to avoid side-slope breakout using Equation 3-7 or Equation 3-8 or a nomograph such as that depicted in Figure 3-7.



**Table 3-1**  
**Design Procedure Considering Mounding on Low-Conductivity Layers in the Vadose Zone (Cont.)**

Step	Task
12	<p>Choose the width (<math>W</math>) of the infiltration field. The actual width must be less than the limiting <math>W_{\max}</math> (for surface or side-slope breakout). Ultimately, the water mounding on the low-K layer will infiltrate to the water table, so maximizing length in the direction perpendicular to regional groundwater flow is desirable. However, uniform delivery of effluent to a long narrow infiltration area may present logistical, physical, construction, and cost issues. Considering these issues, compute <math>W</math> as <math>W = A_T/L</math> where <math>L</math> is the maximum reasonable length perpendicular to regional flow available for the site. If this bounding calculation causes <math>W</math> to exceed <math>W_{\max}</math>, system expectations will need to be reduced. A safety factor may be applied if deemed appropriate.</p> <p>Keep in mind that for cases where <math>W</math> is not <math>\gg</math> the length of the infiltration area, the equations used herein will generally overestimate the mound height, which fortuitously provides a safety factor. Space or other practical constraints must also be considered.</p>
13	Compute required length ( $L$ ) of infiltration area system from $L_T = A_T/W$ , using $W$ from step 12.
14	Compare $L_T$ and $W$ to available area dimensions.
15	Reduce $L_T$ , increase $W$ (with $W < W_{\max}$ ), and alter $f_A$ as necessary to meet space constraints.
16	Use the determined dimensions to evaluate mounding of the water table below the perched zone. If a larger infiltration area is needed for that case, use those dimensions for the final design.

Table 3-2 is an example of a design application for a wastewater infiltration area for a 50-home development (125 persons) in sandy-loam. The example follows the design steps outlined in Table 3-1.

**Table 3-2**  
**Example Design Application Considering Mounding on Low-Conductivity Layer in the Vadose Zone**

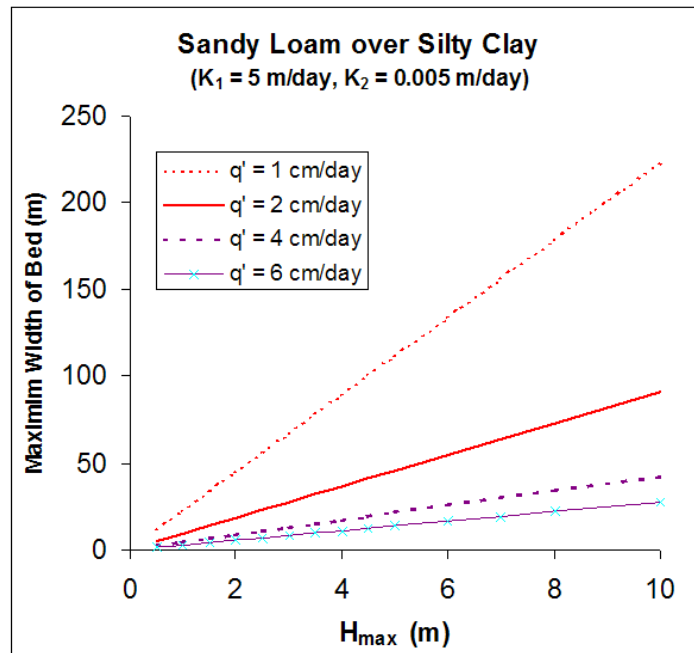
Step	Task
1	The expected wastewater loading for this development is calculated assuming a median per capita wastewater production of 60 gallons person <sup>-1</sup> day <sup>-1</sup> (227 L person <sup>-1</sup> day <sup>-1</sup> ) (McCray <i>et al.</i> 2005 and Kirkland 2001). Note that local regulatory requirements may specify a different design value. Thus, the daily flow rate for the development is 7,500 gallons per day (GPD) (1000 ft <sup>3</sup> /day, 28,388 liters/day, or 28.4 m <sup>3</sup> /day). Note: design flow can be increased to provide a factor of safety or reserve capacity.
2	The design infiltration rate, $q$ , is chosen to be 0.13 ft/day (0.04 m/day or 4 cm/day).
3	The effective infiltration rate, $q' = 0.5 q = 0.067$ ft/day = 2 cm/day = 0.02 m/day.
4	<p>The design area needed for infiltration is</p> $A_T = Q/q = \frac{1,000 \text{ ft}^3/\text{day}}{0.067 \text{ ft/day}} \text{ OR } \frac{28.4 \text{ m}^3/\text{day}}{0.02 \text{ m/day}} = 15,279 \text{ ft}^2 \text{ OR } 1,419 \text{ m}^2$
5	Based on test borings, a low-K layer is located 15.75 ft (4.8 m) below the surface ( $D_1$ ) at the center of the proposed infiltration area.

**Table 3-2**  
**Example Design Application Considering Mounding on Low-Conductivity Layer in the Vadose Zone (Cont.)**

Step	Task
6	The designers desire to have 6 ft (1.8 m) of unsaturated soil below the infiltrative surface ( $D_2$ ).
7	The maximum mound height, $H_{\max} = 9.84$ ft (4.8 m – 1.8 m = 3.0 m)
8	The distance to the nearest side slope, where breakout is of concern is 65.6 ft (20 m) in the lateral direction. The layer is located 11.5 ft (3.5 m) below the base of the side slope of concern. $H_s = 11.5$ ft (3.5 m).
9	Based on several grain-size analyses, the K of the near-surface soil and the low-K layer are estimated to be $K_1 = 16.4$ ft/day (5 m/day) and $K_2 = 0.0164$ ft/day (0.005 m/day), respectively (sandy-loam soil over a silty-clay low-K layer).
10	Now determine $W_{\max}$ to prevent surface breakout. For this case, the criterion to use Equation 3-9 ( $q' \gg K_2$ ) is not met, so the general nomograph (Figure 3-6) unfortunately cannot be used. Rather, Equation 3-6 is used. Figure 3-5 and Figure 3-6 are not appropriate to use for the K values determined in step 9. If a user desires a nomograph, a new one based on Equation 3-6 must be constructed. Figure 3-8 depicts a nomograph for this condition. A maximum infiltration-area width of 90 ft. (27.4 m) is calculated using Equation 3-6. Figure 3-8 produces the same result, but for best use, the plot should be reconfigured so that the y-axis covers a smaller range. At the current scale, a value between about 82 and 98 ft (25 and 30 m) can be determined.
11	Now determine $W_{\max}$ to prevent side-slope breakout. Equation 3-7 cannot be used because the base of the slope does not intersect the low-K layer. Using Equation 3-8, a maximum width of 107.3 ft (32.7 m) is calculated. This width is larger than the $W_{\max}$ to prevent surface breakout, so that width is more limiting, and will be used for design of the infiltration field. Note that, for this case, Figure 3-7 can fortuitously be used. However, the scale of the figure does not allow an accurate determination (a $W_{\max}$ value between 115 and 131 ft (35 and 40 m) can be estimated).
12	A square for the above area would have length dimensions of 124 ft (38 m). However, the width must be less than 90 ft. (27.4 m) (see step 10). In addition, there are space constraints; one dimension of a rectangular field must be less than 98 ft (30 m) and the other must be less than 262.5 ft (80 m). Even if the 262.5 ft (80 m) length were oriented perpendicular to the direction of regional flow, the elongate design would present challenges related to obtaining fairly uniform distribution along the length of the trenches, perhaps requiring pumps. Consequently, first choose a width of 82 ft (25 m). This does not provide much of a safety factor, but reassessment will occur in the next two steps.
13	The resulting length ( $L$ ) is 173 ft (52.6 m).
14	The dimensions in steps 12 and 13 are appropriate within the space considerations for both width and length. Because $L$ is only two times greater than $W$ , the equations used will somewhat overestimate mounding and provide a factor of safety. A single trench that is 174 ft (53 m) long may present challenges for uniform delivery of effluent along the trench, however. For this case, pumps may be necessary for effluent delivery because the design is nearly at the value for $W_{\max}$ . This cost may be considered insignificant compared to constructing fewer homes in the development.

**Table 3-2**  
**Example Design Application Considering Mounding on Low-Conductivity Layer in the Vadose Zone (Cont.)**

Step	Task
15	The length and width are appropriate. Assuming trenches that are 3.28 ft (1 m) wide with the same spacing between trenches, 14 trenches can be provided. Thus, the actual $f_A = 14/27 = 0.537$ , which would result in an updated value for $q' = 0.021$ . Thus, the design procedure can stop here. If $f_A$ were significantly larger than 0.5, then the actual $q'$ might cause unacceptable mounding for the chosen $W$ , so an additional iteration through the procedure might be necessary. If $f_A$ were significantly smaller than 0.5, then the width could be increased and the length decreased.
16	Using these dimensions, evaluate mounding of the water table below the perched zone (see section 3.6.3). If a larger infiltration area is needed for that case, use those dimensions.



**Figure 3-8**  
**General Nomograph for Determining Maximum Infiltration Area Width and Infiltration Rate ( $q'$ ) for the Design Example in Table 3-2.**

In the example used for Table 3-2 the design infiltration rate  $q'$  was 0.066 ft/day, 0.8 in/day (0.02 m/day, 2 cm/day). Note that the design infiltration rate in a single trench ( $q$ ) would thus be 1.57 in/day (4 cm/day), with an assumed actual infiltration area ratio ( $f_A$ ) of 0.5. This is most likely an acceptable long-term infiltration rate for coarser-grained soils receiving typical domestic effluent. For WSAS effluent without advanced pretreatment the literature suggests that rates greater than this are not likely in many hydrologic and climatic regions because of the hydraulic limitations imposed by biomat formation at the infiltrative surface of the trenches (Siegrist *et al.* 2001 and Beach and McCray 2003).

If the design infiltration rate ( $q$ ) for the example was calculated to be greater than 1.18 in/day (3 cm/day), and the same trench system is desired, then failure of the system could occur due to back-up of wastewater in the trench. In this case, the designer may opt for wider trenches with the same spacing between trenches. This option would increase  $f_A$  and lower the overall design infiltration rate ( $q'$ ). Of course, this analysis does not consider the impacts of trench spacing on purification, which may be important.

Changes in  $q'$  or infiltration area size may be required after following the design procedure. In addition, the depth of the low-K layer may not be consistent throughout the site. In such cases, it is useful to construct a nomograph that is specific to the soil conditions at the site. If the criterion  $K_2$  is greater than 0.1  $q'$  is met, then Figure 3-6 would serve this purpose. For the example in Table 3-2, however, this criterion was not met, thus a site-specific nomograph would be constructed from Equation 3-6. Figure 3-8 illustrates a nomograph that would be useful for developing different combinations of  $q'$  or  $W_{\max}$  that would meet design criteria for the example presented in Table 3-2.

### 3.5.4 Limitations of Analytical Modeling

Hydraulic conductivity cannot be accurately estimated from simply knowing the soil type, which is an important consideration. For example, according to Freeze and Cherry (1979), the K for any particular soil type can vary over at least an order of magnitude. An order of magnitude error in  $K_1$  estimation would impart an error of about a factor of three for design width in the design equations. An order of magnitude error in  $K_2$  estimation would impart at least a factor of three error for design width. Therefore, obtaining reliable measurements of K when performing engineering analysis for cluster systems is important.

Suggested methods for measurement of K in unsaturated and saturated soil are outlined in Chapter 2, sections 2.6 and 2.7. Errors on the order of a factor of ten would not be unusual, however, even if specific measurements are collected. Analyzing the statistics on several measurements can lead to considerable insight into the error in K measurements. If the designer has not collected detailed measurements of K, but has obtained a reasonable estimate based on soil classification or a few measurements, then a factor of ten error in K is reasonable to assume. Thus, a factor of safety of 3 for  $W$  or  $q'$  is probably more appropriate than the typical safety factor of 2 or 1.5.

#### 3.5.4.1 The Khan Solution

The Khan solution is used for mounding on a low-K layer in the vadose zone. However, unsaturated-flow physics are not considered in these solutions. That is, the influence of variable water saturation on K and the influence of capillarity are not considered. The solution inherently assumes that once a mound exists, the soil is saturated. However, provided the criteria in the previous sections are met, then the assumption of saturated flow is probably conservative for some cases but not in others. For example, capillarity of a low-K layer would increase the rate of water flow through it. However, the reduced K in an unsaturated system could tend to retard lateral spreading and thus increase mound heights. In addition, negative pressures (rather than zero pressure) may occur at the base of the low-K layer, increasing the gradient across the layer and decreasing the mound height. The use of a numerical model is recommended to investigate these influences.

The Khan solution also does not account for anisotropic soil. That is, the horizontal and vertical hydraulic conductivities are assumed the same for the solution. This assumption is primarily an issue for the top layer of soil because it is assumed vertical  $K$  of the low- $K$  layer is used for  $K_2$ . If values used for  $K_1$  are representative of the horizontal  $K$ , and the vertical  $K$  is actually significantly lower, then the Khan solution would under predict mound height but would over predict the extent of the mound ( $L$ ). However, if  $K_1$  is representative of the vertical  $K$  and the horizontal  $K$  is actually significantly larger, then the Khan solution will over predict the mound height; however, the extent of the mound may be slightly under predicted. For the low- $K$  layer, the effect would be important only if the vertical  $K$  for the layer is less than the assumed value of  $K_2$ . Then, the Khan solution would under predict the mound height and the extent of the mound.

Anisotropy may result from the way the grains are aligned in a homogeneous medium. In this case, the anisotropy is not likely to be noticed by the designer. However, if thin layers of low- $K$  material cause the anisotropy, then obtaining estimates for the horizontal and vertical  $K$  is worthwhile. For thin layers, grain-size analyses are likely to be the most feasible method to estimate  $K$ . In this case, the estimated  $K$  for the fine-grained layers can be assumed equal to the vertical  $K$ , although the true vertical  $K$  would be slightly higher. The product of the  $K$  value of the coarse layers and their fractional thickness is more representative of the effective horizontal  $K$ . Obtaining horizontal and vertical cores to obtain  $K$  values by conducting permeameter tests may also be possible. Falling head tests could be conducted on one or more of the vertical layers if the soil above them can be excavated.

Once the designer obtains values for vertical and horizontal  $K$ , he or she could use the vertical  $K$  values in the Khan solution to obtain a conservative estimate of mound height, and the horizontal  $K$  values to obtain a conservative estimate of mound extent ( $L$ ). A more rigorous analysis requires use of a numerical model to estimate mound height and  $L$ .

The Khan solution also does not account for heterogeneities other than the assumed two-layer system. If heterogeneities were randomly distributed, then the best values to use for  $K$  would be the geometric mean of the various  $K$  values. However, this approach is not feasible. Thus, a conservative (low) value for  $K$  must be chosen, probably based on the results of several estimates or measurements of  $K$  at locations throughout the infiltration area.

If a discontinuous layer exists, then assuming that the layer is continuous and using the Khan solution provides a conservative estimate (over prediction) of the mound height and extent, because some of the wastewater would travel between the discontinuous low- $K$  zones and would not mound in these areas.

For severely heterogeneous systems, numerical modeling is not likely to improve estimates of mound height because the data collection requirements would be cost prohibitive. Thus, several pilot-scale infiltration tests that involve applying clean water at the design rate to an area and monitoring mound height should be conducted. While the steady-state behavior may take too long to achieve, the mounding behavior under various rates may provide insight to infiltration rates that are acceptable. The provision of specific guidance on pilot-scale tests is not intended here. These tests are designed based on site conditions, probably by a hydrogeologist with training in infiltration processes. The test could be expensive if a long period of time is required to achieve steady mounding levels, but may be less expensive than a detailed site characterization. The relative costs are highly site specific.

Finally, note that the Khan *et al.* (1976) solution does not allow consideration of the influences of heavy rainfall on the mounding. To address this issue, one would need to use a numerical model that can simulate transient, unsaturated flow. However, as a conservative assumption, the designer could assume that the mound height would increase by the total rainfall accumulated during the storm divided by porosity of the soil. A more reasonable estimate could be obtained by subtracting an estimated amount for runoff. This calculation is beyond the scope of this document; however, the SCS rainfall-runoff method (for example, Viessman and Lewis 2003 or most engineering hydrology texts) is recommended.

Constructing numerical models is time consuming and requires a significant level of expertise in hydrology, soil physics, numerical methods, and computer operation, and is therefore quite expensive. However, if the risks associated with excessive mounding are serious, the expense may be worth the effort. The following section demonstrates the utility of numerical modeling for this problem. Several examples are provided; however, these form only a small subset of the potentially useful examples of mounding under WSAS systems.

### **3.5.5 Numerical Solutions**

Considerable expertise is required to apply a numerical model, particularly an unsaturated flow model. This report provides some theory and background on mathematical modeling for the benefit of those who may implement the model. The intention is not that the “layman” follow the theory (although an attempt is made to provide some practical descriptions for parameters discussed in the theory that all readers may find useful). Those not conversant with hydrologic modeling should focus their attention on the modeling results, to avoid becoming “bogged down” in the specifics of model theory and applications.

#### **3.5.5.1 HYDRUS-2D Model**

The HYDRUS-2D code (Simunek *et al.* 1995) was used for these simulations. HYDRUS-2D is a two-dimensional finite element numerical model based on the Richards’ equation for unsaturated flow. HYDRUS-2D can also simulate complex reactive transport, although that feature is not used in this project. HYDRUS-2D was selected because it is reasonably priced (\$1,200 for the Windows-based version and the mesh generator) and user friendly. Other similar models are available at lower cost but without a graphical-user interface (GUI). A disadvantage for numerical models such as HYDRUS-2D is the relatively long computer execution time. HYDRUS-2D simulates the non-linear Richards’ equation, so iterative techniques must be used to solve the partial differential equation. This requires many more computations than models solving linear equations, even when iterative solvers are used to obtain solutions for the linear equations. A significant advantage of the finite-element model is the ability to simulate irregular meshes (for example, soil mounds, hill slopes, valleys, and stream banks).

##### **3.5.5.1.1 Numerical Formulation of HYDRUS-2D**

HYDRUS-2D solves the mixed form of Richards’ equation (Celia *et al.* 1990) for variably saturated water flow using the standard Galerkin linear finite-element method. The capillary pressure head versus water content relationships in HYDRUS-2D are based on the van Genuchten (1980) relationships shown in the following equations:

$$|h| = \alpha^{-1} [\Theta^{1/m} - 1]^{1/n}$$

Equation 3-12

$$\Theta = (\theta - \theta_r) / (\theta_s - \theta_r)$$

Equation 3-13

$$m = 1 - 1/n$$

Equation 3-14

where:

$h$	pressure head [L]	$\theta_s$	saturated water content (typically assumed to be equal to the porosity)
$\theta$	volumetric water content	$\alpha$	empirical constant that is inversely related to the air-entry pressure value [L <sup>-1</sup> ]
$\Theta$	effective water content	$n$	empirical parameter related to the pore-size distribution
$\theta_r$	residual water content		

The pressure head in an unsaturated system is likely to be negative with respect to atmospheric pressure. Measurement of pressure head in unsaturated soils requires use of a tensiometer, generally available from soil-physical instrument suppliers. The residual water content is usually defined as the asymptotic water content value at large negative pressures (dry conditions) on a pressure-head versus water content graph. These data should be obtained for a numerical modeling effort, although methods exist to estimate it (see a soil-physics or unsaturated-zone hydrology textbook). Some soil physicists contend that this value is merely a fitting parameter. In practice, this value would likely be less than the field capacity, but larger than the wilting point water content. The air-entry pressure is the pressure head required for air to enter a saturated system, or the finite negative pressure required to withdraw water from a soil system. The air-entry pressure head for a particular soil (in units of length) is hypothetically the same as the height of the capillary fringe at the water table for that soil type.

The  $K$  varies with water content for an unsaturated soil. Thus, the term “unsaturated hydraulic conductivity,” denoted by  $K(\theta)$ , is used in soil physics and vadose-zone hydrology. The maximum value for  $K(\theta)$  is the saturated  $K$ . As water content decreases, the value of  $K(\theta)$  decreases non-linearly to a value of zero at the residual water content (no flow exists below this value because the water in the pores is assumed to be disconnected). For a modeling effort, a relationship between  $K(\theta)$  and  $\theta$  is required. Directly obtaining  $K(\theta)$  for various pressure heads (and thus water contents) is possible using a tension-disk infiltrometer for near-surface soils. However, estimating this relationship from the easier-to-measure  $h(\theta)$  versus  $\theta$  relationships is more common.

For this effort, the unsaturated  $K$  relationship is obtained by combining the van Genuchten (1980) function with the Mualem (1976) pore-size distribution model, and is shown as follows in Equation 3-15.

$$K(\theta) = K_s k_r(\theta) = K_s \theta^l [1 - (1 - \theta^{1/m})^m]^2$$

Where  $K(\theta)$  is the unsaturated K [ $L_T^{-1}$ ] and is a function of water content;  $K_s$  is the saturated K [ $L_T^{-1}$ ];  $k_r(\theta)$  is the relative K of the soil-water system, which is a function of water content; and  $l$  is an empirical parameter assumed to be associated with pore-connectivity that is typically set equal to 0.5 (Simunek *et al.* 1999).

The parameters used in these simulations are provided in Table 3-3. The relative hydraulic conductivity varies between 0 and 1 (as a function of  $\theta$ ) and can be thought of as a multiplier to transform the saturated K to the proper  $K(\theta)$  value.

**Table 3-3**  
**van Genuchten Parameters used in HYDRUS-2D**

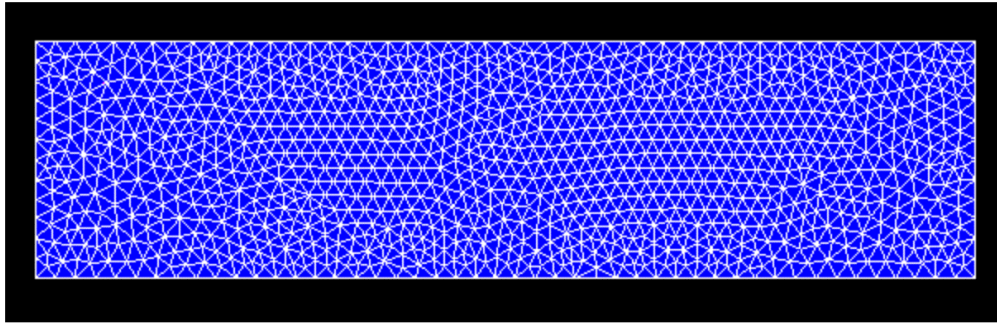
Soil Type	$\theta_r$	$\theta_{\text{Sat}}$	$\alpha$ ( $\text{m}^{-1}$ )	$n$	$K_s$ (m/day)
Sandy-Loam	0.057	0.41	12.4	2.28	5
Silty-Clay	0.07	0.36	0.5	1.09	0.005

### 3.5.5.2 Numerical Mesh and Initial and Boundary Conditions

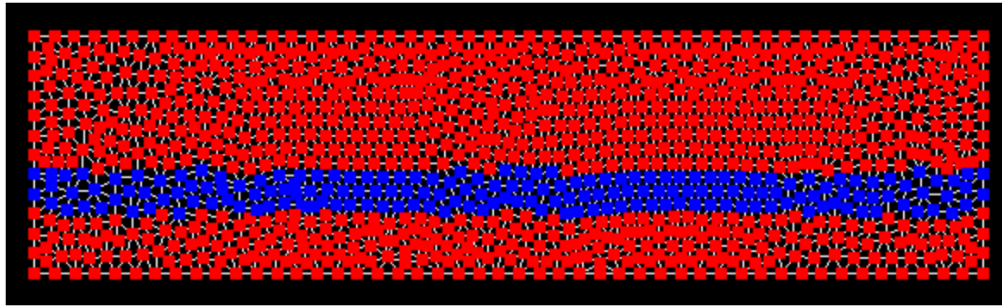
The numerical mesh used for all the simulations in this report is shown in Figure 3-9. The model is 20 m (approximately 66 ft) in the x-direction, and 5 m (approximately 16 ft) in the y-direction. The spatial dimensions of this model are significantly scaled down (5 m deep by 2 m wide) to provide for computational efficiency. For this simulation, a 3.1-m-wide trench infiltration zone in the center of the mesh above a 0.5-m-thick layer with its top approximately 3 m below the infiltrative surface is being simulated (see Figure 3-10). The 3.1-m-wide trench could represent two 1-m-wide trenches with a 1-m spacing. Note that the surface of the layer is uneven because of the finite element discretization. A triangular discretization could have been used, which would have provided a rectangular layer; however, the numerical model runs more efficiently when the curvilinear elements are generated. In reality, a layer in the subsurface would not be smooth, so the numerical model is reasonable. The layer is continuous and thereby provides an acceptable comparison for the analytical model. In Figure 3-10, red nodes represent the native soil below the infiltration area; blue nodes represent the low-K layer (located approximately 3 m (10 ft) below the ground surface).

To simulate a wider, more realistic, cluster system (for example, 30-m wide), a 200-m-wide numerical mesh is necessary to avoid edge effects of the lateral boundary conditions on the simulation results. A deeper mesh would also be desired to allow for large mounds that can develop beneath infiltration areas with large flow rates. These larger-scale simulations required 30 times more elements than the current mesh, and resulted in approximately a 100-fold increase in execution time. The models presented here require five minutes to an hour to execute. The corresponding larger meshes would result in model run times of several hours to several days, and therefore a variety of cases could not be examined for this project if the larger mesh were used. The purpose of this section is to show the usefulness of numerical models compared to analytical models, and to evaluate the accuracy of analytical models, so the smaller mesh is appropriate.





**Figure 3-9**  
Finite-Element Mesh Used for HYDRUS-2D Modeling



**Figure 3-10**  
Soil Distribution for Model Cases 1 and 3

Boundary conditions on the model are as follows:

- **Top**—No flow except for a constant flow rate of 2 cm/day (0.02 m/day) over a 3-m section in the middle of the top boundary
- **Sides**—No flow boundary
- **Bottom**—Constant head associated with a water table located about 1 m above the bottom of the mesh

Initial conditions assumed a negative 100 cm of pressure head everywhere. The simulations presented here are steady state, so the effects of the initial conditions should be negligible.

### 3.5.5.3 Case 1: Homogeneous Loamy-Sand Over a Homogeneous Silty-Clay Layer

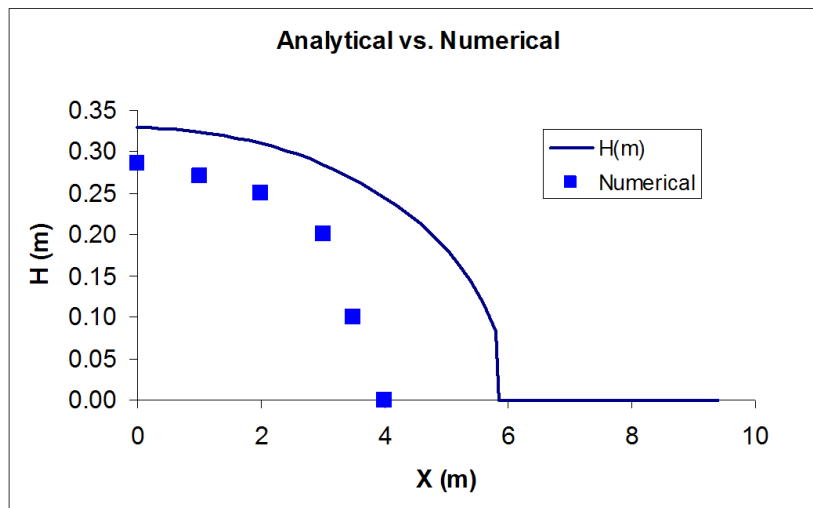
For this case, wastewater infiltration into a loamy-sand media underlain by a silty-clay layer was simulated. Both soils are isotropic and homogenous. The wastewater infiltration rate is 0.02 m per day. For this simulation, the numerical and analytical results are first compared, noting that the analytical solution provides a conservative result as shown in Figure 3-11.

Figure 3-12 shows that the head values for the numerical case do not produce a smooth curve as suggested in Figure 3-11, because the layer surface is uneven, so small capillary gradients exist near the top of the layer. The numerical solution indicates less mounding than predicted by the analytical solution, which occurs because the analytical solution does not consider unsaturated flow physics.

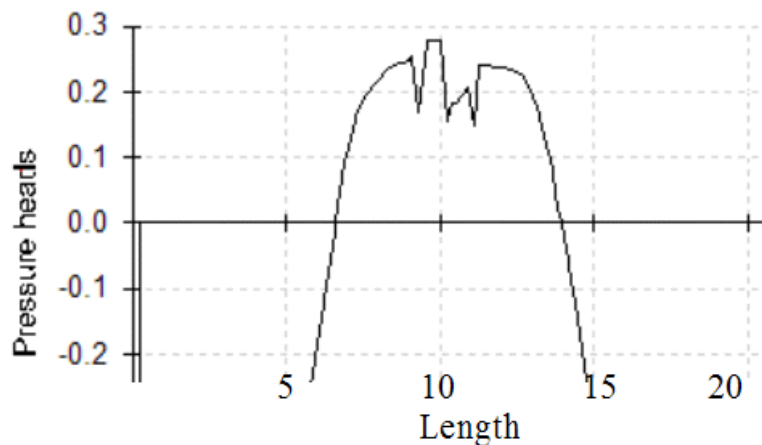
The analytical solution neglects capillary forces. The soil above the water table is actually at a negative pressure-head (relative to atmospheric pressure). Therefore, during infiltration there is a lateral pressure gradient, and thus lateral water flow, out into the negative-pressure zone at all locations around the advancing waterfront.

The analytical solution considers only vertical flow through the low-K layer with zero pressure at the base. Some water is held in tension in the soil above the layer, outside the infiltrating column of water. This water does not contribute to saturated water mounding on the top layer. In addition, tension at the base of the layer increases the gradient through the layer so less mounding is required to transmit the same volume.

Figure 3-12 illustrates the sharp lateral pressure gradient (positive to negative) that exists on the lateral edges of the wetting front. A 10-m wide infiltration zone applying 2 cm/day is shown in Figure 3-11 and Figure 3-12.



**Figure 3-11**  
**Analytical Versus Numerical Solution for Model Case 1**

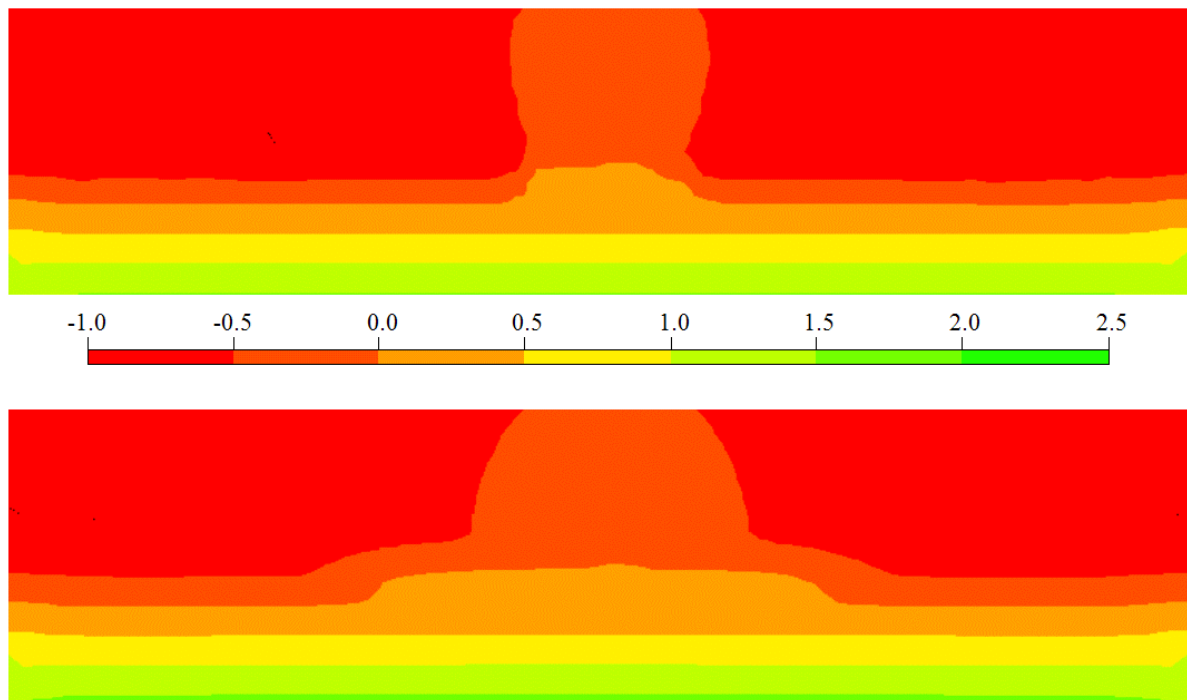


**Figure 3-12**  
**Pressure-Head (m of water) Profile Along the Top of the Low-K Layer**  
**(3 m [approximately 10 ft] below infiltration area) for Model Case 1**

Figure 3-13 shows the wetting profile at 20 days and at 200 days, and also illustrates this phenomenon. The scenario is for a 10-m wide infiltration zone applying 2 cm/day. The bottom of the model domain is 20 m (approximately 66 ft) across and the sides are 5 m (approximately 16 ft) high. The legend depicts water-pressure head (m of water).

The simulation reached steady state in less than 200 days. At 20 days, the soil is unsaturated above and around the infiltrating water, but as capillary forces draw the water laterally, moisture content increases with time above the saturated mound developing on the silty-clay layer.

This case also illustrates the general case of heterogeneous media. If the low-K media below the infiltration field is not continuous with respect to the location and length of the infiltration area, then water will generally be driven around the layers by capillary gradients. However, a relatively small section of low-K media directly below the infiltration area could cause mounding if the layer was sufficiently close to the area because water may mound enough to reach the surface in spite of the capillary gradients that pull water around the layer.

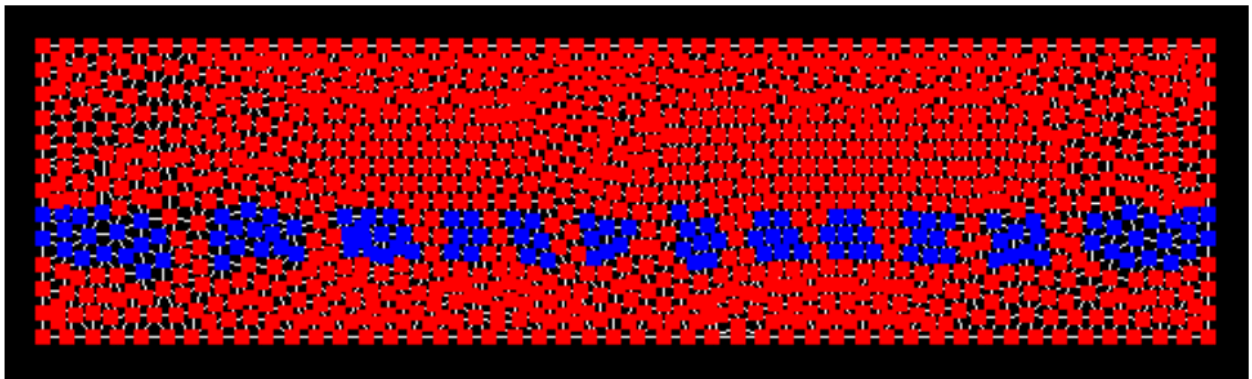


**Figure 3-13**  
**Pressure-Head Distribution for Model Case 1, 20 Days After Starting Infiltration (top), and 200 Days (steady state) After Starting Infiltration (bottom)**

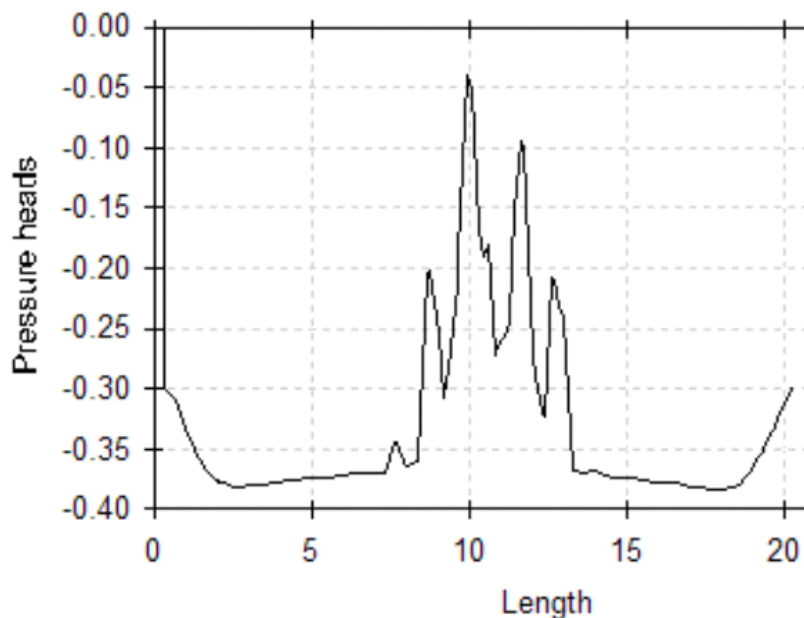
#### 3.5.5.4 Case 2: Homogeneous Loamy-Sand Over a Non-Continuous Silty-Clay Layer

This case is similar to Case 1 except that the low-K silty-clay layer is not continuous (Figure 3-14). The scenario is for a 10-m wide infiltration zone applying 2 cm/day. Red nodes represent the native soil below the infiltration area, blue nodes represent the discontinuous low-K layer. The bottom of the model domain is 20 m (approximately 66 ft) across and the sides are 5 m (approximately 16 ft) high. Although this situation is realistic, the analytical model is not capable of simulating this case. The result differs strikingly from the case of a continuous low-K layer (Case 1). There is no mounding for this case.

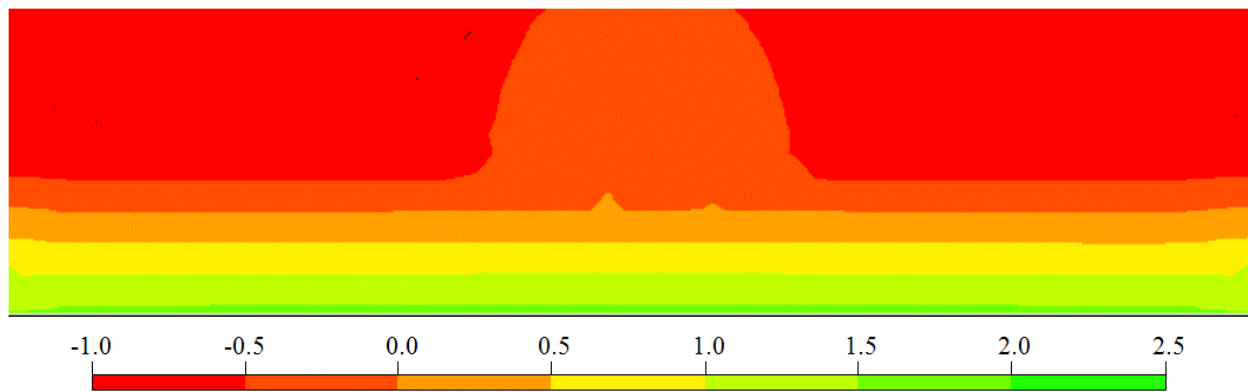
Figure 3-15 shows the pressure head profile at the top of the silty-clay layer (the scenario is for a 10-m wide infiltration zone applying 2 cm/day with 3 m (approximately 10 ft) below infiltration area), while Figure 3-16 illustrates the pressure distribution in the entire model domain. For Figure 3-16, the bottom of the model domain is 20 m (approximately 66 ft) across and the sides are 5 m (approximately 16 ft) high. The legend depicts pressure head (m). Full saturation is not reached anywhere in the domain above the layer because, as water tends to build up on the low-K zones, it is driven by capillary gradients toward the unsaturated (more negative pressure) zones between the silty-clay zones (Figure 3-15). If the silty-clay zones were separated by only small cracks, then mounding may occur on the layer. Incidentally, lateral edges in Figure 3-15 illustrate the influence of the outer-boundary conditions. While the results are not significantly influenced by these boundary problems, the figure demonstrates that boundary effects must be considered when running numerical models.



**Figure 3-14**  
Soil Distribution for Model Case 2.



**Figure 3-15**  
Pressure-Head (m of water) Profile Along the Top of the Low-K Layer for Model Case 2



**Figure 3-16**  
**Pressure-Head Distribution for Model Case 2, 200 Days (steady state) After Starting Infiltration**

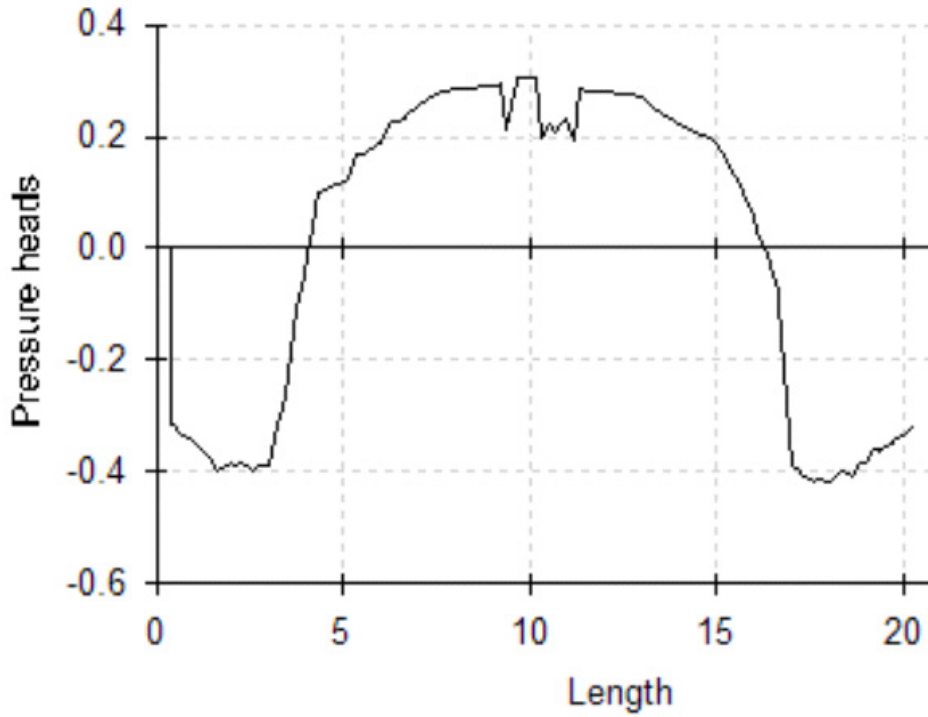
This case also illustrates the general case of heterogeneous media. If the low-K zone below the infiltration field is not continuous with respect to the location and length of the infiltration area, then water will generally be driven around the zone by capillary gradients. However, a relatively small section of low-K material directly below the infiltration area could cause mounding if the layer was sufficiently shallow because the water may mound enough to reach the surface in spite of the capillary gradients that pull water around the layer.

### 3.5.5.5 Case 3: Anisotropic Loamy-Sand Over a Silty-Clay Layer With Vertical Hydraulic Conductivity a Factor of Two Less Than the Horizontal Hydraulic Conductivity

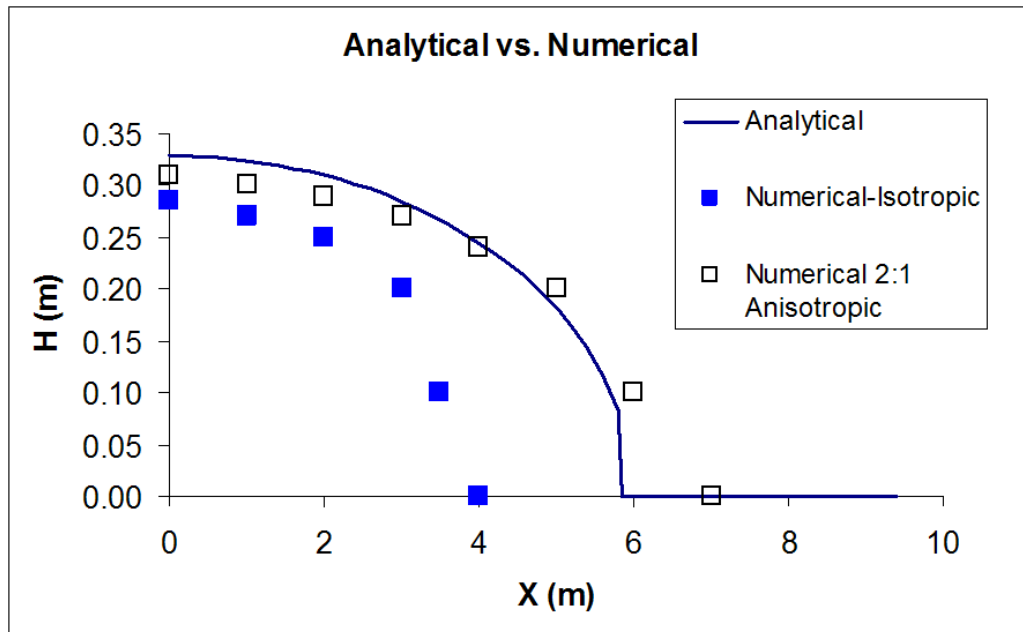
This case is similar to Case 1, except the materials are anisotropic, whereby the vertical K is one-half the horizontal conductivity in both layers. An anisotropy ratio of 100:1 was attempted, but this simulation would not converge at time steps larger than  $1 \times 10^{-5}$  seconds, even after several days of simulated time. The projected execution time for this scenario was approximately one week. As a result, the anisotropy ratio was reduced to 2:1. This simulation required 23 hours of execution time on a Pentium 3 with 512 MB of RAM at 0.7 GHz, to simulate 150 days of wastewater infiltration, and still had not quite reached steady state, but was nearly at steady state.

Figure 3-17, Figure 3-18, and Figure 3-19 show the results, which are considerably different from the isotropic Case 1. While the mound height is not considerably greater, the lateral extent of mounding is larger, which occurs because the water tends to flow laterally due to the reduced vertical K. The scenario is for a 10-m wide infiltration zone applying 2 cm/day. Model dimensions are the same as for Figure 3-13. The legend in Figure 3-19 depicts water-pressure head.

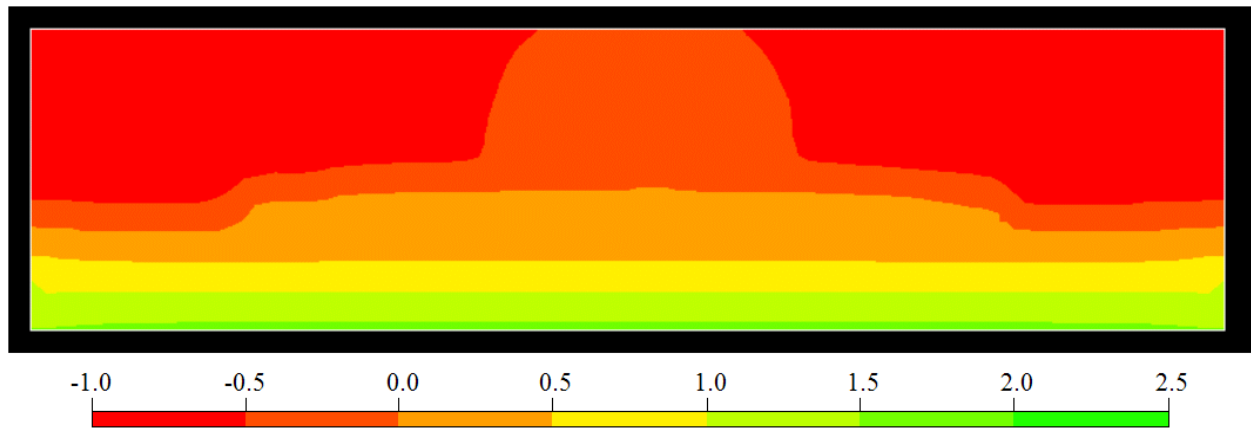
An anisotropy ratio of at least 2:1 is likely in soils; however, this small ratio would probably not be noted by a soil scientist via visual inspection. A ratio of 100:1 is likely to cause considerably more mounding and lateral spread. A ratio of 100:1 might be noticeable due to soil-grain patterns or micro layering. In any case, these simulations show that the analytical solution clearly will not simulate mounding accurately in an anisotropic system. For cases that are clearly anisotropic, a numerical model is required.



**Figure 3-17**  
**Pressure-Head Profile for Model Case 3 (2:1 anisotropy), 150 Days After Starting Infiltration (near steady state)**



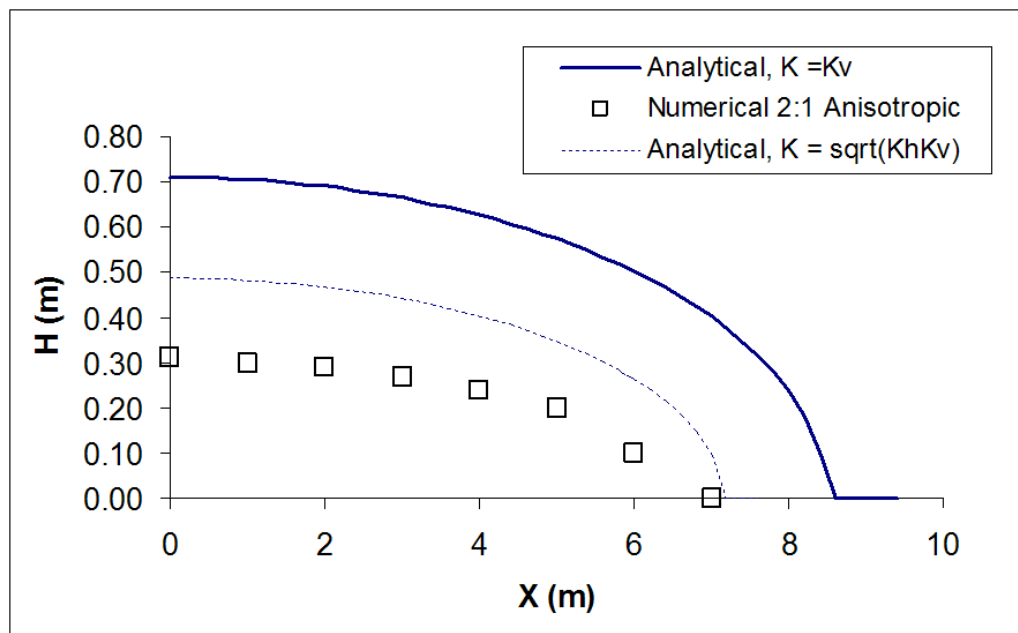
**Figure 3-18**  
**Analytical Versus Numerical Solutions for Mounding for Cases 1 and 3**



**Figure 3-19**  
**Pressure-Head Distribution for Model Case 3, 200 Days (steady state) After Infiltration Begins**

To be conservative, an analytical solution could use the vertical  $K$  of the subsoil for model input. (The same could be done for the layer if it was also deemed anisotropic.) In this case, the analytical model significantly over-predicts both the height and lateral extent of mounding as shown in Figure 3-20.

Another option is to use the square root of the horizontal and vertical  $K$  values for an equivalent homogenous  $K$  value in the analytical model. This approach is often used in the hydrologic literature to develop analytical solutions for anisotropic media. This substitution is not rigorously applicable to the Khan solution. However, Figure 3-20 illustrates that this approach appears to simulate the lateral extent of mounding calculated by the numerical model rather well, and still provides a conservative over-prediction for the mounding height.



**Figure 3-20**  
**Comparison of Numerical Solutions for 2:1 Anisotropic Case with Two Modified Analytical Solutions**

### 3.5.5.6 Summary of Numerical Model Examples

These numerical simulations show only a few specific cases of many possible situations that may be encountered at a field site. Additional numerical modeling for other cases, while time consuming, would lend considerable insight into mounding behavior below wastewater infiltration areas in the unsaturated zone. The purpose of these simulations, however, is to show the utility of numerical modeling for cases that cannot be adequately predicted using the analytical model.

The vadose zone offers storage capacity that is not considered by the analytical model. Consequently, the analytical model is generally a worst-case predictor for mounding, because it does not consider this storage capacity.

Heterogeneities will tend to redirect the flow around low-K layers, and the analytical model overestimates the mounding. However, if the width of a low-K lens below the infiltration area is relatively long compared to the width of the infiltration area, then mounding will develop. A conservative application of the analytical model in such a case is to assume a continuous layer at the location of the lens.

The analytical model is not conservative for the anisotropic case. Here, the analytical model under predicts the lateral extent of mounding. We suggest modifying the analytical model by using the square root of the product of the horizontal and vertical K values as an equivalent homogeneous K value in the analytical model. Then, the model is conservative with respect to the height of mounding and appears to predict reasonably the extent of mounding.

The errors associated with theoretical considerations of an analytical model described above, however, are much less severe than errors associated with using incorrect K values in the analytical model. Clearly, the important task, for the designer who wishes to use the analytical model to assess mounding, is to characterize accurately the soil below the infiltration area, as well as the lower K layer.

## **3.6 Estimating Mounding of the Water Table Below a Wastewater Infiltration Area**

This section provides design tools to estimate mounding of the water table below the infiltration area. A number of analytical solutions for mounding below a source of infiltrating water for a variety of applications have been discussed in Chapter 1, section 1.5.

The most useful analytical method for estimating water table mounding under a high-density or cluster WSAS is that of Hantush (1967). Finnemore and Hantzsche (1983) suggested some simplifications, which were reasonable approximations, but the more exact calculation, valid for  $\alpha_2 + \beta_2 < 0.04$  ( $\alpha$  and  $\beta$  are defined with Equation 3-16) is used here because the reasonable range of parameters and the need to estimate long-term mounding satisfy this criterion.



Hantush offers solutions for a rectangular (Figure 3-1) and circular infiltration area. The rectangular source solution is most relevant to WSAS cluster system analysis, so that is the only solution presented. The aquifer is assumed homogeneous, isotropic, and bounded by a horizontal water table overlying a horizontal impermeable base. The infiltration water is assumed to move vertically to the water table such that flux to the water table occurs directly below and over the same area as the infiltration area. That is, the solution assumes that materials in the vadose zone do not cause spreading of the infiltrating water before it reaches the water table. If such spreading were to occur, the water table mounding would be less than predicted by this analytical model.

If the solutions presented in section 3.5 were used to predict the potential for perching in the vadose zone, the source zone for this analysis could be assigned the dimensions of the perched mound. However, note that the seepage will not be uniform throughout the mound (seepage will be greater at the center), which will underestimate the maximum height of water table mounding. If the regional flow field has a significant slope, mounding may be offset and increased. The analytical solution assumes the  $K$  is isotropic. Consequently, if the vertical hydraulic conductivity,  $K_v$ , is less than the horizontal hydraulic conductivity,  $K_h$ , mounding will be under-predicted if the  $K_h$  value is used as the homogeneous  $K$  in the analytical solution, and over-predicted if the  $K_v$  value is used in the analytical solution. Numerical models are used to investigate conditions, such as a sloping regional water table and anisotropy, which are not considered by this analytical solution. These are discussed in section 3.6.5

### 3.6.1 Hantush (1967) Analytical Solution

For a horizontal impermeable base and initially horizontal water table (Figure 3-21), the maximum head rise,  $z_{\max}$ , occurs at the center of the infiltration area ( $x = 0$ ,  $y = 0$ ) and is calculated using Equation 3-16. The equation is complex as is the approximation of the equation. For this reason, a spreadsheet is included with this report ([WaterTableMounding\\_EnglishUnits.xls](#) or [WaterTableMounding\\_SIUnits.xls](#)) to facilitate use of Equation 3-16.

Equation 3-16

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

where:

$$z_{\max} \quad h_{\text{avg}} - h_i$$

$q'$  effective wastewater infiltration rate per unit area of the infiltration zone

$h_i$  initial saturated thickness

$h_{\text{avg}}$  iterated head at location and time of interest:  $0.5(h_i(0)+h(t))$

$K_h$  horizontal hydraulic conductivity

$l$   $\frac{1}{2}$  overall infiltration area length,  $\frac{1}{2} L$ , (Figure 3-2)

$w$   $\frac{1}{2}$  overall infiltration area width,  $\frac{1}{2} W$ , (Figure 3-2)

$S_y$  specific yield (use 0.001 to obtain conservative long-term solution)

$t$  time since infiltration began (use 10 years to obtain conservative long-term solution)

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

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

$$\alpha = \frac{l+x}{D} \quad (x = 0 \text{ for } z_{max})$$

$$\beta = \frac{w+y}{D} \quad (y = 0 \text{ for } z_{max})$$

The spreadsheet included with this report ([WaterTableMounding\\_EnglishUnits.xls](#) or [WaterTableMounding\\_SIUnits.xls](#)) uses the following approximation for  $S^*$  and is accurate for  $\alpha^2 + \beta^2 < 0.04$ .

**Equation 3-17**

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

The head rise at any position,  $z(x,y)$ , can be used to evaluate the potential for breakout on nearby slopes, and is calculated as:

**Equation 3-18**

$$z(x,y) = \sqrt{h_i^2 + \frac{q'h_{avg}t}{2S_y} \left[ S^*\left(\frac{l+x}{D}, \frac{w+y}{D}\right) + S^*\left(\frac{l+x}{D}, \frac{w-y}{D}\right) + S^*\left(\frac{l-x}{D}, \frac{w+y}{D}\right) + S^*\left(\frac{l-x}{D}, \frac{w-y}{D}\right) \right]} - h_i$$

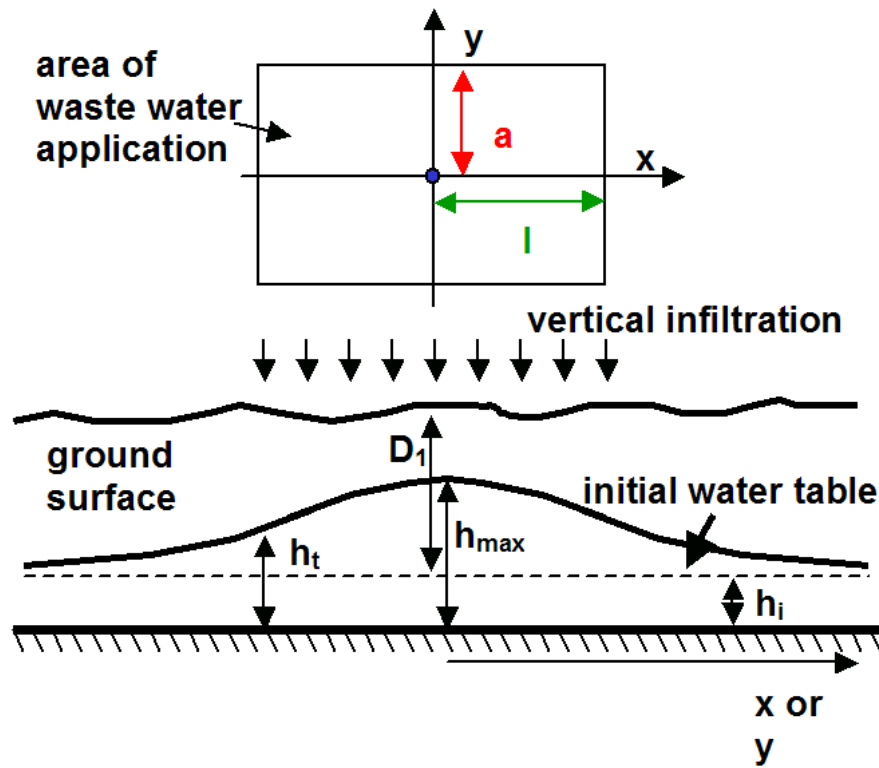


Figure 3-21  
Conceptual Model for Hantush (1967) Solution

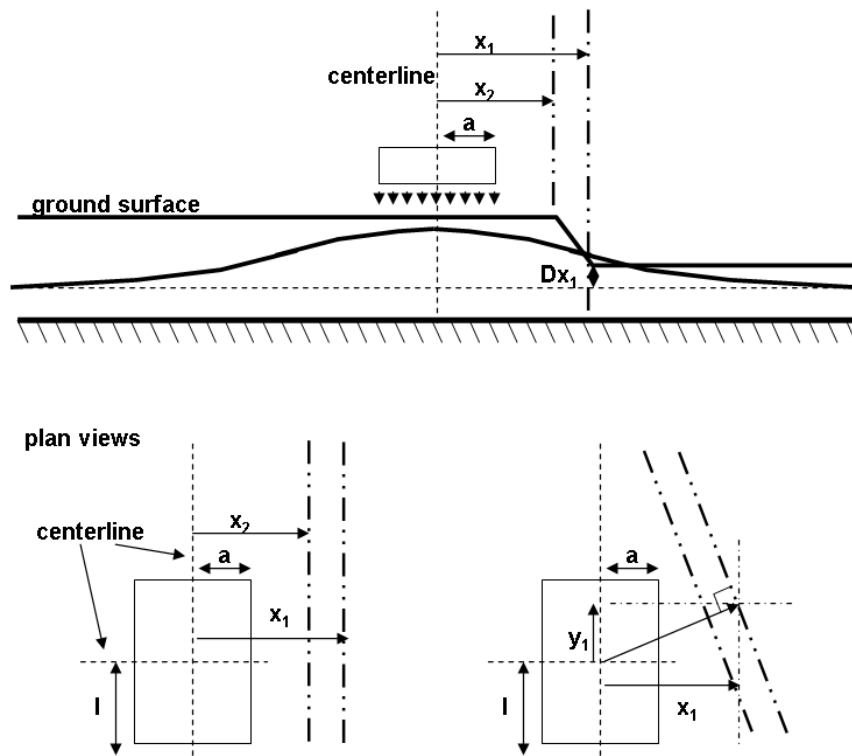


Figure 3-22  
Evaluate Breakout on a Nearby Side Slope at  $x_1, y_1$

**The parameters  $x$  and  $y$  are defined as  $x_1$  and  $y_1$  in Figure 3-22 for the orthogonal and the askew cases. In the plan view figure on the left,  $y_1$  is zero. On the right,  $x_1$ ,  $y_1$  are measured from the location where a line perpendicular to the slope intersects the center of the drain field. If the slope contours and elevation of the impermeable base are highly irregular, the designer needs to assess the most vulnerable location (the lowest, closest point to the infiltration area) and determine  $(x_1, y_1)$  for that location. If the most vulnerable location is not obvious, evaluate for all the potentially vulnerable locations.**

When considering breakout on a slope, the allowable water table rise is the entire depth to water less an increment of safety ( $Dx_1$ –Increment-of-Safety). The goal is to prevent breakout, not to allow sufficient vadose zone thickness to treat the wastewater, because the wastewater arrives at this location via lateral flow in the saturated zone. If mounding is above the surface at  $x_1, y_1$ , the WSAS can be moved further from the slope and the orientation, dimensions, or the loading can be adjusted to decrease mounding at the slope.

Mounding conditions for the case where the infiltrating water reaches the water table should be evaluated along with the potential for mounding of wastewater on low-K layers in the vadose zone because the water will eventually reach the water table. The vadose zone may increase the source area due to lateral spreading on a low-K layer. The resulting infiltration rate will decrease overall. Use of the original source zone size and rate will yield conservative results.

### **3.6.2 Discussion of Analytical-Solution Results**

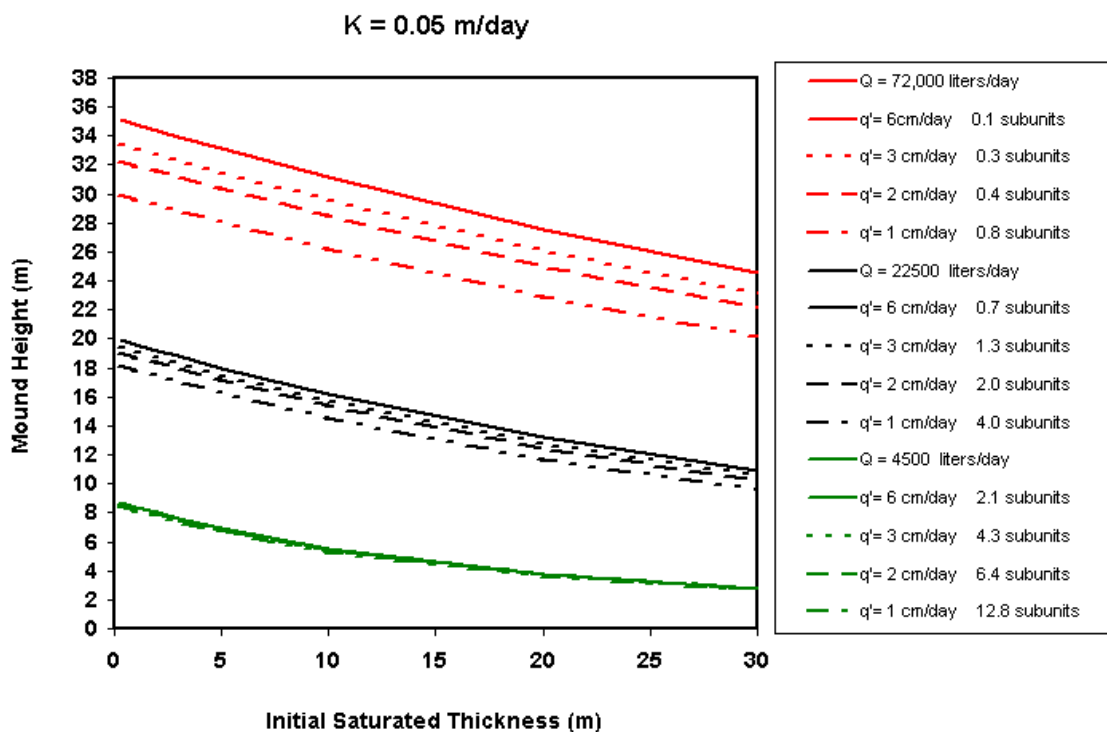
Predicted mounding for a range of hydraulic conductivities (0.05, 0.5, 5, and 50 m/day) is presented in Figure 3-23 through Figure 3-30. The maximum rise is determined using a spreadsheet and Equation 3-16. Figure 3-23 through Figure 3-30 indicate predicted mounding for a range of hydraulic conductivities for effective infiltration rates of 1, 2, 3, and 6 cm/day. The number of subunits needed to attain each effective infiltration rate is noted on the legend. These are fractions of subunits in Figure 3-23 through Figure 3-26. Figure 3-27 through Figure 3-30 are presented to consider full subunits. Assuming that subunit dimensions,  $l_s$ ,  $w_s$ ,  $S_p$ , and  $f_A$  are 30 m, 15 m, 7.5 m, and 0.5, respectively, Figure 3-27 through Figure 3-30 exhibit mounding for designs using 1, 2, 4, and 8 subunits. In some cases these result in effective infiltration rates,  $q'$ , greater than 3 cm/day. Consequently, trench infiltration rates,  $q$ , would be greater than 6 cm/day. Rates greater than 6 cm/day are unlikely to be achieved unless pretreatment is employed due to mounding on the biomat in the trenches.

The closeness of the curves for a given infiltration rate indicates the limited potential for decreasing mounding by increasing the size of the infiltration area, the primary design variable that controls infiltration rate. Often, reevaluation of the volumetric loading is necessary.

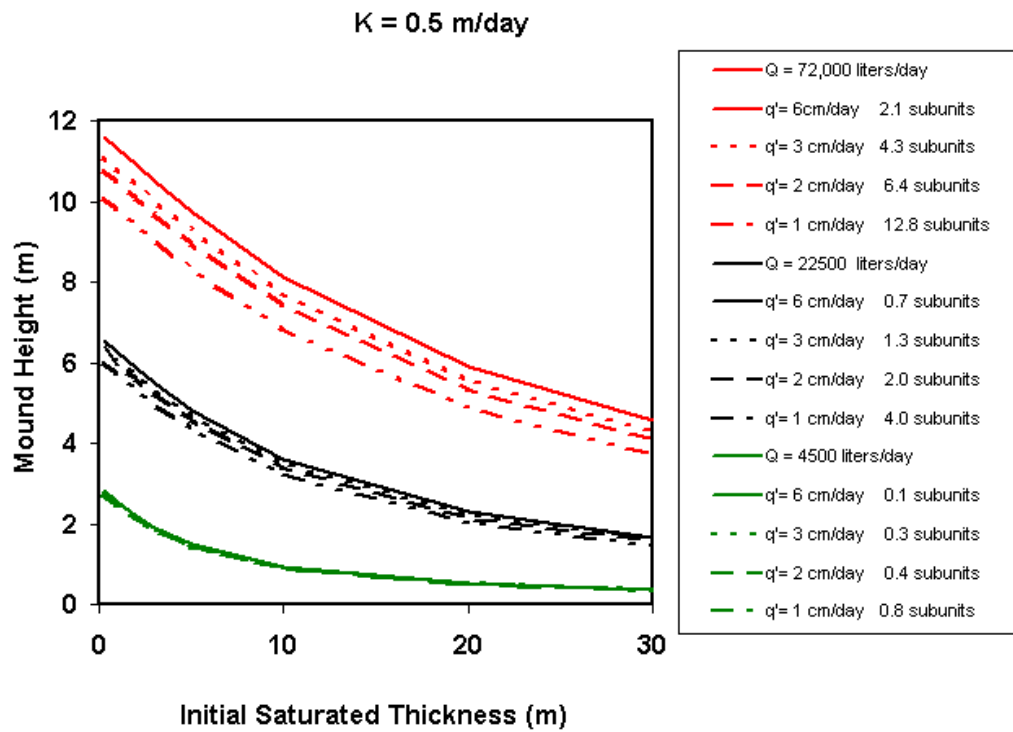
Mounding decreases more rapidly with saturated thickness for higher K values because a given rise in head increases transmissivity more in a high-K material.

The most influential parameter is  $K$  as illustrated by the fact that an order of magnitude variation of  $K$  (the difference between figures) causes larger differences in mounding height than an order of magnitude of saturated thickness (the difference across each figure). This situation is problematic because it is most difficult to measure  $K$  accurately, while saturated thickness is readily determined in the field. Simple field methods cannot determine the effective  $K$  to a high degree of accuracy. Freeze and Cherry (1979), indicate the value of  $K$  can vary by two orders of magnitude for a particular soil type.  $K$  typically varies by an order of magnitude spatially due to heterogeneities within an apparently homogeneous (based on visual inspection) soil. Therefore, trying to obtain accurate measurements for  $K$ , but recognizing that  $K$  is uncertain is critically important.

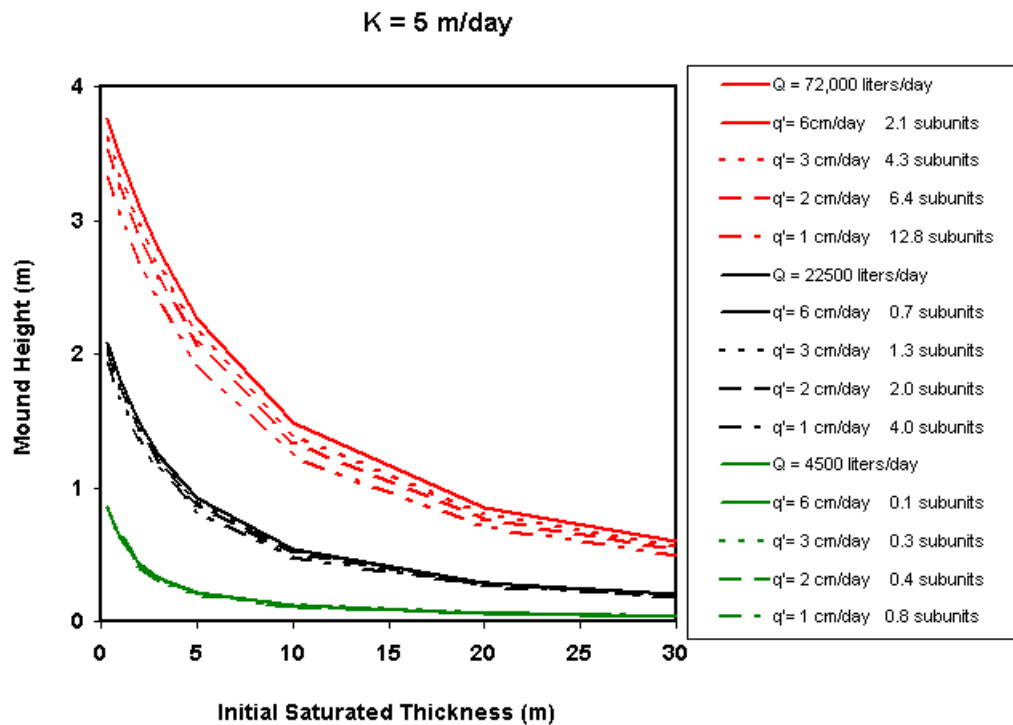
The analytical solution does not consider the impact of anisotropy ( $K_v < K_h$ ) or a sloping water table. For the case where  $K_v < K_h$ , use of  $K_v$  in the analytical expression will yield a conservative result. If the predicted mound is acceptable then further evaluation is not necessary. Another option is to use the square root of the product of the horizontal and vertical  $K$  values ( $[K_h * K_v]^{-0.5}$ ) for an equivalent homogenous  $K$  value in the analytical model. This approach is often used in the hydrologic literature to develop analytical solutions for anisotropic media and should provide an intermediate prediction. Otherwise, numerical modeling can be used to predict mounding.



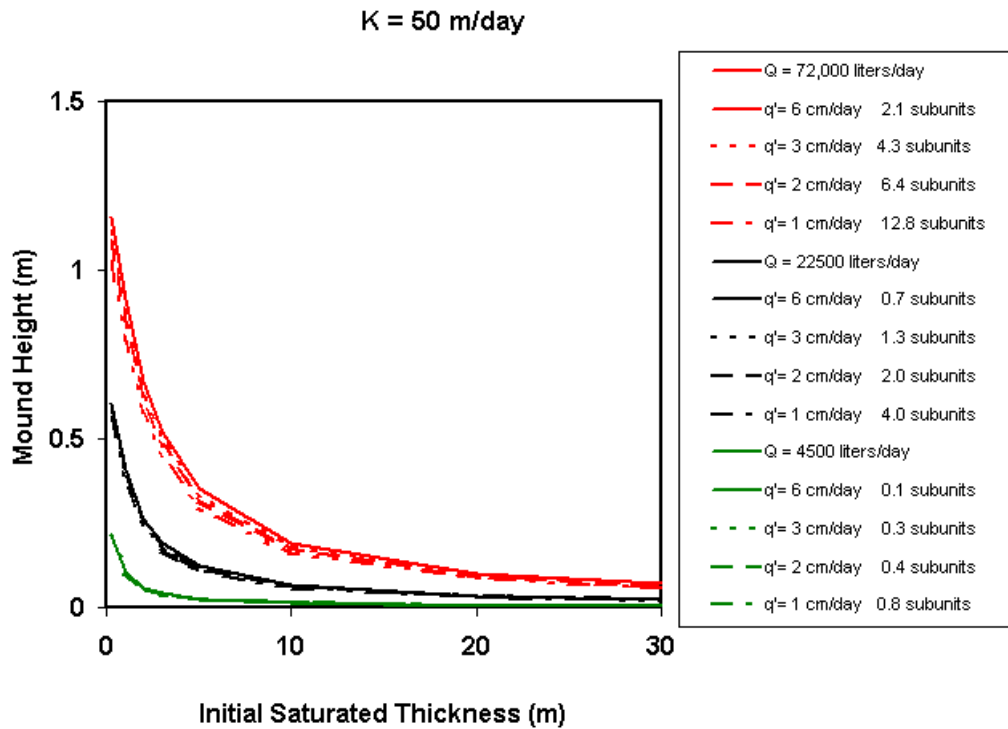
**Figure 3-23**  
Mounding as a Function of Saturated Thickness (distance from water table to aquifer bottom, Figure 3-21) for Specified Effective Infiltration Rate and  $K = 0.05 \text{ m/day}$



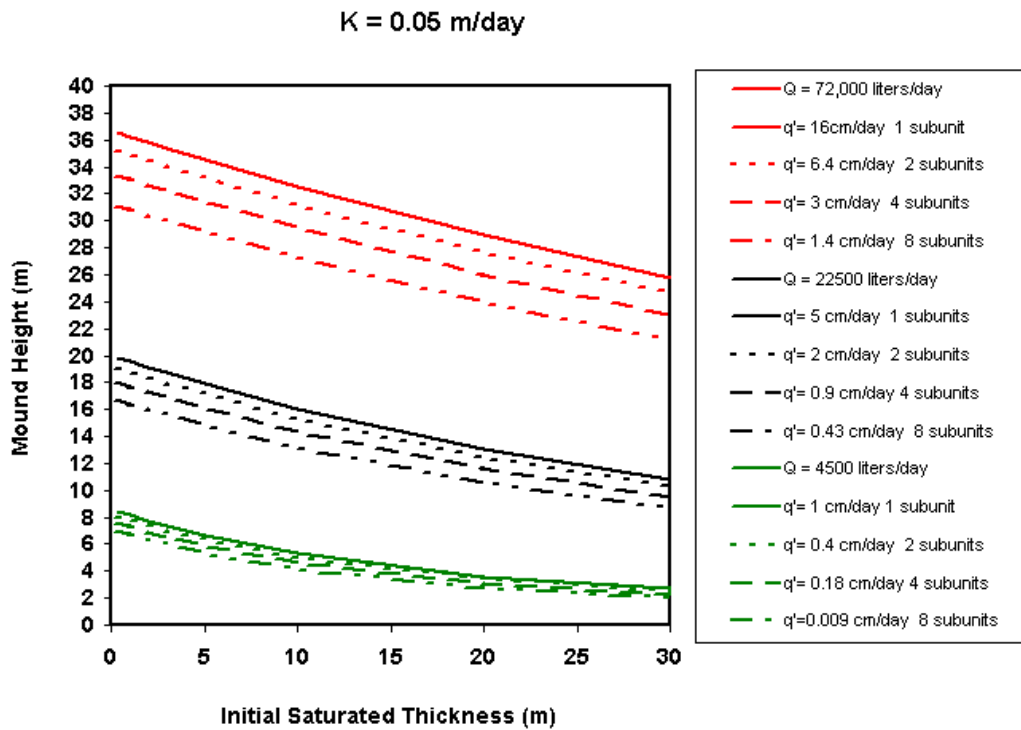
**Figure 3-24**  
**Mounding as a Function of Saturated Thickness for Specified Effective Infiltration Rate and K = 0.5 m/day**



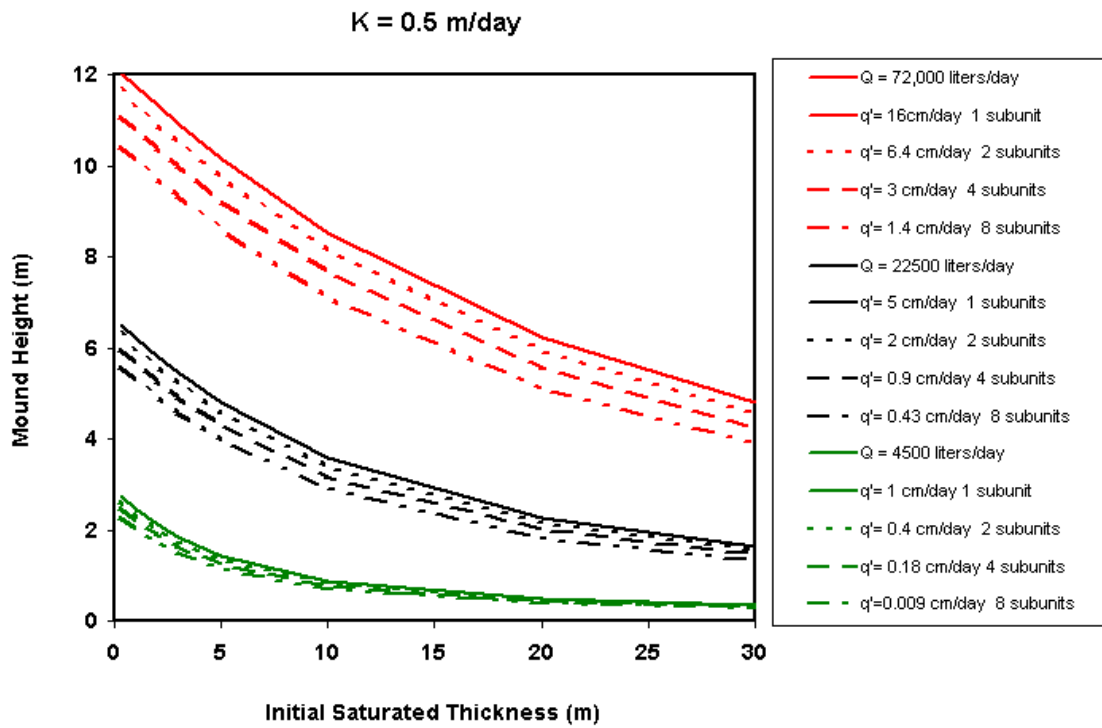
**Figure 3-25**  
**Mounding as a Function of Saturated Thickness for Specified Effective Infiltration Rate and K = 5 m/day**



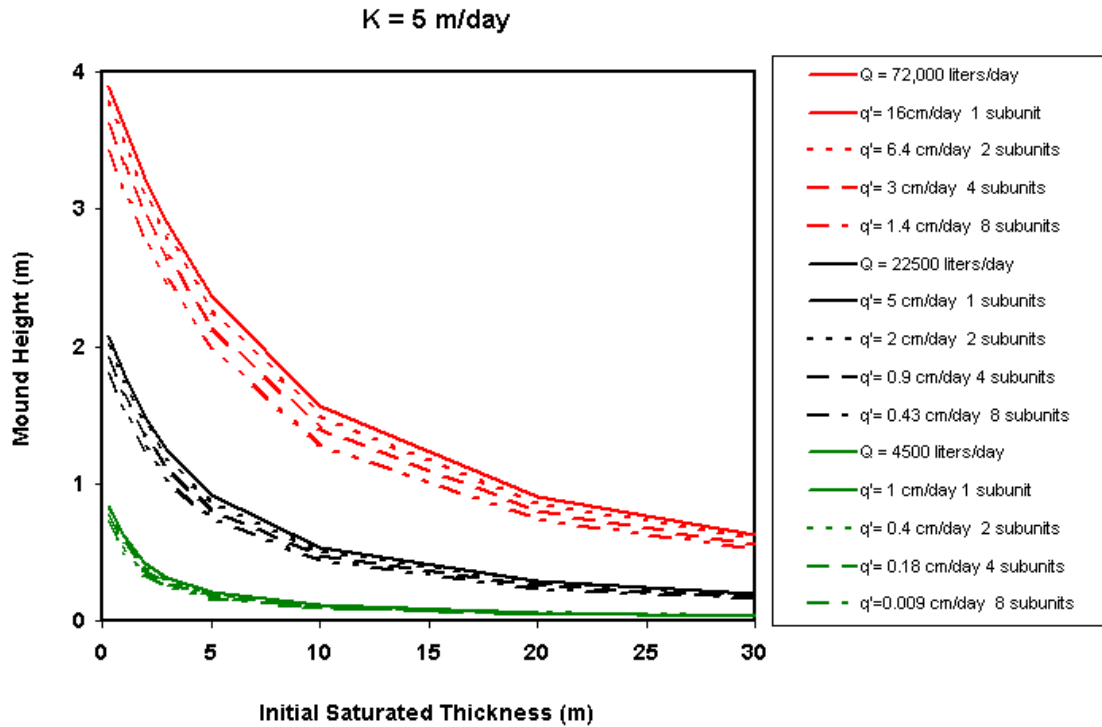
**Figure 3-26**  
Mounding as a Function of Saturated Thickness for Specified Effective Infiltration Rate and K = 50 m/day



**Figure 3-27**  
Mounding as a Function of Saturated Thickness for Specified Number of Subunits and K = 0.05 m/day

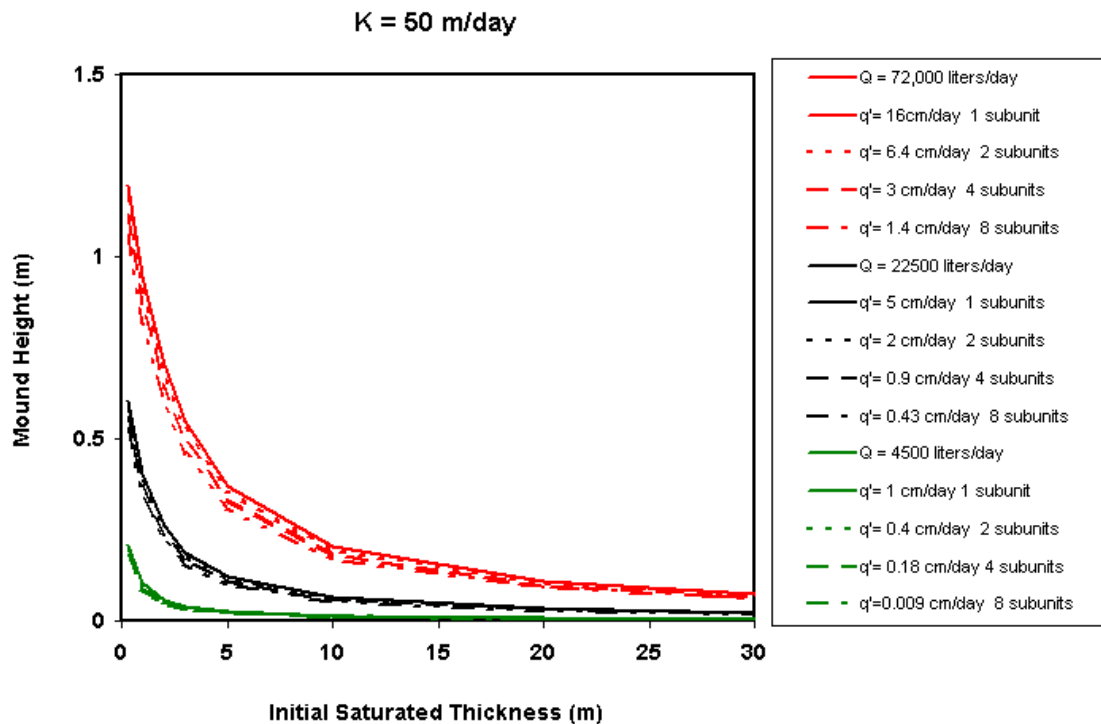


**Figure 3-28**  
**Mounding as a Function of Saturated Thickness for Specified Number of Subunits and K = 0.5 m/day**



**Figure 3-29**  
**Mounding as a Function of Saturated Thickness for Specified Number of Subunits and K = 5 m/day**





**Figure 3-30**  
**Mounding as a Function of Saturated Thickness for Specified Number of Subunits and**  
**K = 50 m/day**

### 3.6.3 Designing Wastewater-Infiltration Areas for Cluster Systems Using Analytical Modeling

The Hantush solution assumes uniform infiltration over the infiltration area. However, typical systems are comprised of a series of trenches. Consequently, wastewater infiltration does not occur over the entire width,  $W$ , of the infiltration area. For spaced trenches,  $q'$  in the Hantush solution is the design infiltration rate per unit of the total infiltration area. As described in the section 3.6.3, the parameter  $q'$  is given by:

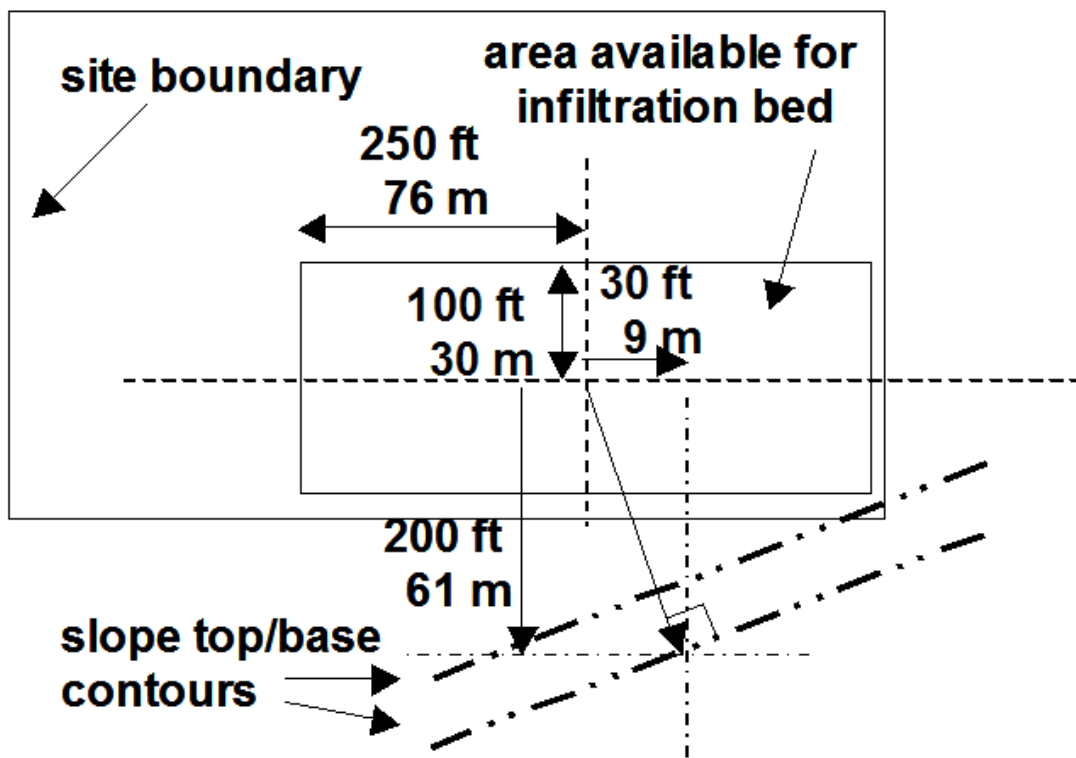
$$q' = Q/A_W = q f_A$$

**Equation 3-19**

where,  $f_A$  is the fraction of infiltrative-surface area ( $A_W$ ) divided by the total surface area for the infiltration-area system ( $A_T$ ), and  $q$  is the estimated long-term infiltration rate (the volumetric rate divided by only the trench area rather than the entire infiltration area).

The nomographs (Figure 3-23 through Figure 3-30) are presented as examples. To be generally useful to the practicing community, many nomographs for a variety of conditions would be required. Such a task is beyond the scope of this document. Rather, this study provides a methodology that can be used to develop nomographs. We present these example nomographs so potential users can see the layout of the final product. Professionals can better prepare appropriate nomographs for a variety of locally relevant conditions based on geology, soil characteristics, and probable locations for installment of systems.

The occurrence of the design parameters,  $L$ ,  $W$ ,  $Q$ ,  $x_1$ , and  $y_1$ , within complex functions of Equation 3-16 and Equation 3-18 make it unreasonable to solve for these parameters directly, thus warranting a design approach involving an estimate of these values followed by prediction of mounding. If the calculated mound height is unacceptable, common sense is used to adjust the design parameters and mounding is reevaluated until an acceptable situation is attained. The spreadsheets included with this report ([WaterTableMounding\\_EnglishUnits.xls](#) or [WaterTableMounding\\_SIUnits.xls](#)) are set up so that a designer can enter values appropriate for their site and determine the maximum water table rise at the center of the infiltration area and the rise at various distances where breakout on a nearby slope may be of concern. Steps of the design approach are outlined in Table 3-4, which relies on spreadsheets illustrated in Figure 3-32. An example application is presented in Table 3-5. The example application of the design procedure is presented for a housing development of 66 units, assuming two people per unit in a sandy-loam soil with a near horizontal water table. Reserved open space at the site is 500 ft × 200 ft (152 m × 61 m) (Figure 3-31).



**Figure 3-31**  
**Example Problem Site Dimensions and Slope Position**

**Table 3-4**  
**Design Procedure Considering Mounding of the Water Table on Low-Hydraulic Conductivity Layers in the Vadose Zone**

Step	Task
1	<p>Estimate design volumetric flow rate (such as gallons/day or m<sup>3</sup>/day) (<math>Q_w</math>) and enter in the column for <math>Q</math> in the spreadsheets supplied with this report (<a href="#">WaterTableMounding_EnglishUnits.xls</a> or <a href="#">WaterTableMounding_SIUnits.xls</a>), Figure 3-32. Note: Cells containing data items to be entered by the designer are highlighted in green.</p>
2	<p>Choose infiltration-area subunit dimensions (<math>l_s</math> and <math>w_s</math> in the spreadsheet), their separation distances (<math>S_p</math> in the spreadsheet), the fractional area occupied by trenches (<math>f_A</math> in the spreadsheet), and the number of subunits, <math>n</math> (Figure 3-2) and enter into the green cells of the spreadsheet below the appropriate labels. If preliminary design has been conducted considering mounding on low-K layers in the vadose zone, the dimensions selected here should be consistent with those determined by the procedures outlined in Table 3-1.</p> <p>The supplied spreadsheets are set up for subunit dimensions of 49.2 ft × 98.4 ft (15 m × 30 m), which equal (4,842 ft<sup>2</sup>, 450 m<sup>2</sup>) and 1 to 8 subunits with a separation distance of 7.5 m.</p> <p>NOTE: For most effective wastewater dissipation, the longest dimension of the infiltration area should be oriented perpendicular to the direction of regional groundwater flow.</p>
3	<p>After the appropriate values are entered in the spreadsheet, the spreadsheet calculates the overall infiltration area dimensions <math>L</math> and <math>W</math> as follows:</p> $L \quad \text{if } (n \cdot f_A) + (n-1) \cdot s < l_s \text{ then } L = l_s \quad \text{else } L = (n \cdot f_A) + (n-1) \cdot s$ $W \quad \text{if } (n \cdot f_A) + (n-1) \cdot s < l_s \text{ then } W = (n \cdot f_A) + (n-1) \cdot s \quad \text{else } W = l_s$ <p>the spreadsheet also calculates <math>q</math>, the infiltration rate in the trenches</p> $q = Q_w / (L \cdot W \cdot f_A)$ <p>and <math>q'</math>, the effective wastewater infiltration rate over the entire area</p> $q' = Q_w / ((n \cdot l_s \cdot w_s) + (n-1) \cdot s)$ <p>NOTE: If the desired maximum trench infiltration rate, <math>q</math>, is known, <math>q'</math> must be less than half that rate for a distribution trench geometry with 50% trench area. If <math>q'</math> is calculated to be greater than this, divide <math>q'</math> by that excessive rate to re-estimate the number of subunits needed for the site.</p>
4	<p>Determine depth to the water table (<math>D_1</math>) and depth to the impermeable boundary (<math>D_4</math>) (Figure 3-21). Calculate the saturated thickness as (<math>D_4 - D_1</math>) and enter in the green cells of the spreadsheet column labeled Initial Saturated Thickness.</p>
5	<p>Determine the depth of the bottom of the infiltration trenches (<math>D_3</math>), and the desired or required thickness of unsaturated below the infiltration area (<math>D_2</math>).</p>
6	<p>Calculate maximum allowable water table rise as <math>z_{\text{allow}} = D_1 - D_2 - D_3</math>. A factor of safety may be applied to decrease the mound height if desired.</p>
7	<p>If a break in slope occurs nearby, measure the horizontal distance from the center of the infiltration area to the base of the slope (<math>x_1</math>) (Figure 3-22). If the slope and the infiltration area are not parallel, determine the shortest distance from the base of the slope to the center of the infiltration area (<math>x_1, y_1</math>), and the associated depth to the water table that <math>x, y</math> location (<math>Dx_1</math>) (Figure 3-22). If the slope contour and base are highly irregular, assess the most vulnerable location. The allowable water table rise at this location is <math>Dx_1</math> less an increment of safety.</p>

**Table 3-4**  
**Design Procedure Considering Mounding of the Water Table on Low-Hydraulic Conductivity Layers in the Vadose Zone (Cont.)**

Step	Task
8	Measure or estimate the $K_h$ and $K_v$ of the material in the saturated zone. Enter $K_h$ in the green cell in the $K_h$ column of the spreadsheet.
9	Calculate the mound height $z_{max}$ and water table rise $z(x_1, y_1)$ . Keep in mind that for cases where $W$ is not $\gg$ the length of the trench, the equations used herein will generally overestimate the mound height, which fortuitously provides a safety factor
10	Compare $z_{max}$ with maximum allowable water table rise $z_{allow}$ from step 6. Compare water table rise at $x_1, y_1$ to $DX_1$ less an increment of safety.
11	<p>If <math>z_{max}</math> is:</p> <p>a) Less than the allowable height, the water table rise along the slope is acceptable, and <math>K_v</math> is greater than or equal to <math>K_h</math> (or the value of <math>K_v</math> was used for <math>K_h</math> in the analysis), then preliminary assessment indicates the design is acceptable.</p> <p>b) Greater than allowable height and water table rise along the slope is acceptable, increase the dimension of fields (<math>l_s</math> and/or <math>w_s</math>), or the number of fields, <math>n</math>, until a desirable <math>z_{max}</math> is obtained and water table rise along the slope remains acceptable. The longest dimension of the infiltration area should be oriented perpendicular to regional saturated flow unless construction logistics prevent it or the presence of a break in slope causes unacceptable mounding in the slope vicinity.</p> <p>c) Greater than allowable height and water table rise along the slope exceeds the thickness of the unsaturated zone along the slope, shift the field away from the slope and/or adjust the dimensions, orientation, and/or number of fields (<math>l_s, w_s, n</math>) until desirable <math>z_{max}</math> and <math>z(x_1, y_1)</math>, are obtained.</p>
12	If $K_v$ is less than $K_h$ , repeat the assessment by entering $K_v$ as $K_h$ . If the result is not acceptable, use numerical models and adjust $l_s, w_s, n$ , and perhaps $Q_w$ , until the water table rises are acceptable.
13	If there is a significant slope of the water table, use numerical models to evaluate whether the current design is acceptable and, as necessary, adjust $l_s, w_s, n$ , and perhaps $Q_w$ , until the water table rises are acceptable.
14	Compare the overall infiltration area dimensions to the available area and site dimensions to confirm the design can be accommodated at the site.
15	If a design was developed considering mounding on low-K layer in the vadose zone, ensure that the design determined in this procedure is compatible. Reconsider that mounding using this design. Adjust the design as necessary.
16	If the required design cannot be accommodated at the site, develop an alternative plan for water disposal, or decrease the number of wastewater disposal units planned for the site.

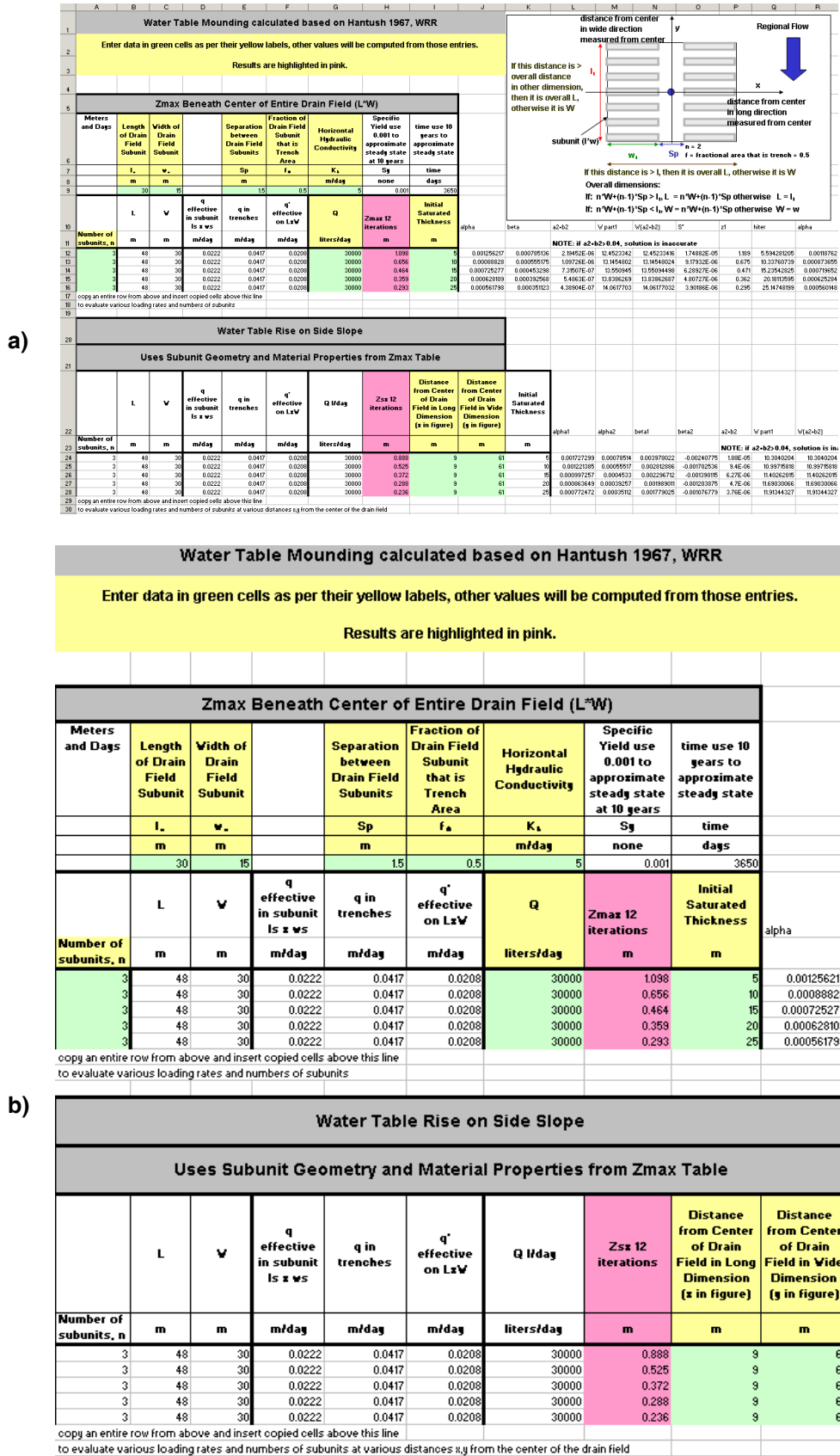


Figure 3-32 Example Problem in Spreadsheet: a) Overview b) Close Up of Calculations

The example provided in Table 3-5 is for the design of an infiltration area for a housing development of 66 units, assuming two people per unit, in a sandy-loam soil with a near horizontal water table considering mounding of the water table beneath the infiltration area. Reserved open space at the site is 500 ft × 200 ft (152 × 61 m) (Figure 3-31).

**Table 3-5**  
**Example Application of Design Procedure Considering Mounding of the Water Table**

Step	Task
1	The expected wastewater loading for this development is calculated assuming a median per capita wastewater production of 60 gallons person <sup>-1</sup> day <sup>-1</sup> (227 L person <sup>-1</sup> day <sup>-1</sup> ) (McCray <i>et al.</i> 2005 and Kirkland 2001). Thus, the daily flow rate for the development is 7,920 gallons per day (GPD) (29,960, or rounding approximately 30,000 liters per day (LPD), 30 m <sup>3</sup> /day). These values are entered in the spreadsheets that accompany this report ( <a href="#">WaterTableMounding_EnglishUnits.xls</a> or <a href="#">WaterTableMounding_SIUnits.xls</a> ).
2	Infiltration area subunit dimensions ( $l_s$ and $w_s$ ) are 98.4 ft (30 m) and 49.2 ft (15 m) with separation distance $s = 4.9$ ft (1.5 m). Construction specifications call for trenches that are 3.28 ft (1 m) wide with 3.28 ft (1 m) spacing between them. Thus, $f_A = 0.5$ .
3	A range of subunit numbers: 1, 2, 4, and 8 are input initially to provide an approximation of the mounding for various configurations. Note that $q'$ ranges from 0.8 to 6.7 cm/day. Unless pretreatment is employed, the 6.7 cm/day is likely too large, and will cause mounding in the trenches on the biomat, so at least two subunits are expected to be required.
4	Depth to the water table below the center of the proposed infiltration area is 15.75 ft (4.8 m) below the surface ( $D_1$ ) and depth to the impermeable boundary ( $D_4$ ) is 28.9 ft (8.8 m). Calculate the saturated thickness as $(D_4 - D_1) = 13.15$ ft (4 m).
5	The designers plan for the bottom of the infiltration trench to be 6 ft (1.8 m) deep ( $D_3$ ) and desire to have 6 ft (1.8 m) of unsaturated soil below the infiltrative surface ( $D_2$ ).
6	The maximum allowable water table rise is ( $z_{max}$ ) is 3.75 ft (15.75 – 6 – 6) or 1.2 m (4.8 – 1.8 – 1.8).
7	The distance to the base of the nearest slope, where breakout is of concern is 29.5 ft (9 m) in the long orientation of the infiltration area, and 200 ft (61 m) in the short orientation from the center of the proposed infiltration area. The water table is located 9.8 ft (3 m) below the base of the side-slope at the point of concern.
8	Based on several falling head tests in piezometers, the horizontal K of the saturated zone is determined to be $K_h = 16.4$ ft/day (5 m/day), while an infiltrometer suggests $K_v = 1.64$ ft/day (0.5 m/day), respectively (typical of a sandy-loam soil with subtle layering of fine- and coarse-grained materials). The $K_h$ is entered in the spreadsheet.  Results appear in pink boxes in the spreadsheet. Obtain the mound height $z_{max}$ (1.15 to 1.34 m for 8 to 1 subunits respectively) and water table rise at the base of the break in slope $z(x_1, y_1)$ (approximately 1.0 m for all subunit numbers) from the spreadsheet (Figure 3-32).
9	Comparing $z_{max}$ (1.1 to 1.34 m) with maximum allowable water table rise $z_{allow}$ 1.2 m from step 6 indicates this criterion is on the borderline. Comparing water table rise at $x_1, y_1$ (approximately 1.0 m) to $Dx_1$ (3 m) suggests breakout on the side slope is not an issue.

**Table 3-5**  
**Example Application of Design Procedure Considering Mounding of the Water Table (Cont.)**

Step	Task
10	The criterion can be met, with no factor of safety, if eight subunits are used. Entering a larger number of subunits provides some improvement, decreasing the rise by perhaps 0.15 ft (0.05 m) for 12 units. However, the overall dimensions exceed the available space. A combination of increased subunit size 200 ft (60 m) and 49.2 ft (15 m) and number (9 or 10) utilizes the available area but does not improve the water table rise. Sufficient alteration of the field size to attain the desired maximum head rise will clearly require unreasonable space.
11/12	Using the value for $K_v$ , 1.64 ft/day (0.5 m/day) rather than $K_h$ , 16.4 ft/day (5 m/day) in the analysis yields water table rise on the order of 16.4 to 19.7 ft (5 to 6 m) below the infiltration area and about 16.4 ft (5 m) on the slope. Either the design requires substantial revision or a numerical model should be used to evaluate the anisotropic conditions. This is presented in section 3.6.5.
13	The slope of the water table is considered insignificant, but this could be confirmed with numerical modeling.
14	The 8-subunit infiltration area covers an area of (98.4 ft × 426 ft) (30 m × 130 m), which could be accommodated at the site if the load were reduced.
15	An evaluation of mounding in the vadose zone was not undertaken for this site due to the lack of a low-K layer, so the design obtained from that analysis need not be considered.
16	The system cannot be accommodated at the site, so an alternative plan for water disposal should be developed, or the number of wastewater disposal units planned for the site should be decreased.

Depth to water and the impermeable surface may vary across the site and a range of values may be evaluated. As noted earlier, the anisotropy will be considered by numerical modeling. If the site was heterogeneous and the distribution of K was known, the heterogeneity could be included in the numerical model as well. Finally, the slope of the water table and natural recharge could be considered if a numerical model were used.

### **3.6.4 Limitations of Analytical Modeling**

K cannot be accurately estimated from simply knowing the soil type, which is important to realize. For example, according to Freeze and Cherry (1979), the K for any particular soil type can vary over at least an order of magnitude. Thus, obtaining reliable measurements of K when performing engineering analysis for cluster systems is important. Suggested methods for measurement of K in unsaturated and saturated soil are outlined in Chapter 2, sections 2.6. and 2.7. Errors on the order of a factor of ten would not be unusual, however, even if specific measurements are collected. Analyzing the statistics on several measurements can lead to considerable insight into the error in K measurements. If the designer has not collected detailed measurements of K, but has obtained a reasonable estimate based on soil classification or a few measurements, then a factor of ten error in K is reasonable to assume.

The Hantush solution also does not account for anisotropic materials. That is, the horizontal and vertical hydraulic conductivities are assumed the same for the solution. If values used for  $K_h$  are representative of the horizontal K, and the vertical K is actually significantly lower, then the Hantush solution will under predict mound height but would over predict the extent of the mound. However, if  $K_h$  is representative of the vertical K and the horizontal K is actually significantly larger, then the Hantush solution will over predict the mound height, but the extent of the mound may be under predicted.

Anisotropy may result from the way the grains are aligned in a homogeneous medium and may not be noticed by the designer. In such a case, only directional hydraulic tests will identify the situation.  $K_h$  and  $K_v$  can be interpreted from a pump test in an unconfined aquifer that includes an observation well and captures early- and late-time draw down. If thin layers of low-K material cause the anisotropy, a pump test will be the most reliable means of estimating  $K_h$  and  $K_v$ ; however, grain-size analyses of materials from the different layers may be used to estimate  $K_h$  and  $K_v$ . If unique values of K are determined for the low- and high-K layers, the effective  $K_h$  is the weighted arithmetic mean K (Equation 3-20), while the effective  $K_v$  is the weighted harmonic mean (Equation 3-21).

**Equation 3-20**

$$K_h = \frac{\sum_{i=1}^n K_i \text{thickness}_i}{\sum_{i=1}^n \text{thickness}_i}$$

**Equation 3-21**

$$K_v = \frac{\sum_{i=1}^n \text{thickness}_i}{\sum_{i=1}^n \frac{\text{thickness}_i}{K_i}}$$

The Hantush solution also does not account for heterogeneities. If heterogeneities were randomly distributed, then the best value to use for K is the geometric mean of the various K values (Equation 3-22).

**Equation 3-22**

$$K_{\text{geometric mean}} = 10^{\left(\frac{1}{N}(\log K_1 + \log K_2 + \dots + \log K_N)\right)}$$

However, gathering enough K measurements to make this evaluation is not feasible. Consequently, a conservative (low) value for K must be chosen, probably based on the results of several spatially distributed measurements of K. For severely heterogeneous systems, numerical modeling probably will not improve estimates of mound height because the data collection requirements would be cost prohibitive. Therefore, several pilot-scale, flooding infiltration tests should be conducted.



Finally, note that the Hantush solution does not allow consideration of the influences of isolated events of heavy rainfall on the mounding that might cause temporary hydraulic failure of the system. To address this issue, one would need to use a numerical model that can simulate short-term transient flow. However, as a conservative assumption, the designer could assume that the mound height would increase by the total depth of rain generated by the storm divided by porosity of the soil. This assumes no surface run-off, no delay of arrival of the storm water at the water table, and no lateral dissipation of water during the storm event, and as a result, provides a maximum rise. A more reasonable estimate could be obtained by subtracting an estimated amount for runoff. This calculation is beyond the scope of this document. However, the SCS rainfall-runoff method is recommended (see Viessman and Lewis 2003 or most engineering hydrology texts).

### **3.6.5 Numerical Modeling**

This section presents approaches to numerical modeling of water table mounding due to WSAS infiltration. Two conceptual models are considered for numerical modeling as described earlier in this chapter (Figure 3-21 and Figure 3-22). Two generic numerical models are discussed to evaluate modeling issues that are not considered in analytical solutions (such as anisotropy and sloping water tables) and to illustrate the magnitude of influence that can result from these variations.

Elaborate, site-specific numerical simulations are appropriate in cases where the risk of mounding is high and the consequences are serious. Site-specific simulations should be developed by an experienced modeler.

#### **3.6.5.1 Conceptual Models for Estimating Mounding of the Water Table**

The first conceptual model considers mounding for a situation where regional flow is negligible and is similar to the analytical model presented in section 3.6.1. However, the numerical model is steady state and has finite boundaries. The numerical model is bounded by:

- An impermeable base at an elevation of zero
- Constant heads on the east and west equal to the initial saturated thickness
- No flow boundaries on the north and south
- A phreatic surface (water table) on the top, which is initially horizontal and of an elevation equal to the saturated thickness (Figure 3-33)

A steady-state solution for mounding is obtained with recharge specified on each subunit equal to the quotient of the total volumetric loading and the subunit area. A combination of high  $K$  and thickness, coupled with a small volumetric rate of infiltration will cause convergence difficulty, which occurs because such cases exhibit extremely small water table rise.

The second conceptual model represents a regional flow field. The datum for this model is defined as 100 m at the base of the trenches. The boundaries include:

- An impermeable base at an elevation of 100-D (the depth from the bottom of the trench to the impermeable base of the aquifer)
- A no-flow boundary to the west, a stream (constant head) boundary on the east
- No-flow boundaries on the north and south
- A uniform, constant recharge to the phreatic surface (Figure 3-34)

To attain the initial saturated thickness below the infiltration area, the appropriate combination of recharge rate, K, and constant head need to be used. Given a recharge rate and K, the required head at the stream is given by:

**Equation 3-23**

$$h_{strm} = \sqrt{(s_{thk})^2 - \frac{r}{K_h} \left( \left( 1 - \frac{x_{midpt}}{2 L_{mdl}} \right) (2 L_{mdl})^2 - \left( \left( 1 - \frac{x_{midpt}}{2 L_{mdl}} \right) 2 L_{mdl} \right)^2 \right)} + (dtm - D)$$

$h_{strm}$  = constant head at the stream

$s_{thk}$  = desired saturated thickness

$L_{mdl}$  = constructed length of model

$d_{tm}$  = datum at base of trenches

Some combinations of natural recharge, K, and saturated thickness will yield a physically impossible situation that cannot be modeled. In these cases, a head value for the stream cannot be calculated.

Both conceptual models assume that the WSAS water is evenly distributed over each subunit area, and thereby arrives at the water table directly below the infiltration area footprint. Both models are steady state, and as a result reflect long-term infiltration.

Q	loading rate	[L <sup>3</sup> /T]
A (L*w)	A = drain field area	L = length (normal to page) W = width in flow direction
R	loading rate per unit area = Q/A	[L/T]
d	Pre-infiltration distance to water table from trench bottom	[L]
D	distance bottom of trench to impemeable layer	[L]
Kh	saturated horizontal hydraulic conductivity	[L/T]
Kv/Kh	ratio of vertical to horizontal hydraulic conductivity	[ ]

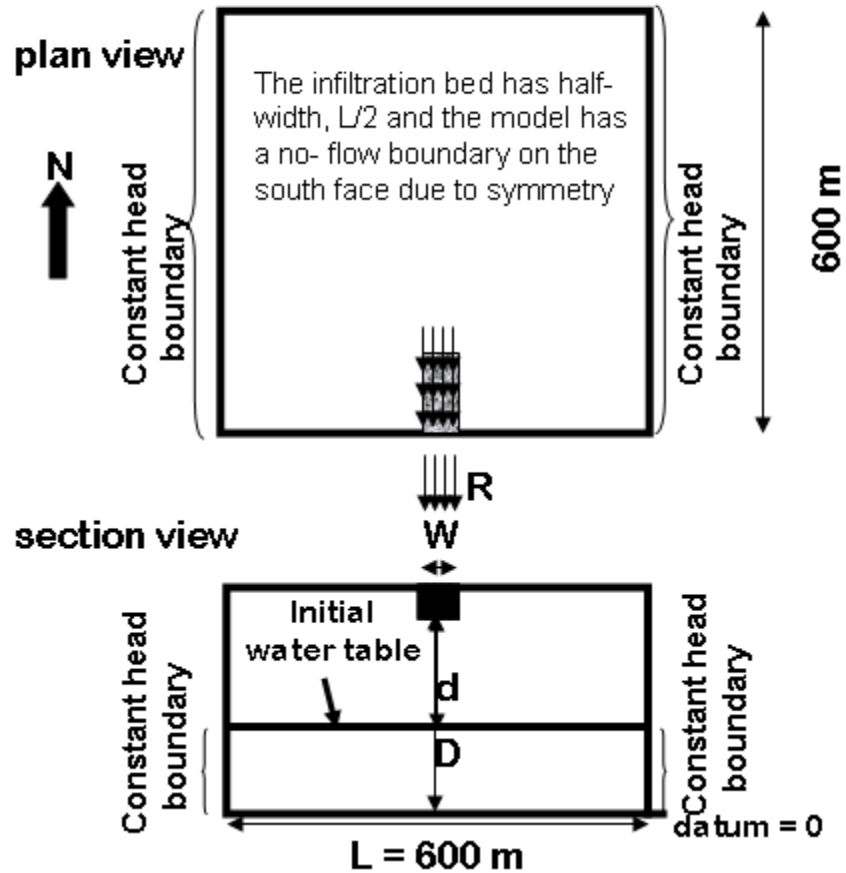
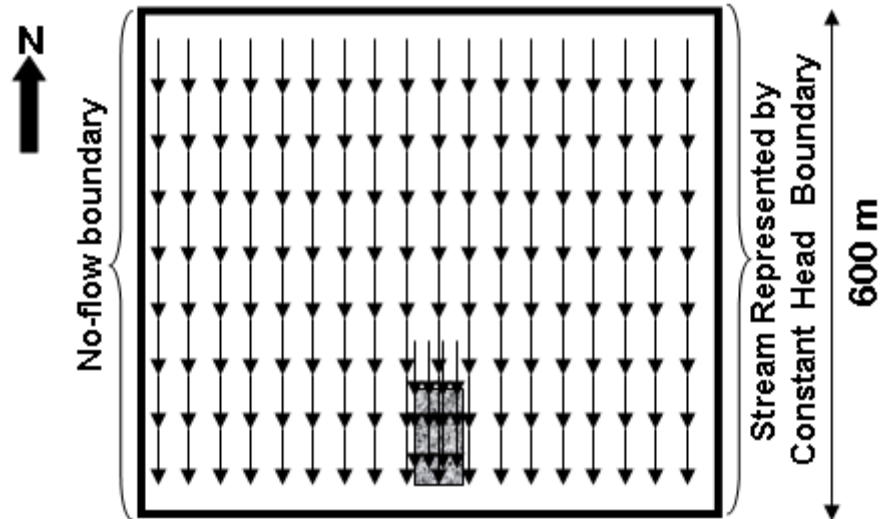
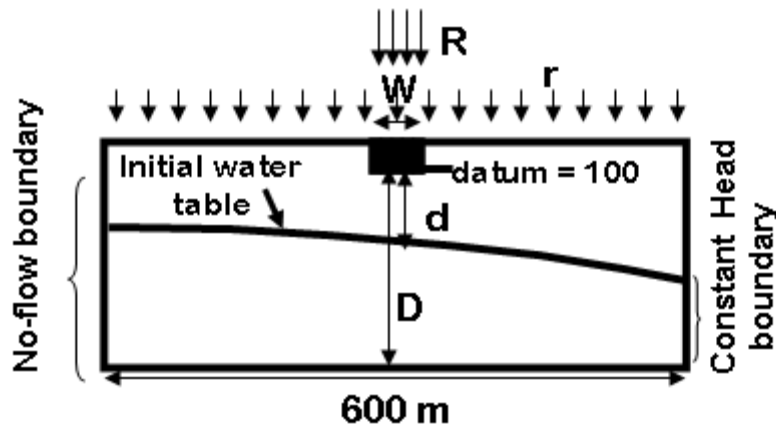


Figure 3-33  
 First Conceptual Model for Numerical Modeling (horizontal water table without natural recharge or lateral regional flow)

Q	loading rate	[L <sup>3</sup> /T]
A (L*w)	A = drain field area	L = length (normal to page) W = width in flow direction
R	loading rate per unit area = Q/A	[L/T]
r	natural recharge rate	
d	Pre-infiltration distance trench bottom to water table	[L]
D	distance to impermeable layer from bottom of trench	[L]
Kh	saturated horizontal hydraulic conductivity	[L/T]
Kv/Kh	ratio of vertical to horizontal hydraulic conductivity	[ ]



The infiltration bed has half-width,  $L/2$  and the numerical model has a no-flow boundary on the south face due to symmetry



**Figure 3-34**  
**Second Conceptual Model for Numerical Modeling (sloping water table with natural recharge, and thus lateral regional flow)**

### 3.6.5.2 Comparison of Numerical and Analytical Results:

MODFLOW (Harbaugh *et al.* 2000) is used more than any other numerical groundwater code. MODFLOW is a three-dimensional finite-difference, saturated groundwater flow code, designed to solve the partial differential equations describing saturated flow in porous media:

**Equation 3-24**

$$\frac{\partial}{\partial x} \left( K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial h}{\partial z} \right) - W = S_s \frac{\partial h}{\partial t}$$

$K_x$	= hydraulic conductivity in the x direction
$K_y$	= hydraulic conductivity in the y direction
$K_z$	= hydraulic conductivity in the z direction
$h$	= hydraulic head
$W$	= source/sink volumetric flux per unit volume
$S_s$	= specific storage
$t$	= time

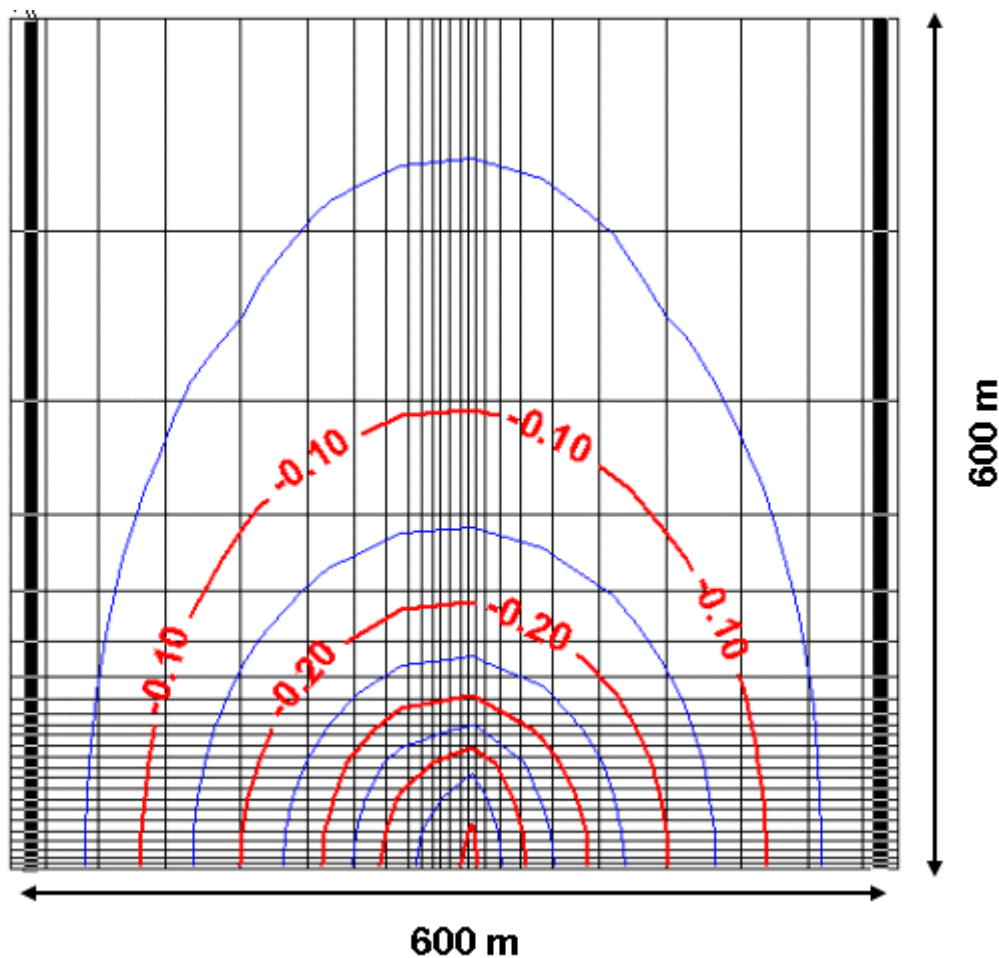
For some situations, only the saturated zone response to infiltration will be important, but the details of the material distributions and the boundary conditions will be more than an analytical model can address. In such a case, MODFLOW can be used to simulate the site. Given its good reputation and public domain status, there is no reason to recommend any other saturated flow model. Use of another model is acceptable if the designer is more familiar with that model. If the results are contentious, then it is prudent to make some comparison simulations between MODFLOW and the selected code to demonstrate its accuracy.

MODFLOW was used with a graphical user interface (GUI), Groundwater Vistas (GWV) (Rumbaugh and Rumbaugh 2001) for the simulations undertaken to provide examples in this report. The examples evaluate the analytical model, as well as the affect of boundaries, anisotropy, and a sloping water table. WSAS designers who use numerical models for their work should understand the fundamentals of numerical modeling and the details of the selected software code. There are numerous university and short courses available for such training.

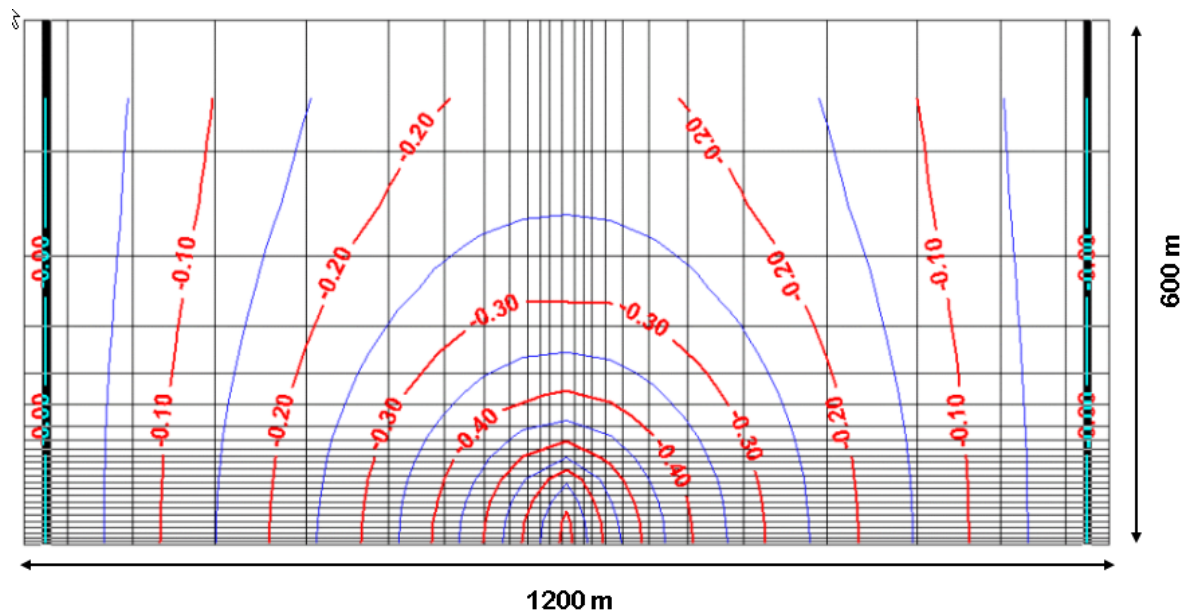
The analytical model for the example in section 3.6.3 indicated a maximum water table rise of 3.64 ft (1.11 m), while the numerical model with overall model dimensions as shown in Figure 3-33 indicates only 1.67 ft (0.508 m) (see Figure 3-35). The numerical model yields a lower maximum water table rise because of the boundary conditions.

If the model is lengthened so that the distance between the constant head boundaries is doubled, the maximum water table rise is 2.31 ft (0.703 m) because a larger gradient is required to drive the same amount of recharge out of the model given the longer path length (Figure 3-36). This illustrates that a generic model cannot be constructed for determination of the water table rise in all field cases. Since the analytical model is infinite, it provides a worst-case scenario, provided sufficient time is used in the calculation. Ten years is a reasonable time, because it is likely that natural hydraulic boundaries will influence the mound within that time, so that the calculated rise at 10 years in an infinite aquifer is representative of a steady-state condition. In addition, the mound height changes slowly at late time, so if the initial example is evaluated for 20 years, the mound grows only an additional three to five percent, depending on the number of subunits, in the second 10 years.

The numerical results are approximate due to discretizing the problem and iterating to obtain an approximation of the solution, which is important to note particularly in these examples where rewetting of numerical model layers is necessary to simulate the rising mound.



**Figure 3-35**  
First Conceptual Model Solved for the Isotropic Case Evaluated in the Example from Section 3.6.3



**Figure 3-36**  
**First Conceptual Model (Figure 3-21) With Twice the Distance Between the Constant Head**  
**Boundaries, Solved for the Isotropic Case Evaluated in the Example from Section 3.6.3**

### 3.6.5.2 Influence of Anisotropy

Numerical models can be used to explore the effects of anisotropy on mounding by comparing the modeling results for different cases. When a 10/1 ( $K_h/K_v$ ) anisotropy is introduced to the first conceptual model (the horizontal water table) for the example problem, the maximum water table rise calculated by the numerical model is 1.68 ft (0.512 m) compared with only slightly less for the isotropic case 1.67 ft (0.508 m). A 100/1 ( $K_h/K_v$ ) anisotropy increases the rise to 1.9 ft (0.59 m). The degree of impact is site specific and depends on the saturated thickness as well as the absolute value of the  $K$  relative to the loading and the proximity to hydraulic boundaries.

Water table rise for a range of  $K$  values for both isotropic and 10:1 anisotropic cases as a function of saturated thickness (Figure 3-37) show that the influence of anisotropy is more significant in thicker aquifers. Transmissivity,  $K_H$  \* thickness, controls the increased gradient needed to carry water away from the site. However, horizontal  $K$  spans a much larger range of values than saturated thickness, so it is most important to the magnitude of mounding as indicated by the order of magnitude differences in water table rise between graphs in contrast to the factor of 2 or less rise for 10:1 anisotropy.

Note that the scale changes between graphs in Figure 3-37, and site conditions include:

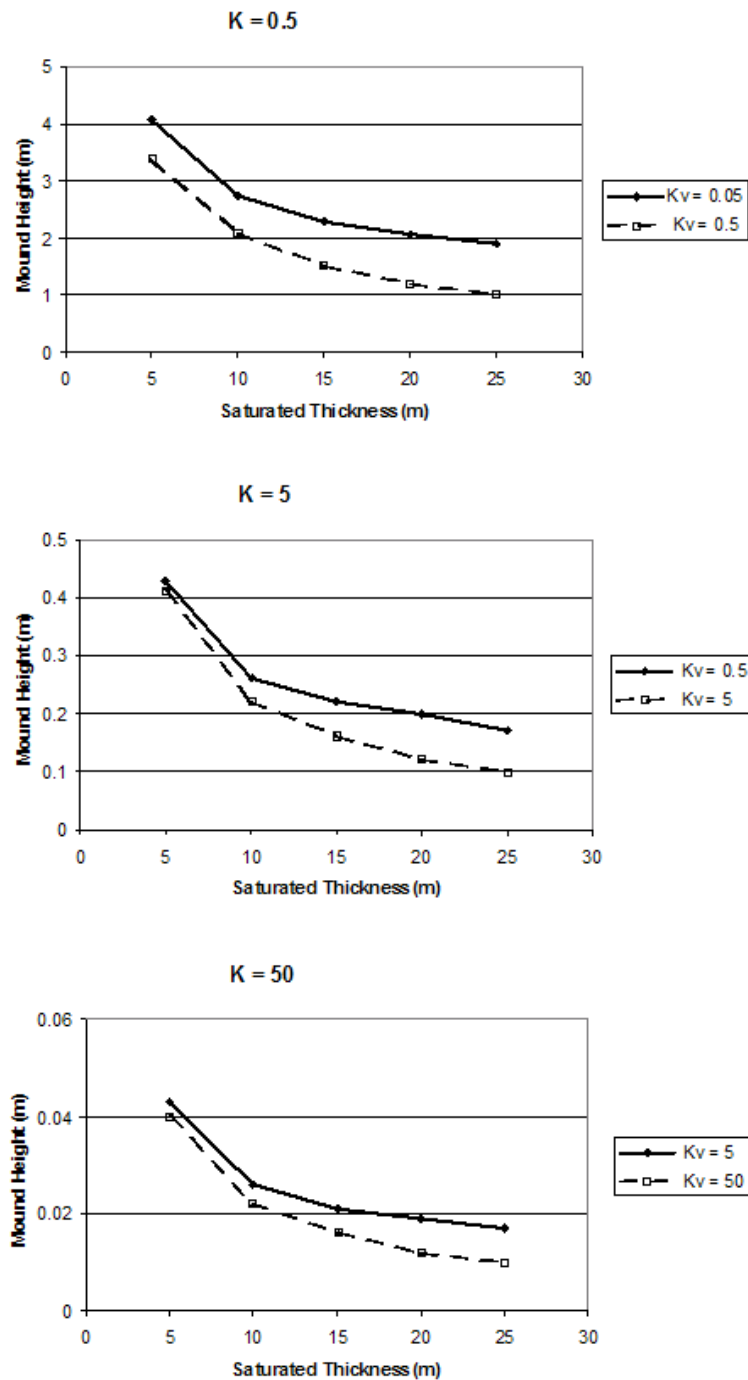
$$Q = 60,000 \text{ GPD (22,500 LPD)}$$

2 subunits

$$l_s = 98.4 \text{ ft (30m)}$$

$$w_s = 49.2 \text{ ft (15m)}$$

$$f = 0.5$$



**Figure 3-37**  
**First Conceptual Model (Figure 3-21) With Varying K for the Isotropic and Anisotropic ( $K_h:K_v = 10:1$ ) Cases**

This dominance of horizontal K suggests that using  $K_v$  in the analytical solution is reasonably conservative, not extremely conservative (or less conservatively  $[K_h * K_v]^{-0.5}$ ), because the differences for a one order of magnitude increase in  $K_h$  the water table rise increases on the order of a factor of three (Figure 3-24 through Figure 3-30).



### 3.6.5.3 Influence of Sloping Water Table and Anisotropy

Many sites are underlain by a sloping water table. In this case, heads will rise on the upgradient side of the WSAS, but all of the infiltrated water will eventually move downgradient, essentially decreasing the flow area by a factor of two. The decrease in flow area may be offset by the increased gradient, depending on the aquifer thickness, regional flow rate, and increased load. Consequently, the impact on mounding is not intuitively obvious. A numerical model can be used to sort out the effects of the competing processes.

Simulations for a few sets of conditions are presented here to facilitate understanding of the complexity of the relationship between parameters that control the system. They illustrate that the response at a specific complex site cannot be determined with simple generic methods.

For cases utilizing the second conceptual model with a groundwater divide on the left and natural recharge distributed uniformly across the surface, water table rise was computed for a range of  $K$  values for isotropic and anisotropic (10:1) cases as a function of vertical  $K$ , saturated thickness, and approximate hydraulic gradient. The natural recharge rate must be adjusted in the model to create a simulated unconfined situation that approximates the specified gradients for each combination of  $K$ , anisotropy, and saturated thickness. The gradient was achieved by finding a natural recharge rate that would yield approximately an average gradient of 0.02 between the infiltration area and the stream in one case, and 0.002 in the other. The necessary recharge values are noted on the figures that are discussed as follows.

Mound heights for ( $Q = 60,000$  GPD, 2 subunits,  $l_s = 98.4$  ft,  $w_s = 49.2$  ft,  $f=0.5$ )  $q' = 0.025$ m/d are shown in three graphs comparing isotropic and anisotropic conditions, one for each of three different saturated thicknesses, in Figure 3-38 and some of the associated flow fields are illustrated in Figure 3-39 through Figure 3-41.

The complexity of the response illustrates that site-specific modeling is needed to assess these conditions. As illustrated by the series of graphs in Figure 3-38, in the thin, anisotropic aquifer, 30 ft (10 m), mounding increases with decreasing gradient and decreasing  $K_v$ . In the moderately thick aquifer, 60 ft (20 m), mounding follows the same general relationship but the effect of decreasing  $K_v$  is not as important as it was in a thin aquifer, and the effect of decreasing gradient is exacerbated. In the thick aquifer, 90 ft (30 m), the mounding also increases with decreasing  $K_v$ , but decreases with decreasing gradient. The flow fields for these cases are illustrated in Figure 3-39 through Figure 3-41. The unintuitive response in the thick aquifer is related to magnitude of the natural recharge rate and the capacity of the aquifer to carry water. The thick aquifer's capacity to transmit flow is not taxed in the low recharge, low gradient case (lower diagram of Figure 3-41), so only a small increase in gradient is required to carry the additional flow from the WSAS as opposed to the high-gradient case illustrated at the top of Figure 3-41.

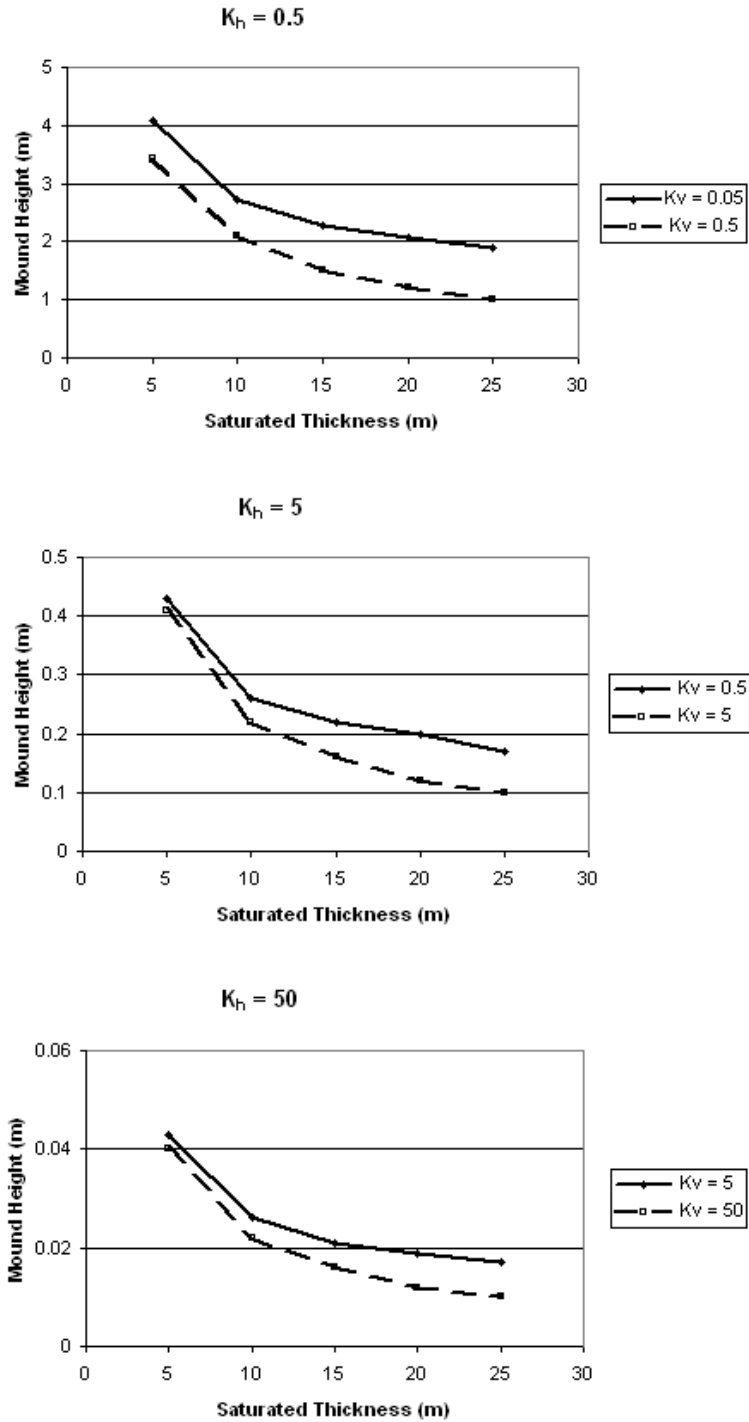
At complex sites, if the predicted mounding poses significant risk, and particularly when the consequences of failure are serious, detailed evaluation is warranted and numerical modeling is appropriate.

Note that Figure 3-38 site conditions include:

$$Q = 60,000 \text{ GPD (22,500 LPD)}$$

2 subunits

$$l_s = 98.4 \text{ ft (30m)}$$



**Figure 3-38**  
**Second Conceptual Model (Figure 3-22) With Varying K for the Isotropic and Anisotropic**  
**( $K_h:K_v = 10:1$  and  $100:1$ ) Cases for High and Low Gradients Achieved by Varying Recharge**

When comparing Figure 3-39 through Figure 3-41, note that the contour magnitudes change between figures.

For Figure 3-39:

- Top—High recharge 0.008 in./d (0.02 cm/d) yielding a gradient of approximately 0.02
- Bottom—Low recharge 0.006 in./d (0.015 cm/d) yielding a low gradient of approximately 0.002
- Both are contoured at 0.05 m intervals

Site conditions for Figure 3-39 through Figure 3-41 include:

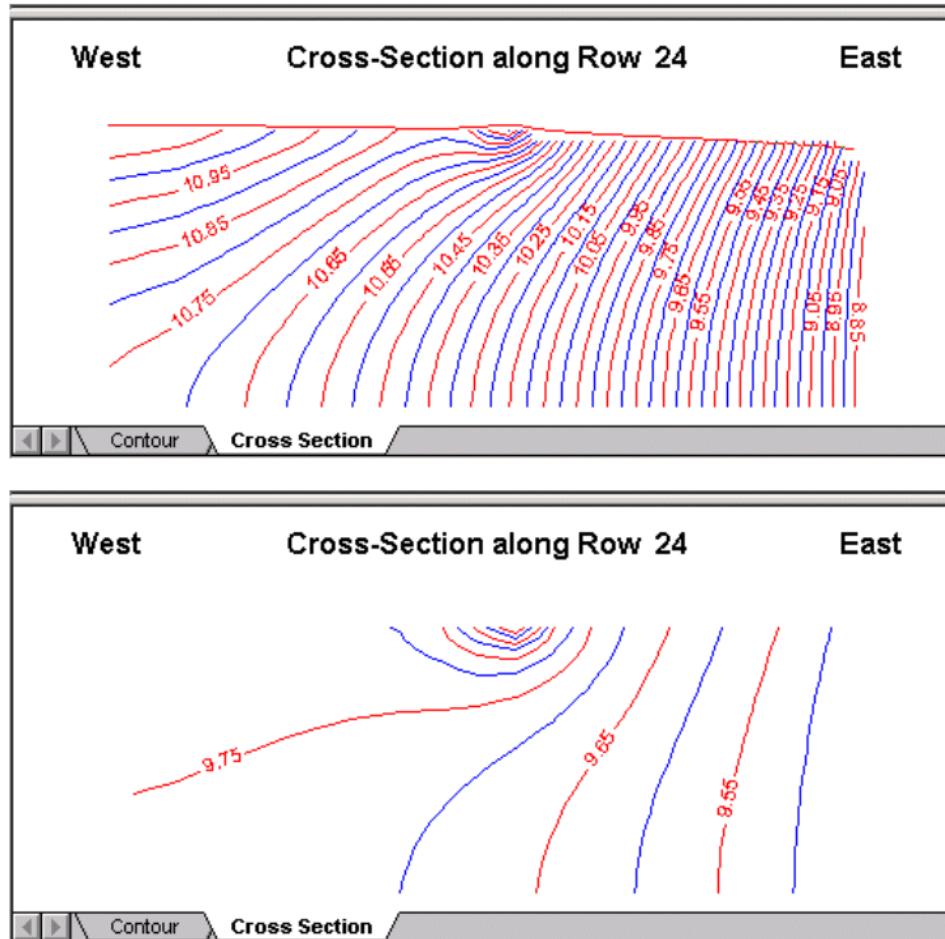
$$Q = 60,000 \text{ GPD (22,500 LPD)}$$

2 subunits

$$l_s = 98.4 \text{ ft (30m)}$$

$$w_s = 49.2 \text{ ft (15m)}$$

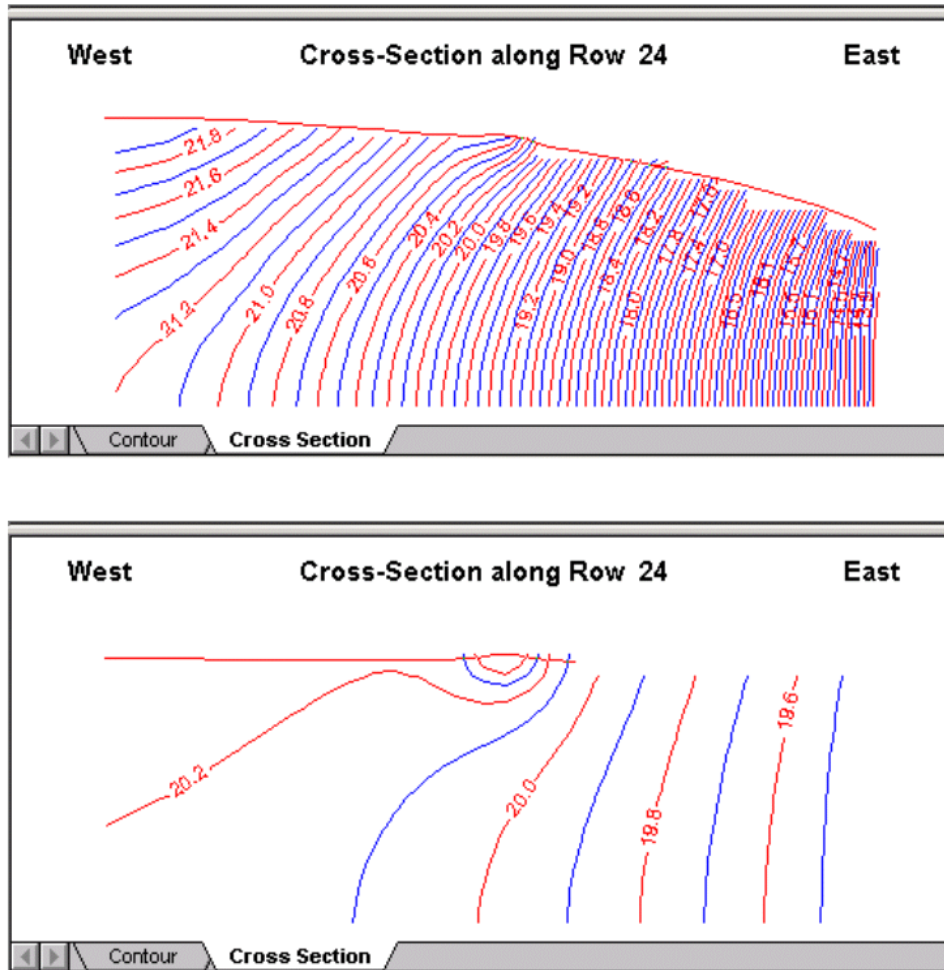
$$f = 0.5$$



**Figure 3-39**  
**Second Conceptual Model (Figure 3-22) With Saturated Thickness of 32.8 ft (10 m),**  
**K = 16.4 ft/d (5 m/d), and 100:1 Anisotropy**

For Figure 3-40:

- Top—High recharge 0.16 in./d (0.4 cm/day) yielding a gradient of approximately 0.02
- Bottom—Low recharge 0.016 in./d (0.04 cm/d) yielding a low gradient of approximately 0.002
- Both are contoured at 0.1 m intervals

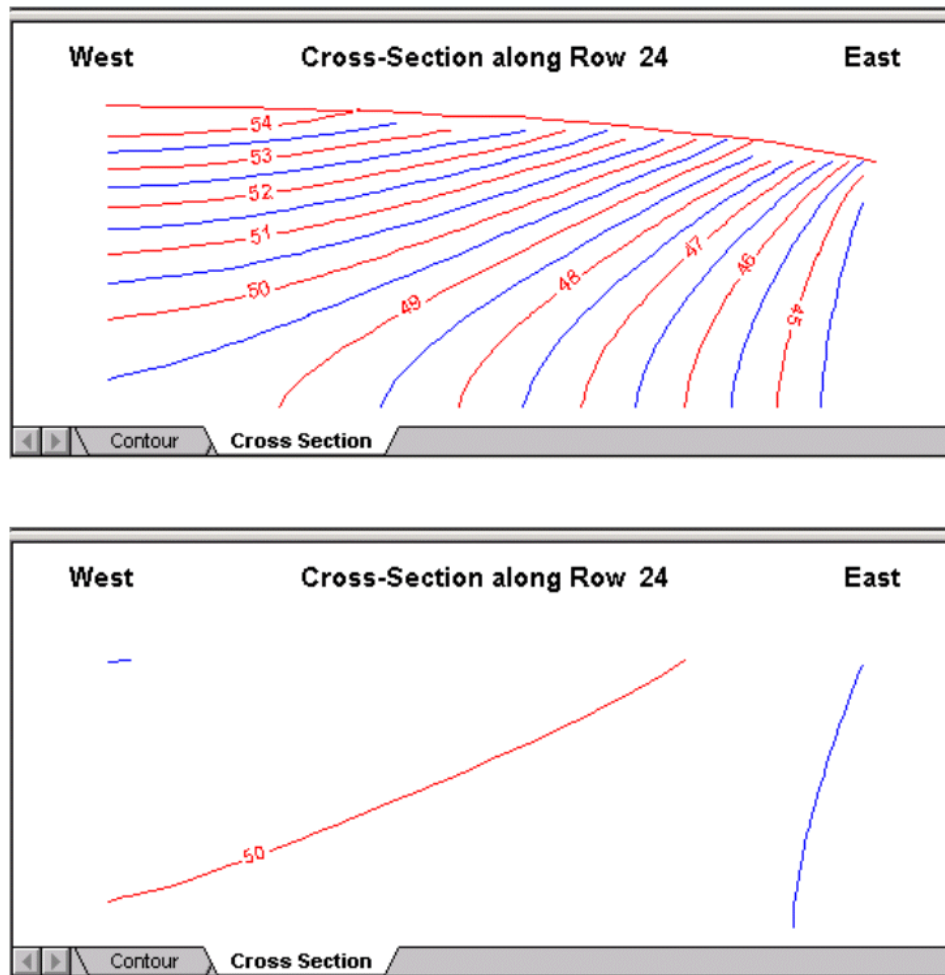


**Figure 3-40**  
Second Conceptual Model (Figure 3-22) With Saturated Thickness of 65.6 ft (20 m),  
K = 16.4 ft/d (5 m/d), and 100:1 Anisotropy

For Figure 3-41:

- Top—High recharge 2.54 in./d (1 cm/day) yielding a gradient of approximately 0.02
- Bottom—Low recharge 0.26 in./d (0.11 cm/d) yielding a low gradient of approximately 0.002
- Both are contoured at 0.5 m intervals

Mounding is greater in the case with a steeper gradient because the large natural flow required to create the gradient reduces the excess carrying capacity of the system.



**Figure 3-41**  
**Second Conceptual Model (Figure 3-22) With Saturated Thickness of 164 ft (50 m),**  
 **$K = 16.4 \text{ ft/d}$  (5 m/d), and 100:1 Anisotropy**

#### 3.6.5.4 Summary of Numerical Model Evaluations

These numerical simulations show only a few specific cases of many possible situations that may be encountered at a field site. A generic model cannot be constructed for determination of the water table rise in all field cases because the result is dependent on the hydraulic properties and boundary conditions. The analytical model is infinite. Therefore, it provides a worst-case scenario when used to evaluate an identical system in the numerical model, provided sufficient time is simulated in the analytical model to approach a steady-state condition. This condition will be caused by hydraulic boundaries in the field that are not included in the analytical model. The purpose of the numerical simulations is to demonstrate the utility of numerical modeling for cases that cannot be adequately predicted using the analytical model.

For anisotropic cases where  $K_h > K_v$ , the numerical model results show that the analytical model under predicts the height of mounding for the anisotropic case if the  $K_h$  is used and over predicts height if  $K_v$  is used. Similarly, the analytical model over predicts the lateral extent of mounding for the anisotropic case if the  $K_h$  is used and under predicts lateral extent if  $K_v$  is used. Conservative estimates can be obtained by solving both problems. Using the square root of the product of the horizontal and vertical K values as an equivalent homogeneous K value provides an intermediate estimate.

Predicting mounding in situations with a combination of a sloping water table and anisotropy is complex, depending not only on the slope and anisotropy but also on the natural recharge rate. For isotropic conditions, variation in gradient is irrelevant for the range of parameters evaluated. In a thin, anisotropic aquifer, mounding increased with decreasing gradient, and the effect was exacerbated in a moderately thick aquifer. In the thickest aquifer, mounding decreased with decreasing gradient because the capacity of the aquifer was large relative to the additional flow from the WSAS.

The results indicate the need for site-specific numerical modeling in complex cases. As noted previously, the errors associated with theoretical considerations necessary to simplify systems for modeling are much less severe than those associated with using incorrect values for K. The most important task, when using models to assess groundwater mounding, is to characterize accurately the aquifer below the infiltration area.

### 3.7 Model Acquisition and Implementation

Analytical models are available in the literature. Many of the analytical models can be evaluated with a calculator, as the Khan model presented in section 3.5. Some of the solutions are more involved but are readily solved using a spreadsheet, as for the Hantush solution presented in section 3.6. Spreadsheets for that solution are included with this report ([WaterTableMounding\\_EnglishUnits.xls](#) or [WaterTableMounding\\_SIUnits.xls](#)).

The spreadsheets are set up so a designer can enter values appropriate for their site in the green cells and determine the maximum water table rise at the center of the infiltration area and the rise at various distances where breakout on a nearby slope may be of concern in the pink cells. Two similarly titled sheets with “Example” added to the titles hold the same information but are read-only files so that the original configuration can be reclaimed if the editable versions are corrupted.

For saturated zone numerical modeling, the United States Geological Survey (USGS) MODFLOW code is recommended and can be downloaded from the USGS at no charge:

[http://water.usgs.gov/software/ground\\_water.html](http://water.usgs.gov/software/ground_water.html). Most users prefer to manage MODFLOW modeling using a GUI. The most commonly used GUIs and their prices in 2004 are:

- Groundwater Modeling System (GMS) \$1,500 to \$7,000 depending on the selected packages
- Visual MODFLOW (VM) approximately \$2,000
- Groundwater Vistas (GWV) \$925, which was used to obtain illustrations for this report

Numerous outlets are available and can be found by entering the name of the software package in an Internet search.

For unsaturated zone numerical modeling, a number of codes are available as summarized in Appendix B, *Numerical Unsaturated Flow Codes*. HYDRUS-2D was used to present the work in this report. HYDRUS-2D is a two-dimensional finite element numerical model based on Richards' equation for unsaturated flow. HYDRUS-2D was selected because it is reasonably priced (\$1,200 for the Windows-based version and the mesh generator) and user friendly. Other similar models are available at lower cost but without a GUI. A disadvantage for numerical models such as HYDRUS-2D is the relatively long execution time that results from solving the non-linear Richards' equation, which requires iterative techniques. A significant advantage of the finite-element model is the ability to simulate irregular meshes (such as soil mounds, hill slopes, valleys, and stream banks).

### **3.7.1 Model Implementation**

Implementation of analytical models requires understanding of the hydraulics and basic computational, calculator, and spreadsheet skills. Spreadsheets for that solution are included with this report ([WaterTableMounding\\_EnglishUnits.xls](#) or [WaterTableMounding\\_SIUnits.xls](#)). These spreadsheets are set up so a designer can enter values appropriate for their site and determine the maximum water table rise at the center of the infiltration area and the rise at various distances where breakout on a nearby slope may be of concern, respectively.

For designers to conduct their own numerical modeling studies, they should have a theoretical knowledge of the underlying hydraulic processes (for example, saturated and unsaturated groundwater flow) and knowledge of basic modeling concepts. Individual study can access knowledge and background at: <http://www.mines.edu/~epoeter/583/index.shtml>. Courses on the fundamentals of numerical modeling and on the use of specific GUIs are instrumental in developing understanding. Some short courses are occasionally listed at: <http://typhoon.mines.edu/short-course/>. Additional courses are offered by many companies and organizations. These can be found by searching the Internet. Suggested key words for a search are "Short Course Groundwater Modeling."

Alternatively, a consultant can be hired to conduct the modeling work, but the designer should be informed about modeling so he or she can assess the benefits and limitations of the consultants work.

### **3.7.2 Modeling Costs**

Groundwater modeling of WSAS projects varies considerably. The site may be low-risk and a few analytical calculations may suffice. In this case, the effort may take only a day. If limited numerical modeling is required, the project may take a week. For a complex site, with high risk and a wealth of data, the project may require one or more months.

If commercial software is used, the cost may range from a few hundreds to a few thousands of dollars. Labor costs for modeling a WSAS project can range from a few hundred dollars for the simplest project, to thousands of dollars for a moderate project and tens-of-thousands for complex, high-risk projects. In such situations, the modeling work may support legal procedures associated with permitting the site. In addition, employees may require training before conducting the modeling work.

Costs associated with numerical modeling are estimated by level of experience and project complexity in Table 3-6. Adjustments can be made depending on specific cases, for example, whether preparation costs are required for the employee, or whether unsaturated and/or saturated zone modeling is required. Unsaturated flow modeling is assumed to be required. Specific costs can be omitted if only saturated zone modeling is necessary.



**Table 3-6**  
**Costs Associated With Evaluation of Groundwater Mounding Using Numerical Models Based on Level of Expertise**

**Unsaturated flow modeling is assumed to be required, specific costs can be omitted if only saturated zone modeling is necessary.**

	<sup>1</sup> Technical degree B.S./M.S. Geology or Engineering, but no formal training in Hydrogeology	<sup>1</sup> Technical degree with several Hydrogeology courses	<sup>2</sup> M.S. Degree in Hydrology, No significant modeling experience	<sup>3</sup> M.S. Degree in Hydrogeology with significant modeling experience, but not in unsaturated flow	<sup>4</sup> M.S. Degree in Hydrogeology, experience with other unsaturated zone software
Purchase software (HYDRUS with mesh generator for example)	\$1600	\$1600	\$1600	\$1600	\$1600
Additional field characterization costs to support unsaturated zone flow modeling <sup>5</sup>	\$5000	\$5000	\$5000	\$5000	\$5000
Employee takes short course on software use. 24 lost billable hours	\$1000 course \$1200 travel \$1200 lost hours	\$1000 course \$1200 travel \$1200 lost hours	\$1000 course \$1200 travel \$1400 lost hours	\$1000 course \$1200 travel \$3120 lost hours	\$1000 course \$1200 travel \$3600 lost hours
Employee takes semester course in vadose zone hydrology. 90 lost billable hours	\$1500 course \$4500 lost hours	\$1500 course \$4500 lost hours	\$1500 course \$6300 lost hours	\$ 1500 course \$11700 lost hours	
Employee takes semester course in hydrogeology. 90 lost billable hours	\$1500 course \$4500 lost hours				
<b>Preparation Cost</b>	\$22,000	\$16,000	\$17,800	\$23,200	\$10,000
<b>Modeling ranging from minimal to complex<sup>6</sup></b>	\$ 5,000 - 40,000	\$ 4,000 - 35,000	\$ 4,000 - 40,000	\$ 6,000 - 65,000	\$ 5,000 - 60,000
<b>Total Cost</b>	\$27,000 - 62,000	\$20,000 – 51,000	\$22,000 – 60,000	\$29,000 – 88,000	\$15,000 – 70,000

<sup>1</sup>\$50 <sup>2</sup>\$70 <sup>3</sup>\$130 <sup>4</sup>\$150 per billable hour

<sup>5</sup>Capillary pressure curves on samples from several locations and shallow coring to evaluate heterogeneity

<sup>6</sup>Hours ranging from 100-800 for the least experienced person, to 32-400 for the most experienced



## 4 SUMMARY

Cluster and high-density wastewater soil-absorption systems (WSAS) (those receiving more than 2,000 gallons per day [GPD]) are increasingly required to serve development. In the past, system designers and regulators focused on vertical movement of water from WSAS because most systems are small and isolated. However, insufficient capacity may result in:

- Significant groundwater mounding on low hydraulic conductivity lenses or by elevating the water table (which may alter saturated flow direction or reach the surface)
- Lateral movement of water, which may affect nearby water supplies or water bodies, or may cause effluent breakout on slopes in the vicinity

### 4.1 Hydrologic Evaluation

Hydrologic evaluation is important because it ensures a site has sufficient capacity to assimilate water in excess of natural infiltration. Practitioners and stakeholders must be informed of the issues so they will be able to complete the proper investigations and evaluations. This report presents a methodology for:

- Evaluation of site-condition and system-design influences on the potential for groundwater mounding and lateral spreading
- Selection of investigation techniques and modeling approaches based on site conditions, system parameters, and the severity of the consequences of excessive mounding

Once the magnitude of mounding is known, the designer must determine whether the WSAS function will be acceptable based on treatment requirements and local regulations.

Evaluation of the potential for groundwater mounding and break-out on the surface or side slopes requires different levels of effort depending on the characteristics of the subsurface and the consequences of system failure. The phased approach indicates more investigation as the risk of mounding increases and the consequences of failure due to mounding become more severe. A flowchart guides preliminary assessment and indicates subsequent steps, based on preliminary site investigation to determine depth to groundwater and soil types (Chapter 2, Figure 2-1). Specific sections of the report elaborate on these steps.

## 4.2 Decision-Support Tool

A decision-support tool quantifies a subjective strategy level that defines the intensity of site characterization and modeling appropriate for a given site, following the philosophy that the degree of characterization and associated cost should be considered in light of the potential for mounding and the consequences should mounding occur. The decision-support tool utilizes additional qualitative information relative to the flowchart as well as site-specific quantitative data from field investigations to determine the strategy level for site assessment. The strategy level provides a guide to the magnitude and intensity of field investigation and the sophistication of modeling. Guidance on site investigation is provided in Chapter 2, *Site Evaluation for Groundwater Mounding Potential*, while guidance on modeling is presented in Chapter 3, *Evaluating Groundwater Mounding With Models*. Associated costs of field investigations and model assessment are discussed at the end of Chapters 2 and 3.

Sites with hydraulic conditions that indicate low risk of mounding, and have minimal consequences in the case of mounding, can be assessed using minimal site investigation (Chapter 2, sections 2.2 and 2.4) and using analytical solutions to estimate mound height (Chapter 3, section 3.5 for evaluation of vadose zone mounding; and section 3.6 for saturated zone modeling). Spreadsheets for evaluating mounding of the water table are included with this report ([WaterTableMounding\\_EnglishUnits.xls](#) or [WaterTableMounding\\_SIUnits.xls](#)). In these low-risk cases, the estimated height of mounding is added to the high water table to determine if the design will be acceptable.

Sites with hydraulic conditions that indicate risk of mounding, and where the consequences of mounding are severe, require more intense field investigations (Chapter 2, sections 2.5 and 2.6) and sophisticated numerical models to estimate mound height (Chapter 3, section 3.5.5 for evaluation of vadose zone mounding of water on low hydraulic conductivity layers; and section 3.6.5 for mounding of the water table based on flow in the saturated zone). Advanced assessment is particularly important for sites where mounding has serious consequences, and sites that exhibit strong heterogeneity and/or anisotropy, sites with complicated boundary conditions, and those with significant time-varying hydraulic conditions.

## 4.3 Hydraulic Conductivity of the Soil and Aquifer

For evaluation of mounding, the most significant factor is the hydraulic conductivity of the soil and aquifer, as indicated by example calculations presented in this report. Measuring hydraulic conductivity (K) accurately is difficult because its value varies substantially over short distances due to heterogeneity. Therefore, careful attention must be given to this important parameter.

Hydraulic conductivity cannot be accurately estimated from simply knowing the soil type because K of a given soil type may vary by orders of magnitude. Consequently, obtaining reliable measurements of K is important when performing engineering analysis for cluster systems.

Suggested methods for measurement of K in unsaturated and saturated soil are outlined in Chapter 2, section 2.6. Errors on the order of a factor of 10 would not be unusual, even when site-specific measurements are collected. Analyzing the statistics on several measurements provides insight on the error associated with K measurements. If the designer has not collected detailed measurements of K, but has obtained a reasonable estimate based on soil classification or a few measurements, then the site should be evaluated using a range of K, including the expected value and a factor of 10 above and, most importantly, below the expected value for estimating mound height.

#### 4.4 Analytical and Numerical Modeling

Whether the assessment requires analytical or numerical modeling, the designer must consider two possibilities:

1. Wastewater may mound on low hydraulic conductivity layers in the vadose zone
2. Wastewater may cause mounding of the water table beneath the infiltration area or the perched mound

Practitioners seeking to utilize the methods presented in this report can best accomplish this by working through the recommendations of Chapter 2, *Site Evaluation for Groundwater Mounding Potential*, and moving on to sections of Chapter 3, *Evaluating Groundwater Mounding With Models*, as needed.

The first consideration in design of a large system is to specify an overall size of the infiltration area that, when coupled with the anticipated volumetric loading rate, results in an infiltration rate that is less than the vertical hydraulic conductivity of the soil to prevent the development of ponding of wastewater over the infiltration area. That is,  $Q/A < K_v$ , for consistent dimensional units of volume, length, and time.

Next, recognizing spatial constraints of the site and reasonable dimensions for construction, the designer should strive to elongate the infiltration area in the direction perpendicular to groundwater flow beneath the site. Preliminary data acquisition as outlined in Chapter 2, *Site Evaluation for Groundwater Mounding Potential*, will provide approximate values for  $K_v$  and flow direction. Site-scale hydraulic conductivities are extremely important to the performance of the WSAS, but are difficult to determine with certainty. Chapter 2 guides the designer in evaluating the amount and type of field investigation appropriate for a site and refers the designer to Chapter 3, *Evaluating Groundwater Mounding With Models*, for analytical and, if necessary, numerical modeling.

After establishing this reasonable design, the designer must consider the potential for perching and mounding of water on low-K layers in the vadose zone and ultimately the rise of the water table required to carry the wastewater away from the site.

#### **4.4.1 Analytical Modeling**

The analytical modeling recommended in this report is readily accomplished using a calculator in the case of estimating mounding on low-K layers in the vadose zone, and the spreadsheets that accompany the report ([WaterTableMounding\\_EnglishUnits.xls](#) or [WaterTableMounding\\_SIUnits.xls](#)) in the case of water table mounding of the saturated zone. If one or more low-K layers occur in the vadose zone below the infiltration area, the designer needs to evaluate perching on that layer using Equation 3-6 or an approximation of it presented as Equation 3-9. If the land surface is not flat, the designer should further this evaluation by calculating the head rise as a function of distance from the center of the infiltration area using Equation 3-3 and Equation 3-4. If a topographic slope occurs near the infiltration area, the designer needs to evaluate the potential for breakout of the mound on the slope using Equation 3-7 if the slope intersects the low hydraulic conductivity layer and Equation 3-8 if it does not.

Whether low hydraulic conductivity layers occur in the vadose zone or not, mounding of the water table needs to be evaluated. When water perches on layers in the vadose zone, it will eventually infiltrate to the water table (barring evapotranspiration for the perched zone). The equation for evaluating water table mounding, Equation 3-16, is too complex to solve with a calculator. Consequently, spreadsheets accompany this report ([WaterTableMounding\\_EnglishUnits.xls](#) or [WaterTableMounding\\_SIUnits.xls](#)). The designer enters the appropriate values in the green cells and the results are shown in pink cells. The spreadsheets predict both the height of mounding below the infiltration area and at side slopes.

#### **4.4.2 Numerical Modeling**

Unless the designer is knowledgeable in the area of numerical modeling, he or she will likely enlist a modeler to assist with the work. In spite of this, the sections on numerical modeling (Chapter 3, sections 3.5.5 and 3.6.5) are recommended reading because they are not directions on how to conduct numerical modeling, but rather they illustrate how mounding is likely to vary for conditions that cannot be evaluated with analytical models. The insight they provide is useful to all phases of investigation and design. Hypothetical site dimensions and conditions are evaluated to illustrate generic system responses. Actual values of mound height and extent can only be determined for site-specific properties, dimensions, and boundary conditions.

#### **4.4.3 Limitations of Analytical Modeling**

Analytical models provide estimates of both types of mounding with little investment of the designer's time. If the analyses use conservative parameter values and the results indicate mounding is not excessive, then more expensive and time-consuming analyses are not required. Limitations of analytical models should be recognized so that conservative parameter values can be selected. These limitations include:

- The analytical solutions provided for estimating mounding on a low-K layer in the vadose zone do not consider unsaturated-flow physics due to the computational complications such consideration would generate. Consideration of these processes would delay the time of mound development but decrease its magnitude, so their omission is reasonable.

- The analytical solutions do not account for anisotropic hydraulic conductivity. Hydraulic conductivity is a soil property describing how easily water flows through the soil. Anisotropy is the situation where  $K$  varies with direction. Generally the vertical hydraulic conductivity is less than the horizontal, however this is sometimes reversed as may be found in soil deposited by wind. The analytical solutions assume that  $K_h$  and  $K_v$  are the same. If values used for  $K$  in the analysis are representative of the horizontal hydraulic conductivity and the vertical hydraulic conductivity is actually significantly lower, then the solutions under predict mound height but over predict the lateral extent of the mound. However, if  $K_v$  is used in place of  $K_h$ , when  $K_h$  is significantly larger, then the solutions will over predict the mound height and under predict the lateral extent of the mound.
- The analytical solutions do not account for heterogeneity. Heterogeneity is the variation of  $K$  in space. If heterogeneities are randomly distributed, then the best value to use for  $K$  is the geometric mean of the various  $K$  values; however, it is not feasible to collect sufficient data for a reasonable assessment of the geometric mean. Thus, a conservative (low) value for  $K$  must be chosen, probably based on the results of several spatially variable estimates or measurements of  $K$ . If a discontinuous layer exists, then assuming the layer is continuous would provide a conservative estimate (over prediction) of the mound height and extent because some of the wastewater would travel between the discontinuous low- $K$  zones and would not mound in these areas. For severely heterogeneous systems, numerical modeling probably will not improve estimates of mound height because the data collection requirements would be cost prohibitive. Therefore, several pilot-scale infiltration tests should be conducted. This guidance document does not discuss procedures for conducting pilot tests. Briefly, such a test is essentially a pilot study of the actual system, applying clean water at a design rate to an area or trench and monitoring mound development. While achieving steady-state conditions might take longer than a designer can reasonably conduct the test, the mounding behavior under various rates may provide insight to infiltration rates that are acceptable. These tests are designed based on site conditions by a hydrologist with training in infiltration processes. The test could be expensive if a long period of time is required to achieve steady mounding levels, but may be less expensive than a detailed site characterization. The relative costs are highly site specific.
- The analytical solutions do not consider the possibility of heavy rainfall causing short-term increased mounding. To address this issue, one needs to use a numerical model that can simulate transient, unsaturated flow. However, as a conservative assumption, the designer could assume that the mound height would increase by the total rainfall accumulated during the storm divided by porosity of the soil. A more reasonable estimate could be obtained by subtracting an estimated amount for runoff.

Although simplifying assumptions are made when using analytical models, their expediency warrants their use before numerical modeling is considered. When there is potential for problematic mounding as judged by preliminary assessment and design changes cannot sufficiently reduce that potential, then use of a numerical model is appropriate. Setting up numerical models for a specific site is time consuming and requires a significant level of expertise in hydrology, soil physics, numerical methods, and computer operation, and is therefore quite expensive. However, if the risks associated with excessive mounding are serious, the expense may be worth the effort.



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# A DEFINITIONS

## Acronyms and Abbreviations

cm	centimeter
d	day
ft	feet
GMS	groundwater modeling system
GPD	gallons per day
GUI	graphical-user interface
GWV	groundwater vistas
LPD	liters per day
m	meter
NDWRCDP	National Decentralized Water Resources Capacity Development Project
USDA	United States Department of Agriculture
US EPA	United States Environmental Protection Agency
VM	Visual MODFLOW
WSAS	wastewater soil absorption system

## Technical Terms

Anaerobic	A condition resulting in the absence of atmospheric oxygen
Analytical model	The exact solution to a mathematical equation
Anisotropy	A condition where one or more of the hydraulic properties of an aquifer vary according to direction
Aquic soil	Soil series subgroup with a silt-loam surface texture and a silty-clay loam subsoil (horizon B) texture of low to very low hydraulic conductivity
Biomat	A relatively low-permeability mass made up of organisms
Boundary conditions	A condition specified for the solution to a set of differential equations
Bulk density	The mass or quantity of a substance per unit volume
Capillarity characteristics	Characteristics of flow due to capillary forces, or the forces acting on soil moisture in the vadose zone, attributable to molecular attraction between soil particles and water
Capillary pressure	Energy per unit area associated with maintaining an interface between two immiscible fluids (in this case air and water), practically measured as the pressure difference between the water and air phases for a given water content (Note: Capillary pressure increases nonlinearly as the water content decreases)
Cemented soil zone	Zones of soil with grains held together by a cement (for example, calcite)
Conceptual model	Description or visual representation of a flow system and the stresses applied to it
Confined aquifer	An aquifer that is overlain by a confining bed with a significantly lower hydraulic conductivity than the aquifer such that the hydraulic head in the aquifer is higher than the elevation of the top of the aquifer
Constant head boundary	A location at which the head is held constant in a model; the flow will be calculated so as to maintain this constant head
Darcy's Law	The equation governing flow through a porous medium, $velocity = hydraulic\ conductivity \times gradient$ , or $volumetric\ flow\ rate = hydraulic\ conductivity \times gradient \times area\ perpendicular\ to\ flow$
Discretization	The division of a system into pieces that are represented by uniform properties and for which one value of each dependent variable is calculated



Dupuit-Forchheimer Theory	Early theoretical approach developed to linearize the description of groundwater flow, using the horizontal distance between locations rather than the length of the flow path to calculate the gradient and the average saturated thickness to determine the flow area
Dystric soil	Unit having a base saturation of less than 50% in a region within 20 to 100 cm of the soil surface
Eutrudept soil	Soil unit with high base saturation in the near surface region (upper meter)
Falling head test	A hydraulic test in which a slug is added to water in a piezometer (which initially raises the water level) and the falling water level is measured as a function of time to estimate hydraulic conductivity
Finite-Element model	A numerical model where the discrete elements are polygonal shaped and form a spatial mesh (mass and energy calculations within each element depend on the element shape and the number and shapes of the sides)
Gaining stream	A stream that is receiving water from inflow of groundwater
Groundwater mounding	A mound of water in the ground formed by either a perched water table on a low hydraulic conductivity layer below localized infiltration, or a rise of the water table cause by localized infiltration
Head (hydraulic head)	The sum of the elevation head, the pressure head, and the velocity head (normally assumed zero) at a given point in an aquifer, reflected by the elevation to which water will rise in a pipe open at the point of interest
Heterogeneity	The spatial variation of properties within a material
Horizontal hydraulic conductivity	The hydraulic conductivity of a material for water flowing in the horizontal direction
Hydraulic conductivity	The rate at which a porous medium can transmit water under a hydraulic gradient of one, units are L/T
Hydraulic gradient	The change in total head along a flow line divided by the distance along the flow line between the locations where the heads are measured
Hydrograph	A graph showing the elevation of groundwater or surface water as a function of time
Isotropy	Properties are identical in all directions
Lens	A biconvex optical lens shaped object, such as a lens of sandstone
Leon hardpan soil	Poorly draining soil typically found in the southeastern US that has a carbonate cemented layer that impedes drainage

Loam	Soil composed of 20 to 50% sand, 30 to 50% silt, and less than 20% clay fractions
Losing stream	A stream that is losing water by seepage into the ground
Moisture content	Quotient of the weight of water and the weight of solids in a sample
No-flow boundary	A model surface at which the flow of water is specified as zero
Nomograph	A chart representing multiple quantitative relationships
Numerical model	A discrete representation of a system to allow evaluation of differential equations describing flow to be solved for complex geometry and heterogeneous material properties and boundary conditions
Perched zone	A saturated subsurface zone that is higher than the average water table, due to the occurrence of a lens or layer of low hydraulic conductivity
Percolation test	Test performed to determine ability of soil to allow water to infiltrate by pouring a known volume of water into a hole and measuring the amount of time required for the water to infiltrate
Piezometer	A non-pumping well, generally of small diameter, that is used to measure the elevation of the water table or potentiometric surface
Piezometric map	A map of the elevation of the water table or potentiometric surface
Ponding	A collection of water on the ground subsurface
Pore throat size	Size of the opening between pores formed by grains of a soil
Porosity	The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment
Porous medium	A granular medium that allows water to enter and flow through it
Pump test	A test made by pumping a well for a period of time and observing the change in hydraulic head in nearby wells
Residual water content	The volumetric water content that cannot be drained by reasonable pressure forces; sometimes defined as the water content below which the water phase is discontinuous and the water-phase relative permeability reduces to zero
Slug test	Hydraulic test conducted in a well to determine hydraulic conductivity
Soil moisture content	The volume of water in a sample of soil divided by the total volume of a sample
Soil sorting	The degree of variation of grain sizes in a soil; poorly-sorted includes many grain sizes, while well-sorted contains few sizes

Storage, specific	The amount of water released from or taken into storage per unit volume of a porous medium per unit change in head
Storativity	The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head
Tensiometer	Device used to measure soil-moisture tension in the unsaturated zone
Tension-disk infiltrometer	Device used to measure infiltration in soils, which under controlled conditions can be used to calculate the soil hydraulic conductivity
Transient flow	Flow conditions that vary with time
Transient model	A model that represents time-varying flow conditions; heads may rise and fall, flow rates and velocities vary accordingly
Unconfined aquifer	An aquifer for which the upper boundary is determined by the location of the water table
Unsaturated flow	The flow of a water through soil in which the pores are partially filled with air
Vadose zone	Unsaturated zone, or the zone between land surface and the water table where pores are filled with some air and some water
Vertical hydraulic conductivity	The hydraulic conductivity of a material for water flowing in the vertical direction
Volumetric loading rate	Volumetric rate (volume per time) that water is applied to a surface
Wilting point water content	Water content below which a particular plant cannot uptake water from the soil; a plant-specific value

## Frequently Used Variables

Variables are defined as they occur. Variables used only occasionally in the text are not repeated here, but are defined at the location where they are used.

$\theta$	volumetric water content
$\theta_r$	residual water content
$\theta_s$	saturated water content (typically assumed to be equal to the porosity)
$\Theta$	effective water content
$\alpha$	empirical constant that is inversely related to the air-entry pressure value
$A_W$	infiltrative-surface area; the area of the bottom of the trenches
$A_T$	total surface area of the infiltration system; includes trenches and the area between trenches
$a \gg b$	a is much greater than b
$a \ll b$	a is much less than b
DTW	depth-to-water
$f_A$	the fraction of infiltrative-surface area ( $A_W$ ) divided by the total surface area for the infiltration- area system ( $A_T$ )
$h$	pressure head
$K_h$	hydraulic conductivity in the horizontal direction
$K_{sat}$	hydraulic conductivity of the saturated part of the aquifer or soil
$K_v$	hydraulic conductivity in the vertical direction
$L$	length of infiltration area
$n$	empirical parameter related to the pore-size distribution
$Q$	a volume of water
$q'$	the effective wastewater infiltration rate per unit width of infiltration area
$S_I$	international scientific units
$S_y$	specific yield
$S_s$	specific storage
$W$	width of the infiltration area
$z_{max}$	maximum height of the mound
$z_{allow}$	maximum allowable height of the mound



## **B** NUMERICAL UNSATURATED FLOW CODES


VS2DI (Hsieh *et al.* 2000) is a graphical software package from the United States Geological Survey (USGS) for simulating fluid flow and solute or energy transport using finite differences in variably saturated porous media. VS2DI controls VS2DH (Healy and Ronan 1996), which simulates energy transport in variably saturated porous media. This software was a modification of VS2DT, which simulates solute transport in variably saturated porous media, and is based on VS2D (Lappala *et al.* 1987 and Healy 1990), which solves the equations of fluid flow in two dimensions for variably saturated porous media. The code is publicly available from the USGS. The ease of use of the VS2D codes via the graphical interface makes hypothesis testing easy. For example, one can evaluate the response of mounding to various shapes and continuity of low hydraulic conductivity units. The code has been applied to study groundwater recharge, surface-water-groundwater interaction, and contaminant transport from waste disposal sites.

HYDRUS (Simunek *et al.* 1999) is a numerical finite element model that simulates flow of water and chemicals in saturated and unsaturated systems. The model is based on Richard's equation, and uses different forms of the equation, as required, to handle unsaturated or saturated flow. The model can simulate mounding and subsequent lateral flow of a saturated region in a multidimensional setting. This model has been successfully used to simulate transport of unsaturated wastewater flow through and below an infiltrative surface (Beach and McCray 2003). Currently, only the two-dimensional version is available to the public, but a three-dimensional version should be available soon. The two-dimensional version may be obtained free of charge from the US Salinity Laboratory. The three-dimensional version and a graphical user interface (GUI) may be purchased from the International Groundwater Modeling Center of Colorado School of Mines.

TOUGH2/T2VOC (Falta *et al.* 1995) is a numerical integral finite difference model that simulates flow and transport of water, air, and chemicals in saturated and unsaturated multiphase systems. Unlike HYDRUS, the model is fully multiphase because it can also account for pressure forces associated with the air phase, which may be important, for example, as air is compressed between a shallow surface confining layer and a saturated region during mound development. Of course, to take advantage of the multiphase features of the code, more input data are required compared to HYDRUS. TOUGH2/T2VOC is a fully-supported model that may be purchased from the US Department of Energy. A GUI for this model is called PETRSIM and is available at [www.petrasim.com](http://www.petrasim.com).

STOMP (White and Oostrom 1996) is a model developed by researchers at Pacific Northwest National Laboratories. Like TOUGH2/T2VOC, it is a true multiphase fluid flow code, and is similar to TOUGH2/T2VOC in capabilities. However, STOMP and TOUGH2/T2VOC have certain advantages associated with numerical solution techniques, the ability to handle various capillary pressure and relative hydraulic conductivity relationships, which are different between the two codes. A multiphase flow code may be necessary for some unusual mounding-related problems. The model is public domain and may be purchased from the US Department of Energy.

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