FINAL REPORT ADDENDUM

ASSESSMENT OF THE RELATIVE IMPORTANCE OF HYDRAULIC PARAMETERS ON INFILTRATION BASIN PERFORMANCE

Prepared for

Massachusetts Department of Environmental Protection

Project 99-06/319

Development of a Rational Basis for Designing Recharging Stormwater Control Structures and Flow and Volume Design Criteria

April 2001

Prepared by

Gokhan Askar, Project Engineer
David Ahlfeld, Ph.D., Co-Investigator
Eric Winkler, Ph.D., Principal Investigator

Contact:
Eric Winkler, Ph.D.
Center for Energy Efficiency and Renewable Energy
University of Massachusetts at Amherst
160 Governors Drive
Amherst, MA 01003-92650
Email: winkler@ecs.umass.edu

CEERE
Center for Energy Efficiency and Renewable Energy

UMASS

Disclaimer:

This project was financed with Federal Funds from the Environmental Protection Agency (EPA) to the Massachusetts Department of Environmental Protection (DEP) under an s.319 competitive grant. The contents and views expressed are those of the author and do not necessarily reflect the views and policies of EPA, DEP or the University of Massachusetts. The contents of this Handbook are offered as guidance. The University of Massachusetts and all technical sources referenced herein do not (a) make any warranty or representation, expressed or implied, with respect to accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe on privately owned rights; (b) assume any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this report. Mention of trade names or commercial products does not constitute endorsement or recommendation of use.

Copyright:

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Infiltration basins are an important tool for implementation of the Massachusetts Stormwater Management Policy. Successful use of infiltration basins requires that they operate effectively over the long term. Present design practice may not account for all of the components of an infiltration basin that will affect its long-term performance. The objective of this work is to examine, using a detailed numerical simulation model, the relative importance of hydraulic and hydrologic parameters on the performance of infiltration basins. The understanding gained in this study may assist basin designers in improving the long-term effectiveness of infiltration basins as a tool for implementing the Stormwater Policy.

This study focuses on those characteristics of basin geometry and subsurface hydrogeology that affect the drainage of water from the infiltration basin. The study considers the filling of the basin in response to a storm event, the drainage of stormwater through the soils beneath the basin and the eventual dispersal of the water to the water table aquifer. Parameters that can affect performance of a basin include the basin geometry, the depth to the water table, and the depth to the bottom of the saturated aquifer unit, the various soil properties such as hydraulic conductivity, porosity and percent saturation. These and other parameters are varied in a systematic sensitivity analysis using a series of simulated infiltration basins. Approximately 900 individual simulations are performed using a mathematical modeling framework specifically constructed for this work.

The major findings of this study are as follows:

1. The volume of water that can be captured and infiltrated by a basin in a single storm event generally exceeds the volume of the basin. This is due to the infiltration that begins while the basin fills. Depending on storm length, our results suggest that a basin can accommodate two to three times or more of its volume, especially for high permeability soils. This excess water volume is primarily stored in the portion of the subsurface we refer to as the initially unsaturated zone. This zone is measured by the distance between the bottom of the basin and the top of the pre-infiltration water table. As infiltration proceeds the water table rises and this zone becomes saturated. For high permeability soils the thickness of this zone has a large impact on the volume of water that can be accommodated. For low permeability soils the thickness of the zone has only a modest effect on total recharge volume but has a substantial impact on drainage time. In general, the thicker the initially unsaturated zone the better the performance. However, performance can be satisfactory even when the unsaturated zones are quite thin (e.g. 2 feet).

2. The thickness of the saturated zone beneath the basin (that is, the distance between the pre-infiltration water table and the bedrock) does have an effect on drainage performance in an individual storm event. Generally, larger thicknesses improve performance. For most cases, the marginal improvement in performance disappears after the thickness exceeds 6 to 8 feet. The impact on performance is most pronounced when the thickness of the initial unsaturated zone is small. While larger thicknesses are preferred, drainage can be effective even when the saturated zone thickness is quite small (e.g. 1 foot) if the initially unsaturated zone is sufficiently thick.

3. As expected hydraulic conductivity has a substantial impact on basin performance. This results both from the ability of high permeability soils to rapidly fill voids during the initiation of infiltration and the ability of soils to drain away infiltrated water. Increasing hydraulic conductivity tends to increase the volume of water that is infiltrated during the filling phase and tends to decrease the time required to drain away the water from the filled basin. In the initially unsaturated zone, the vertical hydraulic conductivity tends to be a more important parameter than the horizontal hydraulic conductivity. The reverse is true in the saturated zone.

4. The specific yield (a measure of water content in unsaturated soils) has a significant impact on both the total volume of water infiltrated and the time required to complete drainage. The effect is especially pronounced for soils with high permeability. Modeling of decreased specific yield is equivalent to modeling soils that have not fully drained after a storm event. Generally, the larger the specific yield the more water can be accommodated before the basin fills. This is due to the additional available pore space. Increased specific yield also decreases the drainage time since lateral movement into nearby unsaturated soils is made easier.

The implications of this study for design can be summarized as follows. Present design practice often encapsulates the subsurface response to infiltration into a single constant infiltration rate that depends on soil properties. The present results show that other factors also play a role. Most significant of these is the thickness of the initially unsaturated zone. Our results suggest that a basin set in moderate permeability soils, such as sandy loam, over a thick unsaturated zone may have performance characteristics similar to those of a basin set in high permeability soils, such as sand, over a thin unsaturated zone. Additional research focused on this specific relationship may lead to design procedures and regulations with greater flexibility.

While the main focus of this study is the response of a basin to a single storm event, the work also has implications for long-term sustainability of basin performance. Simulations of repeated storms with a three-day interstorm interval indicate that the performance of a basin can degrade with the accumulation of water in the subsurface. If the water table has not returned to its initial state then the combined basin/subsurface system will not be able to accommodate as much water volume as under fully drained conditions. Hence, in assessing long-term success of infiltration system it is not adequate to only require that the basin be empty within 72 hours. The state of the water table and the moisture content of unsaturated soils must also be considered.

1 INTRODUCTION

1.1 History of Artificial Recharge

Artificial recharge applications have been documented from the early 19th century, when European countries first attempted to ease the stress on their groundwater supplies. Artificial recharge operations in the U.S. can be traced back to late 19th century. Two driving forces for the first infiltration applications were flooding problems and increased water demands unmatched by groundwater reserves. Surface spreading as recharge was attempted in Denver, CO around 1880 (Dvoracek and Peterson, 1971). As early as 1895, floodwaters were spread over the alluvial fan at the mouth of San Antonio Canyon to sustain many flowing wells in the upper Santa Ana Valley in southern California (Toups, 1974). By the 1930's all the major groundwater basins in southern California were in an overdraft condition. During 1950's groundwater levels in Los Angeles and Orange counties of California had dropped below sea level, and saline water intrusion occurred. The practice of artificial recharge using the waters of Colorado River started in the late 1950's, and several million-acre feet were recharged (Toups, 1974). Texas started artificially recharging their groundwater aquifers in 1950's because of a long drought period.

The threshold for taking action are not well defined, nor is there a widely accepted criterion for defining dangerous groundwater deficits. The motivation for and extent of artificial recharge is highly dependent on the region. While some states practice recharge to match pre-development levels, others go beyond these levels to create temporary storage for dry seasons. Coastal regions are more concerned about saline water intrusion, and industrialized communities might see artificial recharge as an alternative means for treated wastewater disposal.

1.2 Methods for Artificial Recharge

Groundwater recharge may be natural or artificial and water sources may vary. Direct percolation through the unsaturated zone is a common form of natural recharge. Artificial recharge is accomplished by manipulating and/or optimizing natural recharge mechanisms to increase infiltration rates or constructing recharge facilities, such as pits or wells. The water supply for recharge may be precipitation, imported water, or reclaimed water.

A variety of methods have been developed to recharge groundwater. Most practices are slightly improved versions of the earliest approaches. Although no two projects are identical, most use variations or combinations of direct-surface, direct-subsurface, or indirect techniques:

Direct surface techniques: flooding, ditch and furrow systems, basins, stream-channel modification, stream augmentation, over irrigation

Direct subsurface techniques: natural openings, pits and shafts, reverse drainage, wells

Combination surface-subsurface techniques: subsurface drainage (collectors with wells), basins with pits, shafts, or wells

Indirect techniques: induced recharge from surface-water sources, aquifer modification

Infiltration basins are probably the most favored method of recharge because they allow efficient use of space and require only simple maintenance. Unlike ponds that maintain water permanently or detention basins, which modulate peak flows, infiltration basins are intended to capture a large fraction of storm flow and drain this water to the subsurface completely between intermittent inflows. Basins are either excavated or are enclosed by dikes or levees. Basin geometry is flexible, allowing construction to be adapted to the terrain. Basins may be constructed individually, such as in small drainage areas to collect urban runoff, or in series for infiltration of stream or stormwater.

The feasibility of infiltration methods in general depends on the local soil and hydrologic properties. These properties include:

1. Permeability of unsaturated subsurface deposits and depth to groundwater, which determine the allowable sustained infiltration rate for surface applications. High permeability enables high intake rates, while greater depths allow more temporary storage before all the water is transferred to the saturated zone.
2. Permeability, specific yield, thickness of saturated subsurface deposits, and the position and allowable fluctuation of the water table, which establish the total water storage capacity. Permeability of the saturated zone might be a limiting factor in the distribution of the water within the saturated zone.
3. Transmissivity and hydraulic gradient, which determine the rate of groundwater movement away from recharge areas.
4. Underground structural and lithologic barriers, which affect transmissivity and hydraulic gradient, which in turn affect direction and rate of groundwater movement

1.3 The Subsurface Hydraulics of Recharge

Improving the performance of infiltration basins depends in part on reliable design methods. This, in turn, requires an understanding of the factors that affect basin performance. The amount of water entering an aquifer depends on three factors: (1) the infiltration rate; (2) the percolation rate; and (3) the capacity for horizontal water movement.

Infiltration is the transfer of water into the subsurface. It is usually associated with the boundary of the unsaturated soil and the water source. It may also be called the entry, intake, or acceptance rate. As the interface becomes less permeable (clogging), the infiltration rate decreases. Percolation rate is the rate at which the water is able to move downward through the soil. The capacity for horizontal water movement depends on the horizontal hydraulic conductivity, the horizontal hydraulic gradient and the thickness or area of the saturated region through which flow occurs.

If water is applied to a soil surface at an increasing rate, the rate of supply may exceed the rate of entry, and excess water will accumulate. Not so obvious is the fact that if water is supplied to a soil surface at a constant rate, the water may at first enter the soil quite readily, but eventually, will infiltrate at a rate that decreases with time. Horton (1933) was the first to point out that the maximum permissible infiltration rate decreases with increasing time. This limiting rate is called the infiltration capacity of the soil.

The infiltration process saturates the higher portions of the soil first and further water movement occurs with the downward expansion of saturation. The boundary between the saturated top portions and the unsaturated zone is called the water front. As the front propagates downward it also spreads laterally. If the groundwater is not very deep in the soil, the wetting front soon reaches the water table, and a saturated hydraulic connection is established between the water source and the aquifer to be recharged. From this moment on, the incoming water will flow mainly below the water table. The water table starts rising, and the resistance to infiltration increases more and more as a groundwater mound develops. The groundwater mound may have a conical geometry centered at the saturated hydraulic connection. The mound eventually tends to dissipate due to the hydraulic head gradient in the horizontal direction, which moves water away from the zone of recharge.

1.4 Motivation for Present Study

Despite their relatively long application history as runoff control and/or groundwater replenishment practices, and the abundance of standardization efforts, infiltration basins are far from being reliable best management practices. This might be due to the complexity of measuring the parameters involved in basin performance, or over-simplification of their tasks, mechanisms, and evaluation. It has been demonstrated (Northern Carolina State University Water Quality Group, 1998) that properly designed infiltration devices can closely reproduce the water balance that existed prior to development, provide groundwater recharge, control peak flows from stormwater and protection of stream banks from erosion due to high flows. However, infiltration basins are well known for one of the highest failure rates of any Best Management Practice (Schueler et al, 1987). Annual operation costs generally vary from 3 to 5 percent of the capital cost. Field studies demonstrated that 60 –70 percent of the infiltration basins do not get the maintenance they need. Infiltration basins have a 60 - 100% failure rate within the first 5 years of use (Schueler, 1992).

Consideration of the complex interactions between infiltration, percolation and lateral flow during the recharge process suggest the challenges faced by designers. The relative low cost and small size of recharge structures means that expensive design techniques are rarely practical. Instead, current methods for design of infiltration basins often employ rules-of thumb and safety factors, either dictated by local expertise, or long-term practice.

An example would be the depths to the water table and bedrock: some states and most literature suggest that the seasonally high groundwater table should be located at least 4' below the bottom of the basin. Likewise, the bottom of the basin is advised to be located at least 4' above the bedrock.

While the unsaturated zone storage capacity is related to the depth to the water table it also depends on such factors as soil porosity and percent saturation. One approach that implicitly accounts for these additional factors is the utilization of a design safety factor of 2 when selecting the basin volume: "Design for a two-year runoff to fill less than one-half of the unsaturated soil mantle should provide a reasonable chance of keeping the basin from backing up and failing." (American Society of Civil Engineers, Manual of Practice No.77, 1992)

Without performance evaluation tools and appropriate knowledge of subsurface flow/redistribution/storage mechanisms, designers end up building and maintaining infiltration basins which may be improperly sized and which may frequently fail. While the possible impacts of groundwater mounding and sediment accumulation are known, they are rarely quantified in design analysis.

1.5 Study Objectives

The objective of this study is to examine the parameters of the infiltration basin/groundwater system that are most important in controlling long term performance of the infiltration basin. Many of the parameters that are examined are not normally included in basin design procedures. The validity of excluding these parameters from the design process is examined. Some of the parameters considered are governed by rules-of-thumb in common design practice. The analysis in this study examines the validity of these rules of thumb.

The main technique used in this study is sensitivity analysis on a numerical simulation model of an infiltration basin. The objective of the analysis is to define the set of parameters affecting infiltration basin performance and to assess the trends of sensitivity, and any possible parameter-parameter interactions, which could amplify or suppress the impacts under certain circumstances. Approaches for the definition of the typical storm event for performance analysis are evaluated. Sensitivity trends are confirmed by the use of multiple-storm simulations. Sustainability of basin performance is also tested.

2 REGULATORY BACKGROUND AND DESIGN OF THIS STUDY

2.1 State Guidelines for Artificial Recharge and Infiltration Basin Design

In 1996 MA Department of Environmental Protection of Massachusetts (MADEP) released a Stormwater Management Policy. This policy was designed to protect the wetlands and waters of the Commonwealth from the adverse impacts of stormwater runoff. The stormwater management standards, developed by MADEP and the state's Stormwater Advisory Committee, address both water quality (pollutants) and water quantity (artificial recharge and flood control) by establishing the level of required controls which can be achieved through the use of site planning, nonstructural measures, and Best Management Practices (BMPs). The water quantity-related purposes of the standards are (1) to preserve hydrologic conditions that closely resemble pre-development conditions; and (2) to reduce or prevent flooding by managing the peak discharge and volumes of runoff.

The Stormwater Management Standards apply to industrial, commercial, institutional, residential subdivision, and roadway projects, including site preparation, construction, redevelopment, and on-going operation. The Stormwater Management Standards do not apply to:

1. Single-family house projects,
2. Residential subdivisions with four or fewer lots, provided any discharge will not affect a critical area, or

3. Emergency repairs to roads or their drainage systems.

The Stormwater Management Standards apply to the extent practicable to:

1. Residential subdivisions with four or fewer lots with a discharge potentially affecting a critical area,
2. Five to nine residential lots, provided any discharge will not affect a critical area.

BMPs for compliance "to the extent practicable" must, at a minimum, include: extended detention pond, water quality swale, dry well (rooftop runoff only), sand and organic filter, and/or pretreatment devices. Project proponents must demonstrate that they are implementing the highest practicable level of stormwater treatment. Any residential subdivision of 10 or more lots falls into the category to which the Stormwater Management Standards apply.

There are a total of nine Stormwater Management Standards. Standard 1 states that no new stormwater conveyances may discharge untreated stormwater directly to or cause erosion in wetlands or waters of the Commonwealth. Only rooftop runoff, except from certain metal roofs, may be considered uncontaminated for the purposes of these standards and therefore can be infiltrated directly without treatment. No other type of stormwater may be infiltrated directly without pretreatment. Standard 2 requires that stormwater management systems must be designed so that post-development peak discharge rates do not exceed pre-development peak discharge rates. Standard 3 regulates the recharge to groundwater. Loss of annual recharge to groundwater should be minimized through the use of infiltration measures to the extent practicable. The annual recharge from the post-development site should approximate the annual recharge from the pre-development or existing site conditions, based on soil types. Implementation of stormwater infiltration is required when more than 15 percent or 2,500 square feet of any lot, whichever is greater, in the recharge area (Zone II) of a public well is rendered impervious.

Structural best management practices for stormwater infiltration covered by the Stormwater Management Standards include infiltration basins, infiltration trenches, and dry wells. Dry wells may only be used to infiltrate rooftop runoff, and are not generally recommended. Infiltration basins may be designed for full infiltration, providing storage and infiltration for the entire volume of runoff from the design storm, or partial infiltration, providing storage and infiltration for the first flush or the first half-inch. The following paragraphs describe Massachusetts Stormwater Management Standards' requirements or recommendations regarding the design of infiltration basin:

Infiltration basins must have a minimum separation from the seasonal high groundwater table or bedrock of 2 feet. The design of the infiltration basin should be based on the slowest rates obtained from the infiltration tests performed at the site. The minimum acceptable final soil infiltration rate is 0.5 inches per hour. Maximum soil infiltration rates should not exceed 2.4 inches per hour. Infiltration basins should not be used at sites where soils have 30% or greater clay content, or 40% or greater silt clay content. The basins should not be placed over fill materials. The contributing drainage area to any individual infiltration basin should be restricted to 15 acres or less. Basin inlets should include devices that dissipate incoming runoff to control erosion. Slopes of the drainage area should not exceed 5 percent. The side slopes of the basin should be no steeper than 3:1 (H:V), to allow for proper vegetative stabilization, easier mowing, easier access, and public safety. A storage time of 72 hours is recommended. Forty eight hours is recommended as the minimum storage time. They should be inspected at least twice a year.

The following setback requirements apply to infiltration basin installations: (1) Distance from any slope greater than 15%: a minimum of 50 feet; (2) Distance from any septic system component: a minimum of 100 feet; (3) Distance from any private well: a minimum of 100 feet; (4) Distance from any public groundwater drinking supply wells: Zone I radius; (5) Distance from any surface drinking supply: Zone A, and 100 feet from tributaries; (6) Distance from any surface water of the Commonwealth: a minimum of 100 feet; and (7) Distance from any building foundations: a minimum of 10 feet downslope and 100 feet upslope.

2.2 Supplemental Guidance for Stormwater Standard #3

Subsequent to the issuance of the Stormwater Standard further work has been conducted by the Stormwater Advisory Committee to provide additional guidance for recharge basin design. The resulting supplemental guidance (still in draft form) contains a specific design procedure that requires the following data: (1) Total site post-development area, (2) Actual contributing impervious area, (3) Basin depth, (4) Soil type, (5) Annual rainfall depth. Given these parameters, the design procedure helps calculate the area of the basin (actually the ratio of the basin area to site area). Basin depths vary from 1 foot to 6 feet.

The annual rainfall depth for the proposed site is obtained from the Massachusetts Mean Annual Precipitation Map, developed by the Oregon Climate Service at Oregon State University. Evapotranspiration is assumed constant across the state. The soil type is considered during the calculation of the annual recharge, and when an infiltration rate is needed. The U.S.D.A. Natural Resources Conservation Service classifies soils into four hydrologic groups, A through D. A soils are very sandy/gravelly with high permeability values and D soils are textured soils with low permeability values or other limitations. The soil textures falling into these groups are: (A) Sand, loamy sand; (B) Sandy loam, loam; (C) Silt loam, sandy clay loam; (D) Clay loam, silty clay loam, sandy clay, silty clay, clay. D soils and some C soils (sandy clay loam) are not considered suitable for infiltration applications. The remaining soil types feasible for infiltration basins are listed in Table 2.1.

Texture	**Minimum Infiltration (inches per hour)**	**NRCS Soil Group**	**Max. depth of basin* (inches)**
Sand	8.27	A	595
Loamy sand	2.41	A	174
Sandy loam	1.02	B	73
Loam	0.52	B	37
Silt loam	0.27	C	19

*: Maximum depth in the basin that can drain completely within 72 hours after a storm, given the soil infiltration rate

Table 2.1: Soil Limitations for Infiltration Basins (Schueler, 1987)

2.3 Methodology for the Study

The hypothesis examined in this study is that subsurface hydraulic and hydrologic parameters that are not normally considered in infiltration basin design have an impact on basin performance and hence should be considered when designing basins. This hypothesis is tested by examining the relative importance of subsurface hydraulic and basin parameters on the performance of infiltration basins. The study was conducted by constructing a detailed numerical simulation model of a series of hypothetical infiltration basins with different geometries, soil conditions and hydrologic properties. By repeated simulation of basin filling and draining under different parameter sets it was possible to determine what parameters are important and what parameters are not important in predicting basin performance.

The modeling procedure has several components, which are described in detail in the sections indicated.

1. Identification of parameters (model inputs) to be varied and the ranges over which this variation should occur (Section 2.3.1),
2. Definition of measures for basin performance (Section 2.3.2),
3. Identification of design storm input (2.3.3),
4. Assembly of the numerical and computational apparatus needed to perform the simulations (Chapter 3),
5. Analysis of the results of the simulations (Chapter 4).

2.3.1 Parameters Analyzed in the Sensitivity Analysis

The focus of this study is on subsurface hydraulic and hydrologic parameters. The following parameters are considered in this study: (1) Slope of the water table; (2) Geometry of the basin; (3) Conductance of the basin bed; (4) Anisotropy and heterogeneity in the initially unsaturated and the saturated zones (horizontal and vertical hydraulic conductivities of strata beneath the basin); (5) Porosity (or specific yield) of the soil; (6) Thickness of the initially unsaturated zone, or depth to water table (with the exception of a required minimum value); (7) Thickness of the saturated zone; (8) Storativity of the saturated zone; and (9) Rainfall characteristics.

These parameters were varied over a wide range of values based as indicated in Table 2.2. These ranges were determined by considering the soil types for which basins are considered feasible in Massachusetts, the hydrogeologic conditions typically encountered in basin construction in Massachusetts and the guidelines given in the Stormwater Management Standards. Hydraulic properties of the soil types of interest were taken from Dingman (1984). The table provided typical saturated hydraulic conductivity, porosity, and specific yield values. Horizontal conductivity was assumed to be the same for both dimensions (Horizontal anisotropy factor = 1.0). Except for the simulations performed to verify the individual impacts of horizontal and vertical conductivity values, a ratio of 1:10 was assumed between the vertical and horizontal conductivity values. In most cases, homogenous media were assumed. The vertical discretization (layering) served mainly for analysis precision. Both the initially unsaturated (vadose) and saturated zones generally had the same soil characteristics. Although the values of storativity have a wide range ($5x10^{-5}$ to $5x10^{-3}$), its insignificant impact on the infiltration process allowed the use of a single value of $1x10^{-3}$ throughout the study. Specific yield, and conductivities were assumed to be constant over a layer.

2.3.2 Measures for Basin Performance

In order to evaluate the performance of infiltration basins for the sensitivity analysis, possible measures of performance were investigated. The Stormwater Management Standard #3 has very few performance criteria: (1) complete drainage of the basin in a given time frame; and (2) the amount of annual recharge required. The acute and sustained performance of the basin depends on the characteristics of the water input, that is, the timing and intensity of storm events, and these are not defined in the standard. Standard #2 (on peak discharge rates) requires controls must be developed for the 2-year and the 10-year 24-hour storm events, but these events can not be the criteria to verify sustainability of the basin performance. Derivation of simple performance indices, and selection of performance indicator points within the model domain were investigated.

Parameter	Range
Regional slope	0 – 0.015
Geometry	32 ft x 25 ft, 40 ft x 20 ft
Conductance of the basin bed	0.1 – 1.0 times vertical soil conductance
Horizontal hydraulic conductivity	0.2 in/hr - 24.9 in/hr
Vertical hydraulic conductivity	0.1 in/hr - 9.8 in/hr
Specific yield	0.050 – 0.374
Initially unsaturated thickness	1 ft - 11 ft
Saturated thickness	1 ft - 15 ft
Storativity	5×10^{-5} - 5×10^{-3}
Rainfall intensity	0.02 in/hr - 0.2 in/hr
Basin Depth	2 ft – 5 ft

Table 2.2 Ranges of parameters used in the study

The method chosen for performance assessment was simulating a constant-intensity rainfall event until the basin filled up. The software was constructed so that when the basin filled the precipitation input ended. The depth of the water within the infiltration basin was recorded frequently during simulations, at intervals of several seconds at the initial stages, and minutes at the end. The hydraulic heads within the vadose zone and the saturated zone were recorded at hourly intervals due to data storage limitations.

The main criterion for performance comparison was the capability of the basin to drain within a typical three-day period from the start of the storm event. For drains, which were completely drained before the end of the simulation, the exact drainage times were recorded, while the “unsuccessful” drains could be compared using the depth of standing water within them at the end of the simulation.

During the course of the study, some basin/soil configurations were exposed to multiple storm events to generate data to assess sustainable performance. This methodology doubled the simulation run times, and initiated another storm event with the same characteristics at the beginning of the second period (at the end of 3 days). In this case, the fill-up times and the drainage capability, or the recharge potential of the basin was strongly dependent on the water content in the vadose zone. Trends of the total recharge and the drainage time over the prolonged periods give insight about the long-term failure risk of, or cumulative recharge through the basin. An ideal design should not indicate any significant recharge reduction or drainage time increase over these multi-period runs.

The hydraulic heads within the soil surrounding the infiltration basin were occasionally used to verify the degree of saturation, or water table increases during simulations. An attempt was made to identify a minimal number of indicative points in the vadose zone, which would enable comparison of the performance of different configurations via the times required for the water leaving the basin to reach those points.

The performance of infiltration basin designs may be compared in several other ways, although not utilized in this study. One idea is to fix the amount of water entering the system. This can be accomplished by using a constant-intensity, constant-duration storm event on the input side of the system. In this case, all the successful configurations will recharge the same amount of water to the soil, and the practical observer will be left with a single major output to compare: the drainage time. Obviously, some configurations will not be able to handle the storm event and they will top-off, forcing the researcher to find a way to integrate the spilled water back into the system or to disregard it for the sake of numerical stability. This approach will help optimize the designs to handle a certain amount of desired recharge.

Alternatively, instead of fixing the precipitation and altering the designs and testing their performance, one could construct a model to identify storm events that would push the design performance to the limits. This approach might be helpful in predicting the performance of already-built designs under seasonal or non-typical changes in storm characteristics. The maximum water input before basin top-off may be used as a comparison criterion in that case.

All of the methods mentioned above may be adapted to cases with more realistic precipitation data. Actual storm records may be incorporated into the software, the practical complexities of the results caused by the simplification of the simulation conditions would be reduced, and more accurate predictions about the performance of infiltration basins would be made.

2.3.3 Simulated Storm Input

The simulation model is intended to represent an actual infiltration basin that serves a given drainage area. For purposes of the simulation model the storm is represented as a flow over time input to the basin. The details of time varying precipitation and overland flow are not considered in the model.

The time of concentration of the precipitation across the associated drainage area was assumed to be zero. It is expected that in most sites the actual time of concentration is on the order of minutes. Since the storm duration is on the order of hours neglecting the initial accumulation of flow is assumed to produce minimal error. Since the design storm is assumed constant intensity the assumption of zero time of concentration produces a uniform hydrograph inflow to the basin. The flow rate into the basin is simply the rainfall intensity times the impervious area that drains to the basin. For this analysis the basin area is arbitrarily assumed. While sensitivity analysis is performed on rainfall intensity, this can be considered to be sensitivity analysis for a given flow rate into the basin for any combination of rainfall intensity and drainage area whose product equals the inflow. Details of this calculation are provided in Chapter 4.

3 NUMERICAL MODEL CONSTRUCTION AND DATA HANDLING PROCEDURES

The study utilized an efficient integration of new modeling packages and a data processing interface. The development environment was designed to enable representation of all the design parameters, implementation, and testing of new design-related parameters and features. A large database for the transient groundwater mound analysis performed was generated, along with tools to extract information from the database. Approximately 900 individual simulations were conducted during the course of this study.

Modeling of the infiltration process was performed on the IBM-PC platform. Both the hardware and the software components of the setup were important factors in determining the scope of research, accuracy of analysis, and scheduling of research. Computers used were state-of-the-art machines as of 1999, but their capabilities were limited with respect to desired goals of the proposed research .

The core of the software environment used was MODFLOW, a public-domain groundwater flow simulation program coded in FORTRAN by the United States Geological Survey (McDonald and Harbaugh, 1983 - 1996), MODFLOW was backed up with pre-processors and post-processors coded in JAVA. Other software used were text/binary editors, spreadsheet editors and data transformation/storage utilities running under MS Windows 95/98/NT operating systems. This chapter describes details of model construction

3.1 Infiltration Basin Simulation Model

Groundwater flow between two points is driven by the difference of hydraulic heads at these points. The point with the higher hydraulic head will be the source, while the other is the sink. How fast the transport takes place depends on two factors: (1) the resistance the soil exerts to flow; and (2) the distance between the two points. Factor (2) can be combined with the head difference, such that the velocity of flow is dependent on the hydraulic gradient (difference of heads divided by the distance) and the resistance between the two points. While the governing equations for groundwater flow have been defined, their solutions and applications to real problems is not an easy task.

MODFLOW stands for the modular finite-difference groundwater flow model. It is capable of simulating groundwater flow in a three-dimensional heterogeneous and anisotropic medium provided that the principal axes of hydraulic conductivity are aligned with the coordinate directions. Basic assumptions of the model include a constant-density fluid and saturated flow conditions. MODFLOW is a compilation of packages (hence the name, modular) that perform input/output operations, mathematical equation solving, and hydrogeological process implementation/integration. While basic groundwater flow problems may be solved using input/output modules and the solver options, it is often necessary to utilize other available packages when formations or processes such as rivers, wells, recharge, and evapotranspiration are to be coupled to the model. One important part of this research constituted identification and integration of a package to simulate a surface water body with all the characteristics of an infiltration basin. There were very few options capable of simulating basins and handling basin stage as a dependent variable. Discussion of the selected package is presented in a later section.

MODFLOW solves the partial-differential equation representing the three-dimensional movement of constant-density groundwater. Because analytical solutions of this equation are not available for complex geometries or heterogeneous settings a numerical method of solution is preferred. MODFLOW employs the finite-difference method to obtain approximate solutions to the governing equation. The continuous system described by the equation is replaced by a set of discrete points in space and time, and the partial derivatives are replaced by differences of hydraulic heads at these points. Discretization of the system, in this case, requires the representation of the subsurface by numerous rectangular-prism-shaped units (cells). The resulting model consists of rows, columns, and layers of cells. Layers generally correspond to horizontal geohydrologic units or intervals. Hydraulic properties of the cells (conductivities, storage coefficients) can be defined individually, while there may be only one horizontal anisotropy factor for each layer. Time has to be discretized if a transient solution instead of a steady solution is needed.

3.1.1 Inputs and Outputs

MODFLOW was designed as a batch program, or a noninteractive program that requires all the inputs be prepared before execution. All inputs have to be generated and stored as ASCII (American Standard Code for Information Interchange) files. The data inputs can be grouped into: (1) discretization parameters; (2) hydraulic parameters; (3) boundary and initial conditions; (4) output management; (5) Solver parameters; and (6) Package-specific inputs.

Discretization parameters include number of rows, number of columns, number of layers, layer thicknesses, and time steps (intervals over which the finite-difference equation is solved). Parameters of hydraulic importance are soil-specific properties (hydraulic conductivity, specific yield, storativity) and aquifer parameters (thickness, type). Boundary conditions (constant head, constant/no flow) and initial conditions (hydraulic heads at each cell) help define the problem, while solver parameters (type of solver, convergence criteria, relaxation parameters) fine tune the solution process. Output management inputs select the types of data to be reported, reporting format, reporting frequency. Package-specific parameters are water source / sink definitions that are required when extra hydraulic structures and / or hydrological processes are being implemented within the model.

The basic input/output packages of MODFLOW are capable of reporting a variety of outputs; hydraulic heads, drawdowns, cell-by-cell flows, model-wide water balances terms and discrepancies. In addition, every add-on package may report outputs. Some of these outputs are in the form of matrices, containing entries for every cell in the model. Such outputs are reported in binary form in order to make efficient use of data storage. Other outputs are reported in a directly displayable/printable text format.

3.1.2 Pre-processing and Post-processing

A significant portion of the study required developing and calibrating the software tools to create input files and handle the output data. For models of small scale, where the user is interested in simulation outputs that are recorded by MODFLOW in text format, a simple text editor may be sufficient to create/modify inputs, and retrieve the outputs. The model setups used in the study, however, contain more than 100,000 cells each of which has several defining parameters. The study required that the input files be generated more than a thousand times, which required a robust pre-processor capable of generating and modifying input files quickly, with an efficient and friendly user interface. The system was designed, and updated continuously to satisfy emerging modeling / data handling needs.

The retrieval of the outputs poses another difficulty for the experimenter. Even when run at a minimal-output configuration, large models yield huge text output files containing repetitive patterns. The outputs of interest need to be parsed from within these files by post-processing subroutines. In cases where binary-coded outputs have to be retrieved, parsers with more than text editing capability are required. Due to the diverse nature of outputs, post-processing was performed by parameter-specific batch parsers, which in turn reformatted them into files compatible with common spreadsheet applications.

3.1.3 Suitability of MODFLOW for Basin Simulation

A concern about MODFLOW's suitability for the modeling of infiltration through a basin arose from the very nature of the groundwater flow model utilized by the software. MODFLOW assumes saturated flow conditions. The filling of the voids in the subsurface is visualized as an upward motion; hence water tables expand towards the ground surface as they receive water. The cells forming the discrete model of the unsaturated zone in MODFLOW can accommodate flow when unsaturated conditions prevail. Consequently, MODFLOW simulates the early stages of infiltration as vertically stacked, partially saturated cells. This is quite different from how infiltration actually occurs.

The mechanism of infiltration depends on the comparison of water input rate and saturated hydraulic conductivity. If the water input rate is greater than the saturated hydraulic conductivity, which typically was the case with the infiltration basins studied in this project, ponding occurs on the surface once upper soil layers are saturated. This saturation propagates downward, almost as a horizontal plane (wetting front). If, however, the water input rate is lower than the saturated hydraulic conductivity, then the input rate will be matched by the hydraulic conductivity before the soil saturates, and precipitation will keep infiltrating without ponding, or saturating any layers (unless it intercepts with the water table, or a low-conductivity layer, in which case saturation from below may be observed). None of these cases are exactly how MODFLOW models infiltration.

The suitability of MODFLOW for simulating infiltration depended on the extent of disagreement between its predictions and the analytical solutions of unsaturated flow during the early stages of infiltration. There are several methods to model infiltration, or vertical unsaturated flow. This kind of analysis applies to soils that contain randomly distributed connected intergrain pores, with void volumes that are large with respect to the typical particle size. Darcy’s law for vertical unsaturated flow is combined with the principal of conservation of mass, and the result is Richard’s equation, which is the basic theoretical equation for vertical unsaturated flow in a homogenous porous medium. Predictions of Richard’s equation have been tested to have good agreement with field measurements. Yet, numerical solutions of this equation are very complex, and a simpler model, the Green & Ampt model is widely used instead. Green & Ampt models the infiltration in a 1-dimensional manner, and offers simplicity without sacrificing much of the accuracy. The flow assumption verification was done comparing MODFLOW estimations versus Green & Ampt predictions.

The setup constructed for the test included a 4-foot-deep basin with 2 feet of initially unsaturated zone under it. The comparison criterion was the time to saturation, which can be defined as the moment when a continuous water column formed between the bottom of the basin and the water table. Five types of homogenous soils were tested: sand, loamy sand, sandy loam, and silt loam. Soil properties were taken from Dingman, 1994. Vertical hydraulic conductivity was assumed to be 10 percent of horizontal hydraulic conductivity in both Green & Ampt and MODFLOW cases.

Soil type	**K_{hsat}(cm/s)**	**ϕ**	**$\lvert\Psi_f\rvert$ (cm)**	**θ_{sr}**
Sand	0.01760	0.395	12.1	0.222
Loamy sand	0.01560	0.410	9.0	0.231
Sandy loam	0.00347	0.435	21.8	0.187
Loam	0.00070	0.451	47.8	0.138
Silt loam	0.00072	0.485	78.6	0.117

Table 3.1 Soil properties

Where

K_{hsat} = Saturated hydraulic conductivity

ϕ = Porosity of the soil

| Ψ_f| = Effective tension at the wetting front

θ_o = Specific yield of the soil

A computer program was developed to estimate the infiltration using the Green & Ampt model in a finite-difference fashion with time steps of 0.001 second. The rainfall intensity used for Green & Ampt was equal to the water intake rate for the MODFLOW basin. A storm event of 0.1 inch per hour intensity over a drainage area, which is 68.8 times the basin area, was employed. Both models were dry at the beginning of the simulation. Saturation times were compared. For Green & Ampt, this value was the time required for the wetting front to propagate 2 feet below the surface. In the MODFLOW case, the time was measured when a saturated connection between the basin bottom and the water table was established. Table 3.2 presents the results. While the Green & Ampt software could report saturation times with several decimal digits, MODFLOW was set to report hourly intervals in which a saturated connection was established.

Green & Ampt predictions fell within the ranges of saturation times reported by MODFLOW for all soil types. MODFLOW estimated longer saturation times than Green & Ampt due to the horizontal dissipation of infiltrated water, but even if that existed, such a delay was not immediately obvious. The sample case was a true-scale model, with typical water input rates and hydraulic parameters. The results confirmed that MODFLOW is capable of simulating the initial (unsaturated flow) stages of infiltration without causing significant errors, and it is an acceptable tool to be used throughout the groundwater mounding analysis of infiltration basins. If that were not the case, secondary software tools would have to be employed for the simulation of early stages of basin infiltration.

	Saturation Times (hours)	
Soil type	**Green & Ampt**	**MODFLOW**
Sand	1.5	1 - 2
Loamy sand	1.7	1 - 2
Sandy loam	3.8	3 - 4
Loam	7.9	7 - 8
Silt loam	6.2	6 - 7

Table 3.2 Saturation times predicted by Green & Ampt and MODFLOW

3.1.4 Spatial Discretization

As stated before, MODFLOW represents the aquifer as a set of rectangular-prism-shaped cells. These cells are defined by two horizontal dimensions and a thickness. More accurate simulation results are achieved when smaller cells are used, but as the number of cells increases, the computing requirements (CPU time, storage space) also increase. The goal of discretization analysis was to find trade off points for a certain setup where further shrinking of cell dimensions would not be worth the extra computing power required.

The test model consisted of a drainage area of 0.2 acre (114.3 ft by 76.2 ft) with an infiltration basin positioned at the center, having an area of 0.005 acre (19.05ft by 11.43 ft) and a depth of 5 ft. The basin was assumed to be completely full at the beginning of every simulation. The groundwater table was 5 ft below the basin bottom, and the saturated zone extended 8 ft towards the bedrock. For simplification, cells were assumed to be square prisms in shape, leaving a single horizontal dimension to vary. All cells within a layer (aquifer) were identical in size (all three dimensions). The soil was homogenous and isotropic, with a very high-saturated conductivity of 100 ft/day. Given these conditions, the basin drained completely within 2 hours; therefore a total simulation time of 0.1day (2.4 hours) was chosen. Results were compared on the basis of time required for complete drainage of the infiltration basin. The ground surface, infiltration basin bottom, and the water table were assumed to be perfectly flat.

In the horizontal discretization analysis, the model consisted of 4 layers with thicknesses of 3ft, 3ft, 4 ft, and 8 ft, listed in descending elevation. The last layer listed is the saturated zone, or the groundwater layer specified at the beginning of the simulation. The simulation period was divided into 1000 time steps with a multiplier of 1.01, meaning each time step is 1 percent longer than the preceding one. Four different horizontal cell dimensions were tested: 3.81ft, 1.91 ft, 1.27 ft, and 0.95 ft. Table 3.3 summarizes the sensitivity of the drainage time of the scaled-down basin to cell size.

Side Length of Cell (ft)	Drainage Time of Basin (minutes)
3.81	103
1.91	91
1.27	88
0.95	85

Table 3.3 Impact of horizontal cell dimensions on drainage time

Common practice does not push cell dimensions down below 1 ft. Table 3.3 shows a 7% change in the drainage time as the side lengths were reduced from 1.91 ft to 0.95 ft. Such a size reduction quadruples the number of cells, and computing requirements increase almost linearly with the number of cells. The marginal benefit of shrinking the cell further will be much less. Hence, it was concluded to use side lengths around 1 ft. The model was constructed such that the cells in the vicinity of the basin had side lengths of 1 foot, and the cells enlarged towards the edges of the rectangular domain (cell size : 12 feet x 12 feet at the corners). Figure 4.1 shows the horizontal griding of the cells used throughout the study. In each soil layer, there are 150 rows and 100 columns, totaling 15,000 cells. The size of the model domain was approximately 750 feet x 350 feet.

To assess the vertical sizing of cells the layer thicknesses were decreased from 3 - 4 ft to 1 ft to see the impact of higher resolution on the drainage time. The cells were sized at 0.95 ft by 0.95 ft horizontally. The simulation period was divided into 1000 time steps, with the multiplier varying between 1.007 and 1.010. Since that parameter has a very slight effect, it is also listed in Table 3.4, along with reported drainage times of the basin under different vertical discretization schemes.

Thickness of Layers(ft)	Time Step Multiplier	Drainage Time of basin(minutes)
3 - 4	1.010	85
2	1.007	74
1	1.009	68

Table 3.4 Impact of reducing the layer thicknesses on drainage time

The decrease in the drainage time as layer thicknesses decrease is due to the way MODFLOW handles rewetting of the dry aquifer cells by the neighboring cells that are wet above the threshold level.

As the number of cells within a column increases, the dry column next to that will be wetted partially at every time step, while the coarser-grid model will ignore the flow between columns until all the tall, dry column is wetted in a single time step. The computing requirements linearly increase with increasing number of layers, and the 9% improvement from 74 minutes to 68 minutes caused a 100% increase in the computing power requirements. As before, one might suggest a maximum precision of 1 ft for typical applications. The precision may be sacrificed if there are other system performance measures which are less sensitive to the layer thickness than the basin drainage time. Layers thinner than 1 ft should only be used when a very accurate one-time analysis is required of the model. The layers below the water table were allowed to have greater thicknesses, typically 4 feet each. Figure 4.2 shows a typical setup from the study with a 2-feet-deep basin placed in the center. Layer thicknesses in the initially unsaturated zone are 1 foot. The total thickness of the initially unsaturated zone is 4 feet. The saturated zone layer thicknesses are set to 4 feet. (Drawing not to scale).

3.1.5 Temporal Discretization

As stated before, MODFLOW solves the governing equation of groundwater flow after the differential equation is transformed into linear algebraic difference equations. These equations are iteratively solved over a series of time steps. The finite-difference method is an approximation, and the accuracy of that approximation depends on the size of these time steps. Accuracy increases, as the time steps get smaller. But the total number of time steps require more computing power to get the solution in a reasonable time. There is a lower limit to the size of the time steps, and this limit is determined by the capability of the computer platform used to represent real numbers. Few real numbers can be represented in the binary form without being distorted (i.e., concatenated), and as the numbers get smaller, the relative error caused by this misrepresentation increases. While infinitely small time steps would yield almost exact solutions to a differential equation, in reality, accuracy starts degrading beyond some finite time step size. This accuracy degradation in MODFLOW simulations might cause high discrepancies in water balance terms or even simulation crashing. Delays caused by "dead" time steps (time steps in which the state changes are smaller than can be represented with the current digital precision of the environment) can be significant over the results. Although MODFLOW solvers can perform iterations separate from each other by only billionths of a second, certain packages integrated with the software might (and did) fail to function over infinitesimal state differences caused by such small time steps.

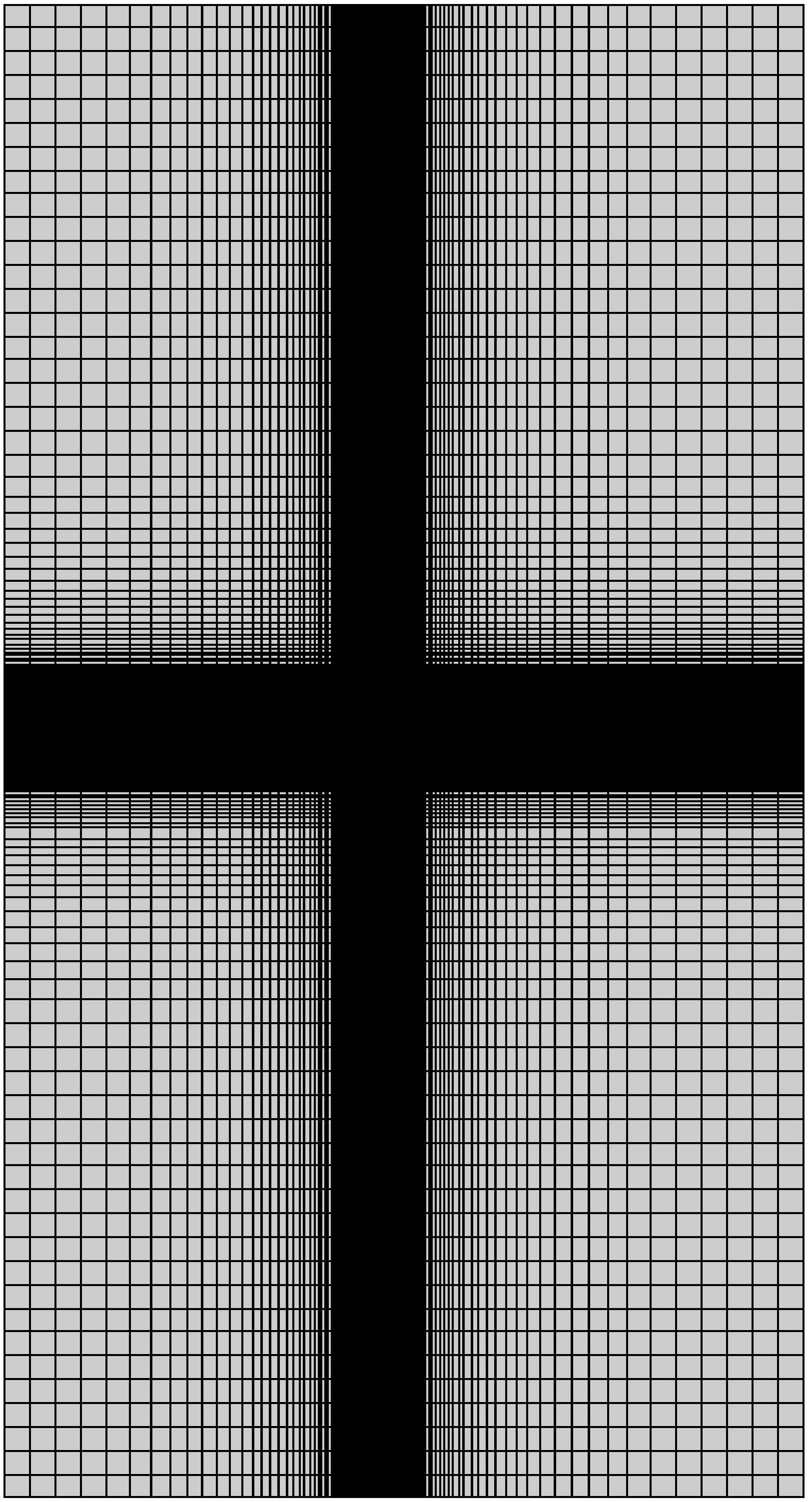


Figure 3.1 The horizontal grid

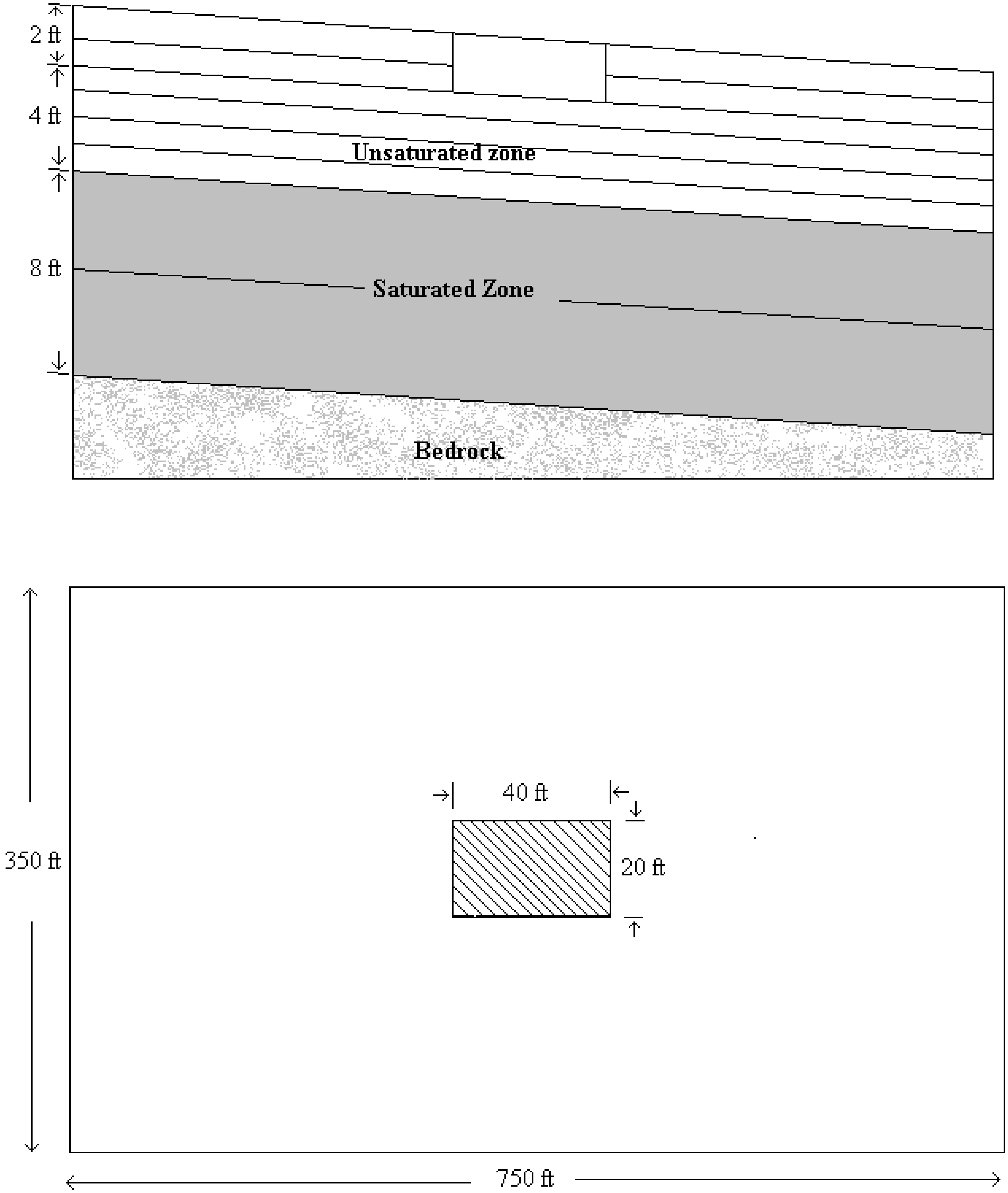


Figure 3.2 The model (side view and top view)

MODFLOW requires the time steps to be defined as a geometric series, characterized by an initial step size and a multiplier. Given a total period length for the simulation, the number of time steps and the time step multiplier determine the size of the initial step. The number of time steps and the time step multiplier also has a great impact on the solver stability of MODFLOW. Hence it may not be possible to run a simulation without crashing until one uses a certain combination. This is why different time step multipliers were reported along with the results of vertical discretization tests.

The goal of the temporal discretization analysis was to determine the average number of time steps that a period should be divided into. In this part of the analysis, layers of 3 - 4 ft thickness and cell dimensions of 0.95 ft by 0.95 ft were used. Table 3.5 presents the drainage times reported by MODFLOW for a small, initially full basin under different temporal discretization schemes.

Number of Time Steps	Time Step Multiplier	Drainage Time (minutes)
400	1.023	91.4
400	1.025	92.3
720	1.010	85.8
1000	1.007	84.1
1000	1.008	84.4
1000	1.009	84.9

Table 3.5 Impact of increasing the number of time steps on drainage time

For the setup used in the analysis, the number of time steps lost significance beyond a partitioning of the 0.1 day into 720 time steps. An increase from 720 time steps to 1000 time steps altered the result by less than 2 percent, indicating an unnecessary investment in computing resources. While not adding much to model complexity, the time discretization increases the computing time linearly. This factor needs to be considered when running a large number of simulations, since it is possible to have simulations completing in almost the same real-life times as their simulation period. A final suggestion might be preferring time step multipliers greater than 1.0, due to two reasons: (1) the equation solvers of MODFLOW became unstable when equal-size time steps were used in this study; and (2) the initial stages of the simulation are of greater importance in the mounding analysis and hence deserve being observed in greater detail (i.e., using smaller time steps).

When the simulation period was scaled up to 3 days, it was concluded that no more than 20,000 time steps would be necessary for the purposes of the groundwater mounding analysis. Further tests of 3-day-long simulations with actual-size models using time step numbers of 10,000 to 30,000 revealed that the results were reasonably accurate at the lower end of the range (10,000 time steps) provided that the initial time step size is several seconds. The final set of parameters used for temporal discretization were :

Number of time steps = 10,000

Time step multiplier = 1.0003

Initial time step length = 4.07 seconds

3.1.6 Add-on Packages to MODFLOW

The modular structure of MODFLOW requires at least these three software packages be present in a standard simulation: (1) basic input-output package (2) block-centered flow package, and (3) a numerical equation solver package. In this study, a later release of the block-centered flow package was used to simulate infiltration. An extra package was integrated in order to simulate an infiltration basin: the Lake Package. The following discussion details the importance of these two packages for the study.

The Block-Centered Flow Package is an essential component of every model simulated in MODFLOW. It computes the conductance components of the finite-difference equation which determine flow between adjacent cells. It also computes the terms that determine the rate of movement of water to and from storage. To make the required calculations, it is assumed that a node is located at the center of each model cell; thus the name Block-Centered Flow is given to the package.

The modular nature of MODFLOW enables packages to be upgraded individually. The Block-Centered Flow Package used in the analysis is a late version (BCF5), and its most remarkable feature was that it could perform rewetting of dry cells. Rewetting is an important capability with respect to inclusion of all cells of a model in the simulation. MODFLOW creates a matrix representing the groundwater equation and fills in the entries with hydraulic properties, heads, and other physical data for every active cell before attempting to solve it. Active cells are those that contain water (in addition to the field capacity) as of the time of matrix generation. If a cell is not active, in other words dry, it is excluded from the problem, hence the equation matrix. The exclusion may occur if a cell is dry at the beginning of the simulation or if it loses all its transportable water content along the course of the simulation. In previous versions of the Block-Centered Flow Package, this exclusion was permanent; any cell that would go dry during a simulation would stay that way.

Gregory W. Council (1999) developed the Lake Package (LAK2) for simulating lake-groundwater interaction. The term "lake" covers any size water body, hence includes infiltration basins. The Lake Package provides boundary conditions for the mathematical formulation of the groundwater flow system. It contains routines to calculate water budgets for a lake that overlies many groundwater cells, and can subsequently update the lake water level, volume, and area. The traditional methods of simulating lakes were: using original MODFLOW boundary conditions (constant-head, river, drain, well, recharge, general-head) or using high-conductivity, high-storage aquifer cells. Other lake and reservoir packages were also available, but the greater functionality of the Lake Package lies within its capability of treating lake stage as a dependent variable of the system. It enables the user to assign stream inflow/outflow, surface runoff, precipitation, and evaporation water budget components along with groundwater inflow/outflow. It offers fixed-stage, steady state and transient stage solution options.

3.1.7 Integration of Packages

Two sets of minor modifications were necessary in the MODFLOW code. The Block-Centered Flow Package (BCF5) and the lake package (LAK2) were not suitable for immediate use in the study.

It was mentioned that the Block-Centered Flow Package enables rewetting of the dry cells, provided that there is at least one neighboring cell with a water content greater than the defined rewetting threshold. However, it did not perform rewetting of dry portions of the domain in the way required for this research. The package allows a dry cell to be wetted by a neighboring cell, as long as the neighboring cell is not on top of the dry cell. This constraint would prevent MODFLOW from modeling infiltration accurately. Since the actual process involves downward wetting front motion, the capability of rewetting from the top had to be integrated into the package. This integration required a simple update in the subroutines of the source code that makes decisions about rewetting dry cells during the simulation. The update, or the patch, was several lines of FORTRAN code.

The verification of this code change had to answer the following: (1) Are the dry cells with a single wet neighboring cell on top rewetted? And (2) Is the water balance disturbed by the code change?

Simple models containing fewer cells and yet all the crucial components of the actual design were exposed to storm events to validate the downward propagation of water. The focus was on the early stages of the simulation, since the wetting of the initially dry cells occurs within a few time steps, or less than a minute. Data from three consecutive time steps was examined. Hydraulic head assignment to previously dry cells indicated they were turned on, or switched to active, or rewetted. The water balance required intra-cell flux data output, and manual recalculation of the fluxes around several cells using the reported heads revealed that the water balance computations within MODFLOW were not disturbed.

The modification to the lake package was relatively simple. The package requires a steady precipitation input for the entire simulation. While the maximum stage of the basin can be fixed, it was not possible to prevent further water input from precipitation as soon as the stage went below the maximum. Since the study was designed such that the storm event stopped when the basin filled up, the code had to be changed so that the precipitation value entered in the input files was internally reset to zero once the maximum stage was reached. The package's basin stage and water balance output options enabled verification that the rainfall resetting was performed at the moment of fill-up, and was permanent.

The Lake Package also required special precautions for preventing inaccuracies from occurring as the basin drained. Another problem related to the Lake Package was that in certain cases (high precipitation rates, and/or high hydraulic conductivities) it failed to balance the water budget, this problem may have been due to real number precision or timing parameters used in MODFLOW. To ensure simulation results were acceptable, the discrepancies in the reported water budgets during simulations were closely observed, and the simulations, which exhibited more than 1 percent of discrepancy in the cumulative water budget, were discarded.

3.1.8 Implementation Issues

Both packages mentioned above were subject to numerical instability risks after integration. The Lake Package updates the basin stage after each MODFLOW iteration, leading to a nonlinear aquifer boundary condition. Hence, the user has to be careful in selecting initial conditions and solver parameters for the model, and the Lake Package itself.

The Block-Centered Flow Package was configured to attempt to identify rewetting candidates frequently in every simulation. In doing so, it faced the challenge of estimating water flow to a cell with no pre-assigned hydraulic head many times, which in turn made it harder for MODFLOW solver routines to meet the convergence criteria within the given iteration limits.

The combined potentials of the two packages for instability resulted in "simulation crashing", which showed itself as unexpected endings of simulations due to convergence criteria that could not be met. Even after precautionary measures had been taken for numerical optimization, instability problems were responsible for the loss of 10 % of all simulations.

The Block-Centered Flow Package provides the opportunity to decrease the instability by manipulating the rewetting characteristics. Rewetting thresholds, rewetting attempt frequency, and first guesses about the head to be assigned to a wetting cell were options for fine-tuning the numerical performance. Thresholds were lowered and alternative equations for head assignment were used. The rewetting-capable Block-Centered Flow package offers two choices for the initial head guess for a newly rewetted cell. One option defines the initial head as a function of the hydraulic head in the neighboring cell that wets the formerly dry cell; the second option always assigns a head value that is a factor of the wetting threshold. The first option is a more realistic approach, but caused numerical instability problems and was abandoned for the study. The frequency of rewetting attempts, however, was not compromised. Rewetting attempts were set for each MODFLOW iteration, which did not favor stability. In part this was due to concerns about infiltration modeling accuracy.

The convergence criteria for MODFLOW solvers were raised to decrease crashes, but were kept at a level to ensure less than 1 percent error in the water budgets. Acceleration/relaxation parameters for solvers were fine tuned, and values around 0.9 were used rather than the typical value of 1.0. The Strongly Implicit Procedure solver proved to be more stable with the configuration used in this study.

An attempt was made to convert all MODFLOW packages used in the study from single arithmetic precision to double precision. The motive of the attempt was to decrease instability problems during simulations and to be able to use more stringent convergence criteria. This process failed. The reasons for the failure were timing of the attempt (late in research when maximizing the number of simulations instead of technical corrections was of the essence), and the lack of documentation on such conversion. One guide was reviewed (part of MODFLOW 84 – 88 user's manual), but did not cover all the packages. If, in the future, such conversion is accomplished, the rate of simulation crashes due to numerical instability may be reduced.

3.2 Computer Hardware and Simulation Model Performance

A network of 10 computers was used in data generation and analysis. They were equipped with Intel Pentium (Series II and III) processors running at speeds of 333 - 550 MHz. Some of them were multi-processor machines. All satisfied the memory requirement of 128 MB for the development environment, and had non-volatile storage capacity of at least 4 GB. The configurations listed above yielded a simulation run time of 6 - 8 hours for typical model setups simulating the filling and draining performance of an infiltration basin over 3 days. A single simulation required 15 minutes of input generation and output gathering/reformatting, which was a labor-intensive process. The total number of simulations was over 850.

The average amount of data generated per simulation was 200 MB, which -due to its highly repetitive text-oriented character- could be software compressed to 15 MB. The huge amount of data generated was permanently stored in a series of CD-ROMs. Simulations were executed in a batch-mode fashion to the extent possible in order to minimize the idle time of the processors. Running the model on a network had the advantage of distributed temporary storage of data for backup and process queuing.

4 RESULTS OF SENSITIVITY ANALYSIS

Approximately 900 simulations were conducted as part of this sensitivity analysis. The entire set of simulations is summarized in Appendix A. This chapter contains an analysis of these results to reveal the impacts of the individual parameters. In most cases, a parameter value is varied while all other parameters are held constant. Criteria used for performance comparisons were: (1) Basin fill-up time, (2) Basin drainage time; and (3) Standing water, if any, in the basin. All cases integrate a constant-intensity storm event into the simulation. Basins are initially dry, and the fill-up time is the time required to top-off the basin. Precipitation input was cut off from the simulation at the time of fill-up. The basin drainage time is the interval between the start of the precipitation and the complete drainage of the basin. This should not be confused with the drainage time of a full basin after fill-up, which was also utilized in some cases. If the basin fails to drain completely within the given time frame (3 days), the amount of water standing in the basin is reported and utilized for comparison. The parameters analyzed were:

1. Storativity
2. Groundwater (saturated zone) thickness
3. Initially unsaturated zone thickness
4. Basin geometry
5. Basin bed conductance
6. Rainfall intensity
7. Hydraulic conductivity
8. Specific yield

The sensitivity analysis reports include parameter sets used for each case, purpose of the sample case construction, results, and discussion. For all cases, unless otherwise specified, the basin is coupled to the initially unsaturated zone through a bed of 0.02-foot thickness. The ratio of the basin area to drainage area (impervious area that drains into the basin) was assumed as 0.01453. Surface area of the infiltration basin was 800 square feet. Rainfall intensity was 0.1 inch per hour. Storativity values were set to 0.001. Regional head gradient and surface slope was 0.01 foot per foot. Soil type-specific parameters were hydraulic conductivity and specific yield. The values of hydraulic conductivity and specific yield were taken from Dingman (1984). Aquifers were assumed to be horizontally isotropic. Horizontal conductivity was constant in all directions. Vertical hydraulic conductivity values, except during the sensitivity analysis for hydraulic conductivity, were 10 percent of horizontal hydraulic conductivity values.

Parameters regarding basin geometry (depth, horizontal dimensions) and aquifer geometry (saturated / initially unsaturated zone thicknesses) are reported for every case. The entire model setup is described more fully in Chapters 2 and 3.

The performance evaluation was done in terms of fill-up and drainage times. Although not provided, the amount of precipitation input to the system in every case can be calculated as in equation 4.1. Substituting the typical rainfall intensity value of 0.01 inch per hour, the basin area / drainage area ratio of 0.01453, and employing unit conversion factors, equation 4.1 reduces to equations 4.2 and 4.3, giving the amount of precipitation that has entered the basin. Fill-up times are reported in hours, and can be directly used in equation 4.2. The amount of water that has infiltrated into the initially unsaturated zone at any time can be calculated via equation 4.4.

Precipitation = (rain intensity) **X** (drainage area) **X** (fill-up time) (4.1)

Precipitation (cubic feet) = 458.8 X (fill-up time) (4.2)

Precipitation (feet) = 0.5735 X (fill-up time) (4.3)

Infiltrated water = precipitation (feet) – (basin stage) (4.4)

Section 4.9 includes plots of basin stage (depth of water in the basin) versus time for parameter adjustments around a base case. These plots are presented in order to help visualize the impacts of parameters on performance. Section 4.10 discusses cascaded runs, which are multi-period (one period = 3 days) simulations, and their significance in evaluating the performance of a basin/soil configuration.

Although experiments focused on the performance of infiltration basins on typical soil types, effort was spent on generating data for various combinations of soil properties, in order to be used for a regression analysis to quantify the relation between parameters and basin performance. Unsuccessful attempts were made to derive empirical equations relating basin fill-up and drainage times to different sets of parameters.

4.1 Storativity

Storativity values for all soil types are at least an order of magnitude lower than specific yield values, and they are not as readily available as other parameters. Dingman (1994) simply defined a range of $5x10^{-5}$ to $5x10^{-3}$ for storativity values for all soil types. With the proposition of insignificance of storativity as a performance-tuning parameter, a single case was constructed to test the sensitivity of the infiltration process to variations in storativity. Case 1 covers the range defined above in three steps.

4.1.1 Case 1

A shallow basin with minimal initially unsaturated zone backup was tested, soil was silt loam (low infiltration capacity soil). Table 4.1 presents the results for three different storativity values.

Basin depth: 2 feet

Basin dimensions: 40 feet x 20 feet

Initially unsaturated zone thickness: 2 feet

Groundwater thickness: 8 feet

Storativity	Drained?	Standing water (feet)
$5x10^{-5}$	NO	0.81
$5x10^{-4}$	NO	0.81
$5x10^{-3}$	NO	0.80

Table 4.1 Sensitivity of infiltration basin performance to changes in storativity

Discussion:

Storativity of the soil layers determines the amount of water inflow/outflow required for given head changes in the saturated portion of the aquifers. This parameter is used in calculations for layers that are saturated in our simulations; therefore it is utilized for the groundwater zone throughout the simulation, while it comes into use in upper layers only when they become saturated. By definition, higher storativity values allow more inflow/outflow per head change in the aquifer, hence an increase in the performance of the basin (shorter drainage times) might be expected at higher storativity values. This impact will be more important in cases with narrow initially-initially unsaturated zones. Case 1 utilized the minimum initially unsaturated zone thickness tested during the study. The storativity values covered the typical range ($5x10^{-5}$ – $5x10^{-3}$). The impact of storativity over this range was negligible, although the highest storativity value ($5x10^{-3}$) caused a very slight increase in performance (reduced standing water depth). The insignificance of the impact may be attributed to the fact that specific yields of the layers in question were at least two orders of magnitude higher than the storativity values. Given this fact, one can conclude that storativity, being important only while layers stay saturated, does not affect the basin performance over the typical range.

The insignificance of storativity in the infiltration basin performance was also verified on several occasions while experimenting with sandy loam, a soil with higher infiltration capacity. One order of magnitude change in storativity values did not result in any difference in the performance. Therefore, a storativity value of 1×10^{-3} was used for all remaining runs.

4.2 Groundwater Thickness

The models in this study assumed the groundwater extended from the water table down to bedrock. The separation between the water table and the bedrock was called the saturated zone thickness, or the groundwater thickness. This thickness may vary from nearly zero to hundreds of feet in Massachusetts. It is not a soil property, but a site-specific hydrologic parameter. The goal in the study was to identify, if there is any, the lower limit of this thickness that would not impair infiltration performance, such that a single groundwater thickness value could be assumed when performing sensitivity analysis for other parameters. Cases 1 – 4 represent the response of the system to the groundwater thickness under different basin geometry / initially unsaturated zone thickness combinations for sandy loam.

4.2.1 Case 1

Groundwater thicknesses from 1 foot to 10 feet were tested for sandy loam soils. Separation between the basin bed and the water table was 6 feet, at the high end of the range of values used in the study. Results are listed in Table 4.2. The conductance of the basin bed in this case was set to 4 times the vertical conductance of sandy loam.

Basin depth: 2 feet

Basin dimensions: 40 feet x 20 feet

Initially unsaturated zone thickness: 6 feet

Groundwater Thickness (feet)	Fill-up Time (hours)	Drained ?	Drainage Time (hrs)
1	10.4	YES	69.7
3	10.4	YES	64.7
6	10.4	YES	62.6
8	10.4	YES	62.4
10	10.4	YES	62.5

Table 4.2 Impact of groundwater thickness on basin performance for sandy loam.

4.2.2 Case 2

Groundwater thickness was varied from 4 feet to 10 feet, in a sandy loam soil with medium-thickness initially unsaturated zone, and basin geometry closer to square. Results are listed in Table 4.3.

Basin depth: 3 feet

Basin dimensions: 32 feet x 25 feet

Initially unsaturated zone thickness: 4 feet

Groundwater Thickness (feet)	Fill-up Time (hours)	Drained ?	Drainage Time (hrs)
4	7.0	YES	64.5
6	7.0	YES	62.0
8	7.0	YES	60.9
10	7.0	YES	60.6

Table 4.3 Impact of groundwater thickness on basin performance for sandy loam.

4.2.3 Case 3

Sandy loam with a thin initially unsaturated zone was tested over a groundwater thickness range of 4 – 10 feet. Results are listed in Table 4.4.

Basin depth: 4 feet

Basin dimensions: 32 feet x 25 feet

Initially unsaturated zone thickness: 2 feet

Groundwater Thickness (ft)	Fill-up Time (hrs)	Drained ?	Standing Water (feet)
4	9.3	NO	1.07
6	9.3	NO	0.94
8	9.3	NO	0.88
10	9.3	NO	0.85

Table 4.4 Impact of groundwater thickness on basin performance for sandy loam.

4.2.4 Case 4

A shallow basin with a large separation from the water table was tested. Soil type was sandy loam. Results are listed in Table 4.5

Basin depth: 2 feet

Basin dimensions: 32 feet x 25 feet

Initially unsaturated zone thickness: 5 feet

Groundwater Thickness (ft)	Fill-up Time (hrs)	Drained ?	Drainage Time (hrs)
4	4.5	YES	37.1
6	4.5	YES	36.7
8	4.5	YES	36.7
10	4.5	YES	36.7

Table 4.5 Impact of groundwater thickness on basin performance for sandy loam.

Discussion:

The thickness of the groundwater at the beginning of the simulation has an impact on the storage / redistribution of the incoming water. Higher thicknesses allow greater removal of the recharge water laterally. Very thin saturated zones may impair infiltration performance, especially if the separation between the basin bottom and the water table is small. In Case 1, where the thickness of the initially unsaturated zone (6 feet) is not a limiting factor, drainage time decreased by 10 percent as the saturated zone thickness increased from 1 foot to 6 feet. The impact would become even larger if the thickness of the initially unsaturated zone was smaller. Case 3 shows this trend: in the presence of a thin initially unsaturated zone, the amount of standing water in the basin after 3 days increased by 12 percent with a small reduction in the saturated zone thickness (from 6 to 4 feet). The impact of such reduction was much smaller in cases where the initially unsaturated zone thickness was far from being a limiting factor. In Case 4, for instance, where the initially unsaturated zone thickness was 150 percent greater than basin depth, decreasing the saturated zone thickness from 6 feet to 4 feet caused a 1% increase in the drainage time of the basin. The impact can again be seen by comparing across tables, for example, for a 4 foot groundwater thickness, the drainage time increases as the initially unsaturated zone decreases. The can be seen in Tables 4.3, 4.4 and 4.5.

The groundwater thickness did not have any significant impact on the fill-up time in any of the cases. Hence, it does not determine the total amount of recharge, but plays a role in the drainage characteristics, affecting the sustainability of basin performance over multiple storms. It is also noteworthy that the fill-up time exceeds the likely time to saturation for each case. This combined with the fact that the fill-up time is independent of groundwater thickness in each case implies that the comparisons within each case are of the impact of the groundwater thickness on dissipation of the groundwater mound.

In all cases, the marginal benefit of increasing the groundwater thickness for performance improvement vanished at or soon after 6 ft. This helped select a groundwater thickness that would have no limiting effects on performance in further simulations, enabling independent sensitivity analysis of other parameters. A thickness of 8 feet became the standard groundwater thickness assumption after this part of the analysis.

4.3 Initially Unsaturated Zone Thickness

Initially unsaturated zone thickness is the separation between the basin bottom and the water table before infiltration begins. It is assumed that this zone is practically dry (i.e., at field capacity) at the beginning of the simulations. The study investigated thicknesses of 2 feet to 6 feet. It should be noted, however, that the initially unsaturated zone also extends from the basin bottom elevation to ground surface, surrounding the basin. The thickness of this initially unsaturated extension is equal to the depth of the basin in all cases. The typical basin geometry was 32 feet x 25 feet x 3 feet.

4.3.1 Case 1

Low infiltration capacity soil (silt loam) was tested. Results are listed in Table 4.6

Basin depth: 3 feet

Basin dimensions: 32 feet x 25 feet

Groundwater thickness: 8 feet

Unsaturated Thickness (ft)	Fill-up Time (hrs)	Drained ?	Standing Water (ft)
2	5.7	NO	1.84
3	5.7	NO	1.65
4	5.7	NO	1.51
5	5.7	NO	1.41
6	5.7	NO	1.34

Table 4.6 Impact of initially unsaturated zone thickness on basin performance for silt loam.

4.3.2 Case 2

Soil type was set to loam, which has a slightly higher infiltration capacity than silt loam. Table 4.7 presents the impact of initially unsaturated zone thickness on basin performance.

Basin depth: 3 feet

Basin dimensions: 32 feet x 25 feet

Groundwater thickness: 8 feet

Unsaturated Thickness (feet)	Fill-up Time (hours)	Drained ?	Standing Water(ft)
2	5.8	NO	1.83
3	5.8	NO	1.65
4	5.8	NO	1.50
5	5.8	NO	1.41
6	5.8	NO	1.36

Table 4.7 Impact of initially unsaturated zone thickness on basin performance for loam.

4.3.3 Case 4

Sandy loam, a soil with medium infiltration capacity was tested. Basin/soil configurations involving sandy loam formed the majority of the runs in the study. Table 4.9 lists the results.

Basin depth: 3 feet

Basin dimensions: 32 feet x 25 feet

Groundwater thickness: 8 feet

Unsaturated Thickness (ft)	Fill-up Time (hrs)	Drained ?	Drainage Time (hrs)	Standing Water (ft)
3	7.0	NO	-	0.05
4	7.0	YES	60.9	-
5	7.0	YES	53.0	-
6	7.0	YES	48.7	-

Table 4.9 Impact of initially unsaturated zone thickness on basin performance for sandy loam.

4.3.4 Case 3

This case was constructed as a supplement to case 4, the sandy loam case. It examines the amplification of the impact of initially unsaturated zone thickness with increased depth of the basin. The basin depth of 4 feet is typically the largest value used during the study. Table 4.8 indicates the fill-up times are also affected by the initially unsaturated zone thickness, unlike in case 4.

Basin depth: 4 feet

Basin dimensions: 32 feet x 25 feet

Groundwater thickness: 8 feet

Unsaturated Thickness (ft)	Fill-up Time (hrs)	Drained ?	Drainage Time (hrs)	Standing Water (ft)
2	9.3	NO	-	0.88
3	9.7	NO	-	0.49
4	9.9	NO	-	0.17
6	10.0	YES	63.2	-

Table 4.8 Impact of initially unsaturated zone thickness on basin performance for sandy loam.

4.3.5 Case 5

SOIL TYPE WAS SET TO LOAMY SAND. RESULTS ARE LISTED IN TABLE 4.10

Basin depth: 3 feet

Basin dimensions: 32 feet x 25 feet

Groundwater thickness: 8 feet

Unsaturated Thickness (ft)	Fill-up Time (hrs)	Drained ?	Drainage Time (hrs)
2	12.0	YES	39.9
3	14.7	YES	35.0
4	17.9	YES	34.5
5	21.7	YES	36.3
6	26.6	YES	39.8

Table 4.10 Impact of unsaturated zone thickness on basin performance for loamy sand.

4.3.6 Case 6

Sand, the soil type with highest infiltration capacity was tested. Initially unsaturated zone thickness of 4 feet was omitted from the analysis due to numerical stability problems. Table 4.11 presents the fill-up and drainage times for other thickness values tested.

Basin depth: 3 feet

Basin dimensions: 32 feet x 25 feet

Groundwater thickness: 8 feet

Unsaturated Thickness (ft)	**Fill-up Time (hrs)**	**Drained ?**	**Drainage Time(hrs)**
(ft)	**(hrs)**		**(hrs)**
2	13.1	YES	39.0
3	16.7	YES	35.6
5	28.0	YES	41.8
6	38.0	YES	50.8

Table 4.11 Impact of unsaturated zone thickness on basin performance for sand.

Discussion:

Initially unsaturated zone thickness is a major parameter in infiltration basin performance. The initially unsaturated zone provides temporary storage and its thickness affects both fill-up and drainage characteristics. In this study, the maximum possible amount of recharge for every simulation was determined by the fill-up time of the basin. Very thin initially unsaturated zones may limit the rate of water seepage from the basin due to quick head build-up around the basin. In this case, fill-up time were reduced, also decreasing the maximum amount of possible recharge. While it is possible to conclude that increasing the thickness of the initially unsaturated zone always favors the initial stage of infiltration, this impact is not so visible when low-conductivity soils are of concern. Cases 1 (Silt loam) and 2 (Loam) are good examples: soil characteristics (low conductivity, low specific yield) are limiting factors in these two cases, and the fill-up times are not determined by initially unsaturated zone thickness. The 3-foot basin filled up in 5.7 hours in the silt loam case, and 5.8 hours in the loam case. Additionally, increasing the initially unsaturated zone thickness from 2 feet to 6 feet had no impact on the fill-up time. The depth of the basin also may suppress the impact of initially unsaturated zone thickness on the basin fill-up process, such as in case 4. Cases 3 and 4 were identical except for the depth of the infiltration basin. The thickness of the initially unsaturated zone had no affect on the time to fill-up when basin depth was 3 feet (case 4). Whereas, increases in the initially unsaturated zone thickness induced fill-up lags when basin depth was 4 feet (case 3).

Initially unsaturated zone thickness has a very pronounced impact on drainage characteristics. The general observation is that increases in initially unsaturated zone thickness lower the basin drainage times. This impact was best observed with lower-infiltration-capacity soils, where initially unsaturated zone thickness did not affect fill-up times (thus recharge amounts), and differences in drainage times could be attributed directly to initially unsaturated zone thickness. In cases 1 (silt loam) and 2 (loam), the basins failed to drain, and the depths of the standing water after 3 days were compared. The depths of standing water in both cases were similar, and they both showed 10 percent reduction in response to 1-foot increase in the initially unsaturated zone thickness when the initial thickness was 2 feet. Every added foot of initially unsaturated zone induced a smaller reduction, and the decrease in standing water depth was only 5 percent when the initially unsaturated zone thickness was increased from 5 feet to 6 feet.

Cases 3 and 4, both for sandy loam, show examples of transition from malfunctioning basin to complete drainage. The basins tested in case 3 had identical fill-up times, creating the same amount of potential recharge. At an initially unsaturated zone thickness of 3 feet, the basin still held 0.05 feet of water in it at the end of 3 days, but as the thickness of the initially unsaturated zone was increased, the basins could drain before 3 days, exhibiting significant time jumps at each thickness increment. As the initially unsaturated zone thickness was increased from 5 feet to 6 feet, the drainage time of the basin reduced by 4.3 hours, an 8 percent decrease. In case 4, the basin fails to drain in 3 days until the initially unsaturated zone thickness increases beyond 4 feet, but the decreases in standing water depths at every thickness increment are larger than their counterparts in the silt loam and loam cases.

As the soil infiltration rates increase, in the cases of loamy sand (case 5) and sand (case 6), the initially unsaturated zone thickness starts inducing larger performance changes. The basin drainage times show first a decrease and then an increasing trend, which is a result of increased fill-up times due to initially unsaturated zone thickness increases. In these two cases, the initially unsaturated zone thickness has a large impact on the filling characteristics of the basin (Fill-up time increases from 13.1 hours at 2-feet initially unsaturated zone to 38.0 hours at 6-feet initially unsaturated zone for sand, hence tripling the water entering the system). For these cases, it is harder to isolate and quantify the drainage-time improvements, but if the time lag between the basin fill-up and drainage is examined in detail, it shows a decreasing trend as the thickness of the initially unsaturated zone increases. The full basin of case 6 (sand) drains completely in 25.9 hours at an initially unsaturated zone thickness of 2 feet, and in 12.8 hours with a 6-foot-thick initially unsaturated zone. In addition to this improvement, the amount of water infiltrated at any moment during the simulations is higher when thicker initially unsaturated zones exist.

4.4 Basin Geometry

The most common basin geometry is rectangular. To test the efficiency of different geometries, rectangles with surface area of 800 square feet were sought. The two rectangular basin geometries tested were: 40 feet x 20 feet and 32 feet x 25 feet. These were tested with depths of 2, 3 and 4 feet. At any depth, both designs had the same volume. Further analysis requires selection of a surface area with a wider set of factors, or the ability to compensate for performance changes caused by minor surface area differences between selected geometries. While not a complete sensitivity analysis the results indicate that basin geometry has a minor impact.

4.4.1 Case 1

The performance of the geometries was compared over a range of basin depths and initially unsaturated zone thicknesses. Soil type was sand, which amplified efficiency differences due to high infiltration rates. Results are shown in Table 4.12. Groundwater thickness was 8 feet for all runs.

4.4.2 Case 2

The soil type was selected from the lower end of the infiltration capacity scale. Table 4.13 presents the results for 2 – 4 feet deep basins with different initially unsaturated zone thicknesses on loamy soils.

Groundwater thickness: 8 feet

Basin Geometry (ft x ft)	Basin Depth (ft)	Unsat Zone (ft)	Fill-up time (hrs)	Drain Time (hrs)	Standing Water (ft)
40 x 20	2	2	7.4	24.3	-
32 x 25	2	2	7.3	23.9	-
40 x 20	2	4	10.8	20.7	-
32 x 25	2	4	10.5	20.3	-
40 x 20	2	6	14.8	22.8	-
32 x 25	2	6	14.2	22.0	-
40 x 20	3	2	13.5	39.9	-
32 x 25	3	2	13.1	39.0	-
40 x 20	3	6	41.4	54.5	-
32 x 25	3	6	38.0	50.8	-
40 x 20	4	2	24.0	62.8	-
32 x 25	4	2	23.2	60.7	-
40 x 20	4	4	49.8	-	0.15
32 x 25	4	4	46.4	70.3	-

Table 4.12 Impact of basin geometry on basin performance for sandy soil.

Basin Geometry (ft x ft)	**Basin Depth** (ft)	**Unsat Zone** (ft)	**Fill-up time** (hrs)	**Drain Time** (hrs)	**Standing Water** (ft)
40 x 20	2	2	3.9	-	1.11
32 x 25	2	2	3.9	-	1.12
40 x 20	2	6	3.9	-	0.71
32 x 25	2	6	3.9	-	0.71
40 x 20	3	2	5.8	-	1.82
32 x 25	3	2	5.8	-	1.83
40 x 20	3	6	5.8	-	1.34
32 x 25	3	6	5.8	-	1.36
40 x 20	4	4	7.7	-	2.14
32 x 25	4	4	7.7	-	2.18

Table 4.13 Impact of basin geometry on basin performance for loam.

Discussion:

For all soil types, the 40 feet x 20 feet geometry had longer fill-up times. The difference was more obvious in soils with higher infiltration capacity (i.e., sand, loamy sand). The fill-up times in case 2 (loam) exhibit the same difference, but at a magnitude of less than a minute, which is not significant at the decimal precision used. The fill-up lag of the 40 feet x 20 feet geometry increased as : (1) soil infiltration capacity increased; (2) depth of basin increased; and (3) initially unsaturated zone thickness increased. The time lags were as long as 3.4 hours in case 1 at 4-foot basin depth and a 4-foot initially unsaturated zone thickness. The increasing trend seems likely to continue into the untested parts of the basin depth / initially unsaturated zone thickness domain.

The time lag generated in the fill-up stage propagated into the draining stage in all cases. The total time to drainage and the time required to drain the basin after it was filled were generally shorter for the 32 feet x 25 feet geometry. The latter might be due to the lower water content of the system at the fill-up point of this geometry, which happens earlier. At some critical design state, the differences between drainage times could swing the design from completely draining performance to standing water condition, such as the 4-foot deep basin with 4-foot initially unsaturated zone in case 1. When soils did not have high filtration capacity, such as loam and silt loam, the performances (both fill-up times and drainage times) of the two geometries were very similar.

The slight improvement in basin performance as basin geometry converges to square can be attributed to infiltration through the sides of the basin. Although bottom areas of the two geometries were the same, areas of the side surfaces were different (Larger for the 40 feet x 20 feet configuration for all cases, increasing infiltration capability of the basin). A 4-feet deep basin with 40 feet x 20 feet configuration has a total contact area (including the bottom surface) of 1280 square feet, whereas the contact area for the 32 feet x 25 feet configuration is 1256 square feet, 2 percent lower than the former. It should be noted, however, that not all the side contacts are active unless the basin is full. This fact dampens the impact of basin geometry.

4.5 Basin Bed Conductance

The software used for modeling the infiltration basin performs the flow calculations using conductance values instead of conductivities. Hence, the sensitivity analysis uses the term "conductance" in the following cases. The conductance is proportional to bed conductivity and inversely proportional to bed thickness. Bed thickness was generally chosen as 0.02 feet. Normal bed conductance was set equal to the vertical conductance of soil layers beneath the basin bed.

4.5.1 Case 1

The impact of basin bed conductance on basin performance was tested. A shallow basin (2 feet) supported with a thin initially unsaturated zone (2 feet) was simulated. Soil type was sandy loam, and basin bed conductance varied from 10 percent of the vertical conductance of loam to 110 percent. The conductance figures in Table 4.14 are scaled.

Basin dimensions: 32 feet x 25 feet

Groundwater thickness: 8 feet

Bed Conductance*	Fill-up Time (hours)	Drained ?	Standing Water (ft)
0.1	4.0	NO	0.18
0.2	4.2	NO	0.09
0.3	4.3	NO	0.06
0.4	4.4	NO	0.04
0.5	4.4	NO	0.03
0.6	4.4	NO	0.03
0.7	4.4	NO	0.02
0.8	4.4	NO	0.02
0.9	4.5	NO	0.01
1.0	4.5	NO	0.01
1.1	4.5	NO	0.01

* Bed conductance is scaled; 1.0 stands for vertical conductance of sandy loam

Table 4.14 Impact of basin bed conductance on basin performance for sandy loam.

.

4.5.2 Case 2

This case is similar to case 1, but has a thicker initially unsaturated zone. Three bed conductance values were selected to cover a 1-order-of-magnitude range. Results are listed in Table 4.15.

Basin depth : 2 feet

Basin dimensions: 32 feet x 25 feet

Groundwater thickness: 8 feet

Initially unsaturated zone thickness: 4 feet

Bed Conductance*	Fill-up Time (hours)	Drained ?	Drainage Time (hours)	Standing Water (feet)
0.1	4.0	NO	-	.03
0.5	4.4	YES	44.7	-
1.0	4.5	YES	41.2	-

* Bed conductance is scaled; 1.0 stands for vertical conductance of sandy loam

Table 4.15 Impact of basin bed conductance on basin performance for sandy loam.

.

4.5.3 Case 3

The initially unsaturated zone thickness was increased to 5 feet. Results are in Table 4.16.

Basin depth: 2 feet

Basin dimensions: 32 feet x 25 feet

Groundwater thickness: 8 feet

Initially unsaturated zone thickness: 5 feet

Soil type: Sandy loam

Bed Conductance*	Fill-up Time (hours)	Drained ?	Drainage Time (hours)	Standing Water (feet)
0.1	4.0	NO	-	0.03
0.5	4.4	YES	40.4	-
1.0	4.5	YES	36.7	-

* Bed conductance is scaled; 1.0 stands for vertical conductance of sandy loam.

Table 4.16 Impact of basin bed conductance on basin performance for sandy loam.

Discussion:

Basin bed conductance is another major parameter in basin performance. The first stage of recharge is the seepage of the water from the basin to the initially unsaturated zone. Basin bed conductance affects the fill-up and drainage processes, and is no longer relevant after the basin dries. Lower basin bed conductance lead to faster head build-up within the basin, reducing fill-up times, and the amount of water recharged. As the bed conductance approaches zero, the basin stage curve converges to a linear function of time. If one assumes no seepage from the basin, the fill-up of the basins in the cases 1, 2, and 3 would be 3.5 hours, not far below the minimum-conductance test results. The fill-up times increased as conductance values higher than the vertical soil conductance were employed. In these cases the bed conductance was no longer a limiting factor in seepage.

Even when the fill-up time of the basin is not sensitive to the bed conductance, and the amount of the water to be recharged is almost the same, basins with different conductivities may (and usually do) have different drainage capabilities. In cases 2 and 3, doubling the bed conductance increased the fill-up time by a mere 6 minutes, while decreasing the drainage time by several hours. This impact is amplified by the presence of thicker initially unsaturated zones where an 8% reduction in the drainage time was recorded with a 4-foot initially unsaturated zone while it was 10 percent with a 5-foot initially unsaturated zone.

The basins draining in around 40 hours of the beginning of the storm event failed to drain in 72 hours when the bed conductance was reduced to 10 percent of the normal conductance of the soil. Such reductions can be practically considered clogging of the bed.

4.6 Rainfall Intensity

There are two parameters determining the water input rate to the basin / soil system: (1) rainfall intensity, and (2) basin area to drainage area ratio. With runoff travel times set to zero, as in this study, either of the parameters can be manipulated to alter the input conditions to the infiltration performance problem. Rainfall intensities were changed in the following cases. A detailed sensitivity analysis involving the testing of all soil types and basin configurations was not considered necessary since rainfall intensity affects only the filling time of the basin.

4.6.1 Case 1

A deep basin / thin initially unsaturated zone combination was simulated with rainfall intensities varying from 0.03 inch per hour to 0.1 inch per hour, the typical rainfall intensity used in the study. To overcome numerical stability problems and get a wide range of results, the basin bed conductance was set to twice the vertical conductance of the sandy loam. Table 4.17 presents the performance comparison.

Basin depth: 4 feet

Basin dimensions: 40 feet x 20 feet

Initially unsaturated zone thickness: 2 feet

Groundwater thickness: 8

Rainfall Intensity (in/hr)	Fill-up Time (hours)	Drained ?	Standing Water (ft)
0.03	50.8	NO	2.53
0.04	32.0	NO	1.70
0.06	18.1	NO	1.18
0.07	14.8	NO	1.06
0.08	12.5	NO	0.97
0.10	9.5	NO	0.86

Table 4.17 Impact of rainfall intensity on basin performance for sandy loam.

4.6.2 Case 2

Basin geometry and subsurface conditions in this case were the same as in case 1. However, the basin bed conductance was lowered to 10 percent of the value in case 1 to expose the impact of clogging. Results are listed in Table 4.18.

Basin depth: 4 feet

Basin dimensions: 40 feet x 20 feet

Initially unsaturated zone thickness: 2 feet

Groundwater thickness: 8

Rainfall Intensity (in/hr)	Fill-up Time (hours)	Drained ?	Standing Water (ft)
0.03	42.2	NO	2.20
0.04	27.6	NO	1.61
0.06	16.1	NO	1.21
0.07	13.3	NO	1.11
0.08	11.3	NO	1.04
0.10	8.7	NO	0.95

Table 4.18 Impact of rainfall intensity on basin performance for sandy loam.

Discussion:

Rainfall intensity, or the water input rate in general, is an important factor in the infiltration basin performance. As the rainfall intensity increases, the water input rate exceeds the seepage rate and the time to fill the basin decreases. Consequently, the amount of water the basin has to recharge decreases, increasing the chances of complete drainage within 72 hours. If the rainfall intensity is sufficiently low in a constant-intensity storm event, it is possible to infiltrate water for prolonged periods, never filling up the basin - unless complete saturation of the vadose zone occurs. In cases 1 and 2, when the rainfall intensity was lowered to 0.02 inch per hour, which is not listed among the results, the basin failed to fill-up in 72 hours. Hence, when analyzing the performance of an infiltration basin, the intensity and time of concentration are of great importance. Even when the total precipitation amounts are identical, different rainfall intensities will result in highly variable degrees of performance.

As the basin bed conductance was lowered, fill-up times decreased due to lower rates of water removal from the basin. The drainage capability was significantly impaired. Drainage times increased, or, when the basin could not drain, standing water amounts were greater for similar water intake volumes. The impact of rainfall intensity variations on basin performance was smaller in cases with clogged or low-conductance basin beds.

4.7 Hydraulic Conductivity

MODFLOW assumes saturated conditions for subsurface flow. Consequently, the conductivity values of concern here are the saturated hydraulic conductivities. The values of saturated hydraulic conductivities for the soil types investigated are as follows:

Sand: 24.94 inches per hour

Loamy sand: 22.11 inches per hour

Sandy loam: 4.9 inches per hour

Loam: 0.985 inch per hour

Silt loam: 1.02 inches per hour

The vertical conductivities were set to 10 percent of the saturated hydraulic conductivity. For most of the study, the saturated and the initially unsaturated zones were assumed to have the same conductivity values. The sensitivity analysis was performed in the form of varying the conductivity in a single direction. In several occasions, the saturated zone conductivities were varied independently.

4.7.1 Case 1

A deep basin with a thick initially unsaturated zone combination was tested. Basin bed conductance was increased to 50 times its original value to ensure it was not a limiting factor in the recharge process. Soil type was sandy loam. The vertical conductivity of the soil was varied from the typical sandy loam value up to 10 times that value. The conductivity entries in Table 4.19 are scaled.

Basin depth: 4 feet

Basin dimensions: 40 feet x 20 feet

Initially unsaturated zone thickness: 6 feet

Groundwater thickness: 8 feet

Vertical Conductivity*	**Fill-up Time (hours)**	**Drained ?**	**Drainage Time (hours)**	**Standing Water (feet)**
1	11.2	NO	-	0.02
2	13.0	YES	59.4	-
5	16.5	YES	53.3	-
10	19.3	YES	53.6	-

* Scaled values, 1 equals the typical vertical conductivity of sandy loam.

Table 4.19 Impact of vertical conductivity on basin performance for sandy loam.

4.7.2 Case 2

The vertical conductivity was varied from half to twice the typical vertical conductivity of sandy loam. The basin bed conductance was kept constant at the typical vertical conductance of sandy loam. A shallow basin with a 2-foot depth and a moderately thick (4 feet) initially unsaturated zone was tested. Table 4.20 presents the results.

Basin dimensions: 40 feet x 20 feet

Groundwater thickness: 8 feet

Vertical Conductivity*	**Fill-up Time (hours)**	**Drained ?**	**Drainage Time (hrs)**
0.50	4.3	YES	56.1
1.00	4.5	YES	41.3
2.00	5.1	YES	33.6

* Scaled values, 1 equals the typical vertical conductivity of sandy loam.

Table 4.20 Impact of vertical conductivity on basin performance for sandy loam.

4.7.3 Case 2a

The horizontal conductivity was varied from half to twice the typical horizontal conductivity of sandy loam. The basin bed conductance was kept constant at the typical vertical conductance of sandy loam. A shallow basin, 2 feet deep, with a moderately thick initially unsaturated zone (4 feet) was tested. Table 4.21 presents the results.

Basin dimensions: 40 feet x 20 feet

Groundwater thickness: 8 feet

Vertical Conductivity*	Fill-up Time (hours)	Drained ?	Drainage Time (hrs)
0.50	4.4	YES	53.6
1.00	4.5	YES	41.3
2.00	4.7	YES	33.5

* Scaled values, 1 equals the typical horizontal conductivity of sandy loam.

Table 4.21 Impact of horizontal conductivity on basin performance for sandy loam.

4.7.4 Case 3

The horizontal conductivity below the water table was varied for the setup in case 1, with one difference: the basin bed conductance was only 10 times higher, which resulted in significant amounts of standing water in the basin at the end of the runs. Vertical conductivity in both zones and horizontal conductivity in the initially unsaturated zone were equal to the typical values for sandy loam. Table 4.22 compares the fill-up times and standing water amounts for different saturated zone conductivities.

Basin depth: 4 feet

Basin dimensions: 40 feet x 20 feet

Initially unsaturated zone thickness: 6 feet

Groundwater thickness: 8 feet

Horizontal Conductivity*	Fill-up Time (hours)	Drained ?	Standing Water (feet)
0.25	22.0	NO	2.89
0.50	22.1	NO	2.85
1.00	22.2	NO	2.80
2.00	22.2	NO	2.77

* Scaled values, 1 equals the typical horizontal conductivity of sandy loam.

Table 4.22 Impact of saturated zone horizontal conductivity on basin performance (sandy loam).

4.7.5 Case 4

The vertical conductivity of the saturated zone was varied. The setup was identical to that of case 3. Vertical conductivity in the initially unsaturated zone, and horizontal conductivity in both zones were equal to the typical values for sandy loam. The results are in Table 4.23.

Basin depth: 4 feet

Basin dimensions: 40 feet x 20 feet

Initially unsaturated zone thickness: 6 feet

Groundwater thickness: 8 feet

Vertical Conductivity*	Fill-up Time (hours)	Drained ?	Standing Water (feet)
1.00	22.2	NO	2.80
2.00	22.1	NO	2.78
4.00	22.1	NO	2.77
8.00	22.0	NO	2.75

* Scaled values, 1 equals the typical vertical conductivity of sandy loam.

Table 4.23 Impact of saturated zone vertical conductivity on basin performance (sandy loam).

Discussion:

Hydraulic conductivity in the horizontal and vertical directions is a primary factor controlling water flow within the saturated and initially unsaturated zones once the water enters the subsurface. All of the cases above involve imaginary soil types, since a soil type is generally associated with a set of conductivities. However, both conductivity terms may vary independently around the tabulated average values, yielding different subsurface water flow patterns, or groundwater mound geometries. Higher conductivity values can directly be associated with higher water removal rates, but the impact of the change in conductivity values on infiltration basin performance may not be visible in certain circumstances. Some of these conditions include: very low basin bed conductance and very thin initially unsaturated zones. In case 1, basin bed conductance is set relatively high to ensure the bed conductance is not the limiting factor in infiltration capacity, and the initially unsaturated zone is adjusted to a less restrictive 6-foot thickness. Horizontal conductivity is kept constant at 4.9 inch per hour, the average value for sandy loam. Vertical conductivity was varied from the average values for sandy loam up to 10 times this value. At the lowest value, horizontal dispersion of water dominates over vertical flow, making the performance very sensitive to vertical conductivity changes. The basin, which failed to drain completely in 3 days at this configuration, could drain in 59.4 hours after a doubling in the vertical conductivity. The amount of infiltrated water was also higher due to increased fill-up time. The fill-up time kept increasing as the vertical conductivity increased, simply because this change accommodated faster removal of water from the vicinity of the basin. The marginal benefit of increasing the vertical conductivity decreased (but did not vanish) as the vertical conductivity approached the horizontal conductivity value, simply because it was no longer the limiting conductivity term. It should be noted that such a large variation in the vertical conductivity of a soil is rare in reality.

Cases 2 and 2a employed a basin bed conductance identical to typical vertical conductance of sandy loam. Increasing the conductivity in either direction increased the fill-up time, and lowered the drainage time, by increasing removal rates. The variations in the vertical hydraulic conductivity had greater impacts on the performance than the variations in the horizontal conductivity. This supports the hypothesis that vertical flow in this configuration is more of a limiting factor than the horizontal removal.

Case 3 aimed to test the impact of the horizontal conductivity of the groundwater zone on infiltration performance. This parameter plays a role in the removal of water away from the basin vicinity once it connects with the groundwater. The saturated zone horizontal conductivity did not have a significant impact on the fill-up time, but the drainage performance improved slightly as the conductivity increased. With thinner initially unsaturated zones and higher basin bed conductance, both impacts are amplified.

The vertical conductivity of the saturated zone was also examined, in case 4. Vertical migration within the saturated zone is not a main redistribution mechanism for recharge water, and the test revealed no significant potential to influence infiltration basin performance.

4.8 Specific Yield

The specific yield values were varied from half to twice the typical values for different soil types. Typical specific yield values for the soil types of interest are as follows:

Sand: 0.222

Loamy sand: 0.231

Sandy loam: 0.187

Loam: 0.138

Silt loam: 0.117

4.8.1 Case 1

A deep basin with a thick initially unsaturated zone was simulated. The soil type was sandy loam and basin bed conductance used was several times higher than the typical vertical conductance for sandy loam. The results are on Table 4.24.

Basin depth: 4 feet

Basin dimensions: 40 feet x 20 feet

Initially unsaturated zone thickness: 6 feet

Groundwater thickness: 8 feet

Specific Yield	Fill-up Time (hours)	Drained ?	Drainage Time (hours)
0.050	9.4	YES	66.6
0.094	9.8	YES	64.4
0.187	10.6	YES	61.7

Table 4.24 Impact of specific yield on basin performance for sandy loam.

4.8.2 Case 2

The basin depth was lowered, a moderate-thickness initially unsaturated zone was employed, and the basin bed conductance was set to typical values. Soil type was changed to silt loam. Table 4.25 lists the results.

Basin depth: 2 feet

Basin dimensions: 40 feet x 20 feet

Initially unsaturated zone thickness: 4 feet

Groundwater thickness: 8 feet

Specific Yield	Fill-up Time (hours)	Drained ?	Standing Water (feet)
0.060	3.7	NO	0.92
0.117	3.8	NO	0.82
0.180	3.9	NO	0.74
0.230	4.0	NO	0.68

Table 4.25 Impact of specific yield on basin performance for silt loam.

4.8.3 Case 3

The setup in case 2 was used, with sandy loam as the soil type. The results appear in Table 4.26.

Basin depth: 2 feet

Basin dimensions: 40 feet x 20 feet

Initially unsaturated zone thickness: 4 feet

Groundwater thickness: 8 feet

Specific Yield	Fill-up Time (hours)	Drained ?	Drainage Time (hours)
0.09	4.3	YES	45.6
0.15	4.4	YES	42.4
0.19	4.5	YES	41.3
0.24	4.6	YES	39.6
0.28	4.7	YES	38.6

Table 4.26 Impact of specific yield on basin performance for sandy loam.

4.8.4 Case 4

A 2-foot basin was simulated with different specific yield values and initially unsaturated thicknesses. Soil type was sand. Basin bed conductance was equal to the vertical conductance defined for the initially unsaturated zone. The specific yield was varied from 0.5 times to 1.5 times the typical value. The results are listed in Table 4.27.

Basin depth: 2 feet

Basin dimensions: 40 feet x 20 feet

Groundwater thickness: 8 feet

Specific Yield	Unsaturated Thickness (feet)	Fill-up Time (hours)	Drained ?	Drainage Time (hours)
0.111	2	6.4	YES	24.0
0.111	3	7.6	YES	20.0
0.111	4	8.8	YES	18.9
0.111	6	11.8	YES	19.6
0.222	2	7.4	YES	24.3
0.222	3	9.0	YES	21.1
0.222	4	10.8	YES	20.7
0.222	6	14.8	YES	22.8
0.333	2	8.2	YES	24.9
0.333	3	10.3	YES	22.3
0.333	4	12.5	YES	22.4
0.333	6	17.8	YES	25.8

Table 4.27 Impact of specific yield on basin performance for sand.

4.8.5 Case 5

A shallow basin with a moderate-thickness initially unsaturated zone was simulated. The soil type was a loam. The specific yield was varied from half to twice the typical value. Basin bed conductance was typical. The results are listed in Table 4.28.

Basin depth: 2 feet

Basin dimensions: 40 feet x 20 feet

Initially unsaturated zone thickness: 4 feet

Groundwater thickness: 8 feet

Specific Yield	Fill-up Time (hours)	Drained ?	Standing Water (feet)
0.07	3.7	NO	0.92
0.10	3.8	NO	0.86
0.14	3.9	NO	0.80
0.20	4.0	NO	0.74
0.28	4.1	NO	0.67

Table 4.28 Impact of specific yield on basin performance for loam.

4.8.6 Case 6

A shallow basin with variable initially unsaturated zone thicknesses was tested with loam as the soil type. The specific yield was varied from half to twice the typical value. Basin bed conductance was typical. The results are listed in Table 4.29.

Basin depth: 2 feet

Basin dimensions: 40 feet x 20 feet

Groundwater thickness: 8 feet

Specific Yield	Unsaturated Thickness (feet)	Fill-up Time (hours)	Drained ?	Standing Water (hours)
0.07	2	3.7	NO	1.22
0.07	3	3.7	NO	1.05
0.07	4	3.7	NO	0.92
0.07	5	3.7	NO	0.84
0.07	6	3.7	NO	0.78
0.28	2	4.1	NO	0.95
0.28	3	4.1	NO	0.76
0.28	4	4.1	NO	0.67
0.28	5	4.1	NO	0.67
0.28	6	4.1	NO	0.67

Table 4.29 Impact of specific yield on basin performance for loam.

Discussion:

Specific yield is a storage parameter; it denotes the portion of soil porosity available for water intake when the soil is at field capacity, where the water content of the soil was assumed never to fall below field capacity. Hence, increasing the specific yield directly increases the temporary storage available for recharge water in the initially unsaturated zone. In the sandy loam example (case 1), values at 27 and 50 percent of the typical specific yield were tested. Decreasing the specific yield value is equivalent to increasing the initial percent saturation of the soil and essentially models a soil that has not fully drained before a storm event. As the specific yield approached the typical value, fill-up time of the basin increased, yet the drainage time decreased. Higher specific yields in the initially unsaturated zone allow faster removal of the water from the basin, hence increasing the fill-up time. Head build-up, while water is transferred to the initially unsaturated zone, is reduced with increasing specific yields, helping sustain the flow rate out of the basin and within the initially unsaturated zone. This mechanism also improves drainage performance after fill-up. In case 1, a 50 percent decrease in the specific yield caused a 10 percent decrease in the fill-up time and a 10 percent increase in the total drainage time. The impact on the after-fill-up drainage time was even greater.

Soils with low infiltration capacity are not affected by variations in specific yield as much as soils with higher infiltration capacities. Cases 2 and 3 demonstrate this relationship where doubling the specific yield increased the fill-up time by 3 percent for silt loam, whereas the change in the fill-up time was 5 percent for sandy loam. This lower sensitivity of the silt loam to variations in the specific yield may be due to the fact that the conductivity is the major limiting factor in the case of silt loam. The results of case 5 (loam) were almost identical to the results of case 2 (silt loam).

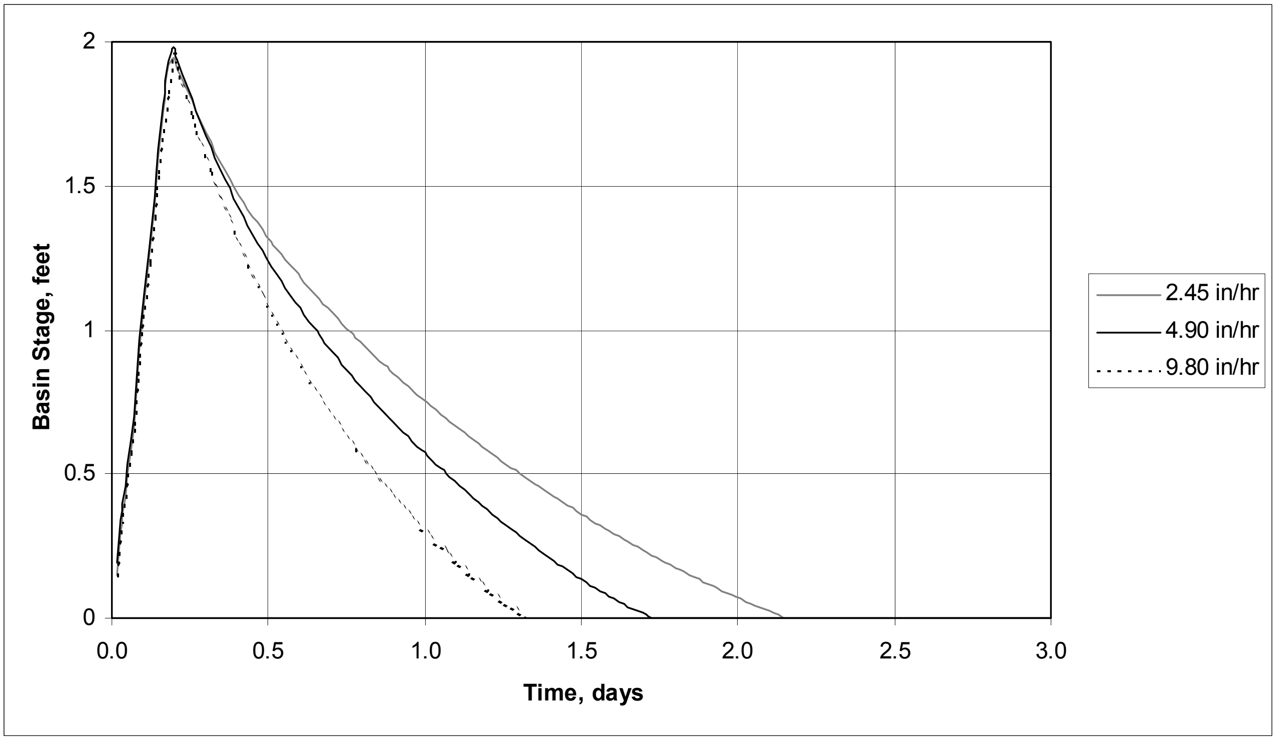
As the thickness of the initially unsaturated zone increased, the impact of specific yield variation on the performance is amplified. In case 4 (sand), doubling the specific yield of the 2-foot-initially unsaturated zone system resulted in a 16 percent increase in the fill-up time, while the response of a configuration with a 6-foot initially unsaturated zone resulted in a 25 percent increase.

Case 6 demonstrates the importance of soil type in specific yield sensitivity analysis. In this case, the soil type was loam (low infiltration capacity), and the response of the system to specific yield variations at different initially unsaturated zone thicknesses was not obvious. Increasing the specific yield from half to twice the original value caused a 10 percent increase in the fill-up time for all initially unsaturated zone thicknesses. In this case it may be concluded that its impact was independent of the thickness of the initially unsaturated zone.

4.9 Basin Stage Plots

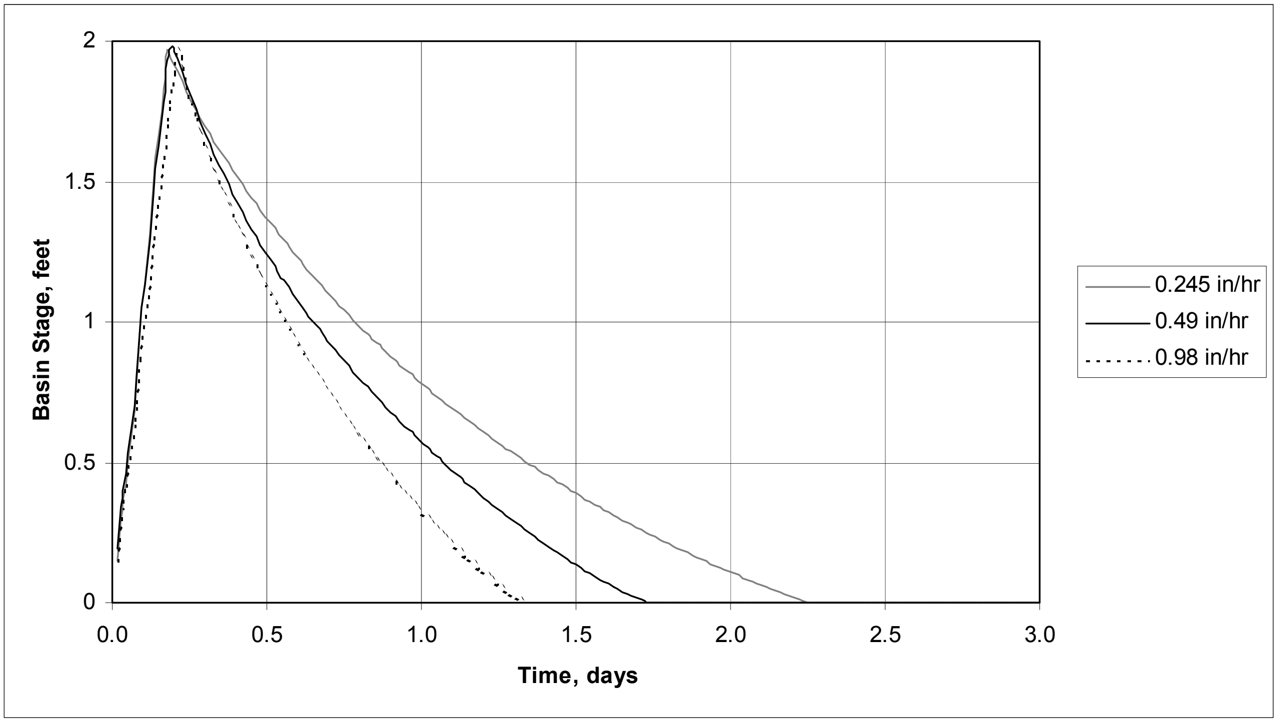
In this section, basin stage versus time plots are provided for variations of major parameters from a base case. Basin stage is the depth of the water in the basin. The base case consists of a shallow basin (2 feet deep) and a moderately thick initially unsaturated zone (4 feet). The groundwater thickness is set to 8 feet in all cases except the plots comparing the impact of groundwater thickness. The soil type is sandy loam. The parameters for which the basin stage was plotted were : (1) horizontal conductivity, (2) vertical conductivity, (3) initially unsaturated zone thickness, (4) groundwater thickness, (5) specific yield, and (6) basin bed conductance.

Plot 4.1 shows the response of the system to horizontal conductivity changes. The saturated horizontal conductivity for sandy loam is 4.90 inches per hour. Included in the plot are 2 other runs, one with half the typical conductivity, the other with twice the typical conductivity. Differences in fill-up times are not visible, but drainage times are significantly different.



Plot 4.1 Impact of horizontal hydraulic conductivity on basin performance.

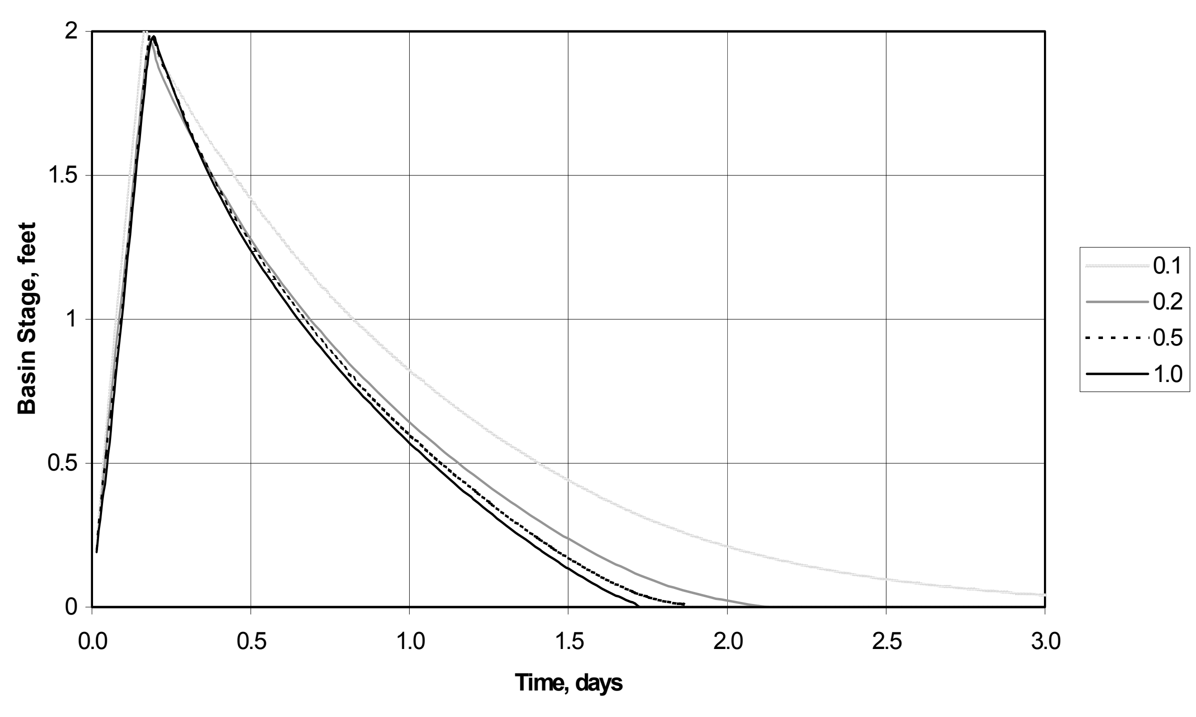
The vertical conductivity was also varied (Plot 4.2) from half to twice the typical value, 0.49 inch per hour. The impact of varying the vertical conductivity was slightly greater.



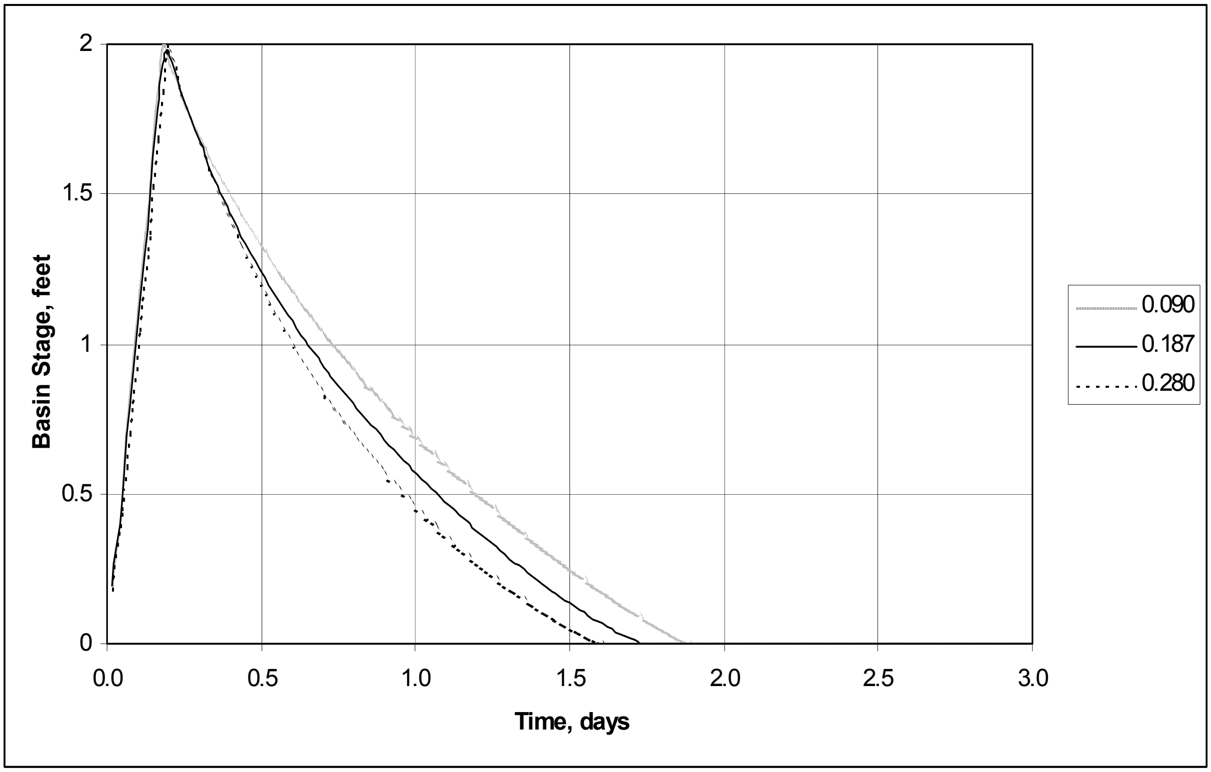
Plot 4.2 Impact of vertical hydraulic conductivity on basin performance.

The typical basin bed conductance is equal to the vertical conductance of the soil in question. As basin bed conductance increases, the fill-up time increases. The drainage capability of the basin is enhanced at higher bed conductivities. Plot 4.3 illustrates the bed conductance variation from 10 percent of the typical value to the typical value. The conductance values on the plot are scaled, 1.0 being equal to the typical bed conductance. There is a limit to the enhancement created by higher bed conductance. At high bed conductance, beyond those depicted in Figure 4.3, the initially unsaturated zone can fill to the point that drainage is impaired.

Plot 4.4 demonstrates the impact of specific yield variations. The specific yield was varied from half the typical value to 1.5 times the typical value. The typical specific yield value for sandy loam is 0.187. While the drainage time decreases due to increased specific yield are obvious, it is harder to notice a change in the fill-up time.

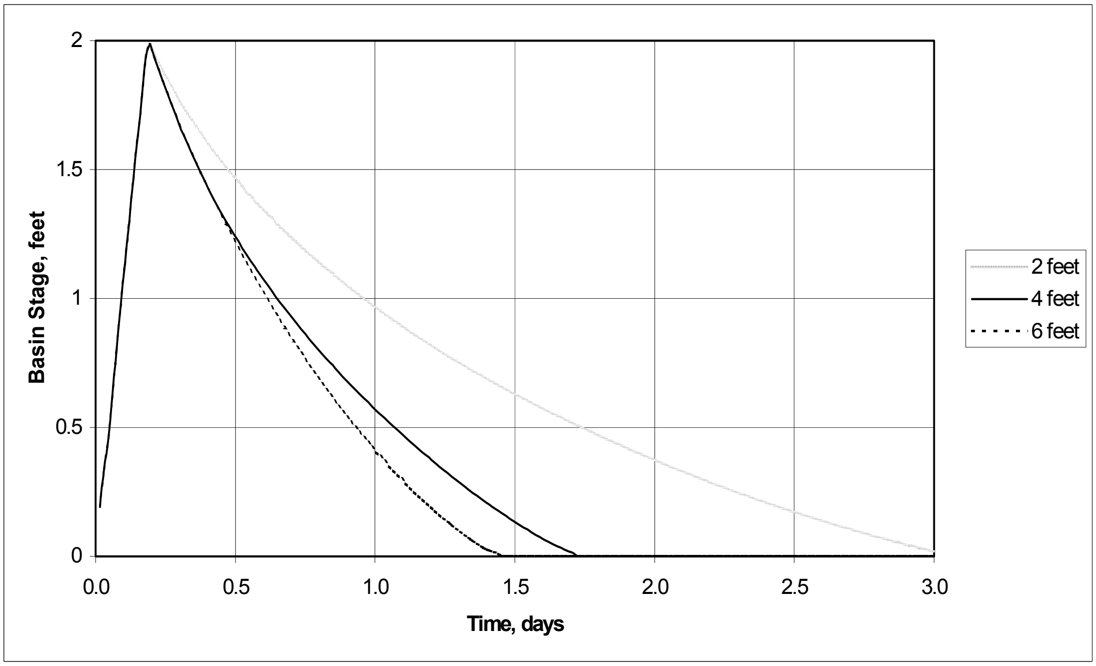


Plot 4.3 Impact of basin bed conductance on basin performance.



Plot 4.4 Impact of specific yield on basin performance.

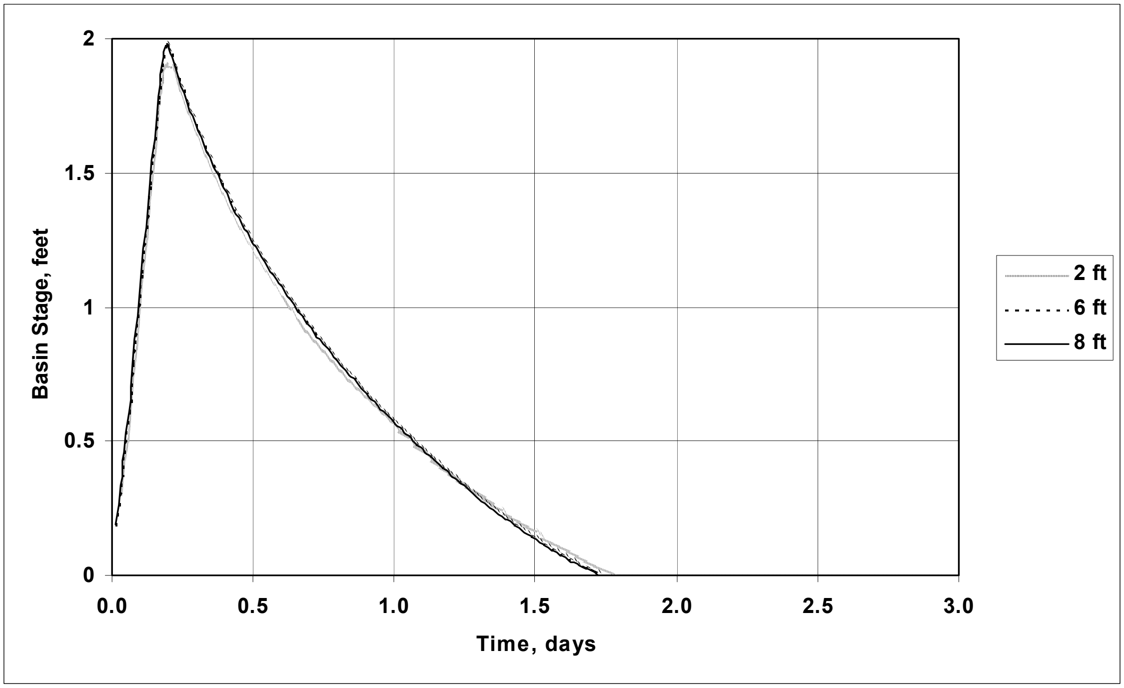
The initially unsaturated zone thicknesses used in the study ranged from 2 feet to 6 feet. Plot 4.5 illustrates this being applied to a sandy loam soil. As the initially unsaturated zone thickness increases, the drainage time decreases. Changes in the fill-up time are very small, mainly due to the medium infiltration capacity of sandy loam.



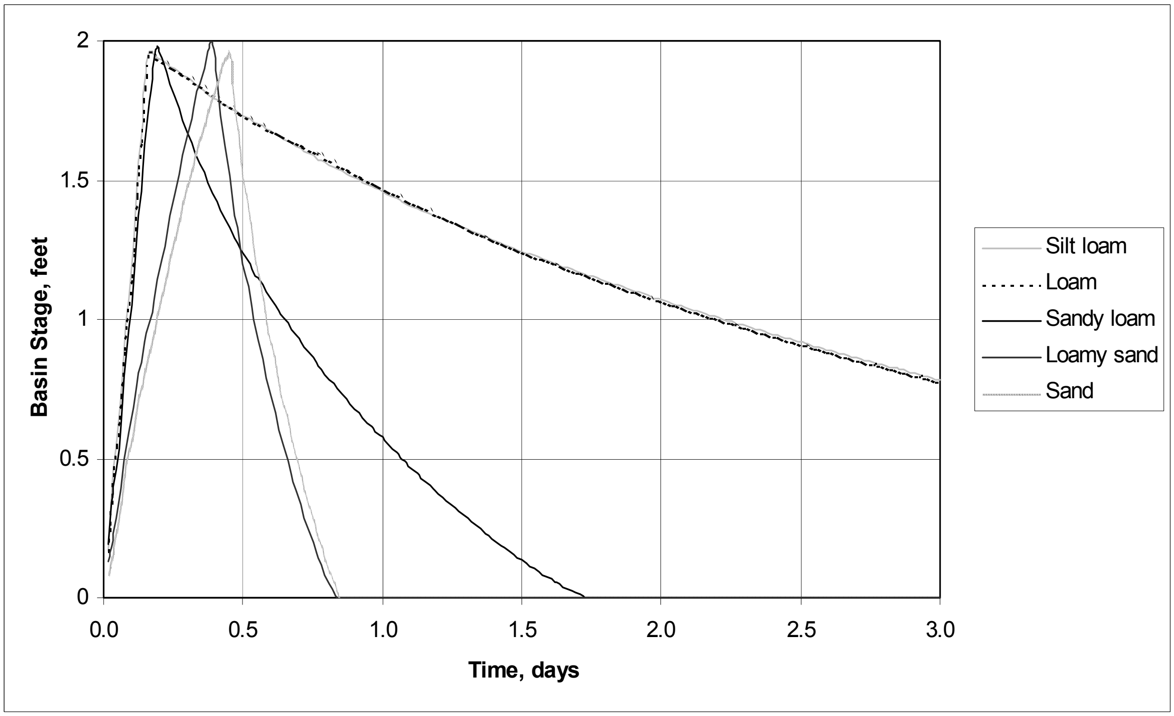
Plot 4.5 Impact of initially unsaturated zone thickness on basin performance.

Plot 4.6 demonstrates the performance of the basin with different groundwater thicknesses. As stated before, the groundwater thickness may play a role in the performance only when it is small. Practically, any thickness greater than 6 feet is the same for the base case, and most others.

The last plot (4.7) illustrates the performance of the same basin for all the soil types investigated in this study. The differences between plots (or runs) were: horizontal conductivity, vertical conductivity, and specific yield. The performance of silt loam and loam are almost identical, while the performances of sand and loamy sand are similar.



Plot 4.6 Impact of groundwater thickness on basin performance.



Plot 4.7 Performance of the base design over different soil types.

4.10 Cascading and Sustainability

In order to evaluate performance over a series of storm events, some simulations were designed to cover a longer time period than the usual 3-day case. The results of these sensitivity analyses were evaluated to determine whether the basin would be able to provide the same drainage/recharge performance over the long term. The question about the amount of actual recharge to groundwater also is difficult to ascertain if the status in the initially unsaturated zone is not known at the end of the first (and following) periods. To answer these questions, several storm events were introduced to the system at 3-day intervals, and outputs were recorded throughout the consecutive runs. This methodology was referred to as cascading. The sensitivity analysis results from previous sections also apply to the cascaded runs, i.e., the earlier a basin drains, the less water content in the initially unsaturated zone or the more standing water at the end of the first run, the less the potential recharge for the next periods. The basic concept idealized herein, is that as long as the water content of the initially unsaturated zone at the end of a period is greater than a threshold (depending on the design life and recharge requirements, aquifer dimensions, etc.), it will impair the performance of the system in the following runs, or storm events. If this happens, the degradation of performance will surely cause basin failure in the long (or perhaps not so long) term due to continuous trend of water accumulation in the initially unsaturated zone. The following is an example of how the cascaded simulations can help identify possible failures.

4.10.1 Case 1

This case demonstrates the significance of the remaining water in the initially unsaturated zone after a usual 3-day run for the sustained performance of the infiltration basin. Ideally, all the infiltrated water should be added to groundwater as recharge before the next periodic storm event occurs. If that cannot be achieved, the drainage capacity of the system will gradually decrease in further events. The two basins and soils in this example are identical; the only difference is the thickness of the saturated zone. Recharge is received by a saturated zone of 1-foot thickness in the first case, and 8 feet in the second. In order to identify long-term performance trends, both systems were simulated for a total of 9 days, or three consecutive runs of 3 days with the application of storm events with the same intensity at the beginning of each 3-day period.

Basin depth: 4 feet

Initially unsaturated zone thickness: 6 feet

Basin dimensions: 40 feet x 20 feet

Rainfall intensity: 0.1 inch per hour

Soil type: Sandy loam

Basin bed conductance: 4 times the vertical initially unsaturated zone conductance.

Results:

Tables 5.30, 5.31, and 5.32 summarize the fill-up / drainage characteristics of the basins for days 0-3, 3-6, and 6-9 respectively. Table 4.33 provides water balances for the basin in terms of incoming water and seeped water.

Plot 4.8 is the basin stage plot for the two basins over the 9-day simulation period.

Saturated Thickness (feet)	Fill-up Time (hours)	Drained?	Drainage Time (hrs)
1	10.4	YES	69.7
8	10.4	YES	62.5

Table 4.30 Basin performance in the first 3-day period.

Sat. Thickness (ft)	Fill-Up Time (hrs)	Drained?	Drain Time (hrs)	Standing Water (ft)
1	9.4	NO	-	0.39
8	10.0	YES	70.4	-

Table 4.31 Basin performance in the second 3-day period.

Saturated Thickness (feet)	Fill-up Time (hours)	Drained?	Standing Water (ft)
1	8.2	NO	0.59
8	9.6	NO	0.05

Table 4.32 Basin performance in the third 3-day period.

(feet)	Period 1		Period 2		Period 3	
Saturated Thick	Intake (cf)	Seepage (cf)	Intake (cf)	Seepage (cf)	Intake (cf)	Seep (cf)
1	4800	4800	4300	4050	3750	3650
8	4800	4800	4650	4650	4450	4400

Table 4.33 Water balances for the basin.

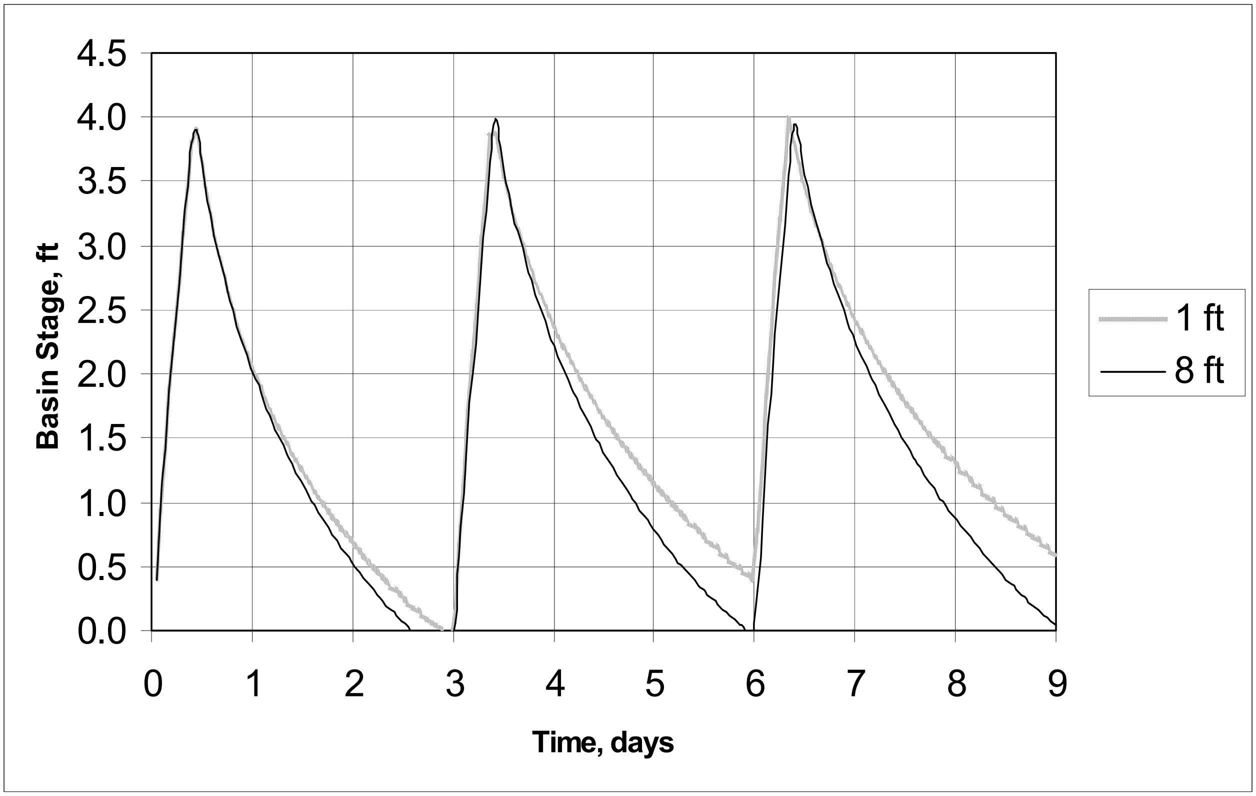
Discussion:

In cases where the infiltrated water cannot leave the initially unsaturated zone within the design time frame, the increased water content of the initially unsaturated zone impairs infiltration performance during consecutive storm events. This water build-up impacts both the fill-up times and drainage times. When precipitation starts before the time the basin returns to pre-storm conditions, the seepage rates from the basin reduce rapidly, resulting in shorter fill-up times. Since the water input to the system in this study was shut off when the basin fills up, shorter fill-up times also mean lower water intake for possible recharge. Different basin/soil configurations with the same fill-up time during a single-period (3 days) run will have different fill-up times in consecutive runs due to water build-up in the initially unsaturated zone. In that sense, one can introduce the “secondary fill-up time” as another basin performance parameter. The secondary and tertiary drainage times, however, are even more sensitive to the water content of the initially unsaturated zone. The differences between fill-up times are not apparent in basin stage plots, where as the drainage times / drying points can be easily compared for that case.

The basin with a 1-foot saturated zone failed to drain at the end of the second 3-day run. The total water intake decreased at every 3-day period, with each succeeding event. In the water balance analysis infiltrated water amounts also decreased, but the values of these two parameters showed a converging pattern towards each other. It is possible that this trend will continue until both values are equal, or, in other words, the basin is capable of draining the precipitation. This stabilization point, however, is far from the successful operation point, with the basin probably being wet at all times. At this point, the existence of an initially unsaturated zone between the basin bed and the water table is doubtful. In this case, the extremely thin saturated zone in this case caused major performance degradation due to low water removal rates from the initially unsaturated zone. The time required to drain the basin completely after fill-up also increased in consecutive runs.

The second configuration provided greater storage/removal capacity below the water table. However, it still was not able to sustain the performance in the first 3 days for long periods, and failed to drain completely at the end of the third run (9th day). The performance degradation was of lower magnitude. Reductions in the amount of water intake were less than 5 percent between runs, and fill-up times decreased by less than 30 minutes in each case.

The ideal sustainability criterion would be zero decrease in fill-up times, and zero increase in the drainage times in consecutive storm events. For practical purposes, one can define an upper tolerance limit for the decreases / increases mentioned, so that the basin does not fail within its design life.



Plot 4.8 Impact of groundwater thickness on basin performance (3 cascaded runs)

5 CONCLUSIONS

Artificial recharge through infiltration basins can be modeled as a water transport process with three stages. The stages correspond to three water storage and flow media: (1) the infiltration basin, (2) the initially unsaturated zone, and (3) the saturated zone. The basin is the initial storage component for the incoming water (precipitation, runoff). The initially unsaturated zone provides temporary storage while mediating flow to the saturated zone. Once the water reaches the saturated zone, recharge is accomplished by definition; but the efficiency and extent of recharge depends on the redistribution within the saturated zone.

This study demonstrates that the input side of the system cannot be isolated from the other stages involved in recharge. Even when constant-rate inflows are applied to the basin, the fill-up is not a linear process (i.e., doubling the rainfall intensity does not halve the fill-up time). Linearity can only be achieved by blocking the output from the basin into the initially unsaturated zone, which is clogging, and does not apply to normal working conditions. These data suggest the accumulation of water in the basin is governed by a dynamic balance (and not equilibrium) between the water input and water removal processes. As the water builds up within the basin, the tendency to infiltrate increases. Infiltration occurs through the basin bed, and the counter-active force that balances the driving force is the water content of the soil surrounding the basin bed, or the hydraulic heads in that same region. Given the geometry (i.e., basin bed thickness), the infiltration rate is determined by the difference between these driving forces and the capability of the basin bed to transport water. In simpler terms, the two factors that determine the infiltration rate are: (1) hydraulic head difference between the basin and its surroundings, and (2) the conductance of the basin bed. Even if the hydraulic head in the surrounding soil can be kept constant by removing the water immediately to lower/further soils, the infiltration rate cannot be constant throughout the fill-up and drainage. The parameters that affect this first stage of transport can be grouped as: (1) rainfall characteristics, (2) basin configuration, and (3) subsurface conditions.

The water input to the basin is a function of rainfall intensity, basin area, and the associated drainage area. Given the ratio between basin area and drainage area, the water input rate is directly proportional to rainfall intensity. Higher rainfall intensities result in faster head build-up in the basin, and higher infiltration rates during early seepage. While higher infiltration rates may be expected to increase the total amount of seepage, or the amount of water entering the basin/soil system before fill-up occurs, this was not observed during the study. At rainfall intensities (around 0.1 inch per hour) and the area ratio (0.01453) used in the study, the water input rate was much higher than the infiltration capacity of the soil types tested (sand, loamy sand, sandy loam, loam, silt loam); therefore the result of increasing the rainfall intensities was reduced fill-up times. Since the water input to the basin was shut off after fill-up, the total amount of water intake (and finally recharge) was lower at higher rainfall intensities.

The geometry of the basin may impact the infiltration performance by providing different contact areas for infiltration. In this study, basins were allowed to infiltrate through their side walls, and geometries with larger side wall areas for the same volume (i.e., rectangular instead of square) demonstrated higher infiltration capability by increasing the fill-up times.

This study also concludes that the conductance of the basin bed is a very important parameter in determining infiltration rates. As the conductance increases up to the magnitude of vertical conductance of the underlying soil, basin performance is improved; greater amounts of water are allowed into (and through) the basin before fill-up, and drainage of the basin is accomplished faster. Reducing the basin bed conductance can simulate the impact of clogging on basin performance. The response of the system to any decrease in bed conductance was in all cases observed to be performance reductions in the form of faster fill-up and slower drainage. While no-flow, or complete clogging requires the conductance to be set to zero, dropping the bed conductance to 10 percent of the original values typically increased the drainage time by several factors, and rendered the basin practically useless.

The subsurface conditions affecting infiltration basin performance are the parameters that affect (1) the water storage capacity of the soil, and (2) the rates of water transport in the soil. These parameters are either soil properties (hydraulic conductivity, specific yield, storativity) or aquifer geometry (thicknesses of the saturated and initially unsaturated zones). The water storage capacity of the soil beneath (and around) the infiltration basin is increased by higher specific yields, thicker initially unsaturated and saturated zones. The water transport rates are higher within soils with higher hydraulic conductivities.

While recharge is the ultimate goal of the infiltration basin design, the performance of the basin as defined by the regulatory approach is strongly dependent on the temporary storage, or the storage/redistribution in the initially unsaturated zone. The water transport rate and the water storage capacity of the initially unsaturated zone play important roles in all stages of the recharge process. Initially unsaturated zones with high hydraulic conductivities (in both horizontal and vertical directions) allow faster removal of water away from the basin, hence increasing fill-up times and the total water input to the system, which is the maximum possible recharge amount at the same time. Soils with higher specific yields exhibited higher infiltration capability; they were able to temporarily store more water at given volumes, consequently increasing water seepage through the basin and reducing drainage times. Thicker initially unsaturated zones favored infiltration, as they provided greater storage and water removal capability.

The saturated zone, which is the final destination of the incoming water, affects recharge potential and also infiltration capability of the system. The thickness of the saturated zone, along with the hydraulic conductivity, determines the efficiency of water redistribution after it enters the saturated zone. Redistribution is mainly in the horizontal direction, and the variations in the horizontal hydraulic conductivity of the saturated zone have greater impacts on system performance than the variations in the vertical hydraulic conductivity. Thicker saturated zones allow more water removal in the horizontal direction, and improve basin performance. However, this benefit does not increase infinitely. In any type of soil, extra-saturated thickness greater than 6 – 8 feet does not improve infiltration performance any further. The storativity in the saturated zone was found to be insignificant to infiltration performance.

The three-staged recharge process is a dynamically linked process. The rate of the process is limited by the slowest stage. This study demonstrates that there are numerous parameters that limit overall infiltration basin performance. Clogging is a good example: the superior subsurface conditions that favor further removal of water are under-utilized, since the basin can not provide the initially unsaturated zone with high amounts of water due to low bed conductance. In such a case, the performance of the system is most sensitive to variations of the parameter(s) related to the limiting stage. Doubling the basin bed conductance will create a significant impact, where as doubling the conductivity of the initially unsaturated zone will not make a large difference in basin performance. This limiting-factor issue makes it difficult to identify the relative importance of the parameters mentioned on basin performance. Increasing the specific yield of a test setup at very low hydraulic conductivities will not improve the performance significantly. Other types of importance shadowing are also possible. The role of the saturated zone in the infiltration process can be underestimated if the observation is done on a setup with a very thick initially unsaturated zone. This exclusion severs the interaction between the saturated zone and the basin, at least for the initial stages of the process (i.e., fill-up). To overcome these difficulties in the sensitivity analysis, the experiments had to cover a wide range of subsurface conditions. Table 6.1 demonstrates the typical relevance of the parameters tested to the basin performance.

Once the infiltration basin drains completely, the parameters related to the water input side of the system (i.e., basin geometry, basin bed conductance) lose their impact on the fate of the water. From then on the dominant process is lowering of the head gradients that built up in the soil. The groundwater mound keeps enlarging horizontally, and starts losing its height above the water table. Depending on the time between storm events, and the subsurface parameters, the water may totally leave the initially unsaturated zone as recharge, or result in a moisture content in the initially unsaturated zone that is higher than the pre-storm conditions. If the latter occurs, the infiltration capability of the system is degraded. The least important of the problems this might cause is that the amount of recharge in long term will be lower than design goals. If system hydraulics is not improved, the water build-up will continue, and it will reduce fill-up times (if same kind of storm events are applied) and increase drainage times (for the same amounts of water intake) at every storm event. Ultimately, the initially unsaturated zone will remain saturated, and the basin bottom will no longer be above the water table, significantly reducing the effectiveness of the basin for infiltration. How fast this process will occur depends on the residual water in the initially unsaturated zone per storm, or the incremental increase of the water content of the initially unsaturated zone.

Importance In Basin Performance			
Parameter	**None**	**Low to Medium**	**Medium to High**
Rainfall intensity			X
Basin geometry		X	
Basin bed conductance			X
Initially unsaturated thickness			X
Saturated thickness		X	
Specific yield		X	
Storativity	X		
In the initially unsaturated zone:			
Horizontal conductivity			X
Vertical conductivity			X
In the saturated zone:			
Horizontal conductivity		X	
Vertical conductivity		X	

Table 6.1. Relative importance of parameters on infiltration basin performance

6 BIBLIOGRAPHY

Asano, T. 1985. *Artificial Recharge of Groundwater.* Butterworth Publishers, Stoneham, MA.

Cochran, R. May 1981. "Artificial recharge and its potential for Oklahoma's Ogallala Aquifer". *Oklahoma Water Resources Board*, Oklahoma City, OK.

Department of Environmental Protection / Massachusetts Office of Coastal Zone Management. March 1997. *Stormwater Management Volume One: Stormwater Policy Handbook.* Massachusetts.

Department of Environmental Protection / Massachusetts Office of Coastal Zone Management. March 1997. *Stormwater Management Volume Two: Stormwater Technical Handbook.* Massachusetts.

Dingman, S. Lawrence. 1994. *Physical Hydrology.* Prentice-Hall, Inc., New Jersey.

Cohen, P., O.L. Franke, and B.L. Foxworthy. 1968. “An atlas of Long Island’s water resources”. *New York Water Resources Comission Bulletin* 62. Albany, NY.

Dvoracek, M.J., and Peterson, S.H. 1971. "Artificial recharge in water resources management". *Journal of Irrigation and Drainage Division, American Society of Civil Engineers*, Vol. 97, No. IR2, pp. 210 - 232.

Horton, R.E. 1933. “The role of infiltration in the hydrologic cycle”. *American Geophysical Union Transactions* 14:446-460.

Huisman, L., and Olsthoorn, T.N. 1983. *Artificial Groundwater Recharge.* Pitman Advanced Publishing Program, Boston, MA.

Minnesota Pollution Control Agency, Division of Water Quality. 1989. *Protecting Water Quality in Urban Areas – Best Management Practices for Minnesota*. Minneapolis, MN.

Motts, Ward S. January 1983. *Feasibility of Increasing Water Supplies and Preventing Environmental Damage by Artificial Recharge in Massachusetts.* University of Massachusetts, Amherst, MA.

O'Hare, Margaret P., Deborah M. F., Paris A. H., and Larry W. C. 1986. *Artificial Recharge of Groundwater : Status and Potential in the Contiguous United States.* Lewis Publishers, Inc., Chelsea, MI.

Pioneer Valley Planning Commission. November 1996. *Artificial Recharge: Evaluation and Guidance to Municipalities.*

Pratt, Joel M., and Coler, Robert A. March 1979. *Ecological Effects of Urban Stormwater Runoff on Benthic Macroinvertebrates inhabiting the Green River, Massachusetts.* Water Resources Research Center, University of Massachusetts, Amherst, MA.

Rushton, K. R., and Redshaw S. C. 1979. *Seepage and Groundwater Flow – numerical analysis by analog and digital methods.* John Wiley and Sons, New York, NY.

Schueler, Thomas R., Peter Kimble, and Maureen Heraty. 1992. *A Current Assessment of Urban Best Management Practices.* Metropolitan Washington Council of Governments, Washington, DC.

Schueler, Thomas R. 1987. *Controlling Urban Runoff: A practical Manual for Planning and Designing Urban BMPs.* Metropolitan Washington Council of Governments, Washington, DC.

Todd, D.K. 1980. *Groundwater Hydrology.* 2nd ed., Wiley Publishing, New York, NY.

Toups, J.M. March 1974. "Water Quality and Other Aspects of Ground Water Recharge in Southern California". *Journal American Water Works Association*, pp. 149 - 151.