MIKE SHE Code Verification and Validation for RFETS Site-wide Water Balance Model

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1.0 INTRODUCTION

After review of a number of computer codes, MIKE SHE (developed by the DHI-Water and Environment [DHI]) was selected to build a Site-wide Water Balance (SWWB) Model of the Rocky Flats Environmental Technology Site (RFETS or Site). To establish the suitability of the code and its ability to simulate the hydrologic processes that were identified in the conceptual model, a code verification and validation study was conducted. This report will summarizes code verification and validation testing of MIKE SHE code. These tests were designed to evaluate its performance and appropriateness for application at RFETS. This report is prepared by Dr. Tissa H. Illangasekare at the Colorado School of Mines in Golden, Colorado with the assistance of Mr. Robert Prucha of RMC Consultants. Dr. Torsten Jacobsen and Mr. Douglas Graham of DHI were responsible for the implementation of the validation simulations required in the testing.

In the development and application of the SWWB model, generally accepted methods and protocols are used. These include verification of the code, establishing the validity of the code and "*calibrating*" the model developed using the code for site-specific conditions. To avoid confusion with the terminology, appropriate working definitions are provided in this report. The focus of this report is on the verification and validation of the code. As a part of this effort, the equations/numerical methods that are used in the design of MIKE SHE code will be reviewed to evaluate their ability and appropriateness to represent the primary hydrological processes that are relevant to conditions at RFETS. The code verification is done by evaluating the code's ability to simulate setups that represent Site conditions. With proper assumptions and simplifications these can be solved using analytical methods (or closed form analytical solutions). As such analytical solutions do not exist for all the interactive processes between different components of the code, a validation methodology that rely on semi-quantitative evaluation of results from a set of test problems is presented. The code is also bench marked against other existing codes.

2.0 TERMINOLOGY

A "*model"* is a simplified representation of a physical *system*. A hydrologic model is always a simplified representation as it is not possible to reproduce the exact behavior of hydrologic systems that are very complex by their nature. The goal in developing a model is to use it as a tool to make predictions through "*simulations"* on how the modeled system is expected to behave when different *"excitations"* are applied on the system.
In this application, system refers to the hydrologic system whose components include the natural streams, canals, ground surface on which overland flow occurs and the unsaturated zone (UZ) (vadose zone) and saturated zone (SZ) of the subsurface. These components are in continuous dynamic interaction requiring the model to capture and simulate the integrated behavior the system.

The primary goal of the study at RFETS is to develop a water balance management tool to evaluate how the local hydrologic cycle is expected to change from current conditions as a result of various scenarios that will define the final Site configuration. The model in this case becomes a decision making tool that will be used to simulate the system response to different management scenarios. These scenarios will affect the model excitations and/or change the model parameters. The reliability and accuracy of the model predictions rely on how accurately the model captures the underlying natural processes of the hydrologic system. The term *"validation"* is widely used to define this process of testing models. However, because of the inadequacy of data in different spatial and chronological scales needed to understand, quantify and characterize all processes to be represented in hydrologic models, the question has been raised on whether such models could be validated. Oreskes and Beltiz (2001) states, "*validation is still widely used in ways that asserts or imply assurance that the model accurately reflects the underlying natural process, and therefore provides a reliable basis for decision-making*". The same authors, referring to reasoning by Konikow and Bredehoeft, 1992 and Oreskes et al, 1994, state that the usage of the term validation is misleading as models can not be validated. However, in the general modeling context as well as for groundwater modeling, definitions for model verification and validation have been provided (Schlesinger et al., 1979; Konikow, 1978; Tsang, 1991 and Anderson and Woessner, 1992). These definitions are used in a sequence of steps in hydrological model applications that is often referred to as a modeling protocol (Refsgaard, 1996). With the expectation that such a protocol will be used in the SWWB model development and application, a terminology for verification and validation is provided. These terms are largely similar to those proposed in the EPA guidelines (EPA, 1997), and with Anderson and Woessner (1991).

To introduce the terminology specific to integrated hydrologic models, it is necessary to provide clear and consistent definitions for *code* and *model* that will be used in this report. "*A code is a set of programming statements that solves the mathematical equations describing the flow processes in different components of the hydrologic system"*. In most hydrologic codes designed to simulate spatially- and chronologicallydistributed processes, the mathematical equations are first converted to a set of algebraic equations (linear or non-linear) using numerical methods that rely on spatial discretization of the solution domain. The most commonly-used numerical methods are finite differences and finite elements. Code by its definition is generic in the sense that it can be applied to any hydrologic system whose conceptual model requires the simulation of flow processes that are represented in the code. Refsgaard (1996) defines conceptual model as *"verbal descriptions, equations, governing relationships, or 'natural laws' that purport to describe reality."* A "*model*" on the other hand is designed for specific site conditions using a generic code. The specificity for a site comes from the incorporation of parameters of the site and its boundary conditions specific to the site. Hence, a model simulates the response of the hydrologic system to various excitations or stresses that are applied at the site. Figure 1 schematically shows how a code is used to develop a model. It should be noted that in the case of an integrated hydrologic code such as MIKE SHE, the code is developed by integrating (or coupling) independent modules that solve the governing mathematical equations of the primary components of the hydrologic systems (e.g. surface flow system, SZ, UZ, etc.).

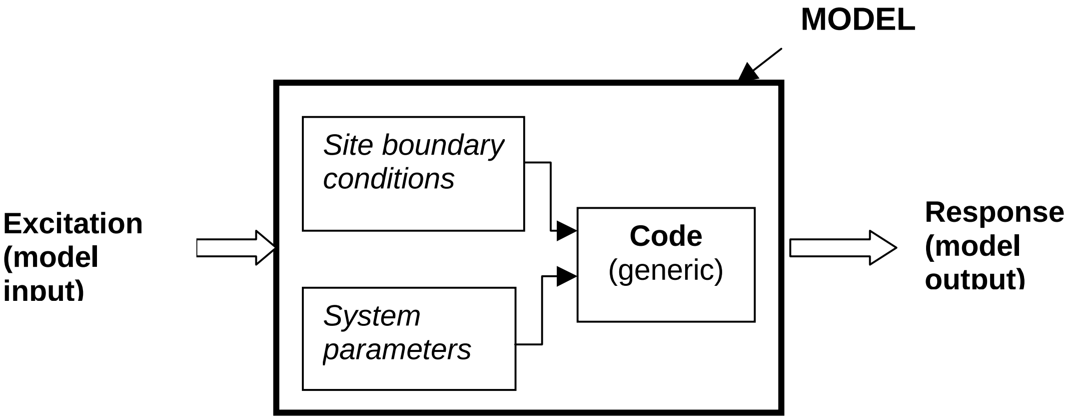


Figure 1: Definitions of code and model

The following working definitions are provided for code verification and code validation. This report will only address code verification and code validation. *"Model validation"* will not be considered, but will be performed as part of the RFETS SWWB Integrated Modeling effort using actual Site data. The overall approach that will be used in the numerical code validation is summarized in Figure 2.

(1) Code verification:

The process designed to establish that a generic code accurately solves the mathematical equations that describe the basic processes of the physical system. The standard approach of verification uses the code to simulate conditions for with simplifying assumptions (e.g., homogeneous parameters and simple geometry) are made

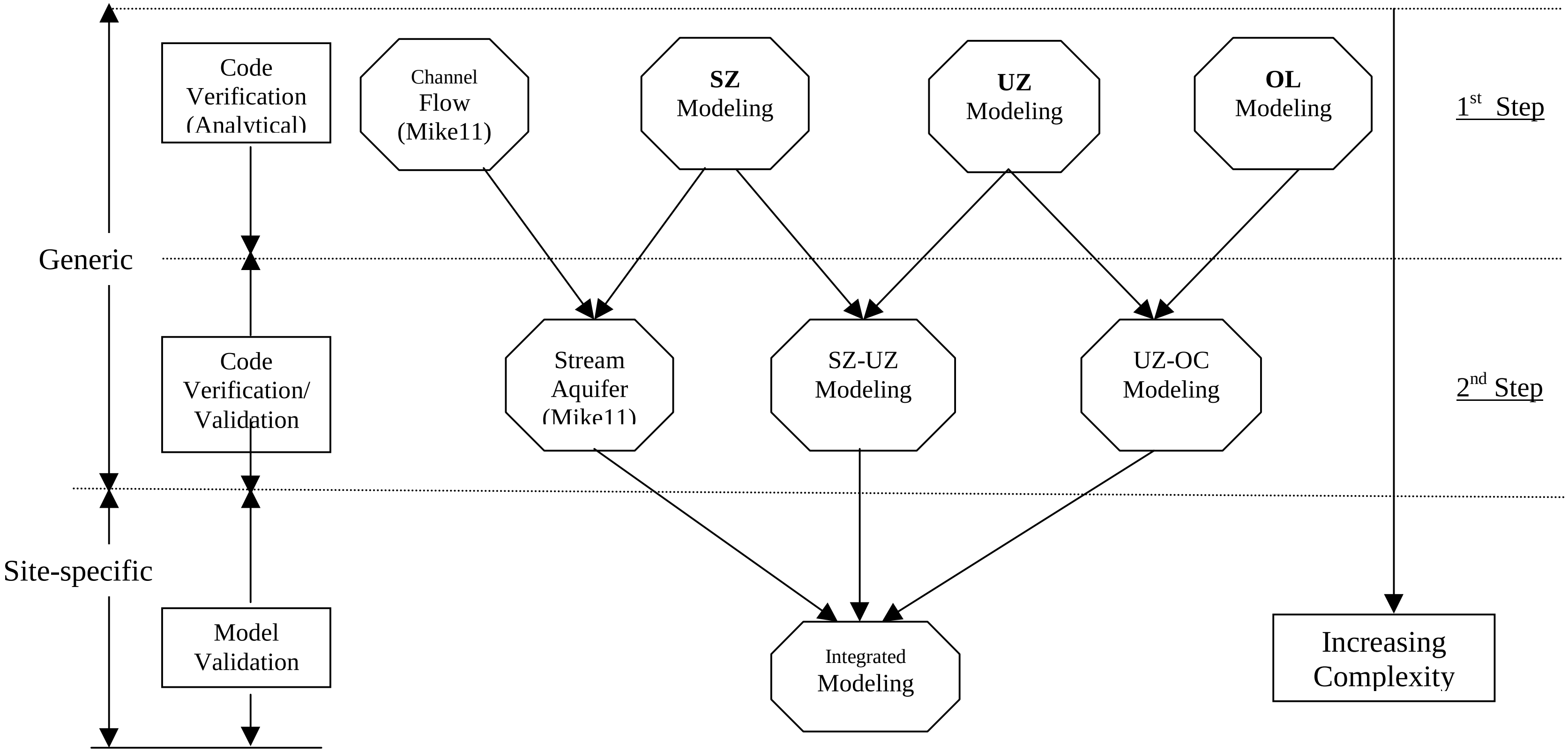


Figure 2. Code Verification and Validation Approach

Type of Verification

MIKE SHE Hydrologic Process/Processes

Description:**SZ** -- Saturated Zone Flow **UZ** -- Unsaturated Zone Flow **OL** – Overland to obtain closed form analytical solutions to the equations of the mathematical model. This approach does not evaluate whether the mathematical equations used in the code best represent the physical process, as the code and the closed form analytical solutions solve the same equations. It only checks whether the algorithms used to convert the mathematical equations to algebraic equations are solved with an acceptable accuracy and any coding errors (or programming “bugs”) are introduced in the process.

(2) Validation of integrated code:

In this study, validation of integrated code is defined as the process of establishing whether the different components of the code are coupled properly to simulate the dynamic interactions accurately to represent the integrated behavior of the hydrologic system. For all possible cases of interaction between different modules of the code simulating the primary components if the hydrologic system, closed form analytical solutions do not exist. Ideally, the integrated code could be validated using either comprehensive field data or controlled laboratory data sets. In the absence of such data for validation of a generic code for its general applicability for all possible and anticipated field conditions, a code validation approach needs to be proposed.

3.0 MIKE SHE CODE REVIEW

The selection of MIKESHE, as the most appropriate code for the RFETS SWWB Integrated Modeling effort, is presented in the Model Code and Scenario Selection Report (Kaiser Hill, 2001). In this section, a review of equations/numerical methods used in MIKE SHE is presented evaluate whether it uses appropriate methods to represent the primary hydrological processes and the conditions of the Site.

According to MIKE SHE user's manual, the code has been designed with modular programming structure comprising of six process-oriented components, each describing major flow processes of the hydrologic cycle. Five of them are listed as: (1) Interception/evapotranspiration (ET); (2) Overland and channel flow (OC); (3) UZ; (4) Saturated zone (SZ); and (5) Snow melt.

This review is for four primary components of the code that are central to the proposed SWWB model. These include: (1) overland flow, (2) channel flow; (3) UZ of aquifer; and (4) SZ of aquifer. Where appropriate, the methods used in coupling of some of these components are also reviewed and commented on.

3.1 Overland Flow

The overland flow module is based on a kinematic wave approximation of the Saint Venant Equation. This equation, written for a two dimensional plane (x-y), fully describes the overland flow. Kinamatic wave approximation of Saint Venant Equation results in expressions that relate the flow velocities to depth of flow and ground surface elevation. Strickler coefficients defined for both x and y directions over the flow plane become the model input parameters.

Kinematic approximation is commonly used in the modeling of overland flow for its ability to simplify the input parameters. Complete solution of Saint Venant Equation without simplifying assumptions will need data for characterization processes that are not readily available. Use of a single parameter (Strickler coefficient) to characterize overland flow simplifies the solution of the overland flow processes at RFETS. These coefficients can be used as calibration parameters.

The simplified flow equations are solved using the finite difference method. This is an acceptable solution method that is used in the solution of flow equations. As an implicit method is used, the solution is unconditionally stable, thus allowing for the selection of any spatial and time discretization. However, as the relation between discharge and depth of flow is non-linear, second order terms in the Taylor series (a higher order term in the finite difference approximation of the first derivative that is generally truncated) are included for the correction of water levels. The method as used may produce internal mass balance errors. The methodology that is used to avoid these errors seem to place conditions for the selection of Δx, Δy and Δt. Also, in some cases the initially-calculated outflow has to be reduced by a factor of 0-1. The length of simulation time step is automatically reduced, when rapid changes occur in rainfall. The time stepping procedure prevents the solution from becoming unstable. The user manual presents the algorithm that is used to couple the overland flow and the SZ. Under normal conditions, the overland flow and the SZ are coupled through the UZ. That is, the depth of flow computed by the overland flow model is used as a boundary condition in the UZ model. The UZ equation is solved to provide the time-varying soil water distribution and compute the rate of infiltration that produce recharge to the SZ. In situations where the UZ from the ground surface to the water table becomes fully-saturated, MIKE SHE disables the UZ calculations. This situation can occur at RFETS close to the streams and at locations where the water table is shallow. Under these conditions, when there is ponded water on the ground surface, the vertical hydraulic conductivity of the upper layer of the SZ is used to estimate the recharge rate (application of Darcy's law using the saturated hydraulic conductivity and the gradient of head between the ground surface and the ground water table). In the RFETS application, caution should be exercised in selecting the appropriate hydraulic conductivity as the value based on the top layer of the SZ may not be representative of the conditions of the soil close to the ground surface. The manual suggests the use of a leakage coefficient that could be determined during calibration. If this option is used, it is important to check whether these leakage coefficients are compatible with the condition of the soil (soil type, macropores, etc.).

In summary, MIKE SHE uses generally accepted mathematical representation of the flow processes and numerical solution methods for the modeling of the overland flow. Attention should be given when the UZ become fully-saturated to determine what parameters need to be used to describe the recharge process to the ground surface and affects overland flow (such as near streams and seeps).

3.2 Channel Flow

The original channel flow module of MIKE SHE adopts the diffusion approximation of the Saint Venant equation. The MIKE SHE version that is used in the REFTS water balance model contains the river module MIKE 11 HD that has all the capabilities of the original module as well as additional features that allow for higher order fully-dynamic wave approximation of the Saint Venanat equation. MIKE 11 HD allows for the inclusion of a suite of hydraulic structures and has the ability to simulate flood plains. This version also allows for the full dynamic coupling of the surface and subsurface processes. All these features make it possible to use MIKE SHE to simulate the surface flow component at RFETS. In this section we will review the methods used in MIKE SHE to couple the channel flow to other surface flow components and the subsurface.

3.2.1 *Lateral inflow into river*

At many locations along the main flow channels in REFTS, the overland flow will supply lateral inflow to the stream network. The code estimates the lateral flow to a segment of the river using thewater level of the grid cell adjacent to the river and the river bank elevations described by the river section.

3.2.2 Surface water and aquifer exchange

Two options for water exchange between the surface water and aquifer are considered: (1) river-aquifer exchange where the river is considered as a line source and (2) an area-inundation flood plain approach used for wide rivers (flood plains), lakes etc. Both these conditions exist at REFTS.

The river-aquifer flow is calculated using a conductance and the head difference between the river and the aquifer. This approach is similar to that is used in the river module of MODFLOW. Three options are available for estimating the conductance. The first option (option A) assumes that there is no clogging layer at the river bottom and the flow resistance only comes from the soil in the SZ. In the second option (option B), the flow resistance in a clogging layer and the underlying aquifer are considered. The third option (option C) allows for the flow resistance only in the clogging layer. At RFETS, either options B or C could be used. In using options A and B, it will be necessary to use the hydraulic conductivity of the soil in the SZ. If grid refinement is not performed close to the river, the saturated conductivity (estimated during calibration) of the underlying cell should not be used as the river exchange will be controlled by a hydraulic conductivity local to the river. For the options B and C where a clogging layer is assumed, its hydraulic conductivity should be determined during calibration. In most practical situations, data for the leakage coefficient that represents the permeability of the river lining does not exist and hence should be treated as a calibration parameter.

To determine the infiltration from flood plains, the user needs to delineate areas that may be flooded. The locations that have been identified as inundation grid points gets flooded when the water levels are above the ground surface. The exchange rate is calculated using a Darcy's law approximation similar to what was adopted to estimate recharge in overland flow module. The comments that were made with respect to the proper use and selection of the parameters in the overland flow-SZ coupling are also relevant in this case.

3.3 Unsaturated zone

The UZ processes play a critical role at RFETS because it couples the surface flow system to the SZ. Even though the UZ does not store significant volume of water, it acts as a conduit for water flow. The dynamics of how the water table responds to precipitation, evaporation, and surface flow depends on the UZ flow and storage processes. As the flow in the UZ is primarily vertical, MIKE SHE uses the one-dimensional unsaturated flow equation (Richard's Equation). Accurate solution of this equation to simulate unsaturated flow in response to short duration precipitation events requires the use of small computational time steps. As this non-linear partial differential equation in some cases has to be solved at all grid cells, the UZ module may become most computing intensive component of MIKE SHE. The code offers a computationally-efficient option that provides a simplified solution to the Richard's equation. In this simplified formulation, the capillary (or tension) terms are neglected thus assuming only gravitational forces control flow. This may have implications on the accuracy of the model in simulating semi-arid zone conditions that exists at REFETS.

The input parameters needed in the solution of Richard's equation are: (1) soil moisture retention function (capillary pressure versus water content); and (2) unsaturated hydraulic conductivity function (partially saturated hydraulic conductivity versus water content). In most models of unsaturated flow Brooks-Corey (1964) and/or Van Genuchten (1980) models in combination with pore network model by Burdine (1953) or Mualem (1976) are used to provide these inputs. The fitting parameters of the Brooks-Corey or Van Genuchten models are used with Burdine or Mulalem models to obtain the unsaturated hydraulic conductivity functions. MIKE SHE uses similar functional relationships as Burdine (1953) or Mualem (1976), but a parameter *n* that defines this relationship has to be estimated during calibration. The retention function is provided independently in the form of table (interpolated using cubic splines). As the parameter *n* in MIKE SHE is not related to the retention function, the calibrated *n* may be incompatible with the retention function of the soil (during the progress of the study, MIKE SHE was updated to include tabular values for the effective conductivity relationships). MIKE SHE can only handle monatomic retention functions that will not allow for the modeling of hysteresis.

MIKE SHE uses a fully-implicit finite difference formulation to solve the Richard's equation. This technique provides stable solutions that converge. Two types of boundary conditions at the soil surface can be simulated: (1) constant flux; and (2) ponded water. The transition from one type of boundary condition to the other can also be simulated. These conditions exist at RFETS. The lower boundary condition is a specified pressure as determined from the elevation of the water table. It is expected that the vadose zone simulation results will be sensitive to the initial conditions (this determines the antecedent moisture conditions in the soil profile before a storm event). MIKE SHE assumes equilibrium soil moisture pressure profiles as the initial conditions. The retention function of the soil has to be used get the moisture content from the assumed hydrostatic pressure distribution. In heterogeneous systems, it may take very long time periods for the soil profiles to attain hydrostatic conditions. However, the re-initialization capability of UZ component allows for the generation of non-equilibrium initial conditions that may occur for the conditions at RFETS.

For the full coupling of the surface water system to the SZ, the UZ may have to be simulated in all grid squares. Use of small time steps and spatial discretization to get accurate solution to the non-linear equations results in long computational time. A feature in MIKE SHE allows for the lumping of grid cells with homogenous physical characteristics. Caution should be exercised in using this feature at REFTS in areas where the ground slope changes and in zones where the water table fluctuations are different.

One of the most critical processes that need to be represented accurately in the REFTS water balance model is the coupling of the UZ and SZ. The recharge to the water table determined by how the code algorithm solves the unsaturated flow equations (soil moisture distribution or head) while the water table is fluctuating as a result of recharge. The developers of MIKE SHE have recognized this and have employed an iterative procedure that tracks the mass balance in the unsaturated column. In the scheme used, the coupling is done between the entire UZ column and the uppermost calculation layer of the SZ. It is not clear from the documentation in the manual how the coupling is performed if a situation occurs where the water table drops below the bottom of the uppermost SZ layer. However, the coupling appears to be rigorous enough to capture the dynamics through the use of small computational time steps. At RFETS the groundwater table fluctuates across a number of geologic model layers. Hence, in the semi-quantitative evaluations a problem was developed to evaluate the code's coupling performance for this condition.

The simplified solution to Richard's equation ignores the tension terms. This simplification makes the numerical scheme more efficient by allowing for the selection of larger time steps and computational cells. Neglecting the capillary terms will not allow the model to capture the dynamic UZ processes accurately. Hence, this option should be used with caution at REFTS, as coupling of surface systems to SZ that occur through the dynamics in the UZ has to be modeled accurately.

3.4 Saturated Zone

The SZ module of MIKE SHE simulates three-dimensional groundwater flow under both unconfined and confined conditions. An implicit finite difference scheme is used in the numerical solution of saturated groundwater flow equation (Boussinesq equation). Implicit solution schemes allow for the use of any grid size and computational time steps without affecting convergence and stability of the solution. The formulation and solution schemes are closely similar to the saturated groundwater flow simulator MODFLOW, developed by the US Geological Survey (USGS). MODFLOW is well-accepted as a simulator. As the SZ component is very similar, in this report we will not provide a separate review. Later in the report benchmark tests will be performed comparing MODFLOW with SZ component of MIKE SHE.

4.0 CODE VERIFICATION

The objective of this task is to verify whether the mathematical equations are solved accurately using the stated numerical methods. Four primary code components will be verified, specifically: (1) code simulating the SZ processes; (2) code simulating the UZ processes; (3) code components simulating overland flow processes; and (4) code for channel flow. Even though a large number of other secondary (but important) processes are simulated by the code, the code accuracy as determined by the errors in the numerical solution schemes will likely be of most significance for the model performance.

Several MIKE SHE code verification tests were identified. These test cases are analytical solutions selected from a verification test matrix. The matrix listed many different potential test problems that could be used to verify the code against. However, only a subset of these problems was selected to meet the needs and time constraints of the RFETS project. These test problems with some of system characteristics at REFTS were provided to DHI. DHI conducted the simulations and the simulation results were provided in a report prepared by them (Appendix A). In the main text of this report, we will only summarize the analysis of the results of the tests that are presented in detail in Appendix A.

4.1 Verification of SZ module

Three test problems were used to verify the ability of the SZ module of MIKE SHE to solve the saturated flow equation. A close match of steady and transient solutions will demonstrate that the numerical approximation of the saturated flow equation is accurate and the algorithm used to march forward in time to solve the transient behavior is working correctly. Also, this verification test will check the solution accuracy of the method used to solve the linear system of equations.

4.1.1 A single well pumping in a homogenous aquifer bounded by a river

A closed-form analytical solution to calculate the transient piezometric head in a semi-infinite aquifer bounded on one side by a stream (constant head), due to pumping from a single pumping well is available (Theis, 1941 and Hunt, 1999). Both steady-state and transient head distributions were simulated and compared with the analytical solution. The match between MIKE SHE and the analytical solution for steady-state flow was found to be almost exact. The maximum error in the transient drawdown calculated at an observation point half way between the pumping well and the stream was found be by 1 mm (i.e. 0.01 % of saturated thickness). The maximum error at a point closer to the stream (1/10 the distance between stream and well) was less than 1 cm (i.e. less than 0.1% of saturated thickness).

4.1.2 A single well pumping in a homogenous aquifer bounded by a river with a semi-permeable boundary.

A similar comparison was done for this as for the previous case. Only steady-state solutions were compared. The match was very close with errors ranging from 2-3 cm (0.2 –0.3 % of saturated thickness) close to the stream and 1-2 cm rest of the aquifer.

4.1.3 A single well pumping in a circular island

A steady-state solution for a case where a well is pumping in an circular aquifer with a constant head boundary condition was available. In addition to the pumping, a steady recharge is applied on the ground surface. The code simulated and the analytical solution matched closely except at points close to the well. This is expected as the closed form solution assumes that the well is a point singularity (well with zero radius), Where as, the finite difference formulation used in MIKE SHE, the well is represented as a uniformly distributed withdrawal (negative recharge) over a grid cell (100 m x 100m). This suggests that the code computed drawdowns in cells where there is a pumping well, should not be used to predict the point drawdowns within the cell. However, if an accurate drawdown is needed, a finer grid system could be superposed (grid refinement).

The results of the above comparisons verify the computational accuracy of SZ module of MIKE SHE. It should be noted that in the first example it is assumed that the drawdowns are small compared to the saturated thickness of the aquifer (transmissivity remains constant with time).

4.2 Verification of UZ module

Closed form solutions that are of interest in this case are solutions to the one-dimensional Richard’s equation. The analytical solution used in this verification exercise uses a simple analytical model by Gardner (1957) to define the unsaturated hydraulic conductivity as a function of pressure head. One empirical fitting parameter defines this functional relationship. Where as, UZ module in MIKE SHE as in other similar codes use a hydraulic conductivity versus water content (or pressure) and pressure versus water content (retention function) as code inputs. In this case more than one parameter characterizes the inputs. To use MIKE SHE to compare with the analytical solution for a one-dimensional infiltration problem, it is necessary to obtain a relation between the fitting parameter of Gardner model and the fitting parameter n of MIKE SHE. The approach that was used attempts to fit the best value of n for the Gardner model. The comparison of the curves shows that only the pressure head values match at low suction values. A modification was made to input the Gardner model in tabulated form (instead of using the fitted n) in to MIKE SHE. The results as presented were generated using this modified version.

Infiltration of water through a one-dimensional homogeneous soil column was simulated. A flux boundary condition at the soil surface produces unsaturated and unsteady infiltration through the column. The code simulation and the analytical solution matched exactly for both hydrostatic conditions (zero flux at the soil surface) and with boundary flux. The results of this test verify that the UZ model solves the steady state infiltration problem accurately. However, it should be noted that this test does not verify the accuracy of modeling of transient behavior. The stability of the solution can only be verified by conducting a test under transient conditions. Ability to model transient behavior of soil moisture profiles is important at REFTS as the groundwater recharge from storm events is sensitive to antecedent soils moisture conditions.

4.3 Overland Flow

An appropriate analytical solution was not available for the verification of the overland flow module. However, this model component was tested as a part of semi-quantitative analysis.

4.4 Coupled processes

Closed form analytical solutions to some of the coupled processes between different components of the hydrologic system are available. Three such solutions were selected for the following cases: (1) stream and aquifer; (2) overland flow and UZ; and (3) lake and SZ.

4.4.1 Stream/aquifer coupling

Hunt (1999) provided an analytical solution for transient drawdown due to pumping in an aquifer with a stream represented as line source (river loosing or gaining water due to the coupling). The pumping from the well lowers the water table at the river and the head gradient between the river and the aquifer produces leakage. The model was setup by the SZ component of MIKE SHE to the channel flow model MIKE 11. The river/aquifer exchange option where the leakage is calculated using a leakage coefficient of the river lining was used. The steady-state and the solution for the drawdown 23 days into the simulation were compared. They showed perfect agreement with the analytical solution. The transient drawdown at an observation point 50 m from the pumping well was compared. The analytical solution and MIKE SHE again showed close agreement (maximum error less than 0.01% of saturated thickness).

The verification exercise tests the coupling of the flow exchange between the river and the aquifer. However, it should be noted that this test does not evaluate the full dynamic coupling of the two components as the analytical solution assumes that the water level in the river remains constant. In a fully-coupled system, the river stage has to be adjusted for the gain/loss into the river. MIKE SHE when coupled with MIKE 11 has this capability, but this verification test does not evaluate this feature.

4.4.2 Lake and unsaturated zone coupling

An analytical solution for the three-dimensional, steady-state flow to a hemispherical lake in a confined, homogeneous aquifer with a uniform regional gradient and infinite extent and depth was available (Kacimov, 2000). This test case is suitable for testing the interaction between large body of surface water and an unconfined aquifer. This comparison requires utilizing the three-dimensional solution capabilities of MIKE SHE. In the previous verification tests, the groundwater flow was two-dimensional. In the simulation setup, the surface water model MIKE 11 is coupled to the SZ component of MIKE SHE.

For the case where the lake is defined as a constant head boundary, the model compares favorably with the analytical solution, except in zones immediately upstream of the lake and an area below the lake. Still these errors are very small (in the range 1-3 cm head differences). The errors were found to be slightly higher for the case where the lake was defined as a river in MIKE 11. DHI attributes these errors to model discretization along the steep side of the lake. Using relatively thick layer for the first layer adjacent to the lake, it was possible to minimize the errors.

Even though, the situation represented in this problem with a large lake coupled to the aquifer does not exist at REFTS, pond/aquifer and flood plain/aquifer interaction have to be simulated. These interactive processes are modeled using the same coupling of MIKE 11 and SZ module of MIKE SHE that was used in this verification exercise. Hence, attention should be given to the grid geometry issues that were identified in this test when the pond/aquifer and flood plain/aquifer interactions are modeled at REFTS.

5.0 CODE VALIDATION

Code validation is done in two steps. First, the code is compared with other accepted codes such as MODFLOW used for saturated flow simulations or VS2DT used for unsaturated flow simulations. Bench marking the code against other codes allows for the evaluation of the code by conducting simulations of situations that are much more realistic and complex than the ones that were used in code verification. The second method involves a semi-quantitative performance evaluation where the coupling of the various model components is evaluated through a set of simulations. This is the only viable way to test the code's performance for more complex hydrologic conditions (i.e., where simple analytical solutions are not available) in the absence of highly controlled field or laboratory tests.

5.1 Code validation through bench marking

Two commonly used models are used in this exercise. They are: (1) MODFLOW, a modular three-dimensional saturated flow model developed by the USGS, and (2) VS2DT, a two-dimensional variably saturated flow code developed by the USGS. The results of the comparison of these codes to MIKE SHE are evaluated. The details of the problem setup and results are given in Appendix A to this report prepared by DHI.

5.1.1 MODFLOW-Water table conversion

When confined aquifers are pumped, it is possible for the piezometric surface to drop below the top confining layer resulting in unconfined conditions in the aquifer. The yield from the aquifer under confined conditions is controlled by the storage coefficient (generally a very small number defined by the compressibility of the soil matrix and water). Under unconfined conditions, the water is yielded through drainage from pores. In this case the specific yield defines the volume of the water yield. This test is designed to test MIKE SHE's ability to convert from confined to unconfined conditions. An example problem that was used by EPA was used. In this problem, a fully-penetrating well pumps water from a large uniform aquifer. The pumping rate and the problem parameters are such that the aquifer converts from confined to unconfined conditions.

The results show that MIKE SHE and MODFLOW produce exactly the same results. This suggests that MIKE SHE simulates the flow and conversion process as same as the well accepted code MODFLOW.

5.1.2 MODFLOW – Two-dimensional flow in an irregular aquifer

In all the code verification tests, the simple aquifer geometries were assumed. In this problem selected from a EPA test case for a hazardous waste site, an arbitrary aquifer geometry is used.

In the MODFLOW simulation a variable grid size was used. Where as MIKE SHE can only handle uniform grid cells, thus making it not possible to reproduce the solutions at same locations using both models. When the contour map of the water table elevations were compared, they show close agreement except at the boundaries. However, it should be noted that these solution discrepancies at the boundaries are very small. DHI modelers attribute this discrepancy at the boundaries to the differences in the grid sizes.

The simulation of a second EPA test problem for the case of transient flow in an aquitard showed perfect agreement.

5.1.3 VS2DT – steady vertical infiltration

The same test problem that was used in code verification was used in this bench marking test. The algorithms used by VS2DT and UZ component of MIKE SHE to solve the Richard's equation are very similar. Except, VS2DT uses Van Genuchten moisture content and hydraulic conductivity relationships as inputs. Where as, UZ component of MIKE SHE uses tabular data. Also, VS2DT is a more general model that can solve flow in two-dimensional systems where as UZ is restricted to one-dimensional flow.

In the test, Van Genuchten model was fitted to the tabular data used in MIKE SHE. The simulations of both the vertical distribution of water content and the pressures using the two models for the cases of zero boundary flux (hydrostatic) and specified boundary flux matched exactly.

5.1.4 VS2DT- transient vertical infiltration

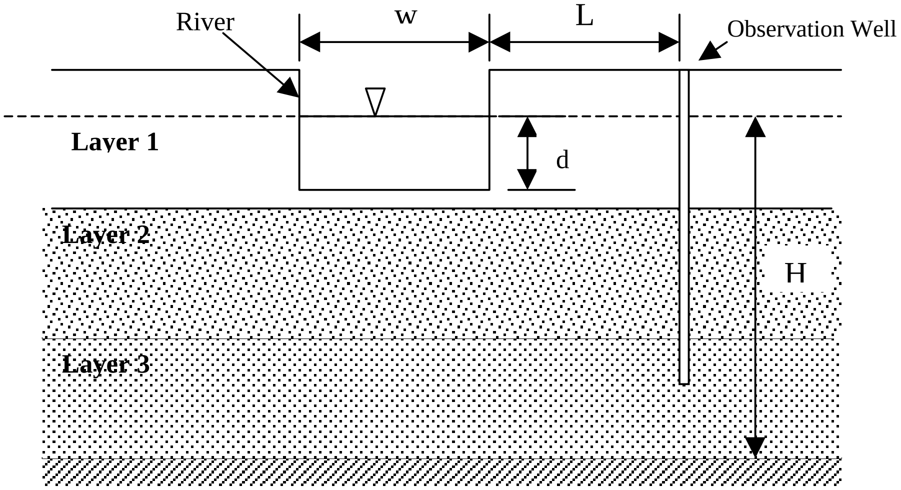
This test problem is similar to the previous steady-state simulation, but soil parameters, the depth to the water table and the precipitation rates are all selected to more closely represent those found at a semi-arid field site such as RFETS. To create transient conditions, an intermittent rainfall event was created by first applying an intense rainfall followed by two longer rainfall events. Each rainfall event was followed by dry period. The simulations of both transient vertical distributions of pressure and moisture contents match exactly with the two codes.

5.2 Semi-quantitative performance evaluation

The tests conducted and presented so far mainly focus on the individual components of the hydrologic cycle and do only to a limited extent test the ability to model some of the complex interactions that occur at REFTS. Based on some of the critical processes and interactions that were identified during the development of the conceptual model for the site, a set of hypothetical problem setups was developed. As no laboratory or field data are available to compare the results against, an approach that relied on a semi-quantitative analysis of the code simulations was used. In this approach, the model predictions were analyzed using these criteria: (1) the predictions qualitatively capture the coupled behavior; (2) the predictions make physical sense; (3) the solutions are stable; (4) mass balance is maintained.

Eight test problems were designed and provided to DHI. DHI conducted the simulations and the input data files were provided to us with the results. After evaluating the results, additional clarifications were requested from DHI. Also, in some cases the data files were used by the reviewers independently to simulate variations of the test problems for QA/QC purposes. The findings from this semi-quantitative performance evaluation are summarized.

5.2.1 Saturated groundwater / surface water model with a transient river stage



Given:

Geometry	*W, L, and layer thickness*
Aquifer parameters	*K and S for layers*
Initial conditions	*H*
Boundary conditions	*Constant head at infinity*
River stage	*Transient d(1), d(2), and d(3)*

Simulate and provide:

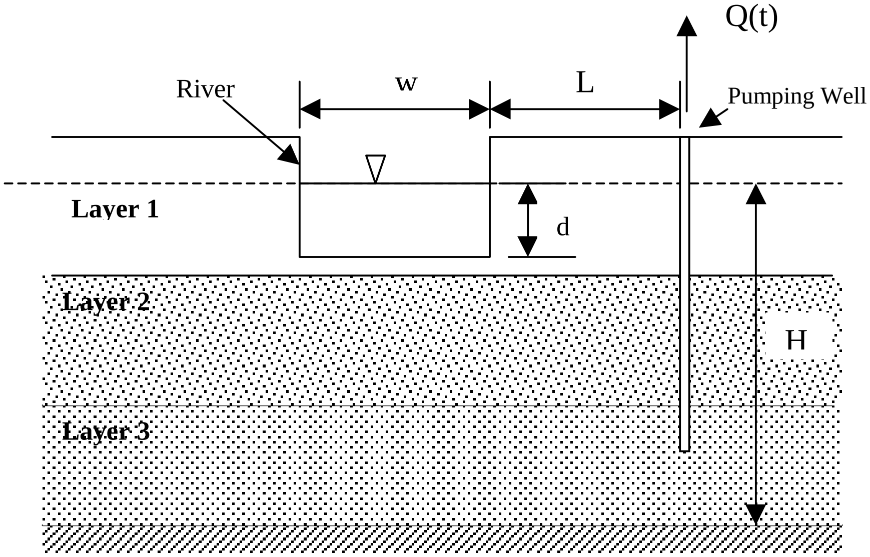
1. Transient water level in the observation well.
2 Transient river gain/loss.
3. Mass balance/water budget.

Figure 3: Problem setup for two-dimensional river-aquifer interaction-river stage fluctuation

Figure 3 shows the problem setup. The goal in this test is to evaluate the code for its ability to simulate the response of the aquifer due to the variation of stage in the river. The three aquifer layers with different properties represent the three model layers that are used in the SWWB model. The situation as represented in this example is important at REFTS as at some locations in the stream system is in hydraulic connection with the aquifer and base flow contributes to the flow in the stream. The simulation results show that the aquifer responds to the stage variation in the river. The lag in the response is controlled by the hydraulic conductivity (K) and storage coefficients.

Using the data files provided by DHI, a number of other simulations were conducted by changing the aquifer properties. When the storage coefficient in the aquifer was changed from 0.25 to 0.01, the water table responded faster as the aquifer acted like a confined aquifer. When the K value in the second layer was increased, as expected the lag in the peak got smaller and the amplitude got bigger. When the observation well was moved further, the responses dampened. When the river stage was dropped and maintained at a constant level, the well drawdown reached a steady value. Based on the results of this analysis, we conclude that the river-aquifer interaction is modeled by the code correctly. The coupling maintained mass balance in the system.

5.2.2 Saturated groundwater / surface water model with transient pumping and river / aquifer interaction



Given:

Geometry	*W, L, layer thickness*
Aquifer parameters	*K and S for layers*
Initial conditions	*H*
Boundary conditions	*Constant head at infinity*
River stage	*Constant d*
Pumping	*Transient Q(1), Q(2), and Q(3)*

Simulate and provide:

1. *Transient water table profile.*
2. *Transient river gain/loss.*
3. *Mass balance/water budget.*

Figure 4: Problem setup for two-dimensional river aquifer interaction-well pumping

The problem setup is similar to the previous case. In this case, the code is evaluated for its ability to simulate the river response to pumping in the river. This exact situation of wells pumping from the aquifer does not exist at REFTS. But, the conditions as represented are conceptually similar to a case where the stream responds to a local recharge event (negative pumping).

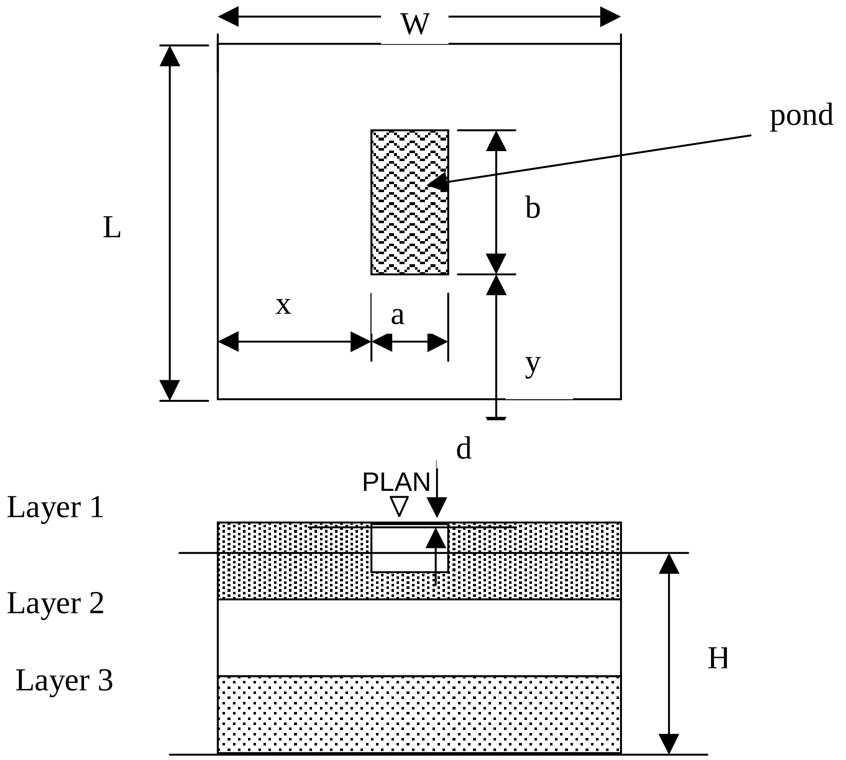
For the problem parameters used, the effect of pumping is primarily seen in the upper layer and a delayed and dampened response was observed in the lower two layers. The lowering of the water table due to pumping resulted in the river loosing water to the aquifer. The water balance analysis shows that the water withdrawal from the well and the return flow from the river to the aquifer balance the net change in storage in the aquifer at any time.

A number of independent simulations were conducted by changing the aquifer parameters and the boundary conditions. These include, increasing the pumping, changing pumping schedule, change in leakance and change in storage coefficient. Based on the results of this analysis, we conclude that the river-aquifer interaction is modeled by the code correctly. The coupling maintained mass balance in the system.

In the previous two test cases, the aquifer flow had to be simulated in two dimensions (x and z). This test is designed to check the ability of the code to simulate three-dimensional flow in response to the water level changes in an isolated pond. The pond is in dynamic interaction with the aquifer. In the problem setup, we requested an isolated pond that acts as a recharge area. However, DHI modelers in setting up the input data files included a river branching from the upstream boundary to a pond represented by wide cross sections and a canal segment to allow surface water flow from the pond across the downstream boundary. They used this method to use MIKE 11 to set the water level in the pond by controlling the upstream and downstream boundary conditions. It is not clear whether this is a limitation in the code that it is not able to represent an isolated pond. At REFTS, it is possible to have situations where an isolated pond (when streams are not flowing) will be in hydraulic connection with the SZ.

The head response in the aquifer seems to capture the interactive behavior well as reflected by correct slopes of the head responses, lag in the peaks, and damping at lower layers.

5.2.3 Saturated groundwater / surface water model with a transient pond stage



SECTIONAL VIEW

Given:

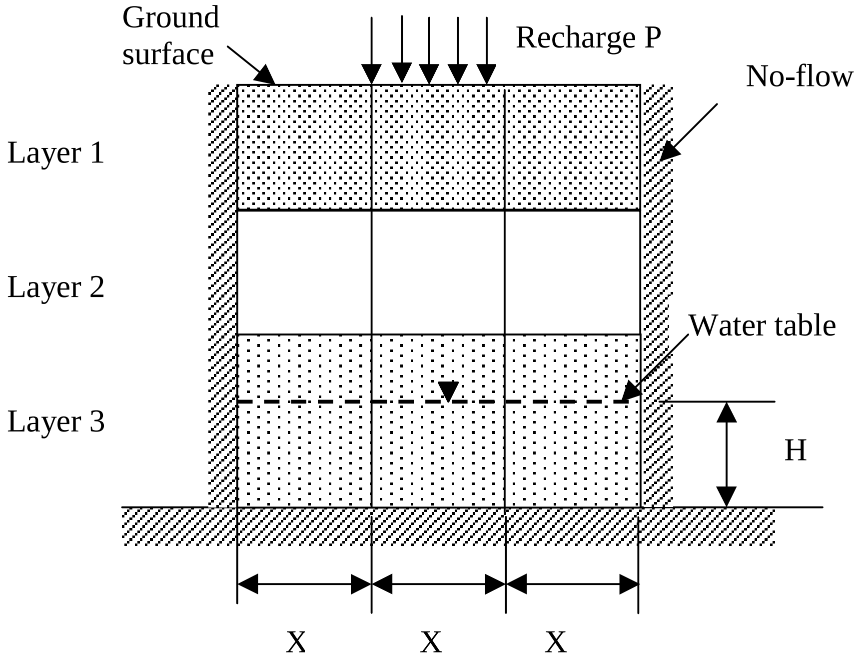
Geometry	*W, L, a, b, x, y and layer thickness*
Aquifer parameters	*K and S for layers*
Initial conditions	*H*
Boundary conditions	*Constant head at H*
Rainfall	Transient d(1), d(2), and d(3)

Simulate and provide:

1. *Transient water table profile.*
2. *Transient river gain/loss.*
3. *Mass balance/water budget.*

Figure 5: Problem setup for fluctuating water table due to water level changes in a pond

5.2.4 Unsaturated zone / saturated groundwater model with transient recharge without ponding



Given:

Geometry	*X and layer thickness*
Aquifer parameters	*1. K and S for layers* *2. Retention functions*
Initial conditions	*H*
Boundary conditions	*No-flow*
Recharge	*Transient P(1), P(2), and P(3)*

Simulate and provide:

1. *Transient water table profile.*
2. *Transient soil moisture profile.*
3. *Transient water table recharge.*
4. *Mass balance/water budget.*

Figure 6: Problem setup for recharge to aquifer with specified flux at the ground surface

This test is designed to evaluate dynamic coupling of the UZs and SZs by MIKE SHE. Water infiltrating through the UZ recharges the aquifer. As a result of recharge, the water table rises. The UZ model uses the water table as the lower boundary condition. Accurate representation of this process is critical at REFTS as the water table response to storm events and snow melt has to be simulated.

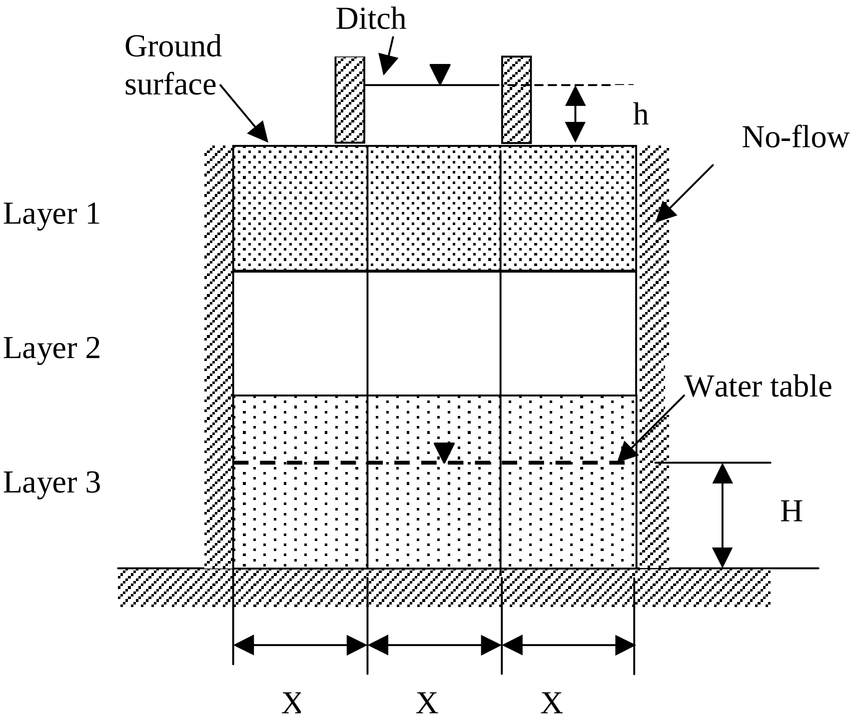
In the problem setup, the initial water table was at a depth –2.5 m thus placing it in the first layer. The shallow water table conditions resulted in the water table rising to the ground surface as a result of infiltration from rainfall. The heads in the three aquifer layers responded to the infiltration event as expected.

The test case shows that MIKE SHE simulations capture the unsaturated and SZ coupling. The situation DHI simulated represents shallow water table conditions. The behavior of the model for situations when the water table is deep and in the third aquifer layer was tested. The test results show that the unsaturated model directly transmits the infiltrating water from the first layer to the water table assuming unit head gradient. This approach of coupling the UZ and water table assumes perched conditions at the bottom of the first layer that may not occur in reality. It is our recommendation that the accuracy of this approximate way of coupling the UZ and SZ under conditions of deep water table should be further tested during the model calibration and validation.

This test case was designed to evaluate MIKE SHE's ability to couple a surface system (a ditch) to the SZ when ponding occurs at the ground surface when the infiltration capacity of the soil column is less than the rate of supply. DHI modelers setup this problem by using the overland component to represent the ditch. Rainfall to the ditch was used to create ponded conditions. Overland flow to the surrounding areas was disabled by using a high value for detention storage. A flux boundary condition was used to bring the UZ to full saturation. Ponding can occur on the ground surface when the infiltration capacity is less than the rainfall intensity. Under these conditions, the soil still remains unsaturated.

We make the same recommendation as for the case of section 5.24 for cases where the water table is deep attention should be given during model calibration and validation to make sure the infiltration process is captured adequately.

5.2.5 Unsaturated zone / saturated groundwater model with transient surface pond water levels



Given:

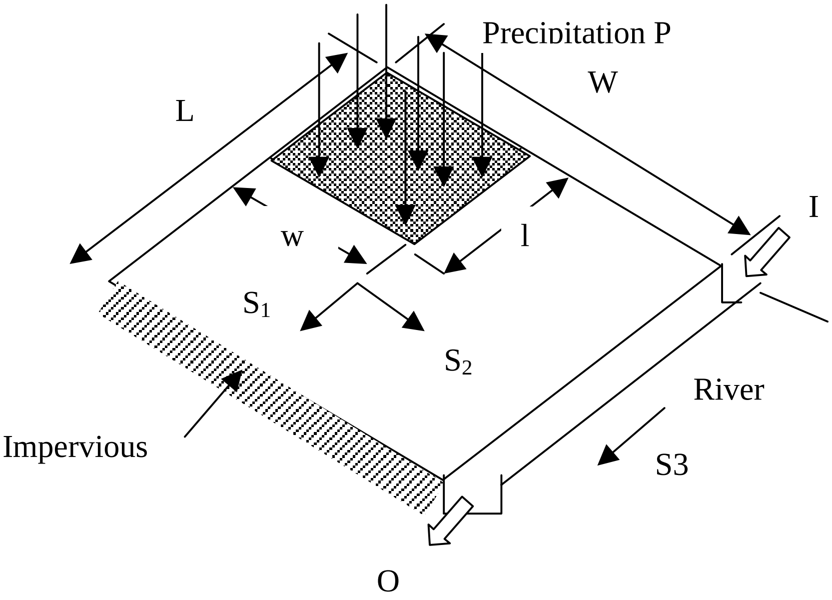
Geometry	*X and layer thickness*
Aquifer parameters	*1. K and S for layers* *2. Retention functions*
Initial conditions	*H*
Boundary conditions	*No-flow*
Water table	*Transient H(1), H(2), and H(3)*
Ponded depth	*Transient h(1), h(2),and h(3)*

Simulate and provide:

1. *Transient water table profile.*
2. *Soil moisture profile.*
3. *Transient water table recharge*
4. *Mass balance/water budget.*

Figure 7: Problem setup for recharge to aquifer with through specified ponded depth at the ground surface

5.2.6 Overland flow / surface water model with an impervious surface



Given:

Geometry	*W,L.w,l, and river section*
Slopes	*S_1,S_2 and S_3*
Initial conditions	*dry*
Boundary conditions	*Impervious*
Inflow hydrograph	*Transient I(1), I(2), and I(3)*
Parameters	*Strikcler coeff. K, and river routing*

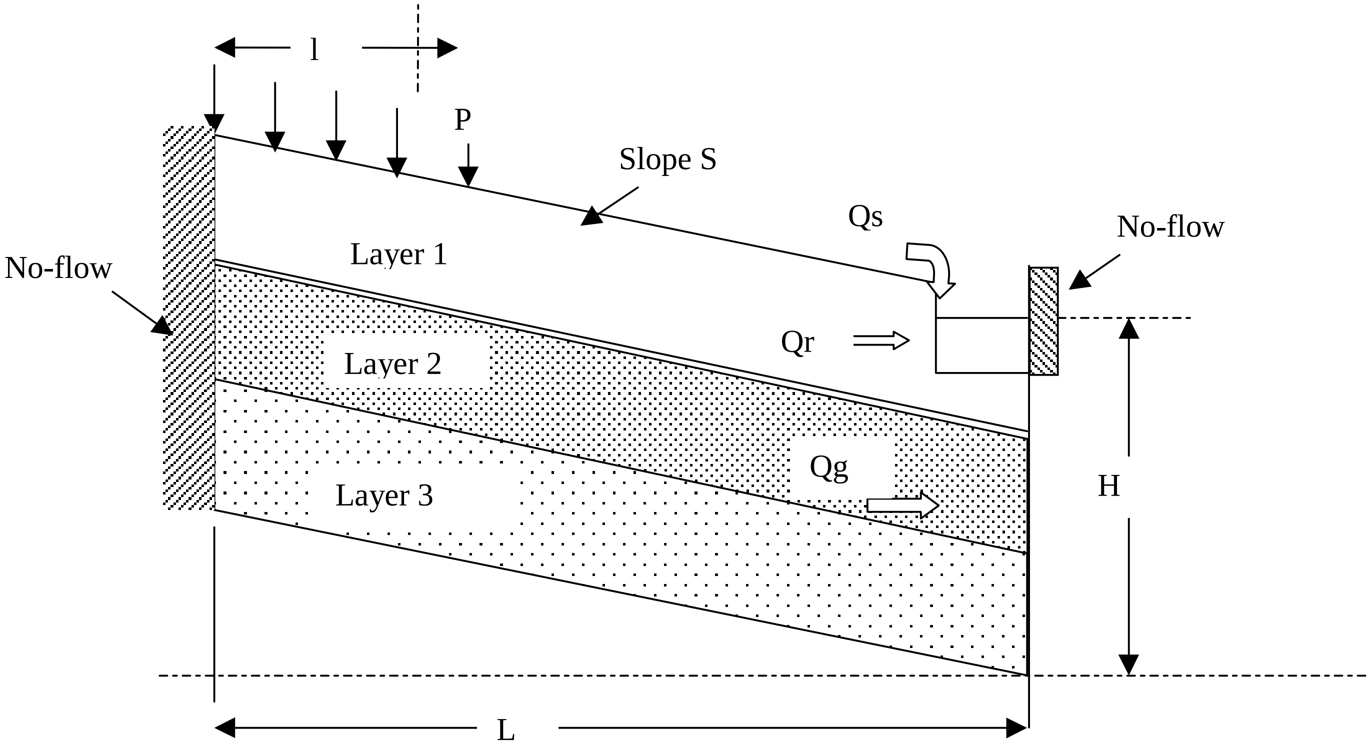
Simulate and provide:

1. *Outflow hydrograph.*
2. *Water budget.*

Figure 8: Problem setup for overland flow-channel coupling

This test case was designed to test MIKE SHE's ability to simulate overland flow in response to a localized rainfall event applied on an inclined surface bounded by a channel. The channel receives lateral flow from the adjacent overland planes. The simulations show mass balance is maintained. The hydrograph of channel flow shows proper lag from the rainfall events. However, the problem was setup causes some water flow across the no-flow boundary. We found there are two options to prevent flow out the boundaries, controlling topography or using overland flow boundaries. A set of independent simulations showed that the model functions well and the surface water gets routed over the ground surface.

5.2.7 Overland flow / unsaturated zone model with a pervious surface



Given:

Geometry	*L, l, S and layer thickness*
Aquifer parameters	*1. K and S for layers* *2. Retention functions*
Initial conditions	*H*
Boundary conditions	*No-flow and H*
Precipitation	*Transient P(1), P(2), and P(3)*

Simulate and provide:

1. *Water table profile.*
2. *Transient Qr.*
3. *Transient Qs.*
4. *Transient Qg.*
5. *Soil-moisture profile.*
6. *Mass balance/water budget.*

Figure 9: Problem setup for overland flow-unsaturated zone coupling

This problem was designed to test MIKE SHE's ability to couple overland flow and UZ. Three aquifer layers were created and simulations were requested to show how return flow to a bounding stream is created as a result of a rainfall event. The model was set up using the SZ component, the UZ component, overland component, and the MIKE11 river component. Overland flow is generated by four rainfall events. The groundwater model includes three layers dipping towards the river. For the condition that was simulated, the model captured the coupling behavior of the overland zone and UZ. We suggest DHI to perform a simulation for the case where the water table is deep if it becomes necessary that such a condition be found to occur at RFETS.

6.0 CONCLUSIONS

This report documents the results of a code validation study conducted to evaluate the suitability of MIKE SHE as an integrated hydrologic modeling code for the development of a water balance model at RFETS. The tests were carefully designed to not only evaluate the strengths but also possible weaknesses of the code. To our knowledge very few codes have been subjected to this level of rigorous testing. The model developers at DHI were very cooperative and supportive of this effort. The authors of the report are very appreciative of this, as without the full cooperation of the code developers and their expertise, it would not have been possible to conduct such a detailed evaluation. Additional tests would have provided more information to conduct further evaluations of many possible combinations of the interactions between the different components. However, the authors are very comfortable that the test cases captured the most important processes to make an evaluation of the suitability of the code to be applied at RFETS. It is also important to note that the authors used the data files provided by DHI for the test cases to conduct independent tests. These independent tests allowed meeting the QA/QC requirements for code validation.

It is the opinion of these authors that integrated modeling of dynamic systems is not a trivial exercise, and no code will be able to capture all the processes accurately to the point that the model becomes an exact representation of the physical system. A comparative analysis was not conducted to evaluate the performance or the accuracy of MIKE SHE in comparison to other similar integrated modeling codes. In addition, we are not aware of any other code that is as comprehensive and user friendly as MIKE SHE to be available to simulate complex semi-arid hydrologic conditions such as the ones that exist at RFETS. Based on the results of the tests and the knowledge we have of other codes that are reported in literature, we conclude that MIKE SHE will be the best code that is currently available to conduct this complex study. We are confident that a model based on this code when properly calibrated will be the best decision tool that could be developed for the Site. The feature of MIKE SHE that can be used for the simulation of contaminant transport will make the SWWB model to be the best flow simulator that could be used in any future decision tools that may become necessary to conduct water quality analysis at the Site.

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APPENDIX A

MIKE SHE Code Verification and Validation

MIKE SHE Code Verification and Validation

Final Report
September 2001

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MIKE SHE Code Verification and Validation

September 2001

Client DHI Internal	Client's representative

Project MIKE SHE Code Verification and Validation	Project No
Authors Douglas Graham Torsten Jacobsen	Date August, 2001 Approved by

	Final File				
Revision	Description	By	Checked	Approved	Date

Key words MIKE SHE, Verification, Analytical Solution, Validation, Modflow, VSZDT	Classification ☒ Open ☐ Internal ☐ Proprietary

Distribution DHI:	No of copies

CONTENTS

1 INTRODUCTION

1.1 The MIKE SHE hydrological modeling system

More than twenty-five years ago that the development of the Système Hydrologique Européen, SHE, was initiated (Abbott et al., 1986). MIKE SHE – an extension of the original SHE code – is today one of the very few commercially available codes that can be described as a physically based and fully distributed hydrological modeling code. Over this period, MIKE SHE has been successfully applied in hundreds of applications on both research and consultancy projects.

MIKE SHE was designed and developed as a fully integrated alternative to the more traditional lumped conceptual rainfall-runoff models such as the NAM model and the stand-alone models representing e.g. groundwater only. The international collaboration during the initial development of the SHE code necessitated a modular process-based structure to the code. Each module describes one of the major hydrological processes in the hydrological cycle and, together, they provide a complete integrated description of all major flow processes of the land-phase of the hydrological cycle (Figure 1). Additionally, each component can be run separately or coupled to one or more of the other components.

MIKE SHE was originally developed with the view that the level of detail should be sufficient to justify the claim of a physically based system. The equations used are, with few-exceptions, non-empirical and well known to represent the physical processes in the different parts of the hydrological cycle. The parameters in these equations can be obtained from measurements and used in the model, so long as they are compatible with the scale of the model. The flow processes represented in MIKE SHE include: snow melt,

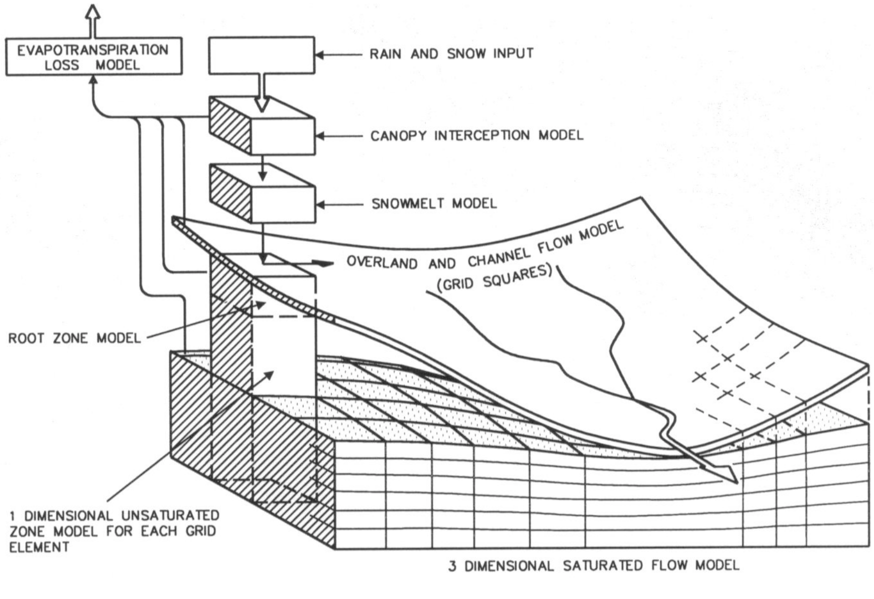


Figure 1-1 Schematic representation of the components in MIKE SHE (Storm and Refsgaard, 1996).

rainfall interception and evapotranspiration, overland flow and channel flow, vertical flow in the unsaturated zone, and 3-D groundwater flow. In MIKE SHE, each of these processes operates spatially and at time steps consistent with their own spatial and temporal scales. For example, daily rainfall may be distributed, due to topographic relief, into a few zones across a watershed. Infiltration and evapotranspiration will vary with vegetation, surface cover, slope, soil properties, etc. and is automatically calculated and distributed in the model based on the values for such parameters. Stream and river flows typically show the quickest response to rainfall events, whereas groundwater typically shows the slowest. However, in areas with shallow groundwater that is in full contact with local surface water, a fully integrated dynamic description of the surface water/groundwater interaction, with hourly or daily time steps, is of particular importance to capture the hydrological behaviour and responses. s

1.1.1 Unsaturated flow

Unsaturated flow is one of the more important processes in MIKE SHE, as the unsaturated zone plays a central part in most model applications. The unsaturated zone is usually heterogeneous and characterized by cyclic fluctuations in the soil moisture as water is replenished by rainfall and removed by evapotranspiration and recharge to the groundwater table. Infiltration may cause a rise in the water table, whereas upward capillary flow from the groundwater table may occur in areas with a high groundwater table and high evaporation rates. Unsaturated flow is primarily vertical since gravity plays the major role during infiltration. Therefore, unsaturated flow in MIKE SHE is vertical, which is sufficient for most applications even though very steep hill slopes with contrasting soil properties in the soil profile may exhibit a 3-D flow pattern. MIKE SHE includes an iterative coupling procedure between the unsaturated zone and the saturated zone to compute the correct soil moisture and the water table dynamics in the lower part of the soil profile.

There are two options in MIKE SHE for calculating flow in the unsaturated zone: the Richard’s equation or a simplified gravity flow procedure. The full Richard’s equation requires tabular input for the moisture-retention curve and the effective conductivity, as well as other properties for each soil type in the vertical profile. The simplified gravity flow procedure assumes a uniform vertical gradient in the soil column and the infiltration and percolation processes are described in terms of gravity flow. The gravity flow option is often chosen when the unsaturated zone is included mainly to provide recharge estimates for the saturated zone or if the soils have limited capillary capacity.

Each cell in the model is assigned to a soil zone, which defines the soil profile. In this way, the unsaturated zone can be nominally ‘classified’, i.e. soil moisture content and flows in a soil column can be transferred to other columns in the model area sharing the same soil properties, the same meteorological inputs, the same vegetation properties etc.. Thus, solving Richard’s equation for each column can be avoided and an appropriate solution can be achieved in a reasonable amount of CPU time. Alternatively, the simplified gravity solution procedure can be chosen to, allowing either more soil zones or a faster execution time.

1.1.2 Evapotranspiration

Accurate prediction of the actual evapotranspiration plays a key role in many water resources studies. Evapotranspiration is the sum of evaporation from soil, vegetation and water surfaces and plant transpiration through uptake of water in the root zone. The spatial and temporal variation in the simulated actual evapotranspiration rate depends on many factors such as water availability in the root zone, the potential evapotranspiration rates given as input to the model and the vegetation characteristics.

Actual evapotranspiration is calculated from potential evaporation data. Two methods are included. The first is based on the Rutter model/Penman-Monteith equation. This calculates the evaporation, the actual storage on the canopy, and the net rainfall reaching the ground surface as canopy drainage and through fall. The actual evapotranspiration rates are calculated by the Penman-Monteith equation using canopy resistances. The potential evapotranspiration is calculated directly using climatological and vegetation data. The second method is based on the Kristensen-Jensen model (Kristensen and Jensen, 1975), where the interception storage is calculated based on the actual leaf area index and an interception capacity coefficient. The net rainfall is calculated by a simple water balance approach. Both methods use the actual soil moisture/retention conditions in the root zone to calculate the actual evapotranspiration loss. The amount of water that can be drawn out of the root zone depends on crop and soil properties. The interception/evapotranspiration component is an integral part of the unsaturated zone component which again determines the timing and magnitude of groundwater recharge and/or overland flow generation.

1.1.3 Overland flow

Overland flow is generated either when the ground water rises above the ground surface or the infiltration capacity of the unsaturated zone is exceeded by the rainfall input. The routing of the water is computed using the two-dimensional kinematic wave approximation of the St. Venant’s equation. Net rainfall, evaporation and infiltration are introduced as source/sinks allowing the surface to dry out on more permeable soil areas. Overland flow is depending on topographical slope directed to local depressions, streams/rivers or across the model boundary. Sub-scale storage capacity may be included as detention storage. By using detention storage overland water does not flow but is subject to evaporation and/or infiltration when the overland water level is below the specified threshold.

1.1.4 Channel flow

Excess overland flow that drains to a river is added to the river as lateral inflow. Other sources of runoff to the river network are drainage flow (interflow) and base flow. MIKE SHE can be coupled directly to DHI’s widely used MIKE 11 river hydraulic model, where floodplains and river structures can be included. MIKE 11 contains an implicit, finite-difference computation of unsteady flows in rivers and estuaries. The formulations can be applied to branched and looped networks and quasi two-dimensional flow simulations on flood plains. The computational scheme is applicable to vertically homogeneous flow conditions ranging from steep river flows to tidally influenced estuaries. Both subcritical and supercritical flow can be described by means of a numerical scheme, which adapts according to the local flow conditions. In MIKE 11, the complete non-linear equations of open channel flow (Saint-Venant) can be solved numerically between all grid points at specified time intervals for given boundary conditions. Alternatively, other more simplified flow descriptions can be used such as the diffusive wave, kinematic wave, and quasi-steady state approximations. The flow over a wide variety of structures can also be simulated, such as broad-crested weirs, culverts, regulating structures, control structures, and user-defined structures.

1.1.5 Saturated groundwater flow

MIKE SHE includes a 3-D groundwater component to simulates sub-surface saturated flow. It computes the transient groundwater flow and head in a regular finite-difference grid based on the given boundary conditions and the interaction with the other components included in the model. Groundwater flow plays a significant role in the hydrological cycle and is the main source for water supply. During drought periods it provides and sustains stream flow via base flow. During storm events it may contribute significantly to the storm flow, as well as influence the magnitude of overland flow due to the rising water table. Groundwater withdrawals for water supply and irrigation may influence natural recharge and discharge and thereby change the entire flow regime in the basin.

All types of commonly used boundary conditions for groundwater modelling are available with the ground water component of MIKE SHE.

1.1.6 Other modules

The **Irrigation Module** simulates a wide range of irrigation practices. Irrigation management can be simulated using distributed temporal crop water demand and crop yield. It includes the conjunctive use of surface and groundwater with the option of setting priorities. For example, if insufficient surface water is available the model can be set up to automatically withdraw groundwater. The irrigation supply may be controlled by pre-specified crop water demand, the actual simulated soil moisture deficit in the root zone or the actual evapotranspiration rates.

The **DAISY Module** links the soil-plant-atmosphere model DAISY (Hansen et al., 1990) to MIKE SHE. The latest version of the model has been restructured and optimized. It now works as an open and flexible agro-ecosystem modeling system, well suited for agricultural related studies. DAISY can be used to model changes in crop yield as a function of water and nitrogen availability, irrigation optimization and nitrate and pesticide leaching.

With the **Advection/Dispersion Module** solute concentrations can be calculated in overland flow, rivers, the unsaturated zone, and the saturated zone. In the case of integrated simulations, the migration of contaminants between surface water and groundwater is fully accounted for. The advection/dispersion equation is solved by an explicit scheme (QUICKEST).

Capture zones, solute contaminant flow paths and transport times can be simulated using the **Particle Tracking Component**. Particle tracking is calculated using the random walk method, including both a deterministic advective term and a deterministic/stochastic dispersive term. The dispersive term may be excluded, in which case the calculated flow paths correspond to the mean streamline.

MIKE SHE also includes several modules for simulating for chemical reactions in groundwater. The **Geochemical Module** includes a dynamic link between the USGS's PHREEQC program and MIKE SHE. The degradation description used in the **Biological Degradation Module** reflects both the sequential use of electron acceptors and a Monod/Michaelis-Menten degradation kinetics. The third element of the biodegradation module describes which species are involved in the degradation reaction. The three elements of the degradation description are fully user-controlled allowing for almost any degradation formulation including mother-daughter systems, co-metabolism, inhibition and more. When the Biodegradation and the Geochemical modules are run together, virtually any kinetic reaction series can be simulated. In addition to these two complex reaction modules, a simpler **Sorption/Degradation** Module is also available, which can be used to calculate

- transport of water and solutes in macropores, through which water is routed separately as gravity flow but with exchange with the surrounding bulk matrix.
- sorption of solutes described by either equilibrium isotherms (Linear, Freundlich or Langmuir) or kinetic isotherms, which can also include hysteresis. Where preferential flow exists, it is possible to distribute the available sorption sites unevenly between the soil matrix and the macropore porosity.
- attenuation of solutes described by first-order decay influenced by soil temperature and soil moisture content. The solute half-life can be specified differently in the macopores versus the soil matrix, since diffusion, for example of oxygen, to and from the soil matrix may be different in the two domains.
- plant uptake of solutes described as passive transport along with the transpiration stream.

MIKE SHE GIS is a set of utilities, developed in cooperation with ESRI, for easily converting MIKE SHE files to and from ArcView. Also included is the GeoEditor, which allows the user to interactively develop a three-dimensional geologic model of their site.

1.2 Approach

The complex and integrated nature of the MIKE SHE modeling system precludes a simple verification and validation of the code. Consequently, a rigorous approach was developed to stepwise verify and test the individual model components and integrated models that include more than one component.

This document summarises the results of the verification and validation testing performed to date on the MIKE SHE code, which is believed to be the most comprehensive test performed on an integrated model to date.

In this report, we refer to MIKE SHE as the code. That is, MIKE SHE is a generic computer code that could be applied to any site. Whereas, in this report the term, model, refers to an integrated simulator that uses site-specific parameters and boundary conditions. This report addresses code verification and code validation of MIKE SHE.

Figure 1 shows the steps involved in code verification and validation. The testing follows a logical progression of increasing complexity. The first step tests individual hydrologic processes and mainly focuses on code verification using analytical solutions of the governing equations and laboratory data. The second and third steps involve coupled hydrologic processes that can only be partly evaluated using analytic methods. A complete validation against analytical solutions is not possible as closed form analytical solutions only exist for a few combinations.

Code verification and validation typically involves the following four primary tasks:

***Task 1*: Review of mathematical models used in code development.**
This is a review of the equations/numerical methods that are used in MIKE SHE to confirm that MIKE SHE uses the most appropriate mathematical models to represent the primary hydrological processes that are relevant to the site conditions. Task 1 is not part of this report.

***Task 2*: Code Verification**
"Code verification" is used to verify whether the mathematical equations are solved accurately using the stated numerical methods. This task is accomplished by comparing the model to available closed form analytical solutions.

Four primary code components are verified, specifically code components simulating: (1) saturated zone flow; (2) unsaturated zone flow; (3) overland flow; and (4) channel flow. Other processes are also simulated by the code. However, the model accuracy primary depends on the numerical solution schemes associated with these components.

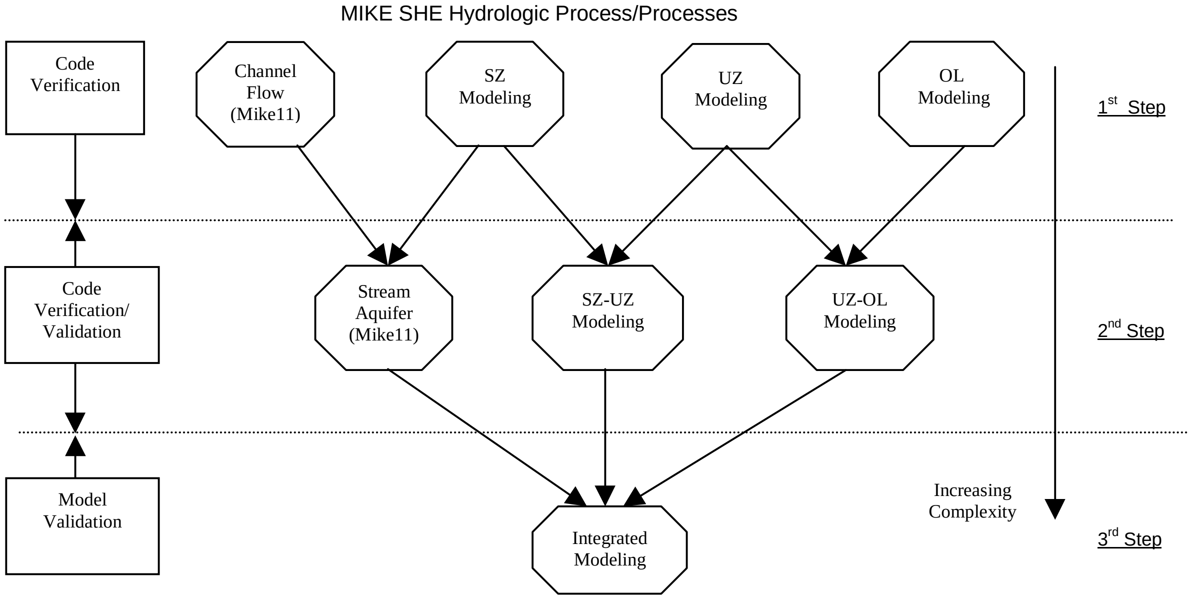


Figure 1.2 Primary steps involved in numerical code validation. (SZ=Saturated Zone, UZ=Unsaturated Zone, OL=Overland Flow)

Several potential code verification tests were identified from the literature. From these potential tests, the following were selected to meet the needs and time constraints of this code verification project:

<u>Single Processes</u>

Saturated Zone (2-dimenssional)
- Theis Solution (2-dimensional)
- Hantush (2-dimensional) (Hantush, 1965)
- Circular Island (2-dimensional)

Unsaturated Zone (1-dimensional)
- Gardner, 1957

<u>Coupled Processes</u>

Stream/Aquifer (3-dimensional)
- Hunt, 1999

Lake/Aquifer (3-dimensional)
- Kacimov, 2001.

Task 3: Code validation

"Code validation" refers to benchmarking the code against other numerical codes. Thus, the code performance can be evaluated against other well tested/verified codes. The objective is to evaluate the code under more complex conditions (step 2 in Figure 1) than those allowed using analytical solutions.

Since no suitable codes exist to test the coupled processes, the saturated zone and unsaturated zone code components were tested independently.

Saturated Zone

For the saturated zone, MIKE SHE was tested against MODFLOW (McDonald and Harbaugh, 1988). MODFLOW is the most widely used code in the world for simulating groundwater flow in the saturated zone. For this test, three test cases were selected from Anderson (1993). This document outlines 20 test problems that were developed for the USEPA for training new MODFLOW users. Thus, these test problems were not developed to test MODFLOW, but rather were developed to demonstrate various features of MODFLOW. As such, the following three problems were selected as being relevant to MIKE SHE:

- Problem 3 – Conversion between confined and unconfined conditions during dewatering.
- Problem 11 – Pressure dissipation in aquitards
- Problem 20 – 2D Flow Scenario

Unsaturated Zone

For the unsaturated zone, MIKE SHE was tested against VS2DT (Lappala et al., 1990). VS2DT is a 2-dimensional, unsaturated zone model developed by the USGS that solves Richard's equation using finite differences.

Task 4: Semi-quantitative performance evaluation

A semi-quantitative performance evaluation provides the only viable way to test the code's performance in more complex hydrologic conditions. In each test case, a hydrologic problem is specified and MIKE SHE's performance (e.g. water balance and water table response) is qualitatively evaluated.

The following seven test cases were selected:

Saturated zone / surface water interaction

- 2D saturated / surface water model with transient river stage
- 2D saturated / surface water model with transient pumping and recharge
- 3D saturated / surface water model with transient pond stage

Unsaturated zone / saturated zone interaction

- 2D unsaturated / saturated model with transient recharge without ponding
- 2D unsaturated / saturated model with transient recharge with surface ponding

Overland flow / surface water interaction

- 2D overland flow /surface water model with an impervious surface
- 2D overland flow /surface water model with a pervious surface

2 CODE VERIFICATION – SINGLE PROCESSES

2.1 Saturated Zone – Theis

Theis (1941) presented an analytical solution for the transient drawdown in an infinite uniform aquifer bounded on one side by a constant head boundary at distance   from a pumping well (See Figure 2.1).

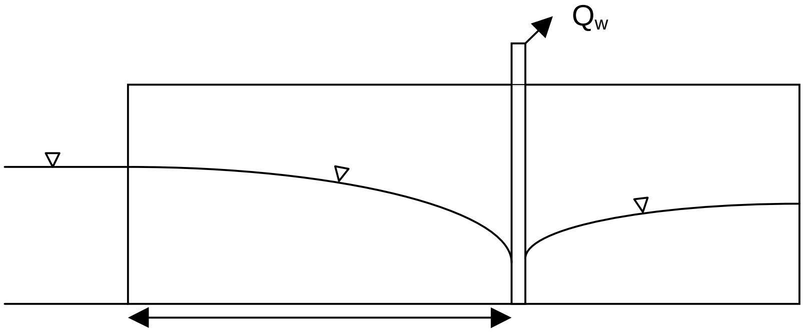


Figure 2-1 The problem considered by Theis *(1941) (from* Hunt*, 1999)*

Analytical Solution

The analytical solution of the drawdown as a function of time and space, ϕ(x, y, t), is given by Hunt (1999) as

$$\phi(x,y,t) = \frac{Q_w}{4\pi T}\left\{ W\left[\frac{\left(\;\; - x\right)^2 + y^2}{4Tt/S}\right] - W\left[\frac{\left(\;\; + |x|\right)^2 + y^2}{4Tt/S}\right]\right\} \tag{2.1}$$

where

Q$_w$	is the constant flow rate abstracted from the well from t = 0 to t = ∞, [L3/T]
S	is the aquifer storage coefficient, specific yield, or effective porosity, [-]
	is the shortest distance between the well and the stream, [L]
T	is the aquifer transmissivity, [L2/T]
t	is the time, [T], and
W	is the well function or exponential integral,

$$W(u) = {}_{u}^{\infty}\frac{e^{-x}}{x}dx = -\gamma - \ln(u) + u - \frac{u^2}{2\cdot 2!} + \frac{u^3}{3\cdot 3!} - .... - \frac{(-1)^n u^n}{n\cdot n!} \qquad (2.2)$$

and $\gamma = 0.577216\ldots$ is Euler's constant.

The steady-state analytical (Theis) solution is found when $t \rightarrow \infty$ in equation (2.1)

$$\phi(x,y) = \frac{Q_w}{4\pi T}\ln\left(\frac{\left(\ +|x|\right)^2 + y^2}{\left(\ -x\right)^2 + y^2}\right) \quad (x, y) \neq (\ , 0) \qquad (2.3)$$

MIKE SHE Components Tested

Time Domain	Component	Boundary Conditions	Component interactions
Steady state Transient	Saturated Zone	Pumping wells Constant head boundaries	none

Model Set Up

The set up of the analytical and MIKE SHE test case used the following parameters:

Q_w = 10,000 m^3/yr = 3.17×10^{-4} m^3/s,

S = 0.2,

= 100 m,

T = 0.001 m^2/s = K_x* thickness = (10^{-4} m/s)*(10 m), and

t = 2.0×10^6 s ≈ 23 days.

The MIKE SHE model consisted of

# of Layers	1
# of Rows	100
# of Columns	100
Cell size	10 m

The MIKE SHE model set up is illustrated in Figure 2.2. The stream cells are defined as constant head cells with a head value of 10m. The left and right constant head boundaries are set to 10 m for the transient simulation. For the steady-state simulation, they are set to the values calculated by the analytical solution. For the transient simulation, the initial condition is 10m everywhere.

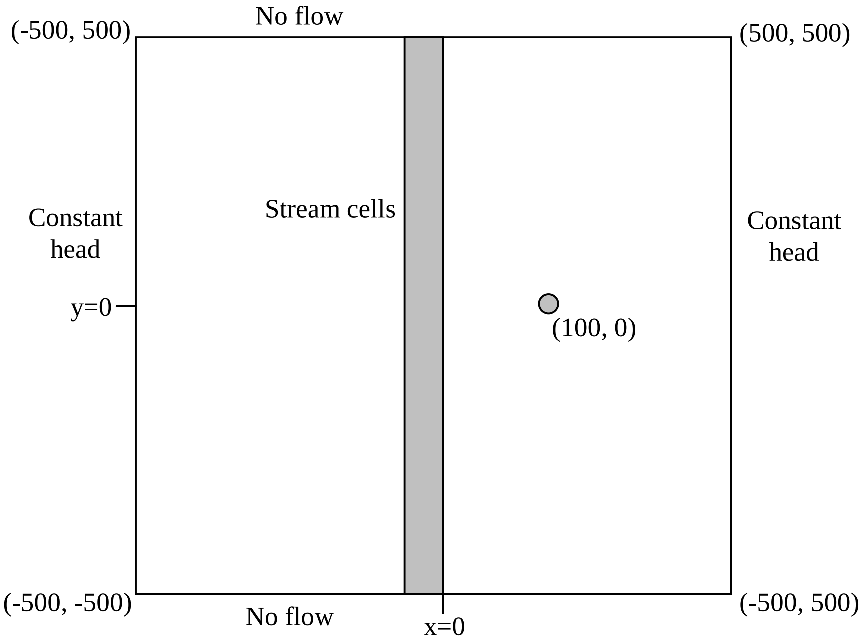


Figure 2.2 Plan view of MIKE SHE model set-up for comparison to the Theis analytical solution.

Analytical solution versus MIKE SHE

Figure 2.3 shows the drawdown along a cross-section through the well and perpendicular to the stream. The steady-state drawdown is calculated using Equation (2.3). For both the steady-state and the transient simulations, the match between MIKE SHE and the analytical solution is almost exact. For the transient case, the MIKE SHE drawdown after 23 days is plotted against Equation (2.1).

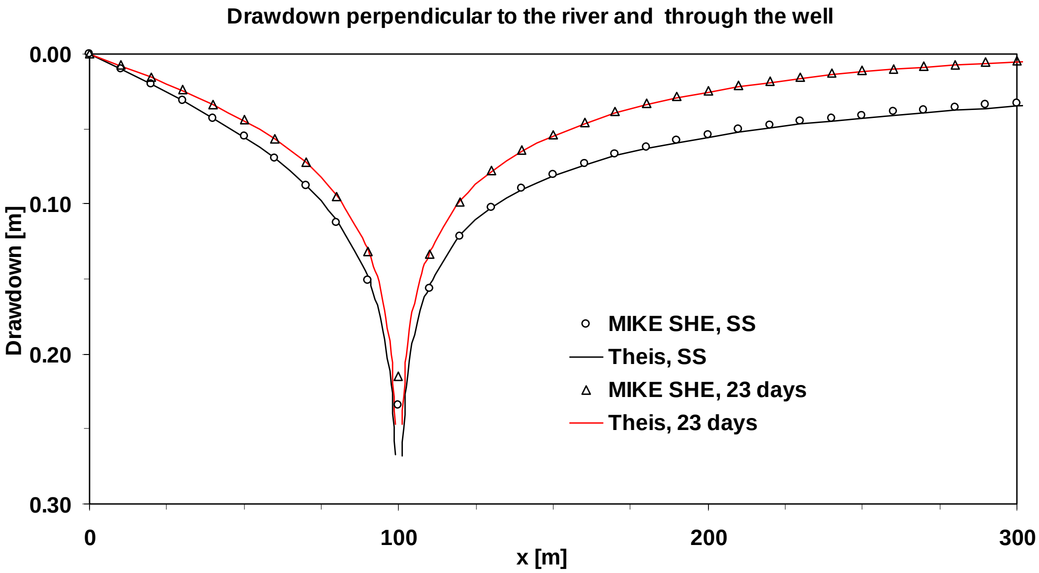


Figure 2.3 Comparison between the Theis analytical solution and MIKE SHE. (Tabular data in Appendix A.)

Figures 2.4 and 2.5 compare the transient MIKE SHE drawdown for the first 23 days against the Theis analytical solution for the same period. In Figure 2.4, the drawdown is calculated at a point half way between the stream and the well. Here the difference between the Theis solution and MIKE SHE is less than one millimetre. In Figure 2.5, the drawdown is calculated at a point close to the well (90 m from the stream; 10 m from the well). Here the difference between the Theis solution and MIKE SHE is slightly greater, but is still less than half a centimetre.

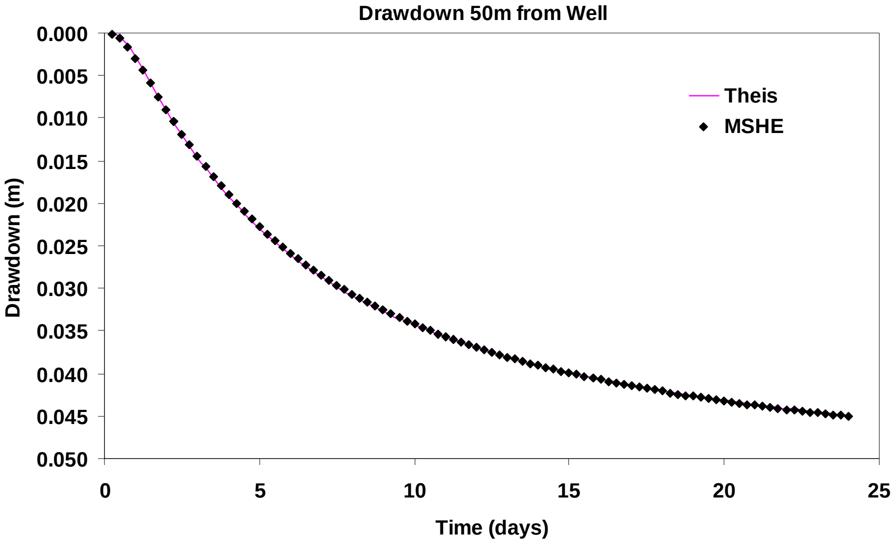


Figure 2.4 *Transient comparison between the Theis analytical solution and MIKE SHE half way between the well and the stream. (Tabular data in Appendix A.)*

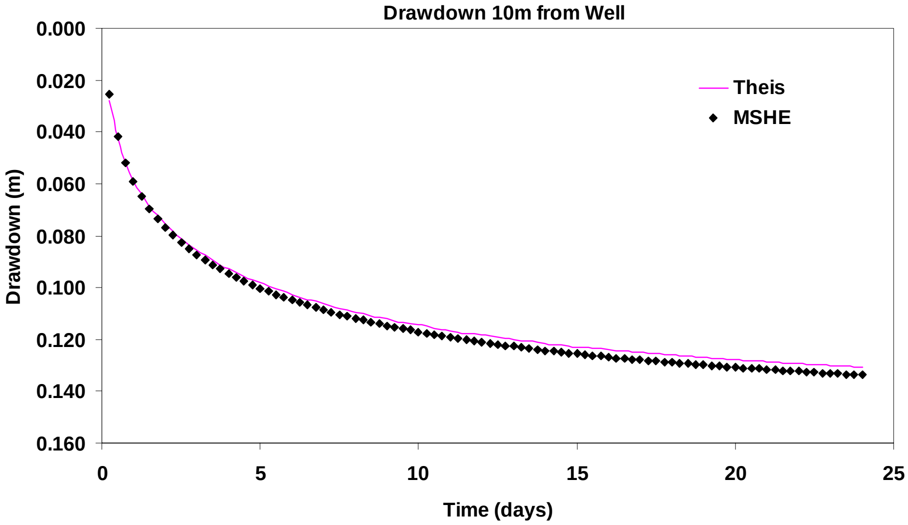


Figure 2.5 *Transient comparison between the Theis analytical solution and MIKE SHE close to the well. (Tabular data in Appendix A.)*

2.2 Saturated Zone – Hantush

Hantush (Hantush, 1965) considered the same problem as Theis, except he accounted for a semi-pervious zone adjacent to the constant head boundary. Again, the aquifer is uniform and of infinite extent, with a constant head boundary along one side (See Figure 2.6).

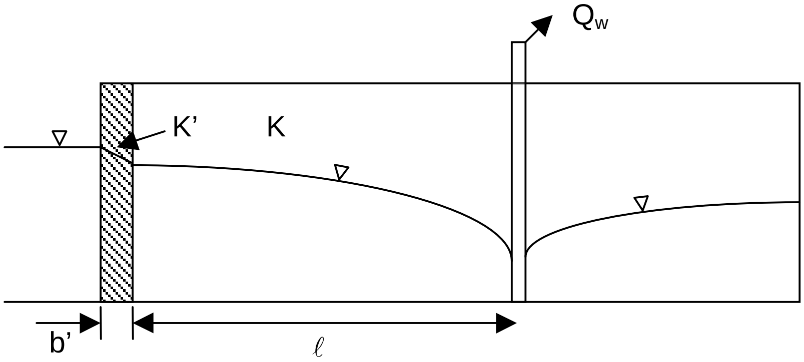


Figure 2.6 The problem considered by Hantush

Analytical Solution

The analytical solution for a steady-state drawdown in the cross section through the well (y=0) is given by

$$\phi(x) - \frac{(\phi(x))^2}{2D_0} = \frac{Q_w}{2\pi K D_0} f(\eta,\mu) \tag{2.4}$$

$$f(\eta,\mu) = \ln\left[(2\eta/\mu) - 1\right] + 2\exp(2\eta - \mu) W(2\eta - \mu) \tag{2.5}$$

$\eta = \ /a$, and

$\mu = |x|/a$

where

D_0 is the initial saturated thickness of the aquifer [L],

a is the stream leakance [L] and is defined as a = K/(K'/b'),

K is the hydraulic conductivity of the aquifer [L/T],

K' is the hydraulic conductivity of the streambed [L/T],

b' is the thickness of the semi-pervious layer [L], and

x is the distance from the well along the x-axis.

Equation (2.4) is valid for x-values between the stream and the well, where x is the absolute distance from the well. For x-values on the opposite side of the well the drawdown is also calculated using Equations (2.4) and (2.5), except that the minus signs in equation (2.5) are replaced with plus signs. The quadratic expression of $\phi(x)$ can easily be solved using the smaller of the two solutions, which for small values of $\phi(x)$ and large values of D_0 is almost identical to the left hand side of Equation (2.4). A drawdown can also be found for y-values different from zero and for a transient case, but will not be considered here, see *Hantush* (1965).

MIKE SHE Components Tested

Time Domain	Component	Boundary Conditions	Component interactions
Steady state	Saturated zone	Pumping wells Constant head boundaries	None

Model Set Up

The set up of the analytical and MIKE SHE test case used the following parameters:

$Q_w = 10{,}000\ m^3/yr = 3.17 \times 10^{-4}\ m^3/s$,

= 100 m,

Model thickness = 10 m,

$K = 10^{-4}$ m/s,

$K' = 10^{-6}$ m/s, and

$b' = 10.0$ m.

This results in a stream leakance of L = 1000 1/m.

The MIKE SHE model consisted of

# of Layers	1
# of Rows	100
# of Columns	100
Cell size	10 m

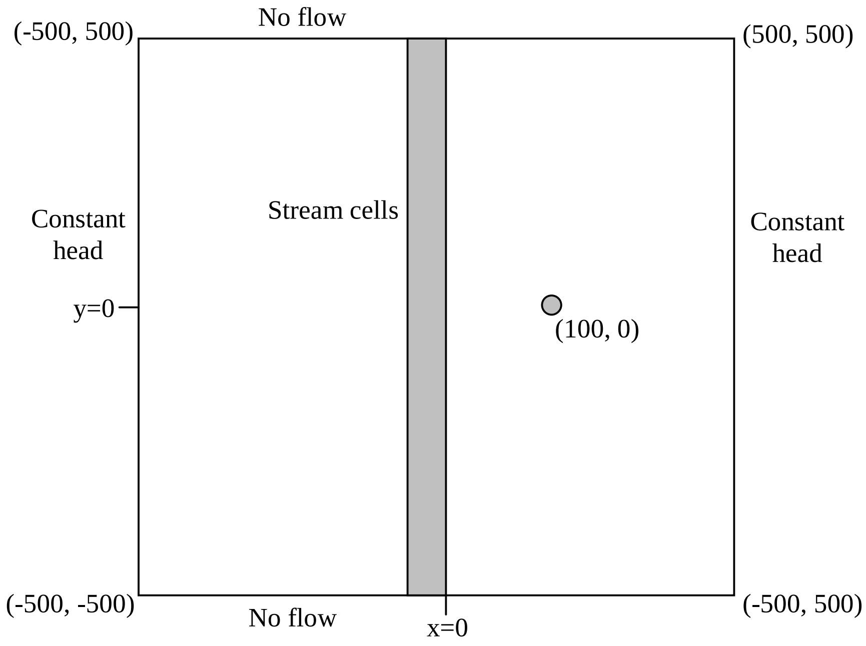


Figure 2.7 Plan view of MIKE SHE model set-up for comparison to the Hantush analytical solution.

The MIKE SHE set up, which is nearly the same as the Theis model in Section 2.2, is show in Figure 2.7. The one exception is the hydraulic conductivity in the stream cells. The rest of the aquifer has a hydraulic conductivity of 10^{-4} m/s.

The transmissivity between two nodes in MIKE SHE is calculated using the harmonic mean of the conductivities of the two cells. Thus, the hydraulic conductivity of the stream cells must be specified such that the hydraulic conductivity between the two nodes is 10^{-6} m/s. Using a drawdown of 20cm in the first cell after the stream and saturated thickness of 10m in the stream cells results in a conductivity of 4.97×10^{-7} for the stream cells.

The left and right constant head boundaries are set to 10m.

Analytical solution versus MIKE SHE

Figure 2.8 shows the MIKE SHE drawdown along a cross-section through the well and perpendicular to the stream. The analytical drawdown was calculated using Equations (2.6) and (2.7). The match between MIKE SHE and the analytical solution is quite close. Compared to the analytical solution, the MIKE SHE drawdown is a 1 to 2cm greater everywhere and 2 to 3cm greater next to the river. This indicates that the flow through the streambed is slightly less in the MIKE SHE model. However, this is probably due to numerical differences resulting from round off errors and the discretization.

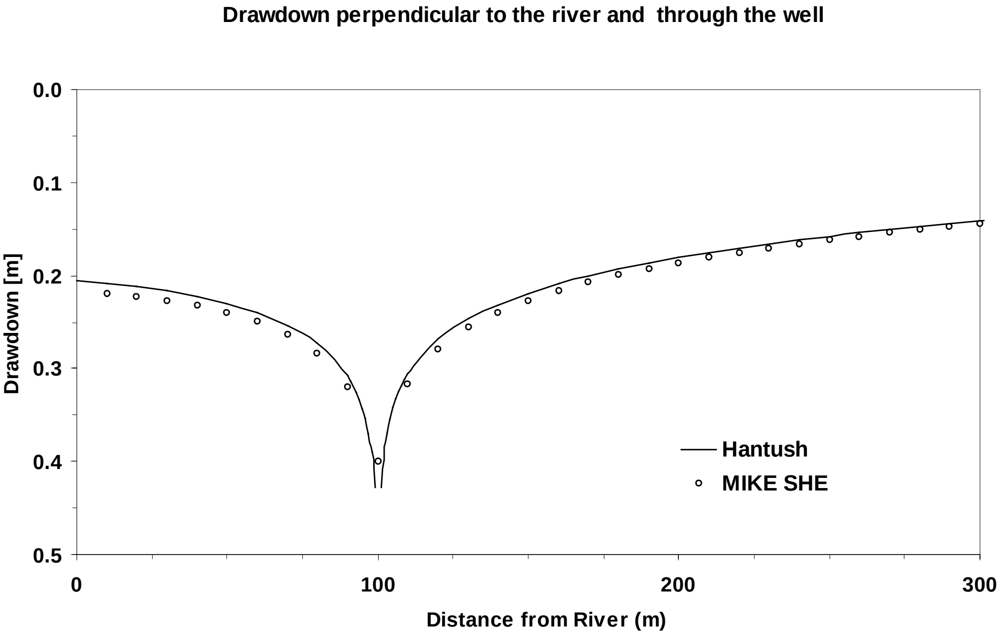


Figure 2.8 Comparison between the Hantush analytical solution and MIKE SHE. (Tabular data in Appendix A.)

2.3 Saturated zone - Circular Island

In this test, MIKE SHE was compared to an analytical solution of the steady state drawdown due to groundwater pumping in a homogeneous aquifer. The drawdown is calculated for a cylindrical island with a constant abstraction rate in a well in the centre of the island. A constant recharge is added on top of the aquifer. (See Figure 2.9)

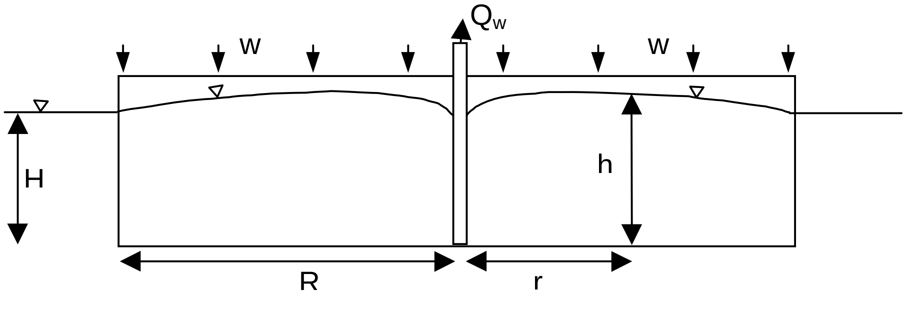


Figure 2.9 The circular island problem

Analytical Solution

The steady-state solution of the hydraulic head, h, as a function of the radial distance from the well, r, is given by:

$$H^2 - h^2 = \frac{Q_w}{\pi K} \ln \frac{R}{r} - \frac{w}{2K}\left(R^2 - r^2\right) \text{, } 0 < r \le R \qquad (2.6)$$

H	is the initial saturated thickness [L],
R	is the radius of the island [L],
Q_w	is the constant flow rate abstracted from the well [L^3/T],
K	is the hydraulic conductivity [L/T], and
w	is the recharge [L/T].

MIKE SHE Components Tested

Time Domain	Component	Boundary Conditions	Component interactions
Steady state	Saturated Zone	Pumping wells Constant head boundaries Recharge	none

Model Set Up

For the analytical solution and the MIKE SHE model, the following parameters were used:

Island radius, $R = 5{,}000$ m,

Constant head boundary, $H = 8$ m,

$K = 10^{-3}$ m/s,

$S_y = 0.2$

recharge = 0.01 mm/h = 2.778×10^{-9} m/s, and

$Q_w = 1{,}000{,}000\ m^3/yr = 0.0317\ m^3/s$.

MIKE SHE model consisted of

# of Layers	1
# of Rows	101
# of Columns	101
Cell size	100 m x 10m thick

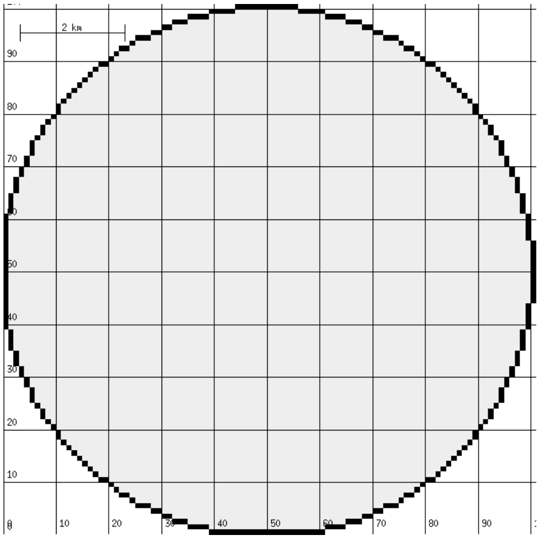


Figure 2.10 MIKE SHE model layout for circular island problem.

The pumping well was located in the center of the island.

Analytical solution versus MIKE SHE

To compare MIKE SHE to the analytical solution the maximum hydraulic head was calculated, which is found by differentiating equation (2.6) with respect to r and setting the derivative equal to zero. Thus, h has a maximum if

$$\frac{dh}{dr} = 0 \qquad r = \sqrt{\frac{Q_w}{\pi w}} \tag{2.7}$$

In the case of no abstraction ($Q_w = 0$), r = 0 and from (2.6)

$$h_{max} = \sqrt{H^2 + \frac{wR^2}{2K}} = 9.9359 \text{ m.} \tag{2.8}$$

With an abstraction rate of $Q_w = 0.0317$ m^3/s and a recharge of 2.778×10^{-9} m/s, $r \approx 1906$ m, and from (2.8) $h_{max} = 9.1620$ m.

The following table summarizes the maximum head values calculated by both MIKE SHE and equation (2.8).

	MIKE SHE	**Analytical Solution**
No pumping	9.9414 m	9.9359 m
With pumping	9.1851 m	9.1620 m

Figure 2.11 compares the head profile along a radius from the pumping well to the edge of the island. The MIKE SHE results are nearly identical to the analytical results. The only exception is near the well, where the discrepancy is due to the 100m discretization used in MIKE SHE.

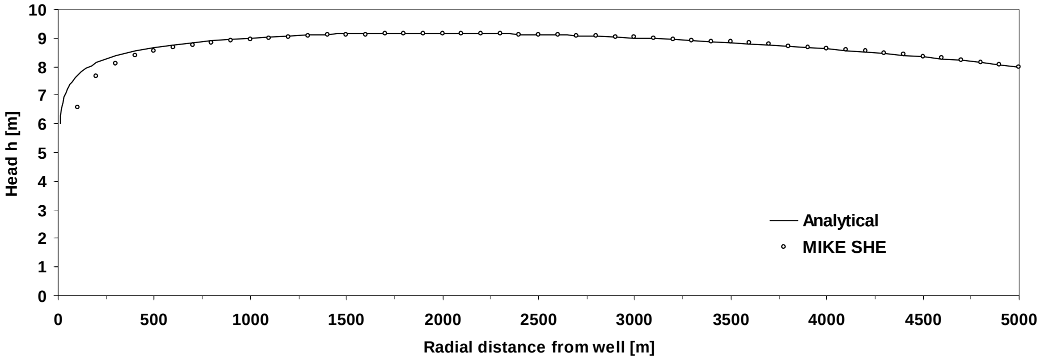


Figure 2.11 The circular island analytical solution compared to MIKE SHE. (Tabular data in Appendix A.)

2.4 Unsaturated Zone – Gardner

All of the available models for the flow of water in the unsaturated zone, as well as the UZ component in MIKE SHE are derived from Richard's equation,

$$\frac{\partial \phi}{\partial t} = \frac{\partial}{\partial z} K(\phi) \frac{\partial \psi}{\partial z} - \frac{\partial K(\phi)}{\partial z} \tag{2.7}$$

where, ϕ is the effective saturation, ψ is the pressure head and $K(\phi)$ is the hydraulic conductivity of the soil to water, which depends on the water content of the soil. The dependent variables, ϕ and ψ, are related through the soil moisture retention curve, $\psi(\phi)$.

The Gardner (1957) analytical model is a simple model, in which the hydraulic conductivity is given as a function of ψ directly,

$$K = K_s e^{\alpha\psi} \tag{2.8}$$

where, K_s is the saturated hydraulic conductivity and α is a fitting parameter.

Integrating (2.7) at steady-state with (2.8) and setting phi=0 and z=0 at the water table gives

$$\psi = \frac{1}{\alpha}\ln\left[\left(1+\frac{q}{K_s}\right)e^{-\alpha z} - \frac{q}{K_s}\right] \quad (2.9)$$

which describes the pressure head at a distance z above the water table for a given steady-state infiltration, q.

The most important limitation of this model is that there is no functional relationship between pressure head and saturation. Thus, the only output from the Gardner model is the pressure head above the water table.

MIKE SHE Components Tested

Time Domain	Component	Boundary Conditions	Component interactions
Steady state	Unsaturated Zone	Recharge	none

Model Set Up

In MIKE SHE, the effective hydraulic conductivity is also described as a power function. However, the power function is in terms of the effective saturation not pressure head

$$K = K_s S_e^n \quad (2.10)$$

where

$S_e = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)}$, θ_r = residual water content and θ_s = saturated water content

and n is a fitting parameter.

The soil moisture retention curve relates saturation to pressure head, which in MIKE SHE is input as tabular data. The effective conductivity values can be calculated using (2.10) for the tabular moisture data for the *fine sand* data in the *finesand.dbf* database file, which is supplied with MIKE SHE. However, when the two fitting parameters, n (MikeSHE) and α (Gardner), are adjusted to try to match the two curves, the Gardner curve and the MikeSHE data are not very similar, especially for high suction values (See Figure 2.12). Given this discrepancy and the need for an accurate comparison, the MIKE SHE code was modified so that K_{eff} as a function of ψ could be input in tabular form similar to the soil moisture retention data. Thus, Figure 2.12 also shows the K_{eff} data used in the modified version of MIKE SHE.

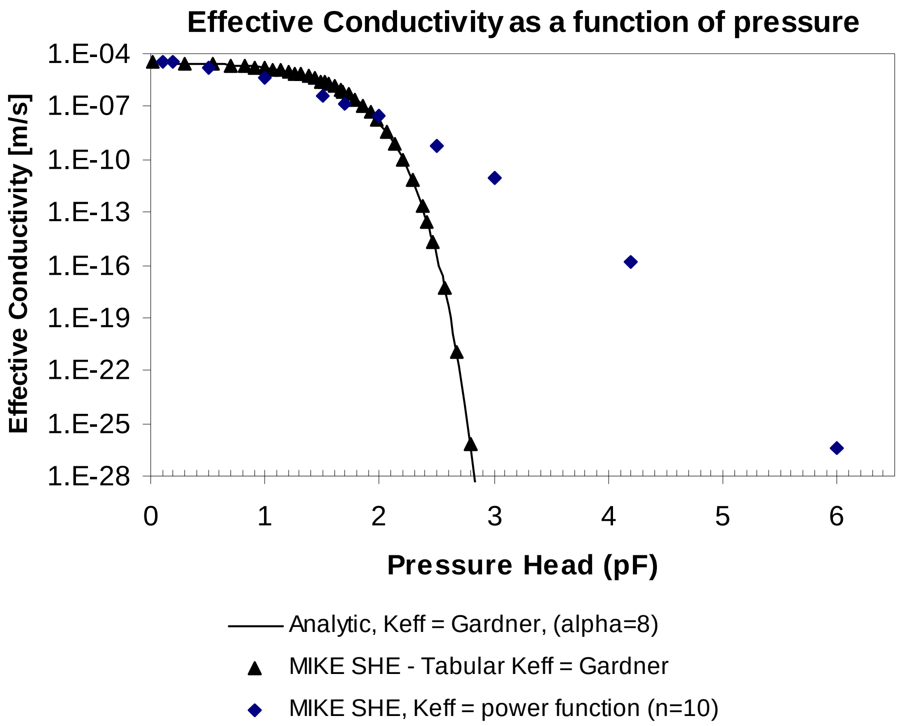


*Figure 2.12 Effective conductivity functions for the Gardner analytical model and MIKE SHE (**finesand** in the **finesand.dbf** database).*

Figure 2.13 shows the 5m-high test column that was set up in MikeSHE and solved analytically using (2.9).

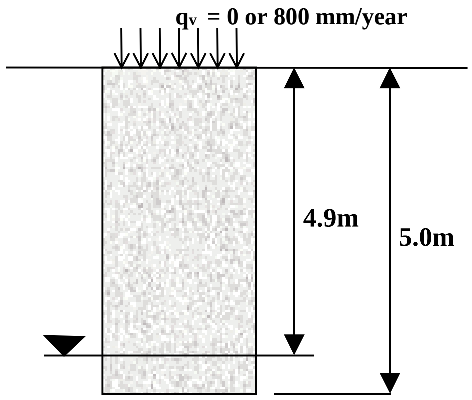


Figure 2.13 Test column for the testing using MIKE SHE and the Gardner equation.

The MIKE SHE model was set up to run only the UZ component with following dimensions and parameters

# of Layers	100
# of Rows	3
# of Columns	3
Cell size	1m x 1m x 5cm thick
K_{sat} =	3.47e-5 m/s
θ_{sat} =	0.42
θ_r =	0.01

Analytical solution versus MIKE SHE

Figures 2.14 and 2.15 show that the pressure head calculated by MIKE SHE is identical to that pressure calculated by the Gardner analytical solution with and without infiltration.

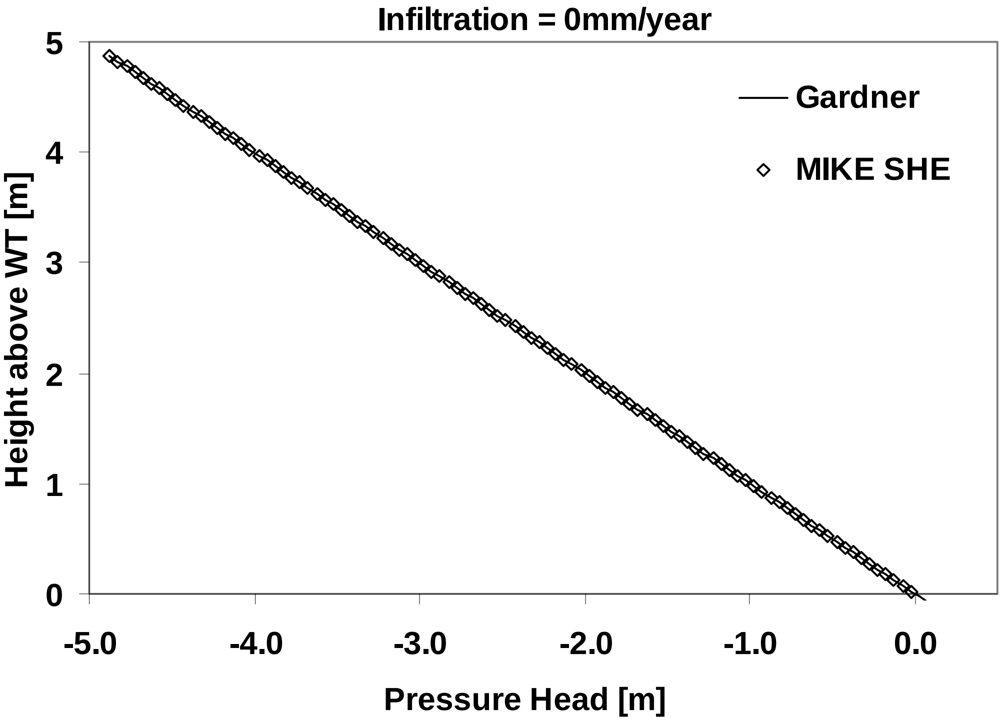


Figure 2.14 Pressure head versus depth for MIKE SHE and the Gardner analytical model with no infiltration. (Tabular data in Appendix A.)

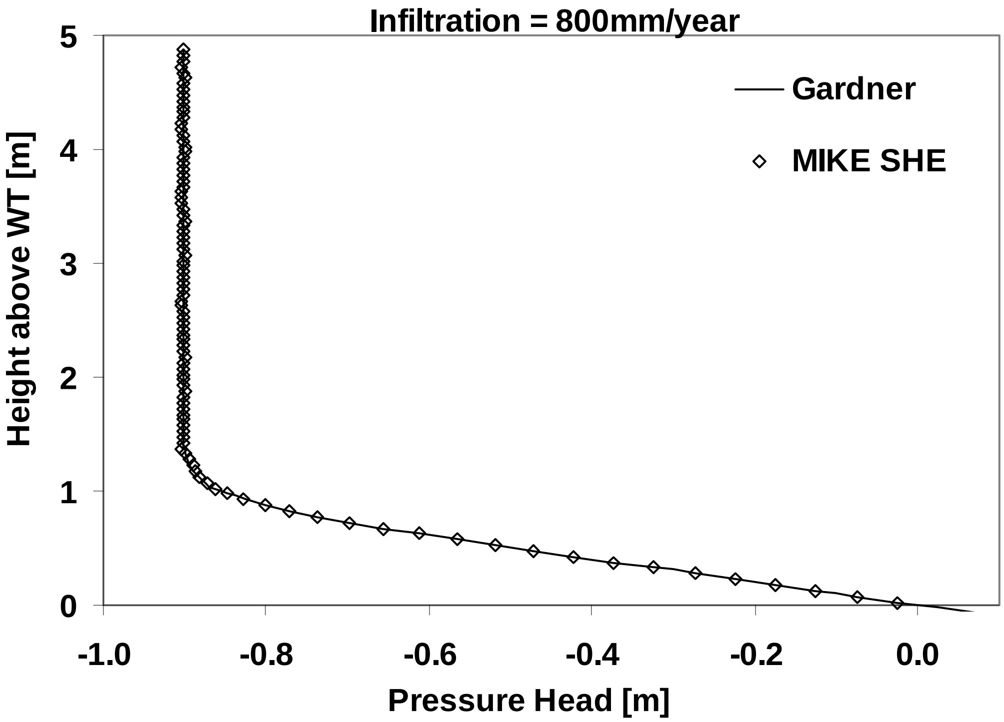


Figure 2.15 Pressure head versus depth for MIKE SHE and the Gardner analytical model with 800mm/year infiltration. (Tabular data in Appendix A.)

3 CODE VERIFICATION – COUPLED PROCESSES

3.1 Stream/Aquifer – Hunt

Hunt (1999) considered the same problem as Hantush and Theis, except the stream is not modeled as a constant head boundary on the side of the model but rather as a line source along the top boundary. A semi-pervious zone adjacent to the stream boundary is also included. Again, the aquifer is uniform and of infinite extent, with no flow boundaries along the sides.

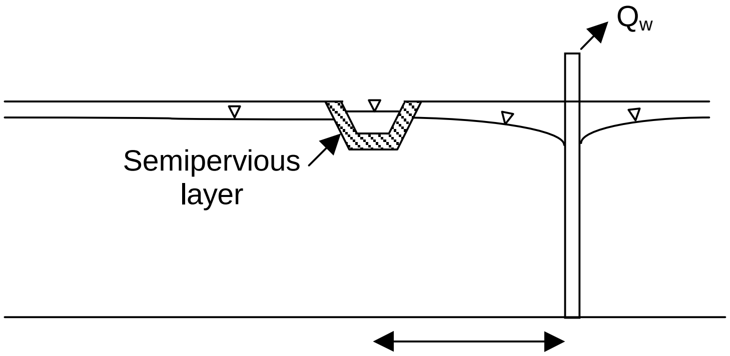


Figure 3-1 The problem considered by Hunt *(1999).*

Analytical Solution

The analytical solution of the drawdown as a function of time and space, $\phi(x, y, t)$, is given by *Hunt* as

$$\phi(x,y,t) = \frac{Q_w}{4\pi T}\left\{ W\left[\frac{(\quad - x)^2 + y^2}{4Tt/S}\right] - {}_{0}^{\infty} e^{-\theta} W\left[\frac{(\quad + |x| + 2T\theta/\lambda)^2 + y^2}{4Tt/S}\right] d\theta \right\} \tag{3.1}$$

where λ [L/T] is a constant of proportionality between the seepage flow rate per unit distance (in the y direction) through the streambed and the difference between river and groundwater levels at x = 0.

The integral on the right hand side of equation (3.1) must be evaluated numerically, which is straight forward since the integrand decays exponentially. A small Fortran program was written to calculate the integral and thereby the drawdown. The program uses a fixed $d\theta$ = 0.01, and infinity is replaced with θ = 9.99. These parameters have shown to give precise results for this test case. However, caution should be taken if the program is used with other parameter values, since the integrand depends on seven parameters.

MIKE SHE Components Tested

Time Domain	Component	Boundary Conditions	Component interactions
Steady state	Saturated zone	Pumping wells	SZ – Surface water exchange
Transient		Constant head boundaries	
	Surface water flow	MIKE 11 river Reduced (b) leakage	

Model Set Up

The set up of the analytical and MIKE SHE test case used the following parameters:

$Q_w = 10{,}000\ \text{m}^3/\text{yr} = 3.17 \times 10^{-4}\ \text{m}^3/\text{s}$,

$S = 0.2$,

$= 100$ m,

$T = 0.001\ \text{m}^2/\text{s} = K_x$* thickness = $(10^{-4}$ m/s $)*(10$ m$)$,

Initial head = 10 m,

Recharge = 0, and

$t = 2.0 \times 10^6$ s $\approx$ 23 days.

The MIKE SHE model consisted of

# of Layers	1
# of Rows	100
# of Columns	100
Cell size	10 m

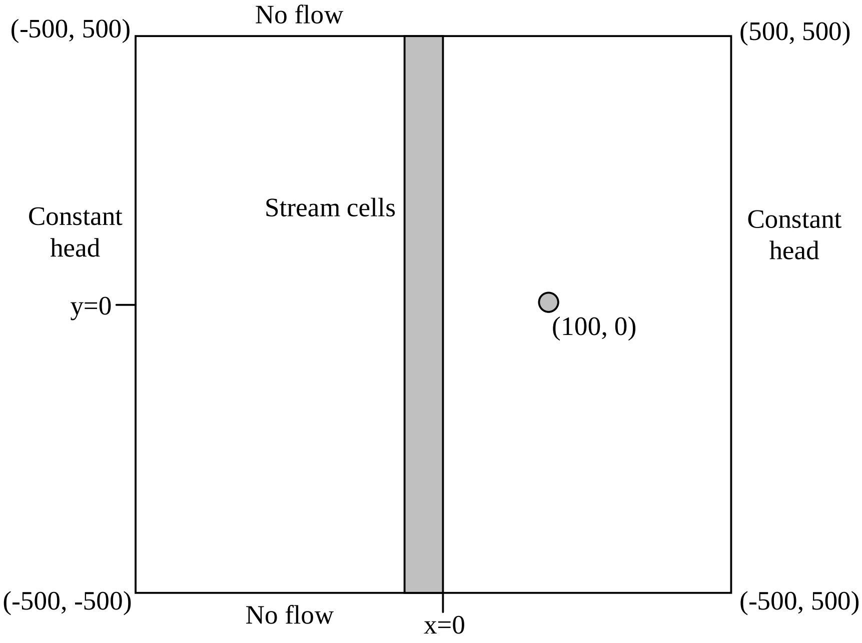


Figure 3.2 Plan view of MIKE SHE model set up with MIKE 11 River

The MIKE SHE set up, which is nearly the same as the Theis model in Section 2.1, is show in Figure 3.2. The left and right constant head boundaries are set to the values calculated by the analytical solution for the steady-state solution. For the transient case, they are kept constant at the initial value of 10 m.

The MIKE 11 setup, which is coupled to MIKE SHE, consists of a simple straight river crossing the model area at x = 0. There are 21 coupling points equally distributed with 50 m between them. The river cross section is symmetric. The river is 10 m wide at the ground surface (at an elevation level of 11 m) and 5 m wide at the river bed (elevation level of 9.5 m). A fixed river depth of 0.5 m (elevation level of 10.0 m) is used as initial value and boundary condition. The leakage is an exchange type '*Reduced (b)*' (exchange flow is calculated only based on the leakage coefficient of the river lining). The leakage coefficient is calculated as λ divided by an approximated wetted perimeter of the river. MIKE SHE calculates the wetted perimeter, w, as

$$w = 2 \times (\text{half width of river} + \text{depth of water})$$

In this setup, the wetted perimeter is calculated to be, $w = 2 \times (3.333 + 0.5)$ m = 7.667 m. Hence, the leakage coefficient becomes $\lambda/w = 10^{-5}$ m/s / 7.667 m = 1.3043×10^{-6} s^{-1}.

Analytical solution versus MIKE SHE

For a cross section through the well, the steady-state drawdown and the drawdown after 23 days is shown in Figure 3.3. The analytical results and the MIKE SHE results are nearly identical.

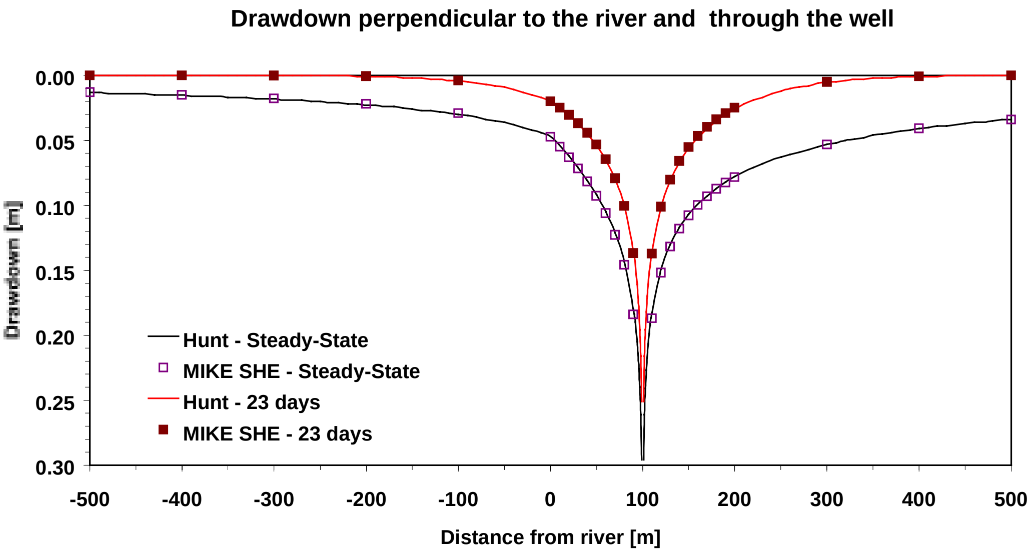


Figure 3.3 Comparison of the Hunt analytical drawdown versus MIKE SHE, perpendicular to the river and through the well. (Tabular data in Appendix A.)

In Figure 3.4, the transient MIKE SHE drawdown from time equals zero to 23 days is compared to the transient analytical solution over the same period. Again, the analytical solution is almost identical to the MIKE SHE numerical solution.

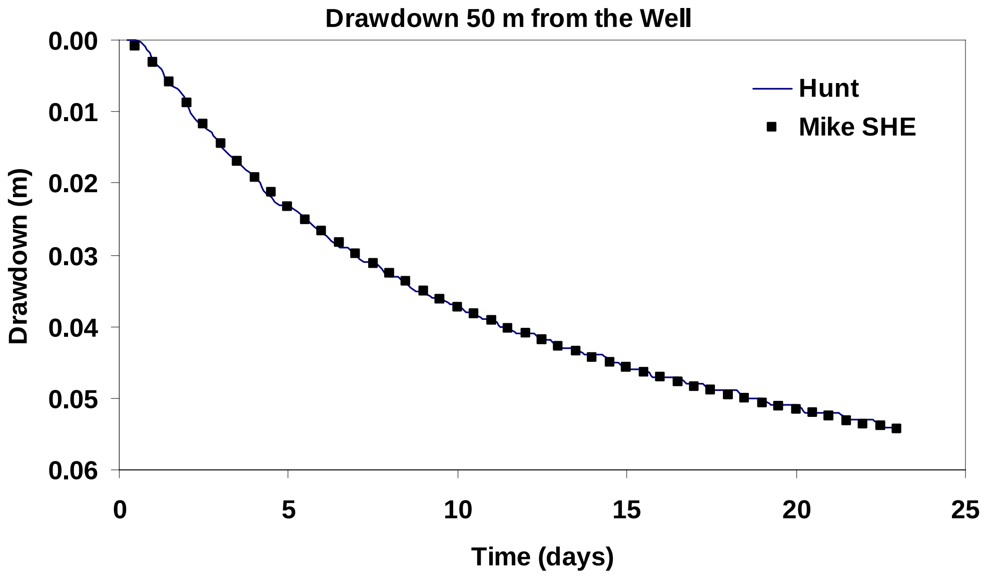


Figure 3.4 Comparison of the Hunt analytical drawdown versus MIKE SHE at a point half way between the river and the pumping well. (Tabular data in Appendix A.)

3.2 Lake/SZ – Kacimov

Kacimov (2000) presents an analytical solution for the 3-dimensional, steady-state flow to a hemispherical lake in a confined, homogeneous aquifer with a uniform regional gradient and infinite extent and depth. This test case is ideal for testing the interaction between large surface water bodies and the aquifer.

Analytical Solution

The lake is hemispherical in shape with a radius, *a*. At infinity, flow in the aquifer is uniform and its specific discharge, U_o, is oriented along the x-axis. The aquifer is uniform with conductivity, *k*, and confined such that there is no vertical flow across the plane that includes the upper surface of the lake. Along the bottom of the lake, h = -H, where H is the free surface head above or below the surface of the lake. Thus, the surface of the lake is not necessarily coincident with the head in the lake. The origin of the coordinate system is located in the center of the lake on its surface.

If the velocity potential equals $\phi = -kh(x, y, z)$ and the dimensionless potential is $\Phi = \phi/(k|H|)$ then the Laplace equation can be written for this system as

$$\frac{\partial^2\Phi}{\partial z^2}+\frac{\partial^2\Phi}{\partial x^2}+\frac{\partial^2\Phi}{\partial y^2}=0 \tag{3.3}$$

Now, knowing that the gradient is uniform far from the lake,

$\Phi \sim \alpha Z$ as $R = r/a = (X^2 + Y^2 + Z^2)^{1/2}$

where $\alpha = aU_o/(kH)$, introducing the dimensionless spherical coordinates,

(X, Y, Z) = (x, y, z)/a,

$Z = R\cos\theta$, $X = R\sin\theta\cos\omega$, and $Y = R\sin\theta\sin\omega$,

and assuming that the lake bottom is an equipotential, equation (3.3) can be solved to yield

$$\Phi=\frac{1}{R}-\frac{\alpha\cos\theta}{R^2}+\alpha R\cos\theta \tag{3.4}$$

Kacimov (2000) also presents a similar set of equations for a lake with a clogged bottom. However, this will not be considered here.

MIKE SHE Components Tested

Time Domain	Component	Boundary Conditions	Component interactions
Steady state	Saturated zone	Constant head boundaries	SZ – Surface water exchange
	Surface water flow	MIKE 11 lake Full leakage	

Model Set-up

The analytical model and the MIKE SHE model were solved with the following parameter values

hydraulic conductivity, k = 0.001 m/s
lake radius, a = 14 m
regional gradient, U_o = 0.004
head in the lake, H = 0.15 m (below the origin)

The MIKE SHE model was set up with the following dimensions and parameters

# of Layers	25
# of Rows	81
# of Columns	81
Cell size	2m x 2m (variable thickness)
Model depth	250 m
left boundary	Constant head = 0.29 m
right boundary	Constant head = -0.34 m

The lake geometry was defined in MIKE SHE by generating a grid of points along the lake bottom using radial coordinates and converting them to x, y, z pairs. This grid of points was then interpolated in MIKE SHE and modified to ensure that the top of the lake cells in Layer 1 were coincident with the bottom of the lake. The cells along the bottom of the lake were generally 2 m thick, except along the steep sides of the lake where they were up to 5 m thick. The MIKE SHE solution immediately upstream of the lake is very sensitive to the size and orientation of the cells along the steep sides of the lake.

The lake boundary was defined in two ways. First the cells in Layer 1 immediately beneath the lake were defined as constant head cells and only the SZ component was calculated. Next, the constant head cells were removed and a MIKE 11 lake was defined along the x-axis at y=0. The MIKE 11 lake was defined with 17 cross-sections that matched the hemi-spherical shape of the lake. Since both the OL and the SZ components were run in this scenario, overland flow in the confined zone upstream of the lake was restricted by sealing the top of the aquifer.

Analytical solution versus MIKE SHE

Figure 3.5 compares the analytical solution to the MIKE SHE model when the lake is defined as a constant head boundary. The solutions compare very favorably. Except for a zone immediately upstream of the lake and a zone below the lake, the difference between MIKE SHE and the Kacimov analytical model is less than 1 cm.

Figure 3.6 compares the analytical solution to the MIKE SHE model when the lake is defined as a MIKE 11 river. The MIKE SHE grid geometry in both models is identical and again the only significant deviation between the analytical solution and MIKE SHE is immediately upstream of the lake. In this case, the MIKE SHE model is up to about 5 cm too high, which is slightly more than in Figure 3.5.

The differences between MIKE SHE and the analytical solution can be attributed to the model discretization along the steep sides of the lake. The steep sides of the lake, and the consequent vertical offset of the adjacent cells, inhibits flow into the constant head and MIKE 11 boundaries. The difference between the solutions is sensitive to the geometry of the discretization around the lake. Using a relatively thick layer (5 m) for Layer 1 adjacent to the lake and thinner layers elsewhere minimized the difference between the analytical solution and MIKE SHE.

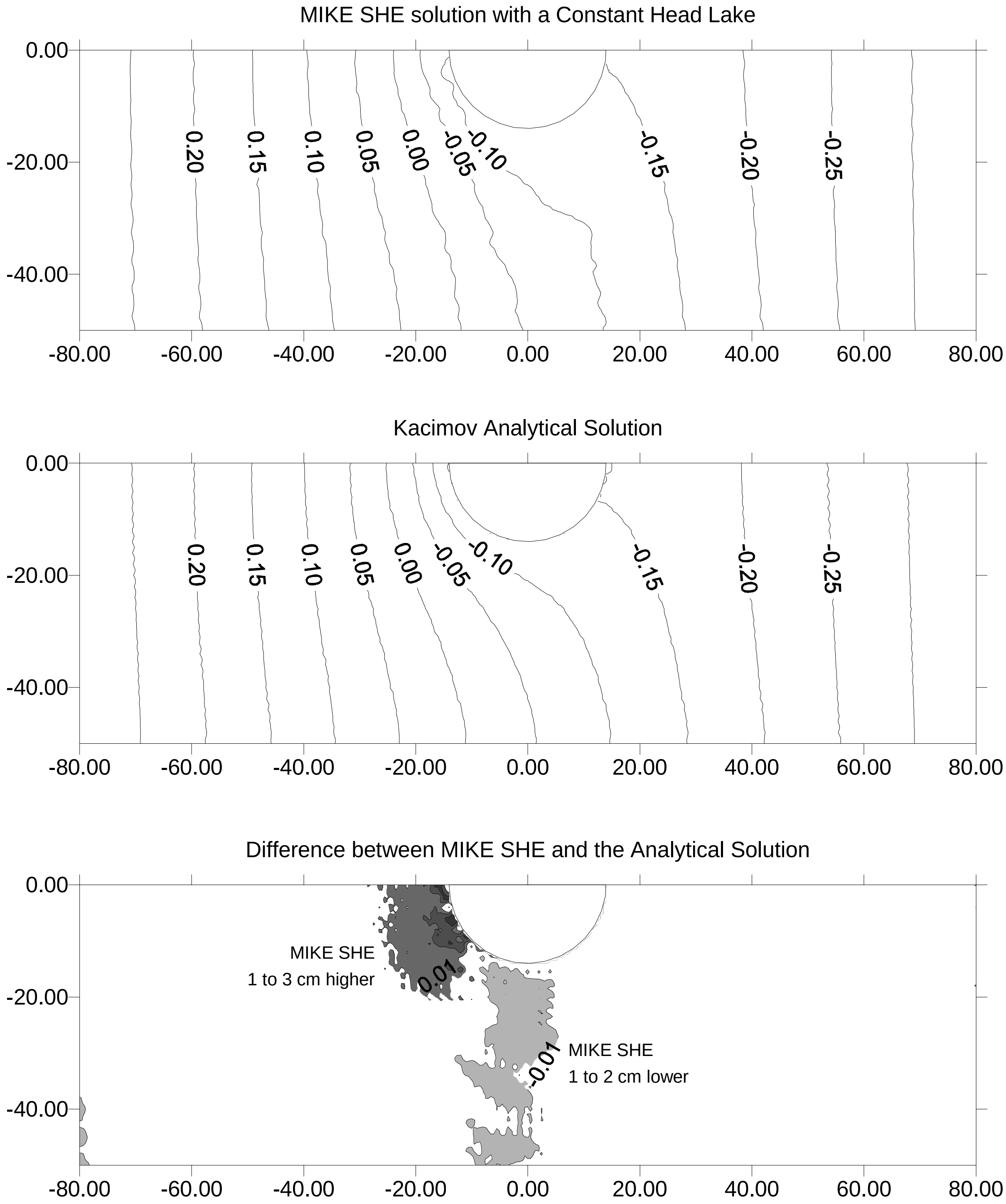
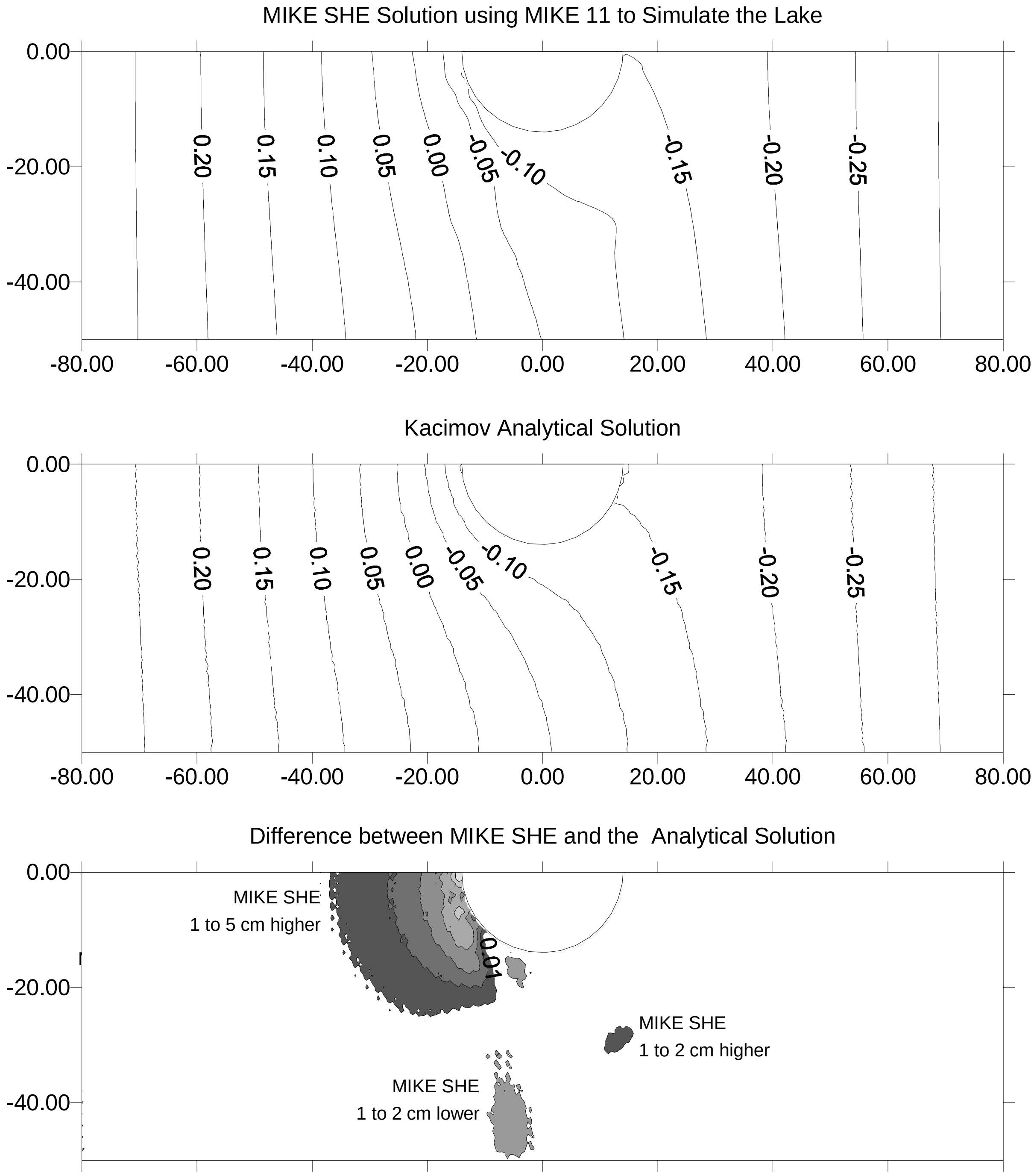


Figure 3.5 MIKE SHE with a constant head lake, compared to the Kacimov analytical model.



MIKE SHE Solution using MIKE 11 to Simulate the Lake

Kacimov Analytical Solution

Difference between MIKE SHE and the Analytical Solution

Figure 3.6 MIKE SHE using MIKE 11 to simulate the lake, compared to the Kacimov analytical model.

4 CODE VALIDATION

4.1 MODFLOW –Water Table Conversion (USEPA Test Case 3)

Model Background

When a confined aquifer is heavily stressed, its potentiometric surface may be drawn down such that the aquifer begins to dewater. While the aquifer is confined, water is released from storage in response to the pressure change and the amount of water released is relatively small. When the aquifer become unconfined, the amount of water released from storage increases as the pore spaces begin to dewater. Thus, as the water table is drawn down, the storage term used to calculate the amount of water released from storage changes from the specific storage coefficient to the specific yield.

This test case demonstrates the transient conversion from confined to unconfined conditions in a large uniform aquifer with a fully penetrating well. The well is located in the center of the aquifer. Since the drawdown in the aquifer is symmetric around the well, we can place the well in the lower left corner of the model and model only a quarter of the aquifer. The drawdown in the aquifer is monitored at a point 1000 ft from the pumping well.

MIKE SHE Components Tested

Time Domain	Component	Boundary Conditions	Component interactions
Transient	Saturated Zone	Pumping wells	none

Model Set up

The original test case from Anderson (1993) used Imperial units. Therefore, the MIKE SHE model was set up to mirror the original scale of the MODFLOW model. The original MODFLOW model was set up using a variable grid and geometrically increasing time steps. To eliminate bias in the comparison, a new MODFLOW model was constructed using the same grid and time steps of the MIKE SHE model. Table 4.1 contains the specific data used in the models.

Table 4.1 Model data for USEPA MODFLOW Test Case 3 – Artesian Water Table Conversion

	Original MODFLOW model	**MIKE SHE / MODFLOW models**
Initial head	0 ft	0 m
Transmissivity	2674 ft^2/d	-
Hydraulic conductivity	-	$2.884(10^{5})$ m/s
Aquifer thickness	-	100 m
Specific yield	0.1	0.1
Storage Coefficient	0.0001	0.0001
Specific storage	-	1.003(10-6) 1/m
Pumping rate	8409.09 ft3/d	86.97 [1000m^3/yr]
Simulation length	100 days	100 days
Timestep length	Variable (Factor = 1.414)	1 hour

Number of timesteps	25	2400
Model size	103,475 x 103,475 ft	3048 x 3048 m (10,000 x 10,000 ft)
Grid spacing	Variable	15.24 m (50 ft)
Number of layers	1	1
Top of aquifer	-1 ft	-0.3048 m
Boundary Conditions	No flow on all sides	No flow on all sides
Observation well	1000 ft from well	328 m from well

MIKE SHE uses the PCG solver for solving the SZ flow, which is derived directly from the published MODFLOW PCG2 solver, which was used for the MODFLOW model.

Comparison between MIKE SHE and MODFLOW

Figure 4.1 shows that MIKE SHE and MODFLOW produce almost exactly the same results in both confined and unconfined conditions. The top of the aquifer is 1 ft below the initial head. Thus, the model is initially confined and becomes unconfined when the drawdown reaches 1 ft. Table 4.2 shows the storage and Layer Type data used in the simulations.

Table 4.2 Storage and Layer Type simulation data for the for USEPA MODFLOW Test Case 3 – Artesian Water Table Conversion

	MODFLOW	**MIKE SHE**
Confined Simulation		
Confined Storage	0.0001	1.003(10^{-6}) 1/m
Unconfined Storage	-	0.0001
Layer Type	0	-
Transition Simulation		
Storage Coefficient	0.0001	1.003(10^{-6}) 1/m
Unconfined Storage	0.1	0.1
Layer Type	2	-
Unconfined Simulation		
Storage Coefficient	-	0.001 1/m
Unconfined Storage	0.1	0.1
Layer Type	1	-

Interestingly, when the model is completely confined, there is an increase in the rate of drawdown after about 5 days. This behaviour is not seen in the original MODFLOW results. It occurs here because the drawdown cone reaches the boundary of the model, which does not occur in the original MODFLOW model because the boundary is 10 times further away.

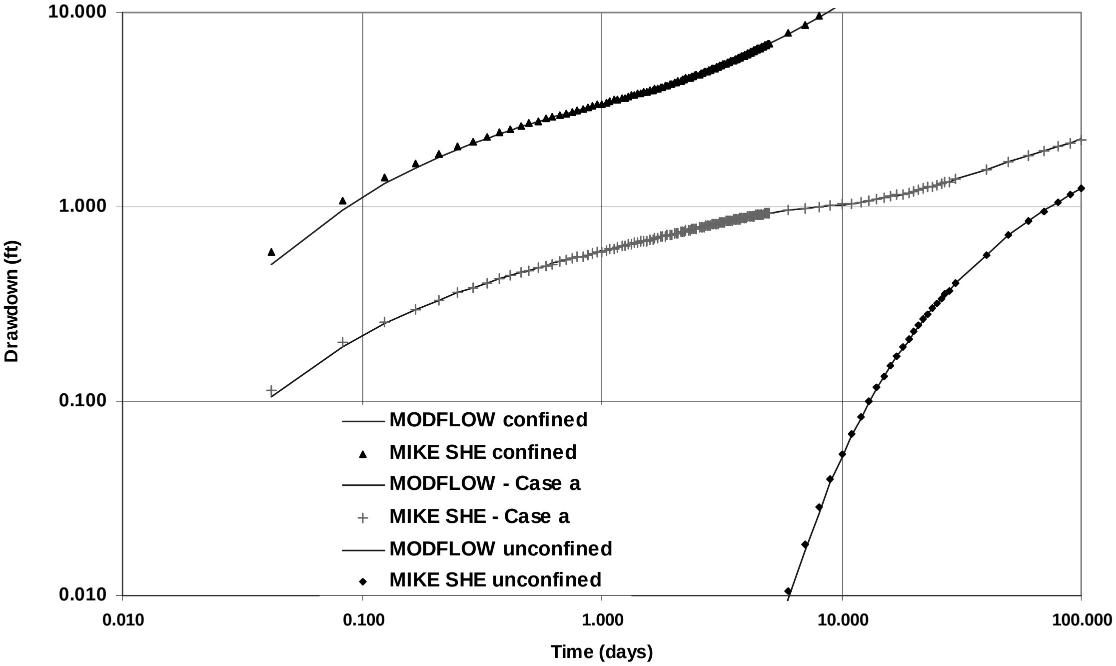


Figure 4-1 MODFLOW versus MIKE SHE for Artesian Water Table Conversion (EPA Test Case 3) (Tabular data in Appendix A.)

4.2 MODFLOW – Representation of Aquitards (USEPA Test Case 11)

Model Background

In multi aquifer simulations there are several ways to represent the confining beds that separate the aquifers. In MODFLOW, the aquifers can be modeled implicitly as leakage terms or explicitly as separate layers. In MIKE SHE aquitards must be modeled as separate layers because the geometry of the model must match reality. However, aquitards can be combined into aquifer layers by varying the vertical hydraulic conductivity. In both MODFLOW and MIKE SHE, however, the degree of vertical discretization is important if vertical processes are to be resolved correctly.

The USEPA Test Case 11 was designed to demonstrate the different means of representing transient vertical leakage in MODFLOW. Thus, it is not relevant to compare MIKE SHE against each of the tests in Test Case 11. Therefore, we have used Case b, which is the most general case, to compare the vertical leakage rates calculated by MIKE SHE and MODFLOW.

MIKE SHE Components Tested

Time Domain	Component	Boundary Conditions	Component interactions
Transient	Saturated Zone	Constant Head	none

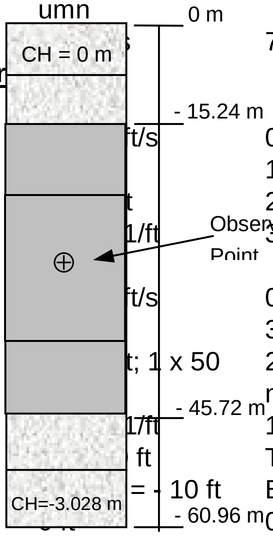
Model Set up

The original test case from Anderson (1993) used Imperial units. Therefore, the MIKE SHE model was set up to mirror the original scale of the MODFLOW model. The original MODFLOW model was set up using geometrically increasing time steps. To eliminate bias in the comparison, a new MODFLOW model was constructed using the same grid and time steps of the MIKE SHE model. Table 4.3 contains the specific data used in the models.

The test is a one-dimensional model, consisting of two aquifers separated by an aquitard. The model simulates the transient redistribution of pressure head across the aquitard.

Table 4.3 Model data for USEPA MODFLOW Test Case 11- Representation of Aquitards

	Original MODFLOW	**MIKE SHE / MODFLOW**
	1 row x 1 column	3 rows x 3 columns
	s	7 layers
Upper and Lower Aquifers		
Conductivity	ft/s	$0.6096(10^{-5})$ m/s
Thickness		15.24 m
Layers	t	2 x 7.620 m
Specific Storage	1/ft	$3.281(10^{-7})$ 1/m
Aquitard		
Conductivity	ft/s	$0.3048(10^{-8})$ m/s
Thickness		30.48 m
Layers	t; 1 x 50	2 x 7.62 m; 1 x 15.24 m
Specific Storage	1/ft	$16.404(10^{-6})$ 1/m
Constant Heads	ft	Top = 0 m
	= - 10 ft	Bottom = -3.028 m
Initial Heads		0 m



Comparison between MIKE SHE and MODFLOW

Figure 4.2 compares the results from the MODFLOW simulation against MIKE SHE. The results are identical except for a small deviation at late times. Note that both simulations were run with 1 hour time steps. However, Figure 4.2 includes hourly data up to 4 days, but only daily data until 30 days and every 10 days until 100 days.

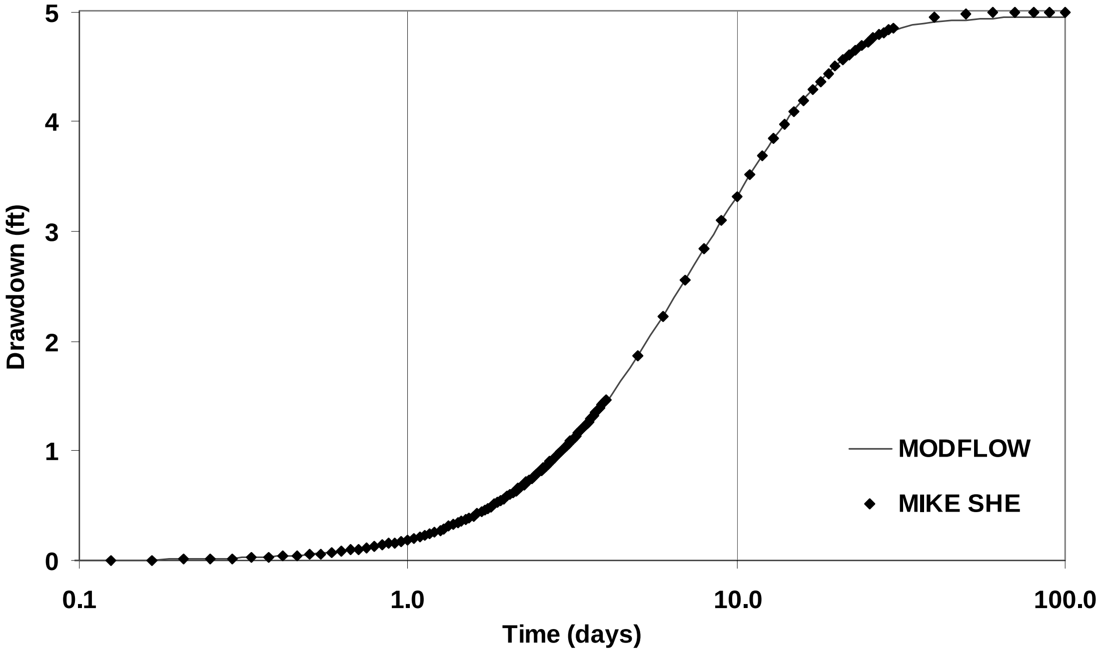


Figure 4-2 MODFLOW versus MIKE SHE for USEPA Test Case 11, Part b.

4.3 MODFLOW – 2D Test Site (USEPA Test Case 20a – steady state)

Model Background

USEPA Test Case 20 was derived from an analysis of conceptual remediation measures at a hazardous waste site. The results of the original groundwater modeling study were used in the remedial design proposed for the site. The original modeling study did not use MODFLOW but rather used the USGS2D code. The USGS2D model was calibrated to observed groundwater levels and stream discharges. These data are not published in the Anderson (1993) report. The model presented in Test Case 20, is a MODFLOW version of the original USGS2D model

Test Case 20 was selected as a more complex comparison between MIKE SHE and MODFLOW. However, there are several limitations associated with the comparison. The published MODFLOW model was developed with a variable grid spacing, which cannot be reproduced exactly in MIKE SHE. A MODFLOW interface for MIKE SHE is currently under development, which will make it much easier to make exact model comparisons in more complex simulations. Thus, the MIKE SHE model was created as close to the MODFLOW model as possible. Despite the different geometries of the models, the results of this test are very good and also demonstrate some of the grid-based differences between MIKE SHE and MODFLOW

MIKE SHE Components Tested

Time Domain	Component	Boundary Conditions	Component interactions
Steady-state	Saturated Zone	Constant Head	none

Model Set up

The MODFLOW model uses an irregular finite difference grid with smaller cells in the vicinity of the landfill. A uniform hydraulic conductivity was used with a variable elevation for the bottom of the aquifer. To recreate the MODFLOW model as closely as possible, the MODFLOW model was imported into MIKE SHE using the MODFLOW import utility. The properties of the MODFLOW and MIKE SHE models are shown in Table 4.4.

Table 4.4 Model properties for the MODFLOW and the MIKE SHE models for USEPA Test Case 20.

	MODFLOW	MIKE SHE
Grid	39 rows x 37 columns variable spacing	150 rows x 128 columns 10m x 10m
Layers	1 layer; variable thickness	1 layer; variable thickness
Recharge	$6.34(10^{-8})$ ft/s (24 in/yr)	0.06954 mm/hr
Conductivity	$4.92(10^{-4})$ ft/s	$1.5(10^{-4})$ m/s
Specific Yield	0.28	0.28

Figures 4.3 and 4.4 illustrate the model grids and boundaries used in the MIKE SHE and MODFLOW models. Since the MODFLOW model was based on a variable grid, the conversion to MIKE SHE is not exact. The most significant difference is related to the boundaries. The MODFLOW model is bounded by constant head boundaries along the south and most of the east and west sides of the model. However, the variable grid spacing in the MODFLOW model means that the boundary conditions are located in very large cells. In contrast, the MIKE SHE model is relatively finely discretized (10mx10m cells) everywhere. To maintain the proper gradients, the constant head boundaries on the east and west in MIKE SHE were placed in the center of the corresponding MODFLOW cells. However, in the north-east the MODFLOW boundary consists of only four constant head cells, whereas the MIKE SHE model is several dozen cells. In this region, the MIKE SHE model boundary was aligned on the diagonal through the mid-points of the MODFLOW cells. Along the south side of the model, the constant head boundaries were assigned as much as possible to correspond to the MODFLOW cell boundaries.

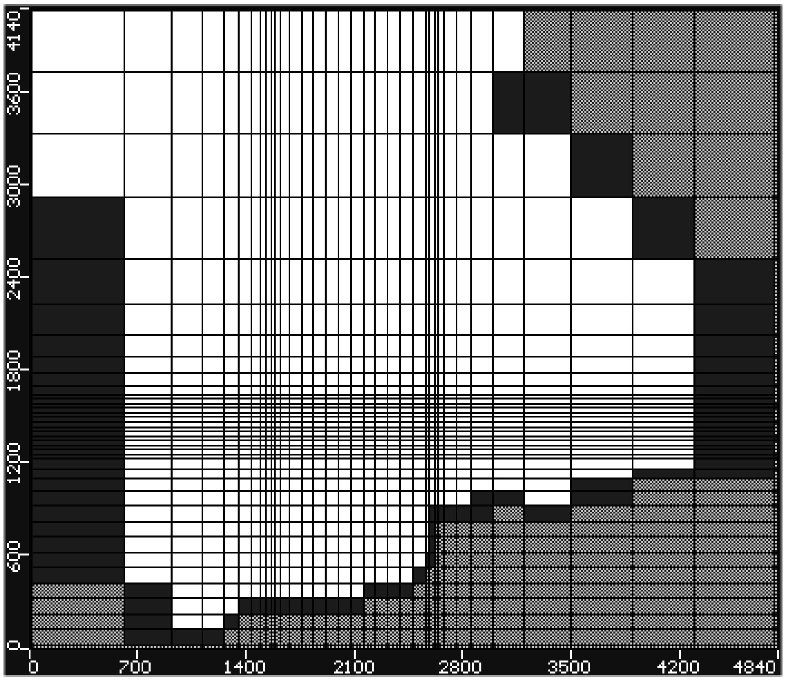


Figure 4-3 MODFLOW model domain and boundaries (from Visual MODFLOW [WHI, 1999]).

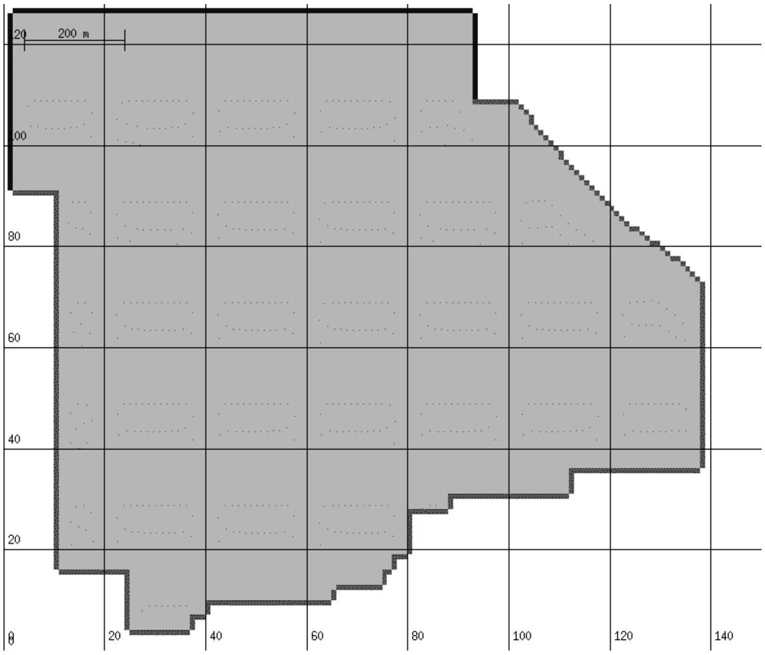


Figure 4-4 MIKE SHE model domain and boundaries

Comparison between MIKE SHE and MODFLOW

Figures 4.5, 4.6 and 4.7 compare the model results from MIKE SHE and MODFLOW. In Figures 4.5 and 4.6, the results from the individual models are plotted with the model nodes plotted in light grey. The MODFLOW contours are dashed so that they can be distinguished when overlain on the MIKE SHE results in Figure 4.7.

Figure 4.7 shows that the MODFLOW and MIKE SHE results are qualitatively and quantitatively nearly identical in the central part of the models. Differences, however, are apparent around the boundaries, which can be attributed to differences in the discretization of the two models. The heads along the boundaries are different because the constant head nodal values do not coincide. The MODFLOW model uses an irregular grid with very large cell sizes near the boundaries (up to 600 x 400 ft), while MIKE SHE uses constant 30 ft square cells. Where the MODFLOW model is finely discretized, such as along the southern river boundary [e.g. (x,y) = (700,200)], differences are quite small. The differences are greatest in the areas where the discretizations are the most disparate (e.g. in the model corners).

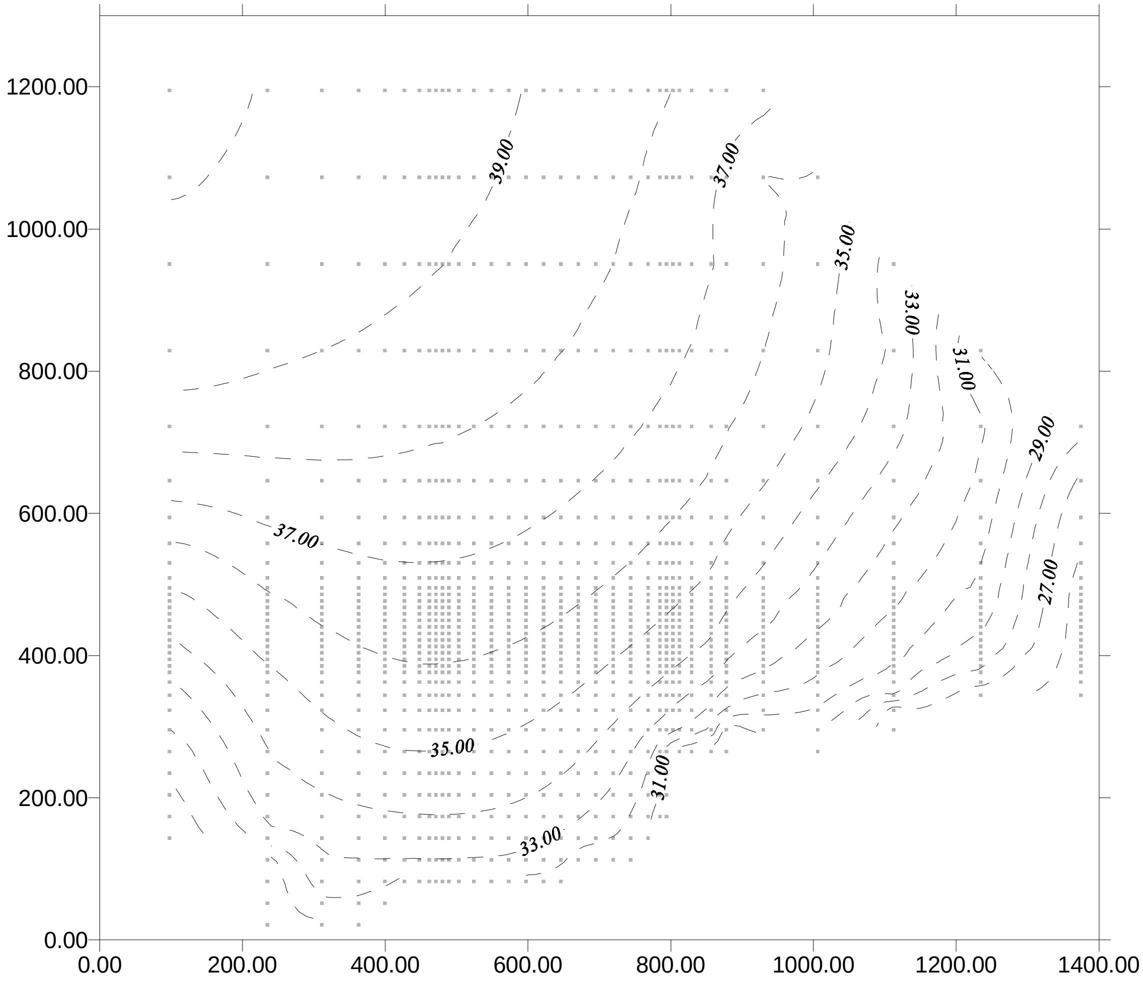


Figure 4-5 MODFLOW model results plotted with model nodes

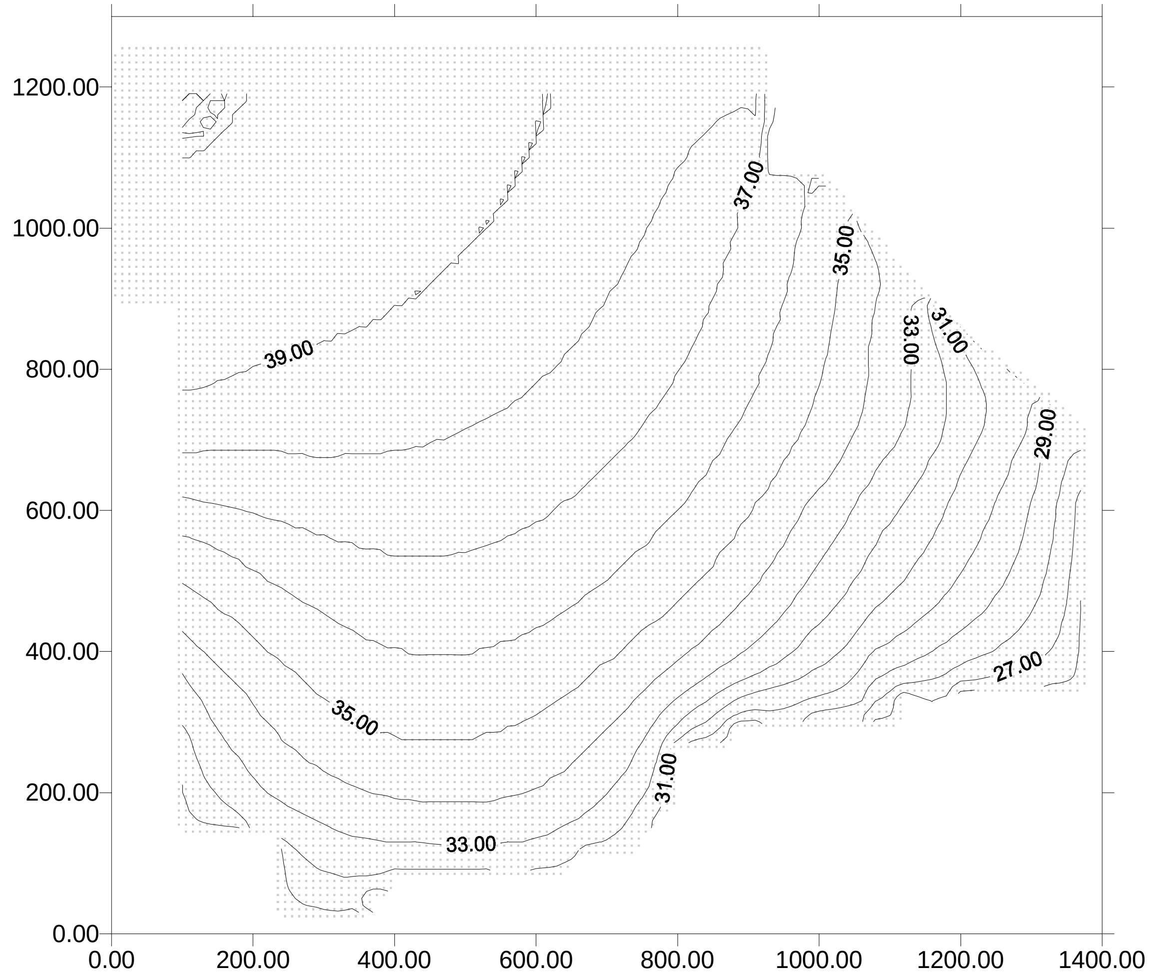


Figure 4-6 MIKE SHE model results plotted with model nodes

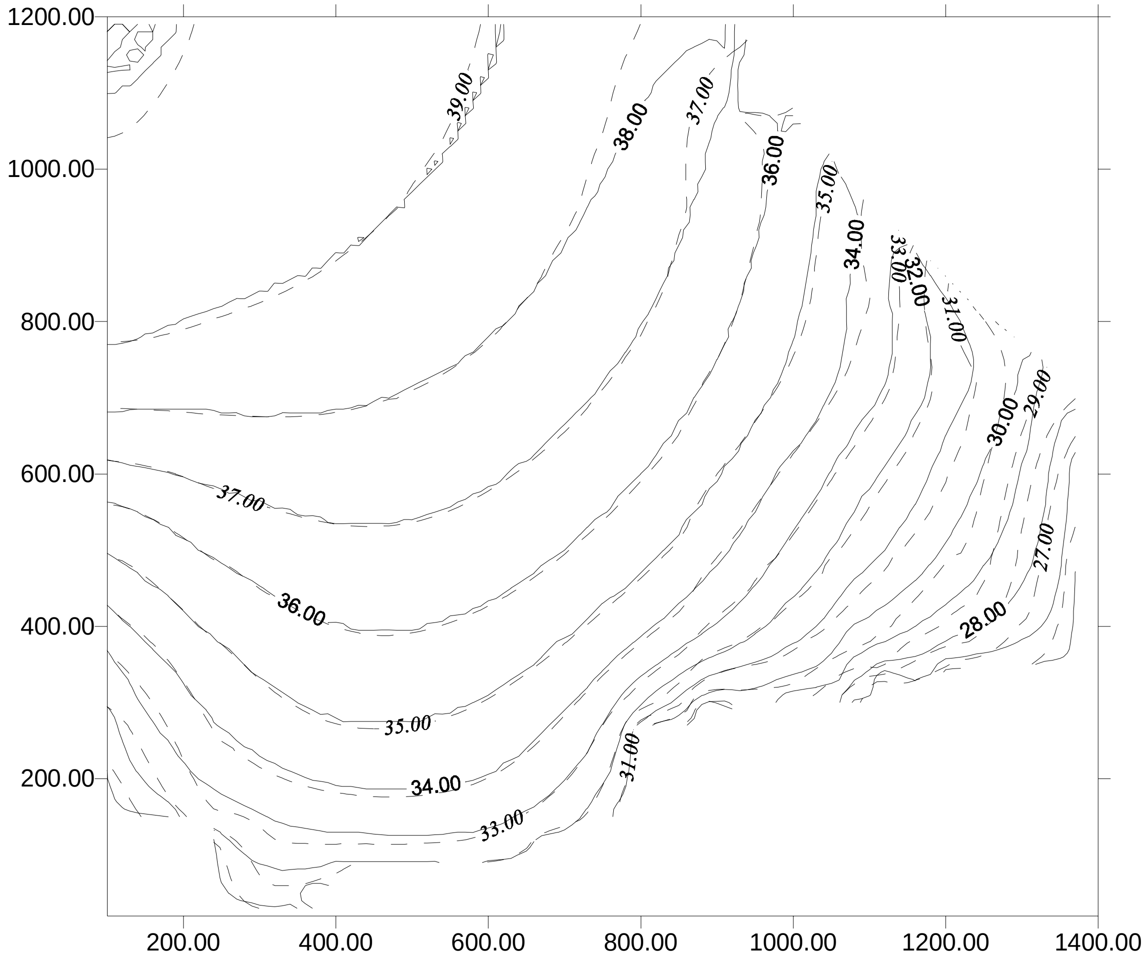


Figure 4-7 MIKE SHE (solid lines) and MODFLOW (dotted lines) results superimposed on one another.

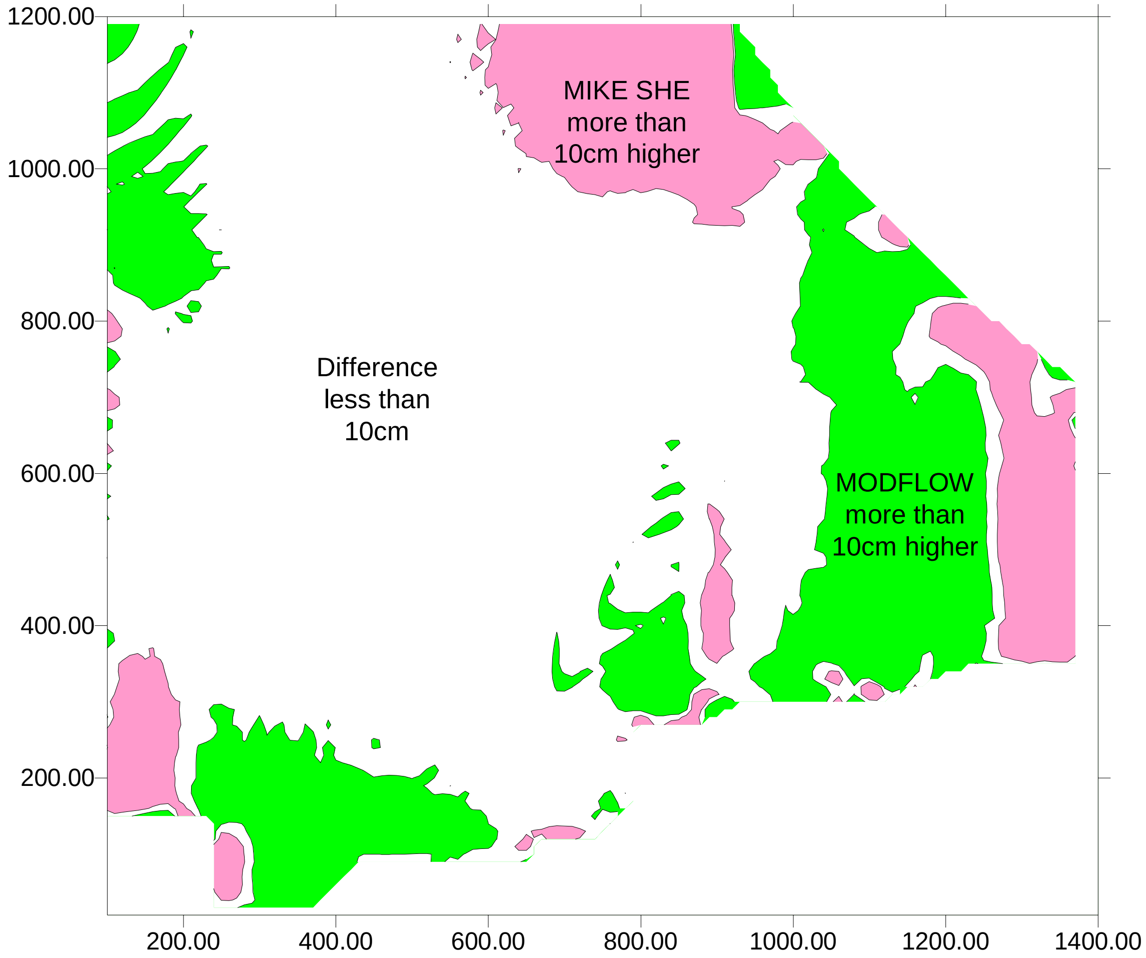


Figure 4-8 Difference between MODFLOW and MIKE SHE for Test Case 20

4.4 VS2DT

Model Background

The USGS's two-dimensional variably saturated flow code, VS2DTI, (Lappala et al., 1990; Hsieh, 2000) was used to validate the UZ component. VS2DT solves Richard's equation by the finite-difference method, very similarly to MIKE SHE.

In this test series the Van Genuchten moisture content and effective conductivity relationships were specified. In the VS2DT code, these relationships are specified by means of parameter values. In MIKE SHE these parametric relationships must be specified as tabular data. This necessitated some minor modifications to the UZ component to allow tabular input for the effective conductivity relationship.

Van Genuchten (1980) presented the following parametric relationships for the soil moisture retention and the effective conductivity curves

$$S_e = \left(1+\alpha|\psi|^n\right)^m, \qquad m = 1-\frac{1}{n}$$

$$K_{eff} = K_s S_e^{1/2}\left(1-\left(1-S_e^{1/m}\right)^m\right)^2$$

where ψ is the pressure head, α and n are the two fitting parameters, Ks is the saturated hydraulic conductivity and Se is the effective saturation defined as

$$S_e = \frac{\theta-\theta_r}{\theta_s-\theta_r}$$

with θ being the water content, θ_r the residual water content, and θ_s the saturated water content.

4.4.1 Steady-State Test

MIKE SHE Components Tested

Time Domain	Component	Boundary Conditions	Component interactions
Steady-state	Unsaturated Zone	Constant Head (bottom)	none
		Constant infiltration (top)	

Model Set up

The test problem, shown in Figure 4.9, is identical to that used in the Gardner analytical test in Section 2.4. The problem is a 1-dimensional uniform column with a constant infiltration at the top boundary and a fixed water table at the bottom boundary.

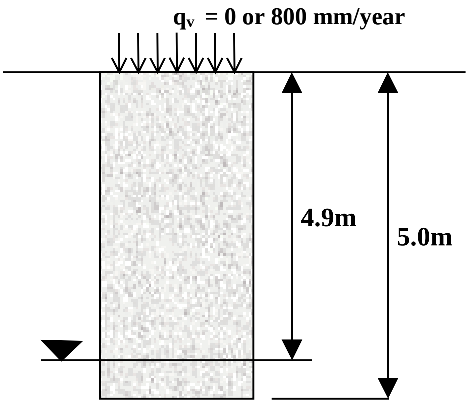


Figure 4-9 Model geometry for the VS2DT and MIKE SHE steady-state test.

The MIKE SHE model, which was set up to run only the UZ component, and the VS2DT model were run using the parameters in Table 4.5.

Table 4.5 MIKE SHE and VS2DT parameters for the steady-state test.

	VS2DT	**MIKE SHE**
K_{sat} =	3.47e-5 m/s	
θ_{sat} =	0.42	
θ_r =	0.01	
Soil functions	VG: α = 9; n = 1.35	VG: tabular
Layers, Rows, Columns	100 x 3 x 3	
Cell size	1m x 1m x 5cm thick	
Infiltration	0 or 800 mm/year	

So that realistic parameters were used for the soil properties, the laboratory data for the *fine sand* in the MIKE SHE *finesand.dbf* database file was used. Figure 4.10 compares this data against the Van Genuchten soil moisture and effective conductivity curves used in this test. The qualitative best fit for the Van Genuchten moisture parameters were found to be α = 9 and n = 1.35.

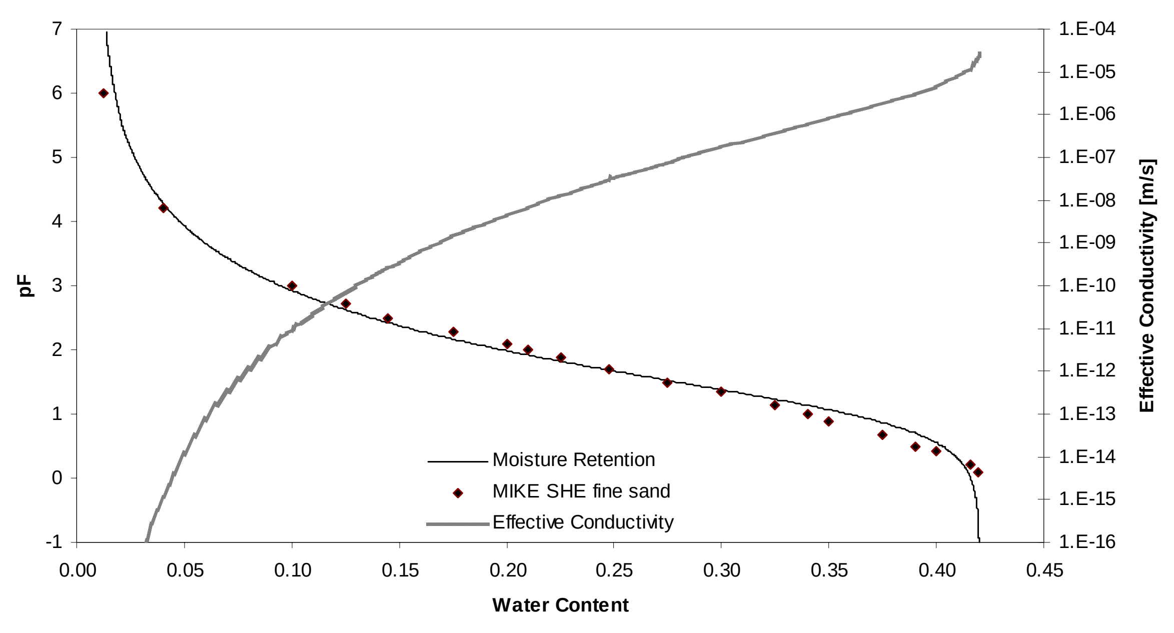
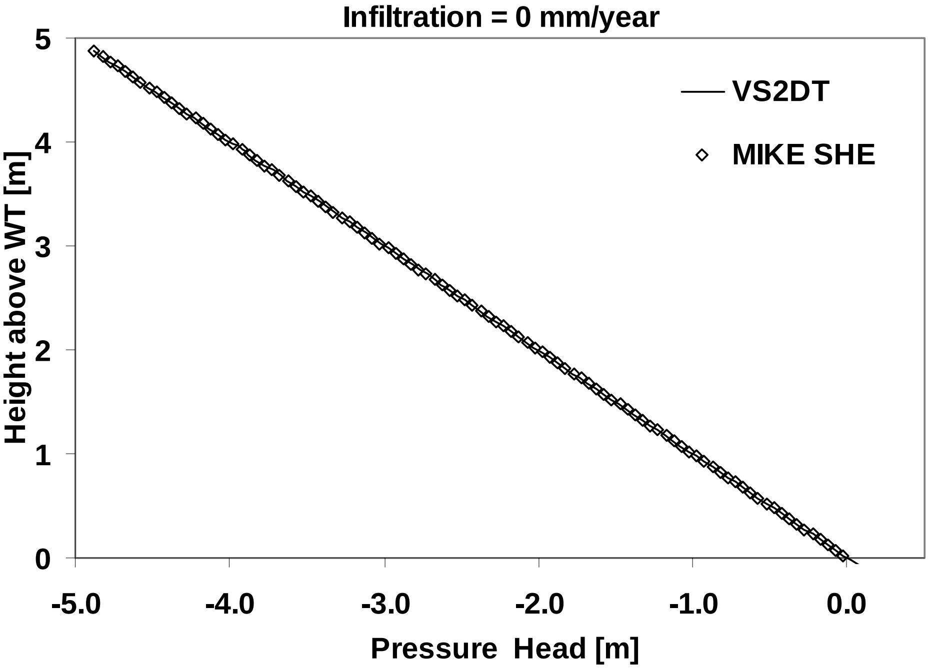


Figure 4-10 Soil moisture retention and effective conductivity curves for MikeSHE's 'fine sand'. Van Genuchten fitting values: α=9 and n = 1.35.

Comparison between MIKE SHE and VS2DT
Figures 4.11 and 4.12 show that the results from MIKE SHE are identical to the pressure head and water content profiles calculated by VS2DT.



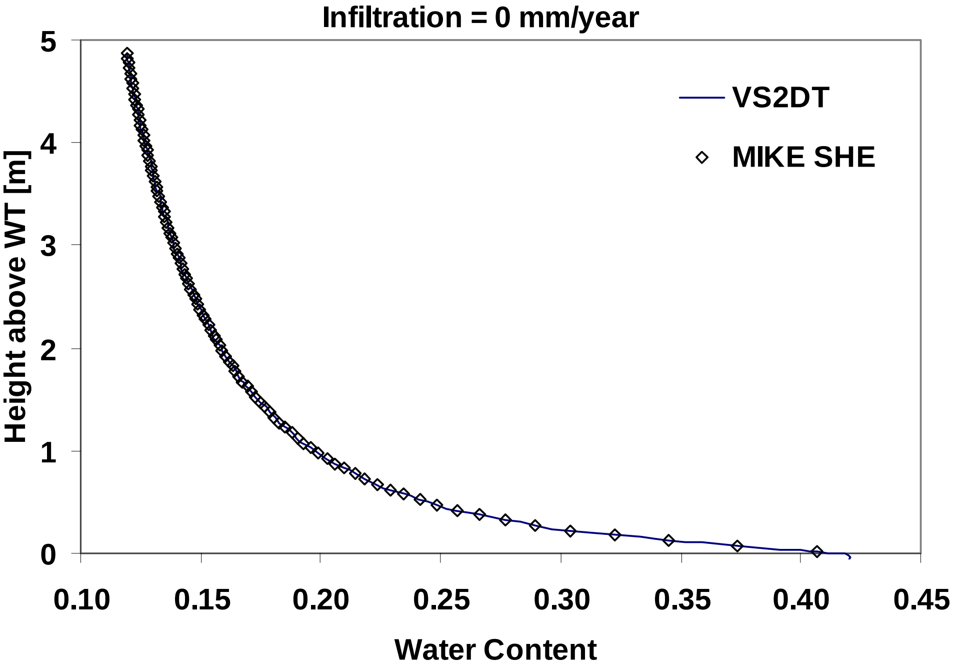
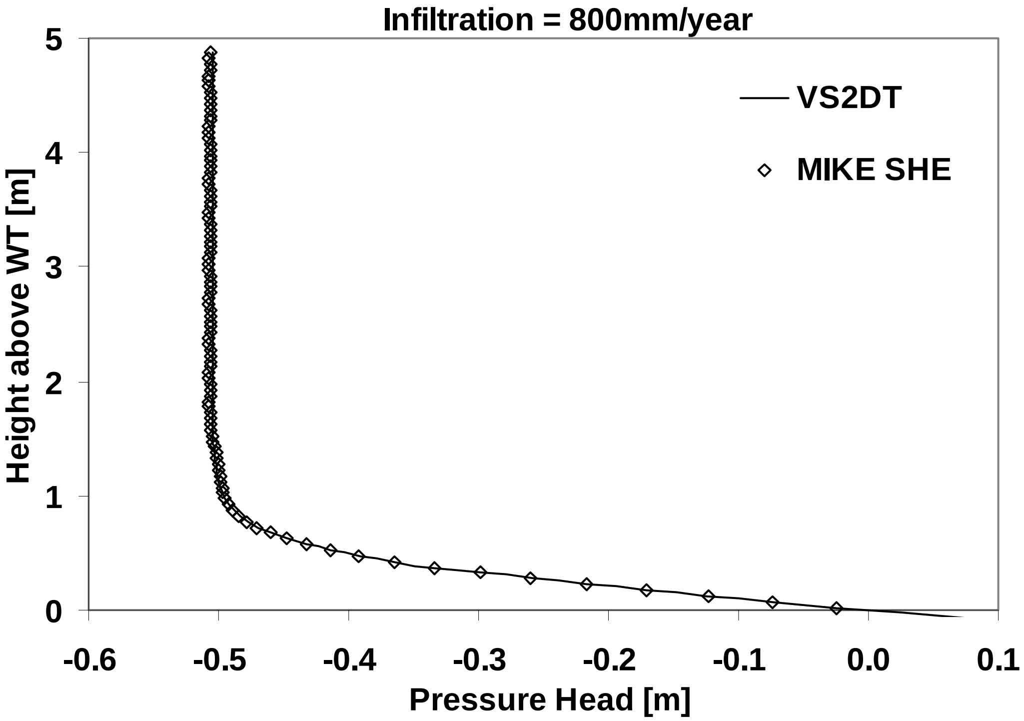


Figure 4-11 Water Content and pressure head versus height for the case with a zero infiltration.



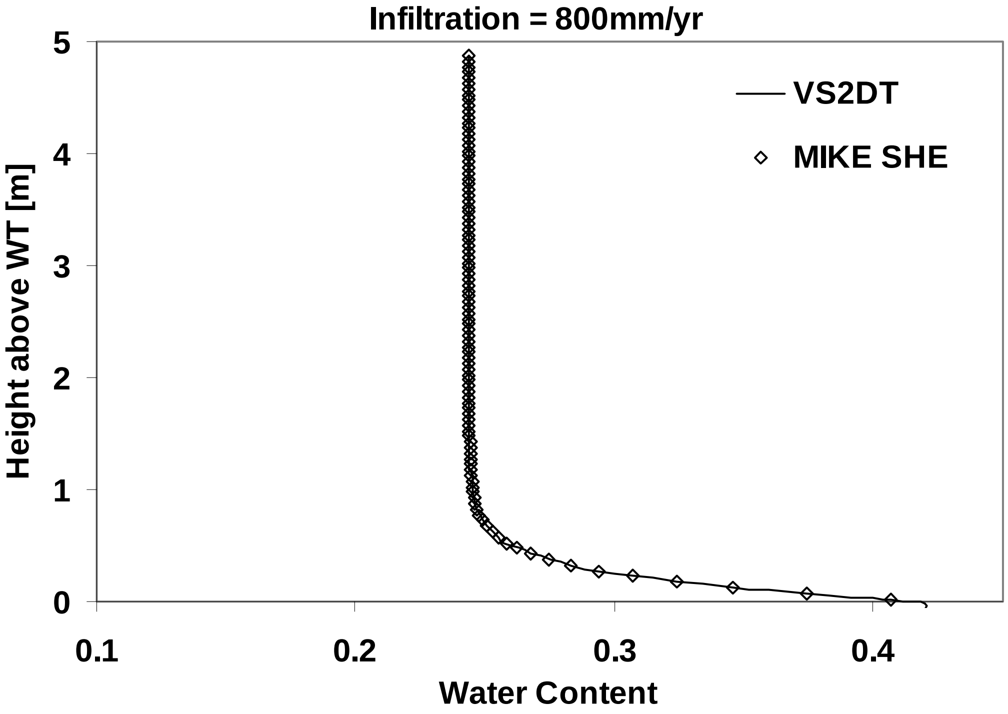


Figure 4-12 Water Content and pressure head versus height for the case with a constant infiltration rate of 800mm/year.

4.4.2 Transient Test

MIKE SHE Components Tested

Time Domain	Component	Boundary Conditions	Component interactions
Transient	Unsaturated Zone	Constant Head (bottom) Variable infiltration (top)	none

Model Set up

The test problem was similar to the steady-state simulation, but soil parameters, the depth to the water table and the precipitation rates were all selected to more closely represent those found at a semi-arid field site. The geometry of the test case is shown in Figure 4.13 and the model parameters are given in Table 4.6. The variable infiltration started as a short (2-hour) intense rainfall period followed by two longer (10-hour) rainfall events. Each rainfall event was followed by dry period. Table 4.7 outlines the transient infiltration data. The soil moisture in the soil column was initially at equilibrium.

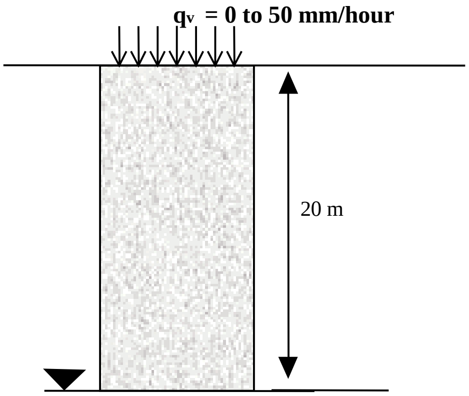


Figure 4-13 Geometry for the transient VST2D / MIKE SHE test case.

Table 4.6 MIKE SHE and VS2DT model parameters for the transient test case.

	VS2DT	MIKE SHE
K_{sat} =	$2.507(10^{-4})$ m/s	
θ_{sat} =	0.4	
θ_r =	0.018	
S_s =	0.01	
Soil functions	VG: α = 1.98; n = 1.72	VG: tabular
Layers, Rows, Columns	81 x 3 x 3	
Cell size	1m x 1m x 2.5cm thick	
Initial Condition	Equilibrium soil moisture content	
Infiltration	Variable: 0 to 50 mm/hour (see Table 4.6)	

Table 4.7 Infiltration data for the transient MIKE SHE / VS2DT test case.

Duration		**Total Time**		**Infiltration rate**	
7200 seconds	2 hrs	7200 seconds	2 hrs	$1.4(10^{-5})$ m/s	50.4 mm/hr
172 800	48 hrs	180 000	2d 2hrs	0	
36 000	10 hrs	216 000	2d 12hrs	$2.78(10^{-6})$	10.008
172 800	48 hrs	388 800	4d 12hrs	0	
36 000	10 hrs	424 800	4d 22hrs	$5.6(10^{-6})$	20.16
604 800	7 days	1 029 600	11d 22hrs	0	

Comparison between MIKE SHE and VS2DT

Figures 4.14 shows that the results from MIKE SHE are identical to the pressure head and water content profiles calculated by VS2DT.

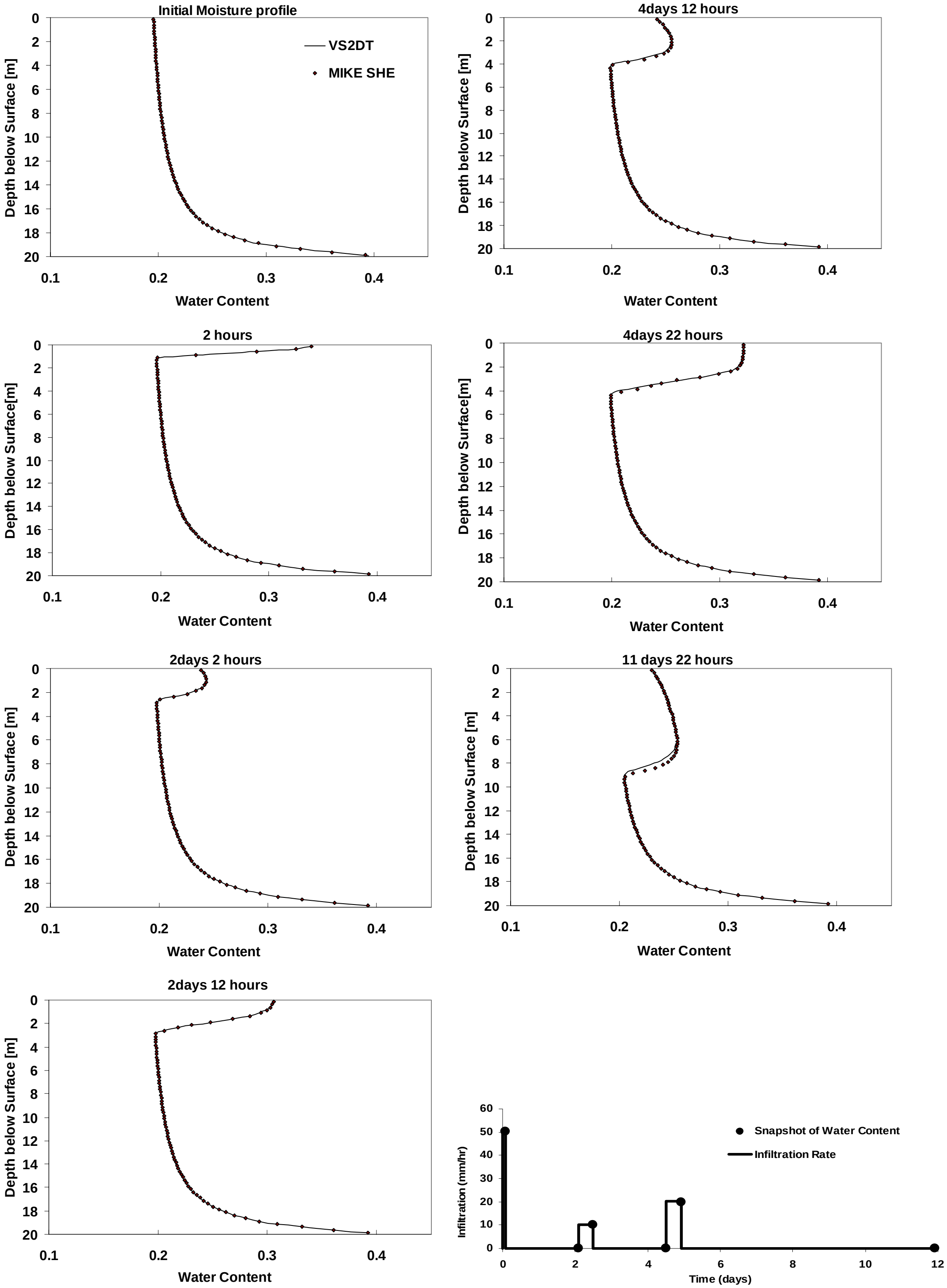


Figure 4-14 Water content profiles at selected times for the transient MIKE SHE / VS2DT test case.

5 SEMI-QUANTITATIVE PERFORMANCE EVALUATION

The semi-quantitative tests are formulated to address the integrated features of MIKE SHE, which cannot be verified by means of analytic test cases. In each test case, a hydrologic problem is specified focusing on individual model components of the modeling system and the exchange flow with other components. All of the major flow components are tested systematically to demonstrate the hydrological models ability to simulate responses to imposed variations in boundary conditions or input data. MIKE SHE's performance (e.g. water balance and water table response) is qualitatively evaluated to assess if the simulated result corresponds to the anticipated.

The following seven test cases were analyzed:

Saturated zone / surface water interaction

- 2D saturated / surface water model with transient river stage
- 2D saturated / surface water model with transient pumping and river / aquifer interaction
- 3D saturated / surface water model with transient pond stage

Unsaturated zone / saturated zone interaction

- 2D unsaturated / saturated model with transient recharge without ponding
- 2D unsaturated / saturated model with transient recharge with surface ponding

Overland flow / surface water interaction

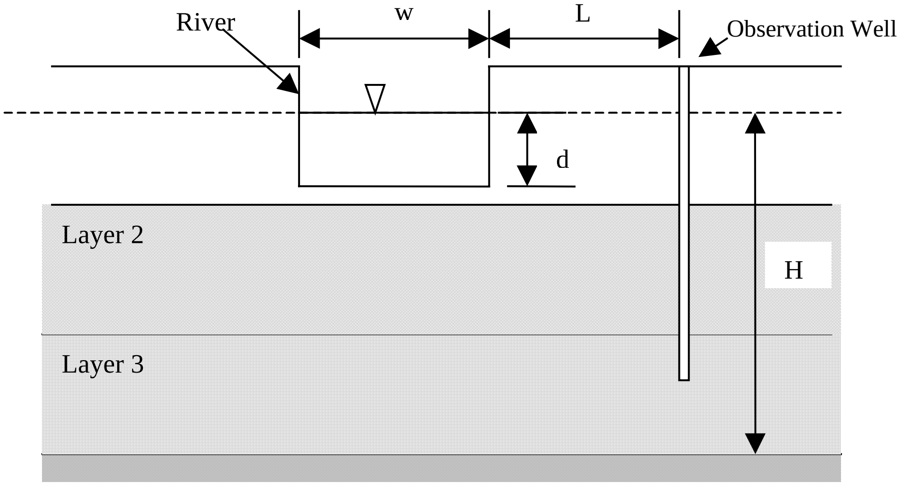
- 2D overland flow /surface water model with an impervious surface
- 2D overland flow /surface water model with a pervious surface

5.1 2D Saturated Groundwater / Surface Water Model with a Transient River Stage

This test case simulates the fluctuation of the groundwater table in response to water level changes in a river boundary condition. The simulation is a three-layer, two-dimensional ground water cross-section model set up using the saturated zone flow component (MIKE SHE SZ) in combination with the river hydraulics model. The river is described by dummy cross-sections in MIKE11, with time varying upstream and downstream water levels.

The specified head boundaries in the river, which control the river stage in the model section, alternate every 12 hours from -1m to -4 m. The gradient between the river and the aquifer is alternately positive and negative causing an alternating net inflow and outflow to the aquifer. A high leakage coefficient and a relatively low storage coefficient of the aquifer were used to increase the aquifer head response. A delayed effect of the river stage fluctuation is seen in the second layer of the groundwater component, while virtually no effect is seen in the deepest model layer. From the top layer to the second layer the head fluctuation is reduced from approximately 0.8 m to 0.1 m.

Table 5.1 Specifications for test case



Geometry :	
W, river width (m)	100
L, distance river- observation well (m)	50
H, Aquifer (layer thickness) (m)	30 (3 x 10)
Model area (grid size) (m)	1 x 12 cells (100)
Aquifer parameters:	
K_h, Horizontal hydraulic conductivity (m/s)	L1: 2.1e-5 L2: 9.3e-6 L3: 2.7e-8
K_v, Vertical hydraulic conductivity (m/s)	$K_v = 0.1\ K_h$
S_y, Specific Yield (-)	0.25
Initial conditions :	
Potential head of layer 1-3 (m)	-2.5 m
River stage	-1.0 m
Boundary conditions :	
SZ layer 1-3, constant head (m)	-2.5 m
d, River stage, transient	Figure 1.1

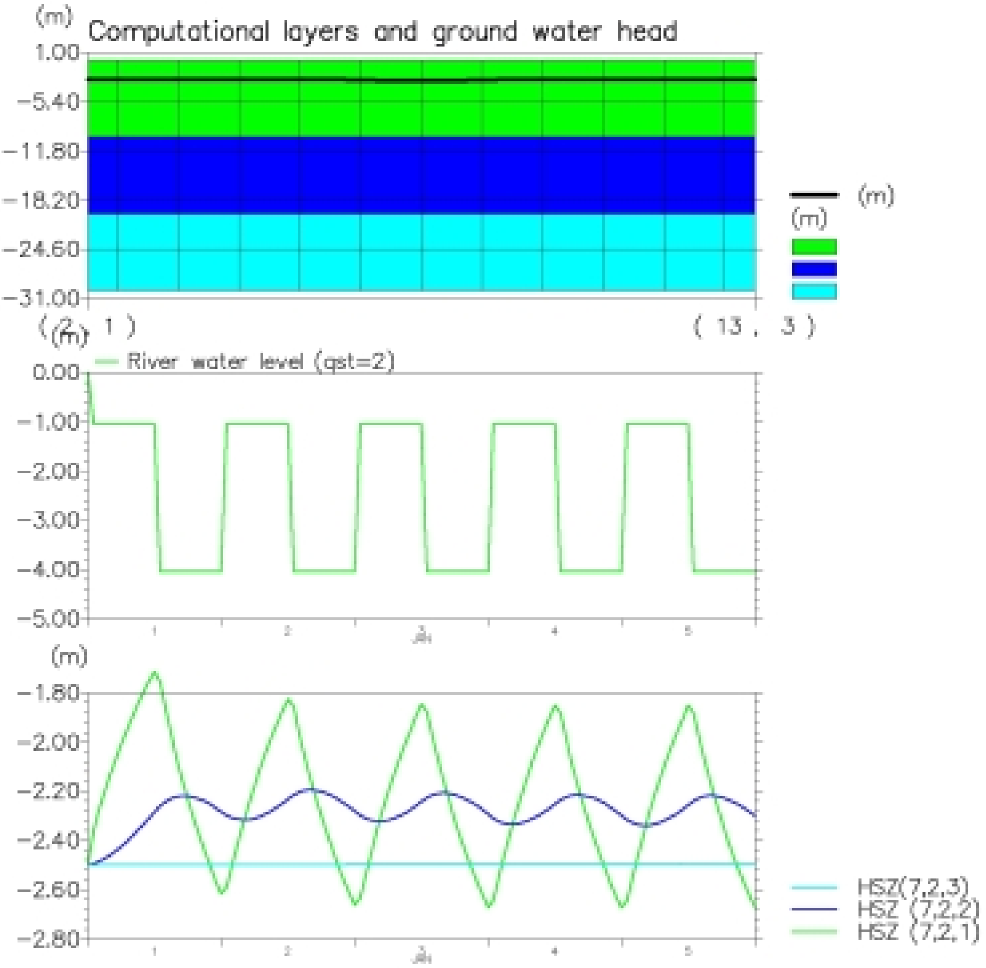


Figure 5-1 Transient river stage and simulated groundwater head at the observation well

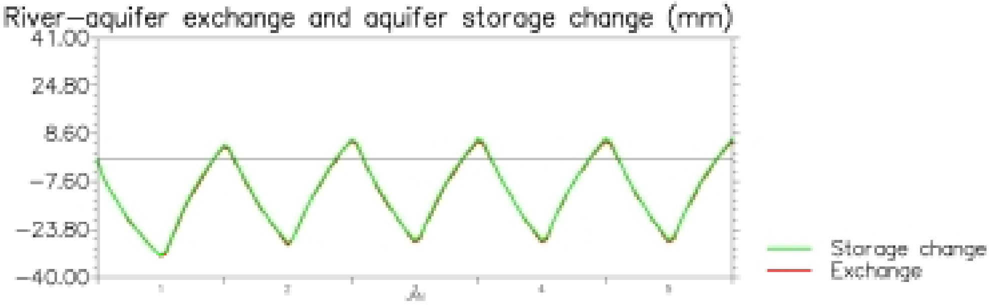


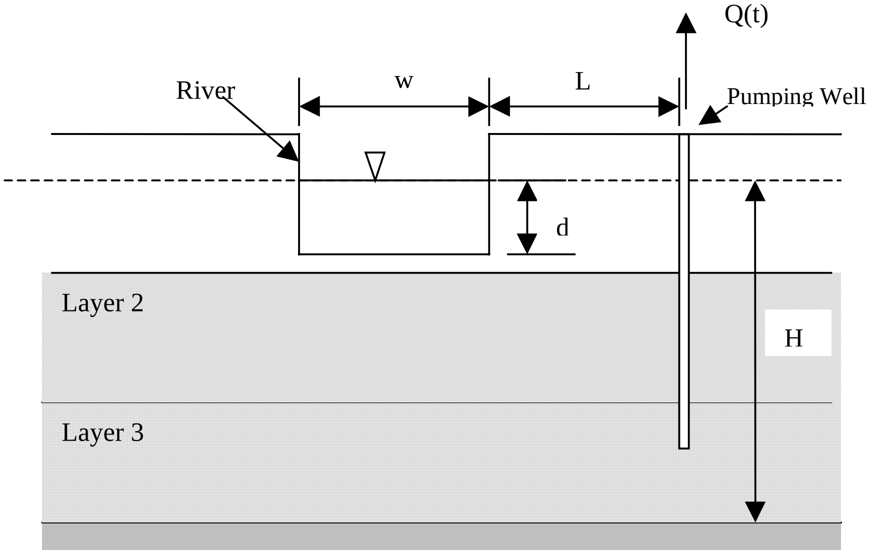
Figure 5-2 Simulated river gain/loss (water balance)

5.2 2D Saturated Groundwater / Surface Water Model with Transient Pumping and River / Aquifer interaction

This test case simulates the fluctuation of the groundwater table in response to changes in the extraction rate in a pumping well. The simulation is a three-layer, two-dimensional cross-section model using MIKE SHE SZ . The river segment is described by dummy cross-sections in MIKE11 and constant water level upstream and downstream boundary conditions..

The time varying groundwater extraction causes head fluctuations of about 0.15 m and a generally decreasing head in the upper groundwater layer over the 6-day simulation period. The effects of the pumping well is seen primarily in the upper layer and a delayed, dampened response can be seen in the second layer. Over the simulation period, the gradient is always positive from the river to the aquifer and there is consequently a net flow of water from the river to the aquifer. The water level fluctuation in the river segment is very small due to the head boundaries . Given the parameters and boundary conditions used, the major part of the extracted ground water is replenished by river.

Table 5.2 Specifications for test case



Geometry :	
W, river width (m)	100
L, distance river- observation well (m)	50
H, Aquifer (layer thickness) (m)	30 (3 x 10)
Model area (grid size) (m)	1 x 12 cells (100)
Aquifer parameters:	
K_h, Horizontal hydraulic conductivity (m/s)	L1: 2.1e-5 L2: 9.3e-6 L3: 2.7e-8
K_v, Vertical hydraulic conductivity (m/s)	$K_v = 0.1\ K_h$
S_y, Specific Yield (-)	0.25
Initial conditions :	
Potential head of layer 1-3 (m)	-2.5 m
River stage	-1.0 m
Boundary conditions :	
SZ layer 1-3, constant head (m)	-2.5 m
Pumping rate	Figure 2.1

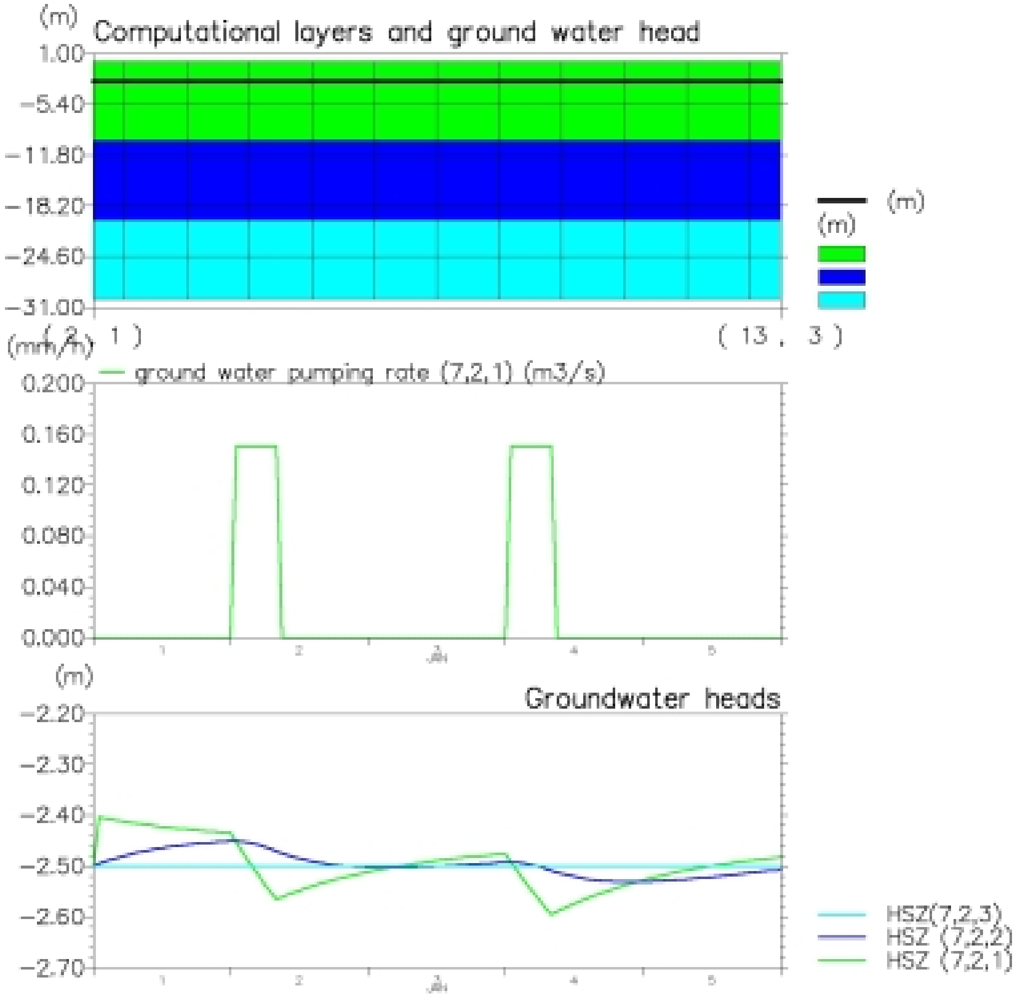


Figure 5-3 Groundwater withdrawal rate and simulated groundwater head at the observation well

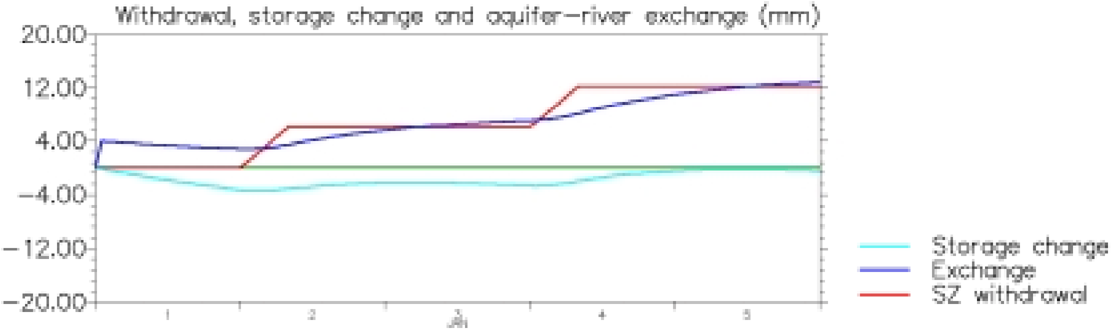


Figure 5-4 Simulated river gain/loss (water balance)

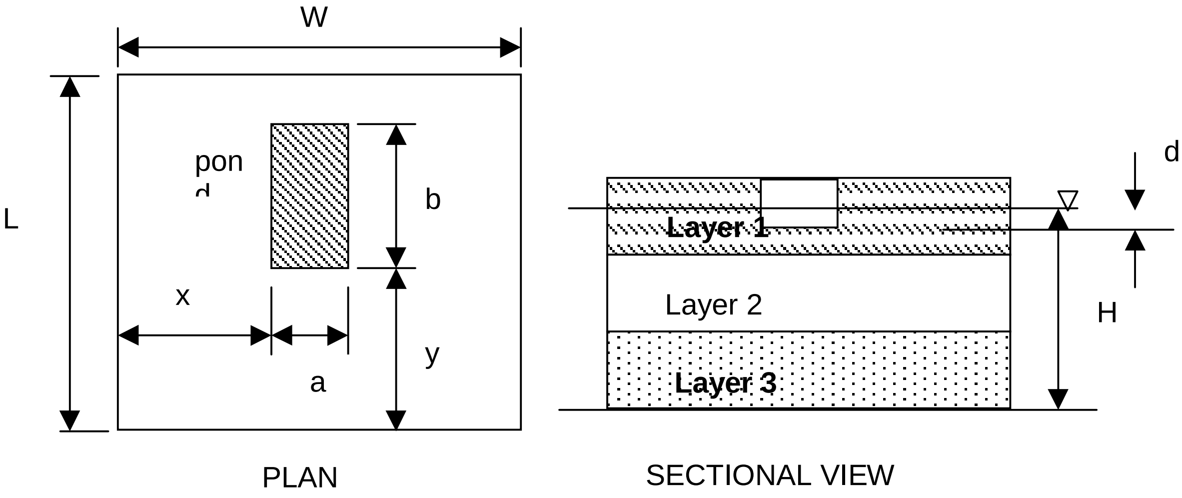
5.3 3D Saturated Groundwater / Surface Water Model with a Transient Pond Stage

This test case simulates the fluctuation of the groundwater table in response to water level changes in a pond and river boundary condition. The model setup comprise a three-layer, three-dimensional SZ mode similar to test case described in Section 5.1. The river set up includes a branch from the upstream boundary to a pond represented by wide cross sections and a canal segment to allow surface water flow from the pond across the downstream boundary. The water level in the pond is thus controlled by the upstream and downstream boundary conditions and the exchange of flow between the aquifer and the pond takes place as a function of the imposed water level gradient. The pond is included in the river setup to allow specification of water level boundaries.

The flood code option available in the MIKE SHE – MIKE11 model is applied to obtain a correct surface water level in the computational cells within the pond. A similar approach is adopted when the dynamic interaction between the main river course and the associated flood plain is simulated in MIKE SHE.

The total length of the river reach where aquifer-stream exchange takes place is considerably larger than in the first case and, thus, a substantially larger exchange flow is seen in response to the fluctuating water levels. The simulated exchange flow at a computational node next to the river (figure 5.6) increases to a maximum rate of 1.8 mm/h (0.005 m^3/s) following the increase in pond water level. As pond water enters the aquifer the head gradient is reduced and the exchange flow rate decreases to approximately 1.2 mm/h in 12 hours.

Table 5.3 Specifications for test case



Geometry :	
W, model area width (m)	1200
L, model area length (m)	1200
a, pond width (m)	200
b, pond length (m)	400
x, west boundary to pond (m)	500
y, south boundary to pond (m)	400
Model area (grid size) (m)	12x12 cells (100)
Aquifer (layer thickness) (m)	30 (3 x 10)
Aquifer parameters:	
K_h, Horizontal hydraulic conductivity (m/s)	L1: 2.1e-5 L2: 9.3e-6 L3: 2.7e-8
K_v, Vertical hydraulic conductivity (m/s)	$K_v = 0.1\ K_h$
S_y, Specific Yield (-)	0.25
Initial conditions :	
Potential head of layer 1-3 (m)	-2.5 m
Boundary conditions :	
SZ layer 1-3, constant head (m)	-2.5 m
d, River stage, transient	Figure 3.1

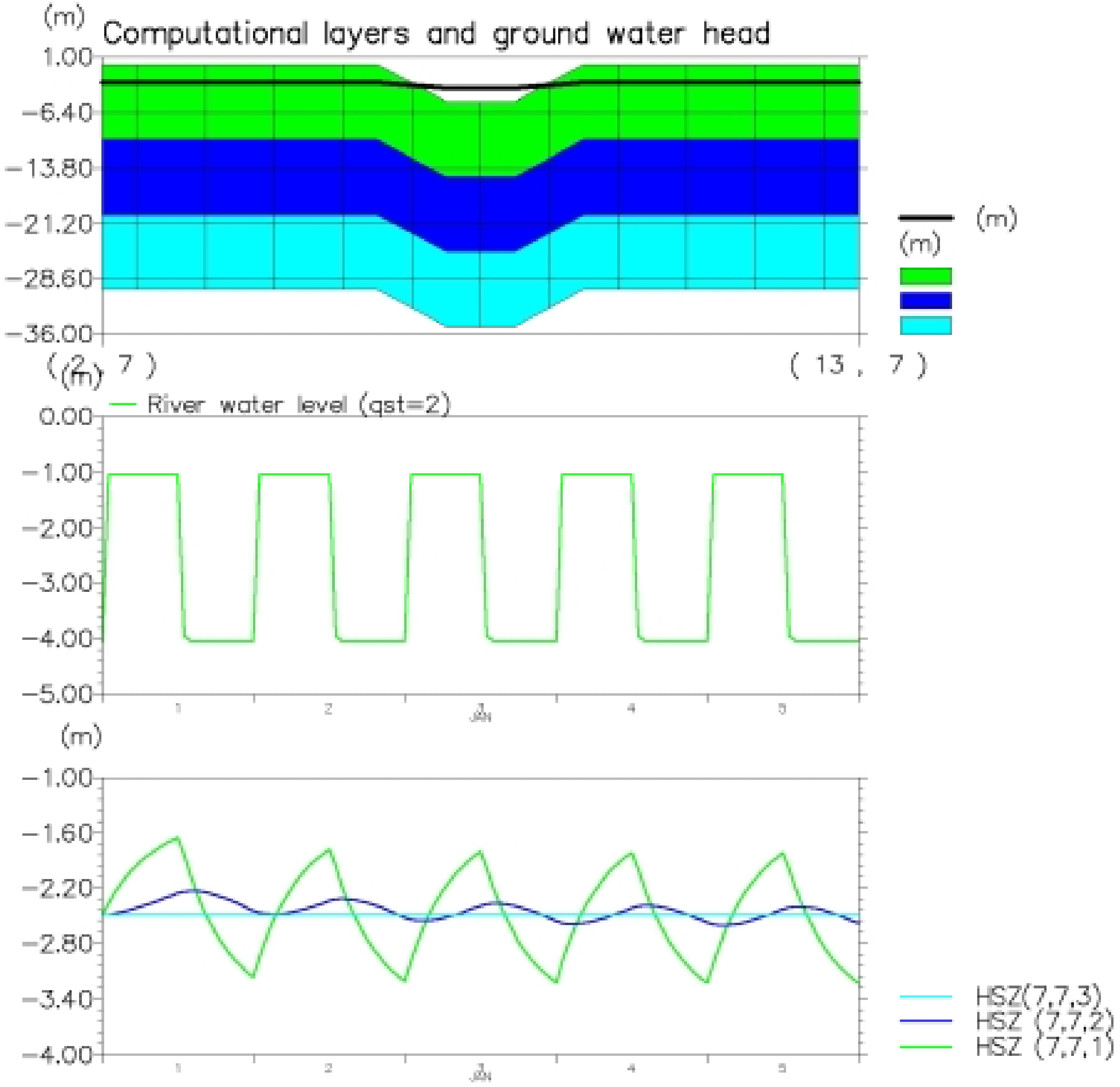


Figure 5-5 Transient water table profile

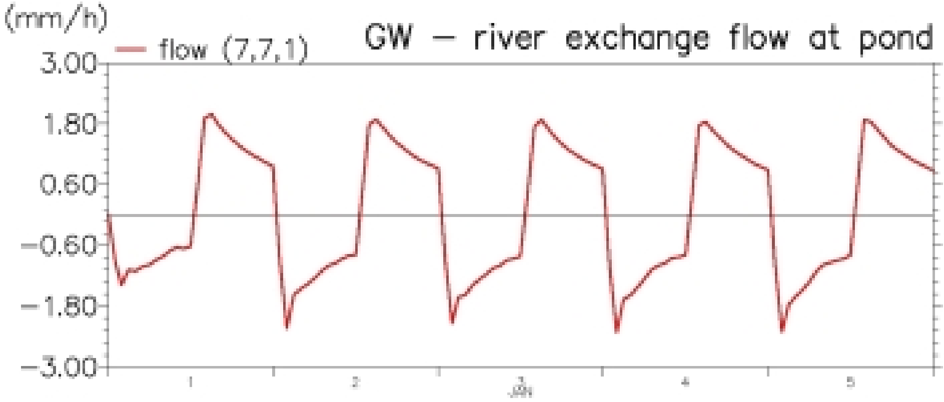


Figure 5-6 Simulated river-aquifer exchange

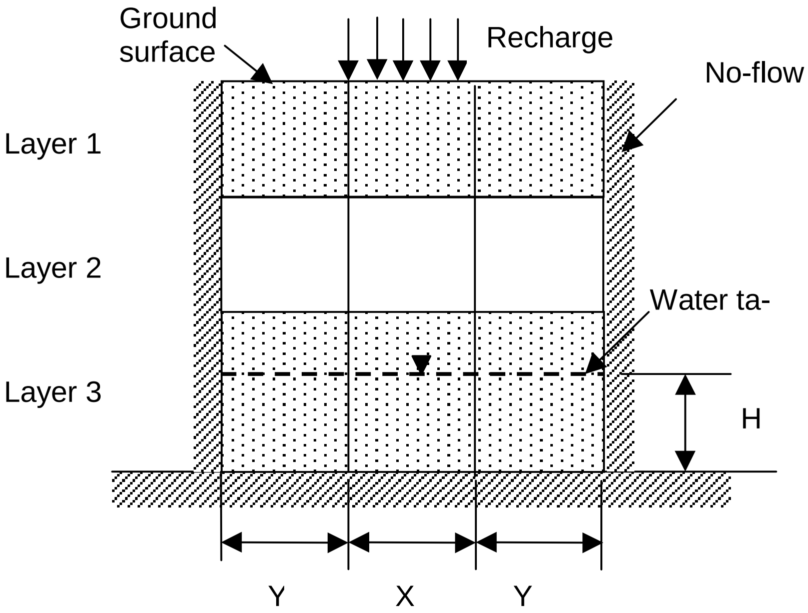
5.4 2D Unsaturated Zone / Saturated Groundwater Model with Transient Recharge without Ponding

This test case simulates the fluctuation of the groundwater table in response to a time varying recharge rate at the soil surface above the unsaturated zone. The simulation is a three-layer, two-dimensional UZ/SZ model.

The soil moisture content in the unsaturated zone increases in response to the infiltration. The recharge to the groundwater causes a rise in the ground water table. At the highest rainfall intensity the groundwater table rises above the ground surface and the unsaturated zone vanishes. Following the last rainfall event, the groundwater table falls and the soil water in the unsaturated zone drains. This is in response to the horizontal flow of groundwater from the central part of the model, where the recharge occurs, to the neighboring areas, which receive no rainfall.

Two test cases have been run with the initial ground water level in layer 1 (the upper layer) and layer 3 (the lower layer). The latter case show how the vertical flow is simulated when the upper layer is dry and gradual wetting of the unsaturated and saturated zone takes place.

Table 5.4 Specifications for test case



Geometry :	
X, infiltration area width (m)	400
Y, distance to boundary (m)	400
H, Aquifer (layer thickness) (m)	30 (3 x 10)
Model area (grid size) (m)	1 x 12 cells (100)
Aquifer parameters:	
K_h, Horizontal hydraulic conductivity (m/s)	L1: 2.1e-5 L2: 9.3e-6 L3: 2.7e-8
K_v, Vertical hydraulic conductivity (m/s)	$K_v = 0.1\ K_h$
S_y, Specific Yield (-)	0.25
Unsaturated zone parameters:	Figure 4.1
Initial conditions :	
Potential head of layer 1-3 (m)	-2.5 m
River stage	-1.0 m
Boundary conditions :	
SZ layer 1-3, constant head (m)	-2.5 m
Rainfall rate	Figure 4.2

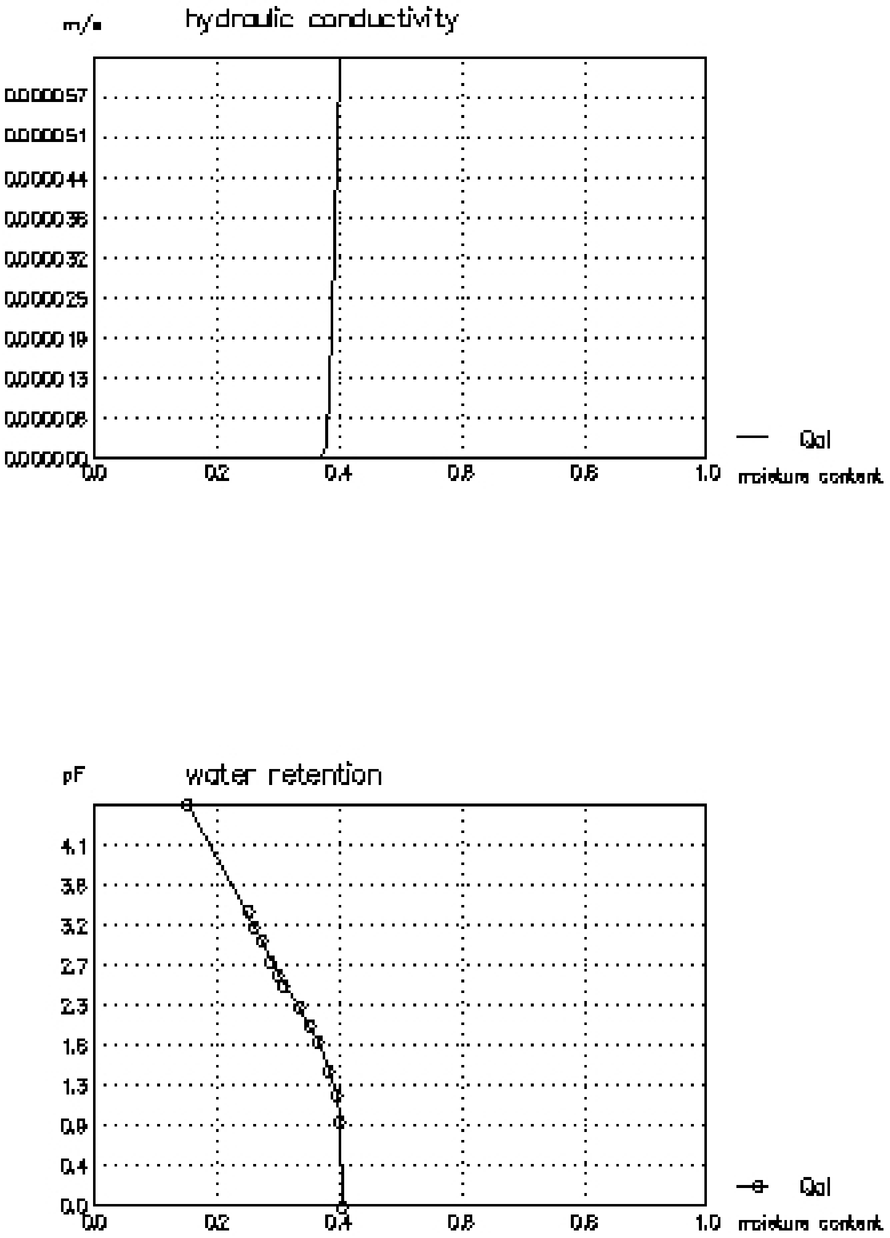


Figure 5-7 Unsaturated soil retention and hydraulic conductivity curve

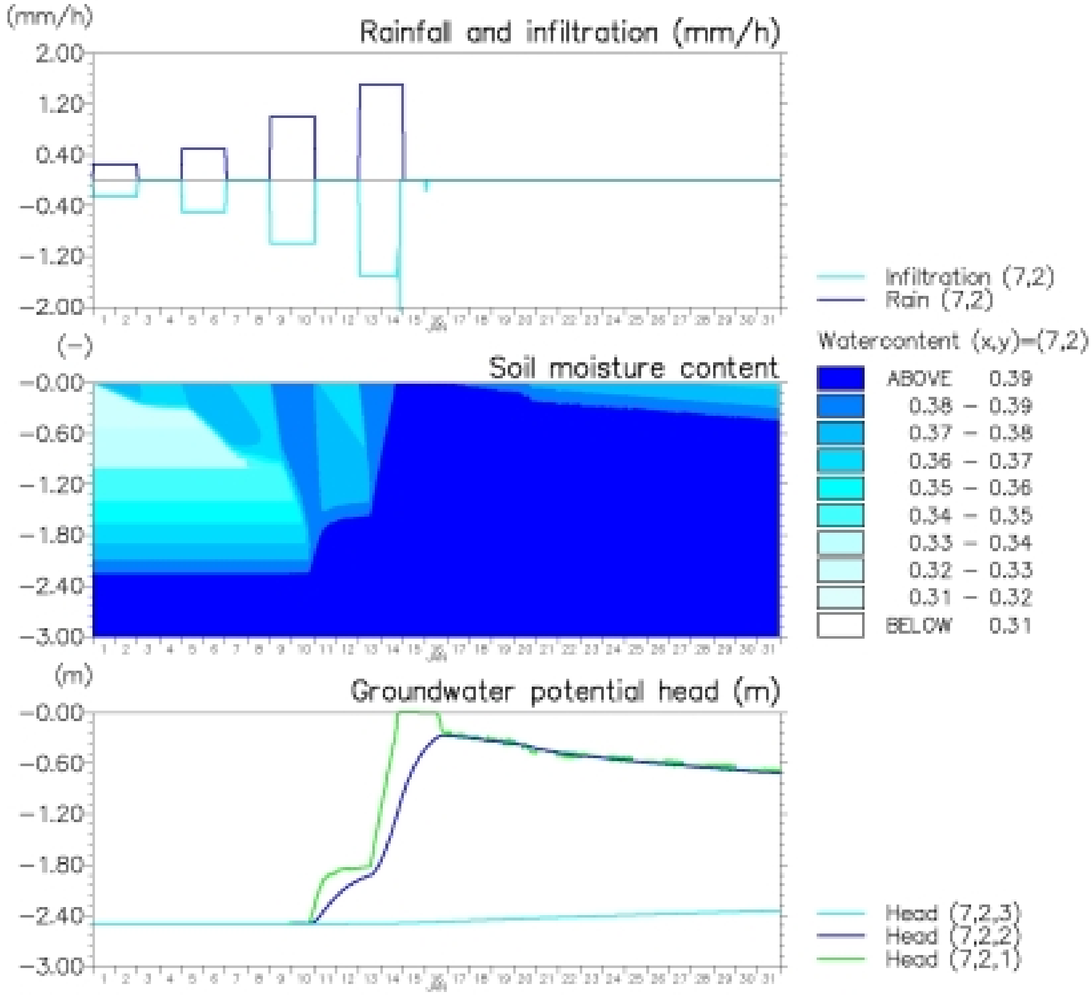


Figure 5-8 Simulated water table and soil moisture profile (initial head in upper layer)

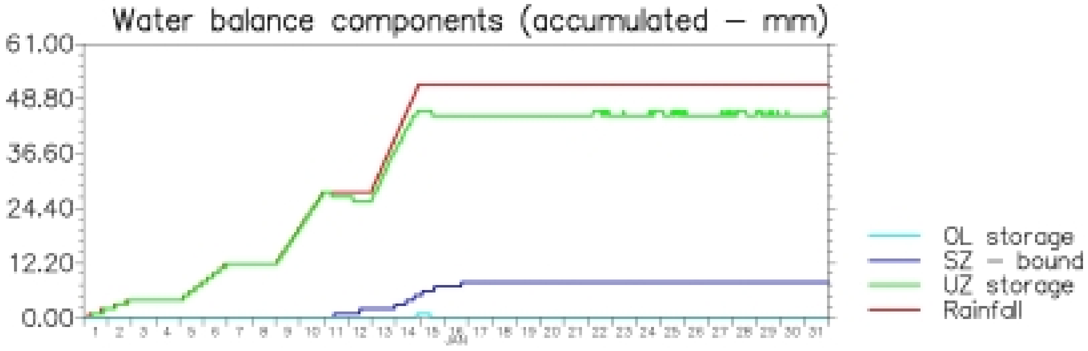


Figure 5-9 Simulated river gain/loss (water balance-initial head in upper layer)

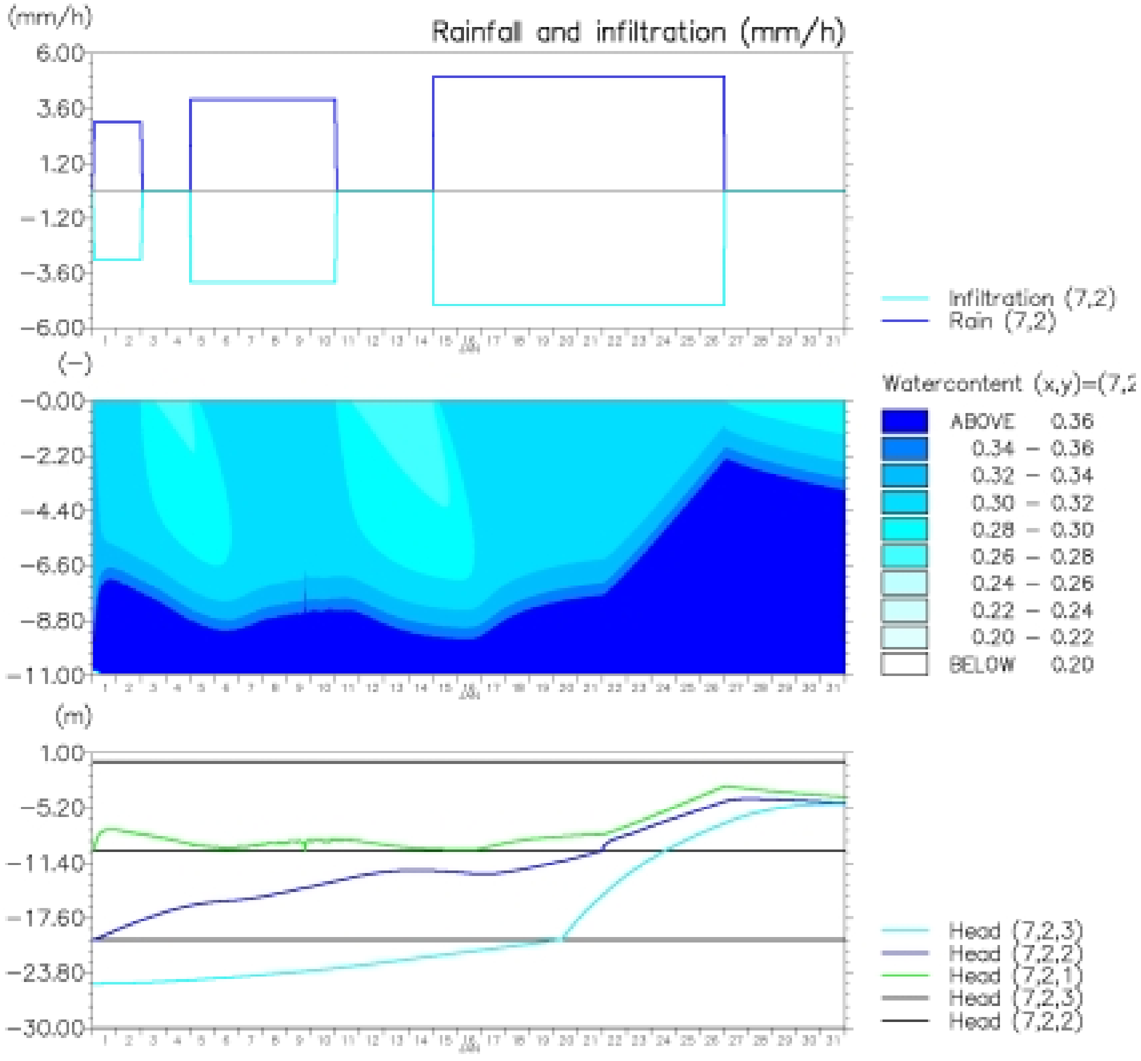


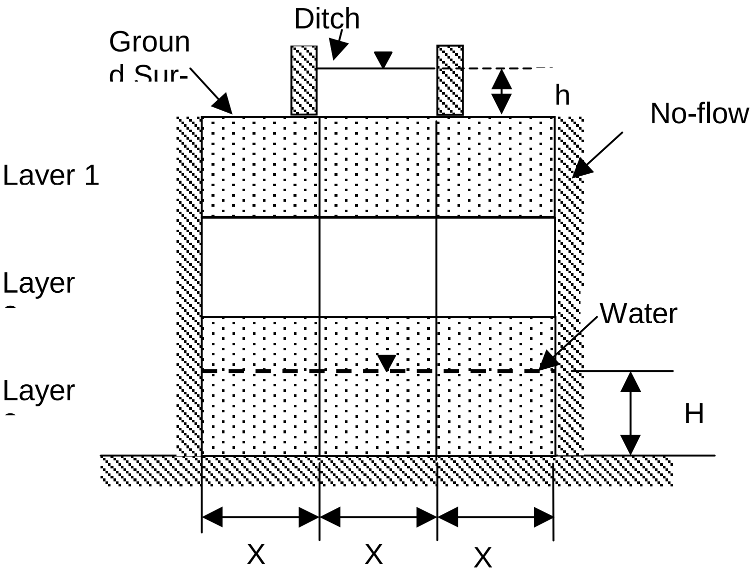
Figure 5-10 Simulated water table and soil moisture profile (initial head in lower layer)

2D Unsaturated Zone / Saturated Groundwater Model with Transient Surface Pond Water Levels

This test case simulates the fluctuation of the groundwater table in response to a time varying recharge rate at the soil surface above the unsaturated zone. The simulation is a three-layer, two-dimensional UZ/SZ model. The ditch is represented using the overland component of MIKE SHE. The computational cells in the pond area receive rainfall. Overland flow to the surrounding areas is disabled by using a high value for detention storage. The water on the surface is subject to infiltration to the unsaturated zone. A flux boundary condition is used initially at the top of the unsaturated zone soil column. As the water level builds up a head gradient is applied. Full contact has been assumed between the overland and ground water component i.e. there is no resistance to flow moving between the surface and the subsurface when the soil becomes fully saturated.

The ditch is initially dry. A high intensity rainfall input fills up the storage capacity in the unsaturated zone and the groundwater table of upper layer rises to the surface. The water table in the ditch increases linearly in response to a second constant rate rainfall event. A delayed increase in recharge to the aquifer is observed.

Table 5.5   Specifications for test case



Geometry :	
X, infiltration area width (m)	400
Y, distance to boundary (m)	400
H, Aquifer (layer thickness) (m)	30 (3 x 10)
Model area (grid size) (m)	1 x 12 cells (100)
Aquifer parameters:	
K_h, Horizontal hydraulic conductivity (m/s)	L1: 2.1e-6 L2: 9.3e-7 L3: 2.7e-9
K_v, Vertical hydraulic conductivity (m/s)	$K_v = 0.1\ K_h$
S_y, Specific Yield (-)	0.25
Unsaturated zone parameters:	Figure 4.1
Initial conditions :	
Potential head of layer 1-3 (m)	-2.5 m
River stage	-1.0 m
Boundary conditions :	
SZ layer 1-3, constant head (m)	-2.5 m
Ponded depth	Figure 5.1

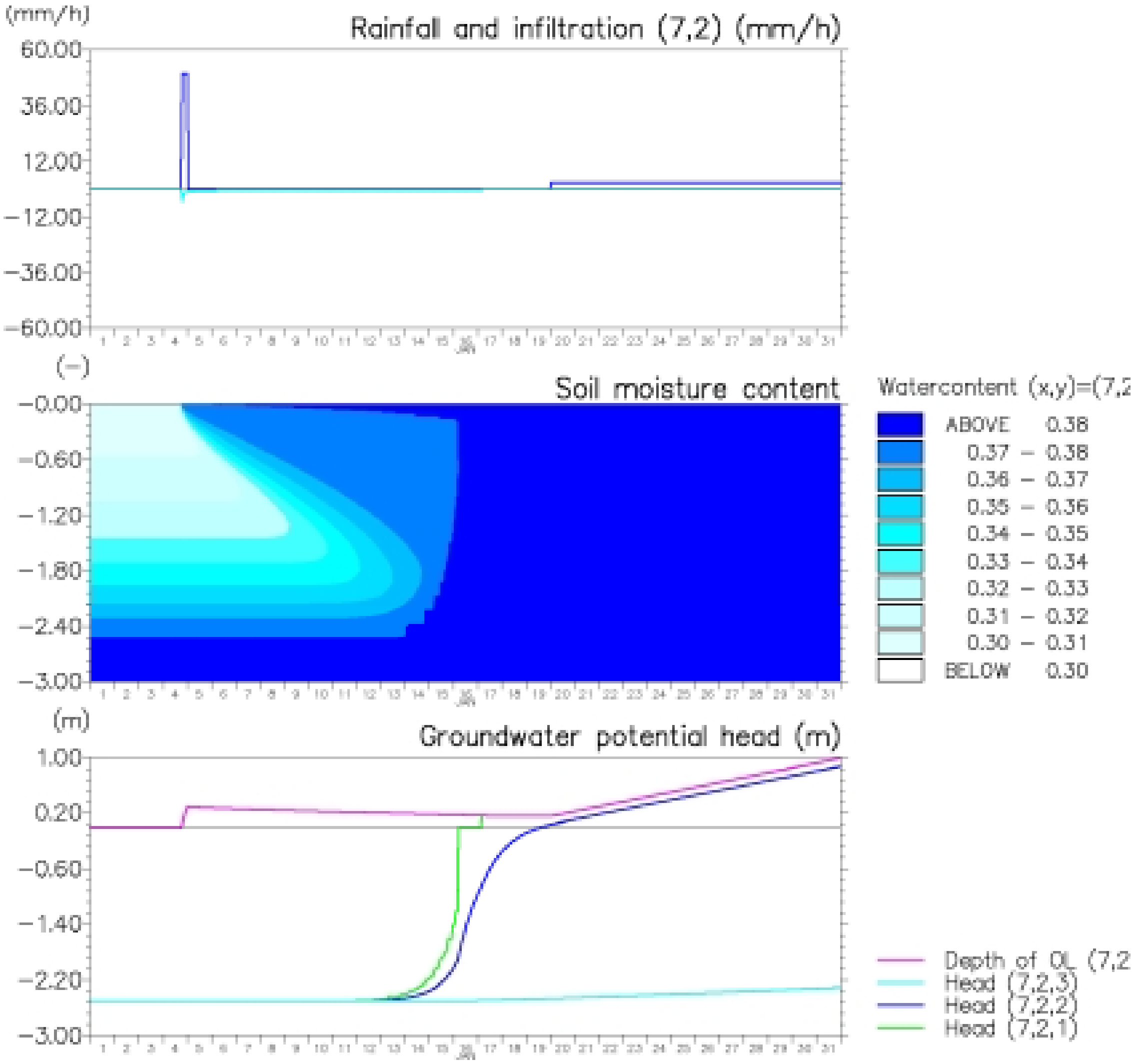


Figure 5-10 Simulated water table and soil moisture profile

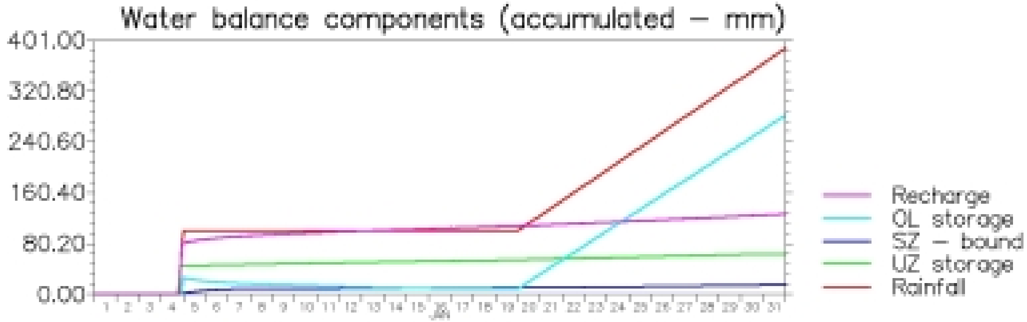


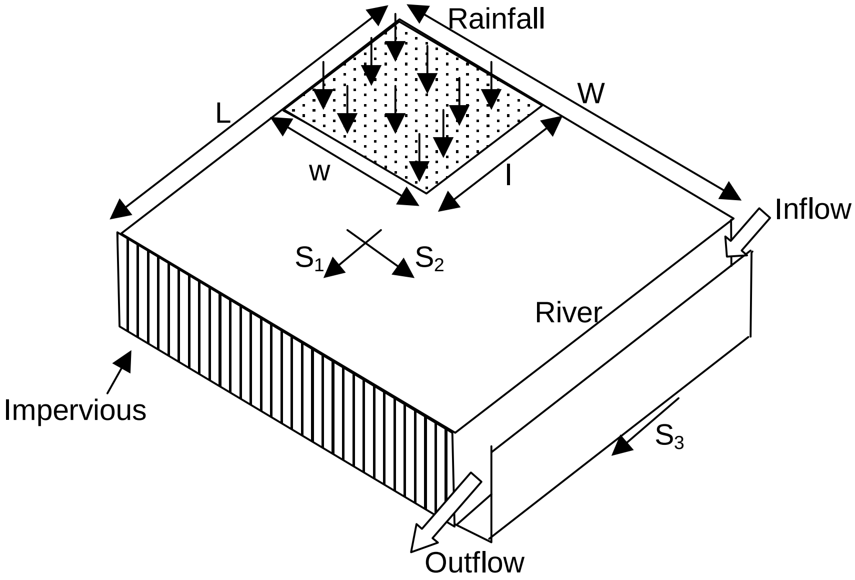
Figure 5-11 Water balance and groundwater recharge

5.5 2D Overland Flow / Surface Water Model with an Impervious Surface

This test case simulates the surface water hydrograph that is generated in response to a series of rainfall events on a two-dimensional impervious surface. Surface runoff is generated by three rainfall events.

The river receives water routed laterally via overland flow to the river. In response, three hydrograph peaks are seen in the simulated river flow. The delay from the start of the rainfall until the flow in the river starts to increase is about one day. The water balance summary shows that a minor part of the overland runoff discharges to the model boundary directly.

Table 5.6 Specifications for test case



Geometry :	
W, model area width (m)	1200
L, model area length (m)	1200
S1, y-slope (%)	0.42
S2, x-slope (%)	0.83
S3, river slope (%)	0.02
Model area (grid size) (m)	12x12 cells (100)
Parameters:	
River Manning No. ($m^{1/3}S^{-1}$)	20.0
Overland Manning No. ($m^{1/3}S^{-1}$)	5.0

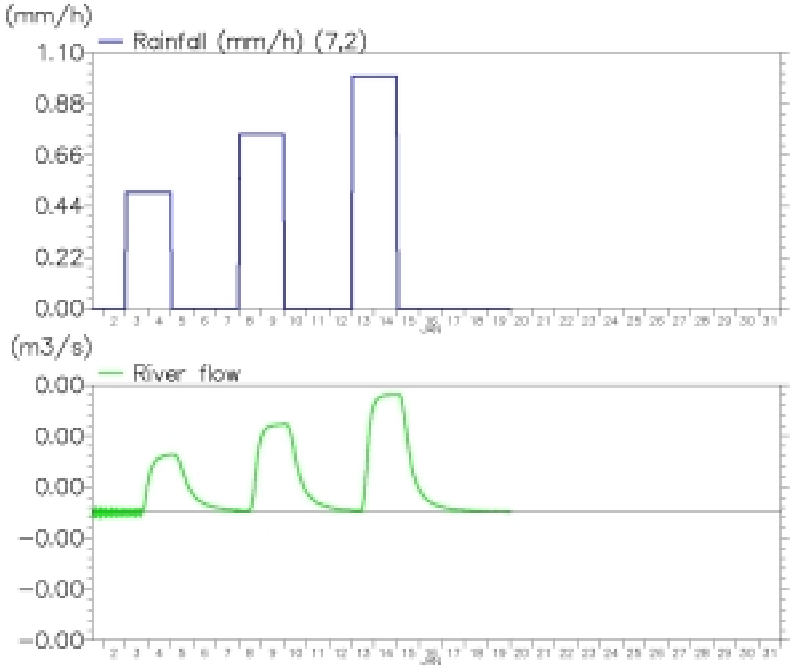


Figure 5-12   Rainfall and runoff

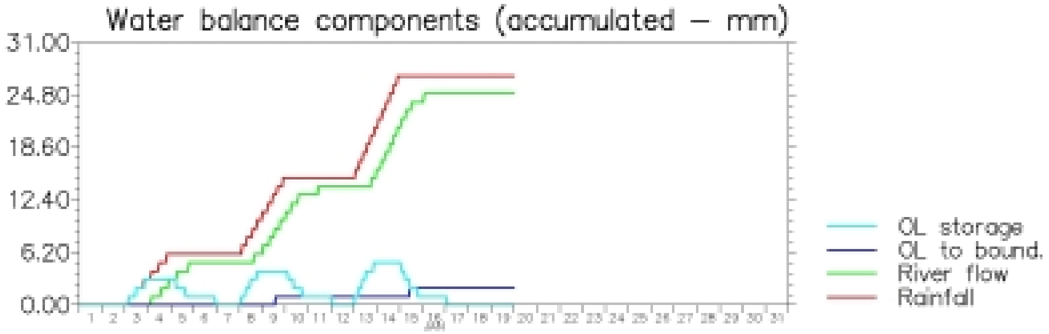


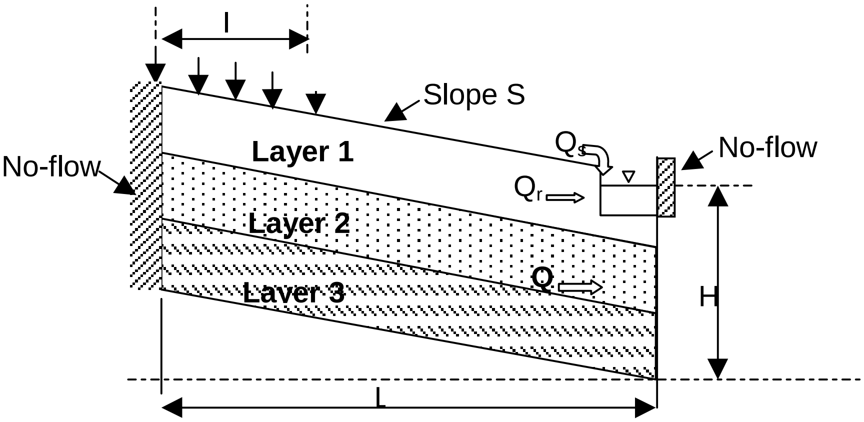
Figure 5-13   Water balance

5.6 2D Overland Flow / Unsaturated Zone Model with a Pervious Surface

This test case simulates the soil moisture changes in the unsaturated zone, the groundwater flow and recharge and river flow in response to overland flow on an infiltrating surface generated by a time varying rainfall rate in the upland portion of the 2-D hill slope model. The model has been set up using the ground water component (MIKE SHE SZ), the unsaturated zone component (MIKE SHE UZ), the overland component (MIKE SHE OL) and the MIKE11 river component. Overland flow is generated by four rainfall events. The groundwater model includes three layers dipping towards the river.

The flow to the river is dominated by base flow due to the majority of the rainfall is infiltrating to the unsaturated zone adding to groundwater flow and subsequent base flow discharge to the river. No drain flow is generated to the river as drains were not included. For the first 20 days, the infiltration capacity of the unsaturated zone is higher than the rainfall intensity, which means that no overland runoff is generated. After 20 days, a higher intensity event occurs for which the soil becomes saturated and the excess rainfall flows to the river via overland flow. Most of the rainfall infiltrating to the soil adds to the unsaturated zone storage. Later the increased volume of water stored in the unsaturated zone will drain and add to the groundwater recharge. The increased head gradient between the aquifer and the river increases groundwater seepage to the river, further increasing the river flow.

Table 5.7 Specifications for the test case



Geometry :	
l, width of rainfall area	400
L, total width of model	1200
S, hillslope (%)	0.83
H, Aquifer (layer thickness) (m)	30 (3 x 10)
Model area (grid size) (m)	1 x 12 cells (100)
Aquifer parameters:	
K_h, Horizontal hydraulic conductivity (m/s)	L1: 2.1e-5 L2: 9.3e-6 L3: 2.7e-8
K_v, Vertical hydraulic conductivity (m/s)	$K_v = 0.1\ K_h$
S_y, Specific Yield (-)	0.25
Unsaturated zone parameters	
See Case 4	
Initial conditions :	
Potential head of layer 1-3 (m)	2.5 m below ground
River stage	-2.4 m
Boundary conditions :	
SZ layer 1-3, constant head (m)	-2.5 m
Precipitation	See Figure 7.1

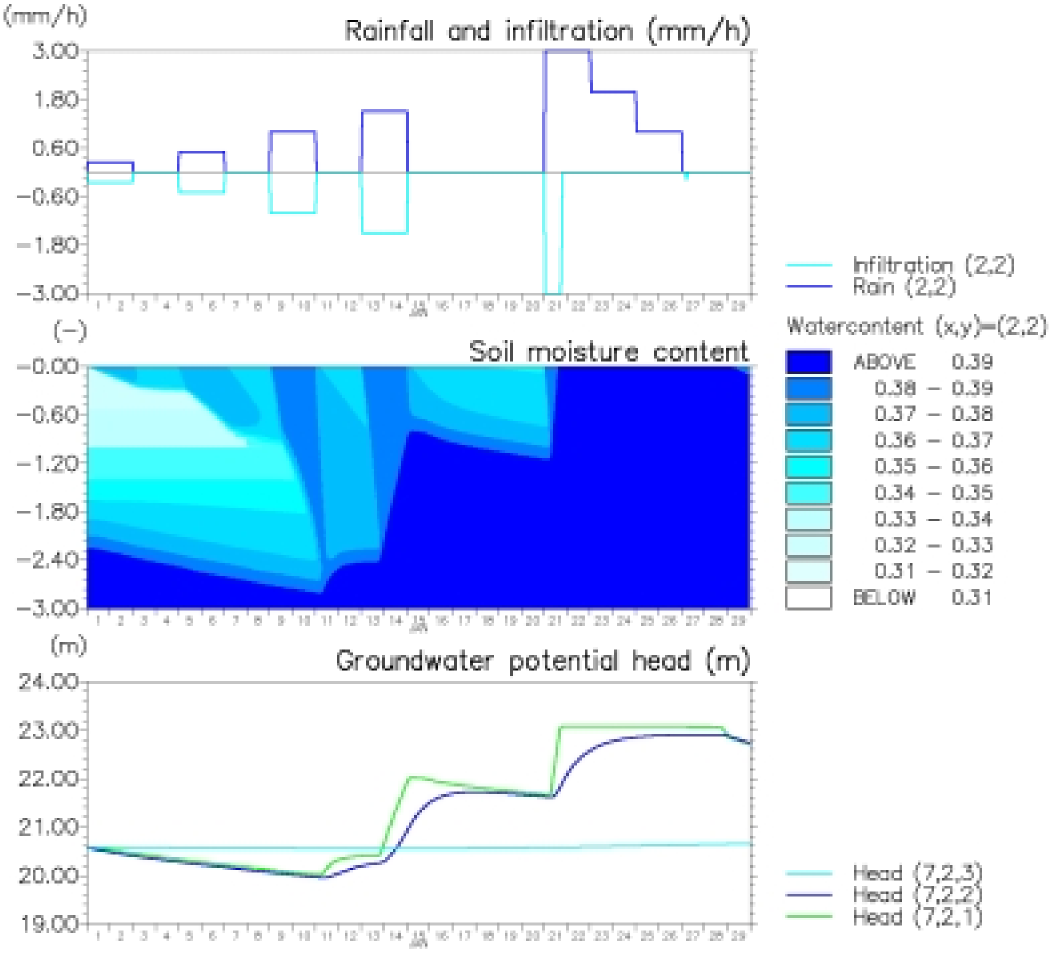


Figure 5-14 Rainfall and runoff

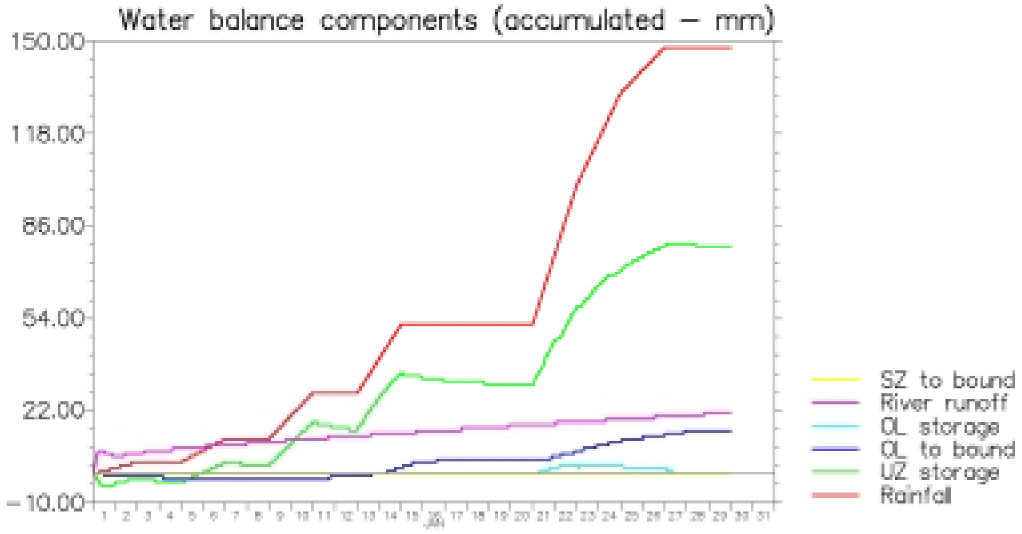


Figure 5-15 Water balance

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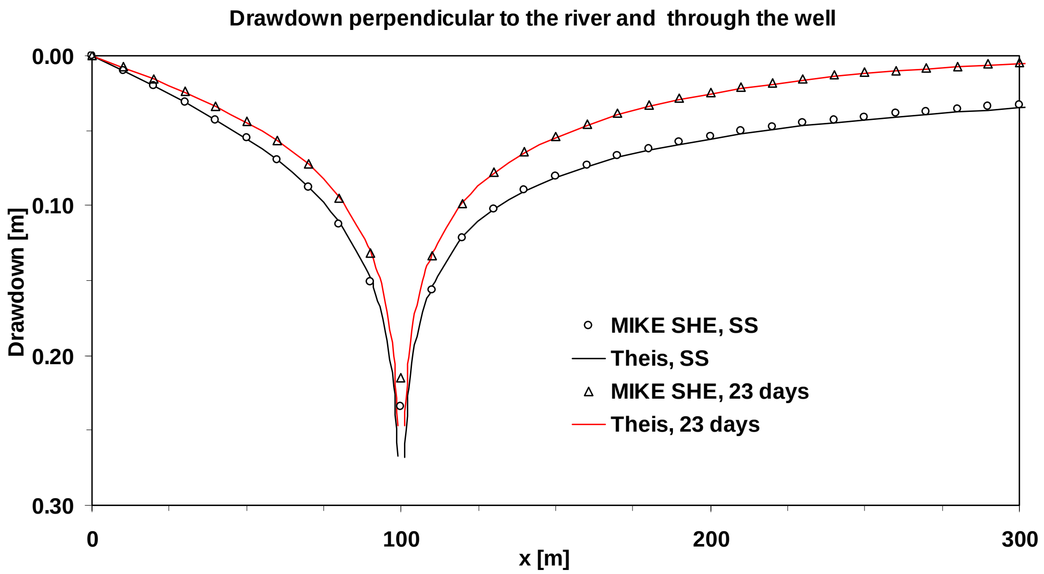
7 APPENDIX A – TABULAR DATA FOR GRAPHS

Figure 2.3

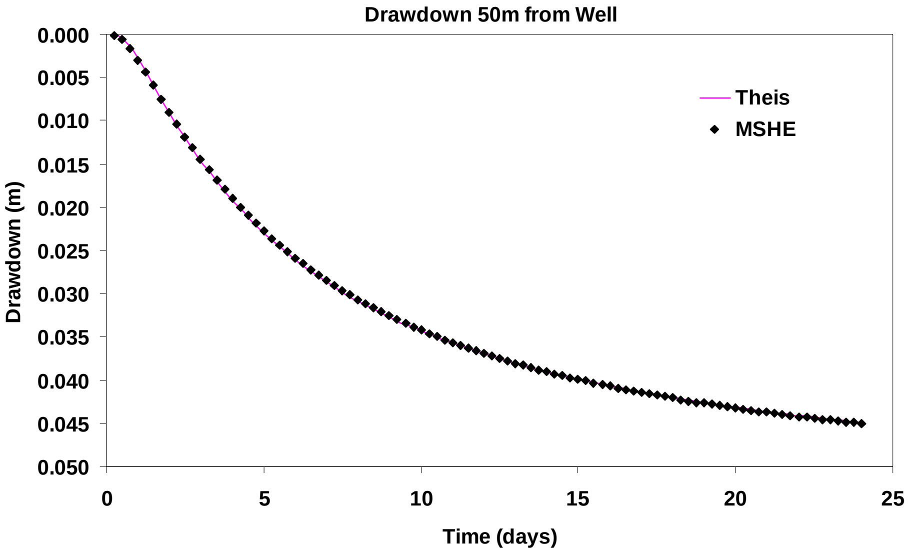


Distance from River (m)	Steady-State		Absolute Difference (m)	Relative Difference	Transient		Absolute Difference (m)	Relative Difference
	MSHE (m)	Theis (m)			MSHE (m)	Theis (m)		
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
10	0.0100	0.0101	-0.0001	-0.0003	0.0078	0.0079	-0.0001	-0.0005
20	0.0203	0.0205	-0.0001	-0.0005	0.0157	0.0160	-0.0003	-0.0009
30	0.0310	0.0312	-0.0002	-0.0007	0.0242	0.0246	-0.0004	-0.0013
40	0.0425	0.0428	-0.0002	-0.0008	0.0335	0.0339	-0.0004	-0.0016
50	0.0553	0.0554	-0.0002	-0.0007	0.0441	0.0445	-0.0004	-0.0016
60	0.0699	0.0700	-0.0001	-0.0003	0.0566	0.0570	-0.0004	-0.0014
70	0.0878	0.0875	0.0003	0.0010	0.0725	0.0726	-0.0001	-0.0003
80	0.1120	0.1109	0.0012	0.0043	0.0949	0.0941	0.0008	0.0028
90	0.1511	0.1486	0.0025	0.0094	0.1321	0.1301	0.0021	0.0077
100	0.2345				0.2150			
110	0.1561	0.1537	0.0024	0.0090	0.1339	0.1319	0.0020	0.0073
120	0.1219	0.1210	0.0009	0.0033	0.0984	0.0978	0.0006	0.0021
130	0.1026	0.1028	-0.0002	-0.0006	0.0780	0.0783	-0.0004	-0.0014
140	0.0898	0.0904	-0.0007	-0.0025	0.0640	0.0648	-0.0008	-0.0029
150	0.0803	0.0812	-0.0010	-0.0035	0.0536	0.0545	-0.0010	-0.0035
160	0.0728	0.0740	-0.0012	-0.0043	0.0454	0.0464	-0.0010	-0.0038
170	0.0668	0.0681	-0.0013	-0.0049	0.0387	0.0397	-0.0011	-0.0039
180	0.0618	0.0632	-0.0014	-0.0054	0.0331	0.0341	-0.0011	-0.0039
190	0.0575	0.0591	-0.0016	-0.0058	0.0284	0.0294	-0.0010	-0.0039
200	0.0538	0.0554	-0.0017	-0.0062	0.0244	0.0254	-0.0010	-0.0037
210	0.0505	0.0523	-0.0018	-0.0065	0.0209	0.0219	-0.0009	-0.0035
220	0.0477	0.0495	-0.0018	-0.0068	0.0180	0.0189	-0.0009	-0.0033
230	0.0451	0.0470	-0.0019	-0.0071	0.0154	0.0162	-0.0008	-0.0031
240	0.0428	0.0448	-0.0020	-0.0074	0.0132	0.0140	-0.0008	-0.0029

250	0.0407	0.0428	-0.0021	-0.0076	0.0113	0.0120	-0.0007	-0.0026
260	0.0388	0.0409	-0.0021	-0.0078	0.0096	0.0103	-0.0006	-0.0024
270	0.0371	0.0392	-0.0022	-0.0080	0.0082	0.0088	-0.0006	-0.0022
280	0.0355	0.0377	-0.0022	-0.0082	0.0070	0.0075	-0.0005	-0.0019
290	0.0340	0.0363	-0.0023	-0.0084	0.0059	0.0064	-0.0005	-0.0017
300	0.0327	0.0350	-0.0023	-0.0085	0.0050	0.0054	-0.0004	-0.0015

*Relative to: Theis drawdown 1m from well = 0.27m

Figure 2.4



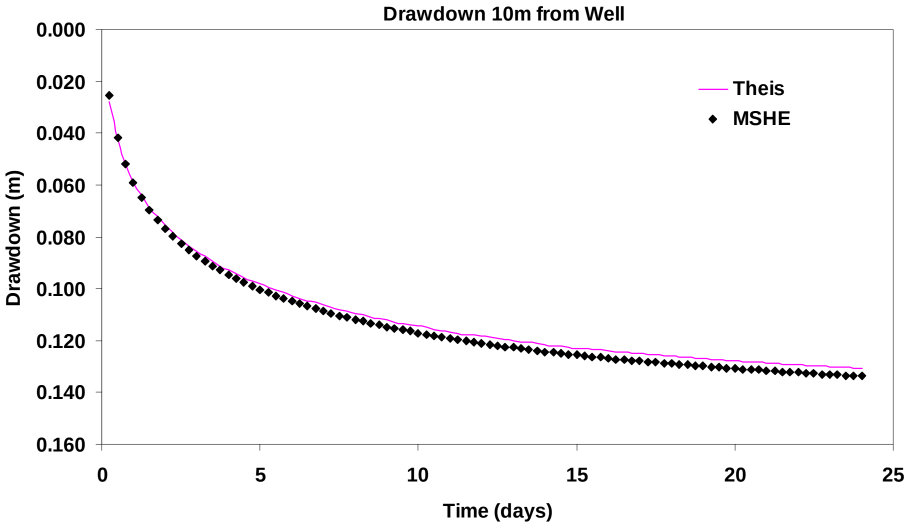
Time (days)	Time (seconds)	MSHE Drawdown	Theis Drawdown	Absolute Difference	Relative Difference*
0	0				
0.25	21600	0.0001	0.0000	-0.0001	-0.0004
0.5	43200	0.0007	0.0004	-0.0003	-0.0011
0.75	64800	0.0017	0.0014	-0.0003	-0.0012
1	86400	0.0030	0.0027	-0.0002	-0.0009
1.25	108000	0.0044	0.0043	-0.0001	-0.0005
1.5	129600	0.0059	0.0059	-0.0001	-0.0002
1.75	151200	0.0075	0.0075	0.0000	0.0000
2	172800	0.0090	0.0090	0.0000	0.0002
2.25	194400	0.0104	0.0105	0.0001	0.0003
2.5	216000	0.0118	0.0119	0.0001	0.0005
2.75	237600	0.0132	0.0133	0.0002	0.0006
3	259200	0.0144	0.0146	0.0002	0.0007
3.25	280800	0.0157	0.0159	0.0002	0.0008
3.5	302400	0.0168	0.0170	0.0002	0.0008
3.75	324000	0.0179	0.0182	0.0002	0.0009
4	345600	0.0190	0.0192	0.0002	0.0009
4.25	367200	0.0200	0.0202	0.0002	0.0009
4.5	388800	0.0209	0.0212	0.0002	0.0009
4.75	410400	0.0219	0.0221	0.0003	0.0009
5	432000	0.0227	0.0230	0.0002	0.0009
5.25	453600	0.0236	0.0238	0.0002	0.0009
5.5	475200	0.0244	0.0246	0.0002	0.0009

5.75	496800	0.0251	0.0254	0.0002	0.0009
6	518400	0.0259	0.0261	0.0002	0.0008
6.25	540000	0.0266	0.0268	0.0002	0.0008
6.5	561600	0.0272	0.0274	0.0002	0.0008
6.75	583200	0.0279	0.0281	0.0002	0.0008
7	604800	0.0285	0.0287	0.0002	0.0007
7.25	626400	0.0291	0.0293	0.0002	0.0007
7.5	648000	0.0296	0.0298	0.0002	0.0007
7.75	669600	0.0302	0.0303	0.0002	0.0006
8	691200	0.0307	0.0309	0.0002	0.0006
8.25	712800	0.0312	0.0314	0.0002	0.0006
8.5	734400	0.0317	0.0318	0.0001	0.0006
8.75	756000	0.0321	0.0323	0.0001	0.0005
9	777600	0.0326	0.0327	0.0001	0.0005
9.25	799200	0.0330	0.0331	0.0001	0.0005
9.5	820800	0.0334	0.0336	0.0001	0.0004
9.75	842400	0.0338	0.0340	0.0001	0.0004
10	864000	0.0342	0.0343	0.0001	0.0004
10.25	885600	0.0346	0.0347	0.0001	0.0003
10.5	907200	0.0350	0.0351	0.0001	0.0003
10.75	928800	0.0353	0.0354	0.0001	0.0003
11	950400	0.0357	0.0357	0.0001	0.0003
11.25	972000	0.0360	0.0361	0.0001	0.0002
11.5	993600	0.0363	0.0364	0.0001	0.0002
11.75	1015200	0.0366	0.0367	0.0000	0.0002
12	1036800	0.0369	0.0370	0.0000	0.0002
12.25	1058400	0.0372	0.0372	0.0000	0.0001
12.5	1080000	0.0375	0.0375	0.0000	0.0001
12.75	1101600	0.0378	0.0378	0.0000	0.0001
13	1123200	0.0380	0.0380	0.0000	0.0001
13.25	1144800	0.0383	0.0383	0.0000	0.0000
13.5	1166400	0.0385	0.0385	0.0000	0.0000
13.75	1188000	0.0388	0.0388	0.0000	0.0000
14	1209600	0.0390	0.0390	0.0000	0.0000
14.25	1231200	0.0393	0.0392	0.0000	0.0000
14.5	1252800	0.0395	0.0395	0.0000	-0.0001
14.75	1274400	0.0397	0.0397	0.0000	-0.0001
15	1296000	0.0399	0.0399	0.0000	-0.0001
15.25	1317600	0.0401	0.0401	0.0000	-0.0001
15.5	1339200	0.0403	0.0403	0.0000	-0.0001
15.75	1360800	0.0405	0.0405	0.0000	-0.0002
16	1382400	0.0407	0.0407	0.0000	-0.0002
16.25	1404000	0.0409	0.0408	0.0000	-0.0002
16.5	1425600	0.0411	0.0410	-0.0001	-0.0002
16.75	1447200	0.0413	0.0412	-0.0001	-0.0002
17	1468800	0.0414	0.0414	-0.0001	-0.0002
17.25	1490400	0.0416	0.0415	-0.0001	-0.0002
17.5	1512000	0.0418	0.0417	-0.0001	-0.0003
17.75	1533600	0.0419	0.0419	-0.0001	-0.0003

18	1555200	0.0421	0.0420	-0.0001	-0.0003
18.25	1576800	0.0422	0.0422	-0.0001	-0.0003
18.5	1598400	0.0424	0.0423	-0.0001	-0.0003
18.75	1620000	0.0425	0.0425	-0.0001	-0.0003
19	1641600	0.0427	0.0426	-0.0001	-0.0003
19.25	1663200	0.0428	0.0427	-0.0001	-0.0003
19.5	1684800	0.0430	0.0429	-0.0001	-0.0004
19.75	1706400	0.0431	0.0430	-0.0001	-0.0004
20	1728000	0.0432	0.0431	-0.0001	-0.0004
20.25	1749600	0.0434	0.0433	-0.0001	-0.0004
20.5	1771200	0.0435	0.0434	-0.0001	-0.0004
20.75	1792800	0.0436	0.0435	-0.0001	-0.0004
21	1814400	0.0438	0.0436	-0.0001	-0.0004
21.25	1836000	0.0439	0.0438	-0.0001	-0.0004
21.5	1857600	0.0440	0.0439	-0.0001	-0.0004
21.75	1879200	0.0441	0.0440	-0.0001	-0.0005
22	1900800	0.0442	0.0441	-0.0001	-0.0005
22.25	1922400	0.0443	0.0442	-0.0001	-0.0005
22.5	1944000	0.0444	0.0443	-0.0001	-0.0005
22.75	1965600	0.0445	0.0444	-0.0001	-0.0005
23	1987200	0.0447	0.0445	-0.0001	-0.0005
23.25	2008800	0.0448	0.0446	-0.0001	-0.0005
23.5	2030400	0.0449	0.0447	-0.0001	-0.0005
23.75	2052000	0.0450	0.0448	-0.0001	-0.0005
24	2073600	0.0451	0.0449	-0.0001	-0.0005

*Relative to: Theis drawdown 1m from well = 0.27m

Figure 2.5



Time (days)	Time (seconds)	MIKE SHE Drawdown	Theis Drawdown	Absolute Difference	Relative Difference*
0	0				
0.25	21600	0.0256	0.0279	0.0023	0.0084
0.5	43200	0.0418	0.0427	0.0009	0.0032
0.75	64800	0.0519	0.0520	0.0001	0.0003
1	86400	0.0592	0.0588	-0.0005	-0.0017
1.25	108000	0.0649	0.0641	-0.0008	-0.0030
1.5	129600	0.0696	0.0685	-0.0011	-0.0040
1.75	151200	0.0736	0.0723	-0.0013	-0.0047
2	172800	0.0770	0.0756	-0.0014	-0.0053
2.25	194400	0.0800	0.0784	-0.0015	-0.0057
2.5	216000	0.0826	0.0810	-0.0016	-0.0059
2.75	237600	0.0851	0.0834	-0.0017	-0.0062
3	259200	0.0873	0.0855	-0.0017	-0.0064
3.25	280800	0.0893	0.0875	-0.0018	-0.0066
3.5	302400	0.0912	0.0894	-0.0018	-0.0068
3.75	324000	0.0929	0.0911	-0.0019	-0.0070
4	345600	0.0946	0.0927	-0.0019	-0.0071
4.25	367200	0.0961	0.0942	-0.0020	-0.0073
4.5	388800	0.0976	0.0956	-0.0020	-0.0074
4.75	410400	0.0990	0.0969	-0.0020	-0.0076
5	432000	0.1002	0.0982	-0.0021	-0.0077
5.25	453600	0.1015	0.0994	-0.0021	-0.0078
5.5	475200	0.1026	0.1005	-0.0021	-0.0079
5.75	496800	0.1038	0.1016	-0.0022	-0.0081
6	518400	0.1048	0.1026	-0.0022	-0.0082

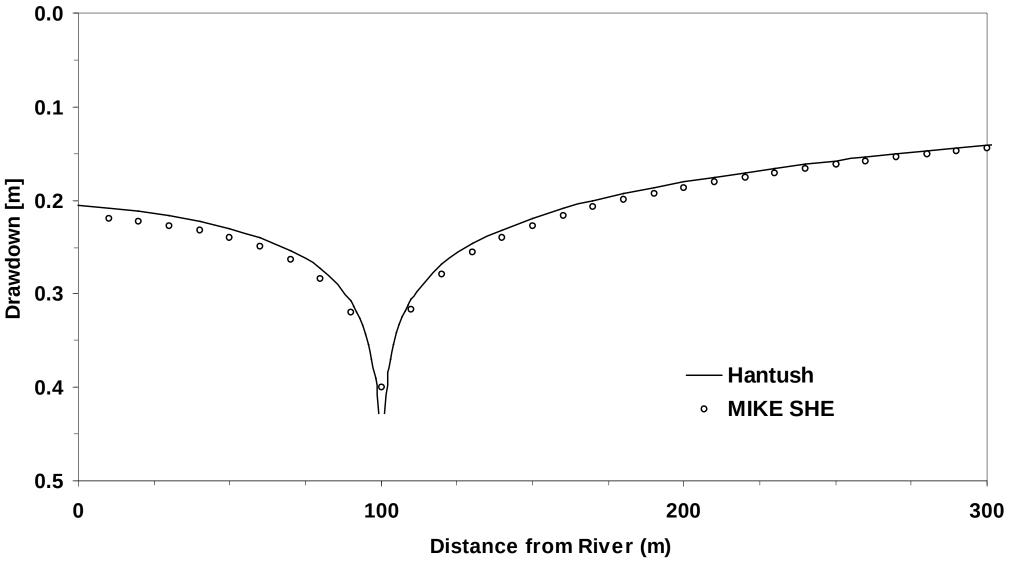
6.25	540000	0.1058	0.1036	-0.0022	-0.0083
6.5	561600	0.1068	0.1045	-0.0023	-0.0084
6.75	583200	0.1077	0.1054	-0.0023	-0.0084
7	604800	0.1086	0.1063	-0.0023	-0.0085
7.25	626400	0.1095	0.1071	-0.0023	-0.0086
7.5	648000	0.1103	0.1079	-0.0023	-0.0087
7.75	669600	0.1111	0.1087	-0.0024	-0.0088
8	691200	0.1118	0.1095	-0.0024	-0.0089
8.25	712800	0.1126	0.1102	-0.0024	-0.0089
8.5	734400	0.1133	0.1108	-0.0024	-0.0090
8.75	756000	0.1140	0.1115	-0.0024	-0.0091
9	777600	0.1146	0.1121	-0.0025	-0.0091
9.25	799200	0.1153	0.1128	-0.0025	-0.0092
9.5	820800	0.1159	0.1134	-0.0025	-0.0093
9.75	842400	0.1165	0.1139	-0.0025	-0.0093
10	864000	0.1170	0.1145	-0.0025	-0.0094
10.25	885600	0.1176	0.1150	-0.0025	-0.0094
10.5	907200	0.1181	0.1156	-0.0026	-0.0095
10.75	928800	0.1186	0.1161	-0.0026	-0.0096
11	950400	0.1192	0.1166	-0.0026	-0.0096
11.25	972000	0.1196	0.1170	-0.0026	-0.0097
11.5	993600	0.1201	0.1175	-0.0026	-0.0097
11.75	1015200	0.1206	0.1180	-0.0026	-0.0098
12	1036800	0.1210	0.1184	-0.0026	-0.0098
12.25	1058400	0.1215	0.1188	-0.0027	-0.0098
12.5	1080000	0.1219	0.1192	-0.0027	-0.0099
12.75	1101600	0.1223	0.1196	-0.0027	-0.0099
13	1123200	0.1227	0.1200	-0.0027	-0.0100
13.25	1144800	0.1231	0.1204	-0.0027	-0.0100
13.5	1166400	0.1235	0.1208	-0.0027	-0.0101
13.75	1188000	0.1239	0.1211	-0.0027	-0.0101
14	1209600	0.1242	0.1215	-0.0027	-0.0101
14.25	1231200	0.1246	0.1218	-0.0027	-0.0102
14.5	1252800	0.1249	0.1222	-0.0028	-0.0102
14.75	1274400	0.1253	0.1225	-0.0028	-0.0103
15	1296000	0.1256	0.1228	-0.0028	-0.0103
15.25	1317600	0.1259	0.1231	-0.0028	-0.0103
15.5	1339200	0.1262	0.1234	-0.0028	-0.0104
15.75	1360800	0.1265	0.1237	-0.0028	-0.0104
16	1382400	0.1268	0.1240	-0.0028	-0.0104
16.25	1404000	0.1271	0.1243	-0.0028	-0.0105
16.5	1425600	0.1274	0.1246	-0.0028	-0.0105
16.75	1447200	0.1277	0.1248	-0.0028	-0.0105
17	1468800	0.1279	0.1251	-0.0028	-0.0105
17.25	1490400	0.1282	0.1254	-0.0029	-0.0106
17.5	1512000	0.1285	0.1256	-0.0029	-0.0106
17.75	1533600	0.1287	0.1259	-0.0029	-0.0106
18	1555200	0.1290	0.1261	-0.0029	-0.0107
18.25	1576800	0.1292	0.1263	-0.0029	-0.0107

18.5	1598400	0.1295	0.1266	-0.0029	-0.0107
18.75	1620000	0.1297	0.1268	-0.0029	-0.0107
19	1641600	0.1299	0.1270	-0.0029	-0.0108
19.25	1663200	0.1301	0.1272	-0.0029	-0.0108
19.5	1684800	0.1304	0.1275	-0.0029	-0.0108
19.75	1706400	0.1306	0.1277	-0.0029	-0.0108
20	1728000	0.1308	0.1279	-0.0029	-0.0109
20.25	1749600	0.1310	0.1281	-0.0029	-0.0109
20.5	1771200	0.1312	0.1283	-0.0029	-0.0109
20.75	1792800	0.1314	0.1285	-0.0029	-0.0109
21	1814400	0.1316	0.1287	-0.0030	-0.0109
21.25	1836000	0.1318	0.1288	-0.0030	-0.0110
21.5	1857600	0.1320	0.1290	-0.0030	-0.0110
21.75	1879200	0.1322	0.1292	-0.0030	-0.0110
22	1900800	0.1324	0.1294	-0.0030	-0.0110
22.25	1922400	0.1325	0.1296	-0.0030	-0.0110
22.5	1944000	0.1327	0.1297	-0.0030	-0.0111
22.75	1965600	0.1329	0.1299	-0.0030	-0.0111
23	1987200	0.1330	0.1301	-0.0030	-0.0111
23.25	2008800	0.1332	0.1302	-0.0030	-0.0111
23.5	2030400	0.1334	0.1304	-0.0030	-0.0111
23.75	2052000	0.1335	0.1305	-0.0030	-0.0111
24	2073600	0.1337	0.1307	-0.0030	-0.0112

*Relative to: Theis drawdown 1m from well = 0.27m

Figure 2.8

Drawdown perpendicular to the river and through the well

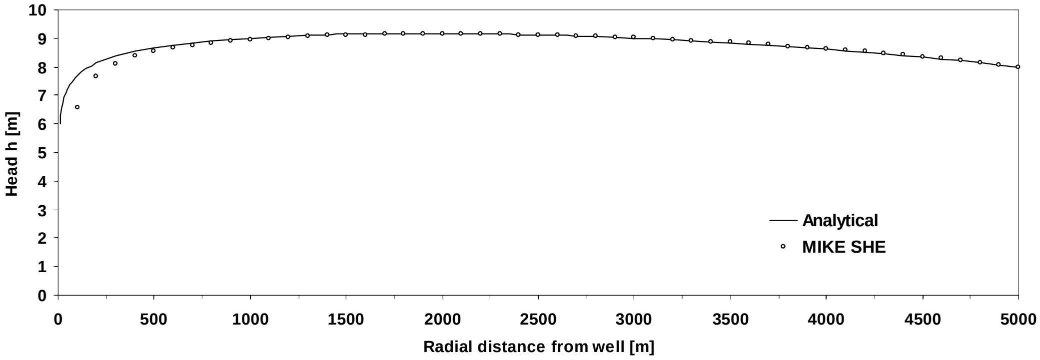


Distance from River (m)	Drawdown MSHE (m)	 Hantush (m)	Absolute Difference (m)	Relative* Difference
0				
10	0.2196	0.2080	0.0116	0.0269
20	0.2228	0.2116	0.0112	0.0261
30	0.2272	0.2162	0.0110	0.0255
40	0.2330	0.2222	0.0108	0.0251
50	0.2405	0.2298	0.0107	0.0248
60	0.2504	0.2398	0.0106	0.0248
70	0.2639	0.2532	0.0107	0.0249
80	0.2842	0.2729	0.0113	0.0263
90	0.3199	0.3077	0.0122	0.0283
100	0.4008			
110	0.3174	0.3056	0.0118	0.0274
120	0.2792	0.2687	0.0105	0.0245
130	0.2563	0.2468	0.0095	0.0220
140	0.2401	0.2312	0.0089	0.0207
150	0.2274	0.2190	0.0084	0.0196
160	0.2170	0.2089	0.0081	0.0188
170	0.2081	0.2004	0.0077	0.0180
180	0.2004	0.1929	0.0075	0.0174

190	0.1935	0.1864	0.0071	0.0166
200	0.1872	0.1805	0.0067	0.0157
210	0.1815	0.1751	0.0064	0.0148
220	0.1762	0.1703	0.0059	0.0138
230	0.1714	0.1658	0.0056	0.0131
240	0.1668	0.1616	0.0052	0.0120
250	0.1625	0.1578	0.0047	0.0110
260	0.1584	0.1542	0.0042	0.0099
270	0.1546	0.1508	0.0038	0.0089
280	0.1509	0.1476	0.0033	0.0077
290	0.1474	0.1446	0.0028	0.0065
300	0.1441	0.1417	0.0024	0.0055

*Relative to: Hantush drawdown 1m from well = 0.43 m

Figure 2.11

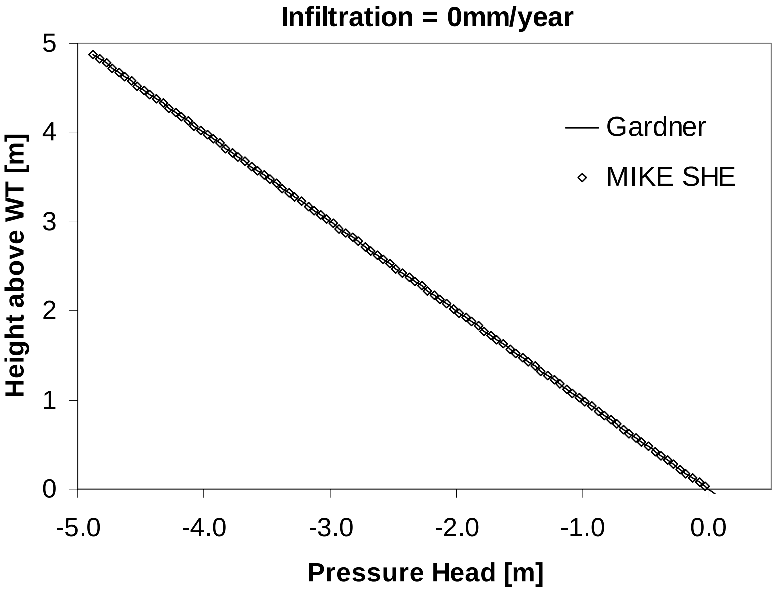


Radial Distance (m)	Analytical Head (m)	MSHE Head (m)	Absolute Difference (m)	Relative Difference
10	5.999557166			
20	6.556720103			
50	7.227467001			
70	7.458494619			
100	7.695594296	6.557542	1.138052296	0.124214508
200	8.134913268	7.670027	0.464886268	0.050740743
300	8.378540913	8.121976	0.256564913	0.028003181
400	8.544381557	8.374253	0.170128557	0.018568949
500	8.667973501	8.542922	0.125051501	0.013648943
600	8.764773632	8.667291	0.097482632	0.010639895
700	8.842885692	8.764126	0.078759692	0.00859635
800	8.907081369	8.841964	0.065117369	0.007107338
900	8.960403742	8.905738	0.054665742	0.005966578
1000	9.004910157	8.958558	0.046352157	0.005059179
1100	9.042054933	9.002514	0.039540933	0.004315757
1200	9.072902832	9.039076	0.033826832	0.003692083
1300	9.09825576	9.06932	0.02893576	0.003158239
1400	9.118731802	9.094051	0.024680802	0.002693825
1500	9.134816595	9.113891	0.020925595	0.002283957
1600	9.14689788	9.129327	0.01757088	0.001917801
1700	9.155289431	9.140746	0.014543431	0.001587366
1800	9.160248043	9.14846	0.011788043	0.001286624
1900	9.161985865	9.152725	0.009260865	0.001010792
2000	9.160679519	9.153751	0.006928519	0.000756224
2100	9.156476959	9.151713	0.004763959	0.00051997
2200	9.149502704	9.14676	0.002742704	0.000299357
2300	9.139861891	9.139016	0.000845891	9.23261E-05
2400	9.127643441	9.128588	-0.000944559	-0.000103095
2500	9.112922565	9.115566	-0.002643435	-0.000288522
2600	9.095762761	9.100025	-0.004262239	-0.000465209

2700	9.076217417	9.082026	-0.005808583	-0.000633987
2800	9.054331118	9.061616	-0.007284882	-0.00079512
2900	9.030140696	9.038835	-0.008694304	-0.000948954
3000	9.003676094	9.013709	-0.010032906	-0.001095057
3100	8.97496108	8.986262	-0.01130092	-0.001233457
3200	8.944013817	8.956508	-0.012494183	-0.001363697
3300	8.910847342	8.924459	-0.013611658	-0.001485666
3400	8.875469953	8.890122	-0.014652047	-0.001599221
3500	8.837885518	8.853498	-0.015612482	-0.001704049
3600	8.798093725	8.814584	-0.016490275	-0.001799857
3700	8.756090278	8.773367	-0.017276722	-0.001885695
3800	8.711867039	8.729828	-0.017960961	-0.001960377
3900	8.665412136	8.683936	-0.018523864	-0.002021816
4000	8.61671002	8.635649	-0.01893898	-0.002067125
4100	8.565741501	8.584913	-0.019171499	-0.002092503
4200	8.512483732	8.53166	-0.019176268	-0.002093024
4300	8.456910178	8.475808	-0.018897822	-0.002062633
4400	8.398990538	8.417254	-0.018263462	-0.001993394
4500	8.338690641	8.355874	-0.017183359	-0.001875505
4600	8.275972312	8.291516	-0.015543688	-0.00169654
4700	8.210793189	8.223992	-0.013198811	-0.001440605
4800	8.143106519	8.15308	-0.009973481	-0.001088571
4900	8.072860903	8.078516	-0.005655097	-0.000617234
5000	8	8	0	0

*Relative to: Hantush drawdown 1m from well = 0.43 m

Figure 2.14



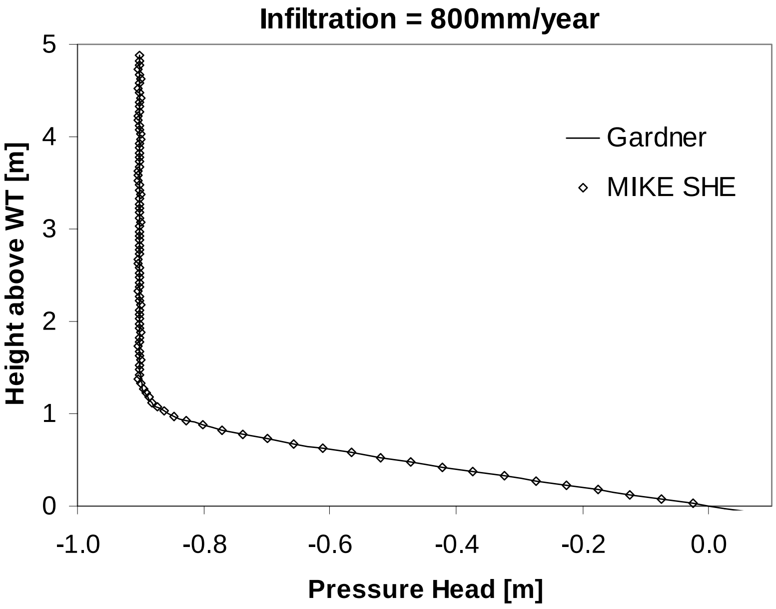
Height above WT (m)	MSHE Head (m)	Analytical Head (m)	Absolute Difference (m)	Relative* Difference (-)
4.8750	-4.8750	-4.8750	0.0000	0.0000
4.8250	-4.8250	-4.8250	0.0000	0.0000
4.7750	-4.7750	-4.7750	0.0000	0.0000
4.7250	-4.7250	-4.7250	0.0000	0.0000
4.6750	-4.6750	-4.6750	0.0000	0.0000
4.6250	-4.6250	-4.6250	0.0000	0.0000
4.5750	-4.5750	-4.5750	0.0000	0.0000
4.5250	-4.5250	-4.5250	0.0000	0.0000
4.4750	-4.4750	-4.4750	0.0000	0.0000
4.4250	-4.4250	-4.4250	0.0000	0.0000
4.3750	-4.3750	-4.3750	0.0000	0.0000
4.3250	-4.3250	-4.3250	0.0000	0.0000
4.2750	-4.2750	-4.2750	0.0000	0.0000
4.2250	-4.2250	-4.2250	0.0000	0.0000
4.1750	-4.1750	-4.1750	0.0000	0.0000
4.1250	-4.1250	-4.1250	0.0000	0.0000
4.0750	-4.0750	-4.0750	0.0000	0.0000
4.0250	-4.0250	-4.0250	0.0000	0.0000
3.9750	-3.9750	-3.9750	0.0000	0.0000

3.9250	-3.9250	-3.9250	0.0000	0.0000
3.8750	-3.8750	-3.8750	0.0000	0.0000
3.8250	-3.8250	-3.8250	0.0000	0.0000
3.7750	-3.7750	-3.7750	0.0000	0.0000
3.7250	-3.7250	-3.7250	0.0000	0.0000
3.6750	-3.6750	-3.6750	0.0000	0.0000
3.6250	-3.6250	-3.6250	0.0000	0.0000
3.5750	-3.5750	-3.5750	0.0000	0.0000
3.5250	-3.5250	-3.5250	0.0000	0.0000
3.4750	-3.4750	-3.4750	0.0000	0.0000
3.4250	-3.4250	-3.4250	0.0000	0.0000
3.3750	-3.3750	-3.3750	0.0000	0.0000
3.3250	-3.3250	-3.3250	0.0000	0.0000
3.2750	-3.2750	-3.2750	0.0000	0.0000
3.2250	-3.2250	-3.2250	0.0000	0.0000
3.1750	-3.1750	-3.1750	0.0000	0.0000
3.1250	-3.1250	-3.1250	0.0000	0.0000
3.0750	-3.0750	-3.0750	0.0000	0.0000
3.0250	-3.0250	-3.0250	0.0000	0.0000
2.9750	-2.9750	-2.9750	0.0000	0.0000
2.9250	-2.9250	-2.9250	0.0000	0.0000
2.8750	-2.8750	-2.8750	0.0000	0.0000
2.8250	-2.8250	-2.8250	0.0000	0.0000
2.7750	-2.7750	-2.7750	0.0000	0.0000
2.7250	-2.7250	-2.7250	0.0000	0.0000
2.6750	-2.6750	-2.6750	0.0000	0.0000
2.6250	-2.6250	-2.6250	0.0000	0.0000
2.5750	-2.5750	-2.5750	0.0000	0.0000
2.5250	-2.5250	-2.5250	0.0000	0.0000
2.4750	-2.4750	-2.4750	0.0000	0.0000
2.4250	-2.4250	-2.4250	0.0000	0.0000
2.3750	-2.3750	-2.3750	0.0000	0.0000
2.3250	-2.3250	-2.3250	0.0000	0.0000
2.2750	-2.2750	-2.2750	0.0000	0.0000
2.2250	-2.2250	-2.2250	0.0000	0.0000
2.1750	-2.1750	-2.1750	0.0000	0.0000
2.1250	-2.1250	-2.1250	0.0000	0.0000
2.0750	-2.0750	-2.0750	0.0000	0.0000
2.0250	-2.0250	-2.0250	0.0000	0.0000
1.9750	-1.9750	-1.9750	0.0000	0.0000
1.9250	-1.9250	-1.9250	0.0000	0.0000
1.8750	-1.8749	-1.8750	0.0001	0.0000
1.8250	-1.8250	-1.8250	0.0000	0.0000
1.7750	-1.7750	-1.7750	0.0000	0.0000
1.7250	-1.7250	-1.7250	0.0000	0.0000
1.6750	-1.6750	-1.6750	0.0000	0.0000
1.6250	-1.6250	-1.6250	0.0000	0.0000
1.5750	-1.5750	-1.5750	0.0000	0.0000
1.5250	-1.5250	-1.5250	0.0000	0.0000
1.4750	-1.4750	-1.4750	0.0000	0.0000
1.4250	-1.4250	-1.4250	0.0000	0.0000
1.3750	-1.3750	-1.3750	0.0000	0.0000
1.3250	-1.3250	-1.3250	0.0000	0.0000
1.2750	-1.2750	-1.2750	0.0000	0.0000

1.2250	-1.2250	-1.2250	0.0000	0.0000
1.1750	-1.1750	-1.1750	0.0000	0.0000
1.1250	-1.1250	-1.1250	0.0000	0.0000
1.0750	-1.0750	-1.0750	0.0000	0.0000
1.0250	-1.0250	-1.0250	0.0000	0.0000
0.9750	-0.9750	-0.9750	0.0000	0.0000
0.9250	-0.9250	-0.9250	0.0000	0.0000
0.8750	-0.8750	-0.8750	0.0000	0.0000
0.8250	-0.8250	-0.8250	0.0000	0.0000
0.7750	-0.7750	-0.7750	0.0000	0.0000
0.7250	-0.7250	-0.7250	0.0000	0.0000
0.6750	-0.6750	-0.6750	0.0000	0.0000
0.6250	-0.6250	-0.6250	0.0000	0.0000
0.5750	-0.5750	-0.5750	0.0000	0.0000
0.5250	-0.5250	-0.5250	0.0000	0.0000
0.4750	-0.4750	-0.4750	0.0000	0.0000
0.4250	-0.4250	-0.4250	0.0000	0.0000
0.3750	-0.3750	-0.3750	0.0000	0.0000
0.3250	-0.3250	-0.3250	0.0000	0.0000
0.2750	-0.2750	-0.2750	0.0000	0.0000
0.2250	-0.2250	-0.2250	0.0000	0.0000
0.1750	-0.1750	-0.1750	0.0000	0.0000
0.1250	-0.1250	-0.1250	0.0000	0.0000
0.0750	-0.0750	-0.0750	0.0000	0.0000
0.0250	-0.0250	-0.0250	0.0000	0.0000
-0.0250	0.0250	0.0250	0.0000	0.0000
-0.0750	0.0750	0.0750	0.0000	0.0000

*Relative to: Maximum suction head with no infiltration = -4.875 m

Figure 2.15



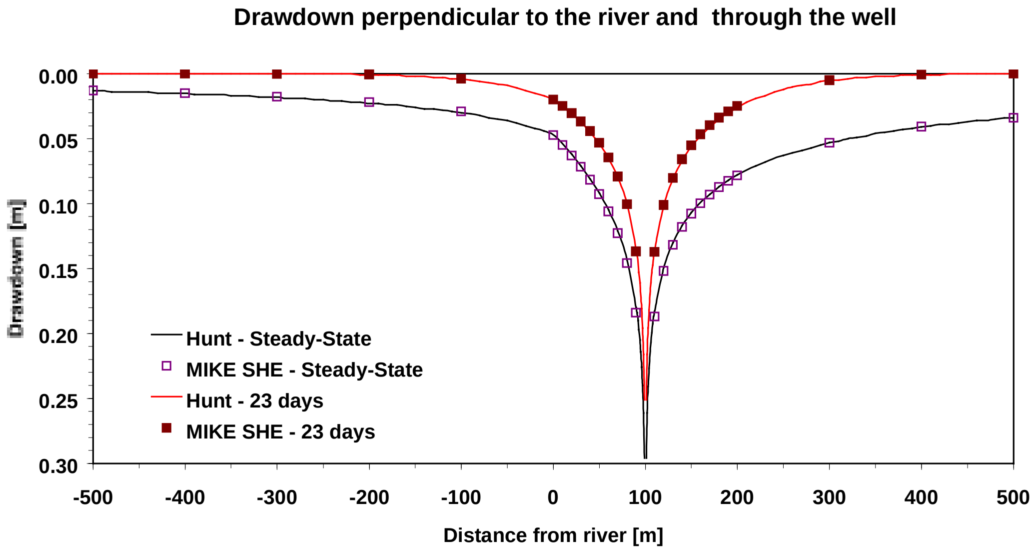
Height above WT (m)	MSHE Head (m)	Analytical Head (m)	Absolute Difference (m)	Relative* Difference (-)
4.8750	-0.9018	-0.9025	0.0007	-0.0002
4.8250	-0.9015	-0.9025	0.0011	-0.0002
4.7750	-0.9026	-0.9025	0.0000	0.0000
4.7250	-0.9033	-0.9025	-0.0007	0.0001
4.6750	-0.9013	-0.9025	0.0012	-0.0003
4.6250	-0.9002	-0.9025	0.0023	-0.0005
4.5750	-0.9018	-0.9025	0.0007	-0.0001
4.5250	-0.9030	-0.9025	-0.0004	0.0001
4.4750	-0.9017	-0.9025	0.0009	-0.0002
4.4250	-0.9006	-0.9025	0.0020	-0.0004
4.3750	-0.9012	-0.9025	0.0014	-0.0003
4.3250	-0.9019	-0.9025	0.0006	-0.0001
4.2750	-0.9027	-0.9025	-0.0001	0.0000
4.2250	-0.9035	-0.9025	-0.0010	0.0002
4.1750	-0.9033	-0.9025	-0.0008	0.0002
4.1250	-0.9021	-0.9025	0.0005	-0.0001
4.0750	-0.9009	-0.9025	0.0017	-0.0003
4.0250	-0.8997	-0.9025	0.0028	-0.0006
3.9750	-0.8997	-0.9025	0.0029	-0.0006
3.9250	-0.9008	-0.9025	0.0018	-0.0004
3.8750	-0.9018	-0.9025	0.0007	-0.0001
3.8250	-0.9028	-0.9025	-0.0003	0.0001
3.7750	-0.9024	-0.9025	0.0001	0.0000
3.7250	-0.9013	-0.9025	0.0012	-0.0003

3.6750	-0.9019	-0.9025	0.0006	-0.0001
3.6250	-0.9031	-0.9025	-0.0005	0.0001
3.5750	-0.9038	-0.9025	-0.0012	0.0003
3.5250	-0.9035	-0.9025	-0.0009	0.0002
3.4750	-0.9024	-0.9025	0.0002	0.0000
3.4250	-0.9010	-0.9025	0.0016	-0.0003
3.3750	-0.9004	-0.9025	0.0022	-0.0004
3.3250	-0.9011	-0.9025	0.0015	-0.0003
3.2750	-0.9023	-0.9025	0.0002	0.0000
3.2250	-0.9028	-0.9025	-0.0003	0.0001
3.1750	-0.9020	-0.9025	0.0006	-0.0001
3.1250	-0.9007	-0.9025	0.0018	-0.0004
3.0750	-0.9002	-0.9025	0.0023	-0.0005
3.0250	-0.9010	-0.9025	0.0015	-0.0003
2.9750	-0.9023	-0.9025	0.0003	-0.0001
2.9250	-0.9028	-0.9025	-0.0003	0.0001
2.8750	-0.9018	-0.9025	0.0007	-0.0002
2.8250	-0.9011	-0.9025	0.0014	-0.0003
2.7750	-0.9015	-0.9025	0.0011	-0.0002
2.7250	-0.9023	-0.9025	0.0003	-0.0001
2.6750	-0.9034	-0.9025	-0.0008	0.0002
2.6250	-0.9033	-0.9025	-0.0008	0.0002
2.5750	-0.9023	-0.9025	0.0002	0.0000
2.5250	-0.9012	-0.9025	0.0014	-0.0003
2.4750	-0.9008	-0.9025	0.0018	-0.0004
2.4250	-0.9015	-0.9025	0.0011	-0.0002
2.3750	-0.9026	-0.9025	-0.0001	0.0000
2.3250	-0.9030	-0.9025	-0.0005	0.0001
2.2750	-0.9021	-0.9025	0.0004	-0.0001
2.2250	-0.9009	-0.9025	0.0017	-0.0003
2.1750	-0.9004	-0.9025	0.0022	-0.0004
2.1250	-0.9011	-0.9025	0.0014	-0.0003
2.0750	-0.9024	-0.9025	0.0002	0.0000
2.0250	-0.9028	-0.9025	-0.0003	0.0001
1.9750	-0.9020	-0.9025	0.0005	-0.0001
1.9250	-0.9008	-0.9025	0.0018	-0.0004
1.8750	-0.9003	-0.9025	0.0022	-0.0005
1.8250	-0.9011	-0.9025	0.0014	-0.0003
1.7750	-0.9024	-0.9024	0.0000	0.0000
1.7250	-0.9030	-0.9024	-0.0006	0.0001
1.6750	-0.9022	-0.9023	0.0001	0.0000
1.6250	-0.9011	-0.9022	0.0011	-0.0002
1.5750	-0.9006	-0.9020	0.0014	-0.0003
1.5250	-0.9013	-0.9017	0.0004	-0.0001
1.4750	-0.9021	-0.9013	-0.0009	0.0002
1.4250	-0.9028	-0.9007	-0.0022	0.0004
1.3750	-0.9032	-0.8997	-0.0035	0.0007
1.3250	-0.9005	-0.8984	-0.0021	0.0004
1.2750	-0.8953	-0.8964	0.0010	-0.0002
1.2250	-0.8906	-0.8934	0.0028	-0.0006
1.1750	-0.8861	-0.8892	0.0031	-0.0006
1.1250	-0.8816	-0.8831	0.0015	-0.0003
1.0750	-0.8733	-0.8745	0.0012	-0.0003
1.0250	-0.8618	-0.8627	0.0009	-0.0002

0.9750	-0.8472	-0.8470	-0.0003	0.0001
0.9250	-0.8277	-0.8267	-0.0010	0.0002
0.8750	-0.8019	-0.8014	-0.0005	0.0001
0.8250	-0.7715	-0.7713	-0.0003	0.0001
0.7750	-0.7372	-0.7366	-0.0006	0.0001
0.7250	-0.6983	-0.6980	-0.0003	0.0001
0.6750	-0.6565	-0.6563	-0.0001	0.0000
0.6250	-0.6124	-0.6122	-0.0002	0.0000
0.5750	-0.5664	-0.5663	-0.0001	0.0000
0.5250	-0.5192	-0.5191	-0.0001	0.0000
0.4750	-0.4711	-0.4711	-0.0001	0.0000
0.4250	-0.4224	-0.4224	0.0000	0.0000
0.3750	-0.3733	-0.3733	0.0000	0.0000
0.3250	-0.3239	-0.3239	0.0000	0.0000
0.2750	-0.2743	-0.2743	0.0000	0.0000
0.2250	-0.2245	-0.2245	0.0000	0.0000
0.1750	-0.1747	-0.1747	0.0000	0.0000
0.1250	-0.1248	-0.1248	0.0000	0.0000
0.0750	-0.0749	-0.0749	0.0000	0.0000
0.0250	-0.0250	-0.0250	0.0000	0.0000
-0.0250	0.0250	0.0250	0.0000	0.0000
-0.0750	0.0750	0.0750	0.0000	0.0000

*Relative to: Maximum suction head with no infiltration = -4.875 m

Figure 3.3

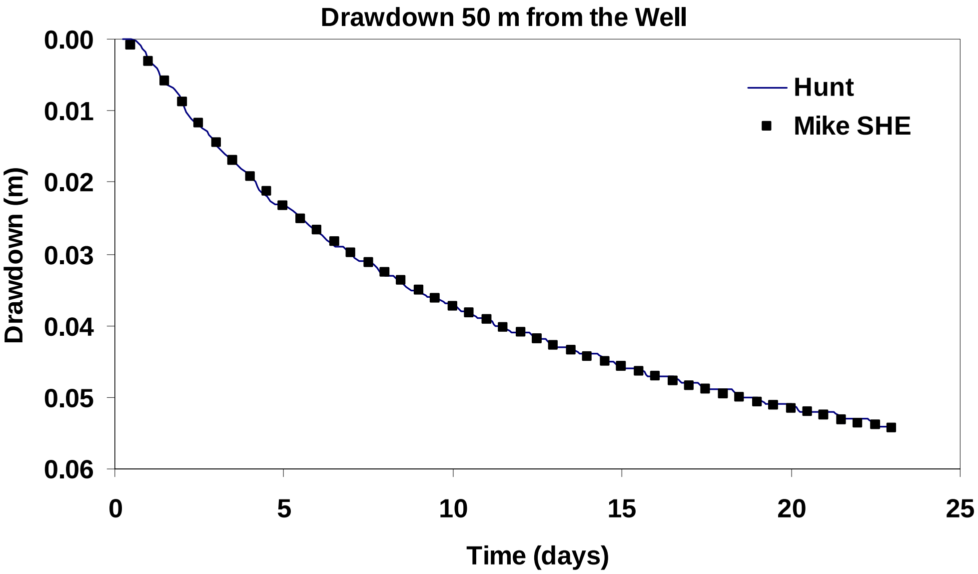


	Steady-state				After 23 days			
x	Hunt Drawdown	MSHE Drawdown	Absolute Difference	Relative* Difference	Hunt Drawdown	MSHE Drawdown	Absolute Difference	Relative* Difference
-500	0.0130	0.0130	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-400	0.0150	0.0150	0.0000	-0.0001	0.0000	0.0000	0.0000	0.0000
-300	0.0180	0.0177	0.0003	0.0009	0.0000	0.0001	-0.0001	-0.0003
-200	0.0230	0.0219	0.0011	0.0038	0.0010	0.0007	0.0003	0.0011
-100	0.0300	0.0291	0.0009	0.0032	0.0040	0.0040	0.0000	-0.0001
0	0.0470	0.0474	-0.0004	-0.0012	0.0200	0.0199	0.0001	0.0004
10	0.0540	0.0549	-0.0009	-0.0031	0.0250	0.0248	0.0002	0.0006
20	0.0620	0.0630	-0.0010	-0.0034	0.0310	0.0304	0.0006	0.0020
30	0.0710	0.0718	-0.0008	-0.0028	0.0370	0.0368	0.0002	0.0007
40	0.0810	0.0816	-0.0006	-0.0020	0.0450	0.0443	0.0007	0.0025
50	0.0920	0.0928	-0.0008	-0.0026	0.0540	0.0533	0.0007	0.0025
60	0.1050	0.1060	-0.0010	-0.0035	0.0650	0.0645	0.0005	0.0019
70	0.1210	0.1227	-0.0017	-0.0058	0.0800	0.0792	0.0008	0.0027
80	0.1430	0.1458	-0.0028	-0.0096	0.1000	0.1005	-0.0005	-0.0017
90	0.1800	0.1840	-0.0040	-0.0135	0.1350	0.1369	-0.0019	-0.0064
100								
110	0.1830	0.1870	-0.0040	-0.0135	0.1360	0.1372	-0.0012	-0.0042
120	0.1490	0.1518	-0.0028	-0.0096	0.1010	0.1012	-0.0002	-0.0006
130	0.1300	0.1317	-0.0017	-0.0058	0.0810	0.0802	0.0008	0.0026
140	0.1170	0.1181	-0.0011	-0.0036	0.0670	0.0659	0.0011	0.0037
150	0.1070	0.1078	-0.0008	-0.0028	0.0560	0.0551	0.0009	0.0029
160	0.0990	0.0997	-0.0007	-0.0025	0.0480	0.0466	0.0014	0.0046
170	0.0930	0.0931	-0.0001	-0.0002	0.0410	0.0397	0.0013	0.0044
180	0.0870	0.0874	-0.0004	-0.0015	0.0350	0.0339	0.0011	0.0036
190	0.0820	0.0826	-0.0006	-0.0020	0.0300	0.0291	0.0009	0.0032

200	0.0780	0.0784	-0.0004	-0.0012	0.0260	0.0249	0.0011	0.0036
300	0.0530	0.0531	-0.0001	-0.0005	0.0050	0.0051	-0.0001	-0.0002
400	0.0410	0.0408	0.0002	0.0006	0.0010	0.0008	0.0002	0.0007
500	0.0340	0.0340	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

*Relative to: Steady-state Hunt drawdown 1m from well = 0.296 m

Figure 3.4



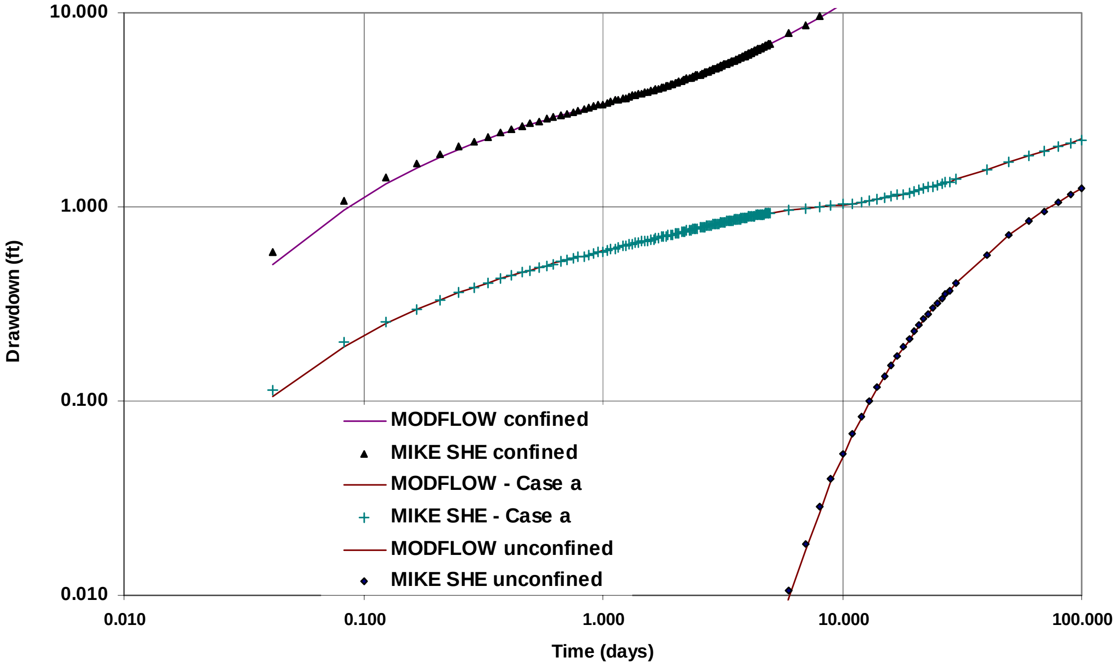
Days	Hunt Drawdown	MIKE SHE Drawdown	Absolute Difference	Relative Difference
0.250	0.0000			
0.500	0.0000	0.0009	-0.0009	-0.0023
0.750	0.0010			
1.000	0.0030	0.0031	-0.0001	-0.0003
1.250	0.0040			
1.500	0.0060	0.0060	0.0000	0.0001
1.750	0.0070			
2.000	0.0090	0.0089	0.0001	0.0002
2.250	0.0110			
2.500	0.0120	0.0118	0.0002	0.0006
2.750	0.0130			
3.000	0.0150	0.0144	0.0006	0.0015
3.250	0.0160			
3.500	0.0170	0.0169	0.0001	0.0003
3.750	0.0180			
4.000	0.0190	0.0192	-0.0002	-0.0004
4.250	0.0210			
4.500	0.0220	0.0213	0.0007	0.0018
4.750	0.0230			
5.000	0.0230	0.0232	-0.0002	-0.0006
5.250	0.0240			
5.500	0.0250	0.0251	-0.0001	-0.0002
5.750	0.0260			
6.000	0.0270	0.0268	0.0002	0.0006
6.250	0.0280			
6.500	0.0290	0.0284	0.0006	0.0016

6.750	0.0290			
7.000	0.0300	0.0299	0.0001	0.0004
7.250	0.0310			
7.500	0.0310	0.0313	-0.0003	-0.0007
7.750	0.0320			
8.000	0.0330	0.0326	0.0004	0.0010
8.250	0.0330			
8.500	0.0340	0.0338	0.0002	0.0004
8.750	0.0350			
9.000	0.0350	0.0350	0.0000	-0.0001
9.250	0.0360			
9.500	0.0360	0.0362	-0.0002	-0.0004
9.750	0.0370			
10.000	0.0370	0.0372	-0.0002	-0.0006
10.250	0.0380			
10.500	0.0380	0.0383	-0.0003	-0.0007
10.750	0.0390			
11.000	0.0390	0.0393	-0.0003	-0.0006
11.250	0.0400			
11.500	0.0400	0.0402	-0.0002	-0.0005
11.750	0.0410			
12.000	0.0410	0.0411	-0.0001	-0.0002
12.250	0.0410			
12.500	0.0420	0.0419	0.0001	0.0001
12.750	0.0420			
13.000	0.0430	0.0428	0.0002	0.0006
13.250	0.0430			
13.500	0.0430	0.0436	-0.0006	-0.0014
13.750	0.0440			
14.000	0.0440	0.0443	-0.0003	-0.0008
14.250	0.0440			
14.500	0.0450	0.0451	-0.0001	-0.0001
14.750	0.0450			
15.000	0.0460	0.0458	0.0002	0.0006
15.250	0.0460			
15.500	0.0460	0.0464	-0.0004	-0.0011
15.750	0.0470			
16.000	0.0470	0.0471	-0.0001	-0.0002
16.250	0.0470			
16.500	0.0470	0.0477	-0.0007	-0.0018
16.750	0.0480			
17.000	0.0480	0.0483	-0.0003	-0.0009
17.250	0.0480			
17.500	0.0490	0.0489	0.0001	0.0001
17.750	0.0490			
18.000	0.0490	0.0495	-0.0005	-0.0013
18.250	0.0490			
18.500	0.0500	0.0501	-0.0001	-0.0002
18.750	0.0500			

19.000	0.0500	0.0506	-0.0006	-0.0015
19.250	0.0510			
19.500	0.0510	0.0511	-0.0001	-0.0004
19.750	0.0510			
20.000	0.0510	0.0517	-0.0007	-0.0016
20.250	0.0520			
20.500	0.0520	0.0521	-0.0001	-0.0004
20.750	0.0520			
21.000	0.0520	0.0526	-0.0006	-0.0016
21.250	0.0520			
21.500	0.0530	0.0531	-0.0001	-0.0002
21.750	0.0530			
22.000	0.0530	0.0536	-0.0006	-0.0014
22.250	0.0530			
22.500	0.0540	0.0540	0.0000	0.0000
22.750	0.0540			
23.000	0.0540	0.0544	-0.0004	-0.0011

*Relative to: Steady-state Hunt drawdown 1m from well = 0.296 m

Figure 4.1



	Case A				Confined				Unconfined			
	MODFLOW	MIKE SHE	Absolute	Relative*	MODFLOW	MIKE SHE	Absolute	Relative**	MODFLOW	MIKE SHE	Absolute	Relative***
Time (days)	Drawdown	Drawdown	Difference	Difference	Drawdown	Drawdown	Difference	Difference	Drawdown	Drawdown	Difference	Difference
0.042	0.106	0.115	-0.009	-0.004	0.507	0.585	-0.078	-0.035	0.000	0.000	0.000	0.000
0.083	0.191	0.200	-0.009	-0.004	0.967	1.076	-0.109	-0.049	0.000	0.000	0.000	0.000
0.125	0.252	0.256	-0.004	-0.002	1.317	1.411	-0.095	-0.042	0.000	0.000	0.000	0.000
0.167	0.296	0.299	-0.003	-0.001	1.586	1.664	-0.078	-0.035	0.000	0.000	0.000	0.000
0.208	0.332	0.332	-0.001	0.000	1.802	1.865	-0.064	-0.029	0.000	0.000	0.000	0.000
0.250	0.361	0.361	0.000	0.000	1.980	2.033	-0.053	-0.024	0.000	0.000	0.000	0.000
0.292	0.386	0.385	0.000	0.000	2.133	2.178	-0.045	-0.020	0.000	0.000	0.000	0.000
0.333	0.407	0.407	0.001	0.000	2.266	2.304	-0.038	-0.017	0.000	0.000	0.000	0.000
0.375	0.427	0.426	0.001	0.000	2.383	2.416	-0.033	-0.015	0.000	0.000	0.000	0.000
0.417	0.444	0.443	0.001	0.000	2.489	2.517	-0.028	-0.013	0.000	0.000	0.000	0.000
0.458	0.459	0.458	0.001	0.001	2.584	2.609	-0.025	-0.011	0.000	0.000	0.000	0.000
0.500	0.474	0.472	0.001	0.001	2.672	2.694	-0.022	-0.010	0.000	0.000	0.000	0.000
0.542	0.487	0.486	0.001	0.001	2.753	2.772	-0.019	-0.009	0.000	0.000	0.000	0.000
0.583	0.499	0.498	0.001	0.001	2.828	2.845	-0.017	-0.008	0.000	0.000	0.000	0.000
0.625	0.511	0.509	0.001	0.001	2.898	2.913	-0.015	-0.007	0.000	0.000	0.000	0.000
0.667	0.521	0.520	0.001	0.001	2.964	2.977	-0.013	-0.006	0.000	0.000	0.000	0.000
0.708	0.532	0.531	0.001	0.001	3.026	3.038	-0.011	-0.005	0.000	0.000	0.000	0.000
0.750	0.541	0.540	0.001	0.001	3.086	3.096	-0.010	-0.004	0.000	0.000	0.000	0.000
0.792	0.551	0.550	0.001	0.000	3.142	3.151	-0.009	-0.004	0.000	0.000	0.000	0.000
0.833	0.559	0.558	0.001	0.000	3.196	3.205	-0.008	-0.004	0.000	0.000	0.000	0.000
0.875	0.568	0.567	0.001	0.000	3.248	3.256	-0.008	-0.003	0.000	0.000	0.000	0.000
0.917	0.576	0.575	0.001	0.000	3.299	3.306	-0.007	-0.003	0.000	0.000	0.000	0.000
0.958	0.584	0.583	0.001	0.000	3.347	3.354	-0.007	-0.003	0.000	0.000	0.000	0.000
1.000	0.592	0.591	0.001	0.000	3.394	3.401	-0.007	-0.003	0.000	0.000	0.000	0.000

1.042	0.599	0.598	0.001	0.000	3.440	3.447	-0.007	-0.003	0.000	0.000	0.000	0.000
1.083	0.606	0.605	0.001	0.000	3.485	3.492	-0.007	-0.003	0.000	0.000	0.000	0.000
1.125	0.613	0.612	0.001	0.000	3.529	3.535	-0.007	-0.003	0.000	0.000	0.000	0.000
1.167	0.620	0.619	0.001	0.000	3.572	3.578	-0.007	-0.003	0.000	0.000	0.000	0.000
1.208	0.626	0.626	0.001	0.000	3.614	3.621	-0.007	-0.003	0.000	0.000	0.000	0.000
1.250	0.632	0.632	0.000	0.000	3.655	3.662	-0.007	-0.003	0.000	0.000	0.000	0.000
1.292	0.639	0.638	0.000	0.000	3.696	3.703	-0.008	-0.003	0.000	0.000	0.000	0.000
1.333	0.645	0.644	0.000	0.000	3.736	3.744	-0.008	-0.004	0.000	0.000	0.000	0.000
1.375	0.651	0.650	0.000	0.000	3.775	3.784	-0.009	-0.004	0.000	0.000	0.000	0.000
1.417	0.657	0.656	0.000	0.000	3.814	3.824	-0.009	-0.004	0.000	0.000	0.000	0.000
1.458	0.662	0.662	0.000	0.000	3.853	3.863	-0.010	-0.004	0.000	0.000	0.000	0.000
1.500	0.668	0.668	0.000	0.000	3.892	3.902	-0.010	-0.005	0.000	0.000	0.000	0.000
1.542	0.673	0.673	0.000	0.000	3.930	3.940	-0.011	-0.005	0.000	0.000	0.000	0.000
1.583	0.678	0.678	0.000	0.000	3.967	3.979	-0.011	-0.005	0.000	0.000	0.000	0.000
1.625	0.684	0.684	0.000	0.000	4.005	4.017	-0.012	-0.005	0.000	0.000	0.000	0.000
1.667	0.689	0.689	0.000	0.000	4.042	4.055	-0.013	-0.006	0.000	0.000	0.000	0.000
1.708	0.694	0.694	0.000	0.000	4.079	4.093	-0.013	-0.006	0.000	0.000	0.000	0.000
1.750	0.699	0.699	0.000	0.000	4.116	4.130	-0.014	-0.006	0.000	0.000	0.000	0.000
1.792	0.704	0.704	0.000	0.000	4.153	4.168	-0.015	-0.007	0.000	0.000	0.000	0.000
1.833	0.709	0.709	0.000	0.000	4.189	4.205	-0.016	-0.007	0.000	0.000	0.000	0.000
1.875	0.713	0.714	0.000	0.000	4.226	4.242	-0.016	-0.007	0.000	0.000	0.000	0.000
1.917	0.718	0.718	0.000	0.000	4.262	4.279	-0.017	-0.008	0.000	0.000	0.000	0.000
1.958	0.723	0.723	0.000	0.000	4.298	4.316	-0.018	-0.008	0.000	0.000	0.000	0.000
2.000	0.727	0.728	0.000	0.000	4.334	4.353	-0.019	-0.008	0.000	0.000	0.000	0.000
2.042	0.732	0.732	0.000	0.000	4.370	4.390	-0.020	-0.009	0.000	0.000	0.000	0.000
2.083	0.736	0.736	0.000	0.000	4.406	4.426	-0.020	-0.009	0.000	0.000	0.000	0.000
2.125	0.740	0.741	-0.001	0.000	4.442	4.463	-0.021	-0.009	0.000	0.000	0.000	0.000
2.167	0.744	0.745	-0.001	0.000	4.477	4.499	-0.022	-0.010	0.000	0.000	0.000	0.000
2.208	0.749	0.749	-0.001	0.000	4.513	4.536	-0.023	-0.010	0.000	0.000	0.000	0.000
2.250	0.753	0.753	-0.001	0.000	4.549	4.572	-0.024	-0.011	0.000	0.000	0.000	0.000
2.292	0.757	0.758	-0.001	0.000	4.584	4.609	-0.024	-0.011	0.000	0.000	0.000	0.000
2.333	0.761	0.762	-0.001	0.000	4.620	4.645	-0.025	-0.011	0.000	0.000	0.000	0.000
2.375	0.765	0.766	-0.001	0.000	4.655	4.682	-0.026	-0.012	0.000	0.000	0.000	0.000
2.417	0.769	0.769	-0.001	0.000	4.691	4.718	-0.027	-0.012	0.000	0.000	0.000	0.000
2.458	0.772	0.773	-0.001	0.000	4.726	4.754	-0.028	-0.012	0.000	0.000	0.000	0.000
2.500	0.776	0.777	-0.001	0.000	4.762	4.790	-0.029	-0.013	0.000	0.000	0.000	0.000
2.542	0.780	0.781	-0.001	0.000	4.797	4.827	-0.030	-0.013	0.000	0.000	0.000	0.000
2.583	0.784	0.785	-0.001	0.000	4.833	4.863	-0.030	-0.014	0.000	0.000	0.000	0.000
2.625	0.787	0.788	-0.001	0.000	4.868	4.899	-0.031	-0.014	0.000	0.000	0.000	0.000
2.667	0.791	0.792	-0.001	0.000	4.903	4.935	-0.032	-0.014	0.000	0.000	0.000	0.000
2.708	0.795	0.795	-0.001	0.000	4.938	4.972	-0.033	-0.015	0.000	0.000	0.000	0.000
2.750	0.798	0.799	-0.001	0.000	4.974	5.008	-0.034	-0.015	0.000	0.000	0.000	0.000
2.792	0.801	0.803	-0.001	0.000	5.009	5.044	-0.035	-0.016	0.000	0.000	0.000	0.000
2.833	0.805	0.806	-0.001	0.000	5.044	5.080	-0.036	-0.016	0.000	0.000	0.000	0.000
2.875	0.808	0.809	-0.001	0.000	5.080	5.116	-0.037	-0.016	0.000	0.000	0.000	0.000
2.917	0.811	0.813	-0.001	-0.001	5.115	5.152	-0.038	-0.017	0.000	0.000	0.000	0.000
2.958	0.815	0.816	-0.001	-0.001	5.150	5.188	-0.038	-0.017	0.000	0.000	0.000	0.000
3.000	0.818	0.819	-0.001	-0.001	5.185	5.225	-0.039	-0.018	0.000	0.000	0.000	0.000
3.042	0.821	0.822	-0.001	-0.001	5.220	5.261	-0.040	-0.018	0.000	0.000	0.000	0.000
3.083	0.824	0.825	-0.001	-0.001	5.256	5.297	-0.041	-0.018	0.000	0.000	0.000	0.000
3.125	0.827	0.829	-0.001	-0.001	5.291	5.333	-0.042	-0.019	0.000	0.000	0.000	0.000
3.167	0.830	0.832	-0.001	-0.001	5.326	5.369	-0.043	-0.019	0.000	0.000	0.000	0.000
3.208	0.833	0.835	-0.001	-0.001	5.361	5.405	-0.044	-0.020	0.000	0.000	0.000	0.000
3.250	0.836	0.838	-0.001	-0.001	5.396	5.441	-0.045	-0.020	0.000	0.000	0.000	0.000

3.292	0.839	0.841	-0.001	-0.001	5.432	5.477	-0.046	-0.020	0.000	0.000	0.000	0.000
3.333	0.842	0.844	-0.001	-0.001	5.467	5.513	-0.047	-0.021	0.001	0.000	0.001	0.000
3.375	0.845	0.846	-0.001	-0.001	5.502	5.549	-0.048	-0.021	0.001	0.000	0.001	0.000
3.417	0.848	0.849	-0.001	-0.001	5.537	5.586	-0.048	-0.022	0.001	0.000	0.001	0.000
3.458	0.851	0.852	-0.001	-0.001	5.572	5.622	-0.049	-0.022	0.001	0.000	0.001	0.000
3.500	0.853	0.855	-0.001	-0.001	5.607	5.658	-0.050	-0.023	0.001	0.000	0.001	0.000
3.542	0.856	0.858	-0.001	-0.001	5.643	5.694	-0.051	-0.023	0.001	0.000	0.001	0.000
3.583	0.859	0.860	-0.001	-0.001	5.678	5.730	-0.052	-0.023	0.001	0.000	0.001	0.000
3.625	0.861	0.863	-0.001	-0.001	5.713	5.766	-0.053	-0.024	0.001	0.000	0.001	0.000
3.667	0.864	0.865	-0.001	-0.001	5.748	5.802	-0.054	-0.024	0.001	0.000	0.001	0.000
3.708	0.867	0.868	-0.001	-0.001	5.783	5.838	-0.055	-0.025	0.001	0.000	0.001	0.000
3.750	0.869	0.871	-0.002	-0.001	5.818	5.874	-0.056	-0.025	0.001	0.000	0.001	0.000
3.792	0.872	0.873	-0.001	-0.001	5.854	5.910	-0.057	-0.025	0.001	0.000	0.001	0.000
3.833	0.874	0.876	-0.001	-0.001	5.889	5.946	-0.058	-0.026	0.001	0.000	0.001	0.001
3.875	0.876	0.879	-0.002	-0.001	5.924	5.982	-0.058	-0.026	0.001	0.000	0.001	0.001
3.917	0.879	0.881	-0.002	-0.001	5.959	6.018	-0.059	-0.027	0.001	0.000	0.001	0.001
3.958	0.881	0.883	-0.002	-0.001	5.994	6.055	-0.060	-0.027	0.001	0.000	0.001	0.001
4.000	0.884	0.885	-0.002	-0.001	6.029	6.091	-0.061	-0.027	0.001	0.000	0.001	0.001
4.042	0.886	0.888	-0.002	-0.001	6.065	6.127	-0.062	-0.028	0.002	0.000	0.002	0.001
4.083	0.888	0.890	-0.002	-0.001	6.100	6.163	-0.063	-0.028	0.002	0.000	0.002	0.001
4.125	0.890	0.892	-0.002	-0.001	6.135	6.199	-0.064	-0.029	0.002	0.000	0.002	0.001
4.167	0.893	0.894	-0.002	-0.001	6.170	6.235	-0.065	-0.029	0.002	0.000	0.002	0.001
4.208	0.895	0.897	-0.002	-0.001	6.205	6.271	-0.066	-0.029	0.002	0.000	0.002	0.001
4.250	0.897	0.899	-0.002	-0.001	6.240	6.307	-0.067	-0.030	0.002	0.000	0.002	0.001
4.292	0.899	0.901	-0.002	-0.001	6.276	6.343	-0.068	-0.030	0.002	0.000	0.002	0.001
4.333	0.901	0.903	-0.002	-0.001	6.311	6.379	-0.068	-0.031	0.002	0.000	0.002	0.001
4.375	0.903	0.905	-0.002	-0.001	6.346	6.415	-0.069	-0.031	0.002	0.000	0.002	0.001
4.417	0.905	0.907	-0.002	-0.001	6.381	6.451	-0.070	-0.032	0.002	0.000	0.002	0.001
4.458	0.907	0.909	-0.002	-0.001	6.416	6.487	-0.071	-0.032	0.003	0.000	0.003	0.001
4.500	0.909	0.911	-0.002	-0.001	6.451	6.523	-0.072	-0.032	0.003	0.000	0.003	0.001
4.542	0.911	0.913	-0.002	-0.001	6.486	6.560	-0.073	-0.033	0.003	0.000	0.003	0.001
4.583	0.913	0.915	-0.002	-0.001	6.522	6.596	-0.074	-0.033	0.003	0.000	0.003	0.001
4.625	0.915	0.917	-0.002	-0.001	6.557	6.632	-0.075	-0.034	0.003	0.000	0.003	0.001
4.667	0.917	0.918	-0.002	-0.001	6.592	6.668	-0.076	-0.034	0.003	0.000	0.003	0.001
4.708	0.919	0.920	-0.002	-0.001	6.627	6.704	-0.077	-0.034	0.003	0.000	0.003	0.001
4.750	0.921	0.922	-0.002	-0.001	6.662	6.740	-0.078	-0.035	0.003	0.000	0.003	0.002
4.792	0.922	0.924	-0.002	-0.001	6.697	6.776	-0.079	-0.035	0.004	0.000	0.004	0.002
4.833	0.924	0.926	-0.002	-0.001	6.733	6.812	-0.079	-0.036	0.004	0.000	0.004	0.002
4.875	0.926	0.927	-0.002	-0.001	6.768	6.848	-0.080	-0.036	0.004	0.000	0.004	0.002
4.917	0.928	0.929	-0.002	-0.001	6.803	6.884	-0.081	-0.036	0.004	0.000	0.004	0.002
4.958	0.929	0.931	-0.002	-0.001	6.838	6.920	-0.082	-0.037	0.004	0.000	0.004	0.002
5.000	0.931	0.933	-0.002	-0.001	6.873	6.956	-0.083	-0.037	0.004	0.000	0.004	0.002
6.000	0.964	0.967	-0.003	-0.001	7.717	7.822	-0.105	-0.047	0.010	0.011	-0.001	0.000
7.000	0.986	0.989	-0.003	-0.001	8.561	8.688	-0.127	-0.057	0.017	0.018	-0.001	-0.001
8.000	1.001	1.003	-0.002	-0.001	9.404	9.554	-0.149	-0.067	0.027	0.028	-0.002	-0.001
9.000	1.013	1.015	-0.003	-0.001	10.248	10.419	-0.171	-0.077	0.038	0.040	-0.002	-0.001
10.000	1.026	1.029	-0.003	-0.001	11.092	11.285	-0.194	-0.087	0.052	0.054	-0.002	-0.001
11.000	1.041	1.044	-0.003	-0.001					0.066	0.068	-0.002	-0.001
12.000	1.057	1.060	-0.002	-0.001					0.082	0.084	-0.002	-0.001
13.000	1.074	1.077	-0.002	-0.001					0.098	0.100	-0.002	-0.001
14.000	1.092	1.094	-0.002	-0.001					0.116	0.118	-0.002	-0.001
15.000	1.110	1.112	-0.002	-0.001					0.133	0.135	-0.002	-0.001
16.000	1.128	1.130	-0.002	-0.001					0.151	0.153	-0.002	-0.001
17.000	1.147	1.149	-0.001	-0.001					0.170	0.172	-0.002	-0.001

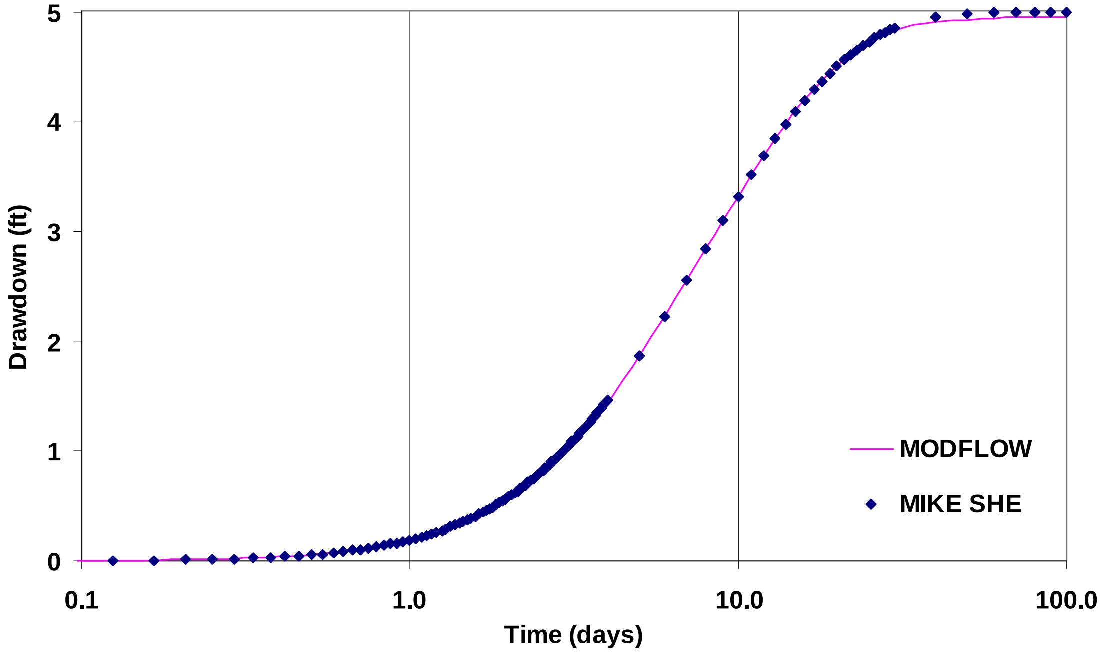
18.000	1.166	1.167	-0.001	-0.001	0.188	0.190	-0.002	-0.001
19.000	1.185	1.186	-0.001	0.000	0.207	0.208	-0.002	-0.001
20.000	1.204	1.205	-0.001	0.000	0.226	0.227	-0.001	-0.001
21.000	1.223	1.224	0.000	0.000	0.244	0.246	-0.001	-0.001
22.000	1.242	1.242	0.000	0.000	0.263	0.264	-0.001	-0.001
23.000	1.261	1.261	0.000	0.000	0.281	0.282	-0.001	0.000
24.000	1.280	1.279	0.000	0.000	0.300	0.301	-0.001	0.000
25.000	1.298	1.298	0.001	0.000	0.318	0.319	-0.001	0.000
26.000	1.317	1.316	0.001	0.000	0.336	0.337	-0.001	0.000
27.000	1.335	1.334	0.001	0.000	0.354	0.355	0.000	0.000
28.000	1.353	1.352	0.001	0.001	0.372	0.372	0.000	0.000
30.000	1.389	1.387	0.002	0.001	0.407	0.407	0.000	0.000
40.000	1.554	1.552	0.003	0.001	0.570	0.570	0.000	0.000
50.000	1.700	1.697	0.003	0.002	0.714	0.713	0.001	0.000
60.000	1.829	1.826	0.004	0.002	0.841	0.841	0.001	0.000
70.000	1.945	1.941	0.004	0.002	0.955	0.954	0.001	0.000
80.000	2.049	2.045	0.004	0.002	1.058	1.057	0.001	0.000
90.000	2.144	2.140	0.003	0.002	1.152	1.151	0.001	0.000
100.000	2.230	2.227	0.003	0.001	1.238	1.237	0.001	0.001

*Relative to: Drawdown at 100 days = 2.23 ft

**Relative to: Drawdown at 10 days = 11.09 ft

***Relative to: Drawdown at 100 days = 1.24 ft

Figure 4.2



Time (days)	MODFLOW Drawdown (ft)	MIKE SHE Drawdown (ft)	Absolute Difference (ft)	Relative* Difference
0.042	0.001	0.000	0.000	0.000
0.083	0.003	0.002	0.001	0.000
0.125	0.005	0.004	0.001	0.000
0.167	0.008	0.007	0.001	0.000
0.208	0.012	0.011	0.001	0.000
0.250	0.017	0.015	0.002	0.000
0.292	0.022	0.020	0.002	0.000
0.333	0.028	0.026	0.002	0.000
0.375	0.034	0.033	0.002	0.000
0.417	0.042	0.040	0.002	0.000
0.458	0.049	0.047	0.002	0.000
0.500	0.058	0.056	0.002	0.000
0.542	0.066	0.065	0.002	0.000
0.583	0.076	0.074	0.002	0.000
0.625	0.086	0.084	0.002	0.000
0.667	0.096	0.094	0.001	0.000
0.708	0.107	0.105	0.001	0.000
0.750	0.118	0.116	0.001	0.000
0.792	0.129	0.128	0.001	0.000
0.833	0.141	0.140	0.001	0.000
0.875	0.153	0.153	0.001	0.000
0.917	0.166	0.166	0.001	0.000
0.958	0.179	0.179	0.000	0.000
1.000	0.193	0.192	0.000	0.000

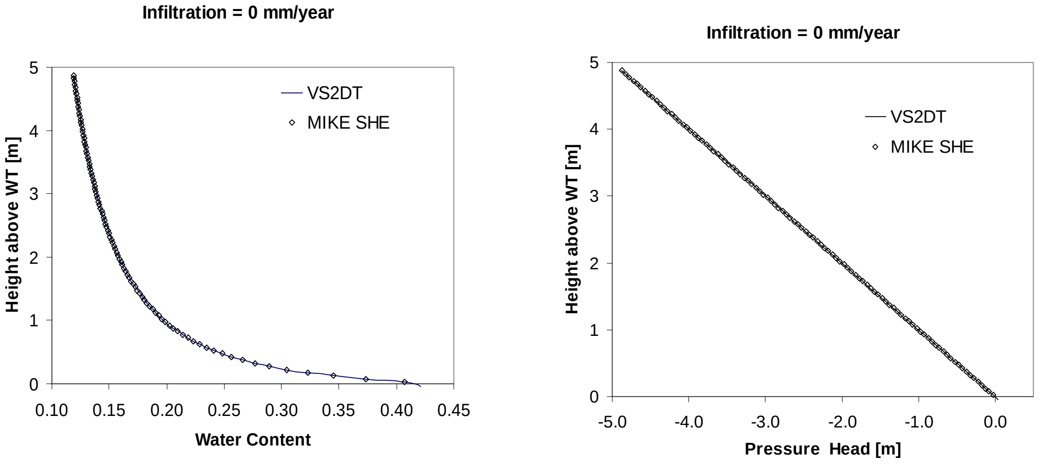
1.042	0.206	0.206	0.000	0.000
1.083	0.220	0.220	0.000	0.000
1.125	0.235	0.235	0.000	0.000
1.167	0.249	0.249	0.000	0.000
1.208	0.264	0.264	0.000	0.000
1.250	0.279	0.280	-0.001	0.000
1.292	0.294	0.295	-0.001	0.000
1.333	0.310	0.311	-0.001	0.000
1.375	0.326	0.327	-0.001	0.000
1.417	0.341	0.343	-0.001	0.000
1.458	0.358	0.359	-0.001	0.000
1.500	0.374	0.375	-0.002	0.000
1.542	0.390	0.392	-0.002	0.000
1.583	0.407	0.409	-0.002	0.000
1.625	0.424	0.426	-0.002	0.000
1.667	0.441	0.443	-0.002	0.000
1.708	0.458	0.460	-0.002	0.000
1.750	0.475	0.478	-0.002	0.000
1.792	0.493	0.495	-0.003	-0.001
1.833	0.510	0.513	-0.003	-0.001
1.875	0.528	0.531	-0.003	-0.001
1.917	0.545	0.549	-0.003	-0.001
1.958	0.563	0.566	-0.003	-0.001
2.000	0.581	0.585	-0.004	-0.001
2.042	0.599	0.603	-0.004	-0.001
2.083	0.617	0.621	-0.004	-0.001
2.125	0.635	0.639	-0.004	-0.001
2.167	0.653	0.657	-0.004	-0.001
2.208	0.671	0.676	-0.005	-0.001
2.250	0.689	0.694	-0.005	-0.001
2.292	0.708	0.713	-0.005	-0.001
2.333	0.726	0.731	-0.005	-0.001
2.375	0.744	0.750	-0.005	-0.001
2.417	0.763	0.768	-0.006	-0.001
2.458	0.781	0.787	-0.006	-0.001
2.500	0.800	0.806	-0.006	-0.001
2.542	0.818	0.824	-0.006	-0.001
2.583	0.837	0.843	-0.006	-0.001
2.625	0.855	0.862	-0.007	-0.001
2.667	0.874	0.881	-0.007	-0.001
2.708	0.892	0.899	-0.007	-0.001
2.750	0.911	0.918	-0.007	-0.001
2.792	0.929	0.937	-0.007	-0.001
2.833	0.948	0.955	-0.008	-0.002
2.875	0.966	0.974	-0.008	-0.002
2.917	0.985	0.993	-0.008	-0.002
2.958	1.004	1.012	-0.008	-0.002
3.000	1.022	1.030	-0.008	-0.002
3.042	1.041	1.049	-0.008	-0.002

3.083	1.059	1.068	-0.009	-0.002
3.125	1.077	1.086	-0.009	-0.002
3.167	1.096	1.105	-0.009	-0.002
3.208	1.114	1.123	-0.009	-0.002
3.250	1.133	1.142	-0.009	-0.002
3.292	1.151	1.160	-0.009	-0.002
3.333	1.169	1.179	-0.009	-0.002
3.375	1.188	1.197	-0.010	-0.002
3.417	1.206	1.216	-0.010	-0.002
3.458	1.224	1.234	-0.010	-0.002
3.500	1.242	1.252	-0.010	-0.002
3.542	1.261	1.271	-0.010	-0.002
3.583	1.279	1.289	-0.010	-0.002
3.625	1.297	1.307	-0.010	-0.002
3.667	1.315	1.325	-0.011	-0.002
3.708	1.333	1.343	-0.011	-0.002
3.750	1.351	1.361	-0.011	-0.002
3.792	1.368	1.379	-0.011	-0.002
3.833	1.386	1.397	-0.011	-0.002
3.875	1.404	1.415	-0.011	-0.002
3.917	1.422	1.433	-0.011	-0.002
3.958	1.439	1.451	-0.011	-0.002
4.000	1.457	1.469	-0.012	-0.002
5.000	1.861	1.867	-0.006	-0.001
6.000	2.227	2.231	-0.004	-0.001
7.000	2.553	2.554	-0.001	0.000
8.000	2.841	2.841	0.001	0.000
9.000	3.096	3.094	0.002	0.000
10.000	3.321	3.317	0.004	0.001
11.000	3.519	3.514	0.005	0.001
12.000	3.693	3.687	0.006	0.001
13.000	3.846	3.840	0.006	0.001
14.000	3.981	3.975	0.006	0.001
15.000	4.100	4.094	0.005	0.001
16.000	4.204	4.198	0.005	0.001
17.000	4.296	4.290	0.006	0.001
18.000	4.377	4.371	0.006	0.001
19.000	4.448	4.442	0.005	0.001
20.000	4.510	4.506	0.004	0.001
21.000	4.565	4.562	0.003	0.001
22.000	4.613	4.612	0.001	0.000
23.000	4.656	4.656	0.000	0.000
24.000	4.693	4.695	-0.002	0.000
25.000	4.726	4.730	-0.004	-0.001
26.000	4.755	4.761	-0.005	-0.001
27.000	4.781	4.788	-0.007	-0.001
28.000	4.803	4.812	-0.009	-0.002
29.000	4.823	4.834	-0.011	-0.002
30.000	4.840	4.852	-0.012	-0.002

40.000	4.914	4.953	-0.039	-0.008
50.000	4.928	4.985	-0.057	-0.011
60.000	4.938	4.995	-0.057	-0.011
70.000	4.946	4.998	-0.053	-0.011
80.000	4.951	4.999	-0.048	-0.010
90.000	4.955	5.000	-0.044	-0.009
100.000	4.958	5.000	-0.041	-0.008

*Relative to: Drawdown at 100 days = 5ft

Figure 4.10



Height above WT (m)	MSHE Moisture (-)	VS2DT Moisture (-)	Absolute Difference (-)	Relative* Difference (-)	MSHE Head (m)	VS2DT Head (m)	Absolute Difference (m)	Relative** Difference (-)
4.8750	0.1190	0.1190	0.0000	-0.0001	-4.8750	-4.8800	0.0050	-0.0010
4.8250	0.1194	0.1190	0.0004	0.0009	-4.8250	-4.8300	0.0050	-0.0010
4.7750	0.1198	0.1200	-0.0002	-0.0006	-4.7750	-4.7800	0.0050	-0.0010
4.7250	0.1202	0.1200	0.0002	0.0004	-4.7250	-4.7300	0.0050	-0.0010
4.6750	0.1206	0.1210	-0.0004	-0.0010	-4.6750	-4.6800	0.0050	-0.0010
4.6250	0.1210	0.1210	0.0000	0.0000	-4.6250	-4.6300	0.0050	-0.0010
4.5750	0.1214	0.1210	0.0004	0.0010	-4.5750	-4.5800	0.0050	-0.0010
4.5250	0.1218	0.1220	-0.0002	-0.0004	-4.5250	-4.5300	0.0050	-0.0010
4.4750	0.1223	0.1220	0.0003	0.0006	-4.4750	-4.4800	0.0050	-0.0010
4.4250	0.1227	0.1230	-0.0003	-0.0007	-4.4250	-4.4300	0.0050	-0.0010
4.3750	0.1232	0.1230	0.0002	0.0004	-4.3750	-4.3800	0.0050	-0.0010
4.3250	0.1236	0.1240	-0.0004	-0.0009	-4.3250	-4.3300	0.0050	-0.0010
4.2750	0.1241	0.1240	0.0001	0.0002	-4.2750	-4.2800	0.0050	-0.0010
4.2250	0.1245	0.1250	-0.0005	-0.0011	-4.2250	-4.2300	0.0050	-0.0010
4.1750	0.1250	0.1250	0.0000	0.0000	-4.1750	-4.1800	0.0050	-0.0010
4.1250	0.1255	0.1250	0.0005	0.0012	-4.1250	-4.1300	0.0050	-0.0010
4.0750	0.1260	0.1260	0.0000	0.0000	-4.0750	-4.0800	0.0050	-0.0010
4.0250	0.1265	0.1260	0.0005	0.0011	-4.0250	-4.0300	0.0050	-0.0010
3.9750	0.1270	0.1270	0.0000	0.0000	-3.9750	-3.9800	0.0050	-0.0010
3.9250	0.1275	0.1280	-0.0005	-0.0012	-3.9250	-3.9200	-0.0050	0.0010
3.8750	0.1280	0.1280	0.0000	0.0001	-3.8750	-3.8800	0.0050	-0.0010
3.8250	0.1286	0.1290	-0.0004	-0.0010	-3.8250	-3.8300	0.0050	-0.0010
3.7750	0.1291	0.1290	0.0001	0.0002	-3.7750	-3.7700	-0.0050	0.0010
3.7250	0.1297	0.1300	-0.0003	-0.0008	-3.7250	-3.7200	-0.0050	0.0010
3.6750	0.1302	0.1300	0.0002	0.0005	-3.6750	-3.6700	-0.0050	0.0010
3.6250	0.1308	0.1310	-0.0002	-0.0005	-3.6250	-3.6300	0.0050	-0.0010
3.5750	0.1314	0.1310	0.0004	0.0009	-3.5750	-3.5700	-0.0050	0.0010
3.5250	0.1320	0.1320	0.0000	-0.0001	-3.5250	-3.5200	-0.0050	0.0010
3.4750	0.1326	0.1330	-0.0004	-0.0010	-3.4750	-3.4700	-0.0050	0.0010
3.4250	0.1332	0.1330	0.0002	0.0005	-3.4250	-3.4200	-0.0050	0.0010
3.3750	0.1338	0.1340	-0.0002	-0.0004	-3.3750	-3.3700	-0.0050	0.0010

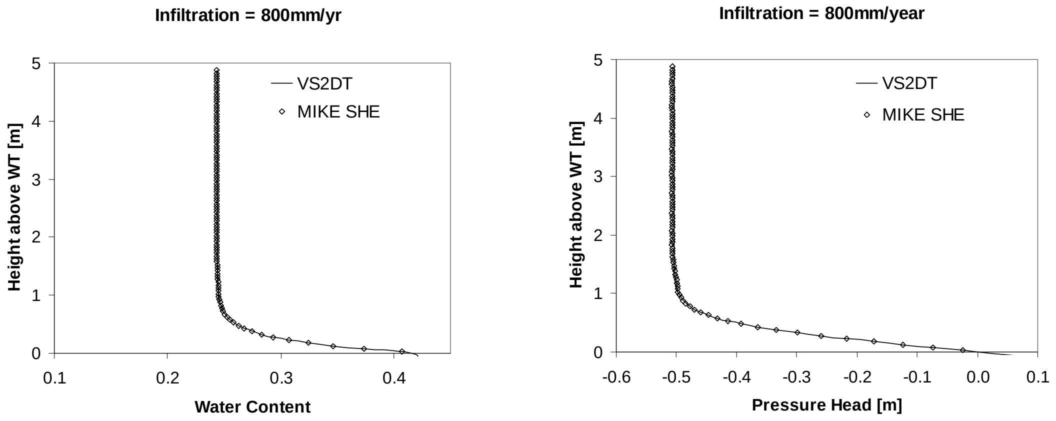
3.3250	0.1345	0.1340	0.0005	0.0011	-3.3250	-3.3200	-0.0050	0.0010
3.2750	0.1351	0.1350	0.0001	0.0003	-3.2750	-3.2700	-0.0050	0.0010
3.2250	0.1358	0.1360	-0.0002	-0.0005	-3.2250	-3.2200	-0.0050	0.0010
3.1750	0.1365	0.1360	0.0005	0.0011	-3.1750	-3.1700	-0.0050	0.0010
3.1250	0.1372	0.1370	0.0002	0.0004	-3.1250	-3.1200	-0.0050	0.0010
3.0750	0.1379	0.1380	-0.0001	-0.0003	-3.0750	-3.0700	-0.0050	0.0010
3.0250	0.1386	0.1390	-0.0004	-0.0009	-3.0250	-3.0200	-0.0050	0.0010
2.9750	0.1394	0.1390	0.0004	0.0008	-2.9750	-2.9700	-0.0050	0.0010
2.9250	0.1401	0.1400	0.0001	0.0003	-2.9250	-2.9200	-0.0050	0.0010
2.8750	0.1409	0.1410	-0.0001	-0.0003	-2.8750	-2.8700	-0.0050	0.0010
2.8250	0.1417	0.1420	-0.0003	-0.0008	-2.8250	-2.8200	-0.0050	0.0010
2.7750	0.1425	0.1420	0.0005	0.0012	-2.7750	-2.7700	-0.0050	0.0010
2.7250	0.1433	0.1430	0.0003	0.0008	-2.7250	-2.7200	-0.0050	0.0010
2.6750	0.1442	0.1440	0.0002	0.0004	-2.6750	-2.6700	-0.0050	0.0010
2.6250	0.1451	0.1450	0.0001	0.0002	-2.6250	-2.6300	0.0050	-0.0010
2.5750	0.1460	0.1460	0.0000	-0.0001	-2.5750	-2.5800	0.0050	-0.0010
2.5250	0.1469	0.1470	-0.0001	-0.0003	-2.5250	-2.5300	0.0050	-0.0010
2.4750	0.1478	0.1480	-0.0002	-0.0004	-2.4750	-2.4800	0.0050	-0.0010
2.4250	0.1488	0.1490	-0.0002	-0.0005	-2.4250	-2.4300	0.0050	-0.0010
2.3750	0.1498	0.1500	-0.0002	-0.0005	-2.3750	-2.3800	0.0050	-0.0010
2.3250	0.1508	0.1510	-0.0002	-0.0004	-2.3250	-2.3300	0.0050	-0.0010
2.2750	0.1519	0.1520	-0.0001	-0.0002	-2.2750	-2.2800	0.0050	-0.0010
2.2250	0.1530	0.1530	0.0000	0.0000	-2.2250	-2.2300	0.0050	-0.0010
2.1750	0.1541	0.1540	0.0001	0.0003	-2.1750	-2.1800	0.0050	-0.0010
2.1250	0.1553	0.1550	0.0003	0.0006	-2.1250	-2.1300	0.0050	-0.0010
2.0750	0.1565	0.1560	0.0005	0.0011	-2.0750	-2.0800	0.0050	-0.0010
2.0250	0.1577	0.1580	-0.0003	-0.0007	-2.0250	-2.0300	0.0050	-0.0010
1.9750	0.1590	0.1590	0.0000	-0.0001	-1.9750	-1.9800	0.0050	-0.0010
1.9250	0.1603	0.1600	0.0003	0.0006	-1.9250	-1.9300	0.0050	-0.0010
1.8750	0.1616	0.1620	-0.0004	-0.0009	-1.8750	-1.8800	0.0050	-0.0010
1.8250	0.1630	0.1630	0.0000	0.0001	-1.8250	-1.8300	0.0050	-0.0010
1.7750	0.1645	0.1650	-0.0005	-0.0012	-1.7750	-1.7800	0.0050	-0.0010
1.7250	0.1660	0.1660	0.0000	0.0001	-1.7250	-1.7300	0.0050	-0.0010
1.6750	0.1676	0.1680	-0.0004	-0.0010	-1.6750	-1.6800	0.0050	-0.0010
1.6250	0.1692	0.1690	0.0002	0.0006	-1.6250	-1.6300	0.0050	-0.0010
1.5750	0.1709	0.1710	-0.0001	-0.0002	-1.5750	-1.5800	0.0050	-0.0010
1.5250	0.1727	0.1730	-0.0003	-0.0007	-1.5250	-1.5300	0.0050	-0.0010
1.4750	0.1746	0.1750	-0.0004	-0.0010	-1.4750	-1.4800	0.0050	-0.0010
1.4250	0.1765	0.1770	-0.0005	-0.0012	-1.4250	-1.4300	0.0050	-0.0010
1.3750	0.1785	0.1790	-0.0005	-0.0011	-1.3750	-1.3800	0.0050	-0.0010
1.3250	0.1807	0.1810	-0.0003	-0.0008	-1.3250	-1.3300	0.0050	-0.0010
1.2750	0.1829	0.1830	-0.0001	-0.0003	-1.2750	-1.2800	0.0050	-0.0010
1.2250	0.1852	0.1850	0.0002	0.0006	-1.2250	-1.2300	0.0050	-0.0010
1.1750	0.1877	0.1880	-0.0003	-0.0007	-1.1750	-1.1800	0.0050	-0.0010
1.1250	0.1903	0.1900	0.0003	0.0008	-1.1250	-1.1300	0.0050	-0.0010
1.0750	0.1931	0.1930	0.0001	0.0002	-1.0750	-1.0800	0.0050	-0.0010
1.0250	0.1960	0.1960	0.0000	0.0001	-1.0250	-1.0300	0.0050	-0.0010
0.9750	0.1991	0.1990	0.0001	0.0004	-0.9750	-0.9750	0.0000	0.0000
0.9250	0.2025	0.2020	0.0005	0.0011	-0.9250	-0.9250	0.0000	0.0000
0.8750	0.2060	0.2060	0.0000	0.0001	-0.8750	-0.8750	0.0000	0.0000
0.8250	0.2099	0.2100	-0.0001	-0.0003	-0.8250	-0.8250	0.0000	0.0000
0.7750	0.2140	0.2140	0.0000	0.0000	-0.7750	-0.7750	0.0000	0.0000
0.7250	0.2185	0.2180	0.0005	0.0011	-0.7250	-0.7250	0.0000	0.0000
0.6750	0.2234	0.2230	0.0004	0.0008	-0.6750	-0.6750	0.0000	0.0000

0.6250	0.2287	0.2290	-0.0003	-0.0008	-0.6250	-0.6250	0.0000	0.0000
0.5750	0.2345	0.2350	-0.0005	-0.0011	-0.5750	-0.5750	0.0000	0.0000
0.5250	0.2410	0.2410	0.0000	0.0001	-0.5250	-0.5250	0.0000	0.0000
0.4750	0.2483	0.2480	0.0003	0.0007	-0.4750	-0.4750	0.0000	0.0000
0.4250	0.2565	0.2560	0.0005	0.0012	-0.4250	-0.4250	0.0000	0.0000
0.3750	0.2658	0.2660	-0.0002	-0.0004	-0.3750	-0.3750	0.0000	0.0000
0.3250	0.2766	0.2770	-0.0004	-0.0009	-0.3250	-0.3250	0.0000	0.0000
0.2750	0.2893	0.2890	0.0003	0.0006	-0.2750	-0.2750	0.0000	0.0000
0.2250	0.3043	0.3040	0.0003	0.0007	-0.2250	-0.2250	0.0000	0.0000
0.1750	0.3226	0.3230	-0.0004	-0.0009	-0.1750	-0.1750	0.0000	0.0000
0.1250	0.3453	0.3450	0.0003	0.0007	-0.1250	-0.1250	0.0000	0.0000
0.0750	0.3737	0.3740	-0.0003	-0.0008	-0.0750	-0.0750	0.0000	0.0000
0.0250	0.4069	0.4070	-0.0001	-0.0003	-0.0250	-0.0250	0.0000	0.0000
-0.0250	0.4200	0.4200	0.0000	-0.0001	0.0250	0.0250	0.0000	0.0000
-0.0750	0.4200	0.4200	0.0000	-0.0001	0.0750	0.0750	0.0000	0.0000

*Relative to: Maximum moisture content = 0.42

**Relative to: Maximum suction head with no infiltration = -4.875 m

Figure 4.11



Height above WT (m)	**MSHE Moisture (-)**	**VS2DT Moisture (-)**	**Absolute Difference (-)**	**Relative* Difference (-)**	**MSHE Head (m)**	**VS2DT Head (m)**	**Absolute Difference (m)**	**Relative** Difference (-)**
-4.8750	0.2436	0.2440	-0.0004	-0.0010	-0.5069	-0.5040	-0.0029	0.0006
-4.8250	0.2436	0.2440	-0.0004	-0.0011	-0.5071	-0.5040	-0.0031	0.0006
-4.7750	0.2436	0.2440	-0.0004	-0.0009	-0.5066	-0.5040	-0.0026	0.0005
-4.7250	0.2436	0.2440	-0.0004	-0.0009	-0.5065	-0.5040	-0.0025	0.0005
-4.6750	0.2436	0.2440	-0.0004	-0.0010	-0.5069	-0.5040	-0.0029	0.0006
-4.6250	0.2435	0.2440	-0.0005	-0.0012	-0.5076	-0.5040	-0.0036	0.0007
-4.5750	0.2435	0.2440	-0.0005	-0.0011	-0.5073	-0.5040	-0.0033	0.0007
-4.5250	0.2436	0.2440	-0.0004	-0.0009	-0.5067	-0.5040	-0.0027	0.0005
-4.4750	0.2436	0.2440	-0.0004	-0.0008	-0.5064	-0.5040	-0.0024	0.0005
-4.4250	0.2437	0.2440	-0.0003	-0.0008	-0.5063	-0.5040	-0.0023	0.0005
-4.3750	0.2437	0.2440	-0.0003	-0.0008	-0.5063	-0.5040	-0.0023	0.0005
-4.3250	0.2437	0.2440	-0.0003	-0.0008	-0.5062	-0.5040	-0.0022	0.0005
-4.2750	0.2436	0.2440	-0.0004	-0.0009	-0.5067	-0.5040	-0.0027	0.0006
-4.2250	0.2435	0.2440	-0.0005	-0.0012	-0.5074	-0.5040	-0.0034	0.0007
-4.1750	0.2435	0.2440	-0.0005	-0.0012	-0.5076	-0.5040	-0.0036	0.0007
-4.1250	0.2435	0.2440	-0.0005	-0.0011	-0.5071	-0.5040	-0.0031	0.0006
-4.0750	0.2437	0.2440	-0.0003	-0.0008	-0.5064	-0.5040	-0.0024	0.0005
-4.0250	0.2437	0.2440	-0.0003	-0.0007	-0.5061	-0.5040	-0.0021	0.0004
-3.9750	0.2437	0.2440	-0.0003	-0.0007	-0.5060	-0.5040	-0.0020	0.0004
-3.9250	0.2437	0.2440	-0.0003	-0.0007	-0.5061	-0.5040	-0.0021	0.0004
-3.8750	0.2437	0.2440	-0.0003	-0.0007	-0.5061	-0.5040	-0.0021	0.0004
-3.8250	0.2436	0.2440	-0.0004	-0.0009	-0.5066	-0.5040	-0.0026	0.0005
-3.7750	0.2435	0.2440	-0.0005	-0.0012	-0.5073	-0.5040	-0.0033	0.0007
-3.7250	0.2436	0.2440	-0.0004	-0.0011	-0.5070	-0.5040	-0.0030	0.0006
-3.6750	0.2436	0.2440	-0.0004	-0.0008	-0.5064	-0.5040	-0.0024	0.0005
-3.6250	0.2437	0.2440	-0.0003	-0.0008	-0.5061	-0.5040	-0.0021	0.0004
-3.5750	0.2437	0.2440	-0.0003	-0.0007	-0.5059	-0.5040	-0.0019	0.0004
-3.5250	0.2436	0.2440	-0.0004	-0.0008	-0.5064	-0.5040	-0.0024	0.0005
-3.4750	0.2435	0.2440	-0.0005	-0.0012	-0.5074	-0.5040	-0.0034	0.0007
-3.4250	0.2435	0.2440	-0.0005	-0.0011	-0.5071	-0.5040	-0.0031	0.0006
-3.3750	0.2436	0.2440	-0.0004	-0.0009	-0.5065	-0.5040	-0.0025	0.0005
-3.3250	0.2437	0.2440	-0.0003	-0.0008	-0.5062	-0.5040	-0.0022	0.0005
-3.2750	0.2437	0.2440	-0.0003	-0.0007	-0.5061	-0.5040	-0.0021	0.0004

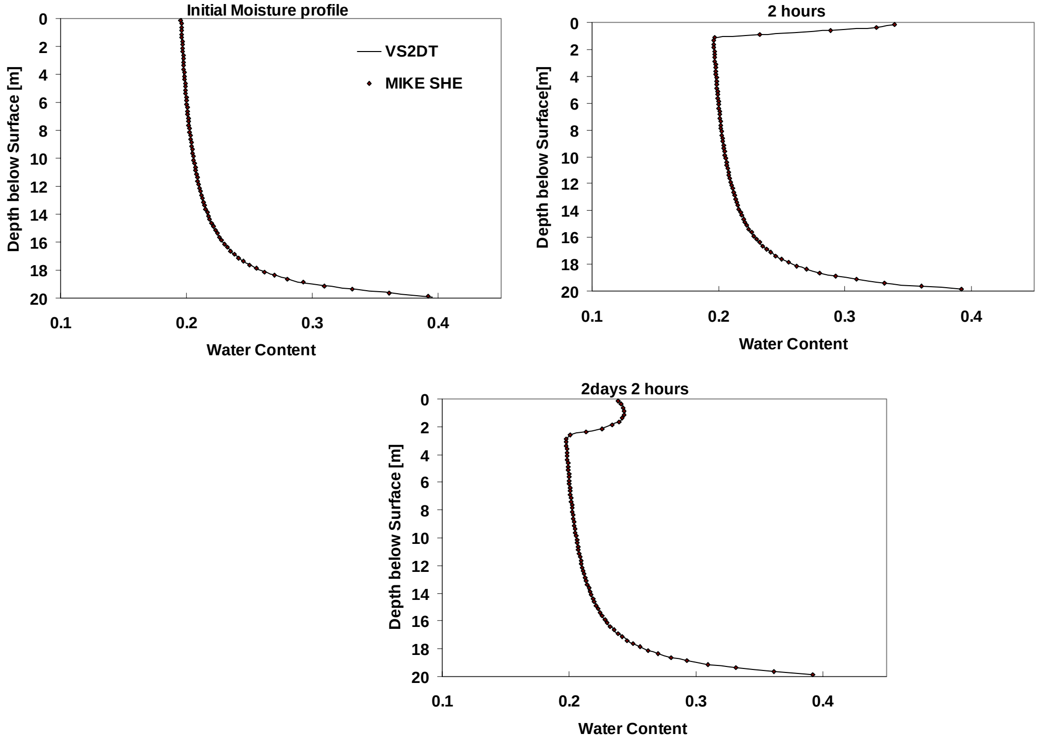
-3.2250	0.2437	0.2440	-0.0003	-0.0007	-0.5061	-0.5040	-0.0021	0.0004
-3.1750	0.2437	0.2440	-0.0003	-0.0007	-0.5061	-0.5040	-0.0021	0.0004
-3.1250	0.2436	0.2440	-0.0004	-0.0009	-0.5066	-0.5040	-0.0026	0.0005
-3.0750	0.2435	0.2440	-0.0005	-0.0011	-0.5073	-0.5040	-0.0033	0.0007
-3.0250	0.2435	0.2440	-0.0005	-0.0012	-0.5075	-0.5040	-0.0035	0.0007
-2.9750	0.2436	0.2440	-0.0004	-0.0010	-0.5070	-0.5040	-0.0030	0.0006
-2.9250	0.2437	0.2440	-0.0003	-0.0008	-0.5063	-0.5040	-0.0023	0.0005
-2.8750	0.2437	0.2440	-0.0003	-0.0007	-0.5060	-0.5040	-0.0020	0.0004
-2.8250	0.2437	0.2440	-0.0003	-0.0006	-0.5058	-0.5040	-0.0018	0.0004
-2.7750	0.2436	0.2440	-0.0004	-0.0008	-0.5064	-0.5040	-0.0024	0.0005
-2.7250	0.2435	0.2440	-0.0005	-0.0012	-0.5074	-0.5040	-0.0034	0.0007
-2.6750	0.2435	0.2440	-0.0005	-0.0011	-0.5072	-0.5040	-0.0032	0.0006
-2.6250	0.2436	0.2440	-0.0004	-0.0009	-0.5065	-0.5040	-0.0025	0.0005
-2.5750	0.2437	0.2440	-0.0003	-0.0008	-0.5063	-0.5040	-0.0023	0.0005
-2.5250	0.2437	0.2440	-0.0003	-0.0008	-0.5062	-0.5040	-0.0022	0.0004
-2.4750	0.2437	0.2440	-0.0003	-0.0007	-0.5061	-0.5040	-0.0021	0.0004
-2.4250	0.2436	0.2440	-0.0004	-0.0009	-0.5066	-0.5040	-0.0026	0.0005
-2.3750	0.2435	0.2440	-0.0005	-0.0011	-0.5073	-0.5040	-0.0033	0.0007
-2.3250	0.2436	0.2440	-0.0004	-0.0010	-0.5070	-0.5040	-0.0030	0.0006
-2.2750	0.2436	0.2440	-0.0004	-0.0008	-0.5064	-0.5040	-0.0024	0.0005
-2.2250	0.2437	0.2440	-0.0003	-0.0008	-0.5062	-0.5040	-0.0022	0.0005
-2.1750	0.2437	0.2440	-0.0003	-0.0007	-0.5061	-0.5040	-0.0021	0.0004
-2.1250	0.2436	0.2440	-0.0004	-0.0009	-0.5066	-0.5040	-0.0026	0.0005
-2.0750	0.2435	0.2440	-0.0005	-0.0012	-0.5073	-0.5040	-0.0033	0.0007
-2.0250	0.2436	0.2440	-0.0004	-0.0011	-0.5071	-0.5040	-0.0031	0.0006
-1.9750	0.2436	0.2440	-0.0004	-0.0009	-0.5065	-0.5040	-0.0025	0.0005
-1.9250	0.2437	0.2440	-0.0003	-0.0008	-0.5063	-0.5040	-0.0023	0.0005
-1.8750	0.2436	0.2440	-0.0004	-0.0009	-0.5067	-0.5040	-0.0027	0.0006
-1.8250	0.2435	0.2440	-0.0005	-0.0012	-0.5074	-0.5040	-0.0034	0.0007
-1.7750	0.2435	0.2440	-0.0005	-0.0011	-0.5072	-0.5040	-0.0032	0.0007
-1.7250	0.2436	0.2440	-0.0004	-0.0009	-0.5066	-0.5040	-0.0026	0.0005
-1.6750	0.2437	0.2440	-0.0003	-0.0008	-0.5063	-0.5040	-0.0023	0.0005
-1.6250	0.2437	0.2440	-0.0003	-0.0007	-0.5060	-0.5040	-0.0020	0.0004
-1.5750	0.2438	0.2440	-0.0002	-0.0005	-0.5054	-0.5040	-0.0014	0.0003
-1.5250	0.2439	0.2440	-0.0001	-0.0003	-0.5047	-0.5040	-0.0007	0.0001
-1.4750	0.2440	0.2440	0.0000	0.0000	-0.5039	-0.5040	0.0001	0.0000
-1.4250	0.2441	0.2440	0.0001	0.0003	-0.5031	-0.5030	-0.0001	0.0000
-1.3750	0.2442	0.2440	0.0002	0.0006	-0.5023	-0.5030	0.0007	-0.0002
-1.3250	0.2444	0.2440	0.0004	0.0009	-0.5014	-0.5030	0.0016	-0.0003
-1.2750	0.2445	0.2440	0.0005	0.0011	-0.5006	-0.5020	0.0014	-0.0003
-1.2250	0.2446	0.2440	0.0006	0.0014	-0.4998	-0.5020	0.0022	-0.0005
-1.1750	0.2447	0.2440	0.0007	0.0017	-0.4990	-0.5010	0.0020	-0.0004
-1.1250	0.2448	0.2450	-0.0002	-0.0004	-0.4983	-0.5000	0.0017	-0.0003
-1.0750	0.2449	0.2450	-0.0001	-0.0002	-0.4977	-0.4990	0.0013	-0.0003
-1.0250	0.2450	0.2450	0.0000	0.0000	-0.4972	-0.4970	-0.0002	0.0000
-0.9750	0.2453	0.2450	0.0003	0.0006	-0.4953	-0.4950	-0.0003	0.0001
-0.9250	0.2457	0.2460	-0.0003	-0.0006	-0.4920	-0.4920	0.0000	0.0000
-0.8750	0.2462	0.2460	0.0002	0.0006	-0.4887	-0.4880	-0.0007	0.0001
-0.8250	0.2469	0.2470	-0.0001	-0.0001	-0.4839	-0.4830	-0.0009	0.0002
-0.7750	0.2479	0.2480	-0.0001	-0.0003	-0.4777	-0.4770	-0.0007	0.0002
-0.7250	0.2491	0.2490	0.0001	0.0002	-0.4701	-0.4700	-0.0001	0.0000
-0.6750	0.2507	0.2510	-0.0003	-0.0007	-0.4598	-0.4600	0.0002	0.0000
-0.6250	0.2527	0.2530	-0.0003	-0.0006	-0.4471	-0.4480	0.0009	-0.0002
-0.5750	0.2553	0.2550	0.0003	0.0006	-0.4322	-0.4320	-0.0002	0.0001

-0.5250	0.2584	0.2580	0.0004	0.0009	-0.4143	-0.4140	-0.0003	0.0001
-0.4750	0.2625	0.2630	-0.0005	-0.0011	-0.3919	-0.3910	-0.0009	0.0002
-0.4250	0.2679	0.2680	-0.0001	-0.0003	-0.3650	-0.3650	0.0000	0.0000
-0.3750	0.2746	0.2750	-0.0004	-0.0009	-0.3338	-0.3340	0.0002	0.0000
-0.3250	0.2830	0.2830	0.0000	0.0000	-0.2986	-0.2990	0.0004	-0.0001
-0.2750	0.2937	0.2940	-0.0003	-0.0008	-0.2594	-0.2590	-0.0004	0.0001
-0.2250	0.3071	0.3070	0.0001	0.0002	-0.2167	-0.2170	0.0003	-0.0001
-0.1750	0.3242	0.3240	0.0002	0.0004	-0.1712	-0.1710	-0.0002	0.0000
-0.1250	0.3460	0.3460	0.0000	0.0001	-0.1235	-0.1240	0.0005	-0.0001
-0.0750	0.3739	0.3740	-0.0001	-0.0002	-0.0746	-0.0746	0.0000	0.0000
-0.0250	0.4069	0.4070	-0.0001	-0.0001	-0.0249	-0.0249	0.0000	0.0000
0.0250	0.4200	0.4200	0.0000	-0.0001	0.0250	0.0250	0.0000	0.0000
0.0750	0.4200	0.4200	0.0000	-0.0001	0.0750	0.0750	0.0000	0.0000

*Relative to: Maximum moisture content = 0.42

**Relative to: Maximum suction head with no infiltration = -4.875 m

Figure 4.13



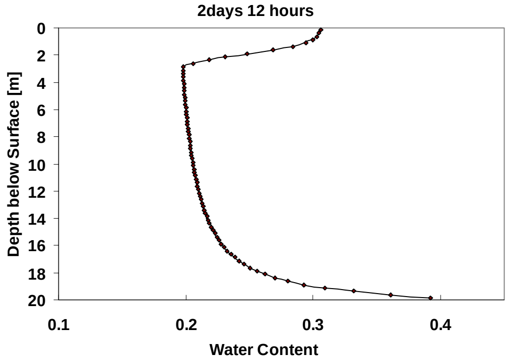
	t = 0 s				t = 2 hours				t = 2 days 2 hours			
Depth	**MSHE**	**VS2DT**	**Absolute**	**Relative***	**MSHE**	**VS2DT**	**Absolute**	**Relative***	**MSHE**	**VS2DT**	**Absolute**	**Relative***
(m)	**θ**	**θ**	**Error**	**Error**	**θ**	**θ**	**Error**	**Error**	**θ**	**θ**	**Error**	**Error**
0.125	0.19	0.196	0.000	0.000	0.339	0.339	0.000	0.000	0.23	0.239	0.000	-0.001
0.375	0.19	0.196	0.000	0.000	0.325	0.325	0.000	0.000	0.24	0.241	0.000	0.000
0.625	0.19	0.196	0.000	0.000	0.289	0.289	0.000	-0.001	0.24	0.243	-0.001	-0.001
0.875	0.19	0.196	0.000	0.000	0.233	0.233	0.000	-0.001	0.24	0.244	-0.001	-0.002
1.125	0.19	0.196	0.000	0.000	0.197	0.197	0.000	0.001	0.24	0.243	0.000	0.000
1.375	0.19	0.196	0.000	0.000	0.196	0.196	0.000	0.001	0.24	0.242	0.000	0.000
1.625	0.19	0.197	0.000	0.000	0.197	0.197	0.000	-0.001	0.23	0.239	0.000	0.000
1.875	0.19	0.197	0.000	0.000	0.197	0.197	0.000	-0.001	0.23	0.233	0.001	0.002
2.125	0.19	0.197	0.000	0.000	0.197	0.197	0.000	0.000	0.22	0.224	0.002	0.004
2.375	0.19	0.197	0.000	0.000	0.197	0.197	0.000	0.000	0.21	0.212	0.002	0.004
2.625	0.19	0.197	0.000	0.001	0.197	0.197	0.000	0.001	0.20	0.201	0.000	0.000
2.875	0.19	0.197	0.000	0.001	0.197	0.197	0.000	0.001	0.19	0.198	0.000	-0.001
3.125	0.19	0.198	0.000	-0.001	0.198	0.198	0.000	-0.001	0.19	0.198	0.000	-0.001
3.375	0.19	0.198	0.000	-0.001	0.198	0.198	0.000	-0.001	0.19	0.198	0.000	-0.001
3.625	0.19	0.198	0.000	0.000	0.198	0.198	0.000	0.000	0.19	0.198	0.000	0.000
3.875	0.19	0.198	0.000	0.000	0.198	0.198	0.000	0.000	0.19	0.198	0.000	0.000
4.125	0.19	0.198	0.000	0.001	0.198	0.198	0.000	0.001	0.19	0.198	0.000	0.001
4.375	0.19	0.199	0.000	-0.001	0.199	0.199	0.000	-0.001	0.19	0.199	0.000	-0.001
4.625	0.19	0.199	0.000	0.000	0.199	0.199	0.000	0.000	0.19	0.199	0.000	0.000
4.875	0.19	0.199	0.000	0.000	0.199	0.199	0.000	0.000	0.19	0.199	0.000	0.000
5.125	0.19	0.199	0.000	0.001	0.199	0.199	0.000	0.001	0.19	0.199	0.000	0.001
5.375	0.20	0.199	0.001	0.001	0.200	0.199	0.001	0.001	0.20	0.199	0.001	0.001

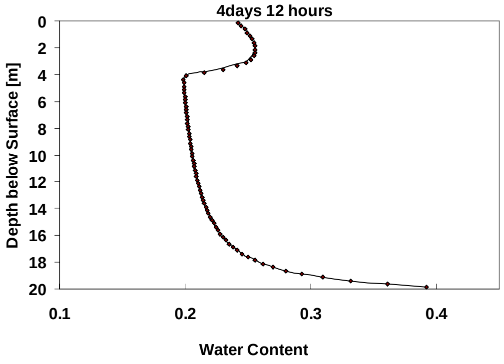
5.625	0.20	0.200	0.000	-0.001	0.200	0.200	0.000	-0.001	0.20	0.200	0.000	-0.001
5.875	0.20	0.200	0.000	0.000	0.200	0.200	0.000	0.000	0.20	0.200	0.000	0.000
6.125	0.20	0.200	0.000	0.001	0.200	0.200	0.000	0.001	0.20	0.200	0.000	0.001
6.375	0.20	0.200	0.001	0.001	0.201	0.200	0.001	0.001	0.20	0.200	0.001	0.001
6.625	0.20	0.201	0.000	-0.001	0.201	0.201	0.000	-0.001	0.20	0.201	0.000	-0.001
6.875	0.20	0.201	0.000	0.000	0.201	0.201	0.000	0.000	0.20	0.201	0.000	0.000
7.125	0.20	0.201	0.000	0.001	0.201	0.201	0.000	0.001	0.20	0.201	0.000	0.001
7.375	0.20	0.202	0.000	-0.001	0.202	0.202	0.000	-0.001	0.20	0.202	0.000	-0.001
7.625	0.20	0.202	0.000	0.000	0.202	0.202	0.000	0.000	0.20	0.202	0.000	0.000
7.875	0.20	0.202	0.000	0.001	0.202	0.202	0.000	0.001	0.20	0.202	0.000	0.001
8.125	0.20	0.203	0.000	-0.001	0.203	0.203	0.000	-0.001	0.20	0.203	0.000	-0.001
8.375	0.20	0.203	0.000	0.000	0.203	0.203	0.000	0.000	0.20	0.203	0.000	0.000
8.625	0.20	0.203	0.000	0.001	0.203	0.203	0.000	0.001	0.20	0.203	0.000	0.001
8.875	0.20	0.204	0.000	-0.001	0.204	0.204	0.000	-0.001	0.20	0.204	0.000	-0.001
9.125	0.20	0.204	0.000	0.000	0.204	0.204	0.000	0.000	0.20	0.204	0.000	0.000
9.375	0.20	0.204	0.001	0.001	0.205	0.204	0.001	0.001	0.20	0.204	0.001	0.001
9.625	0.20	0.205	0.000	0.000	0.205	0.205	0.000	0.000	0.20	0.205	0.000	0.000
9.875	0.20	0.205	0.000	0.001	0.205	0.205	0.000	0.001	0.20	0.205	0.000	0.001
10.12	0.20	0.206	0.000	0.000	0.206	0.206	0.000	0.000	0.20	0.206	0.000	0.000
10.37	0.20	0.206	0.000	0.001	0.206	0.206	0.000	0.001	0.20	0.206	0.000	0.001
10.62	0.20	0.207	0.000	0.000	0.207	0.207	0.000	0.000	0.20	0.207	0.000	0.000
10.87	0.20	0.207	0.000	0.001	0.207	0.207	0.000	0.001	0.20	0.207	0.000	0.001
11.12	0.20	0.208	0.000	0.000	0.208	0.208	0.000	0.000	0.20	0.208	0.000	0.000
11.37	0.20	0.208	0.000	0.001	0.208	0.208	0.000	0.001	0.20	0.208	0.000	0.001
11.62	0.20	0.209	0.000	0.000	0.209	0.209	0.000	0.000	0.20	0.209	0.000	0.000
11.87	0.21	0.210	0.000	-0.001	0.210	0.210	0.000	-0.001	0.21	0.210	0.000	-0.001
12.12	0.21	0.210	0.000	0.001	0.210	0.210	0.000	0.001	0.21	0.210	0.000	0.001
12.37	0.21	0.211	0.000	0.000	0.211	0.211	0.000	0.000	0.21	0.211	0.000	0.000
12.62	0.21	0.212	0.000	0.000	0.212	0.212	0.000	0.000	0.21	0.212	0.000	0.000
12.87	0.21	0.213	0.000	-0.001	0.213	0.213	0.000	-0.001	0.21	0.213	0.000	-0.001
13.12	0.21	0.213	0.000	0.001	0.213	0.213	0.000	0.001	0.21	0.213	0.000	0.001
13.37	0.21	0.214	0.000	0.001	0.214	0.214	0.000	0.001	0.21	0.214	0.000	0.001
13.62	0.21	0.215	0.000	0.001	0.215	0.215	0.000	0.001	0.21	0.215	0.000	0.001
13.87	0.21	0.216	0.000	0.001	0.216	0.216	0.000	0.001	0.21	0.216	0.000	0.001
14.12	0.21	0.217	0.000	0.001	0.217	0.217	0.000	0.001	0.21	0.217	0.000	0.001
14.37	0.21	0.219	0.000	-0.001	0.219	0.219	0.000	-0.001	0.21	0.219	0.000	-0.001
14.62	0.22	0.220	0.000	0.000	0.220	0.220	0.000	0.000	0.22	0.220	0.000	0.000
14.87	0.22	0.221	0.000	0.000	0.221	0.221	0.000	0.000	0.22	0.221	0.000	0.000
15.12	0.22	0.223	0.000	-0.001	0.223	0.223	0.000	-0.001	0.22	0.223	0.000	-0.001
15.37	0.22	0.224	0.000	0.001	0.224	0.224	0.000	0.001	0.22	0.224	0.000	0.001
15.62	0.22	0.226	0.000	0.000	0.226	0.226	0.000	0.000	0.22	0.226	0.000	0.000
15.87	0.22	0.228	0.000	0.000	0.228	0.228	0.000	0.000	0.22	0.228	0.000	0.000
16.12	0.23	0.230	0.000	0.000	0.230	0.230	0.000	0.000	0.23	0.230	0.000	0.000
16.37	0.23	0.232	0.001	0.001	0.233	0.232	0.001	0.001	0.23	0.232	0.001	0.001
16.62	0.23	0.235	0.000	0.000	0.235	0.235	0.000	0.000	0.23	0.235	0.000	0.000
16.87	0.23	0.238	0.000	0.001	0.238	0.238	0.000	0.001	0.23	0.238	0.000	0.001
17.12	0.24	0.242	0.000	-0.001	0.242	0.242	0.000	-0.001	0.24	0.242	0.000	-0.001
17.37	0.24	0.246	0.000	-0.001	0.246	0.246	0.000	-0.001	0.24	0.246	0.000	-0.001
17.62	0.25	0.250	0.000	0.000	0.250	0.250	0.000	0.000	0.25	0.250	0.000	0.000
17.87	0.25	0.256	0.000	-0.001	0.256	0.256	0.000	-0.001	0.25	0.256	0.000	-0.001
18.12	0.26	0.262	0.000	0.000	0.262	0.262	0.000	0.000	0.26	0.262	0.000	0.000
18.37	0.27	0.270	0.000	0.000	0.270	0.270	0.000	0.000	0.27	0.270	0.000	0.000
18.62	0.28	0.280	0.000	0.000	0.280	0.280	0.000	0.000	0.28	0.280	0.000	0.000
18.87	0.29	0.293	0.000	-0.001	0.293	0.293	0.000	-0.001	0.29	0.293	0.000	-0.001

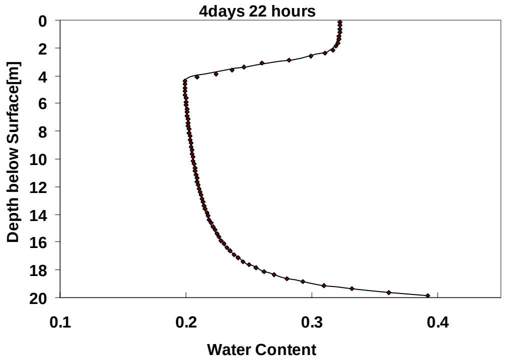
19.12	0.30	0.309	0.000	0.000	0.309	0.309	0.000	0.000	0.30	0.309	0.000	0.000
19.37	0.33	0.331	0.000	0.001	0.331	0.331	0.000	0.001	0.33	0.331	0.000	0.001
19.62	0.36	0.361	0.000	-0.001	0.361	0.361	0.000	-0.001	0.36	0.361	0.000	-0.001
19.87	0.39	0.392	0.000	0.000	0.392	0.392	0.000	0.000	0.39	0.392	0.000	0.000

	t = 2 days 12 hours				t = 4 days 12 hours				t = 4 days 22 hours			
Depth	MSHE	VS2DT	Absolute	Relative*	MSHE	VS2DT	Absolute	Relative*	MSHE	VS2DT	Absolute	Relative*
(m)	θ	θ	Error	Error	θ	θ	Error	Error	θ	θ	Error	Error
0.125	0.306	0.305	0.001	0.001	0.242	0.242	0.000	0.000	0.322	0.322	0.000	0.001
0.375	0.304	0.304	0.000	0.001	0.245	0.245	0.000	0.000	0.323	0.322	0.001	0.001
0.625	0.303	0.302	0.001	0.003	0.247	0.248	-0.001	-0.002	0.322	0.322	0.000	0.001
0.875	0.300	0.299	0.001	0.003	0.250	0.250	0.000	-0.001	0.322	0.322	0.000	0.000
1.125	0.294	0.293	0.001	0.003	0.252	0.252	0.000	-0.001	0.322	0.322	0.000	-0.001
1.375	0.284	0.283	0.001	0.003	0.253	0.253	0.000	0.000	0.322	0.321	0.001	0.001
1.625	0.268	0.269	-0.001	-0.002	0.254	0.255	-0.001	-0.002	0.321	0.320	0.001	0.002
1.875	0.248	0.250	-0.002	-0.005	0.255	0.255	0.000	0.001	0.319	0.318	0.001	0.003
2.125	0.231	0.232	-0.001	-0.003	0.256	0.256	0.000	-0.001	0.316	0.314	0.002	0.006
2.375	0.218	0.218	0.000	0.001	0.256	0.255	0.001	0.001	0.311	0.308	0.003	0.006
2.625	0.206	0.204	0.002	0.004	0.255	0.253	0.002	0.004	0.300	0.298	0.002	0.004
2.875	0.198	0.198	0.000	0.000	0.252	0.250	0.002	0.006	0.281	0.283	-0.002	-0.004
3.125	0.198	0.198	0.000	-0.001	0.248	0.245	0.003	0.008	0.260	0.265	-0.005	-0.011
3.375	0.198	0.198	0.000	-0.001	0.241	0.236	0.005	0.013	0.246	0.247	-0.001	-0.002
3.625	0.198	0.198	0.000	0.000	0.230	0.224	0.006	0.015	0.236	0.231	0.005	0.013
3.875	0.198	0.198	0.000	0.000	0.215	0.209	0.006	0.014	0.224	0.215	0.009	0.023
4.125	0.198	0.198	0.000	0.001	0.201	0.200	0.001	0.002	0.209	0.202	0.007	0.018
4.375	0.199	0.199	0.000	-0.001	0.199	0.199	0.000	-0.001	0.200	0.199	0.001	0.001
4.625	0.199	0.199	0.000	0.000	0.199	0.199	0.000	0.000	0.199	0.199	0.000	0.000
4.875	0.199	0.199	0.000	0.000	0.199	0.199	0.000	0.000	0.199	0.199	0.000	0.000
5.125	0.199	0.199	0.000	0.001	0.199	0.199	0.000	0.001	0.199	0.199	0.000	0.001
5.375	0.200	0.199	0.001	0.001	0.200	0.199	0.001	0.001	0.200	0.199	0.001	0.001
5.625	0.200	0.200	0.000	-0.001	0.200	0.200	0.000	-0.001	0.200	0.200	0.000	-0.001
5.875	0.200	0.200	0.000	0.000	0.200	0.200	0.000	0.000	0.200	0.200	0.000	0.000
6.125	0.200	0.200	0.000	0.001	0.200	0.200	0.000	0.001	0.200	0.200	0.000	0.001
6.375	0.201	0.200	0.001	0.001	0.201	0.200	0.001	0.001	0.201	0.200	0.001	0.001
6.625	0.201	0.201	0.000	-0.001	0.201	0.201	0.000	-0.001	0.201	0.201	0.000	-0.001
6.875	0.201	0.201	0.000	0.000	0.201	0.201	0.000	0.000	0.201	0.201	0.000	0.000
7.125	0.201	0.201	0.000	0.001	0.201	0.201	0.000	0.001	0.201	0.201	0.000	0.001
7.375	0.202	0.202	0.000	-0.001	0.202	0.202	0.000	-0.001	0.202	0.202	0.000	-0.001
7.625	0.202	0.202	0.000	0.000	0.202	0.202	0.000	0.000	0.202	0.202	0.000	0.000
7.875	0.202	0.202	0.000	0.001	0.202	0.202	0.000	0.001	0.202	0.202	0.000	0.001
8.125	0.203	0.203	0.000	-0.001	0.203	0.203	0.000	-0.001	0.203	0.203	0.000	-0.001
8.375	0.203	0.203	0.000	0.000	0.203	0.203	0.000	0.000	0.203	0.203	0.000	0.000
8.625	0.203	0.203	0.000	0.001	0.203	0.203	0.000	0.001	0.203	0.203	0.000	0.001
8.875	0.204	0.204	0.000	-0.001	0.204	0.204	0.000	-0.001	0.204	0.204	0.000	-0.001
9.125	0.204	0.204	0.000	0.000	0.204	0.204	0.000	0.000	0.204	0.204	0.000	0.000
9.375	0.205	0.204	0.001	0.001	0.205	0.204	0.001	0.001	0.205	0.204	0.001	0.001
9.625	0.205	0.205	0.000	0.000	0.205	0.205	0.000	0.000	0.205	0.205	0.000	0.000
9.875	0.205	0.205	0.000	0.001	0.205	0.205	0.000	0.001	0.205	0.205	0.000	0.001
10.125	0.206	0.206	0.000	0.000	0.206	0.206	0.000	0.000	0.206	0.206	0.000	0.000
10.375	0.206	0.206	0.000	0.001	0.206	0.206	0.000	0.001	0.206	0.206	0.000	0.001
10.625	0.207	0.207	0.000	0.000	0.207	0.207	0.000	0.000	0.207	0.207	0.000	0.000
10.875	0.207	0.207	0.000	0.001	0.207	0.207	0.000	0.001	0.207	0.207	0.000	0.001
11.125	0.208	0.208	0.000	0.000	0.208	0.208	0.000	0.000	0.208	0.208	0.000	0.000
11.375	0.208	0.208	0.000	0.001	0.208	0.208	0.000	0.001	0.208	0.208	0.000	0.001
11.625	0.209	0.209	0.000	0.000	0.209	0.209	0.000	0.000	0.209	0.209	0.000	0.000
11.875	0.210	0.210	0.000	-0.001	0.210	0.210	0.000	-0.001	0.210	0.210	0.000	-0.001
12.125	0.210	0.210	0.000	0.001	0.210	0.210	0.000	0.001	0.210	0.210	0.000	0.001
12.375	0.211	0.211	0.000	0.000	0.211	0.211	0.000	0.000	0.211	0.211	0.000	0.000
12.625	0.212	0.212	0.000	0.000	0.212	0.212	0.000	0.000	0.212	0.212	0.000	0.000
12.875	0.213	0.213	0.000	-0.001	0.213	0.213	0.000	-0.001	0.213	0.213	0.000	-0.001
13.125	0.213	0.213	0.000	0.001	0.213	0.213	0.000	0.001	0.213	0.213	0.000	0.001
13.375	0.214	0.214	0.000	0.001	0.214	0.214	0.000	0.001	0.214	0.214	0.000	0.001
13.625	0.215	0.215	0.000	0.001	0.215	0.215	0.000	0.001	0.215	0.215	0.000	0.001
13.875	0.216	0.216	0.000	0.001	0.216	0.216	0.000	0.001	0.216	0.216	0.000	0.001
14.125	0.217	0.217	0.000	0.001	0.217	0.217	0.000	0.001	0.217	0.217	0.000	0.001
14.375	0.219	0.219	0.000	-0.001	0.219	0.219	0.000	-0.001	0.219	0.219	0.000	-0.001
14.625	0.220	0.220	0.000	0.000	0.220	0.220	0.000	0.000	0.220	0.220	0.000	0.000
14.875	0.221	0.221	0.000	0.000	0.221	0.221	0.000	0.000	0.221	0.221	0.000	0.000
15.125	0.223	0.223	0.000	-0.001	0.223	0.223	0.000	-0.001	0.223	0.223	0.000	-0.001
15.375	0.224	0.224	0.000	0.001	0.224	0.224	0.000	0.001	0.224	0.224	0.000	0.001
15.625	0.226	0.226	0.000	0.000	0.226	0.226	0.000	0.000	0.226	0.226	0.000	0.000

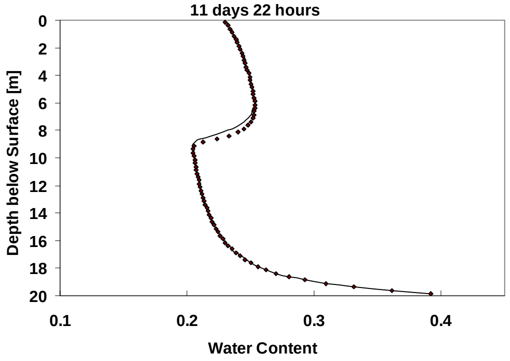
*Relative to: Maximum moisture content = 0.4







*Relative to: Maximum moisture content = 0.4



	t = 11 days 22 hours			
Depth (m)	MSHE θ	VS2DT θ	Absolute Error	Relative Error
0.125	0.230	0.231	-0.001	-0.002
0.375	0.232	0.232	0.000	0.000
0.625	0.234	0.234	0.000	-0.001
0.875	0.235	0.236	-0.001	-0.002
1.125	0.237	0.237	0.000	-0.001
1.375	0.238	0.239	-0.001	-0.002
1.625	0.239	0.240	-0.001	-0.001
1.875	0.241	0.241	0.000	-0.001
2.125	0.242	0.242	0.000	-0.001

2.375	0.243	0.244	-0.001	-0.003
2.625	0.244	0.245	-0.001	-0.003
2.875	0.245	0.246	-0.001	-0.003
3.125	0.246	0.246	0.000	-0.001
3.375	0.247	0.247	0.000	-0.001
3.625	0.247	0.248	-0.001	-0.001
3.875	0.248	0.249	-0.001	-0.002
4.125	0.249	0.250	-0.001	-0.002
4.375	0.250	0.250	0.000	-0.001
4.625	0.250	0.251	-0.001	-0.001
4.875	0.251	0.252	-0.001	-0.002
5.125	0.252	0.252	0.000	-0.001
5.375	0.252	0.252	0.000	0.000
5.625	0.253	0.253	0.000	-0.001
5.875	0.253	0.253	0.000	0.000
6.125	0.253	0.253	0.000	0.000
6.375	0.253	0.252	0.001	0.003
6.625	0.253	0.251	0.002	0.005
6.875	0.253	0.250	0.003	0.006
7.125	0.252	0.248	0.004	0.009
7.375	0.250	0.245	0.005	0.013
7.625	0.248	0.241	0.007	0.018
7.875	0.245	0.235	0.010	0.024
8.125	0.240	0.228	0.012	0.030
8.375	0.233	0.219	0.014	0.035
8.625	0.224	0.210	0.014	0.034
8.875	0.213	0.206	0.007	0.017
9.125	0.206	0.204	0.002	0.004
9.375	0.205	0.205	0.000	-0.001
9.625	0.205	0.205	0.000	0.000
9.875	0.205	0.205	0.000	0.001
10.125	0.206	0.206	0.000	0.000
10.375	0.206	0.206	0.000	0.001
10.625	0.207	0.207	0.000	0.000
10.875	0.207	0.207	0.000	0.001
11.125	0.208	0.208	0.000	0.000
11.375	0.208	0.208	0.000	0.001
11.625	0.209	0.209	0.000	0.000
11.875	0.210	0.210	0.000	-0.001
12.125	0.210	0.210	0.000	0.001
12.375	0.211	0.211	0.000	0.000
12.625	0.212	0.212	0.000	0.000
12.875	0.213	0.213	0.000	-0.001
13.125	0.213	0.213	0.000	0.001
13.375	0.214	0.214	0.000	0.001
13.625	0.215	0.215	0.000	0.001
13.875	0.216	0.216	0.000	0.001
14.125	0.217	0.217	0.000	0.001
14.375	0.219	0.219	0.000	-0.001
14.625	0.220	0.220	0.000	0.000
14.875	0.221	0.221	0.000	0.000
15.125	0.223	0.223	0.000	-0.001
15.375	0.224	0.224	0.000	0.001
15.625	0.226	0.226	0.000	0.000

15.875	0.228	0.228	0.000	0.000
16.125	0.230	0.230	0.000	0.000
16.375	0.233	0.232	0.001	0.001
16.625	0.235	0.235	0.000	0.000
16.875	0.238	0.238	0.000	0.001
17.125	0.242	0.242	0.000	-0.001
17.375	0.246	0.246	0.000	-0.001
17.625	0.250	0.250	0.000	0.000
17.875	0.256	0.256	0.000	-0.001
18.125	0.262	0.262	0.000	0.000
18.375	0.270	0.270	0.000	0.000
18.625	0.280	0.280	0.000	0.000
18.875	0.293	0.293	0.000	-0.001
19.125	0.309	0.309	0.000	0.000
19.375	0.331	0.331	0.000	0.001
19.625	0.361	0.361	0.000	-0.001
19.875	0.392	0.392	0.000	0.000

*Relative to: Maximum moisture content = 0.4