Application and comparison of different methods for aquifer test analysis using TTim

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Abstract

Hydraulic properties of aquifer systems are usually estimated by conducting field experiments, which are called aquifer tests. Different approaches have been applied to simulate the drawdown data, such as graphical type curves, analytical solutions, and grid-based models. Since the type of groundwater system varies greatly from location to location, only a few general solutions have been developed. Computation of hydraulic properties are limited by the size and time step of grid-based model. Determining the boundary conditions is also difficult in actual groundwater system. Thus, in order to better simulate various aquifer systems, semi-analytic approaches have been promoted and used in aquifer test analysis.

In this report, three different softwares aiming at aquifer tests simulation are presented. Both MLU and TTim are based on semi-analytical solutions and need users to build their own aquifer models, while AQTESOLV provides a base model for adding a variety of data and a stack of choices containing both analytical and semi-analytic solutions. Some benchmark analyses have been performed to assess the performance of TTim with limited types of aquifer systems. This research focuses on the application of TTim to different aquifer systems and the investigation of TTim's performance compared to the other two softwares.

In this study, fifteen aquifer tests have been simulated with TTim. Test 0 uses hypothetical data to verify TTim's capabilities of retrieving specified parameters and reporting accurate confidence interval. Test 1 through Test 10 are pumping tests which are taken from reported field experiments and are grouped as confined systems, leaky systems, and unconfined systems. Test 11 through Test 14 present four slug tests with different top boundaries and well construction. The values and confidence intervals of the calibrated parameters are compared to the results of AQTESOLV and MLU. Improvement of conceptual models is carried out by model structure adjustments and parameters set adjustments. Different models' performance are assessed by root-mean-squared-error and AKAIKE Information Criterion (AIC).

Most of the pumping tests and slug tests can be conceptualized using either ModelMaq and Model3D within TTim. Model3D is recommended when conceptualizing unconfined systems. The top boundary needs to be specified as 'confined', and an additional thin aquifer needs to be added to simulate the specific yield, which is calibrated separately. The performance of TTim is similar, in general, to AQTESOLV and MLU. Well construction parameters cannot be calibrated with AQTESOLV, and only one aquifer system is available. TTim is more flexible and accurate than AQTESOLV when the groundwater system has information of multi aquifers and well construction.

Modifications of parameters to be calibrated and model structure have been carried out to improve TTim's performance. It is concluded that aquifers with multi subdivided layers perform better when the well is partially penetrating or the observation wells have different depths. Calibration of well construction parameters may also contributes to a better simulation, but they are usually sensitive to the initial values. It is important to note that adding parameters may give better results, but whether this is significant needs to be tested by the AIC criterion.

Keywords : aquifer tests, semi-analytical solution, conceptual model, parameters calibration

Contents

1 Introduction

When analyzing groundwater flow, reliable values of the hydraulic characteristics of local groundwater system need to be found. Aquifer tests are usually conducted to obtain such values. Various methods have been developed to analyze and evaluate drawdown data measured during aquifer tests. A lot of analytical solutions have been developed for different types of groundwater systems, including Theis (1935) solution for transient drawdown in confined aquifers, Hantush and Jacob (1955) solution for unsteady flow in a leaky aquifer, and so on. Most of the theoretical solutions are focused on solving groundwater problems in specific situations. Only a few general solutions are available and widely used. Grid-based models are developed and applied to simulate groundwater systems, which is more flexible because the boundary conditions and characteristics of the system can be set separately in the process of building the model. In the past 30 years, semi-analytical approaches are applied in the simulation of groundwater system which don't need a grid. Compared to grid-based models, semi-analytical approaches have less limitations in computation of hydraulic head, and needs less specified boundary conditions.

TTim is a free code based on Python for transient flow in multi layer systems consisting of an arbitrary number of layers which applies the semi-analytical approach (Bakker, 2013b). Compared with several common groundwater analysis softwares, such as AQTESOLV and MLU, TTim is open source, and is capable of simulating both arbitrary number of aquifer layers and other types of features besides wells. Some investigations have been performed in Bakker (2013a) to estimate the performance of TTim. Although TTim is a well-structured groundwater model for multi layer systems, the benchmark analyses were conducted for a limited set of groundwater systems. The investigation of various pumping test analyses is necessary for investigating TTim to provide a basis for the widespread application of TTim and to provide examples to support the subsequent development of TTim. This study mainly focuses on investigating the capabilities of TTim to analyze various aquifer tests, with an emphasize on the conceptualization of real aquifer systems.

1.1 Research objective

When modeling is involved in simulating more complicated aquifer systems, e.g. in multi layer systems or fractured groundwater systems, analysis of drawdown data obtained by conducting aquifer tests is more than just parameter estimation. Selection of proper conceptual model and parameterization are also required. Searching for the simplest or the most appropriate conceptual hydrogeologic model that can simulate the measured drawdown is a necessary prerequisite for finding the best values for hydraulic properties of the aquifer system. While identifying the best set of parameters to be optimized ensures the accuracy of model calibration.

Although several benchmark analysis have been performed, it may not be immediately clear how to apply TTim to real aquifer tests under different situations. Also the performance of TTim to simulate various types of aquifer tests have not been verified. The main objective of this research is to test the capabilities and performance of TTim for modeling transient flow and analyzing aquifer tests in different aquifer systems consisting of an arbitrary number of layers.

Based on the above, the research questions of the project are formulated as follows:

- How to transform various aquifer tests into proper conceptual models for TTim?

- How is the performance of TTim compared with other softwares based on semi-analytical approach (MLU) and analytical solutions (AQTESOLV)?

- How to improve the performance of TTim by modifying the conceptual models?

In order to answer these research questions, several aquifer tests are selected covering different types of groundwater systems and are analyzed with TTim. Comparison of the performance of TTim, MLU, and AQTESOLV in terms of accuracy and flexibility are carried out.

1.2 Program involved

Two softwares (MLU and AQTESOLV) that are applied in this study as well as TTim are briefly introduced in this section. The Kruseman and de Ridder (1970) book is also mentioned, since most of the study cases and analytical solutions are well explained and presented in this book.

1.2.1 Kruseman and de Ridder (1970) book

The Kruseman and de Ridder (1970) book 'Analysis and Evaluation of Pumping Test Data' provides basic concepts and definitions of technical terms of groundwater systems. The classical and commonly used solutions for different aquifer systems are also provided in the book with real aquifer tests as examples. Almost all common types of groundwater systems are discussed in this book, and several of the examples cited in this thesis are taken from the book.

1.2.2 Description of TTim

TTim is an analytic element model allowing for the simulation of transient groundwater flow in layered aquifer systems based on application of the theory of Hemker and Maas (1987). The aquifer system may consist of an arbitrary number of aquifer layers, which allows for the simulation of multi aquifer wells, transient flow to streams and areal recharge. Analytic element solutions are computed in the Laplace domain, and the mathematical problem is solved by application of of the Laplace Transform method (Bakker, 2013a). The approach is implemented in the computer program TTim written in Python. Two types of basic models are available: ModelMaq and Model3D. ModelMaq consists of a sequence of aquifer-leaky layer-aquifer-leaky layer, etc, which is suitable for most aquifer systems with confined or leaky top boundaries. Model3D consists of a sequence of aquifer layers with a confined top boundary. The major approximations are as follows: (1) The conceptual model is based on aquifer systems consisting of horizontal aquifer layers and leaky layers. (2) The Dupuit approximation is adopted. The flow is still three-dimensional, while the resistance in the vertical direction is neglected within a horizontal aquifer layer. (3) The flow in leaky layers is approximated to be vertical. (4) Each layer is assumed to be homogeneous and of uniform thickness. (5) The transmissivity is approximated to be constant within an aquifer layer in both space and time. (6) Only systems that can be approximated as linear apply to this approach.

1.2.3 Description of MLU

MLU is a commercial program based on a semi-analytical solution technique described in Hemker(1999) for simulation of transient multi-layer flow. It applies the same theory as used in TTim, but only for modeling wells, with a few different choices in implementation.

MLU conceptualizes the quifer system as a layered model with horizontal flow separated by aquitards or resistance layers controlling vertical flow together with boundary conditions (Hemker and Randall, 2010). The hydraulic properties of each layer can be specified and calibrated separately. Transient well flow is simulated where horizontal flow happens within the layered aquifers, and vertical flow through resistant layers between these aquifers.

Draw-down can only be computed for aquifer layers. MLU can handle both fully and partially penetrating wells by specifying one discharge rate for the combined screened layers. Uniform well-face draw-down condition is applied, which assumes that the draw-down at the well screen is the same at any depth at any time (Hemker and Randall, 2010), and TTim does the same thing.

Although MLU is based on almost the same approximations as TTim, several differences are found between them. First, MLU can add aquifers and aquitards with zero thickness. A thin, low-transmissivity aquifer layer can be inserted within an aquitard, and drawdown of the aquitard layer can be computed within the fake aquifer layer. When an aquifer or subdivided in multiple layers, the aquifer layers are separated by aquitards of zero thickness. TTim can not add zero thickness layers. Instead, the aquifer is subdivided into several sub-layers and simulated by Model3D consisting of a sequence of aquifer layers without sandwiched aquitards, but the mathematical equation is the same for MLU. The resistance between two aquifer layers are calculated automatically by TTim. Second, TTim and MLU define skin effect in a different way. MLU accounts for skin effect the same way as Kruseman et al. (1970) do. A dimensionless skin factor is involved to express the difference between the observed drawdown in a well and loss component of the aquifer. TTim expresses skin effect as an entry resistance. Conversion between the two parameters is presented in Chapter 2. Third, both TTim and MLU optimize the parameters by Least Squares method, but MLU also has the log drawdown curve fitting solution, which takes logarithms of the head before calculating the sum of errors. Forth, only tests involving wells can be simulated by MLU, while TTim has more features, such as line-sinks for flow to streams and areal recharge.

1.2.4 Description of AQTESOLV

AQTESOLV is a well developed software for the design and interpretation of aquifer tests. Instead of creating a specific solution or model to analyze groundwater, AQTESOLV is a package of exact solutions for special cases. It provides a collection of easy-to-use data-entry wizards that streamline and accelerate the process of entering field data (HydroSOLVE). AQTESOLV collects over 50 solutions for confined aquifers, leaky aquifers, unconfined aquifers and slug tests. The user is asked to input the basic parameters and observation data of the system to be simulated, and then choose a solution to start.

Compared with TTim and MLU, AQTESOLV does not have the link of conceptualization. AQTESOLV can handle more types of aquifer tests with wells, including oscillation tests and specific types of fracture systems. The convergence criteria of AQTESOLV can be set by the user in two ways: by determining the number of iterations or the residuals. When it comes to the well bore skin, AQTESOLV involves three skin models as thin skin model, thick skin model and composite model. Thickness of the skin and hydraulic conductivity of the skin are involved into the equations.

1.3 Thesis outline

In Chapter 2, the semi-analytical approach is summarized. After which, the Least Squares approach and the AKAIKE Information Criterion (AIC) are explained, followed by the definitions of several terms involved in this study.

Chapter 3 presents five tests for aquifer systems under confined conditions and one synthetic data test. The capability of TTim retrieving specified parameters and the accuracy of confidence intervals are first verified in the synthetic data test, followed by four confined aquifer tests and one double porosity test with confined top boundary. Chapter 4 and Chapter 5 present three leaky aquifer tests and two unconfined aquifer tests, respectively. Four slug tests are discussed in Chapter 6. All the data of aquifer tests modeled by TTim are obtained from real conducted tests presented in either the book of Kruseman et al. (1970) or examples of MLU and AQTESOLV.

The performance of TTim in simulating different types of aquifer tests and the differences of the three methods are discussed in Chapter 7. Summary of the work, conclusions on the main findings, and recommendations for future research are presented in Chapter 8.

Basic information for the aquifer tests simulated in this thesis are summarized in Table 1.

For each test, conceptual model is built using TTim, and calibration has been done based on drawdown data for different parameters. These tests are also carried out with either AQTESOLV or MLU. The results are compared and evaluated in terms of uncertainty and fitting performance. Then the conceptual model is modified in different ways to improve the performance of TTim. Findings and conclusions are summarized throughout the processes of conceptualization, comparison, and improvement. The flow chart of Figure 1 presents the structure of this research.

Table 1: Basic information of fifteen tests.

Test	Test name	Condition	Applied Softwares	Type
0	Synthetic data test	Confined aquifer (use basic information of Test 1)	TTim	Pumping
1	Oude Korendijk	Confined aquifer	AQTESOLV, MLU, and TTim	Pumping
2	Gridley	Confined aquifer	AQTESOLV, MLU, and TTim	Pumping
3	Sioux Flats	Confined aquifer	AQTESOLV, MLU, and TTim	Pumping
4	Schroth	Confined two-aquifer system	MLU and TTim	Pumping
5	Neveda	Confined double-porosity system	AQTESOLV, MLU, and TTim	Pumping
6	Dalem	Leaky aquifer	AQTESOLV, MLU, and TTim	Pumping
7	Hardinxveld	Leaky aquifer-recovery test	MLU and TTim	Pumping
8	Texas Hill	Leaky aquifer	AQTESOLV and TTim	Pumping
9	Vennebulten	Unconfined aquifer	AQTESOLV, MLU, and TTim	Pumping
10	Moench	Hypothetic test for unconfined aquifer	MLU and TTim	Pumping
11	Pratt County	Slug test Confined aquifer	AQTESOLV and TTim	Slug
12	Falling head	Slug test Unconfined aquifer	AQTESOLV and TTim	Slug
13	Lincoln County	Slug test Multi wells	AQTESOLV, MLU, and TTim	Slug
14	Dawsonville	Slug test Confined aquifer	MLU and TTim	Slug

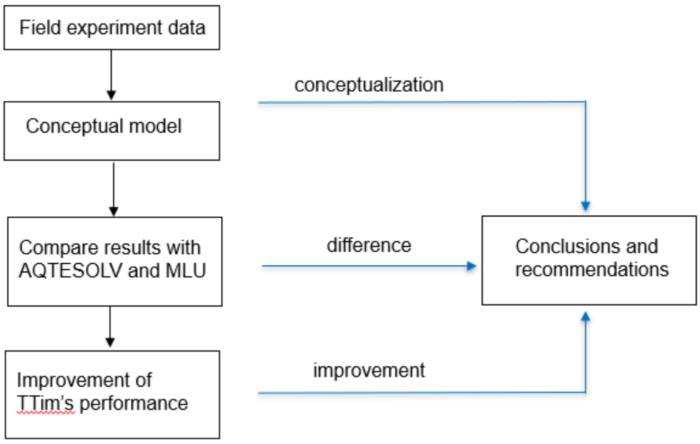


Figure 1: Structure of the research.

2 Methods

2.1 Semi-analytical approach within TTim

Compared to grid-based models, semi-analytical solutions have three major benefits. First, the model domain does not have a grid, which means the accuracy of the solution does not depend on the size or shape of the grid. The computation of hydraulic head is not limited by the location. Second, time step is not applied. Thus, the accuracy does no depend on the length of time step, and the head can be calculated at any time. Third, the model domain is infinite. No boundary conditions need to be specified along the boundaries of the model domain, which is almost impossible to determine in actual groundwater systems.

The approach is developed by application of the theory for transient multi-aquifer flow of Hemker and Maas (1987). The analytic element solutions are computed in the Laplace domain, and the solution is obtained through the numerical back-transformation (Hoog et al., 1982) from the Laplace domain to the time domain. The mathematical model and the derivation of the solution are explained in Bakker (2013a), and the TTim program is discussed in Bakker (2013b).

The governing equation for three-dimensional Dupuit flow in aquifer layer n is:

$$T_n \nabla^2 h_n = S_n \frac{\partial h_n}{\partial t} + q_{b,n} - q_{t,n+1} \tag{1}$$

where T_n is the transmissivity of aquifer layer n, S_n is the storage coefficient of aquifer layer n, $h_n(x, y, t)$ is the head in aquifer layer n, $q_{b,n}$ is the upward leakage through the bottom of leaky layer n, $q_{t,n+1}$ is the upward leakage through the top of leakage layer $n + 1$, t is time, and ∇^2 refers to the two-dimensional horizontal Laplacian. The derivation of the governing system of differential equations applied in TTim can be found in Bakker (2013a). Both MLU and TTim are based on the theory of Hemker and Maas (1987). Difference occurs when the numerical back-transformation are done with different algorithms. TTim applies the method of (Hoog et al., 1982), while MLU applies the method of Stehfest (2005).

2.2 Least Squares approach

AQTESOLV, MLU, and TTim all apply a Least Squares approach in combination with a Levenberg-Marquardt search algorithm to estimate the optimal parameters. Differences may occur because different criteriums are applied. The least squares method is a form of mathematical regression analysis to find the best fit for a set of data by minimizing the sum of the squares of the errors between the observations and the predictions. The objective function SSE is the sum of squared errors defined as follows:

$$r_m = h_{obs} - f(t_{obs}, x_{obs}, y_{obs}, \theta) \tag{2}$$

$$SSE = \sum (r_m(\theta)^2) \tag{3}$$

where h_m is the observed head, t_{obs} is the timing for the observed head, x_{obs} and y_{obs} are the relative coordinates of the observation well, θ is the hydraulic parameters set involved in the model, and $f(t_{obs}, x_{obs}, y_{obs}, \theta)$ is the prediction function of the groundwater model. The basic Least-Squares problem is trying to find the values of the parameter set θ that minimizes the objective function SSE.

When the prediction function is not linear in the parameters, the least squares method iteratively reduces the sum of the squares of the errors through a sequence of updates of parameter values (Gavin, 2011). Different optimization algorithms have been developed to solve this problem. The gradient descent algorithms starts with an initial guess and the SSE is reduced by updating the parameters in the steepest-descent direction. The way to find the parameters set minimized SSE tends to zigzag along the bottom of long narrow canyons. Another widely used method is the Gauss-Newton algorithm, which assumes the least squares function is locally quadratic. The SSE is reduced by finding the minimum of the quadratic. The Levenberg-Marquardt algorithm combines both the gradient descent method and the Gauss-Newton method. A damping factor is involved and adjusted at each iteration. When the parameters set is far from the optimal values, the Levenberg-Marquardt acts more like a gradient descent method to approach the optimum quickly. When the parameters set is close to the optimal values, the Levenberg-Marquardt acts more like a Gauss-Newton method. Usually, the steps are dominated by gradient descent at first, followed by Gauss-Newton dominated steps. Detailed derivation of the three algorithms can be found in e.g. Gavin (2011).

The specifics of the Levenberg-Marquardt algorithm may differ slightly, and the starting values of the search and the criteria to end the search when an optimum is found may differ as well.

2.3 Akaike criterion

The performance of a model can be assessed in terms of the estimated uncertainty of the parameters and the root-mean-squared-error which can be calculated as follows:

$$RMSE = \sqrt{\frac{SSE}{n}} \tag{4}$$

where n is the number of observations, $RMSE$ is the root-mean-squared-error, and SSE refers to the sum of squared errors which is shown in Equation 3.

The choice of different models becomes difficult when different models report similar root-mean-squared-errors. Also when adding extra parameters to optimize a model, the root-mean-squared-error is likely to go down, however the question is whether the root-mean-squared-error decreases enough to decide the model with more parameters is a better model. The AKAIKE criterion is used here to make a choice.

The AKAIKE information criterion (AIC) is a method to evaluate which model is the best for the dataset. The formula for AIC is:

$$AIC = 2K - 2\ln(L) \tag{5}$$

where K is the number of independent variables used in the fitting function, and L is the log-likelihood estimate. The default of K is 2. So the K value equals 2 plus the number of independent variables in the model. The AIC value can be computed for each model separately. A model is considered to be significantly better than another model if it has at least a 2 units lower AIC value. The derivation of AKAIKE criterion and the emergence of the magic number 2 can be found in e.g., Bozdogan (1987).

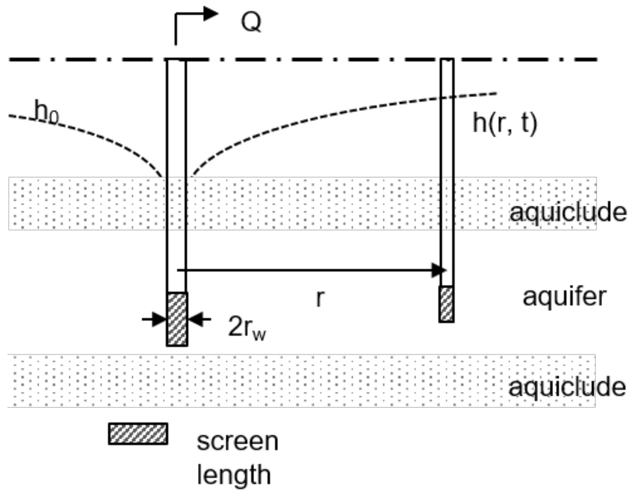
2.4 Basic terms applied

This section summarizes the basic concepts and definitions of relevant terms applied in this study, including basic types of aquifer tests and two well construction parameters.

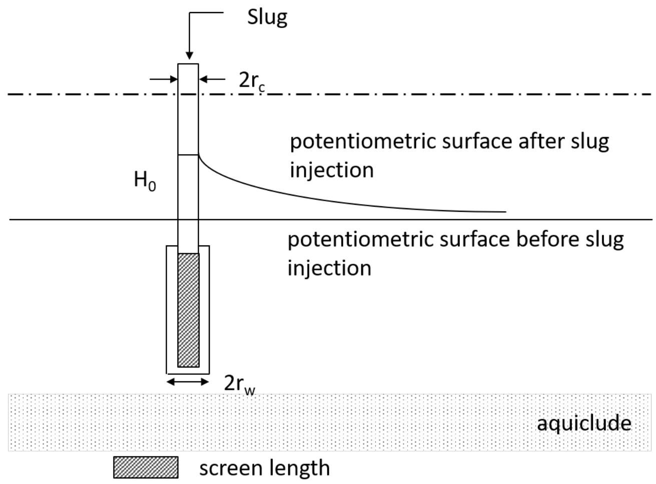
2.4.1 Aquifer tests

Aquifer tests are field experiments that are usually conducted under controlled circumstances to estimate hydraulic properties of aquifer systems such as transmissivity, storativity and resistance of aquitards. Pumping tests, slug tests and constant-head tests are three fundamental types of aquifer testing methods. All of the methods need a control well to impose different types of hydraulic stress. In a pumping test, water is commonly extracted or injected at a constant rate. While in a slug test, a small volume of water is quickly added or removed from the control well. In a constant-head test, the water head in the control well is fixed. The drawdown is measured in either the test well or other piezometers, and is simulated by different methods to estimate the best set of parameters.

Both pumping tests and slug tests are contained in the fifteen tests applied in this study. Figure 2a and Figure 2b give a demonstration of pumping tests and slug tests, respectively.



(a) Pumping test



(b) Slug test

Figure 2: Demonstration of pumping test and slug test.

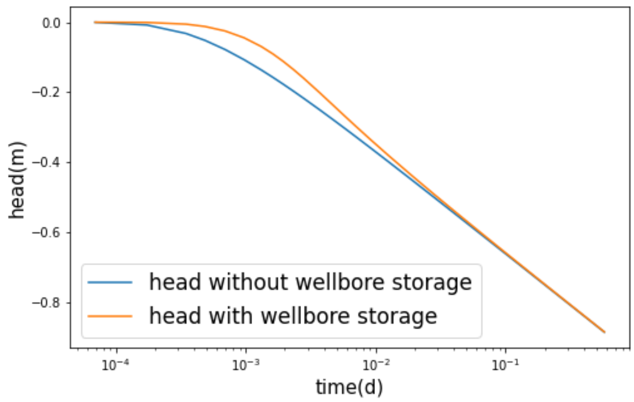


Figure 3: Comparison of drawdown data inside the well with and without well bore storage.

2.4.2 Well bore storage

Well bore storage is the phenomenon that at the beginning of a pumping test, water is pumped from water stored in the well, rather than from the aquifer. The simulation of well bore storage involves the casing radius of a well. The head inside the well is determined by a water balance inside the well, and the equation is (Bakker, 2013b):

$$\pi r_c^2 \frac{dh_w}{dt} = \sum Q_n - Q_w \tag{6}$$

where Q_w is the discharge of the well, Q_n is the discharge entering the well through the screen in layer n, r_c is the casing radius of the well, and h_w is the head measured inside the well.

A set of drawdown data is generated with the basic conceptual model and observed timings of Test 1 as example to illustrate the effect of well bore storage as shown in Figure 3. It can be seen that when well bore storage is simulated, the curve is flat at very early time due to the surplus water in the well before pumping started.

2.4.3 Well skin resistance

Skin effect is the phenomenon that the well is surrounded by low permeable material and the filter has significant resistance to flow. As a result, the head in the well differs significantly from the head just outside the well. The concept of well bore skin is used to account for the difference between measured and predicted drawdown in a pumping well.

The skin effect is presented as skin factor [-] in MLU which is defined in Kruseman et al. (1970) as:

$$s_n = \frac{Q_n}{2\pi T_n} c_s \tag{7}$$

where s_n [m] is the drawdown in layer n caused by skin effect; Q_n [m^3/d] is the discharge of layer n; T_n [m^2/d] is the transmissivity of layer n and c_s [-] is the skin factor.

While in TTim the skin effect is represented by c_e [d], which is the entry resistance and can be converted to c_s as follows:

$$c_s = \frac{T_n}{H_n r_w} c_e \tag{8}$$

where H_n [m] is the thickness of aquifer layer n and r_w [m] is the well radius.

3 Pumping tests for confined aquifers

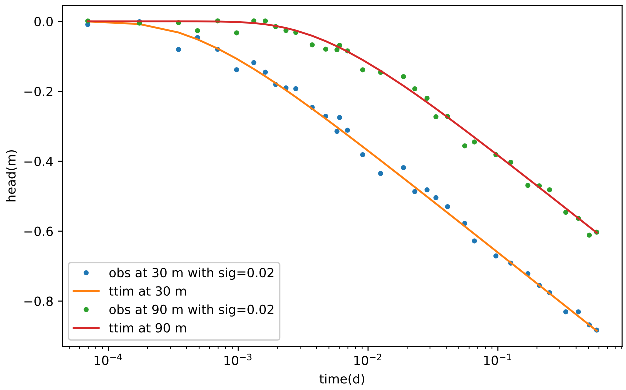
A confined aquifer is one of the most common groundwater systems, which is bounded above and below by an impermeable layer. The pressure of the water in a confined aquifer is usually higher than atmosphere. When a fully penetrating well pumps from a confined aquifer, water is withdrawn from the storage of the aquifer. Theoretically, due to the inevitable reduction in aquifer storage caused by pumping, only transient flow can exist. However, if the pumping rate is constant, the flow to the well reaches steady state. Test 0 verifies the capabilities of retrieving known parameters and uncertainty estimation of TTim by applying a synthetic dataset. Other five tests presented in this chapter are tests conducted under confined aquifer systems. Test 5 is for a fracture system under confined top boundary. Simulation results of each test are compared to that of AQTESOLV or MLU and are presented in each section.

3.1 Test 0 Synthetic data test

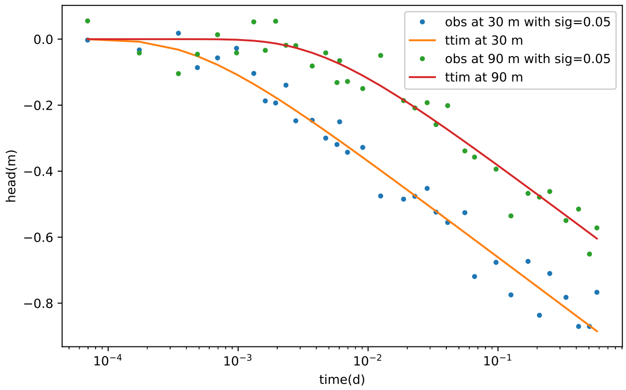
3.1.1 Synthetic model

A test is conducted with a synthetic dataset for a confined aquifer system to verify TTim model. The test is built based on the basic situation of the pumping well test at Oude Korendijk (Kruseman et al., 1970). A fully penetrating well pumps from a confined aquifer. The aquifer is located between 18 m and 25 m below the surface. Both the top and base layer of the aquifer is considered to be impermeable. The well screen is installed over the whole thickness of the aquifer and two observation wells are located at distances of 30 and 90 m from the well. The well is pumped at a constant discharge of 788 m^3/d.

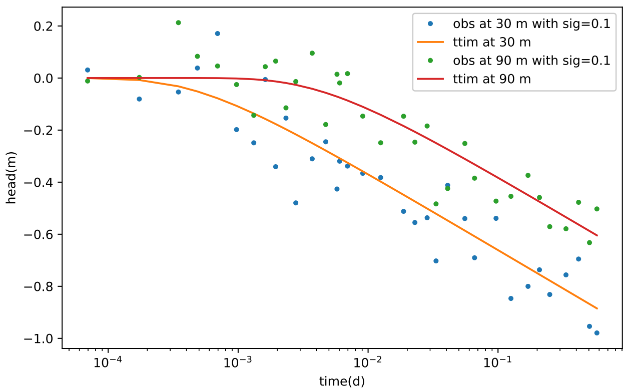
The objective of a synthetic test is to determine if specified parameters can be found back by TTim. The performance of these methods can be assessed since the values of the parameters are known. The value of hydraulic conductivity is set to 70 m/d (k) and the value of specific storage is set to 1e-4 1/m (Ss). The observation time is set the same as observation times of the piezometer at 30 m from the pumping well of test Oude Korendijk. Generating synthetic data starts with calculating drawdowns at 30 m and 90 m away from the pumping well using TTim model and store the results as dataset 1. Next, random noise is added to the true data. The drawdown of observation well located 30 m from the pumping well ranges from 0.1 to 0.3 m. Random errors drawn from a normal distribution with mean zero and standard deviation (σ) of 0.02, 0.05, and 0.1 are added, respectively, and are sorted as dataset 2, dataset 3, and dataset 4. The plots of three datasets are shown in Figure 4.



(a) $\sigma = 0.02$



(b) $\sigma = 0.05$



(c) $\sigma = 0.1$

Figure 4: Synthetic drawdown with different σ.

3.1.2 Results of simulating four datasets

The uncertainty of the optimized parameters is presented by AQTESOLV as the 95 % confidence intervals for two parameters using Student's t-distribution, while TTim and MLU return the standard error. Note that in MLU, the standard error is called the standard deviation. The 95 % confidence intervals are calculated for comparison purpose. In Student's t-distribution, when the degrees of freedom is large, the 95 % confidence interval can be approximated as $\pm 2\sigma$. Thus, both standard errors returned by TTim and MLU are multiplied by factor 2 to compare with the results of AQTESOLV.

The three methods are applied to the four synthetic data sets and results are shown in Table 2 and Table 3. The root-mean-squares of TTim, MLU and AQTESOLV are also given in Table 4.

Table 2: Hydraulic conductivity using synthetic drawdowns added noise.

Hydraulic conductivity [m/d]								
errors	No error		σ=0.02 m		σ =0.05 m		σ =0.1 m	
	value	95% confidence interval	value	95% confidence interval	value	95% confidence interval	value	95% confidence interval
TTim	70.000	0.000%	70.509	2.433%	70.317	6.924%	71.184	13.480%
AQTESOLV	70.000	0.000%	70.510	2.427%	70.320	6.911%	71.180	13.459%
MLU	70.443	0.245%	70.929	2.452%	70.743	6.858%	71.629	13.387%

Table 3: Specific storage using synthetic drawdowns added noise.

Specific storage [1/m]								
errors	No error		σ =0.02 m		σ =0.05 m		σ =0.1 m	
	value	95% confidence interval	value	95% confidence interval	value	95% confidence interval	value	95% confidence interval
TTim	1.000E-04	0.000%	9.711E-05	7.425%	9.822E-05	21.077%	8.060E-05	42.590%
AQTESOLV	1.000E-04	0.001%	9.708E-05	7.409%	9.822E-05	21.046%	8.062E-05	42.528%
MLU	9.746E-05	0.750%	9.470E-05	7.549%	9.571E-05	21.069%	7.834E-05	42.706%

The results of the synthetic model tests present the sensitivity of the three methods to different errors. TTim and AQTESOLV have almost the same performance on analyzing hydraulic conductivity and specific storage. It can be observed from Table 2 and Table 3 that AQTESOLV gives slightly smaller confidence intervals than TTim. The RMSE simulated by both methods are also almost the same, as can be seen in Tabel 4.

Table 4: RMSE of different methods.

RMSE [m]				
errors	No error	σ =0.02 m	σ =0.05 m	σ =0.1 m
TTim	8.824E-09	1.731E-02	4.923E-02	9.915E-02
AQTESOLV	1.375E-06	1.730E-02	4.921E-02	9.915E-02
MLU	1.715E-03	1.753E-02	4.900E-02	9.894E-02

As shown in the above tables, MLU also has a good performance on analyzing both parameters, however compared to TTim and AQTESOLV, the results of both hydraulic conductivity and specific storage are a little more deviated from the true value. Even so, the true values of hydraulic conductivity and specific storage lie within the ranges for all four datasets. Besides, when applying MLU to simulate four datasets, the results are sensitive to the initial values of hydraulic conductivity and specific storage. When the initial results are too far from the true values, some manual trial and error parameter estimation are needed to find better initial values.

In conclusion, all of TTim, MLU and AQTESOLV perform well on finding back known values of hydraulic conductivity and specific storage. AQTESOLV gives a slightly narrower confidence interval, while MLU gives slightly more deviated true values and is more sensitive to initial values.

3.1.3 Verify uncertainty estimation of TTim

A test was conducted to verify the performance of the standard error TTim returns. In statistics, a confidence interval proposes a range of plausible values for an unknown parameter. This means given the true value and standard deviation of the whole datasets, a 95 % confidence interval can be computed, then the probability is 95 % that the true value falls within the range. This means if the confidence level is 95 %, then in hypothetical indefinite data collection, 95 % of the samples the interval estimate will contain the true value. Since in this synthetic test, the true values of hydraulic conductivity and specific storage are known, but the standard deviation of the hypothetical indefinite data collection is unknown, the definition can be tested used to verify TTim performance on analyzing confidence interval. Since the Student's t-distribution arises with when the sample size is small and population standard deviation is unknown, it is applied in this synthetic test. The degrees of freedom in this test is 68 (observation drawdowns of two wells), the factor is approximated as 2.

The same model is used and the random errors are still set to be normal distributed with mean zero and standard deviation of 0.02, 0.05 and 0.1. For each standard deviation, 1000 calibrations were conducted and it is determined whether the true value falls within the 95 % confidence interval calculated for each simulation results. The results are shown in Table 5.

Table 5: Number of true values located within the 95 % confidence interval.

standard deviation	0.02 m	0.05 m	0.1 m
k values within 95% interval	937	952	953
Ss values within 95% interval	937	951	945

The results show that the 95 % confidence interval calculated based on the standard errors returned by TTim contain the true value approximately 95 % of the time.

3.2 Test 1 Oude Korendijk

3.2.1 Basic information

Both methods for steady-state and transient flow are applied to analyze data from a pumping test conducted in the 'Oude Korendijk' polder, south of Rotterdam, The Netherlands (Wit, 1963). The lithological cross-section of the test site is shown in Figure 5. The first 18 m below the surface forms an almost impermeable confining layer. Between 18 m and 25 m below the surface lies the aquifer consisting of coarse sand with some gravel. The base of the aquifer consists of fine sandy and clayey sediments, which are also considered to be impermeable. The well screen was installed over the whole thickness of the aquifer. Piezometers were placed at distances of 0.8, 30, 90, 215 m away from the well. There are two extra piezometers at 30 and 215 m away from the pumping well screened at a depth of 30 m, which showed a small drawdown during pumping which indicated that the clay layer between 25 and 27 m is not completely impermeable. However, the assumption is that all water was withdrawn from the aquifer between 18 and 25 m and both the upper and lower layers are impermeable. Drawdowns during pumping are given for piezometers 30, 90 and 215 m (P_{30}, P_{90}, P_{215}) from the well in Table 30(Kruseman et al., 1970, p. 56). The well was pumped at a constant discharge of 788 m^3/d for nearly 14 hours.

3.2.2 Conceptualization and Simulation

Both steady-state and transient methods are applied to analyze given data. The drawdown in a confined aquifer can be computed as:

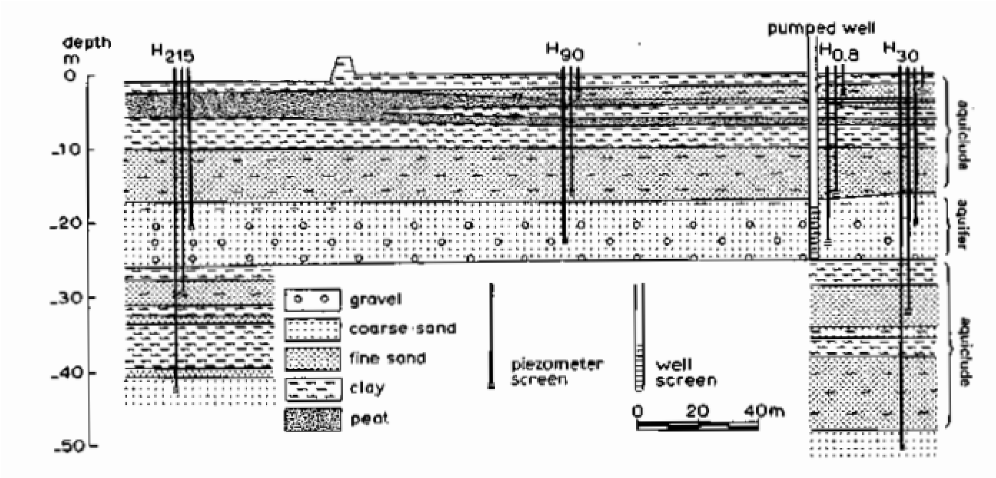


Figure 5: Lithological cross-section of the pumping-test site 'Oude Korendijk'(Kruseman et al., 1970, p. 56)

$$h(r,t) = -\frac{Q}{4\pi T} E_1(u) \tag{9}$$

where

$$u = \frac{r^2 S}{4T(t - t_0)} \tag{10}$$

and

$$E_1(u) = \int_u^\infty \frac{e^{-\tau}}{\tau} d\tau \tag{11}$$

where h [L] is the head in the aquifer layer, Q [L^3/T] is the discharge of the pumping well, T [L^2/T] and S [-] are the transmissivity and storage coefficient of the aquifer layer, r [L] is the distance between observation well and pumping well, t [T] is the time of calculated drawdown, and t_0 [T] is the start time of pumping.

For transmissivity, $T = kH$, where H [m] is the thickness of the aquifer, and k [m/d] is the hydraulic conductivity. The elastic storage S can be expressed in terms of specific storage Ss [1/m] and thickness H [m] as $S = SsH$. Approximations made for the derivation of the Theis solution are that the aquifer is confined, and the flow to the well is in unsteady state. While the well is assumed to penetrate the entire thickness of the aquifer, so that the flow to the well is horizontal in the aquifer. When the thickness of the aquifer is known and the well is pumping at a constant speed, parameter k and Ss determine the drawdown during observation. Thus, the accuracy of estimated hydraulic conductivity k and specific storage Ss are set to be criteria to evaluate the performance of different models.

Thiem's method is applied for steady-state and Theis's method is applied for groundwater flow under transient condition. This test is also simulated by TTim, MLU and AQTESOLV.

Data acquired from Oude Korendijk polder consists of drawdowns and related timings of three piezometers. Piezometers at 30 m (P_{30}) and 90 m (P_{90}) consists same number of drawdowns, while the water level in piezometer at 215 m away (P_{215}) started to decrease much later. The third set of data contains fewer measurements than the first two sets, and it also shows anomalous drawdown behaviour(Kruseman et al., 1970, p. 65), thus the data of P_{215} are excluded.

The conceptual model built by TTim is illustrated in Figure 6. Results calculated and modeled by different models are shown in Table 6. The transmissivity calculated using Thiem's equation based on drawdowns of P_{30} and P_{90} is 370 m^2/d. Divided by the thickness of the aquifer of 7 m, the hydraulic conductivity is 52.857 m/d as shown in Table 6.

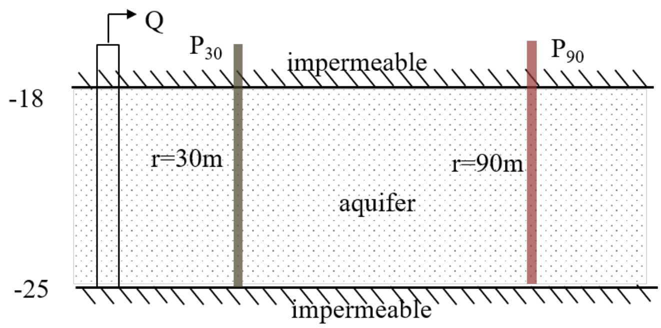


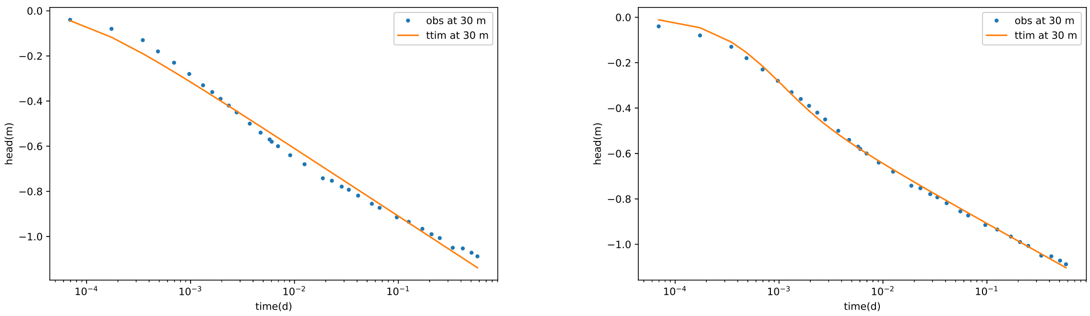
Figure 6: Conceptual model built for TTim.

Table 6: Results of different models.

	k [m/d]	95% ci	S_s [1/m]	95% ci	RMSE [m]
Thiem's	52.857	-	-	-	-
Theis's	66.088	4.957%	2.541E-05	18.777%	0.00603
TTim	66.088	5.008%	2.541E-05	18.904%	0.05006
AQTESOLV	66.086	4.946%	2.541E-05	18.735%	0.05006
MLU	66.850	5.069%	2.400E-05	19.452%	0.05083

TTim, MLU, and AQTESOLV calibrate the conceptual model using datasets of piezometers at 30 m and 90 m away from pumping well simultaneously. The fitted curves of calibration with two datasets simultaneously are shown in Figure

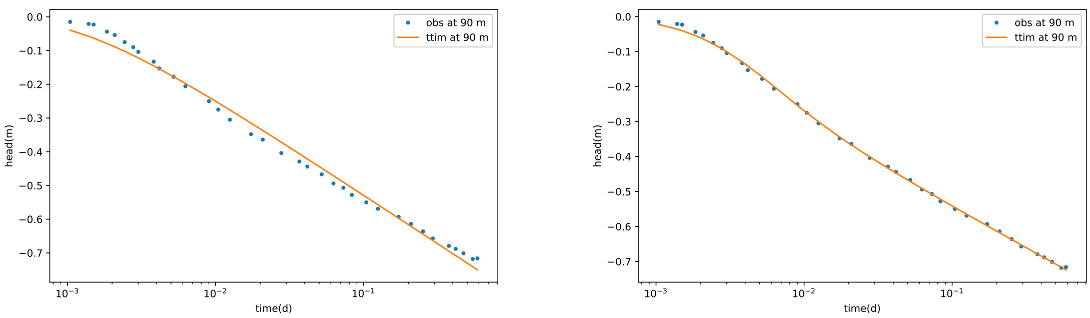
9. The wellbore storage factor r_c is also added trying to reduce the differences. The result shows that adding wellbore storage have little effect on improving model's performance. However, adding wellbore storage improve the fits when simulating two datasets respectively notably. Fitted curves for calibrations with two datasets respectively are shown in Figure 7 and Figure 8.



(a) model without r_c

(b) model with r_c

Figure 7: Fitted curves of piezometer 30 m away.



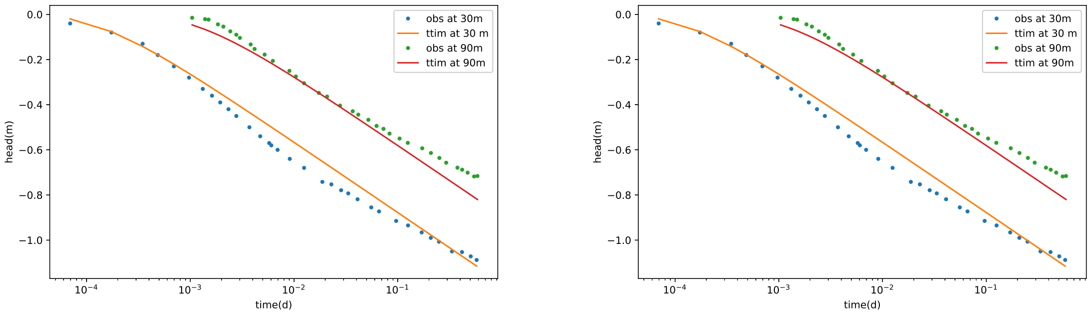
(a) model without r_c

(b) model with r_c

Figure 8: Fitted curves of piezometer 90 m away.

Theis's method has the smallest root-mean-square error. All other three models perform well and return stable estimated values for both hydraulic conductivity and specific storage. The 95% confidence interval given by TTim, MLU and AQTESOLV are also similar. MLU has a slightly larger RMSE than both TTim and AQTESOLV.

The result of Thiem's equation shows difference from other four methods. Thiem's equation requires that the drawdowns in two piezometers to be stablized.



(a) model without r_c (b) model with r_c

Figure 9: Fitted curves of two piezometers simultaneously.

If make a plot of drawdown against the corresponding time on a semi-log paper, Thiem's equation can only be applied when the curves of the two piezometers are parallel which indicates the flow can be considered to be at steady state. The curves of the two piezometers seems to start to run parallel approximately 10 minutes (Kruseman et al., 1970, p. 58), but it's still a rough estimation. Thiem's equation can be applied when the condition that the flow is in steady state is satisfied. When the difference of drawdowns of two piezometers stays constant, the flow can be considered as at steady state. The value of transmissivity calculated by Thiem's method does not match with results of other methods may be due to the short experimental time and the flow has not reached a steady state. The differences in the results may also be because of unaccurate approximations during drawing and reading graphs. Another probable explanation for the differences can be noticed in the drawdown data. Late-time drawdowns increase slower than the computed drawdowns which means the late-time data were likely affected by leakage.

Both methods for analyzing steady and transient flow in confined aquifers are applied in this test. Data from pumping test located at Oude Korendijk are used to examine the performance of TTim model. Through comparing of values for the hydraulic conductivity and specific storage simulated by TTim, MLU and AQTESOLV, the results agree well. All three models give a smaller relative confidence interval of hydraulic conductivity than for the specific storage. The root-mean-square errors of the three methods are also similar.

3.3 Test 2 Gridley

3.3.1 Basic information

Another pumping test for a confined aquifer is chosen to test TTim's performance. A pumping test was conducted on July 2, 1953, on a village well at Gridley, Illinois, as presented by Walton (1962). The pumping well (Well 3) fully penetrates through an 18-ft thick sand and gravel aquifer under confined conditions. Pumping was continued at a constant rate of 220 gallons-per-minute for about eight hours. The effects of Well 3 was measured in observation well 1, which is 824-ft away from the pumping well. The simplified cross section of the test site is presented in Figure 10. The time-drawdown data of one observation well (Well 1) is obtained from the example in AQTESOLV, while the time-drawdown data of the pumped well (Well 3) is obtained from the essay reported by Walton (1962), and both are presented in Table 31. The radius of both pumping well and observation well are assumed to be 0.5 ft according to the test done by AQTESOLV.

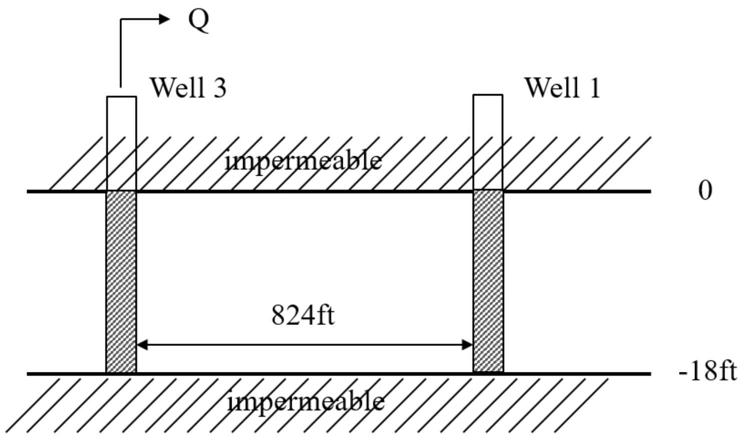


Figure 10: Simplified cross section of test site Gridley.

3.3.2 Conceptualization and Simulation

Walton (1962) reported values of transmissivity as 10,100 gal/d/ft and storativity as 2E-5 for the test using graphical solution. AQTESOLV, MLU and TTim are applied to the pumping test conducted at Gridley, and the accuracy of estimated hydraulic conductivity k and specific storage S_s , as well as the root mean squared errors, are set to be the criteria for evaluating the performance. The conceptual model consists of a one-aquifer system whose top boundary is confined. The bottom of the aquifer is also considered to be impermeable. This simple model applies to all three methods.

Since the well is fully penetrated, and the test is a one layer system. The conceptual model is built same as the cross section figure. Optimized parameters by different models are presented in Table 7. Fitted curve of TTim is shown in Figure 11.

Table 7: Parameters optimized with drawdown of Well 1.

	k [m/d]	95% ci	S_s [1/m]	95% ci	RMSE [m]
Walton	22.863	-	3.645E-06	-	-
AQTESOLV	22.429	2.065%	3.819E-06	6.759%	0.028
MLU	23.075	1.550%	3.536E-06	3.146%	0.022
TTim	22.434	1.985%	3.821E-06	3.886%	0.028

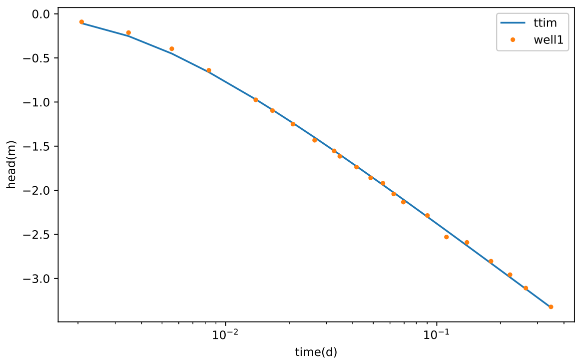


Figure 11: Fitted curve for Gridley using only data at Well 1.

According to the values of root mean squared errors, AQTESOLV and TTim have similar performance, while MLU reports the most accurate fit and the smallest confidence intervals for both hydraulic conductivity and specific storage. Compare AQTESOLV and TTim, TTim has a smaller confidence interval for specific storage, which indicates a smaller uncertainty. Generally, all four methods, including Walton's curve fitting solution, perform well on simulating confined single-aquifer systems.

When adding the time-drawdown data of the pumped well (Well 3), the accuracy of the simulation decreases significantly. A second optimization was carried out for the two datasets of both pumped well and observation well by all three methods. The optimized parameters are shown in the first three lines in Table 8.

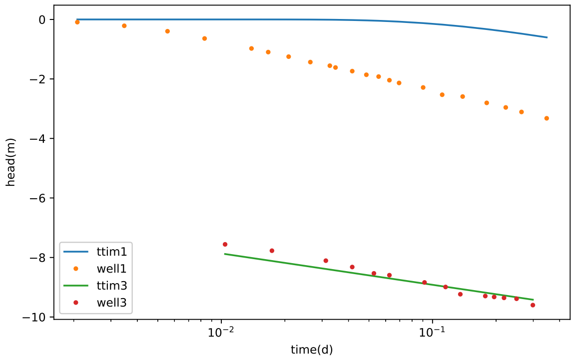
Three methods all have difficulty fittin two datasets simultaneously. MLU has a slightly better fit than AQTESOLV and TTim. Parameters well bore storage rc

Table 8: Parameters optimized with two datasets simultaneously.

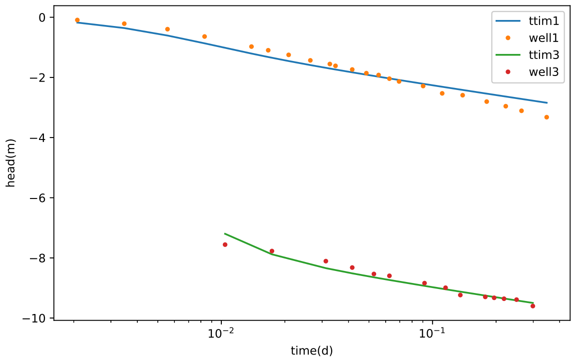
	k [m/d]	95% ci	S_s [1/m]	95% ci	RMSE
AQTESOLV	37.803	2.745%	1.356E-06	32.652%	0.270
MLU	38.094	2.622%	1.193E-06	31.230%	0.259
TTim	38.049	2.757%	1.247E-06	32.364%	0.272
TTim with rc	38.004	2.045%	8.939E-07	26.020%	0.190

and well skin resistance res are added to the conceptual model to improve TTim's performance. When adding both res and rc, the optimized value of res is very close to the minimum limit (zero). This indicates that adding res has little effect on the performance of the simulation. Thus, well screen resistance res is removed. The preference of only including rc also depends on the AIC values. The AIC value of model with both these two parameters is about -111.57. While the AIC value of model with only rc is about -113.69, which is two units smaller. The results presented in the fourth line in Table 8 only includes well bore storage rc. The value of optimized value of rc is 0.422 m, and the 95% confidence interval is 13.067%. The fitted curves of two simulations carried out by TTim are presented in Figure 12.

It can be seen that the second fitted curve is smoother, and fit the observations much better. The trend of early time predictions fits drawdown of Well 1 better, however, the late time fit is not satisfactory enough. For fitted curve of Well 3, the early time fitting shows slightly difference with the observations, while the late time fit performs well. More lithological information of the test site, as well as observed data, could help with the simulation.



(a) Fitted curves of first simulation by TTim.



(b) Fitted curves of second simulation by TTim.

Figure 12: Fitted curves for two datasets simultaneously of Gridley by TTim using data at Well 1 and Well 3.

3.4 Test 3 Sioux Flats

3.4.1 Basic information

Another test chosen to verify TTim's performance for confined aquifer is a pumping test conducted near Sioux Flats, South Dakota. The thickness of the aquifer is 50 ft, and both the overlying layer and underlying layer are considered to be impermeable. The test well was pumped at a constant rate of 2.7 ft^3/sec for 2045 minutes. Three observation wells are located 100, 200 and 400 ft away from the pumped well (OW1, OW2, and OW3), as presented in Figure 13.

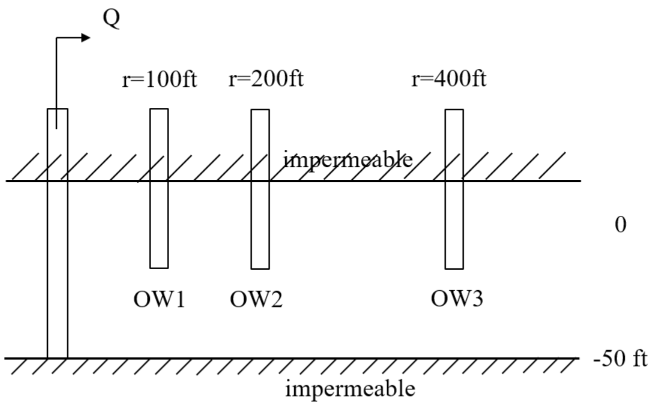


Figure 13: Simplified cross section of test site Sioux Flats.

Data obtained from an example of AQTESOLV consists of drawdowns and related timings of three observation wells, which are presented in Table 32. The radius of all pumping and observation wells are set to 0.5 ft.

3.4.2 Conceptualization and Simulation

TTim, MLU and AQTESOLV are all applied to analyze drawdown of the pumping test at 'Sioux Flats'. The conceptual model is built up as a one-layer aquifer with confined top boundary. Hydraulic conductivity k and specific storage Ss are optimized by three methods for all three piezometers simultaneously, and the results as well as root mean squared error are presented in Table 9.

Generally, AQTESOLV, MLU and TTim all perform well on simulating and predicting pumping test conducted at Sioux Flats. What stands out is that AQTESOLV has a smaller 95% confidence interval of both hydraulic conductivity and specific storage. It is unclear why that is.

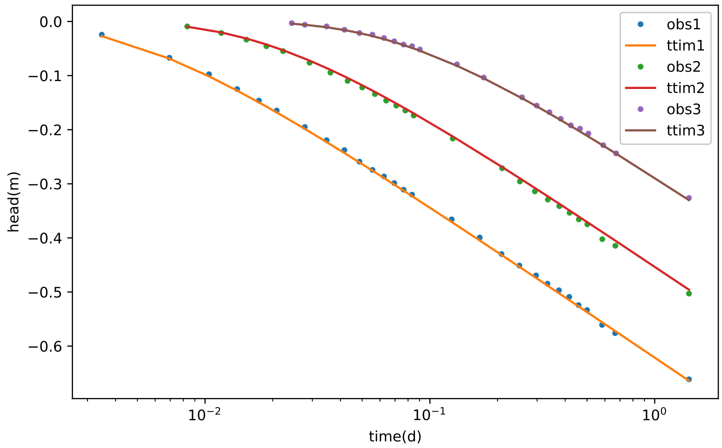
Well bore storage rc, as well as well skin resistance res are added to the conceptual model and optimized by TTim to improve model's performance, . However,

Table 9: Parameters optimized by different methods.

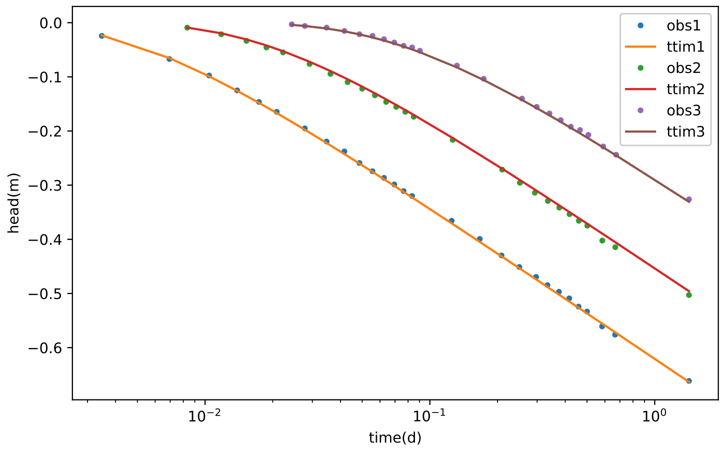
	k [m/d]	95% ci	Ss [1/m]	95% ci	RMSE [m]	AIC
AQTESOLV	282.659	0.394%	4.211E-03	1.539%	0.003925	-
MLU	282.684	0.783%	4.209E-03	1.530%	0.003974	-
TTim	282.795	0.805%	4.209E-03	1.590%	0.003974	-847.29
TTim with rc	283.923	0.905%	4.155E-03	2.112%	0.003885	-848.78

when adding both res and rc into calibration, the optimized value of res is about 1.2e-12, which is very close to the minimum value. Thus, it can be concluded that well skin resistance has no effect on improving conceptual model's performance. Wellbore storage plays a role instead. The best fit is obtained when the conceptual model has hydraulic conductivity, specific storage and wellbore storage as variables. The fitted curves of two simulations carried out by TTim are presented in Figure 14.

Both simulations fit the observed data of three piezometers very well. The fitted curves of second simulation are slightly smoother than that of the first simulation, especially for the very early observations of OW1. The optimized parameters are shown in Table 9 except for rc. The value of optimized rc is 0.790 m. The 95% confidence interval of rc is 53.815%. Although the accuracy of rc stays relatively large, the root mean squared error of second simulation carried by TTim is the smallest as shown in Table 9, which indicates a better fit. However, the AIC value of second model is only one unit smaller than the first one. This indicates that although calibrating rc may leads to a slightly better fit, it's not better enough to say that it's a better model. Thus, well bore storage should be removed.



(a) Fitted curves of TTim's first simualtion.



(b) Fitted curves of TTim's second simulation.

Figure 14: Fitted curves of TTim for test site Sioux Flats.

3.5 Test 4 Schroth

3.5.1 Basic information

Not many published aquifer tests deal with multi-layered aquifer systems. One multi-well aquifer test carried out at a site located about 60 kilometers east of San Francisco can be referred to as a fully confined two-aquifer system. The test was conducted to characterize one area of the site hydraulically and thus help to develop remediation strategies to alleviate the groundwater contamination (Brian et al., 1997).

The subsurface at the test site can be described as a heterogeneous mixture of gravel, sand, silt, and clay based on the information obtained from drilling logs and monitoring wells (Qualheim et al., 1988). There are three wells in the test site. Well $EW-712$ is the extraction well. Well $MW-201$ is an observation well screened in a shallower, unpumped aquifer directly above well $EW-712$. $MW-616$ is the other observation well located 46 m away from the extraction well in the pumped aquifer. Well $EW-712$ has a total depth of 56.7 m. Well $MW-616$ has a total depth of 57.3 m, while $MW-201$ is 64.3 m totally. A simplified cross section is presented in Figure 15. The layer in blue refers to the test layer.

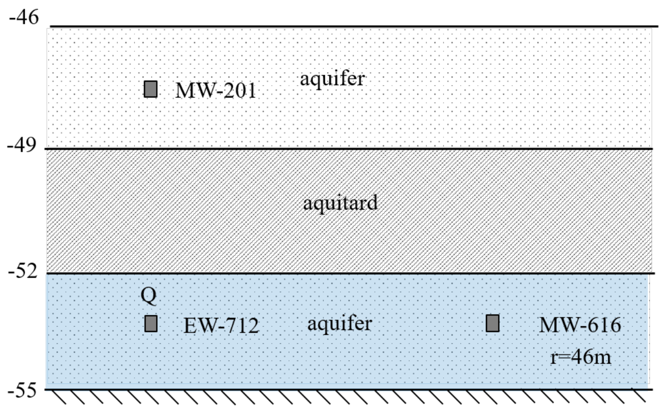


Figure 15: Simplified cross section of test site Schroth

The aquifers are separated by a 3 meter aquitard, and the upper aquifer can be considered to be confined by overlying aquitard. The average depth of the pumped aquifer is about 54 m below ground surface, and the prepumping water levels were at an average depth of about 20 m in all monitored wells. This means that water level reaches a height of 20 meters above the aquifer during the monitoring process. Thus, the assumption can be made that both the pumped aquifer and the unpumped aquifer are confined. The extraction well was pumped at a rate of 9.5E-4 m^3/s, while the rate was variable at very early times. The duration of the pumping was six-hours. Drawdowns were recorded for approximately 8 hours for the extraction well and two observation wells. However, only drawdown data of well $EW-712$ and well $MW-616$ are available in the example of MLU and given in appendix. Both the pumped well and the observation well have a radius of 0.05 m.

3.5.2 Conceptualization and Simulation

Brian et al. (1997) analyzed the drawdown data by type-curve matching method, and considered the situation as a one-aquifer system first. Then they applied finite-difference model for the radial flow and contained the upper aquifer and the aquitard sandwiched in between. The trial and error method was applied to find an acceptable match for six hydraulic parameters. The estimates of hydraulic conductivity and specific storage of the pumped aquifer are used as a starting point and the parameters of the aquitard and the upper aquifer are manipulated iteratively until the drawdowns at three wells are matched simultaneously. There is a gravel pack outside the wellbore as well as a damaged zone. Thus, the skin conductivity and specific storage are also simulated.

MLU analyzes the drawdown data with the log-drawdown-curve-fitting method to mitigate the effects of earlier variable pumping rate. MLU analyzes the pumping test as a three-layered aquifer system with all layer thicknesses assumed to be 3 meters, and the results presented in the tutorial are simulated using data from all three wells. The skin factor is also estimated to adjust for the effect of the gravel pack and the damaged zone. However, when the skin factor is optimized in MLU, it cannot be determined with any accuracy (Hemker and Randall, 2010, p. 32). Thus, to reproduce the solution found by Brian et al. (1997), the hydraulic conductivity of the pumped aquifer is set to be a fixed value as the estimated value of Brian et al. (1997). It is noted that the results presented in the tutorial of MLU are based on the simulations of all three wells, while the results presented in this report are reproduced based on only observations from two wells screened in the pumped aquifer. Thus, the optimized parameters and the conclusions may differ.

When applying TTim to the pumping test data, a single layer conceptual model is built at first. The thickness of the confined aquifer is set to 3 m. The wellbore storage and the well resistance are also optimized. The results are compared to which obtained from type-curve-matching method for one-layer system in Table 10.

The first simulation is carried out without both well bore storage rc and well skin resistance res. The model cannot fit the drawdown data well. When adding rc and res, the fit becomes much better, which can be told from changes of both root mean squared error and AIC values. The parameters optimized by TTim are

Table 10: Results of single layer system.

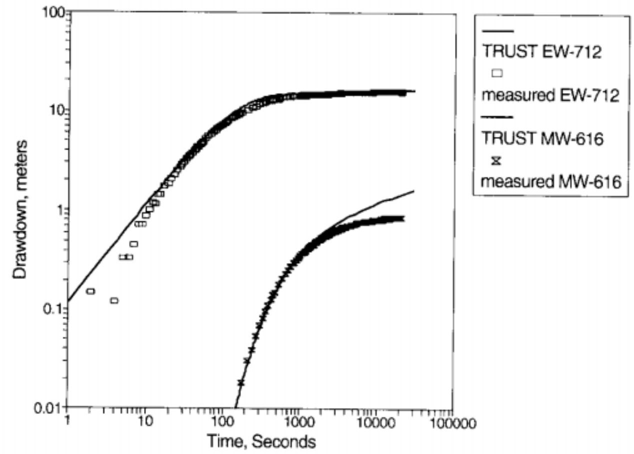
	S&N type-curve matching	TTim single layer	TTim single layer
k [m/d]	0.095	1.032	6.589
95% ci	-	20.299%	21.025%
S_s [1/m]		4.017E-02	4.867E-05
95% ci	5.000E-05	101.104%	48.905%
rc [m]	-	-	0.055
95% ci	-	-	1.943%
res	-	-	0.114
95% ci	-	-	9.271%
RMSE [m]	-	1.667703	0.181002
AIC	-	-44.92	-128.74

much different from the type-curve-matching method's result. The fitted curves are shown in Fig 16.

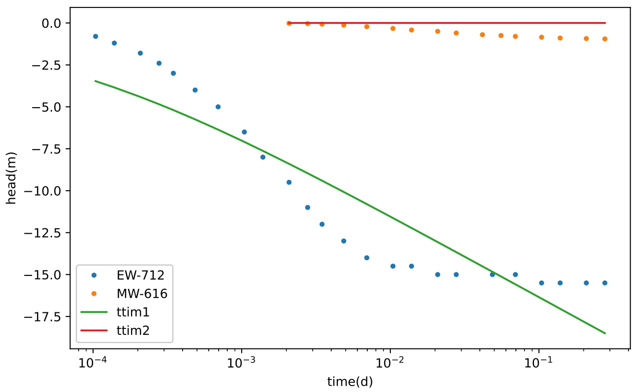
It is shown that fitted curves of single layer model of TTim perform much better when adding rc and res. An optimized three-layer conceptual model is created to account for the information of the upper aquifer. The first calibration is carried out with 6 unknown parameters (hydraulic conductivity and specific storage for the upper, and lower aquifer, and storativity and resistance of the aquitard). After that, to adjust for the gravel pack and damaged zone around the well, well bore storage and well skin resistance are added to the parameters to be optimized.

In this calibration, it is noticed that correlation between the specific storage of the two aquifers is 1, which indicates that overparameterization has happened. Meanwhile, the information of the upper aquifer is limited, and the drawdown data of the observation well screened in the unpumped aquifer are not available. There is less actual field data to simulate parameters of the upper aquifer. Thus, the third calibration is done using the estimated parameters in Brian et al. (1997) for the upper aquifer (hydraulic conductivity and specific storage) and the overlying aquitard (storage). All results of three calibrations are shown in Table 11.

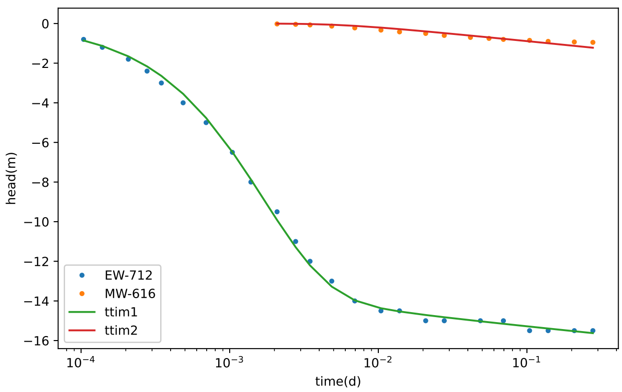
The first calibration done by TTim contains only 6 unknown parameters, and gives the worst performance. Several parameters have incredible values and the confidence intervals are extremely large. The results are not shown in Table 11. After adding well bore storage and well skin resistance, the performance improves significantly. Although some parameters still have incredible large uncertainties, the values of hydraulic conductivity and specific storage of the upper aquifer fall back in a reasonable range. And the value of root mean squared error reduces



(a) Fitted curves of Brian et al. (1997).



(b) Fitted curves of TTim with rc and res.



(c) Fitted curves of TTim with rc and res.

Figure 16: Fitted curves of single layer system.

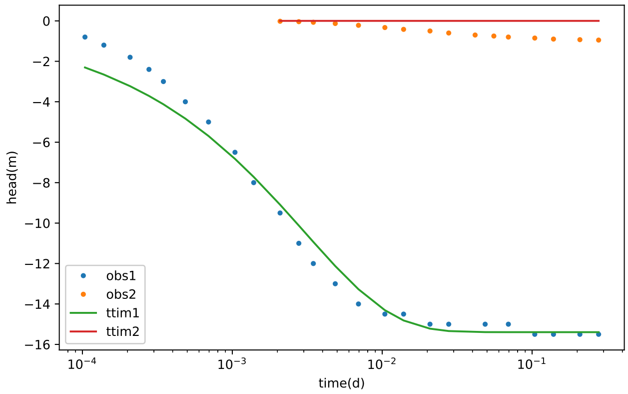
Table 11: Results of three-layered aquifer system.

	S&N	TTim with rc and res	TTim fixed upper layer	MLU
k_1 [m/d]	17.28	0.017	17.280	17.424
95% ci	-	131487%	fixed	124.160%
S_s1 [1/m]	1.2E-04	1.423	1.2E-04	6.027E-05
95% ci	-	163889%	fixed	1076.327%
k_2 [m/d]	3.456	1.530	1.934	1.747
95% ci	-	1607.452%	1.274%	4.521%
S_s2 [1/m]	1.5E-05	7.761E-04	1.317E-05	6.473E-06
95% ci	-	175746%	30.372%	16.107%
c [d]	-	3.296	239.732	216.000
95% ci	-	169947%	17.098%	111.944%
Sll [1/m]	3E-05	2.301E-03	3E-05	3.997E-05
95% ci	-	166489%	fixed	121.651%
rc [m]	-	0.052	0.053	-
95% ci	-	117.346%	1.549%	-
res	-	0.030	-	-
95% ci	-	98505%	-	-
RMSE [m]	-	0.407465	0.118764	0.24
AIC	-	-55.82	-162.45	-

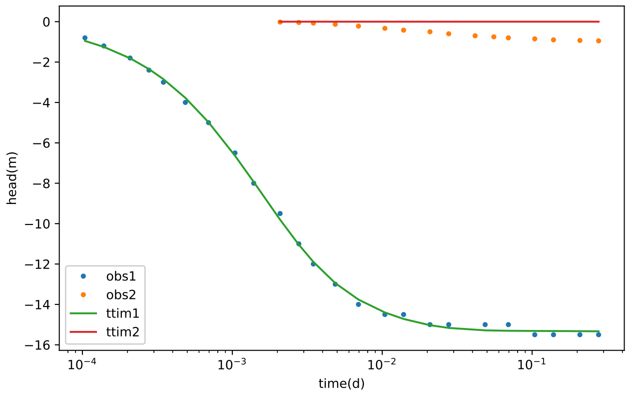
notably. The best fit is obtained when the hydraulic characters of upper system are fixed. When use estimated values of the hydraulic conductivity and specific storage of the upper aquifer as well as the specific storage of the aquitard, most of the parameters are in a stable range except for well skin resistance. The optimized value of the well skin resistance is close to the minimum value, which indicates that well skin resistance has little effect on the performance of the model. It can be found that MLU has a similar hydraulic conductivity of the upper aquifer compared to the curve matching method, however there are still large differences shown for other parameters. The accuracy analysis of MLU are also very large. The fitted curves of three TTim models are shown in Figure 17.

When adding well bore storage and well skin resistance, the fitted curves improve significantly as can be seen by comparing Figure 17a and Figure 17b. When the hydraulic parameters of the upper system are fixed, the fitted curves perform better on fitting the late time drawdowns. After six hours of pumping, the recovery was monitored for another two hours. If the recovery data are available, it could help with a better estimate.

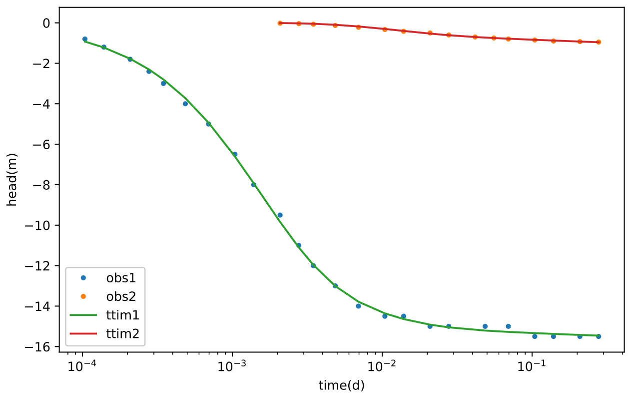
The simulation of the pumping test indicates that the lack of information of the upper system has a significant influence on simulating the underlying aquifer system. The existing unknown system above the pumped aquifer has a non-negligible influence.



(a) Fitted curves of 6 parameters.



(b) Fitted curves of 8 parameters.



(c) Fitted curves of fixed parameters for upper aquifer.

Figure 17: Fitted curves of TTim for three-layered system.

3.6 Test 5 Neveda

3.6.1 Basic information

Some aquifers consist of fractured rock, where water primarily flows through the cracks in the rock. It will be more complicated to study these kind of systems. Conventional equations introduced in former parts are developed mainly for homogeneous aquifers. It's not adequate to describe such a system using these equations. However, when the cracks and fractures are numerous enough and evenly distributed through rocks of very low permeability (the matrix), one approximation is that the fluid flow only occurs through the fractures and it will be similar to an unconsolidated homogeneous aquifer. The radial flow towards the well is considered to be entirely through the fractures, while water is allowed to flow into and out of the low permeable matrix.

The data from pumping test conducted in the fractured Tertiary volcanic rocks in the vicinity of Yucca Mountain at 'Neveda' site, U.S.A., are used for the following test. A pumping well and an observation well were drilled through sequences of fractures and welded rhyolitic, ash flow and bedded tuffs (Moench, 1984). The watertable was at a depth of 470 m below the ground surface. Simplified cross section of the aquifer system is shown as Figure 18.

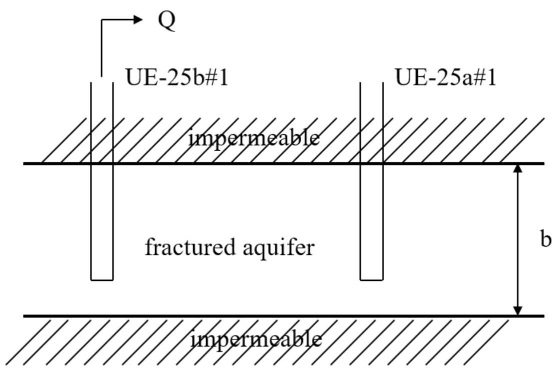


Figure 18: Simplified lithological cross section of test site Neveda.

More details of the geologic setting and rock physical properties of the area are given by Scott et al. (1982). Five major zones of water entry are observed to be over a depth interval of about 400 m. No significant head differences in these intervals under static conditions are found, which suggests good hydraulic connection between these zones. Well test data are available from the pumped well (UE-25b# 1) and the observation well (UE-25a# 1), which is located at 110 m from the pumped well. Both wells have a total depth of 1219 m. Three pumping tests were conducted at the test site. Drawdown data for both wells of the third test are shown in Table 34 and Table 35. The well radius is 0.11 m. The well was pumped at a constant rate of 3093.12 m^3/d for nearly three days. Cores samples show that most of the fractures are mineral-filled low-angle fractures and are coated with deposits of silica, manganese, and iron oxides, and calcite (Kruseman et al., 1970, p. 258).

3.6.2 Conceptualization and Simulation

Kruseman et al. (1970) analyze this test using a graphical method based on a linear interporosity flow model. The transmissivity for the double-porosity system is calculated as a whole, while the storativities for matrix and fracture are calculated separately as shown in Table 12.

MLU, AQTESOLV and TTim are applied to this pumping test. MLU simulates the pumping test by adding a very low-transmissivity aquifer to the top of the system representing the matrix blocks, separated from the fracture flow layer by a zero-storativity aquitard (Hemker and Randall, 2010). The aquitard governs the exchange of water between the fractures and the matrix. The transmissivity of the top layer is set to 0.1 m^2/d to simulate the low-transmissivity matrix. Casing radius of pumped well is set to 0.1 m. The storativity of the matrix is set to be a fixed value calculated by Kruseman et al. (1970) as 0.15 and the other three parameters (resistance of the fictional aquitard, transmissivity and storativity of fracture layer) are calibrated. The results reported in Hemker and Randall (2010) are calibrated with data from the pumped well. The same conceptual model is calibrated with both dataset of pumped well and observation well within this study, and the results are presented in Table 12.

AQTESOLV uses the analytical solution derived by Moench (1984) for predicting water-level displacements in a fractured aquifer assuming a double porosity model with slab-shaped matrix blocks where fracture skin and wellbore skin are included. The double-porosity system is treated as five matrix blocks. The fracture skin model proposed by Moench (1984) is a combination of both pseudo-steady state model and a transient model. The fracture skin factor is involved to represent the effect of a thin skin of low-permeability material deposited on the interface between rocks and fissures. Transmissivity and storativity for both matrix blocks and fractures are calibrated as well as the fracture skin factor. The results are shown in Table 12. The dimensionless fracture skin factor is calculated as 0.766.

The conceptual model simulated by TTim is set up consisting of a 400 m-layer aquifer with limited hydraulic conductivity representing the matrix block and a second 400 m-layer aquifer representing the fracture separated by a 1 m-aquitard with zero storativity as shown in Figure 19.

The first calibration only takes the resistance of aquitard, hydraulic conduc-

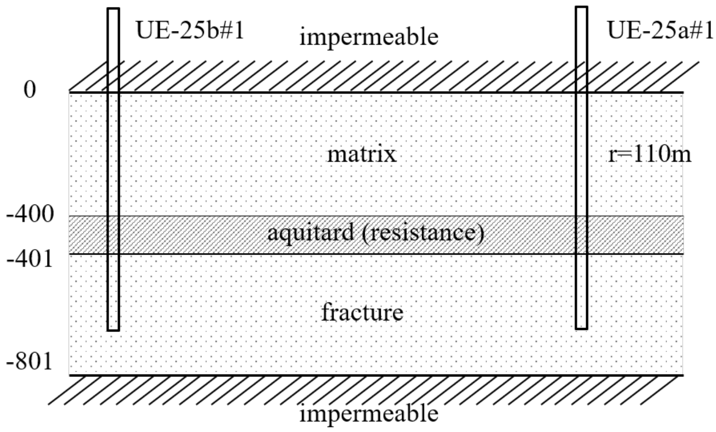


Figure 19: Conceptual model built for TTim.

tivity and specific storage of fracture layer into account. Drawdown of both UE-25b#1 and UE-25a#1 are applied. The specific storage of matrix layer are fixed as the result from Kruseman et al. (1970). Resistance of well skin is assumed to be negligible since the well was drilled using air and detergent, and the major zone in the pumped well contains no casing (Moench, 1984). Two prior production tests also have been conducted before the pumping test. Thus, the pumping well could be considered to be fully developed.

The second calibration is conducted including hydraulic conductivity and specific storage of both matrix and fracture layer. Calibrated parameters for two simulations can be found in Table 12. k_m and k_f represent hydraulic conductivity of matrix layer and fracture layer respectively. Ss_m and Ss_f are specific storage of matrix layer and fracture layer. Fitted curves of two simulations are presented in Figure 20 and Figure 21.

When parameters for the matrix are fixed, the hydraulic conductivity and specific storage simulated by MLU and TTim are similar, while TTim has a smaller RMSE as shown in Table 12. When hydraulic conductivity and specific storage for both matrix layer and fracture layer are calibrated, TTim has a more similar value for hydraulic conductivity of the fracture layer as AQTESOLV gives. TTim cannot estimate the uncertainty of the hydraulic conductivity of matrix layer no matter what initial values are given. According to report by Moench (1984), the parameters of the fracture layer are probably the most reliable. Hydraulic conductivity obtained for the matrix layer is subject to uncertainty, and is two to five orders of magnitude more than the results shown in Table 12. Generally, AQTESOLV has a fit with smaller RMSE, which may indicates that a detailed and slab-shaped conceptual model may fit the double porosity system better.

Table 12: Results of different methods of test site Neveda.

	K&dR	Moench	AQTESOLV	MLU	TTim1	TTim2
k_m [m/d]	0.8325	0.1728	0.149	0.00025	0.00025	7.208E-07
95% ci	-	-	291.236%	fixed	fixed	74118%
Ss_m [1/m]	3.750E-04	3.000E-04	5.512E-04	3.850E-04	3.850E-04	1.442E-04
95% ci	-	-	244.376%	fixed	fixed	20.444%
k_f [m/d]	0.8325	0.864	0.937	0.874	0.877	0.909
95% ci	-	-	1.946%	1.221%	1.594%	1.328%
Ss_f [1/m]	4.000E-06	1.500E-06	5.533E-06	8.053E-06	5.087E-06	3.388E-06
95% ci	-	-	8.527%	17.795%	19.920%	17.725%
c [d]	-	-	-	12.380	13.006	15.570
95% ci	-	-	-	24.604%	24.573%	18.496%
r_c [m]	-	-	0.11	0.1	0.109	0.109
95% ci	-	-	-	-	6.076%	4.666%
AIC	-	-	-	-	-437.37	-494.85
RMSE [m]	-	-	0.031736	0.434638	0.199156	0.159390

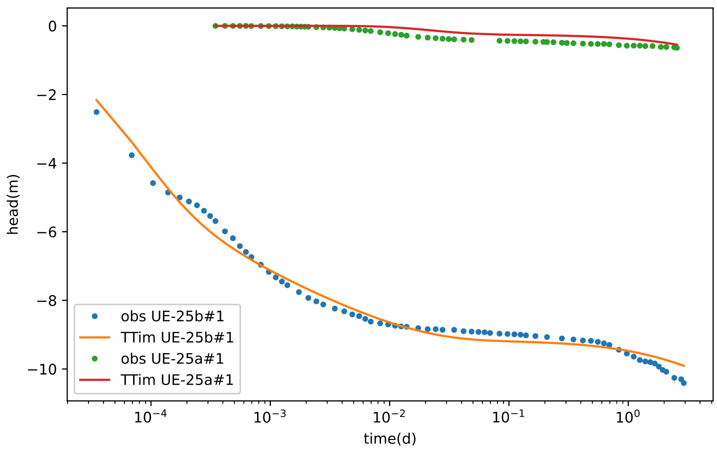


Figure 20: Fitted curves of TTim with calibrated parameters for fracture layer (TTim 1).

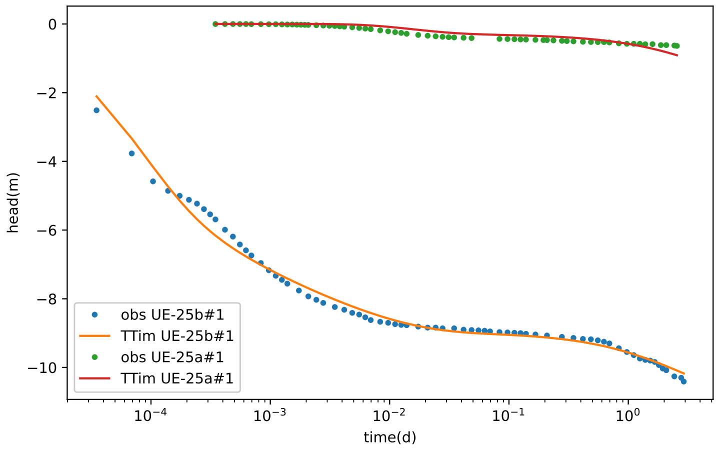


Figure 21: Fitted curves of TTim with calibrated parameters for both matrix and fracture layers (TTim 2).

4 Pumping tests for leaky aquifers

Most aquifers percolate more or less from above or below in practice. The overlying or underlying layers of an aquifer are seldom fully impermeable. When water is withdrawn from a well penetrated in a leaky aquifer, hydraulic gradient is created both in the aquifer itself and the aquitard overlying or underlying it. An important assumption under this situation is that the flow induced by the pumping is considered to be horizontal within the aquifer and vertical through the aquitard. The water not only comes from the storage of the pumped aquifer, but also contributed by the aquitard from the storage within it and leakage through it. Steady-state can be reached when the water primarily comes from the leakage as opposed to from storage, and the well discharge comes into equilibrium with the leakage. Until the steady-state flow is reached, the water withdrawn is derived both from leakage and storage of aquifer pumped.

Three tests conducted for leaky aquifer systems are simulated in this chapter, including two pumping tests and one recovery test. Simulation results of each test are compared to that of AQTESOLV or MLU and are presented in each section.

4.1 Test 6 Dalem

4.1.1 Basic information

Hantush's well function is applied to analyze data from a pumping test conducted at 'Dalem', The Netherlands. The lithostratigraphical section of the test site is shown in Figure 22. The pumping well is fitted with two screens, but only the upper screen, placed from 11 to 19 m below the surface, is unimpeded. The first 8 m below the surface is considered to be an aquitard. The aquifer locates between 8 m and 45 m below the surface. The layer underlying the aquifer is assumed to be an aquiclude. Four piezometers are located 30, 60, 90 and 120 m from the pumping well. The pumping lasted for 8 hours at a constant rate of 761 m^3/d. There is a river lying about 1500 m north of the test site. The level of the river as well as the piezometric surface of the aquifer are affected by the tide. Drawdowns corrected with the tide effect during pumping are given in Table 36(Kruseman et al., 1970, p. 84).

4.1.2 Conceptualization and Simulation

Hantush's well function is a solution of transient distribution of drawdown caused by pumping a well at a constant rate from a perfectly elastic aquifer of uniform thickness in which leakage takes place in proportion to the drawdown (Hantush and Jacob, 1955). The drawdown function is given by Equation 12:

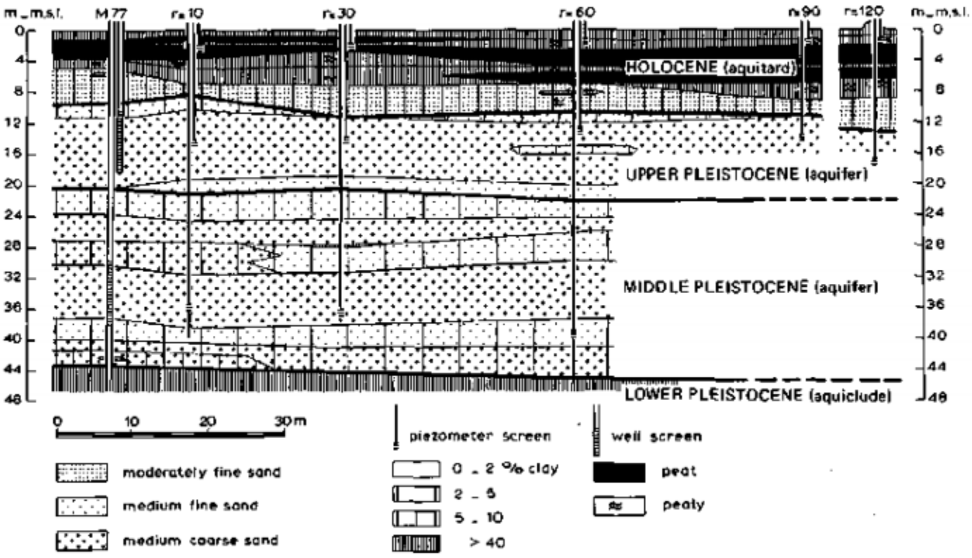


Figure 22: Lithological cross-section of the pumping-test site 'Dalem'(Kruseman et al., 1970, p. 75)

$$h = \frac{Q}{4\pi T} \int_u^\infty \frac{1}{y} \exp(-y - \frac{1}{y}(\frac{r}{2\lambda})^2) dy \tag{12}$$

with

$$u = \frac{r^2 S}{4Tt} \tag{13}$$

$$\lambda = \sqrt{Tc} \tag{14}$$

where Q [L^3/T] is the discharge of the pumping well, T [L^2/T] and Ss [-] are the transmissivity and storage coefficient of the aquifer, r [L] is the distance from pumping well to observation well, t [T] is time of calculated drawdown, and c [T] is the resistance of aquitard.

The aquifer thickness, pumping rate, distance to observation wells and collected drawdown data are known. The hydraulic conductivity k [L/T], specific storage Ss [L^{-1}], and aquitard resistance c [T] are estimated from the test. In addition to Hantush well function, MLU, AQTESOLV and TTim are applied to simulate this test.

When simulating a leaky aquifer system, most analytical solutions neglect the aquitard storage. Kruseman and de Ridder (1970) compared the results of different methods, and most of them assume no storage within aquitard. The initial simulations done with three methods assume no aquitard storage as well. The top boundary of the conceptual model is set to be leaky. The aquitard storage is set to be zero. Conceptual model is illustrated in Figure 23. Four datasets are simulated simultaneously with all four methods. The results are shown in Table 13. All values except for root-mean-square error are rounder to three decimal places. Note that confidence interval for resistance c simulated by AQTESOLV is not available because the uncertainty estimation results are given for leakage factor $1/B$, where $B = \sqrt{kHc}$.

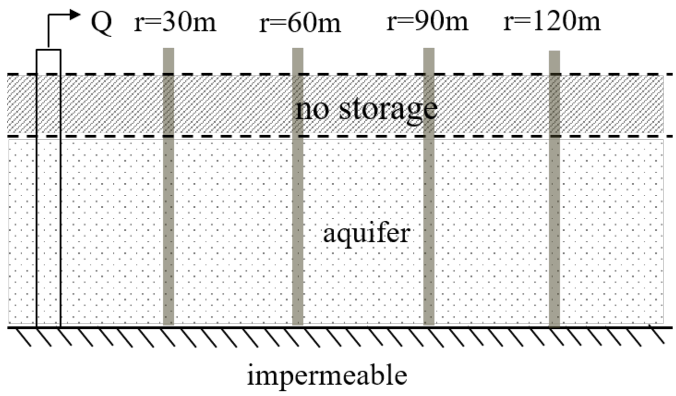


Figure 23: Conceptual model of first simulation.

Table 13: Results of different methods when only leakage considered.

	k [m/d]	95% ci	S_s [1/m]	95% ci	c [d]	95% ci	RMSE [m]
Hantush	45.332	5.194%	4.762E-05	12.977%	331.141	45.472%	0.005917
TTim	45.332	5.229%	4.762E-05	13.037%	331.171	46.012%	0.005917
MLU	45.303	5.202%	4.765E-05	12.955%	328.800	45.499%	0.005941
AQTESOLV	45.332	5.260%	4.762E-05	18.973%	331.043	-	0.005916

MLU, AQTESOLV and TTim all give relative good fits compared to simulation by Hantush's well function. AQTESOLV gives a larger confidence interval for specific storage of aquifer. It can be noticed that the relative confidence interval for resistance c is wider than other estimated parameters. The reason may be that the resistance of the aquitard arises with different locations. The thickness of each component in the top aquitard is not uniform, and this can also be seen in Figrue 22. Although the RMSE are small, when look into the fitted curves of TTim in Figure 24, the difference between predictions given by TTim and field data is significant. The model for piezometer at 120 m are too high, while the model for piezometer at 60 m is too low.

A second conceptual model is built up to verify if the storage within the aquitard will influence model's performance s shown in Figure 25. The top boundary of this model is impervious to ensure only aquitard storage with no leakage

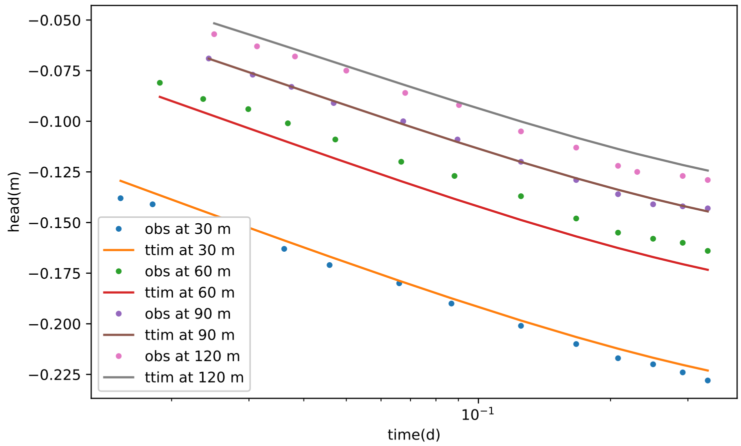


Figure 24: Fitted curves for aquifer test at Dalem.

is involved in the pumping test. A thin, fake aquifer with low-transmissivity is added to the top of the system. The specific storage of the fake aquifer is set to zero. Thus, only aquitard storage and underlying aquifer contribute to the water discharged from the pumping well. While for AQTESOLV, the top boundary cannot be defined separately, so the solution is chose to be Theis's method under confined situation. The results are shown in Table 14, where *Sll* represents the specific storage of aquitard. Since the Theis's method is applied in AQTESOLV, the aquitard storativity value is lacking.

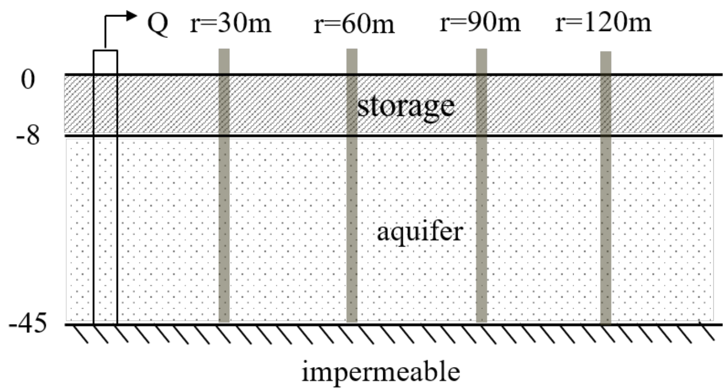


Figure 25: Conceptual model of second simulation.

The accuracy for resistance and aquitard specific storage cannot be obtained from both TTim and MLU. The correlation coefficient between aquitard specific

Table 14: Results of different methods when only storage considered.

	TTim	MLU	AQTESOLV
k [m/d]	45.186	45.186	49.286
95% ci	5.381%	5.314%	5.165%
S_s [1/m]	3.942E-05	3.941E-05	4.559E-05
95% ci	32.977%	17.202%	17.172%
Sll [1/m]	0.2112	3.611E-04	-
95% ci	339386%	107054%	-
c [d]	450483	769.200	745.156
95% ci	342867%	13445%	-
RMSE [m]	0.005895	0.005941	0.007245

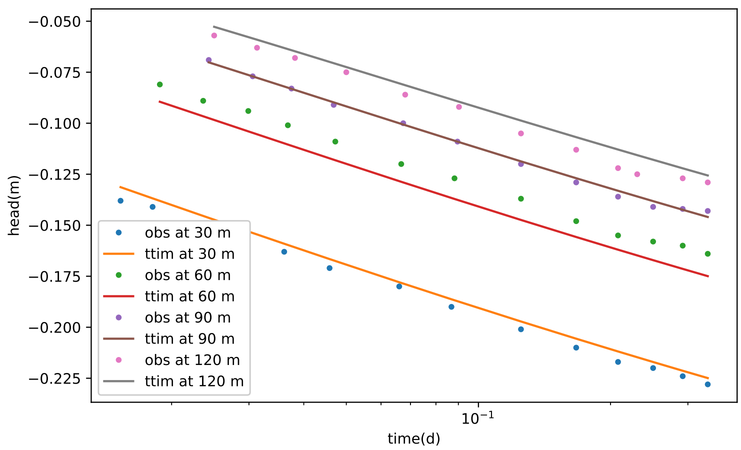


Figure 26: Fitted curves with impervious top for aquifer test at Dalem.

storage and aquitard resistance equals 1.00, which indicates a fully positive correlation. These two parameters can't be optimized simultaneously. The model is overparameterized, which results in increasing of uncertainties. Compared to results shown in Figure 13, the estimation of hydraulic conductivity remains accurate, while the estimations of specific storage of aquifer become different. The results of resistance show great difference as well. However, the root-mean-square errors of all three methods still indicate good fits, especially for TTim and MLU. The fitted curves of TTim are shown in Figure 26. Two different conceptual models fit the drawdown data almost equally well. The storage within aquitard also plays a role in pumping process. Thus, the third conceptual model with pervious top is built up. Both leakage and aquitard storage are considered.

The third conceptual model is almost same with the initial one. The difference is that the storage of aquitard is optimized during calibration instead of setting to zero. The third conceptual model is illustrated in Figure 27. The results of simulating model with both leakage and storage are shown in Table 15. The values of Sll and c are calculated from optimized parameters, thus the uncertainties are not presented in the table.

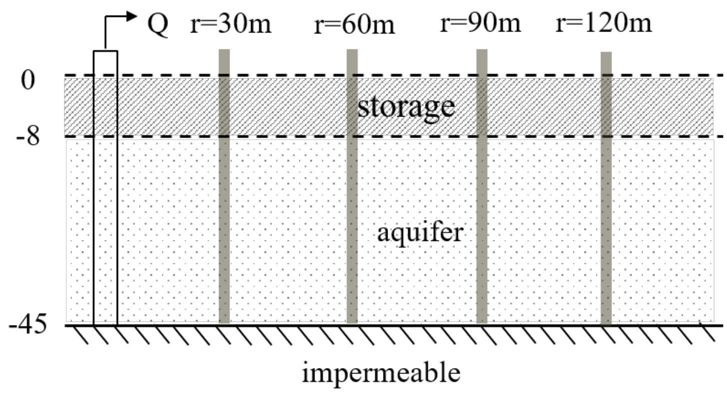


Figure 27: Conceptual model of third simulation.

The simulated values are slightly different than results of conceptual model with only leakage. The uncertainty estimation becomes more difficult. It is apparently that the effect of aquitard storage does exist but remains small. When the aquitard storage is eliminated, all three methods give good fits. While adding the aquitard storage into calibration, TTim gives a more stable estimation compared with MLU and AQTESOLV. Fitted curves of TTim for the model with both leakage and storage are shown in Figure 28.

It can be noticed that for all three fitted figures, the difference between field measurements and model predictions always exist. An additional test has been done to explore this phenomenon. The conceptual model with pervious top and

Table 15: Results of different methods when both leakage and storage considered.

	TTim	MLU	AQTESOLV
k [m/d]	45.161	45.335	45.169
95% ci	5.298%	5.399%	5.277%
S_s [1/m]	4.102E-05	4.668E-05	4.100E-05
95% ci	24.877%	458.830%	24.924%
Sll [1/m]	1.326E-04	1.284E-05	2.868E-05
95% ci	228.955%	93398%	-
c [d]	367.719	331.400	367.577
95% ci	79.877%	46.729%	-
RMSE [m]	0.005861	0.005941	0.005861

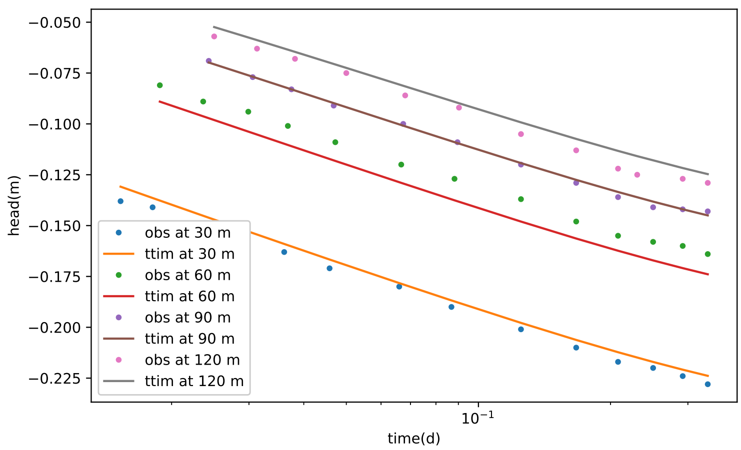


Figure 28: Fitted curves with both leakage and storage considered for aquifer test at Dalem.

no storage within aquitard is chose. The model is calibrated with each piezometer removed respectively. The results of optimized parameters and root-mean-squared errors are shown in Table 16.

Table 16: Results of TTim with each dataset removed respectively.

	k [m/d]	95% ci	Ss [1/m]	95% ci	c [d]	95% ci	RMSE [m]
Data at 30 m removed	57.558	4.496%	3.282E-05	13.212%	999904.474	285572%	0.00323
Data at 60 m removed	45.026	2.343%	4.409E-05	6.375%	349.123	15.178%	0.00263
Data at 90 m removed	45.205	6.482%	4.784E-05	17.150%	318.725	42.045%	0.00673
Data at 120 m removed	41.721	5.886%	5.784E-05	13.775%	180.967	42.288%	0.00541

The model gives better fit when the nearest two piezometers are removed, which indicates that the data of piezometers at 30 and 60 m away are likely inaccurate. When the data of piezometer 30 m away from the pumping well is eliminated, c can not be estimated with any certainty. The piezometers near the well might be influenced by the effects of the partial penetration of the well (Kruseman et al., 1970, p. 76). Another explanation for the difference could be the assumption that the aquifer is homogeneous, isotropic and of uniform thickness. However, it is obvious that the assumption could not be always reached for an aquifer made up of sand and gravel. Thus, the hydraulic characteristics of the aquifer system may vary with locations. As already stated by Neuman and Witherspoon (Neuman and Witherspoon, 1969), it is not sufficient to characterize a leaky system with only data of pumped aquifer. The drawdown of aquitard and of the overlying unpumped layer, whose watertable will not remain constant should also be contained within the simulations. An aquifer test with longer duration and more detailed information would likely help the estimation of a leaky system.

4.2 Test 7 Recovery test at Hardinxveld

4.2.1 Basic information

Recovery tests were conducted on wells at a water supply pumping station near the village of Hardinxveld-Giessendam (Netherlands) in 1981 to quantify the head loss of each pumping well caused by clogging and to assess the variation in transmissivity (Hemker and Randall, 2010). The aquifer system consists of two aquifers. The upper aquifer is 10 to 37 m below ground surface, and the second aquifer is present at a depth of 68 to 88 m shown by regional borehole information.

A simplified cross section of the test site is shown in Figure 29. The aquifer layer in blue refers to the test aquifer.

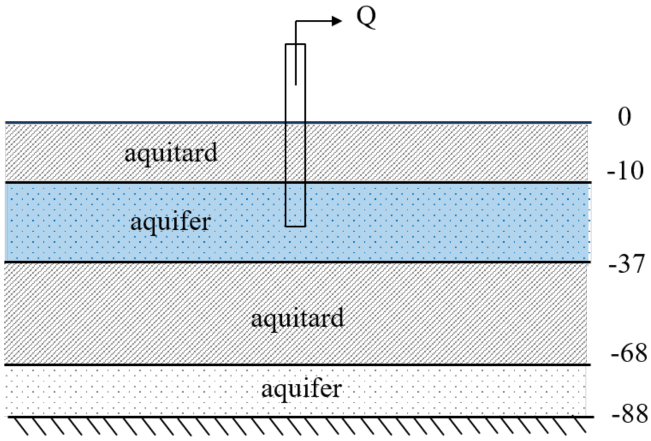


Figure 29: Simplified geographical cross section of test site Hardinxveld.

Five pumping wells are screened in the upper aquifer. Drawdown data of one of them is given in the example simulated by MLU. The well was pumped at a constant rate of 1848 m^3/d for 20 minutes. Drawdowns were measured in the well casing for a total of 50 minutes during and after pumping. Radius of the pumped well is 0.155 m. TTim and MLU are applied to the measured data. Hydraulic conductivity, specific storage, and well skin resistance are optimized. Drawdown data of the pumping well is presented in Table 37.

4.2.2 Conceptualization and Simulation

MLU simulates the model with both log drawdown curve fitting solution and linear curve fitting solution. The difference is that logarithms of measured and calculated heads is taken before computing the sum of squares of the residuals when the log drawdown curve fitting solution is selected (Hemker and Post, 2011). Log drawdown curve fitting is more appropriate when it is assumed that errors of drawdown measurements are not totally independent of their magnitude.

The skin effect is presented as skin factor [-] in MLU which is defined in Kruseman et al. (1970) as:

$$s_n = \frac{Q_n}{2\pi T_n} c_s \tag{15}$$

where s_n [m] is the drawdown in layer n caused by skin effect; Q_n [m^3/d] is the discharge of layer n; T_n [m^2/d] is the transmissivity of layer n and c_s [-] is the skin factor.

While in TTim the skin effect is realized by c_e [d], representing the entry resistance and can be converted to c_s in as follows:

$$c_s = \frac{T_n}{H_n r_w} c_e \tag{16}$$

where H_n [m] is the thickness of aquifer layer n and r_w [m] is the well radius.

The value of entry resistance shown in Table 17 for MLU is converted from the skin factor. Casing radius of well is fixed as 0.155 m. Results simulated by both solutions are presented in Table 17.

The first conceptual model built up for TTim is a two-aquifer system. There isn't much information about the deeper layers. Entered values for resistance of two aquitards and the underlying aquifer are provided by MLU, which is based on regional pumping test information (Hemker and Randall, 2010). The resistance of the two aquitards are set to 1000 d. The transmissivity of the second aquifer is 800 m^2/d, and the storativity is 0.001. Sensitivity testing for parameters of the lower aquifer will be conducted later. The second conceptual model adds well bore storage. Calibration of rc is very sensitive to the initial value. When the initial value is set to 1, the results are very uncertain. When giving the initial value as 0.1, the optimized rc is 0.0035, which is very close to the minimum limit. The root mean squared error of the model with rc stays the same, while the Akaike criteria increases from -358.06 to -356.06. Thus, the conceptual model without well bore storage is considered to be a better model for this test. A new conceptual model with the second lower aquifer removed is calibrated to test the sensitivity of the fixed parameters in the two-aquifer system model.

Results of theses models simulated by TTim are shown in Table 17. Fitted curves of TTim using the linear solution and the log solution are presented in Figure 30 and Figure 31 respectively.

Log drawdown curve fitting solution was chosen by MLU based on comparison of the results. Although both linear curve fitting and log curve fitting solutions fit the data well, log curve fitting returns slightly smaller root mean squared error. Also the accuracy of the measured drawdown during pumping is probably significantly less than the drawdown during recovery (Hemker and Randall, 2010). However, when apply log solution, the optimized specific storage does not have any uncertainty. The difference between values from MLU and TTim maybe due to fixed casing radius of model settings in MLU. When rc is fixed as 0.155 m, optimized values of TTim are similar with MLU's results.

Compare results of the two-aquifer system model to that of the single layer model, values of hydraulic conductivity and well skin resistance are similar. Two simulations have almost the same root mean squared error and AIC. This means values of the fixed parameters for lower aquifer do not have much influence on the model's performance. Simulation with log drawdown curve fitting solution returns

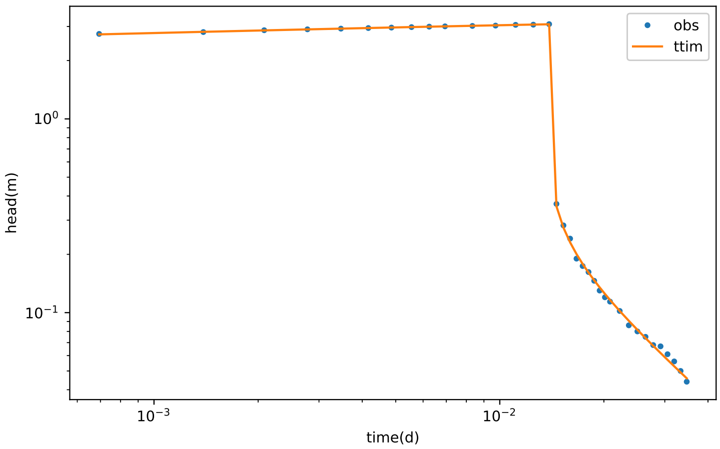


Figure 30: Fitted curves of linear solution by TTim for test at Hardinxveld.

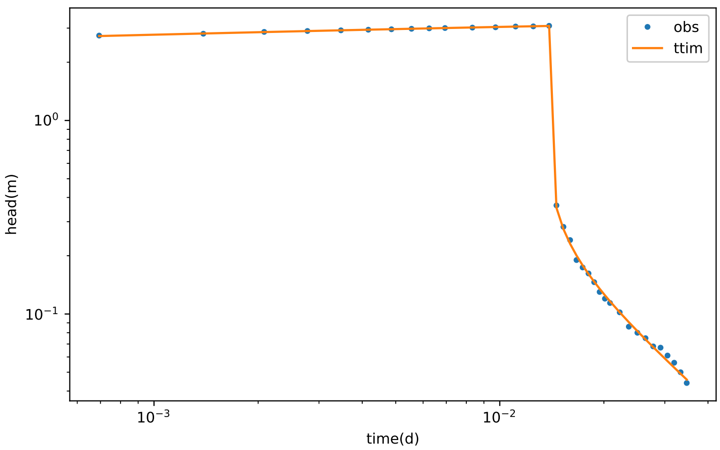


Figure 31: Fitted curves of log solution by TTim for test at Hardinxveld.

Table 17: Results of different methods for test at Hardinxveld.

	MLU-linear	MLU-log	TTim-linear	TTim-log	TTim-single
k [m/d]	51.530	48.938	44.528	45.299	44.552
95% ci	4.000	1.999	2.898	2.849	2.946
Ss [1/m]	1.358E-06	1.044E-05	6.391E-06	7.250E-06	3.231E-06
95% ci	26.000	184.000	30.467	19.666	30.547
res	0.019	0.022	0.016	0.017	0.015
95% ci	-	-	7.157	7.273	7.925
rc	0.155	0.155	-	-	-
AIC	-	-	-358.06	-301.44	-358.02
RMSE [m]	0.00845	0.00756	0.00551	0.01239	0.00551

similar values of the optimized parameters, however, both root mean squared error and AIC increases a lot compared to the simulation using linear solution. Thus, linear solution is a better choice for TTim simulation.

4.3 Test 8 Texas Hill

4.3.1 Basic information

The pumping test conducted at 'Texas Hill' is taken from AQTESOLV and simulated by TTim. The test well was screened at an aquifer overlain by a leaky aquitard. The bottom boundary of the aquifer is considered to be impermeable. The pumping lasted 420 minutes at a constant rate of 4488 gallons-per-minute. The thickness of the aquifer is set to 50 ft, and the thickness of the overlying aquitard is set to 20 ft according to the model settings of AQTESOLV. The pumped well has a radius of 0.5 ft. Three observation wells (OW1, OW2, OW3) were located 40, 80, and 160 ft north of the pumping well. The simplified lithological cross section of the test site is presented in Figure 32. Drawdown data measured at three observation wells are presented in Table 38.

4.3.2 Conceptualization and Simulation

AQTESOLV and TTim are applied to this test. AQTESOLV sets the casing radius as fixed to 0.5 ft, same as well radius. Hydraulic conductivity, specific storage of the aquifer, and resistance of the aquitard are calibrated. The solution developed by Hantush and Jacob (1955) is chosen for leaky confined aquifers. The

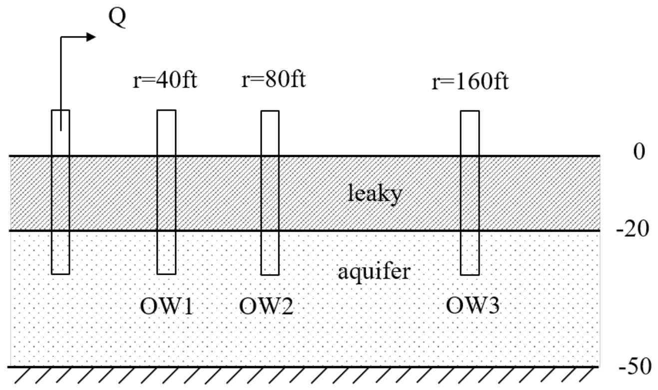


Figure 32: Simplified lithological cross section of test site at Texas Hill.

results are shown in Table 18. Confidence interval for resistance c is not available since estimated parameters of Hantush solution are transmissivity, storativity, and leakage parameter $1/B$, where $B = \sqrt{kHc}$.

The first conceptual model built for TTim contains four unknown parameters: hydraulic conductivity and specific storage of the aquifer, specific storage and resistance of the aquitard. The calibrated specific storage of the aquitard Sll is about 1.748E-06, which is very close to the minimum limit (zero). Thus, Sll is fixed to zero in the second conceptual model. The model is calibrated for three datasets simultaneously, and the root mean squared error of the second simulation is almost the same as that of the first one, while the Akaike value drops from -430.268 to -432.269. Thus the model with fixed Sll is considered to be a better model for this test. Results of the second simulation are shown in Table 18. Since well bore storage rc is fixed to 0.5 ft in AQTESOLV's simulation, a third conceptual model including well bore storage rc and well skin resistance res is built based on the second conceptual model to test if these two parameters have any effect on model performance. When adding both res and rc into calibration and set the minimum limits as zero, the calibrated res value is about 2.8E-08, which indicates that well screen resistance does not have much influence in the pumping process. Thus, res is removed, and the results of model adding rc are presented in Table 18.

As shown in Table 18, values of k, Ss, and c calibrated by TTim's first simulation are similar with that of AQTESOLV. When adding rc, all three parameters show a small difference. The root mean squared error decreases. Comparing fitted curves of two models in Figure 33 and Figure 34, although both models fit the data well, the fitted curves of the model with rc performs slightly better, especially with early timing observation data of OW2 and OW3. The preference for model with calibrated rc is also based on comparison of the AIC criteria. AIC of the third model is much lower than that of the second as shown in Table 18. The values

Table 18: Results of different methods for test at Texas Hill.

	AQTESOLV	TTim	TTim-rc
k [m/d]	224.723	224.635	227.477
95% ci	2.145%	2.196%	2.096%
Ss [1/m]	2.125E-04	2.133E-04	1.919E-04
95% ci	6.970%	7.111%	8.286%
c [d]	43.965	43.884	45.169
95% ci	-	14.291%	12.959%
rc [m]	0.1524	-	0.588
95% ci	fixed	-	20.999%
RMSE [m]	0.059627	0.060240	0.054110
AIC	-	-432.269	-447.012

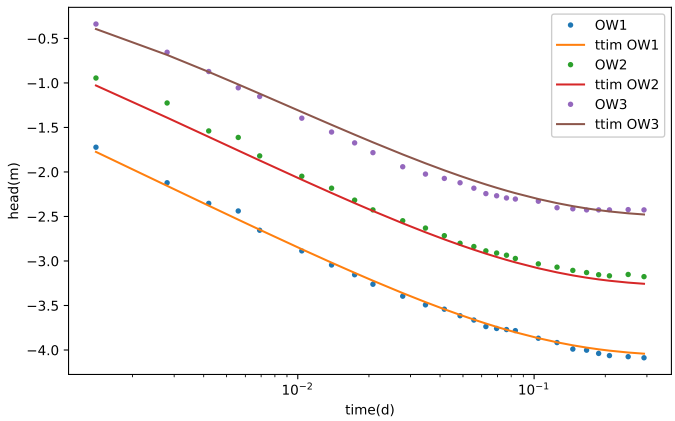


Figure 33: Fitted curves of TTim with fixed Sll.

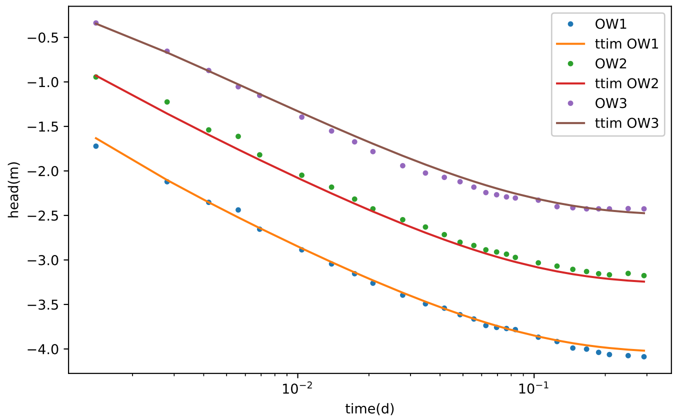


Figure 34: Fitted curves of TTim with rc and fixed Sll.

calibrated by AQTESOLV and the third model of TTim might differ because rc is fixed in AQTESOLV and cannot be added to calibration in AQTESOLV.

5 Pumping tests for unconfined aquifers

When pumping from an unconfined aquifer, a cone of depression in the water table is created and expands through time. Vertical components of flow towards the well are a distinguishing feature of pumping conducted in unconfined aquifers.

Time-drawdown curves usually show a S-shape if plotted on a log-log paper, which is called the delayed watertable response. The early-time segment reacts the same way as a confined aquifer. Water is released instantaneously from the expansion of water and the compaction of the aquifer, so the shape of this segment (usually only for the first few minutes) is similar to a Theis curve. The first steep segment is followed by a flat intermediate-time segment. The late-time segment is steep and reflects lowering of the water table. It is not possible for an unconfined aquifer under pumping to reach steady-state unless there is a source of water nearby. Two unconfined aquifer tests are simulated with TTim in this chapter.

5.1 Test 9 Vennebulten

5.1.1 Basic information

To verify TTim's performance on simulating unconfined aquifers, the data from pumping test 'Vennebulten' is used. Figure 35 shows the lithostratigraphical section of the pumping test conducted at 'Vennebulten'. The aquifer is made up of very coarse sands, and grades upward into very fine sand. The upper layer is made up of very fine sands and loamy sands until about 6 m below the ground surface. The remaining part of the aquifer is at a depth of around 6 to 21 m mainly consists of coarse sands as shown in the lithological section. The base consists of marine clay and is assumed to be impermeable. The screen of pumping well is placed between 10 and 21 m below ground surface. Four deep piezometers are placed at depths ranging from 12 to 19 m respectively. Four shallow piezometers are placed at a depth of about 3 m. Both deep and shallow piezometers are placed at distances of 10, 30, 90, and 280 m from the pumping well. The well was pumping at a constant rate of 873 m^3/d for 25 hours. The observed drawdowns of deep and shallow piezometers at 90 m are shown in Table 39.

5.1.2 Conceptualization and Simulation

The pumping test conducted at 'Vennebulten' is analyzed by MLU, AQTE-SOLV and TTim. Kruseman and de Ridder apply the Neuman cruve-fitting method and the result is compared to results from other methods. In their graphical analysis, only the drawdown data of the deep piezometer is used to estimate values of transmissivity, specific storage, vertical conductivity, and specific yield.

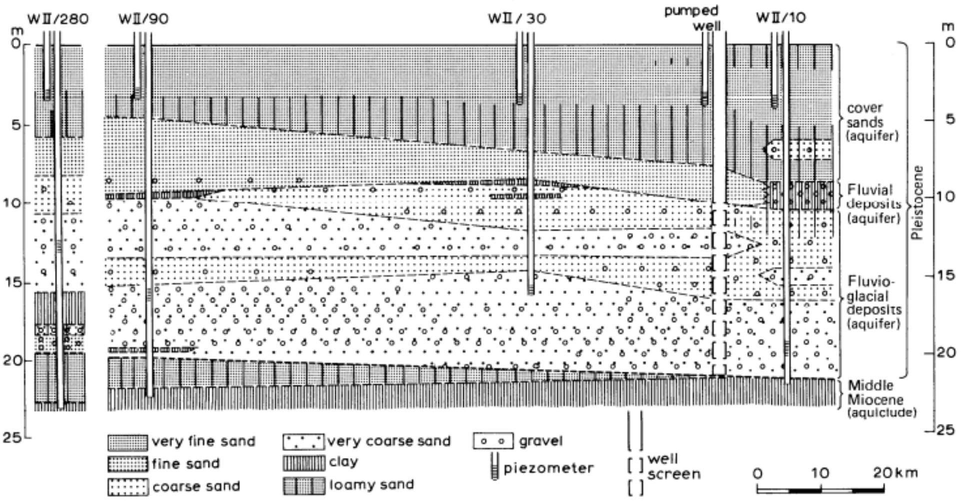


Figure 35: Lithostratigraphical section of pumping test site 'Vennebulten' (Kruseman et al., 1970).

The system is considered to be one 21 m unconfined aquifer. When AQTESOLV is used to analyze the pumping test data, the system is assumed to be one 21 m thick layer and the Neuman method is applied. Since the aquifer is not modeled as stratified, optimization is not possible when two sets of drawdown are applied at the same distance from the pumping well.

To simulate an unconfined top boundary, MLU sets up a two-layer model with a main aquifer and a 0.01 m water-table layer on top separated by a resistance layer (Hemker and Randall, 2010, p. 42). The first simulation only optimizes the specific yield of water-table layer, vertical hydraulic conductivity, transmissivity and specific storage of the main layer. Only drawdown data of the deep piezometer is applied for the first simulation. The predictions fit well for observed data of deep piezometer. However, when adding the shallow piezometer data to the graph, the predictions do not match the observations. A new optimization is conducted for both piezometers. The transmissivity of the top layer is optimized as well. The results for two simulations are shown in Table 19 and Table 20.

The first conceptual model is built as a one-aquifer system with an extra thin layer on top for TTim as shown in Figure 36. Only drawdown data of deep piezometer are applied. Fitted curves are presented in Figure 37. Table 19 summarizes results of different methods when only data of deep piezometer are applied.

After that, the one aquifer model is divided into 21 layers to analyze the datasets of two piezometers. The conceptual model is illustrated in Figure 38. The horizontal hydraulic conductivity k, phreatic storage S_y, elastic storage S_s, and vertical anisotropy k_z/k_h are optimized. The first simulation is done with

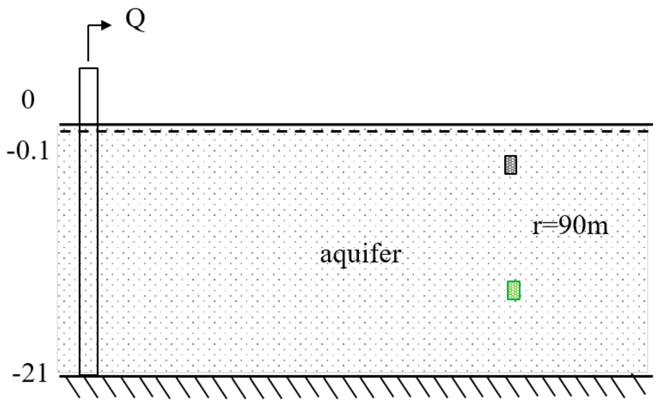


Figure 36: Conceptual model of first simulation.

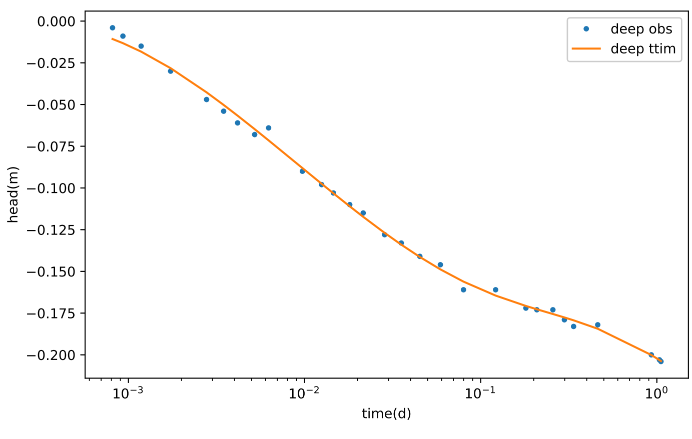


Figure 37: Fitted curves of single layer model by TTim.

Table 19: Results of different methods with data of deep piezometer.

	K&dR	AQTESOLV	MLU	TTim
k [m/d]	73	63.805	74.657	74.425
95% ci	-	9.583%	8.018%	8.271%
S_s [1/m]	2.476E-05	2.663E-05	2.767E-05	2.815E-05
95% ci	-	7.697%	8.699%	8.806%
S_y [-]	0.0050	0.0110	0.0050	0.0051
95% ci	-	32.717%	35.147%	36.164%
kz/kh	0.00055	0.00069	0.00074	0.00080
95% ci	-	42.950%	-	41.038%
RMSE [m]	-	0.003041	0.003216	0.003113

same hydraulic conductivity k and elastic storage S_s over the whole aquifer. The sallow piezometer is placed in the second layer, and the deep piezometer is placed in layer 16. The fitted curves are shown in Figure 39.

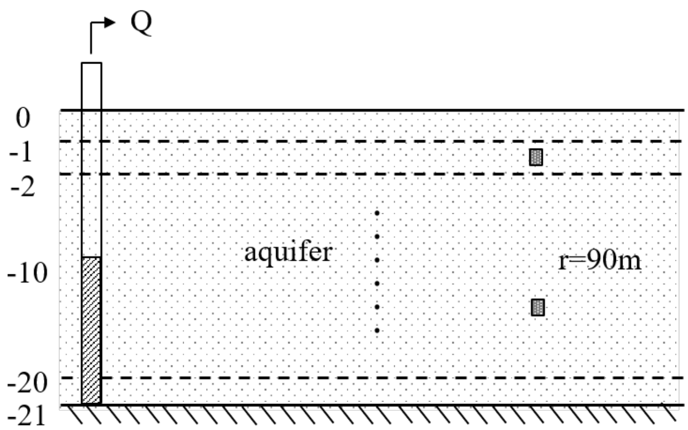


Figure 38: Conceptual model of second simulation.

Although the prediction curves follow the trend of observed drawdowns, they do not fit the observations very well. Separate storage values and hydraulic conductivity values are optimized for the very fine sands and coarse sands to improve the performance of simulation. The boundary is assumed to be 6 m below ground surface according to the lithological cross section. The third conceptual model is illustrated in Figure 40. The fitted curves for the renewed conceptual model are shown in Figure 41. The values of optimized parameters are shown in Table 20.

In order to facilitate comparison, the vertical hydraulic conductivity k_z simulated by K&dR and MLU are converted into anisotropy k_z/k_h. Since the value

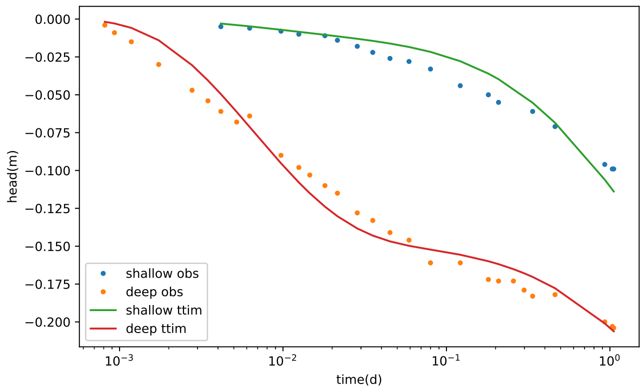


Figure 39: Fitted curves of multi layer model by TTim.

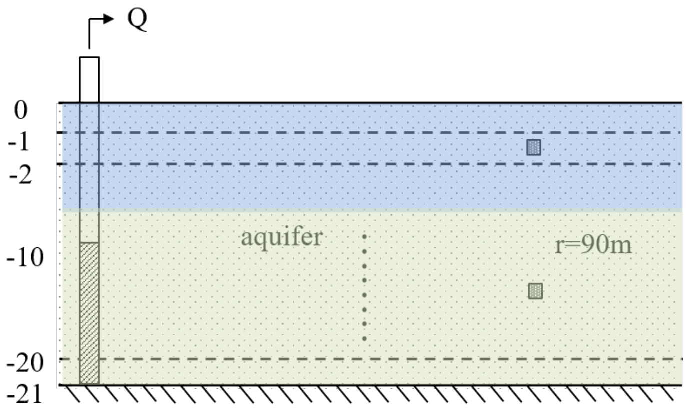


Figure 40: Conceptual model of third simualtion.

of horizontal hydraulic conductivity is involved in the calculation, which also has uncertainty, the confidence intervals for anisotropy of K&dR and MLU are not available.

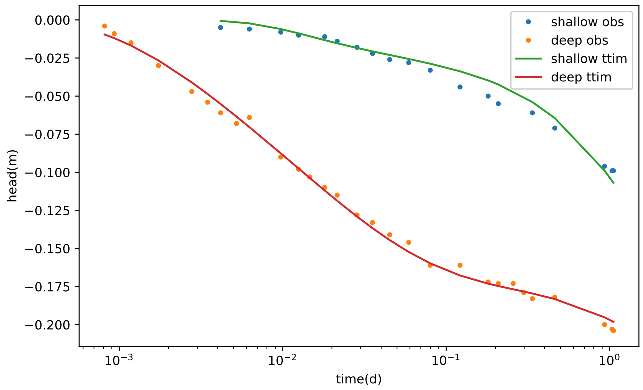


Figure 41: Fitted curves of stratified multi layer model by TTim.

Table 20: Results of multi layer model of TTim and renewed model of MLU.

	MLU	TTim	TTim-stratified
k_1 [m/d]	170000		0.776
95% ci	19.400%		341.955%
S_s1 [1/m]			5.531E-05
95% ci			111.777%
k_2 [m/d]	119.609	48.446	96.776
95% ci	14.469%	4.280%	18.820%
S_s2 [1/m]	5.325E-05	5.545E-05	4.154E-05
95% ci	8.867%	13.512%	13.793%
S_y [-]	0.0012	0.0304	0.0117
95% ci	58.161%	17.900%	56.453%
kz/kh	0.514	0.010	0.065
95% ci	-	0.248%	365.466%
RMSE [m]	0.003536	0.009595	0.004851
AIC	-	-438.070	-499.533

Of the models applied, none of the models can produce results that are completely consistent with all values in the book of K&dR. When only deep piezometer's data is applied, TTim gives similar results of all optimized parameters with MLU. AQTESOLV gives a relative close result as well. However, the results of two simulations carried out with multi layer model give totally different results and larger root mean squared errors. According to the root-mean-square errors simulated by each method, AQTESOLV, the first simulation of MLU, and simulation for one dataset of TTim all fit the observations well. However, the AIC value of first simulation carried out by TTim is about -326.78, which is much larger than the simulations of multi layer model. Stratified simulation has a much smaller AIC value compared to the AIC value of the former simulation for multi layer model.

An optimized conceptual three-layer model is applied with MLU for two times with different fixed parameters, and the results can be found in the tutorial Hemker and Randall (2010). According to the results simulated by the three-layer model of MLU, the values of the horizontal hydraulic conductivity are even larger than the results simulated by the two-layer conceptual model, which means more deviation from the results of Kruseman et al. (1970). This may because no basis for the assumed values of fixed parameters are available, which may results in inaccuracies.

With simulation of multi-layers of one aquifer, TTim is able to be applied for both shallow and deep piezometers located at the same distance. In this case, only data from two observation wells of eight are available. For further optimization, a more detailed stratified model could be built according to both the lithological cross section information and the screened length of the pumping well. More detailed conceptual model is theoretically able to produce better fit for observations, however, it may also be too complicated or overparameterization, which makes it harder to have an evaluation of the overall parameters at the site.

5.2 Test 10 Hypothetic test of Moench

5.2.1 Basic Information

Moench and Allen (1997) developed an analytical solution for flow to a partially penetrating well of finite diameter in a water table aquifer. Two years later, an identical hypothetical model was presented by Barlow and Moench (1999) to demonstrate the application of a computer program $WTAQ$. MLU checked model performance using the analytically derived drawdowns presented in the latter report. TTim is applied to the data to test the performance of simulating drawdowns in a vertically anisotropic water table aquifer in this study.

The position of the well screen and the locations of four piezometers are illustrated in a cross section of the hypothetical, homogeneous water table aquifer in Figure 42. Both the well radius and the casing radius are 0.1 m. The thickness of the saturated aquifer is 10 m. The pumped well is only screened from 5 m to 10 m below the initial water table. Four piezometers are located at two distances and two depths as shown in Table 21. Drawdowns for each of the four piezometers as well as the pumped well are given in Table 40.

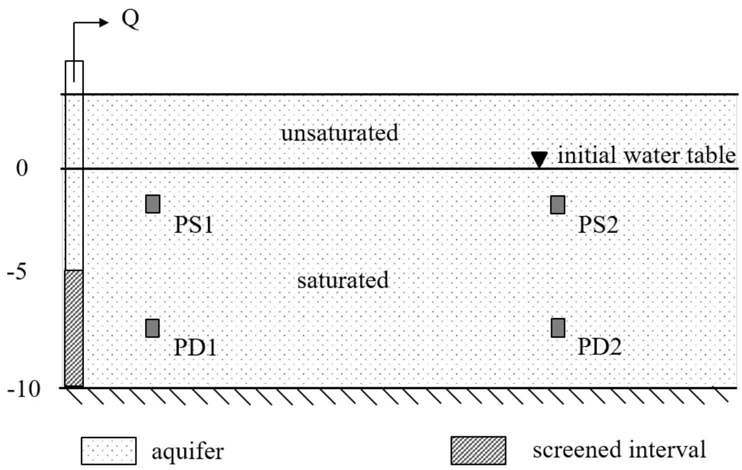


Figure 42: Cross section of the hypothetical aquifer.

Table 21: Locations of four piezometers in hypothetical aquifer.

Piezometer	Radial distance (m)	Depth below initial water table (m)
PD1	3.16	7.5
PD2	31.6	7.5
PS1	3.16	1.0
PS2	31.6	1.0

5.2.2 Conceptualization and Simulation

MLU first sets up a seven layer model. The aquifer is subdivided into layers of 2, 3, and 5 m thick, while an aquitard layer of zero thickness is inserted between every two aquifer layers. Afterwards, an eleventh layer model is added by MLU dividing the 5 m aquifer layer into 2, 1, and 2 m to increase the accuracy. Calculated hydraulic properties in Barlow and Moench (1999) are assigned as the hydraulic conductivity, specific storage, specific yield, and vertical anisotropy ratio of the model. The drawdown curves computed by MLU are compared to the analytical derived drawdowns of Barlow and Moench (1999) as shown in Figure 43.

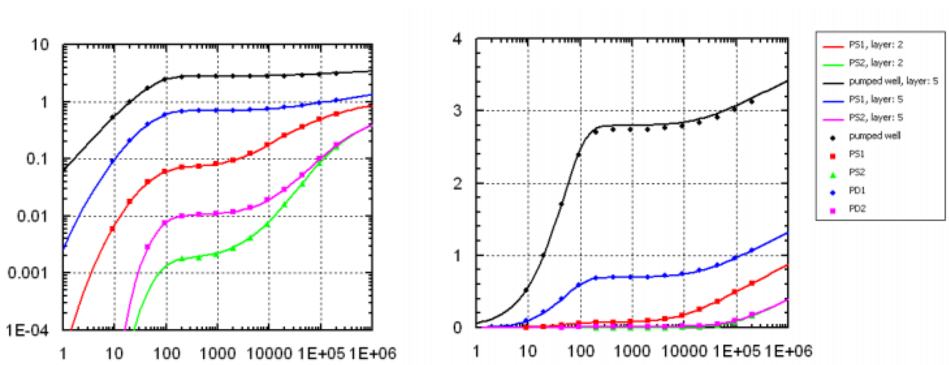


Figure 43: Computed drawdown of MLU (curves) and analysis solution (dots) (Barlow and Moench, 1999).

The conceptual model built up for TTim also consists of three layers with 2, 3, and 5 m thickness to keep the piezometers located in the middle of a sublayer, which is illustrated in Figure 44. An additional layer overlying the system is added to simulate aquifer with unconfined condition. The thickness of this layer is set to 0.1 m. Drawdowns presented in Table 40 are used as observations. Same hydraulic properties are applied in the model and generated drawdowns for the four piezometers and the pumped well are shown in Figure 45.

Generally, the conceptual model of TTim fits the drawdowns very well, however the flat segment of fitted curves for piezometer PD2 and PS2 are a little bit higher than the observations. The root mean squared error is calculated based on the difference between the calculated drawdowns and observations, and is presented in Table 22. Hydraulic conductivity, specific storage, and vertical anisotropy ratio are given different initial values and calibrated based on observations. The results are shown in Table 22. All four parameters show a little difference, while the root mean squared error decreases significantly from the model with fixed parameters. A new conceptual model is built up consisting of 18 layers as shown in Figure 46. Results are given in Table 22 as well. The fitted curves are plotted in semi-log

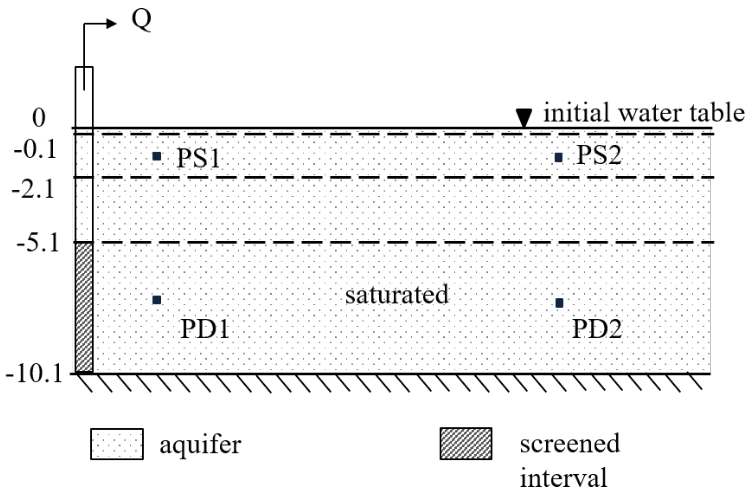


Figure 44: Conceptual model of first simulation.

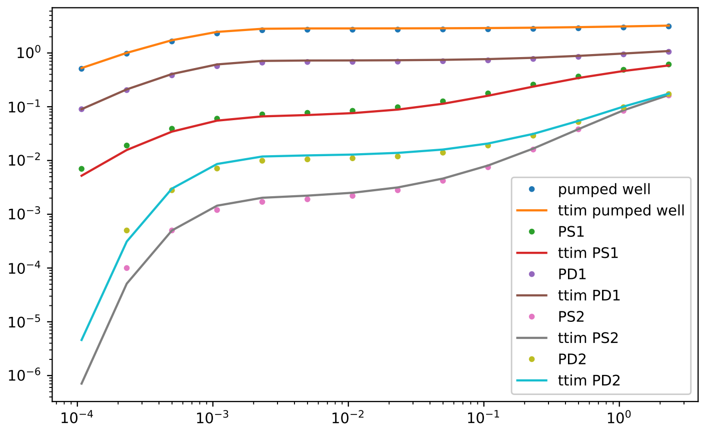


Figure 45: Computed drawdown of TTim (curves) and analysis solution (dots) (Barlow and Moench, 1999).

scale to show the difference between observations and calibrated drawdowns more clearly, except for Figure 45. Fitted curves of two simulations are shown in Figure 47 and Figure 48.

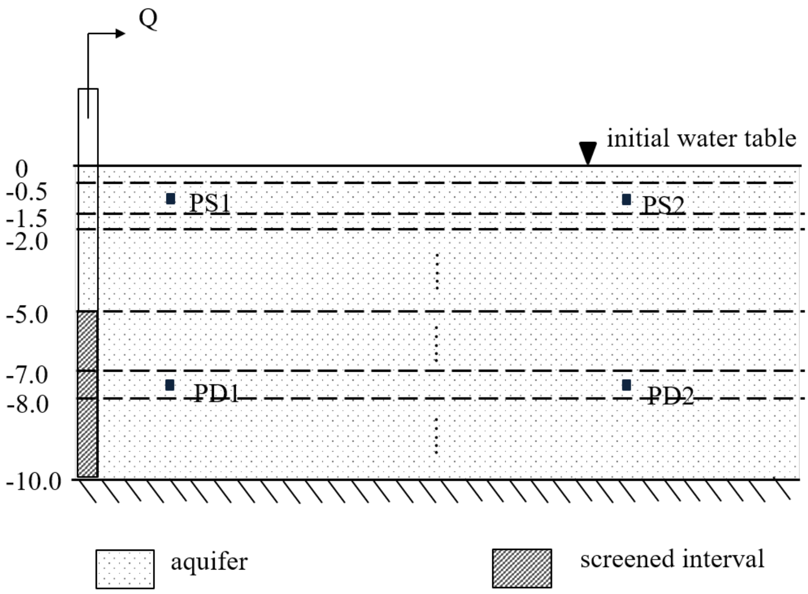


Figure 46: Conceptual model of second simulation.

Table 22: Calibrated parameters of different models for the hypothetical test.

	Moench	TTim	TTim-multi layer
k [m/d]	8.640	8.634	8.699
95% ci	-	1.042%	0.363%
Ss [1/m]	2E-05	2.050E-05	6.232E-05
95% ci	-	13.333%	6.514%
Sy [-]	0.2	0.203	0.192
95% ci	-	3.501%	3.828%
kz/kh [-]	0.5	0.603	0.481
95% ci	-	2.659%	3.126%
AIC	-	-617.570	-1674.675
RMSE [m]	0.007305	0.003752	0.009826

Comparing calibrated four parameters of two simulations, both the values and the confidence intervals are similar except for the specific storage. Curves of both simulations fit the observations very well. However, the AIC value of the multi layer model is significantly smaller than the three-layer model. Although the fitted curves are good enough for the observations, a more detailed model with more subdivided aquifer could be better.

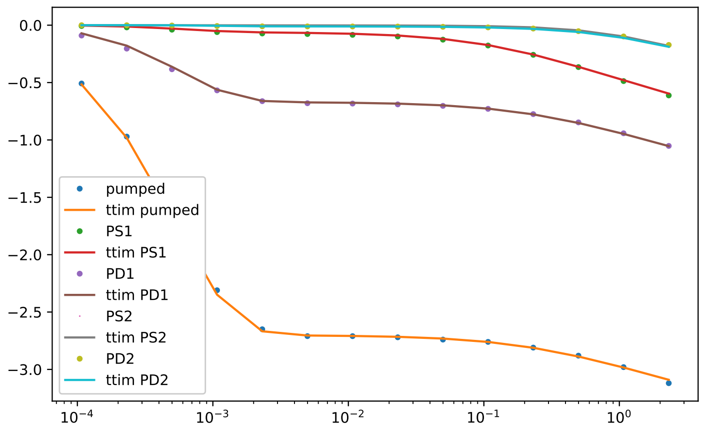


Figure 47: Simulated drawdown of TTim (curves) and analysis solution (dots) (Barlow and Moench, 1999).

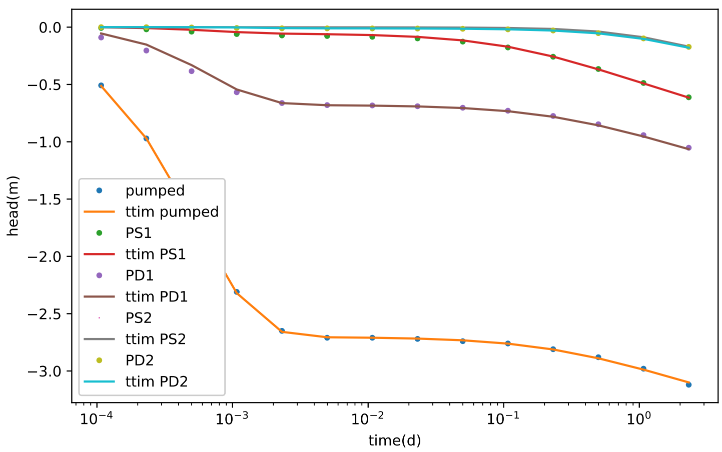


Figure 48: Simulated drawdown of TTim with stratified k (curves) and analysis solution (dots) (Barlow and Moench, 1999).

6 Slug tests

Pumping test are usually conducted in which water is withdrawn from controlled well at a constant rate and time-drawdown data of observation wells are measured to estimate hydraulic properties of aquifer and aquitard. Alternatively, a slug test can be performed since the equipment for conducting a slug test is much simpler and completion time of slug tests is usually much shorter. A small volume of water is suddenly removed or poured into the well, or a slug is suddenly added to raise the water level in the well when conducting a slug test. The rate of rise of water level or the rise and subsequent fall of the water level in the controlled well are measured. However, only characteristics of a small volume of aquifer surrounding the well can be determined by a slug test. While the result simulated by this area of aquifer material is probably disturbed by well drilling or construction (Kruseman et al., 1970).

Four slug tests are simulated with TTim in this chapter. The results are compared to either of AQTESOLV or MLU. Improvement of conceptual model is also carried out with TTim.

6.1 Test 11 Pratt County

6.1.1 Basic information

The information of slug test conducted at Pratt County Monitoring Site is presented by Butler (1998) and is simulated by TTim within this study. A partially penetrating well is screened in unconsolidated alluvial deposits, chiefly consisting of sand and gravel with interbedded clay (Butler Jr, 2019). Figure 49 presents the cross section of the test site, indicating the well screen depth. Table 23 summarizes details of test well construction. The slug displacement is 0.671 m.

Table 23: Well construction details.

Well Radius, rw (m)	Casing Radius, rc (m)	Screen Length, L(m)	Aquifer Thickness, b (m)	Depth to Top of Screen, d (m)
0.125	0.064	1.52	47.87	16.77

The initial displacement in the well can be converted to the volume of recharge by multiplying by the cross-sectional area of the well. Time-drawdown data of the test well is presented in Table 41.

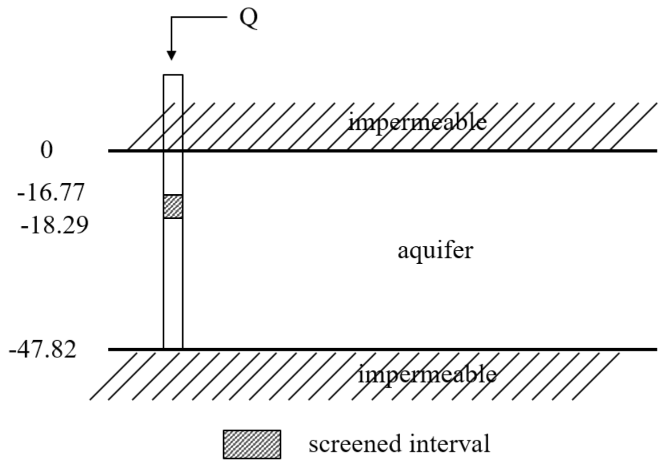


Figure 49: Cross section of test site at Pratt County.

6.1.2 Conceptualization and Simulation

AQTESOLV and TTim are applied to this slug test. The fully transient model reported by Hyder et al. (1994) (also known as KGS Model) is selected to be the solution for AQTESOLV, which is developed for overdamped slug test in confined aquifers for fully and partially penetrating wells. The outer radius of well skin is set to be the same as the well radius. Thus, the well skin effect is eliminated. The slug test is simulated by TTim with Model3D which aims at multi-layer model consisting of many aquifer layers. The first conceptual model is set up consisting of three layers: layer of well screen, overlying and underlying layers. The subdivision of aquifer is presented in Figure 50.

The top and bottom boundaries of the aquifer are impermeable. Parameters to be optimized are the horizontal hydraulic conductivity k and elastic storage S_s. Results from AQTESOLV and three-layer model of TTim are shown in Table 24. Fitted curves of AQTESOLV and TTim are presented in Figure 51.

Table 24: Results of different methods for test at Pratt County.

	k [m/d]	95% ci	S_s [1/m]	95% ci	AIC	RMSE
AQTESOLV	4.034	1.029	3.834E-04	13.865	-	0.002976
TTim-three layer	6.088	0.776	2.035E-04	9.167	-710.00	0.002873
TTim-multi layer	4.267	1.034	4.896E-04	13.071	-706.80	0.002949

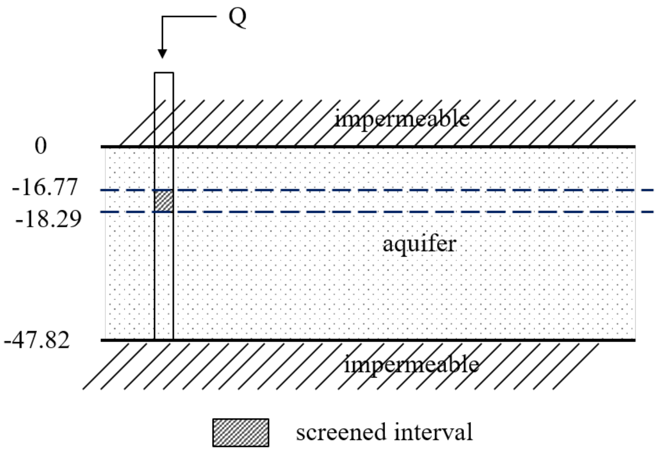
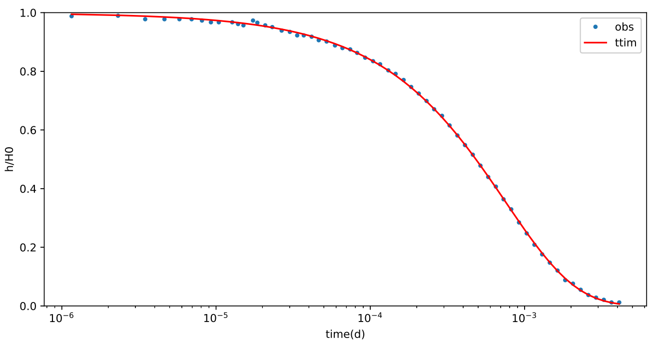
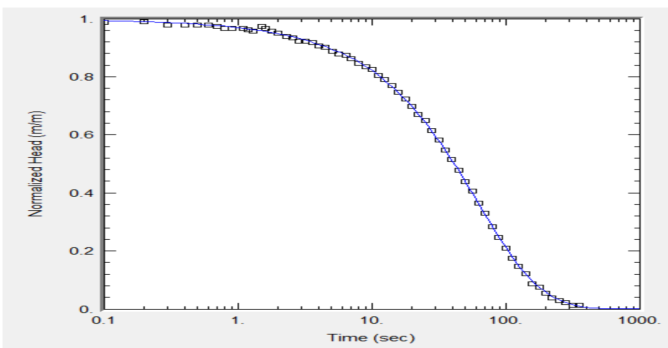


Figure 50: Conceptual model of three layer model.



(a) Fitted curve of three-layer model of TTim.



(b) Fitted curve of AQTESOLV.

Figure 51: Fitted curves for test site Pratt.

Comparing results of TTim three-layer model to that of AQTESOLV, three parameters all show significant differences. However, the fitted curve of both TTim and AQTESOLV give a very good fit. TTim gives smaller confidence intervals for both hydraulic conductivity and specific storage. A conceptual model with more layers of aquifer is built to assess the effect on the solution. The second model consists of fifty layers as shown in Figure 52.

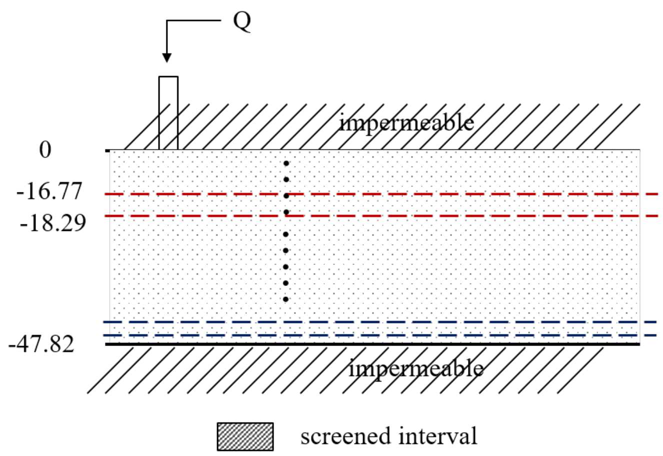


Figure 52: Conceptual model of multi layer model.

The thickness of each sub-layer is about 1 m. Because the top and bottom elevations of the screen are not integers, the thickness of sub-layers above and within the layer with screen are nearly 1 m, but not precisely 1m. Results of optimized values for k and Ss can be found in Table 24. The fitted curve of multi layer model is presented in Figure 53.

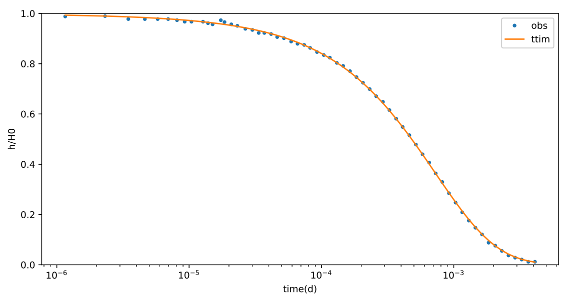


Figure 53: Fitted curve of multi layer model of TTim.

An additional test has been carried out to test if well screen resistance res has an effect on model performance. The res is added into calibration of second conceptual model. When adding res, the root mean squared error almost stays still, and the AIC value drops to -702.19. This indicates that model with fixed *res* as zero is a better model. Compare results of TTim's multi layer model to that of TTim's three layer model. The root mean squared error of increases slightly. The values of both hydraulic conductivity and specific storage of second simulation become similar with that given by AQTESOLV. Although both fitted curves from three-layer model and multi layer model fit observations well, AIC of multi layer model is four units larger than that of three layer model. Thus, the three layer model should be preferable for reflecting the real condition.

6.2 Test 12 Falling-head slug test

6.2.1 Basic information

The data of a falling-head slug test conducted in a sandy unconfined aquifer are presented by Batu (1998). The thickness of the saturated thickness is 32.57 ft, and the initial displacement of the well is 1.48 ft. Table 25 summarizes details of well construction. And the simplified cross section if shown in Figure 54.

Table 25: Well construction details.

Well Radius, rw (inches)	Casing Radius, rc (inches)	Screen Length, L (ft)	Depth to Top of Screen, d (ft)
5.0	2.0	13.80	0.47

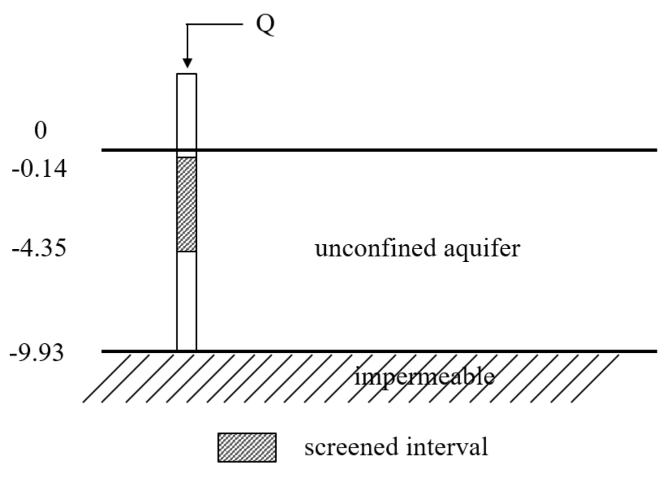


Figure 54: Simplified cross section of test site.

The discharge volume can be calculated by initial displacement and the casing radius. The depth-to-water measured from the test well are presented in following Table 42. The static depth-to-water recorded before the test is given as 10 ft. The given data can be converted to displacement by subtracting 10 ft from all of the measurements.

6.2.2 Conceptualization and Simulation

Both AQTESOLV and TTim are applied to this falling-head slug test. KGS Model solution for unconfined aquifers is selected for AQTESOLV. The well skin radius is set to be the same as the well radius. AQTESOLV does not consider the skin effect in the simulation. Model3D of TTim is chosen to be the basic model to simulate multi-layer aquifer system. The first conceptual model is a three-layer model consisting of overlying aquifer layer, underlying aquifer layer and the well screen aquifer layer (Figure 55). Both top and bottom boundaries of the system are impermeable. Horizontal hydraulic conductivity k and elastic storage Ss are unknown parameters and are optimized in the calibration. Optimized parameters and confidence intervals are presented in Table 26.

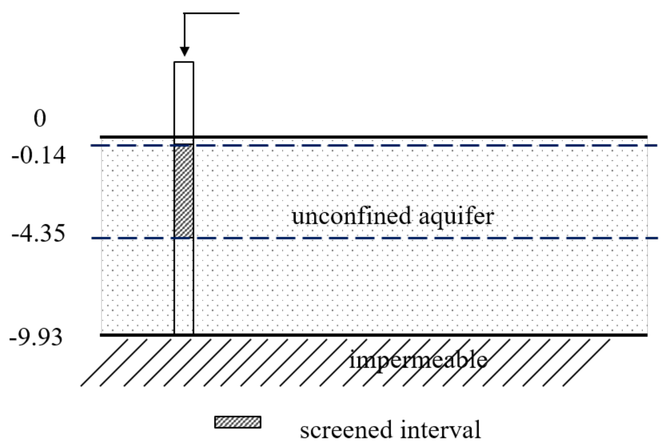


Figure 55: Conceptual model of three-layer model.

The values of hydraulic conductivity as well as the elastic storage deviate significantly from that of AQTESOLV. The optimized elastic storage gives large uncertainty. Also the root mean squared error of the three-layer model of TTim is much larger than that of AQTESOLV. A multi layer model is built consisting of 22 layers trying to improve the model's performance and is presented in Figure 56. Each layer has a thickness of 0.5 m. Hydraulic conductivity and elastic storage are calibrated.

Table 26: Optimized parameters with different conceptual models.

	k [m/d]	95% ci	Ss [1/m]	95% ci	AIC	RMSE
AQTESOLV	0.421	5.179	5.702E-04	15.345	-	0.005965
TTim-three-layer	1.335	8.847	2.147E-10	233.118	-212.00	0.018315
TTim-multi layer	0.495	3.114	4.062E-04	17.504	-2182.31	0.006340

The well resistance of the screen is added as well in an extra calibration. The optimized well skin resistance res is 0.0023, which is very close to the minimum limitation (zero) for the parameter. This indicates that res has little effect on model's performance. The AIC of the model with res is -2182.83, which is similar with the AIC value of model without well skin resistance. So that res is removed. The results of the optimized parameters are also shown in Table 26.

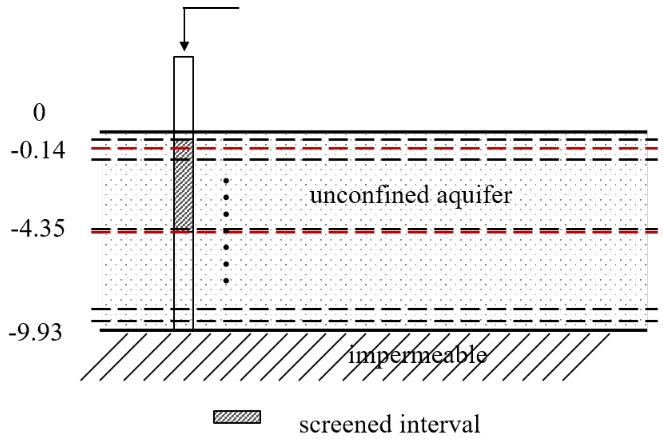
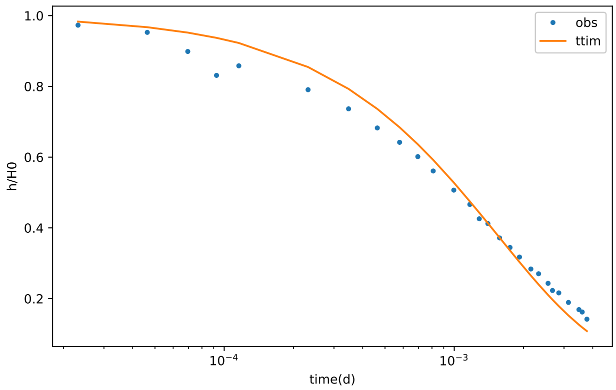


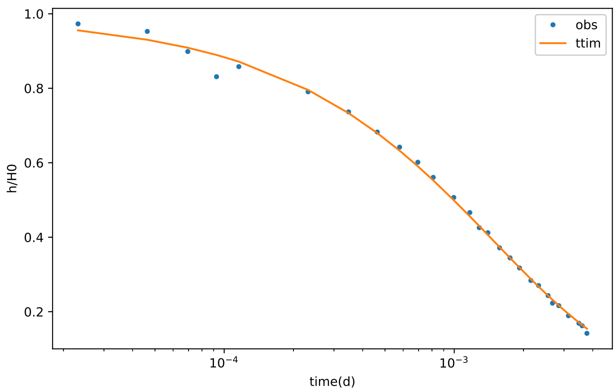
Figure 56: Conceptual model of multi layer model.

Fitted curves for single layer model and multi layer model of TTim are presented in Figure 57.

It can be told from significantly smaller root mean squared error that multi layer model performs much better on fitting observed data than the three-layer model. Both hydraulic conductivity and elastic storage are reasonable, and the confidence intervals decreases notably. The AIC also shows that the second conceptual model simulates this slug test much better than the former one. According to the site information, the aquifer system is under unconfined condition, but both conceptual models are set up with impermeable top boundaries, which may accounts for the little deviations of the fitted curves.



(a) Fitted curve of three-layer model of TTim.



(b) Fitted curve of multi layer model of TTim.

Figure 57: Fitted curve for falling-head slug test by TTim.

6.3 Test 13 Multi well slug test

6.3.1 Basic information

The data of a slug test conducted in a semiconsolidated sand aquifer in Lincoln County, Kansas are presented by Butler Jr and Liu (1997). An observation well (Ln-3) is located at a radial distance of 6.45 m from the test well (Ln-2). The thickness of the aquifer is 6.1 m. Both wells are fully penetrating, and the screened length are 6.1 m. Table 27 summarizes well construction details of the wells. The simplified cross section of test site is shown in Figure 58.

The initial displacement of the test well is 2.798 m. The discharge volume is computed by initial displacement and the casing radius of test well (Ln-2). Depth-

Table 27: Well radius information.

	well radius rw (m)	casing radius rc (m)
Ln-2	0.102	0.051
Ln-3	0.071	0.025

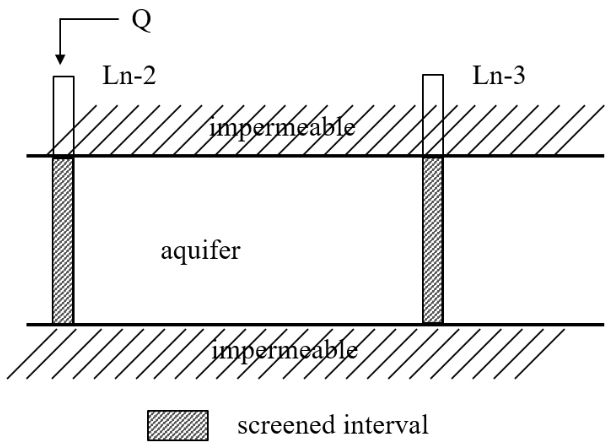


Figure 58: Simplified cross section of test site at Lincoln County.

to-water measurements of both wells are shown in Table 43.

6.3.2 Conceptualization and Simulation

AQTESOLV, MLU, and TTim are applied to this slug test. Hyder et al. (1994) developed a fully transient model, which is also known as KGS Model is selected as solution in AQTESOLV. The effect of well skin is eliminated by setting well skin radius to be the same as the well radius. Hydraulic conductivity and specific storage are calibrated. MLU simulates the slug test as a single confined aquifer system. The difference is that the skin factor of test well (Ln-2) is included into calibration. The calibrated skin factor is converted to well screen resistance res, and the results are shown in Table 28. Since the computation involves the value of calibrated hydraulic conductivity, the confidence interval for res is not provided in the table. TTim also sets up a single layer aquifer, first without well skin effect. The value of well screen resistance parameter res is fixed as zero, and only hydraulic conductivity and specific storage are calibrated, and the results are similar to that of AQTESOLV as shown in Table 28. Fitted curves of this simulation is presented as Figure 59. Since the introduction for this slug test does not provide any information for the casing radius. Although the fitted curves of this simulation give a very good fit, a second simulation is carried out adding well screen resistance res into calibration. The results of the second simulation are also provided in Table 28. Fitted curves of two simulations carried out by TTim are presented in Figure 59 and Figure 60.

Table 28: Results of different methods for test site Lincoln County.

	AQTESOLV	MLU	TTim	TTim-res
k [m/d]	1.166	1.311	1.166	1.242
95% ci	0.503%	1.918%	0.503%	1.766%
Ss [1/m]	9.368E-06	8.197E-06	9.382E-06	9.046E-06
95% ci	2.472%	2.706%	2.470%	2.428%
res	0	0.025	0	0.023
95% ci	fixed	-	fixed	26.372%
AIC	-	-	-1480.51	-1527.30
RMSE [m]	0.010373	0.009151	0.010236	0.008805

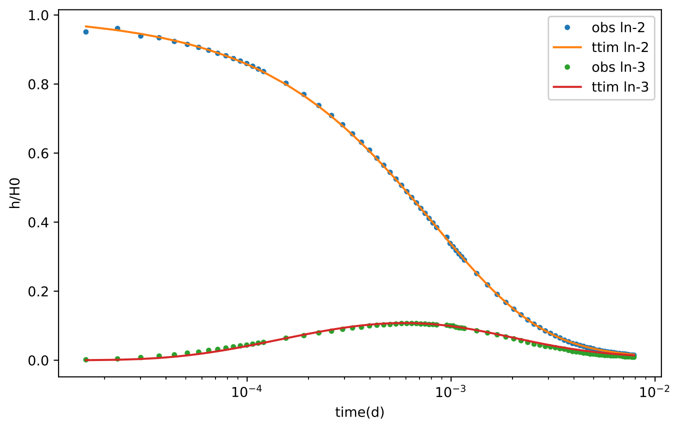


Figure 59: Fitted curves of model by TTim.

As shown in Table 28, the calibrated parameters of model with res are closer to that of MLU comparing to the results of AQTESOLV which does not consider the effect of well skin. The root mean squared error of second simulation of TTim is the smallest among three methods presented. The preference of model including well screen resistance is also based on the AIC value. The AIC value of the second simulation decreases significantly comparing to that of the first simulation, which indicates that the second model is more likely to reflect the reality better.

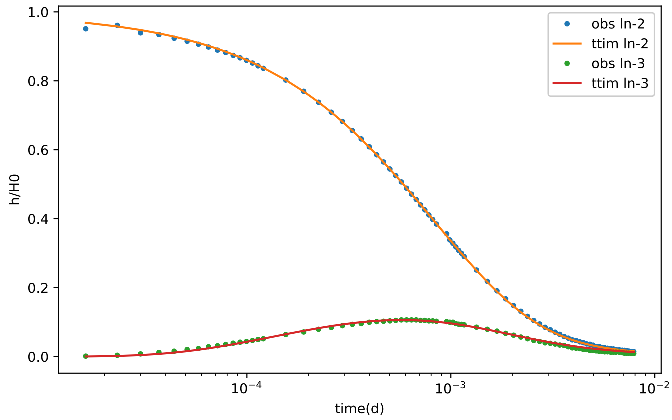


Figure 60: Fitted curves of model with *res* by TTim.

6.4 Test 14 Dawsonville

6.4.1 Basic information

The Dawsonville slug test was reported by Cooper Jr et al. (1967), and is also used by Batu (1998). The test was conducted near Dawsonville, Georgia, USA. The well is drilled to a depth of 122 m, and is considered to be fully penetrating. A cross-sectional view of the test site is shown in Figure 61. Both the well radius

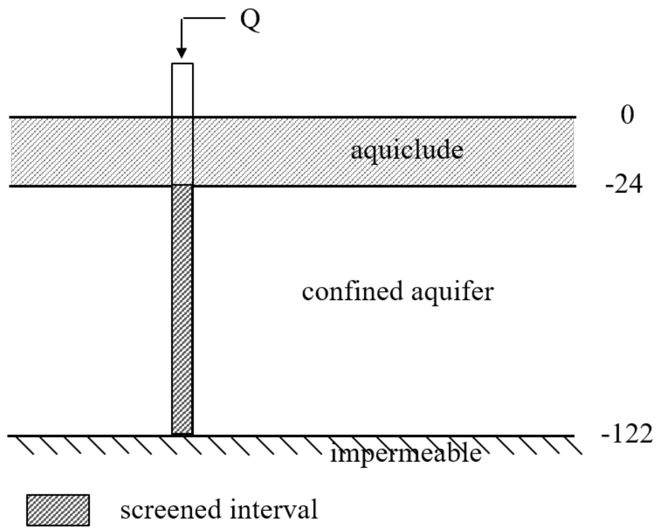


Figure 61: Cross section of test site at Dawsonville.

and casing radius are 0.076 m. The volume of slug is 10.16 liter. Table 44 lists observations used in this research.

6.4.2 Conceptualization and Simulation

MLU and TTim are applied to this slug test. A single layer aquifer system is built with MLU. Hydraulic conductivity and specific storage are calibrated. Skin factor is assigned to zero to neglect the effect of well skin. TTim also applies a single layer aquifer model at first. The well screen resistance res is set to zero. The results of MLU and TTim with single layer model are presented in Table 29. Fitted curves of simulation carried out by TTim are shown in Figure 62.

Table 29: Results of different methods for test at Dawsonville.

	k [m/d]	95%ci	Ss [1/m]	95% ci	res	95% ci	AIC	RMSE [m]
MLU	0.413	8.558%	1.939E-05	59.495%	0	fixed	-	0.004264
TTim	0.421	8.753%	1.703E-05	62.416%	0	fixed	-234.655	0.004410
TTim-res	0.417	15.187%	4.403E-05	830.044%	0.072	951.254%	-232.751	0.004400

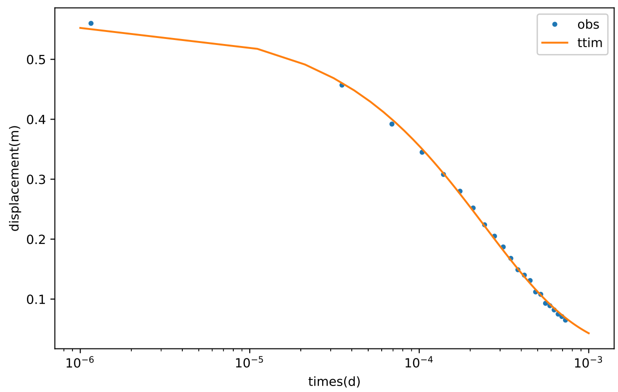


Figure 62: Fitted curves of first simulation of TTim.

Calibrated hydraulic conductivity and specific storage of TTim single layer model are similar with that of MLU. However, confidence intervals for specific storage of both MLU and TTim are very large. Thus, the well screen resistance res is added into calibration of the second simulation. Hydraulic conductivity and specific storage are also calibrated. The results are also shown in Table 29. Fitted curves of second simulation are presented in Figure 63.

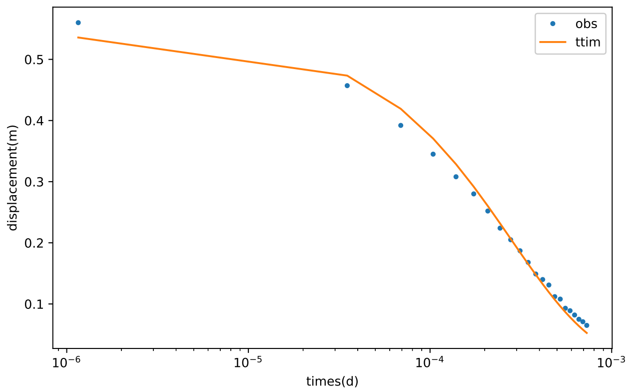


Figure 63: Fitted curves of simulation with *res* of TTim.

The *res* is very sensitive to initial value. When setting the initial value of *res* as 0.1, the model cannot find reliable values for any of three parameters. It can be seen that the second calibration cannot give any uncertainty for both specific storage and well screen resistance. Although the root mean squared error is slightly smaller than that of the first simulation, the AIC value increases by two units. This indicates that the first model is better.

7 Synthesis and Discussion

The results for fourteen field data tests are summarized into four groups: confined aquifers, leaky aquifers, unconfined aquifers, and slug tests. The simulation results of AQTESOLV, MLU, and TTim are compared using the root-mean-squared-error as a standard.

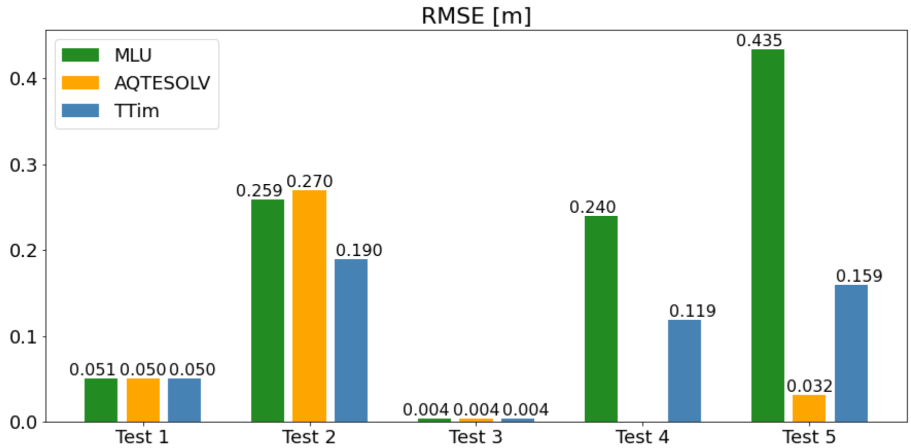


Figure 64: Comparison of three methods by root-mean-squared-error for confined aquifer tests.

The comparison of root-mean-squared-errors for five confined aquifer tests are plotted and presented in Figure 64. For Test 1 and Test 3, the best fits of AQTESOLV, MLU, and TTim all give similar root-mean-squared-errors. For Test 2 at Gridley, the best fit given by TTim, where well bore storage was added into calibration, which leads to a better fit than AQTESOLV and MLU. For Test 4 at Schroth, TTim also added well bore storage into calibration. There is an additional aquifer above the pumped aquifer, but no field information is given. The best fit of TTim applies fixed values for the upper aquifer estimated in Brian et al. (1997). Test 5 at Neveda is a fracture system. TTim gives a better fit than MLU by including well construction parameter into calibration. AQTESOLV has a base model especially for slab-shaped fracture system, and the Moench (1984) solution is applied. AQTESOLV has the best fit for the fracture system.

Comparison for three leaky aquifer tests are presented in Figure 65. AQTESOLV, MLU, and TTim have similar root-mean-squared-error for Test 6. TTim performs better in Test 7 and Test 8. For Test 7 at Hardinxveld, the information for well construction parameters are lacking. MLU uses the same values for casing

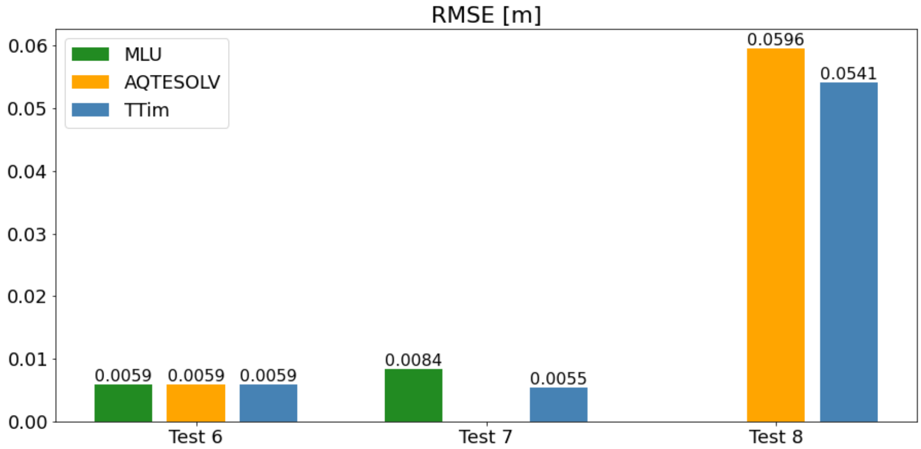


Figure 65: Comparison of three methods by root-mean-squared-error for leaky aquifer tests.

radius and well radius. After adding the casing radius into calibration with TTim, the results show that simulation with well bore storage gives a slightly worse fit and a much larger AIC value, which indicates that well bore storage does not have much effect in this test. When removing well bore storage, TTim gives a slightly smaller root-mean-squared-error than MLU. For Test 8 at Texas Hill, AQTESOLV uses the same value for the casing radius as the value of the well radius. Since no well construction information is given, TTim adds well bore storage into calibration and give a better fit.

Comparison for the unconfined aquifer Test 9 is shown in Figure 66. Test 10 cannot be repeated with demo version of MLU, and the RMSE value is not available. For Test 9 at Vennebulten, TTim has a slightly larger root-mean-squared-error than MLU. Both MLU and TTim simulate unconfined aquifer systems by adding an additional layer on top to simulate specific yield. MLU added the transmissivity of top layer into calibration, which was not done in TTim. The best fit given by TTim simulates this test by subdividing the aquifer into sub-layers.

Root-mean-squared-errors of four slug tests are presented in Figure 67. TTim reports similar RMSE for Test 11, Test 12, and Test 14. For Test 13, well skin resistance is added into simulation conducted by TTim, which leads to a better fit compared to both MLU and AQTESOLV. When simulating slug tests with partially penetrating wells or when the well construction information is not available, TTim is preferred for building conceptual model with multi layers and calibrating well construction parameters.

When the same conceptual model is used and the same parameters are cali-

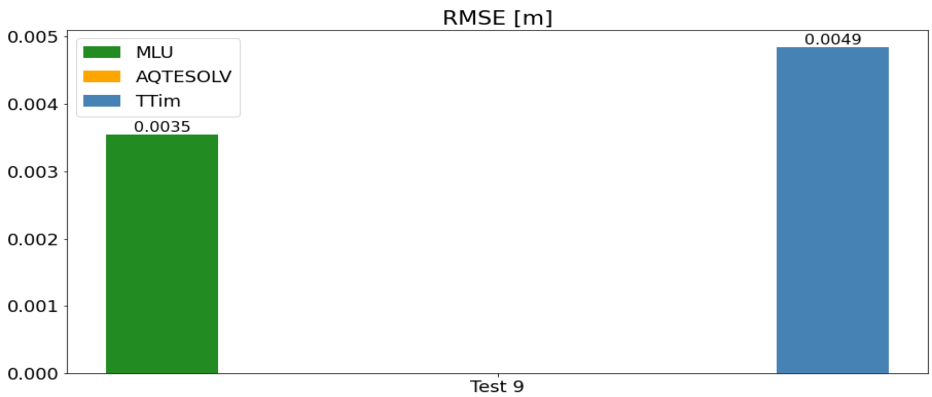


Figure 66: Comparison of three methods by root-mean-squared-error for unconfined aquifer tests.

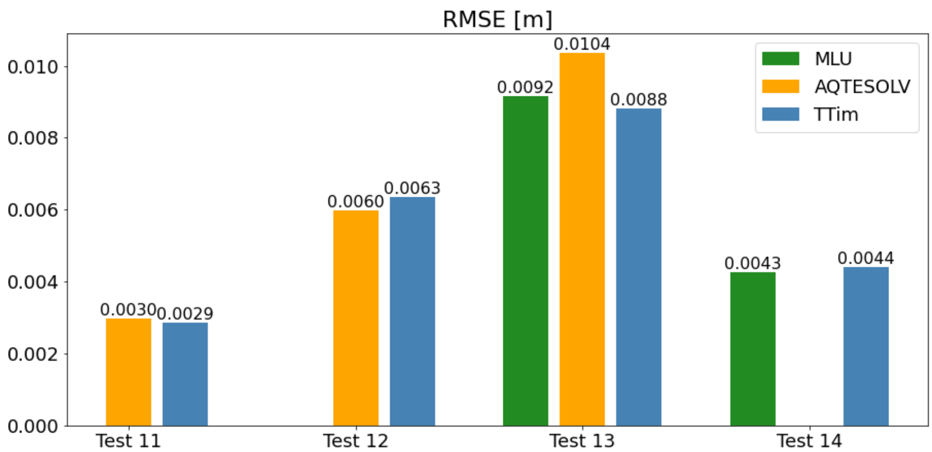


Figure 67: Comparison of three methods by root-mean-squared-error for slug tests.

brated, TTim and MLU give the same results. Small differences may happen due to the parameter estimation routine and possibly the back-transformation of the Laplace transform.

8 Conclusions and recommendations

8.1 Conclusions

This research evaluated three different softwares to analyze pumping test: AQTESOLV, MLU, and TTim. The analysis is based on fourteen aquifer tests taken from various sources and one hypothetical test especially generated for verifying performance of the TTim model. The methods for building proper conceptual models and finding the optimal parameters set are discussed, and the reasons contributing to the differences in the results of the three methods have been investigated. The research questions are answered as follows:

How to transform various aquifer tests into proper conceptual models for TTim?

Aquifer tests have been taken from either Kruseman et al. (1970) or examples from AQTESOLV and MLU. Ten pumping tests and four slug tests have been presented in this report. Aquifer systems with confined, leaky, and unconfined top boundaries have been discussed. For most of the pumping tests conceptualized in TTim, ModelMaq is chosen as the base model, which consists of a sequence of alternating aquifers and aquitards. The top boundary can be specified as confined or semi-confined for confined aquifer systems and leaky aquifer systems, respectively. For unconfined aquifers, Model3D, which represents one aquifer by a sequence of aquifer layers, is recommended. The top boundary is confined and an additional thin aquifer is added to the top to simulate the specific yield. The storage of the top layer, representing the specific yield, needs to be calibrated separately.

In addition to simulating different top boundaries of aquifer systems, the well screen length is another factor that influences the conceptual model. When a partially penetrating well is involved, vertical flow occurs around the well along with horizontal flow. Stratified aquifer analysis may come into play at this point. Model3D is recommended to be applied, and the aquifer is subdivided into separate layers for the screen, and overlying and underlying layers.

How is the performance of TTim compared with other softwares based on semi-analytical approach (MLU) and analytical solutions (AQTESOLV)?

For most of the tests, when applying the same conceptual model in TTim and MLU, the calibrated values and confidence intervals for parameters are very similar. AQTESOLV sometimes performs slightly better than the other two when the correct analytical solution is chosen. One difference between AQTESOLV and both MLU and TTim is that parameters of the well cannot be calibrated. Thus, it is more suitable for simulating groundwater systems with known boundaries and well construction details for fully or partially penetrating wells. Only one single aquifer system can be simulated with AQTESOLV, but for actual practice, aquifer systems can consist of multiple aquifers and aquitards. Thus, when the well is partially penetrating, or observation wells are screened at different depths, MLU and TTim can have a better conceptual model, and the simulation is more realistic. Considering the diversity and flexibility of conceptualization for complicated aquifer systems, MLU and TTim are preferred.

How to improve the performance of TTim by modifying the conceptual models?

In the process of building a proper conceptual model, a model with multiple layers can improve the model performance when the well is partially penetrating or the observation wells are screened at different depths. When a conceptual model has been built for TTim, modifying the parameters set for calibration may also improve the model performance. Adding or removing some parameters from calibration may work. The criteria for choosing better model is not limited on the root mean squared error or ranges of confidence interval. The AIC value is also helpful in determining which model is better when modifying the calibration parameters set. The flexibility of the TTim model is prominent here. A more proper conceptual model with better fit can usually be explored by adding well construction parameters or dividing the aquifer in separate layers with different properties.

There are also some other findings that can be drawn from this research:

- TTim can have an arbitrary number of layers while the MLU software is limited to 3 aquifer layers for the demo version, while AQTESOLV is limited to single layer system. In addition, TTim can model many other features like streams, horizontal well, and recharge.

- Both TTim and MLU report standard errors for each calibrated parameter. AQTESOLV reports 95% confidence intervals using Student's t-distribution. The verification of the confidence interval calculated by the standard error of TTim is presented in test 0, and the results show that the 95% confidence interval of TTim contains the true value approximately 95% of the time for the analyzed synthetic dataset.

- Some parameters to be calibrated are sensitive to the initial values, especially for parameters of well construction in unconfined water systems.

8.2 Observations and recommendations

- Both AQTESOLV and MLU have a well-developed interface, which is easier for users to input basic information for aquifer tests.

- TTim is presently available for limited types of pumping tests and slug test compared to AQTESOLV, which collects a bunch of solutions for various types of aquifer tests. AQTESOLV builds the base model for more types of pumping tests, such as oscillation test, and slab-shaped and cube-shaped fracture system.

- The comparison carried out in this research is limited to the demo versions of AQTESOV and MLU. The demo version of MLU has a limited number of layers. Conceptual models with many layers can be repeated and verified in the full version of MLU.

- During calibration, TTim can assign the same value to a sequence of layers, but this sequence must be continuous. It would be helpful if TTim can do an arbitrary sequence, for example layers 1, 3, and 6.

- TTim can not only handle aquifer tests with wells, but is also available for simulation of transient flow to streams which uses line-sinks functions. This research is limited to aquifer tests with wells. Further verification and simulation carried out for other features of TTim are recommended.

1 Drawdown data

A.1 Test 1 Oude Korendijk

Table 30: Drawdown of pumping test at 'Oude Korendijk'

Piezometer P_{30} Screen depth 20 m			
t(min)	s(m)	t(min)	s(m)
0	0	18	0.680
0.1	0.04	27	0.742
0.25	0.08	33	0.753
0.50	0.13	41	0.779
0.70	0.18	48	0.793
1.0	0.23	59	0.819
1.40	0.28	80	0.855
1.90	0.33	95	0.873
2.33	0.36	139	0.915
2.80	0.39	181	0.935
3.36	0.42	245	0.966
4.00	0.45	300	0.990
5.35	0.50	360	1.007
6.80	0.54	480	1.050
8.3	0.57	600	1.053
8.7	0.58	728	1.072
10.0	0.60	830	1.088
13.1	0.64		
Piezometer P_{90} Screen depth 24 m			
t(min)	s(m)	t(min)	s(m)
0	0	40	0.404
1.5	0.015	53	0.429
2.0	0.021	60	0.444
2.16	0.023	75	0.467
2.66	0.044	90	0.494
3	0.054	105	0.507
3.5	0.075	120	0.528
4	0.090	150	0.550
4.33	0.104	180	0.569
5.5	0.133	248	0.593
6	0.153	301	0.614
7.5	0.178	363	0.636
9	0.206	422	0.657
13	0.250	542	0.679
15	0.275	602	0.688
18	0.305	680	0.701
25	0.348	785	0.718
30	0.364	845	0.716
Piezometer P_{215} Screen depth 20 m			
t(min)	s(m)	t(min)	s(m)
0	0	305	0.196
66	0.089	366	0.207
127	0.138	430	0.214
185	0.165	606	0.227
251	0.168	780	0.250

A.2 Test 2 Gridley

Table 31: Drawdown data of wells at 'Gridley'

Observation Well 1			
t(min)	s(ft)	t(min)	s(ft)
3	0.30	70	6.10
5	0.70	80	6.30
8	1.30	90	6.70
12	2.10	100	7.00
20	3.20	130	7.50
24	3.60	160	8.30
30	4.10	200	8.50
38	4.70	260	9.20
47	5.10	320	9.70
50	5.30	380	10.20
60	5.70	500	10.90
Observation Well 3			
t(min)	s(ft)	t(min)	s(ft)
15	24.8	166	29.5
25	25.5	195	30.3
45	26.6	256	30.5
60	27.3	282	30.6
76	28	314	30.7
90	28.2	360	30.8
132	29	430	31.5

A.3 Test 3 Sioux Flats

Table 32: Drawdown of pumping test at Sioux Flats.

Drawdowns of OW1			
t (min)	s (ft)	t (min)	s (ft)
5	0.08	120	1.05
10	0.22	180	1.2
15	0.32	240	1.31
20	0.41	300	1.41
25	0.48	360	1.48
30	0.54	420	1.54
40	0.64	480	1.59
50	0.72	540	1.63
60	0.78	600	1.67
70	0.85	660	1.72
80	0.9	720	1.75
90	0.94	840	1.84
100	0.98	960	1.89
110	1.02	2045	2.17
Drawdowns of OW2			
t (min)	s (ft)	t (min)	s (ft)
12	0.03	182	0.71
17	0.07	242	0.81
22	0.11	302	0.89
27	0.15	362	0.97
32	0.18	422	1.03
42	0.25	482	1.08
52	0.31	542	1.12
62	0.36	602	1.16
72	0.4	662	1.2
82	0.44	722	1.23
92	0.48	842	1.32
102	0.51	962	1.36
112	0.54	2045	1.65
122	0.57		
Drawdowns of OW3			
t (min)	s (ft)	t (min)	s (ft)
35	0.01	250	0.34
40	0.02	310	0.4
50	0.03	370	0.46
60	0.05	430	0.51
70	0.07	490	0.55
80	0.08	550	0.59
90	0.1	610	0.63
100	0.12	670	0.65
110	0.14	730	0.68
120	0.15	850	0.75
130	0.17	970	0.8
190	0.26	2045	1.07

A.4 Test 4 Schroth

Table 33: Drawdown data of pumping test at Schroth.

Drawdowns of $EW-712$			
t (d)	s (m)	t (d)	s (m)
0.000104	0.8	0.004861	13
0.000139	1.2	0.006944	14
0.000208	1.8	0.010418	14.5
0.000278	2.4	0.013889	14.5
0.000347	3	0.020833	15
0.000486	4	0.027778	15
0.000694	5	0.048611	15
0.001042	6.5	0.069444	15
0.001389	8	0.104167	15.5
0.002083	9.5	0.138889	15.5
0.002778	11	0.208333	15.5
0.003472	12	0.277778	15.5
Drawdowns of $MW-616$			
t (d)	s (m)	t (d)	s (m)
0.002083	0.02	0.027778	0.6
0.002778	0.04	0.041667	0.7
0.003472	0.07	0.055556	0.75
0.0048661	0.13	0.069444	0.8
0.006944	0.22	0.104167	0.85
0.010417	0.33	0.138889	0.9
0.013889	0.42	0.208333	0.93
0.020833	0.5	0.277778	0.95

A.5 Test 5 Neveda

Table 34: Drawdown of pumped well at Neveda (Moench, 1984)

Pumped well (UE-25b # 1)			
t (min)	s (m)	t (min)	s (m)
0.05	2.513	30.0	8.84
0.1	3.769	35.0	8.84
0.15	4.583	40.0	8.86
0.2	4.858	50.0	8.86
0.25	5.003	60.0	8.90
0.3	5.119	70.0	8.91
0.35	5.230	80.0	8.92
0.4	5.390	90.0	8.93
0.45	5.542	100.0	8.95
0.5	5.690	120.0	8.97
0.6	5.960	140.0	8.98
0.7	6.19	160.0	8.99
0.8	6.42	180.0	9.00
0.9	6.59	200.0	9.02
1.0	6.74	240.0	9.04
1.2	6.96	300.0	9.07
1.4	7.17	400.0	9.11
1.6	7.33	500.0	9.14
1.8	7.45	600.0	9.17
2.0	7.56	700.0	9.18
2.5	7.76	800.0	9.21
3.0	7.93	900.0	9.25
3.5	8.03	1000.0	9.30
4.0	8.12	1200.0	9.44
5.0	8.24	1400.0	9.55
6.0	8.32	1600.0	9.64
7.0	8.41	1800.0	9.74
8.0	8.46	2000.0	9.78
9.0	8.54	2200.0	9.80
10.0	8.62	2400.0	9.84
12.0	8.67	2600.0	9.93
14.0	8.70	2800.0	10.03
16.0	8.74	3000.0	10.08
18.0	8.76	3500.0	10.26
20.0	8.77	4000.0	10.30
25.0	8.81	4200.0	10.41
25.0	8.81	4200.0	10.41

Table 35: Drawdown of observation well at Neveda (Moench, 1984)

Observation well (UE-25a # 1)			
t (min)	s (m)	t (min)	s (m)
0.5	0.002	35.0	0.359
0.6	0.002	40.0	0.374
0.7	0.002	45.0	0.384
0.8	0.002	50.0	0.392
0.9	0.002	60.0	0.401
1.0	0.005	70.0	0.411
1.2	0.005	120.0	0.434
1.4	0.007	140.0	0.439
1.6	0.007	160.0	0.444
1.8	0.012	180.0	0.451
2.0	0.015	200.0	0.453
2.2	0.015	240.0	0.461
2.4	0.020	280.0	0.468
2.6	0.022	300.0	0.471
2.8	0.025	340.0	0.478
3.0	0.027	400.0	0.491
3.5	0.037	440.0	0.498
4.0	0.045	500.0	0.506
4.5	0.052	600.0	0.518
5.0	0.059	700.0	0.525
5.5	0.069	800.0	0.528
6.0	0.079	900.0	0.528
7.0	0.097	1000.0	0.538
8.0	0.116	1200.0	0.563
9.0	0.134	1400.0	0.577
10.0	0.151	1600.0	0.577
12.0	0.186	1800.0	0.577
14.0	0.213	2000.0	0.590
16.0	0.238	2300.0	0.587
18.0	0.260	2700.0	0.615
20.0	0.285	3000.0	0.615
25.0	0.320	3500.0	0.627
30.0	0.342	3680.0	0.639

A.6 Test 6 Dalem

Table 36: Drawdown data of pumping test 'Dalem' (Kruseman et al., 1970)

Piezometer at 30 m			
t (d)	s (m)	t (d)	s (m)
1.53E-2	0.138	8.68E-2	0.190
1.81E-2	0.141	1.25E-1	0.201
2.29E-2	0.150	1.67E-1	0.210
2.92E-2	0.156	2.08E-1	0.217
3.61E-2	0.163	2.50E-1	0.220
4.58E-2	0.171	2.92E-1	0.224
6.60E-2	0.180	3.33E-1	0.228
Piezometer at 60 m			
t (d)	s (m)	t (d)	s (m)
0	0	8.82E-2	0.127
1.88E-2	0.081	1.25E-1	0.137
2.36E-2	0.089	1.67E-1	0.148
2.99E-2	0.094	2.08E-1	0.155
3.68E-2	0.101	2.50E-1	0.158
4.72E-2	0.109	2.92E-1	0.160
6.67E-2	0.120	3.33E-1	0.164
Piezometer at 90 m			
t (d)	s (m)	t (d)	s (m)
2.43E-2	0.069	1.25E-1	0.120
3.06E-2	0.077	1.67E-1	0.129
3.75E-2	0.083	2.08E-1	0.136
4.68E-2	0.091	2.50E-1	0.141
6.74E-2	0.100	2.92E-1	0.142
8.96E-2	0.109	3.33E-1	0.143
Piezometer at 120 m			
t (d)	s (m)	t (d)	s (m)
2.50E-2	0.057	1.25E-1	0.105
3.13E-2	0.063	1.67E-1	0.113
3.82E-2	0.068	2.08E-1	0.122
5.00E-2	0.075	2.50E-1	0.125
6.81E-2	0.086	2.92E-1	0.127
9.03E-2	0.092	3.33E-1	0.129

A.7 Test 7 Hardinxveld

Table 37: Drawdown data of test site Hardinxveld.

Drawdown of the pumping well			
t (d)	drawdown (m)	t (d)	drawdown (m)
0.000694	2.746	0.016667	0.19
0.001389	2.807	0.017361	0.174
0.002083	2.869	0.018056	0.162
0.002778	2.9	0.01875	0.146
0.003472	2.923	0.019444	0.13
0.004167	2.944	0.020139	0.12
0.004861	2.96	0.020833	0.114
0.005556	2.977	0.022222	0.102
0.00625	2.993	0.023611	0.086
0.006944	3.004	0.025	0.08
0.008333	3.019	0.026389	0.075
0.009722	3.031	0.027778	0.068
0.011111	3.058	0.029167	0.067
0.0125	3.064	0.030556	0.061
0.013889	3.084	0.031944	0.056
0.014583	0.364	0.033333	0.05
0.015278	0.282	0.034722	0.044
0.015972	0.241		

A.8 Test 8 Texas Hill

Table 38: Drawdown data of observation wells at test site Texas Hill.

t [min]	OW1 [ft]	OW2 [ft]	OW3 [ft]
2	5.65	3.1	1.11
4	6.96	4.02	2.15
6	7.72	5.05	2.86
8	8	5.29	3.46
10	8.71	5.97	3.78
15	9.47	6.72	4.58
20	9.99	7.16	5.09
25	10.35	7.6	5.49
30	10.7	7.96	5.85
40	11.14	8.36	6.64
50	11.46	8.63	6.37
60	11.62	8.91	6.8
70	11.86	9.19	6.96
80	12.02	9.31	7.16
90	12.26	9.47	7.36
100	12.33	9.55	7.44
110	12.37	9.63	7.52
120	12.41	9.75	7.56
150	12.69	9.95	7.64
180	12.85	10.07	7.88
210	13.09	10.19	7.92
240	13.13	10.27	7.96
270	13.25	10.35	7.96
300	13.33	10.39	7.96
360	13.37	10.34	7.95
420	13.41	10.42	7.96

A.9 Test 9 Vennebulten

Table 39: Pumping test data 'Vennebulten'(Kruseman et al., 1970, p. 105).

Deep Piezometer			
t (min)	s (m)	t (min)	s (m)
1.17	0.004	51	0.133
1.34	0.009	65	0.141
1.7	0.015	85	0.146
2.5	0.030	115	0.161
4	0.047	175	0.161
5	0.054	260	0.172
6	0.061	300	0.173
7.5	0.068	370	0.173
9	0.064	430	0.179
14	0.090	485	0.183
18	0.098	665	0.182
21	0.103	1340	0.200
26	0.110	1490	0.203
31	0.115	1520	0.204
41	0.128		
Shallow Piezometer			
t (min)	s (m)	t (min)	s (m)
6	0.005	115	0.033
9	0.006	175	0.044
14	0.008	260	0.050
18	0.010	300	0.055
26	0.011	485	0.061
31	0.014	665	0.071
41	0.018	1340	0.096
51	0.022	1490	0.099
65	0.026	1520	0.099
85	0.028		

A.10 Test 10 Hypothetic test of Moench

Table 40: Drawdowns of four piezometer (Barlow and Moench, 1999).

t (s)	Pumped (m)	PD1 (m)	PD2 (m)	PS1 (m)	PS2 (m)
9.28	0.508	0.090	0.000	0.007	0.000
20	0.971	0.204	0.0005	0.019	0.0001
43.1	1.64	0.384	0.0028	0.039	0.0005
92.8	2.31	0.568	0.0071	0.060	0.0012
200	2.65	0.662	0.0099	0.072	0.0017
431	2.71	0.680	0.0105	0.077	0.0019
928	2.71	0.683	0.0110	0.084	0.0022
2000	2.72	0.690	0.0119	0.098	0.0028
4310	2.74	0.703	0.0140	0.126	0.0042
9280	2.76	0.729	0.019	0.177	0.0075
20000	2.81	0.775	0.029	0.258	0.016
43100	2.88	0.847	0.052	0.365	0.038
92800	2.98	0.942	0.098	0.487	0.084
200000	3.09	1.052	0.172	0.612	0.162

A.11 Test 11 Pratt County

Table 41: Drawdown data of test site Pratt (Butler Jr, 2019).

t (s)	s (m)	t (s)	s (m)
0.1	0.663	12.6	0.531
0.2	0.664	14.2	0.517
0.3	0.656	15.9	0.501
0.4	0.656	17.8	0.486
0.5	0.656	20	0.469
0.6	0.656	22.4	0.45
0.7	0.653	25.2	0.435
0.8	0.649	28.2	0.413
0.9	0.649	31.7	0.39
1.1	0.649	35.5	0.368
1.2	0.645	39.9	0.346
1.3	0.642	44.7	0.321
1.5	0.653	50.2	0.295
1.6	0.648	56.3	0.273
1.8	0.642	63.1	0.244
2	0.638	70.8	0.221
2.3	0.63	79.5	0.191
2.6	0.627	89.2	0.166
2.9	0.619	100.1	0.14
3.2	0.619	112.3	0.118
3.6	0.619	125.9	0.099
4	0.608	141.3	0.081
4.5	0.605	158.5	0.059
5.1	0.596	177.9	0.051
5.7	0.59	199.6	0.037
6.4	0.587	223.9	0.025
7.1	0.579	251.2	0.019
8	0.568	281.9	0.014
9	0.56	316.3	0.008
10	0.553	354.9	0.008
11.3	0.539		

A.12 Test 12 Falling-head slug test

Table 42: Data of Falling-head Slug Test.

t [s]	s [ft]	t [s]	s [ft]
0	8.52	111	9.37
2	8.56	121	9.39
4	8.59	136	9.45
6	8.67	151	9.49
8	8.77	166	9.53
10	8.73	186	9.58
20	8.83	201	9.60
30	8.91	221	9.64
40	8.99	231	9.67
50	9.05	246	9.68
60	9.11	271	9.72
70	9.17	301	9.75
86	9.25	311	9.76
101	9.31	326	9.79

A.13 Test 13 Multi well slug test

Table 43: Measurements of well Ln-2 and well Ln-3.

t (s)	Ln-2 (m)	Ln-3 (m)	t (s)	Ln-2 (m)	Ln-3 (m)	t (s)	Ln-2 (m)	Ln-3 (m)
1.4	2.661	0.004	46.4	1.469	0.294	265.4	0.218	0.108
2	2.689	0.011	49.4	1.418	0.298	280.4	0.198	0.102
2.6	2.628	0.022	52.4	1.367	0.298	295.4	0.181	0.094
3.2	2.614	0.034	55.4	1.319	0.298	310.4	0.163	0.09
3.8	2.584	0.044	58.4	1.276	0.298	325.4	0.15	0.08
4.4	2.56	0.058	61.4	1.231	0.294	340.4	0.136	0.071
5	2.536	0.066	64.4	1.191	0.294	355.4	0.13	0.068
5.6	2.513	0.08	67.4	1.15	0.29	370.4	0.12	0.065
6.2	2.488	0.088	70.4	1.113	0.29	385.4	0.113	0.058
6.8	2.468	0.099	73.4	1.076	0.287	400.4	0.103	0.057
7.4	2.445	0.109	82.4	0.997	0.284	415.4	0.1	0.05
8	2.425	0.117	85.4	0.947	0.279	430.4	0.093	0.05
8.6	2.405	0.123	88.4	0.92	0.279	445.4	0.082	0.047
9.2	2.383	0.131	91.4	0.89	0.268	460.4	0.082	0.043
9.8	2.36	0.139	94.4	0.862	0.263	475.4	0.075	0.043
10.4	2.34	0.145	97.4	0.839	0.262	490.4	0.072	0.039
13.4	2.245	0.179	100.4	0.812	0.258	506.4	0.068	0.039
16.4	2.154	0.2	115.4	0.703	0.239	525.4	0.065	0.036
19.4	2.065	0.222	130.4	0.611	0.222	541.4	0.062	0.036
22.4	1.984	0.236	145.4	0.534	0.207	557	0.058	0.036
25.4	1.909	0.251	160.4	0.469	0.189	578.6	0.055	0.036
28.4	1.835	0.262	175.4	0.414	0.174	598.4	0.052	0.032
31.4	1.767	0.268	190.4	0.368	0.159	613.4	0.051	0.028
34.4	1.703	0.279	205.4	0.327	0.145	628.4	0.048	0.028
37.4	1.638	0.284	220.4	0.293	0.131	643.4	0.045	0.028
40.4	1.58	0.287	235.4	0.265	0.123	666.2	0.042	0.025
43.4	1.523	0.29	250.4	0.238	0.112	681.2	0.041	0.025

A.14 Test 14 Dawsonville

Table 44: Observations of test well as Dawsonville (Cooper Jr et al., 1967).

t (d)	s (m)	t (d)	s (m)
1.5747E-06	0.56	0.000382	0.149
0.000035	0.457	0.000417	0.14
0.000069	0.392	0.000451	0.131
0.000104	0.345	0.000486	0.112
0.000139	0.308	0.000521	0.108
0.000174	0.28	0.000556	0.093
0.000208	0.252	0.00059	0.089
0.000243	0.224	0.000625	0.082
0.000278	0.205	0.00066	0.075
0.000313	0.187	0.000694	0.071
0.000347	0.168	0.000729	0.065

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