MLU for Windows

Well flow modeling in multilayer aquifer systems

UNESCO edition

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INTRODUCTION

MLU for Windows is a groundwater modeling tool to compute drawdowns, analyze all sorts of well flow and aquifer test data and design well fields. MLU for Windows is based on:

- An innovative analytical solution technique for well flow in layered aquifer systems
- Stehfest's numerical method to convert the solution from the Laplace domain into the real domain
- The superposition principle, both in space (multiple wells) and time (variable discharges)
- The Levenberg-Marquardt algorithm for parameter optimization (automated curve fitting).

This unique combination of techniques allows for all tests to be analyzed in a consistent way with a single user interface. Results are printed in ASCII files and plotted as time-drawdown graphs and animated contour plots.

Solution Method

As a rule present day computer codes for aquifer and slug test analysis still use the same analytical solutions and techniques that were common several decades ago. Each type of aquifer test, characterized by a long list of conditions and assumptions, is associated with a particular analytical solution (e.g., Theis, Hantush, Neuman, Boulton, Papadopulos, Moench) for only one (or sporadically two) aquifer(s). The related procedures to determine the (usually two or three) aquifer properties often require straight line fitting or type curve matching with some part of the measured data.

Unlike such traditional aquifer test software, MLU is based on a single analytical solution technique for well flow that handles:

- Layered aquifer systems, i.e. multi-aquifer systems (aquifers and aquitards) and (or) layered (stratified) aquifers (Fig. 1)
- Confined, leaky and delayed yield systems
- Effects of aquifer and aquitard storativities
- One or more pumping or injection wells
- One or more pumping periods for each well
- Finite diameter well screens in any selection of aquifer layers
- Well bore storage and skin effect for each pumping well
- Delayed observation well response
- Individual and grouped parameters to be determined in one run.

Theoretical background information on the applied analytical solution techniques for multiple aquifer systems has been published in e.g.: Journal of Hydrology 90, p. 231-249 (1987) and 225: p. 1-18 and p. 19-44 (1999). The non-linear regression technique is described in Ground Water (1985) 23, no.2, p. 247-253. See the references for further details.

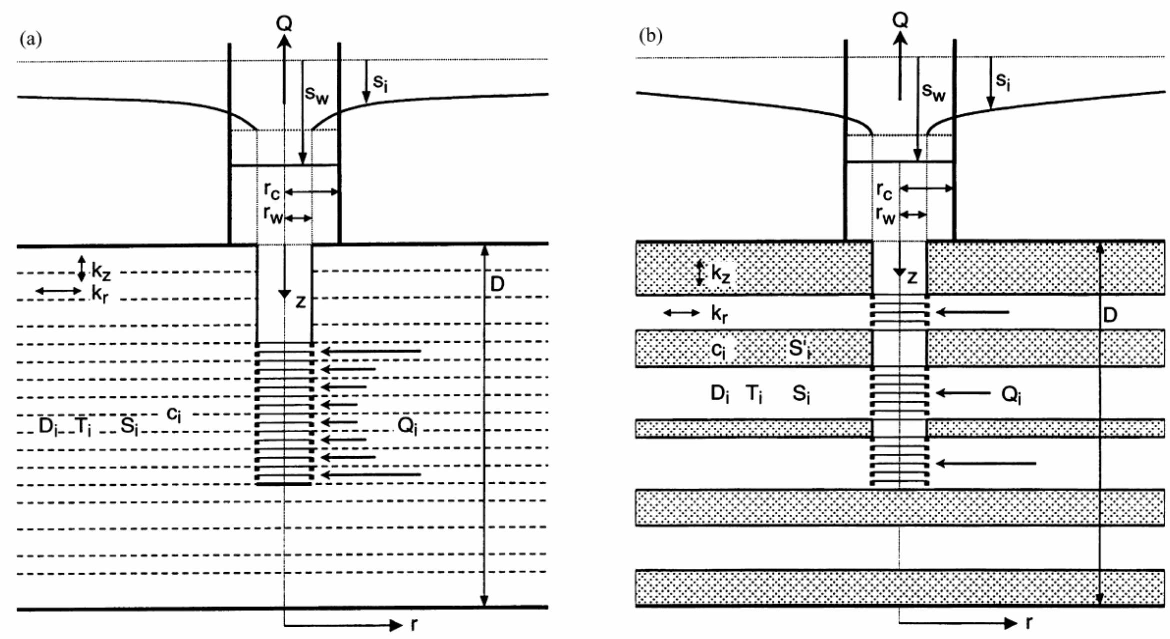


Fig. 1. (a) Schematic diagram of a partially penetrating thin-skin finite diameter well in a horizontally layered aquifer. (b) Schematic diagram of a multiple screened thin-skin finite diameter well skin in a leaky multiaquifer system with crossflow and aquitard storage.

Application

The MLU characteristics allow for all sorts of tests, including recovery tests, variable discharge tests, step-drawdown tests, complex tests in well fields and slug tests. It also handles partially-penetrating and large-diameter wells, bounded aquifers (using image wells) and double-porosity systems. MLU produces (transient) contour plots that may be helpful to design well fields, e.g. as used for ATES (aquifer thermal energy storage). Simple examples of some of these tests and applications are demonstrated in the models supplied with the software. These example models are briefly described hereafter.

Hydrogeologists have found MLU to be very useful for quickly estimating aquifer properties such as layer-by-layer transmissivity, storativity, and vertical resistance/conductance based on aquifer testing data, and efficiently incorporating these properties into numerical groundwater flow models for advanced subsurface flow evaluations. As far as we know, MLU is the only Windows tool for evaluating aquifer response to pumping in a multi-layer aquifer system.

MLU versus numerical models

MLU and numerical models (like Modflow and MicroFEM) can both model stratified aquifers and multi-aquifer systems, but there still is a number of differences that make an analytical model like MLU more favorable in many cases:

- A numerical model with two or more wells requires a 3D model
- A pumping well with multiple screens is a well-known problem in numerical models
- It is not easy to construct numerical models that allow for finite diameter well screens, well bore storage, skin effects and delayed observation well response (in 3D models).
- When designing well fields (e.g. for aquifer thermal energy storage) relocating wells may be cumbersome in numerical models
- When parameter optimization is the purpose of modeling, an analytical model is more suitable (and much faster) since drawdowns can be computed immediately and more accurately for any point in space and time.

On the other hand MLU models have some important restrictions:

- All layers are assumed homogeneous, isotropic and of infinite extent
- Only groundwater flow as a result of pumping and injection wells can be modeled.

Software capacity

The MLU software can handle:

- 40 aquifers (layers) and 41 aquitards
- 300 pumping/injection wells
- 10 pumping periods per well
- 50 observation wells
- 100 measured drawdowns per observation well
- 16 parameters to be optimized in one run.

Data input

- Interactive input
- Data exchange with spreadsheets (copy & paste)
- Modify MLU input data file (ASCII)
- Time conversion: seconds, minutes, hours, days and years
- Length conversion: meters, feet.

Inverse modeling

- Individual and grouped parameters can be determined in one run
- Automated curve fitting is based on the Levenberg-Marquardt algorithm
- Linear and log-transformed least squares solutions
- Statistical data output includes standard errors and correlation matrix
- Parameter optimization and final output results in ASCII-files.

Data output

- Data exchange with spreadsheets (copy & paste)
- MLU data file (ASCII)
- Optimization results, including calculated and observed drawdowns (ASCII)
- Data file that contains computed heads of displayed time graph (FTH-file)
- Data file that contains computed drawdowns of displayed contour map (XYZ-file)
- Data file that contains a MicroFEM finite element model (FEM-file).

Graphical output

- Linear, semi-log and log-log time graphs of drawdown or head
- Time-variant aquifer discharge at a well screened over multiple aquifers
- Animated contour plots of drawdown and build-up cones
- Clipboard bitmap output and vector-based meta-file output.

Free UNESCO edition

The MLU UNESCO edition is a reduced version of MLU for Windows, and is available for teaching, testing and the analysis of one and two-aquifers pumping tests. The UNESCO edition is free, but the application is limited with respect to the number of aquifers, pumping and observation wells and the number of parameters to be optimized.

MLU UNESCO edition can handle:

- 2 aquifers and 3 aquitards
- 2 pumping/injection wells
- 5 observation wells
- 6 parameters to be optimized in one run.

Price and orders

A site license for the Windows-based professional version of MLU costs €450 (about 650 US$). Order directly from the web site: http://www.microfem.com/order/index.html, or e-mail the authors: hemker@microfem.com

Free updates and User support

There are no (yearly) recurring costs. Regular updates (improvements and small extensions) are free. Customer login allows all licensed users to download the latest update anytime. User support is provided by the developers free of charge: support@microfem.com.

USER INSTRUCTIONS

Installing and running MLU

Installing: Unzip the MLU….zip file, double-click the exe-file and follow the installation procedure.

Starting: Double-click the MLU icon.

The MLU window includes standard components:
- Title bar
- Menu bar: File, Edit, View, Calculate, Export, Windows, Help
- Tool bar with buttons: New, Open, Save, Cut, Copy, Paste, Optimize
- Seven tabs to access the data input and result screens
- Status bar.

Menu commands:

File:	New (start a new case), Open (load an existing MLU file), Reopen, Save, Save as …, Close (close the present case), Exit (close MLU)
Edit:	Cut, Copy, Paste, Delete row(s), Insert row(s), Clear, Select all
View:	Status bar, Toolbar
Calculate:	Optimize, Preferences
Import	Import image files
Export:	Copy chart, Copy contours, Save curves as FTH, Save contours as XYZ, Save model as FEM
Windows:	Cascade, Tile horizontally, Tile vertically, Minimize all, Arrange all
Help:	MLU Help, MLU on the web, About….

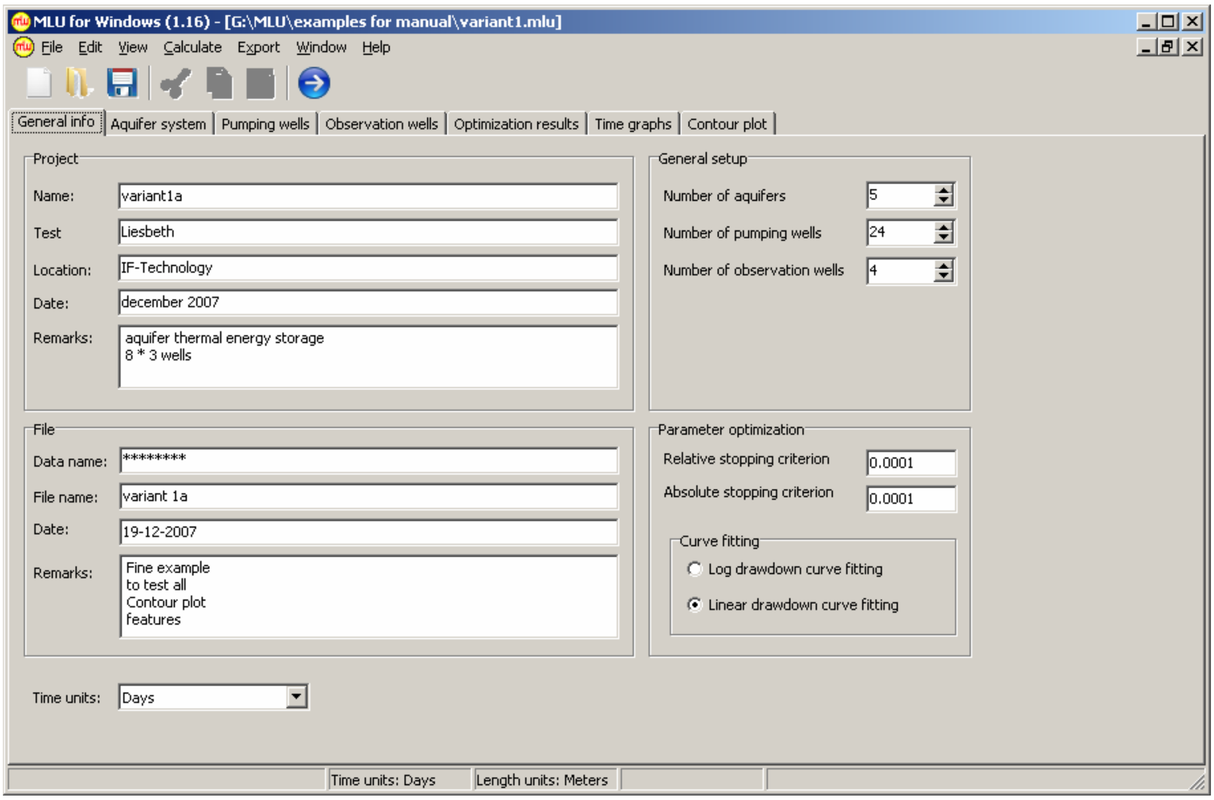
MLU Help as well as <F1> activate the Help system and display help texts corresponding with one of the following tabs:

Tabs 1-7:

1 -	Data input:	General info
2 -	Data input:	Aquifer system
3 -	Data input:	Pumping wells
4 -	Data input:	Observation wells
5 -	Results:	Optimization results
6 -	Results:	Time graphs
7 -	Results:	Contour plot.

Start a new case by pressing the first (left-most) button: "New" and fill out the four input screen pages (tabs 1-4). Or start a session by loading an existing MLU-file: File/Open or press the second button: "Open". MLU can handle many cases at the same time.

Data input 1: General info



At a new start the text fields of “Project” and File” are blank.

The text in the field “File name” determines the default file name when data are saved.

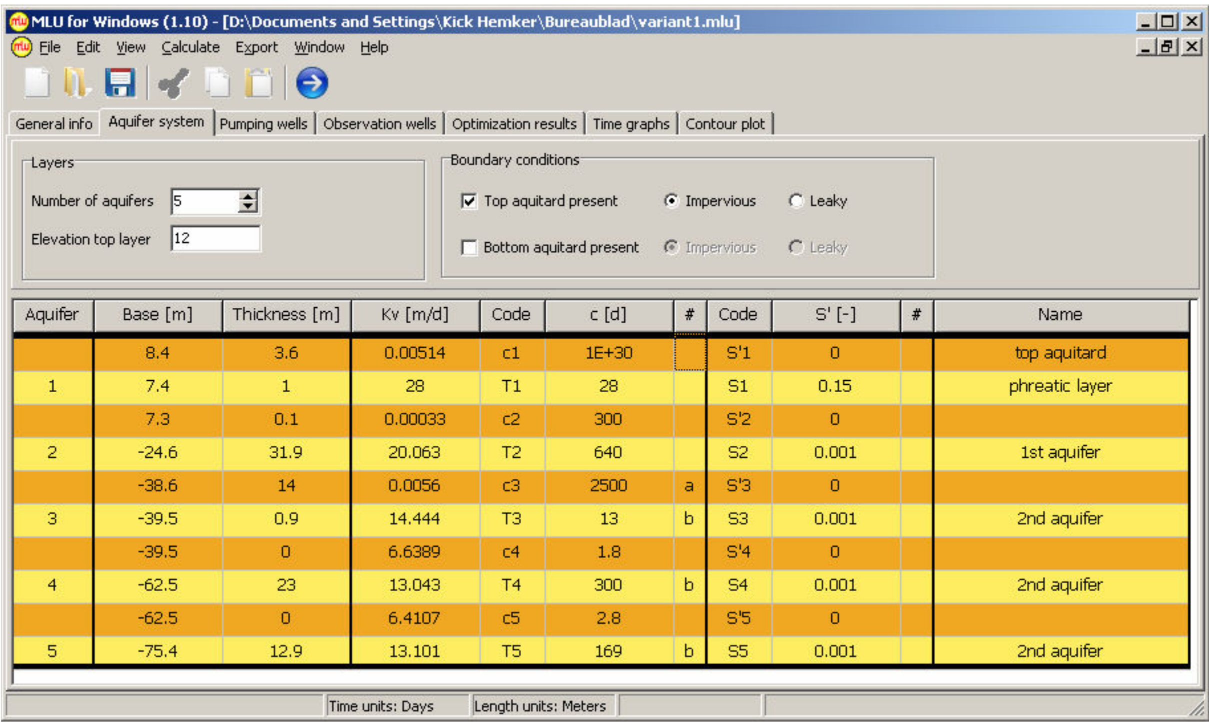
“Time units” is set to “Days” by default. You may select here (or after right-clicking Time units at the Status bar) other time units: seconds, minutes, hours and years. The alternative at the Status bar is always available. The used conversion factor for days per year is 365.24.

“Length units” may be set to either meters or feet. You may change the “Length units” on the Status bar. The conversion factor for meters per foot is 0.3048. The default setting can be changed for future sessions in the Calculate | Preferences window.

General setup: Specify the number of aquifers, the number of pumping (and injection) wells and the number of observation wells (piezometers). In case of a layered (stratified) aquifer, the number of aquifers should be read as the number of aquifer (sub)layers.

Parameter optimization: the preset stopping criteria and linear curve fitting method can be adopted in most cases.

Data input 2: Aquifer system



Aquifer	Base [m]	Thickness [m]	Kv [m/d]	Code	c [d]	#	Code	S' [-]	#	Name
	8.4	3.6	0.00514	c1	1E+30		S'1	0		top aquitard
1	7.4	1	28	T1	28		S1	0.15		phreatic layer
	7.3	0.1	0.00033	c2	300		S'2	0		
2	-24.6	31.9	20.063	T2	640		S2	0.001		1st aquifer
	-38.6	14	0.0056	c3	2500	a	S'3	0		
3	-39.5	0.9	14.444	T3	13	b	S3	0.001		2nd aquifer
	-39.5	0	6.6389	c4	1.8		S'4	0		
4	-62.5	23	13.043	T4	300	b	S4	0.001		2nd aquifer
	-62.5	0	6.4107	c5	2.8		S'5	0		
5	-75.4	12.9	13.101	T5	169	b	S5	0.001		2nd aquifer

MLU always starts a new case with default values for all aquifer system properties.

Elevation top layer is the level of the top of the saturated system above reference level. It is either the top of the upper fully confined aquifer or the water table level in a leaky top aquitard or phreatic aquifer.

The alternating yellow and orange rows of the table indicate aquifers (yellow) and aquitards (orange) in case of a multi-aquifer system, or the aquifer sublayers (yellow) and the intermediate resistances (orange) of a stratified aquifer. The aquifers are numbered from top to bottom.

Aquitards can be present or absent at the top and at the base of the system. When such a top or base aquitard is present, the boundary condition can be specified as leaky, indicated by a blue bar in the table. In all other cases the system boundary is impervious. In case of a phreatic aquifer, the top aquitard is absent.

Within a stratified aquifer there are no aquitards but only aquifer sublayers. The vertical resistance between two such sublayers depends on the thicknesses of these layers and their Kv. In such cases MLU allows to enter a zero thickness and a Kv on the orange line.
The vertical resistance (c-value) is computed as: (thickness upper sublayer + thickness lower sublayer)/(2 * Kv).

Used codes:

T1, T2, … : Transmissivities of aquifers or sublayers = thickness * Kh, [m^2/day, ft^2/sec, etc.]
Kh: horizontal hydraulic conductivity of an aquifer or aquifer-layer

c1, c2, … : Vertical resistances (inverse of conductance) = thickness / Kv, [day, sec, etc.]
Kv: vertical hydraulic conductivity of an aquitard (multi-aquifer system) or between the middles of two adjacent sublayers (stratified aquifer)

S1, S2, … : Storativities of aquifers or sublayers [-]

S'1, S'2, ..: Storativities of aquitards [-].

#-columns:
Use any non-zero character (A .. Z, a .. z, 1 .. 9) to indicate that the current system property is a parameter to be optimized. Two or more parameters that must be optimized as a group (i.e. the same multiplication factor will be applied) should be indicated by the same character.
If the entry is blank the current parameter will be kept constant during optimization. Zero-valued properties (storativity) cannot be optimized.

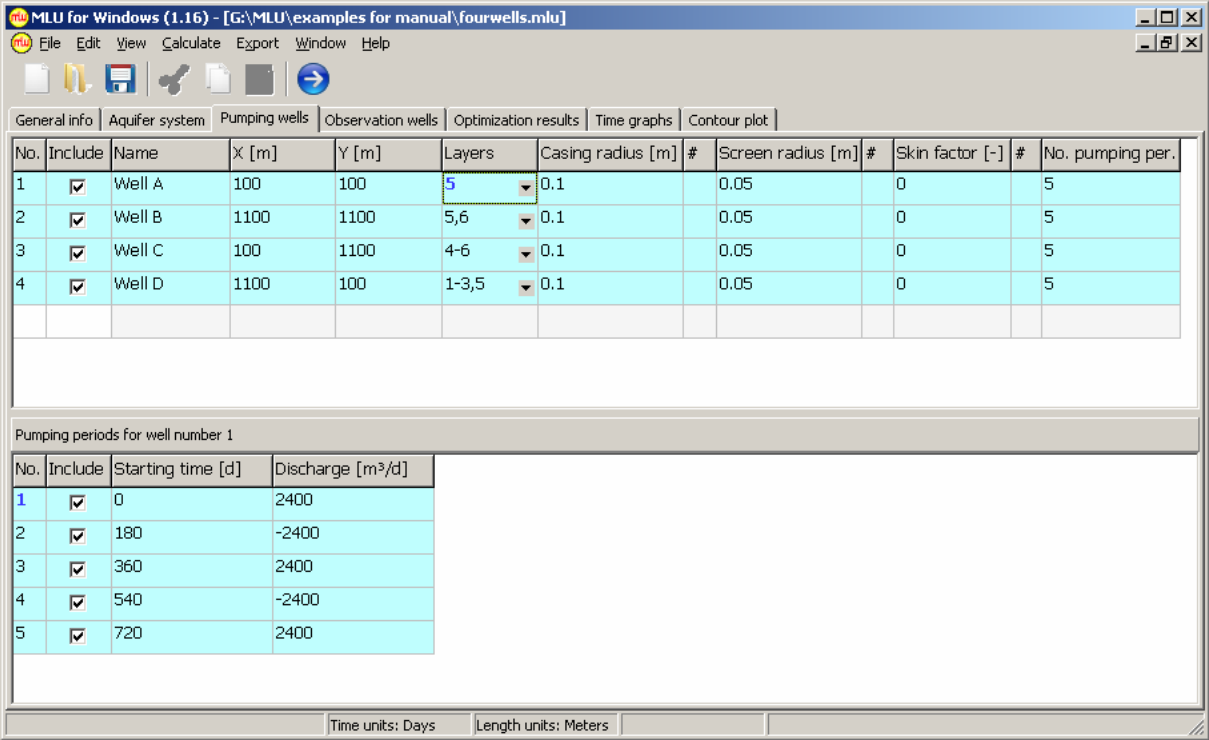
When entering new data in the table, some other values in the table will be updated according to the following rules:

- New input of "thickness" changes "base"
- New input of "base" (if smaller that value above) changes "thickness". It also changes the "base" of all lower layers
- New input of "thickness" or "base" changes "Kv or Kh", but leaves "c", "T", "S" and "S' " unaltered
- New input of "Kv" or "Kh" changes "c" or "T"
- New input and optimization of "c" or "T" changes "Kv" or "Kh"
- New input and optimization of "S" or "S' " has no effect on other values in this table.

And in case of a zero-thickness resistance layer (i.e. within a stratified aquifer)

- New input of “thickness” or "base" of a layer not only changes “Kh” of that layer, but also “Kv” of the adjacent zero-thickness layer(s).

Data input 3: Pumping wells



The upper blue table contains rows with information for all pumping and injection wells; one row for each well.

The “Include” column contains checkboxes that are all “checked” by default. When a pumping well is set to “unchecked”, the well is ignored when computing time graphs, contour plots and when optimizing parameters.

The “Layers” column shows the numbers of the aquifers (layers) in which the well is screened. To select a range of screens in adjacent layers, for example layer 4 up to 6, type 4-6. To select nonadjacent layers, type the numbers separated by a comma (3,5). Alternatively, screened layers can be selected in a drop down list.

Casing radius (code: rc) is the inside radius of the well in the interval where the water level is changing during pumping. Actuality, it should be smaller since the free water surface area is reduced by the e.g. the discharge pipe, while in MLU this surface is computed as: pi * rc^2.

Screen radius (code: rw) is the radius of the well screen or the screened interval of the well (or open hole). The drawdown along the well screen (i.e. in the screened layer(s) at the screen radius) is assumed constant in space at any time: the UWD (Uniform Well-face Drawdown) condition (Hemker, 1999b). Based on this UWD condition individual well-face fluxes can be computed and presented by MLU (see: Time graphs).

For a definition of the skin factor (code: Sk) and more information on well-performance tests (step-drawdown and recovery tests) see e.g. Kruseman & de Ridder [1].

[1] Kruseman & de Ridder, 1990, Analysis and evaluation of pumping test data. Chapter 14. ILRI publication 47, Wageningen, The Netherlands, 377 pp. Also available from Internet http://www.alterra.wur.nl/NL/publicaties+Alterra/ILRI-publicaties/Downloadable+publications/

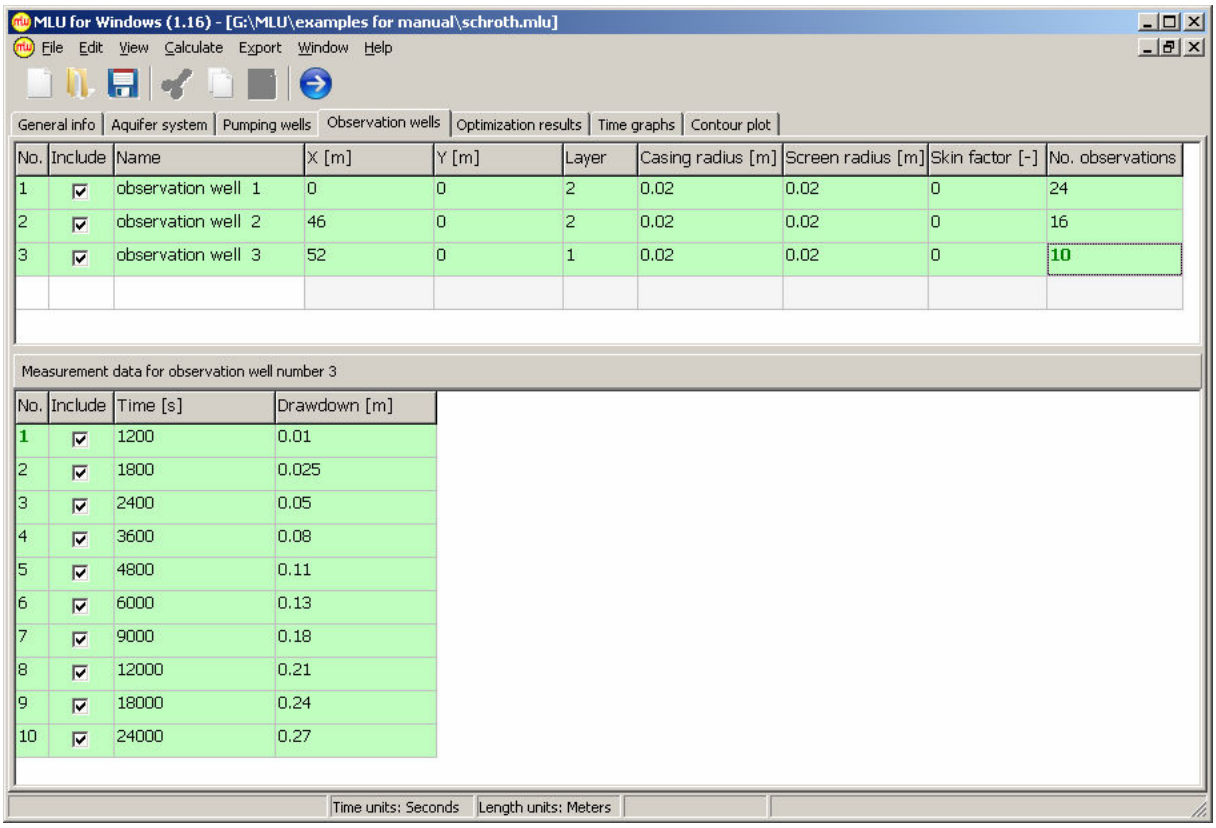
#-columns:
Well characteristics (casing radius, screen radius and skin factor) may also be optimized. Use any non-zero character (A .. Z, a .. z, 1 .. 9) to indicate that the well property is a parameter to be optimized. Two or more parameters that must be optimized as a group (i.e. the same multiplication factor will be applied) should be indicated by the same character. Well characteristics cannot be grouped with aquifer system properties. Zero-valued well characteristics (casing radius, skin factor) cannot be optimized.

The last column is used to indicate the number of constant discharge pumping periods. This number must be 1 or larger (up to 10), and determines the number of rows in the lower table.

The lower table shows how the pumping rate of the well selected in the upper table changes in time, by specifying the starting time and the constant discharge rate of each period. Injection rates are specified by negative discharges, while the discharge rate of a recovery period is zero. Checkboxes allow for (temporarily) ignoring particular pumping (or injection) periods.

The bar between the tables can be shifted upward and downward.

Data input 4: Observation wells



The upper green table contains rows with information for all observation wells (piezometers); one row for each well.

The "Include" column contains checkboxes that are all "checked" by default. When an observation well is set to "unchecked", all measured drawdowns of this well are ignored during optimization. Also, unchecked wells will be disregarded when Time graphs are displayed.

It is recommended to use the same name for wells at the same location (i.e. with same x- and y-coordinates).

The "Layer" column shows the number of the aquifer(layer) in which the well is open (screened). The casing radius (well-bore storage) and skin factor of each observation well are used to compute the delayed observation well response.

The last column is used to indicate the number of drawdown observations in each observation well. This number must be 1 or larger (up to 100), and determines the number of rows in the lower table.

The lower table shows the measured drawdowns for each observation well selected in the upper table. Checkboxes allow for (temporarily) ignoring individual measurements during optimization. Unchecked measurements are disregarded when Time graphs are drawn.

The bar between the tables can be shifted upward and downward.

Results: Parameter optimization

The parameter optimization process requires the setting of two stopping criteria (General info tab). The preset values of 0.0001 can be adopted in most cases. The choice between Linear and Log drawdown curve fitting is subjective. When it is assumed that errors of drawdown measurements are independent of their magnitude, then ‘Linear drawdown curve fitting’ should be selected. On the other hand, when it is supposed that small drawdowns have small measurement errors ‘Log drawdown curve fitting’ may be more appropriate.

Parameter optimization (automated calibration) is started by clicking the Optimize button (blue arrow) or as a menu command: Calculate / Optimize. Only aquifer system and well characteristics selected by a character in the # columns will be optimized. It is recommended to save your model before optimization is started.

The same character for more than one property means that these values are optimized as a single parameter using the same correction factor. For example, when a homogeneous aquifer consists of several layers (i.e. model layers with the same conductivities) their (possibly different) layer transmissivities should be optimized as a group to make sure that the aquifer remains homogeneous during optimization. Hydraulic properties cannot be grouped with well properties.

The objective of the computations is to find that particular combination of parameters that minimizes the sum of squares of the residuals, i.e. the differences between the measured and computed heads. The applied iterative method is called the "Levenberg-Marquardt algorithm". Intermediate results for each iteration are displayed in a separate window, showing the iteration number and the set of parameter values.

When ‘Log drawdown curve fitting’ is selected (General info tab) the logarithms of all measured and computed heads are taken before the sum of squares of the residuals is computed. In this case the sum of squares is dimensionless.

The iterative process is terminated when a minimum sum of squares is reached, i.e. when the values of the last and the one but last computed sum of squares (SS) are sufficiently close, as defined by the Relative stopping criterion (Rel) and the Absolute stopping criterion (Abs):

$$\text{Improvement SS} < \text{Rel} * \text{SS} + \text{Abs} * \text{Abs}$$

Rel and Abs can be specified at the General info tab. Rel is a dimensionless value, while Abs is dimensionless in case of ‘Log drawdown curve fitting’, but has a length unit ([m] or [ft]) in case ‘Linear drawdown curve fitting’ is selected.

When optimizing hydraulic characteristics (T, c, S and S’ values) MLU uses the logarithms of these values internally. So very high and very low values can be used, but they will remain positive. This also explains why zero-valued parameters cannot be optimized.

When MLU for some reason doesn't succeed in finding a proper solution, the optimization process is stopped. The reason for stopping will be displayed. When the calculation is broken off, close the results window. There are different ways to continue:

- Just restart the optimization process.
- First change some or all of the parameter values to be optimized and then restart the optimization process.
- Reset all unrealistic properties and restart with a reduced number of parameters to be optimized.

When MLU has found a solution the computation is stopped (“parameters found”). In this case results are presented as a number of tables in the Optimization results tab window.

The first table shows the calculated optimal parameter values and their most probable ranges (optimal value plus/minus the standard error). Of course the reliability of these results depends on several conditions. The model should be capable of producing the proper values and all non-optimized model values are supposed to be correct. It is also assumed that there are no systematic errors in the observed heads and the random errors are normally distributed. The percentage between brackets (p) is the ratio of the standard error to the parameter value.

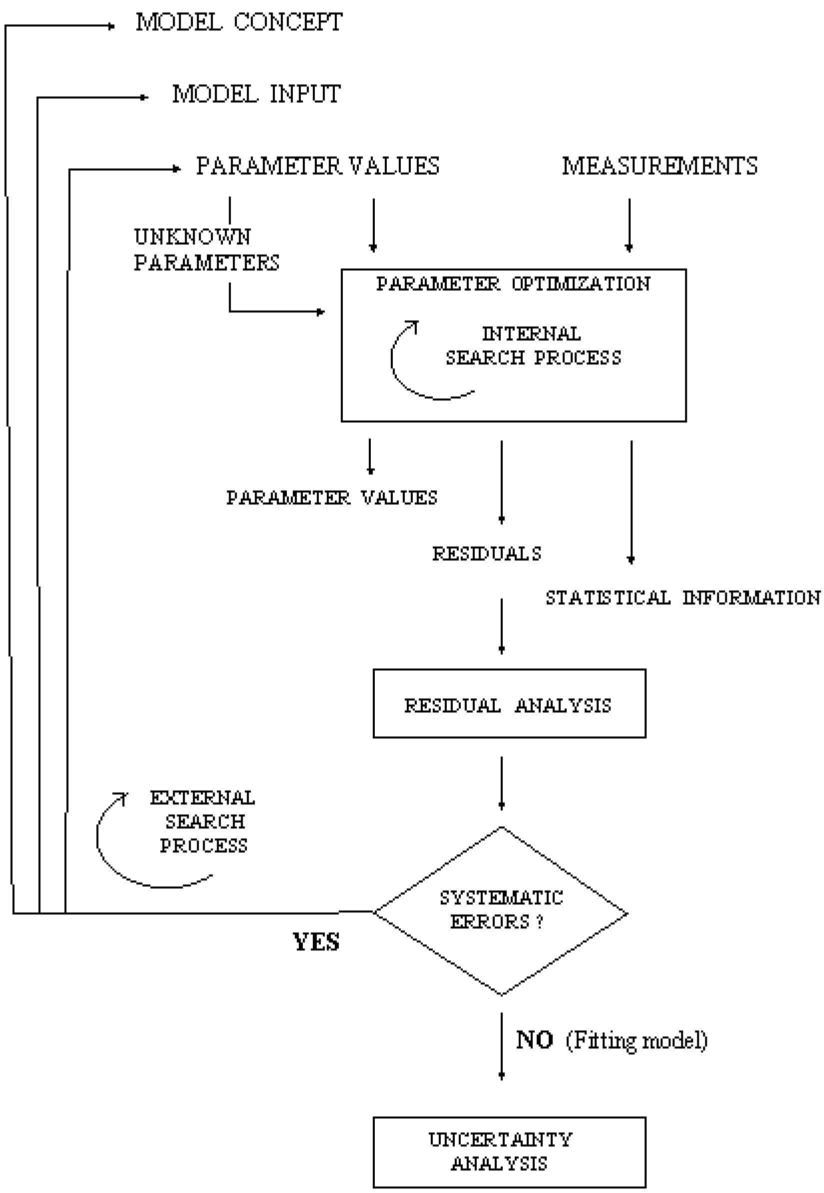
The next table is a list of all calculated (with the latest set of parameters) and observed (measured) heads with their differences (cal-obs). By analyzing the (sign of these) residuals an impression can be obtained of how well the aquifer model simulates reality. Generally speaking it can be said that positive and negative differences should occur randomly.
The same list of calculated and observed heads with their differences (cal-obs) is also presented when no parameters are specified to be optimized.

Based on the analysis of the residuals one has to decide whether the model (the curves) fit the data (observations). When the model does not fit, more or other parameters can be selected. When no set of parameters can be found that produces a fitting model, the model concept may need adjustment (e.g. number of model layers) or the field flow conditions are too complex to be modeled by MLU (e.g. effects of heterogeneity, lateral anisotropy).

Subsequently some numbers are given for the reduction of the sum of squares and the number of iterations. The condition number may be regarded as an expression of the difficulty of finding the least accurate parameter. Large numbers are unfavorable; when the condition number is very large (e.g. 1,000,000) at least one parameter cannot be determined properly.

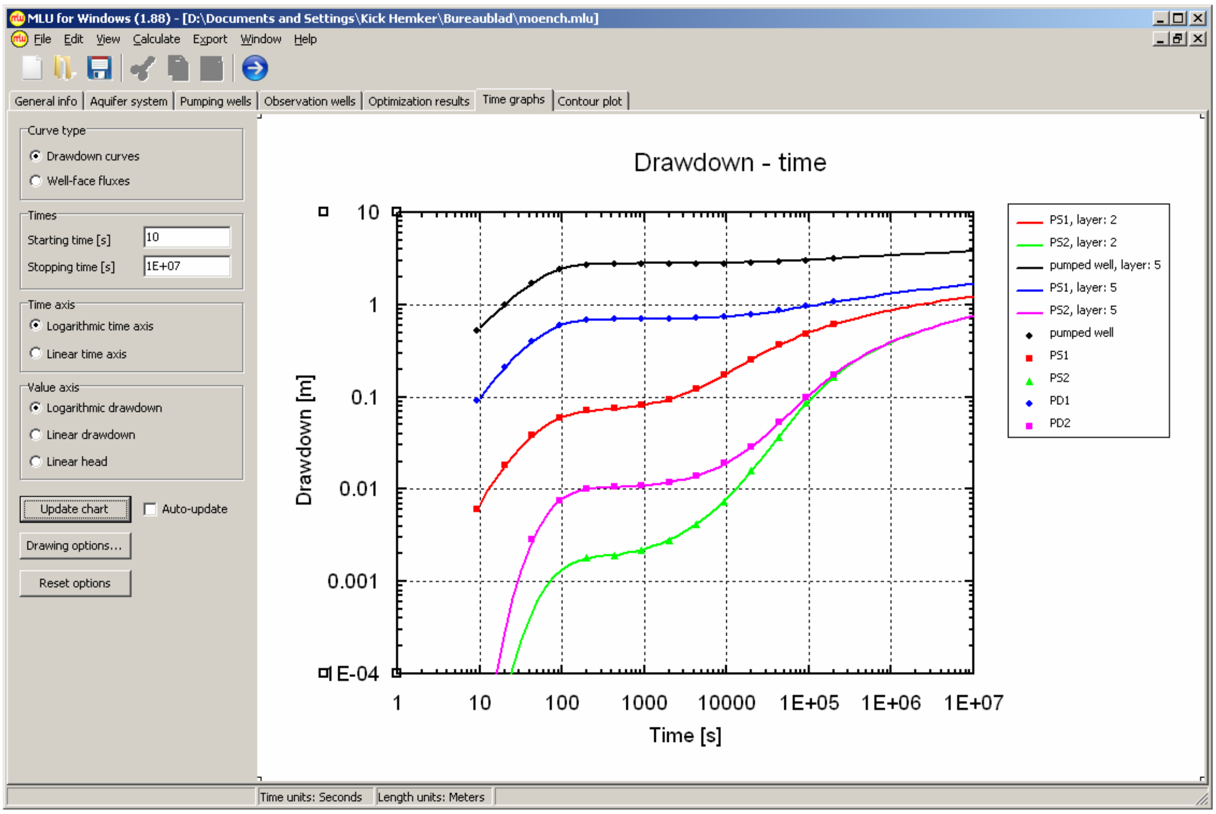
MLU also presents a correlation matrix. The correlation between all pairs of parameters is given as a percentage. High correlations (values near 100% or near -100%) mean that a simultaneous change of both parameters will produce almost the same sum of squares. In such cases the parameters cannot be determined accurately together. The ranges of their standard errors will be very wide, while the condition number will be large. When this happens one parameter (the one best known to the user) may be fixed to compute the remaining set of parameters or positively correlated parameters may be grouped.

Finally the normalized eigenvalues and eigenvectors of the covariance matrix are presented. These eigenvectors are given for (mathematical) completeness only, but are of little use for the practical interpretation of the optimization results.



Above figure represents the full calibration process. MLU takes care of the internal search process only. Residual analysis allows the user to search for the best set of optimization parameters in order to obtain a fitting model.

Results: Time graphs



In the dialog box on the left one may choose between Drawdown curves and Well-face fluxes. When drawdown curves are plotted on a log scale, absolute values are taken. Well-face flux curves show the time-variant fluxes from the aquifer(s) into individual well screens, taking account of well-bore storage.

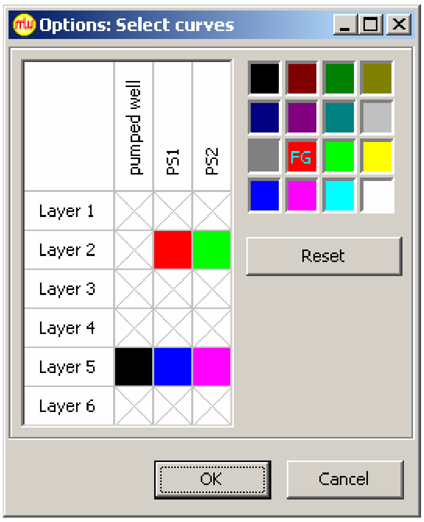
When the auto-update box is not checked (default setting), graphs are only redrawn when the Update chart button is pressed.

Press the “Drawing options” button or right-click in the graph window for a pop-up menu with the following options:

- Select curves …:	select curves to be drawn and select their colors
- Chart area …:	select color of area and border of graph
- Chart title…:	e.g. font, color
- Legend …:	e.g. font, border, placement
- X-axis or y-axis...:	e.g. font, scale
- X-axis or y-axis title…:	e.g. font, color
- Series…:	e.g. color and thickness of the selected curve
- Chart Options…:	e.g. show legend, titles.

The “Reset options” button sets all modified drawing options back to their default settings.

By default only drawdown curves are plotted for (included) observation wells. Similarly only well-face fluxes are plotted for the screened aquifers of all pumping wells. Use the cells in the “Select curves” table to remove individual curves (right mouse click) and to add curves or modify their colors (left mouse click).



The maximum number of curves drawn in the graph is 128.

The accuracy of the calculated graphs can be improved by selecting higher values at the Main menu / Calculate / Preferences:

a) Stehfest parameter: default = 10; options = 6 – 16.
   Effects the accuracy of all computed drawdowns and fluxes.
   A description of Stehfest’s method and a comparison of results as a function of the chosen parameter is given in Hemker & Maas (1987).
b) Number of computations per log cycle: default = 10; options = 2 – 40.

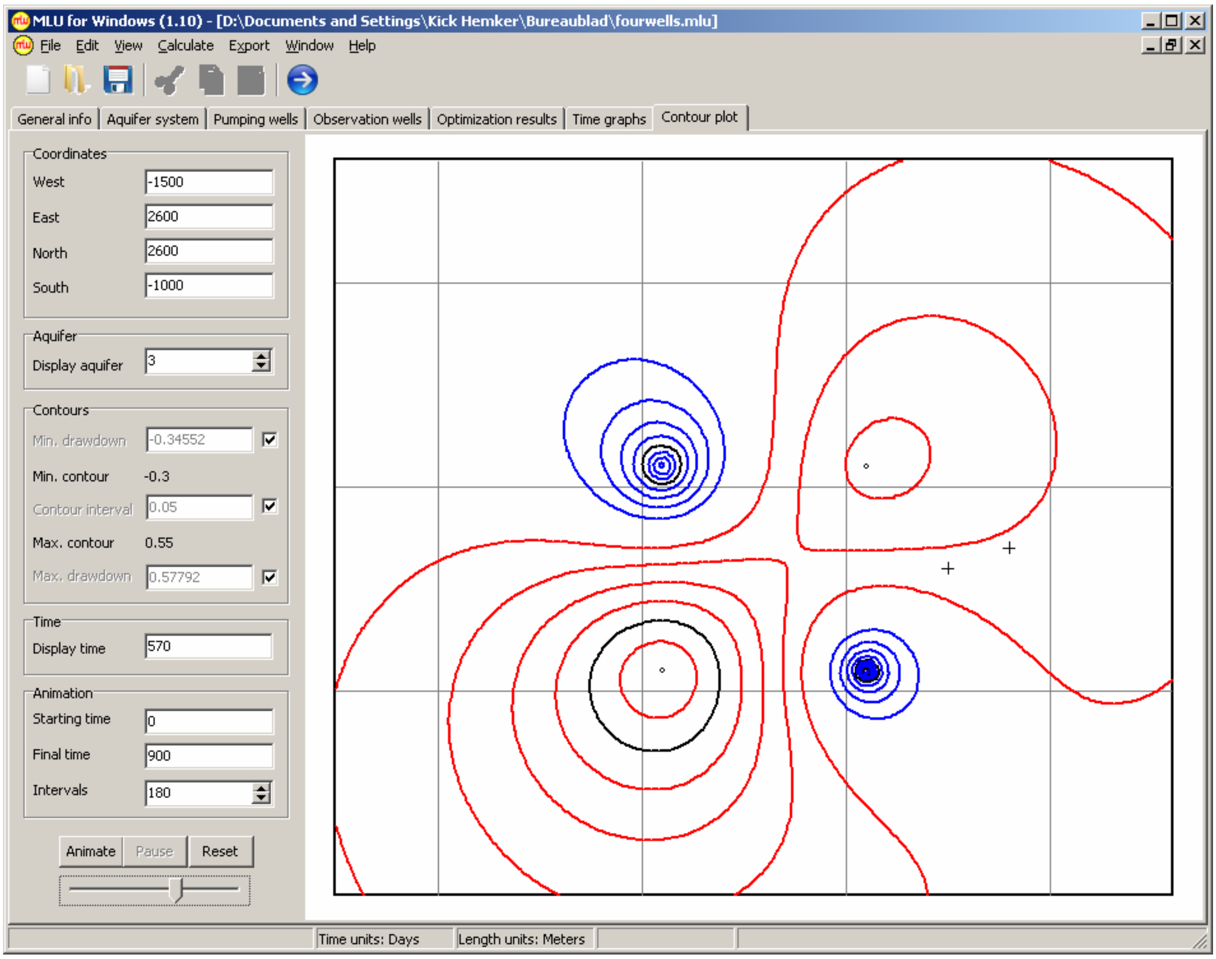
Calculation time increases more or less linearly with these numbers.

For point inspection of observed and calculated drawdowns and well-face fluxes, place the cursor at any particular point or part of a curve. A yellow pop-up window displays the name of the series (as in the legend), the accurate time and corresponding y-axis value of the selected point.

You can save the time graph by selecting in the Main menu: Edit / Copy chart / as metafile or as Bitmap to copy a snapshot of the time graphs to memory. Use Paste to reproduce the figure in your document.

Use Export / Save curves as FTH (File of Times and Heads) to save an ASCII file with all the computed heads or fluxes used to construct the displayed curves on the graph. The file can be opened by e.g. Excel (spreadsheet) and MicroFEM (finite element model). The times and the heads (or fluxes) for each curve are presented in columns.

Results: Contour plot



Only the drawdown contours of a single (selected) aquifer are displayed, together with the location of pumping and observation wells.

Blue contour lines indicate a positive drawdown (negative head); red contour lines a negative drawdown. Zero contours are not drawn. Every fifth contour is black.

During animation a track bar indicates the course of time. If the animation is halted by pressing the Pause button, a single forward or backward time step can be done by pressing one of the arrow keys on the key board. Clicking on the bar, right or left of the indicator will cause the contours to jump two time steps or the indicator can be dragged to a specific time by left-clicking and holding on the indicator itself.

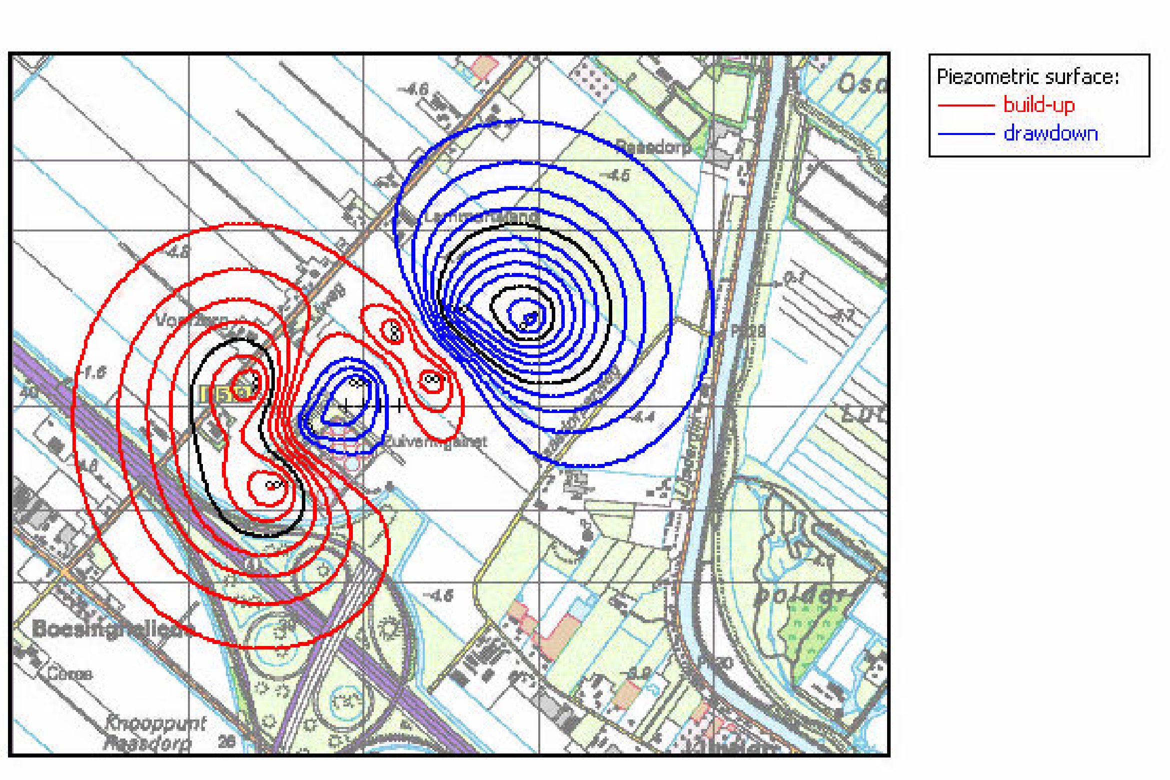
You can save an ASCII file of the contour plot with the x- and y-coordinates and the drawdown values for all points that the contour plot is based on. More details are presented below.

Import (Main menu): Import image files

Rectangular raster image maps can be imported and displayed as background in contour plots. This includes raster files of the types: bmp, png, tif (or tiff), jpg (or jpeg) and gif. Some types of tif-files are not supported: only a grey rectangle will be displayed.

To georeference the image map an associated world file is required with the same file name and the extension .bpw, .pgw, .tfw, .jgw or .gfw respectively.
Further details can be found at http://en.wikipedia.org/wiki/World_file

To import a file use: Main menu Import/Import image files/Add
Several contiguous image maps can be displayed at the same time.



Right clicking in the contour plot//Chart options.../Background allows adjustment of the brightness (transparency). Use Main menu/View/Background images (Ctrl-B) to switch the background images on and off.

All information of loaded image files is saved with an MLU file, to restore the images upon reloading of the project.

Export: Save curves as FTH

When a time graph is drawn, an ASCII file can be saved that contains all computed heads for all included observation wells, from the upper displayed aquifer down to the lowest displayed aquifer. FTH = File of Times and Heads.

The file consists of the following parts. The first three lines contain:

- The header.
- The number of aquifers, the number of observation wells and " 1".
- The actual numbers of these aquifers.

The next four lines show a number for each well, (the last part of) their names and their x- and y-coordinates. This is repeated for each aquifer.

The main part of the file consist of a number of up to 129 columns; the first number on each line represents the time (days), while all the following numbers are calculated heads (or discharges) for all wells and for all aquifers.

Times and discharges are saved in E-format, heads are saved in five decimals.

FTH-files can be read by spreadsheets and by MicroFEM.

Export: Save contours as XYZ

When a contour plot is drawn, a file can be saved that contains all computed drawdowns of the displayed contour plot. Each of the approximately 14000 lines contains three numbers: the x-coordinate, the y-coordinate and the computed drawdown.

XYZ-files can be read by various GIS, CAD and similar mapping or graphics software (Surfer, Arcview).

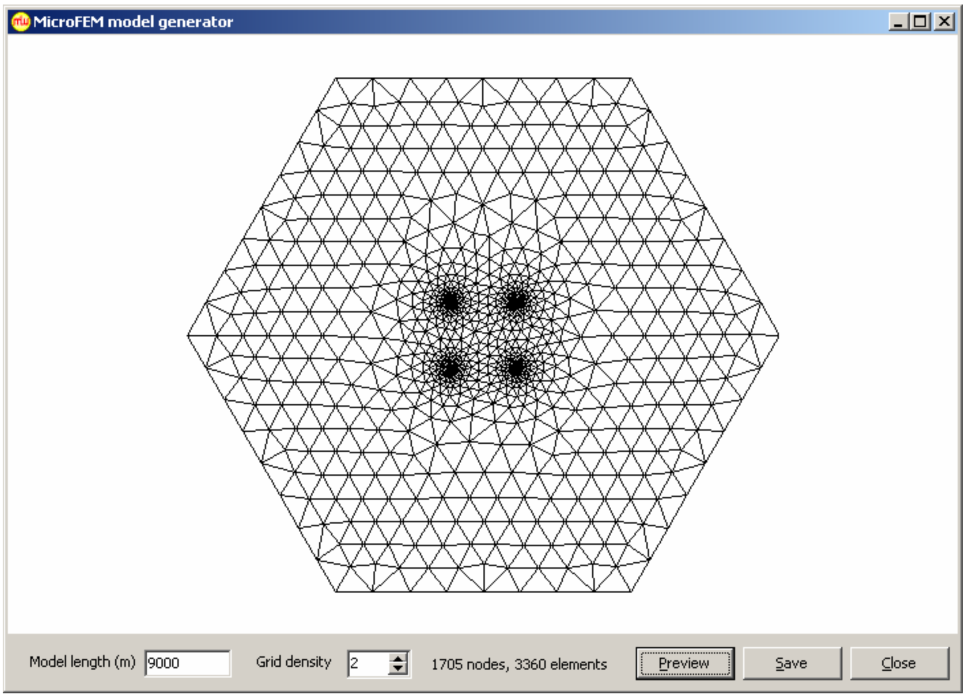
Export: Save model as FEM

Based on the MLU model data, a finite element model can be created and saved as a FEM-file, ready for import by MicroFEM. The number of aquifers is limited to 20 layers. The model shape is always hexagonal, while its length (from West to East) can be specified by the user. The minimum length depends on the system hydraulic characteristics and the maximum length is set to 2.000.000 (m or ft).

The number of nodes may vary between about 1000 and 50.000 for each layer. It largely depends on the specified number for the grid density (1=lowest density; 10=highest density) and the number of wells. Around each well the neighboring nodes are located at a distance equal to six times the screen radius. Nodal distances gradually increase away from each well.

When the Preview button is pressed all nodes are positioned and their total number is displayed. Subsequently the elements are built, which is also displayed as an increasing number at the bottom line. The total number of elements is always nearly twice as large as the number of nodes. The element generation process can be interrupted with the Cancel button. Once the grid is generated, the Save button can be pressed to save the model.

A free version of MicroFEM is available from the MicroFEM site: www.microfem.com. This version is limited to two aquifers and 2500 nodes per layer.



VERIFICATION TESTS AND EXAMPLE MODELS

Verification of MLU for Windows is based on comparison with analytical and numerical solutions of a large number of published test models, e.g. the analytical “moench” model with a partially penetrating well in a phreatic aquifer, and the numerical “two-aquifers” model with piezometers in the aquitard between both aquifers. Also, the file “benchmark.zip”, available from the MicroFEM site, contains five verification tests selected from Ségol’s book: Classic Groundwater Simulations (Cases: 2.1A, 2.1C, 2.2, 6.1.1. and 6.1.2).

Furthermore, a number of MLU example models were set up to demonstrate how some well-known or otherwise interesting well flow problems can be simulated. These example models are supplied with the MLU software and become available in a map “example” upon installation. Example “Bounded aquifer” is used in Ségol’s Case 2.2 verification test.

File name	System	Model layers	Pumping wells	Obs. wells	Optimization parameters	
Bounded aquifer	Confined	1	187	13	0	verification
Dalem-u	Leaky	1	1	4	3	T1 c1 S1
Double-porosity	Confined	2	1	1	3	T2 c2 S2
Fourwells	Phreatic	6	4	2	0	
Moench	Phreatic	6	1	4	0	verification
MW-slugtest	Confined	1	1	2	3	T1 S1 sk1
Recovery	Leaky	2	1	1	3	T1 S1 sk1
Schroth	Confined	2	1	3	7	T1 T2 c2 S1 S2 S’2 rc1
Slugtest	Confined	1	1	1	2	T1 S1
Stepdrawn	Confined	2	6	6	7	T1 sk1 up to sk6
Vennebulten	Phreatic	3	1	2	4	T3 c3 S1 S3
Two-aquifers	Phreatic	6	1	6	0	verification

Main characteristics of the example models

bounded-aquifer.mlu

Ségol (1994) Classic Groundwater Simulations, page 49-51, Case 2.2, Alternative B
Rectangular confined aquifer 9000 * 5000 m
No-flow boundaries at South and West side;
Fixed head boundaries at North and East side.
Solution uses 11 * 17 - 1 = 186 image wells. See e.g. Kruseman & de Ridder (Chapter 6) for a discussion on the use of image wells to model well flow in bounded aquifers.
Drawdowns are obtained along southern boundary for 3 times: 0.05, 0.15 and 2 days.
Comparison with analytical and numerical results (see: "benchmark.zip")

dalem-u.mlu

Kruseman & de Ridder (1994) p. 83-84
Leaky aquifer, 1 pumping well and 4 piezometers (51 observations)
Graphical solution: T=1731 m^2/d; S=0.0019; c=468 d.
Linear drawdown curve fitting: T=1676 m^2/d; S=0.0018; c=328 d.
Log drawdown curve fitting: T=1780 m^2/d; S=0.0016; c=539 d.

double-porosity.mlu

Kruseman & de Ridder (1994) p. 258-261 (after Moench 1984)
Modeled as a two-aquifer confined system. See e.g. Hemker & Maas (1987) for a short discussion on the similarity between layered and fissured formations.
72 observations in pumped well.
Graphical solution: T=333 m^2/d; S=0.0016.
Linear drawdown curve fitting: T=334 m^2/d; S=0.0032.

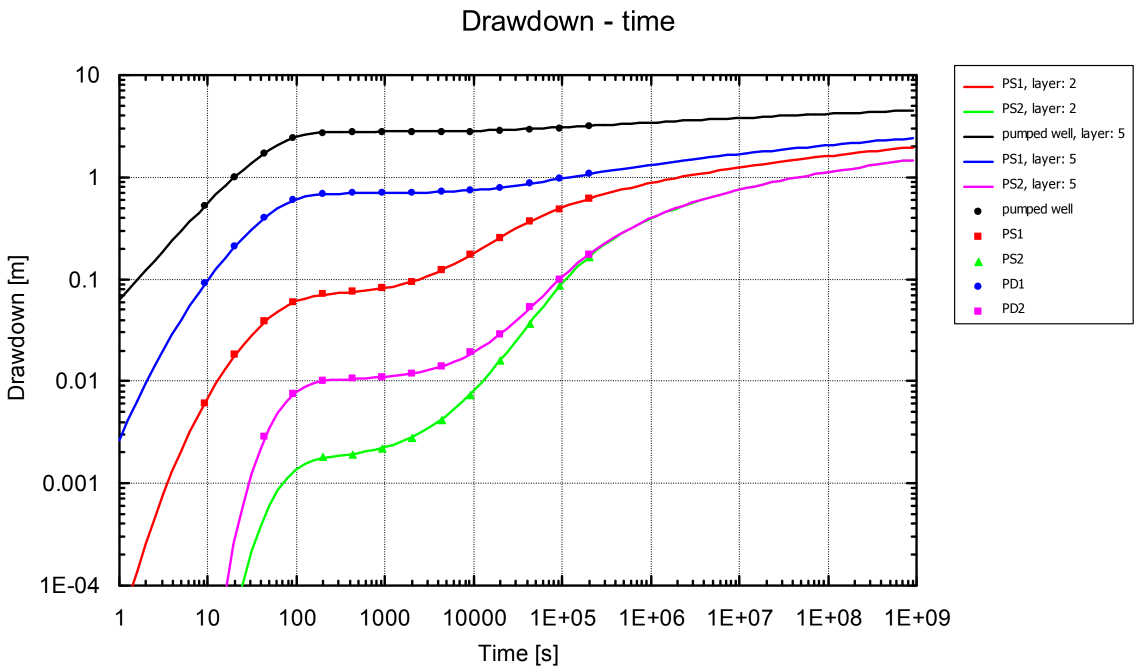
fourwells.mlu

Test example of a 4 wells square ATES (Aquifer thermal energy storage) configuration.
Alternating two-wells discharging and two-wells injecting in a yearly cycle.
Phreatic multi-aquifer system: 6 model layers.
Wells screened in 3rd aquifer = 3 model layers + 2 zero-thickness resistance layers.
Contour plot animation verifies crosswise symmetric drawdown - build-up cone patterns.

moench.mlu

Moench (1997) Flow to a well of finite diameter in a homogeneous, anisotropic water table aquifer: Water Resources Research, v. 33, no. 6, p. 1397–1407. See also Paul M. Barlow and Allen F. Moench, 1999, Water-Resources Investigations Report 99-4225, WTAQ Sample Problem 2. http://ma.water.usgs.gov/publications/WRIR_99-4225/index.htm
Water-table aquifer. Partially penetrating pumping well of finite diameter.
6-Layer MLU model simulates full 3D-analytical solution.

Drawdowns in a partial-penetrating pumping well and 4 piezometers at different distances and different depths in a phreatic aquifer, compared to 3D analytical results (example Moench).



mw-slugtest.mlu

Multiwell slug test = pulse interference test. Butler & Liu (1997). Also: J.J. Butler, The Design, Performance and Analysis of Slug Tests, 1998, p. 191-195. Lincoln County Site, Multiwell slug test #2. Measurements is slugged well and in nearby observation well = 138.
Linear drawdown curve fitting: T = 10.4 m^2/d (2 %), S = 2.1 10^{-5} (4 %), Skin = 1.8 (7 %).
Log drawdown curve fitting: T = 11.4 m^2/d (1 %), S = 1.0 10^{-5} (4 %), Skin = 3.2 (6 %).

recovery.mlu

Well field research program Hardinxveld-Giessendam, 1981, Well B.
Well drawdown measured during 20 minutes pumping and 30 minutes recovery.
Log drawdown curve fitting: T = 1321 m^2/d (1 %), S = 0.00028 (13 %), Skin = 6.1 (4 %).

schroth.mlu

Schroth and Narasimhan (1997) Ground Water 35, p. 371-375.
Confined system of two aquifers and one aquitard with storage. One pumping well.
Drawdown measurements in the pumping well and the two piezometers estimated from published graphs. Optimization parameters are: T1 T2 c2 S1 S2 S'2 and rc1.
Next paragraph shows log drawdown curve fitting results.

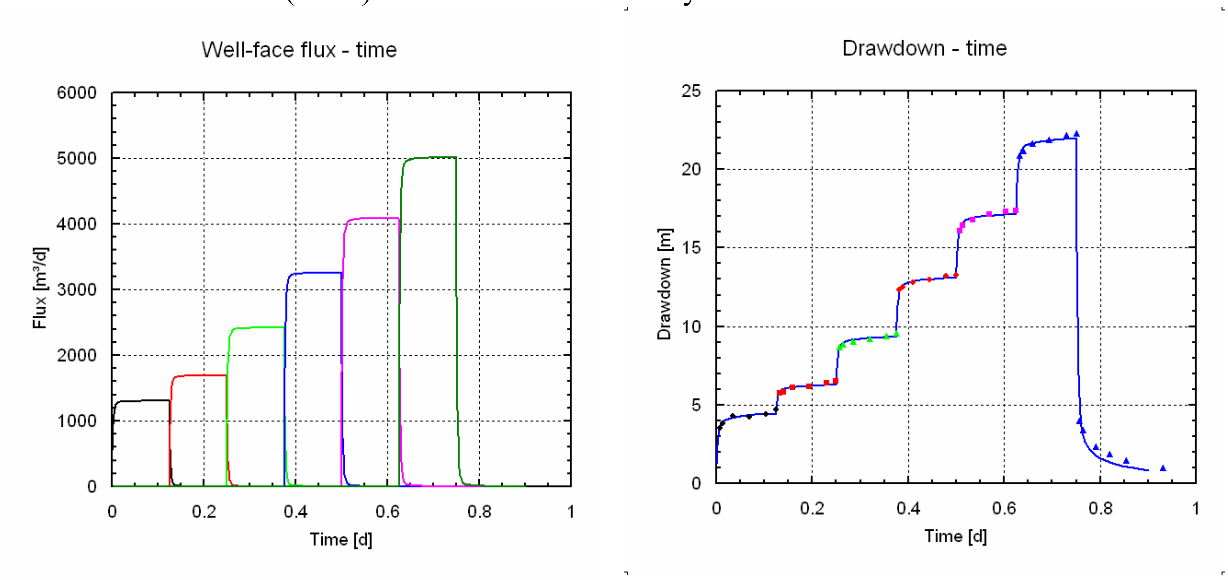
slugtest.mlu

Classical Dawsonville slug test example of Cooper et al. 1967, Table 3.
Also used by e.g. Vedat Batu (1997) p. 667-668.
Slug of 10.16 liter modeled as a pumping rate of 0.1016 m^3/sec during 0.1 sec.
Cooper's method: T = 45 m^2/d, S ~ 10**-3**
Linear drawdown curve fitting: T = 40.6 (4%), S = 0.0019 (29%)
Log drawdown curve fitting: T = 47.3 (4 %), S = 0.00056 (37 %)

stepdrawdown.mlu

Classical step drawdown test example of Lewis Clark (1977) Table 1.
Also used by e.g. Kruseman & de Ridder (1994) p. 203-205.
The increasing skin is modeled with different pumping wells at the same location.
Results: T = 480 m^2/d (7%)

Sk 1 =	1.5 (47%)	Q = 1306 m**3**/d
Sk 2 =	2.2 (35%)	1693
Sk 3 =	2.6 (30%)	2423
Sk 4 =	3.0 (27%)	3261
Sk 5 =	3.4 (24%)	4094
Sk 6 =	4.0 (22%)	5019 + recovery.



vennebulten.mlu

Kruseman & de Ridder (1994) p. 104-106.
Unconfined aquifer pumping test example Vennebulten.
Table 5.1 presents data of the deep and shallow piezometer at 90 m.
Fitting the shallow drawdown measurements requires an additional layer between the pumped aquifer and the water table.

Two-aquifers.mlu

Lebbe & de Breuck (1995) use a synthetic pumping test for the validation of their numerical model. The phreatic system is composed of two aquifers and an anisotropic aquitard, which is discretized in three layers to model elastic storage. Water is discharged from the lower aquifer. Piezometers are installed in the aquitard and in the lower aquifer at three distances.
In two-aquifers.mlu the flow conditions of the numerical model are represented as good as possible by discretizing the aquitard in three layers with horizontal flow and elastic storage, and four layers with vertical flow. The largest drawdown differences occur after one minute of pumping: numerically 0.286 and 0.042 m drawdown at 5.01 and 15.85 m distance respectively, while MLU computes 0.298 and 0.050 m. Of all 151 drawdowns, most differences are 0.001 m or less.

Optimization results Example Schroth.mlu

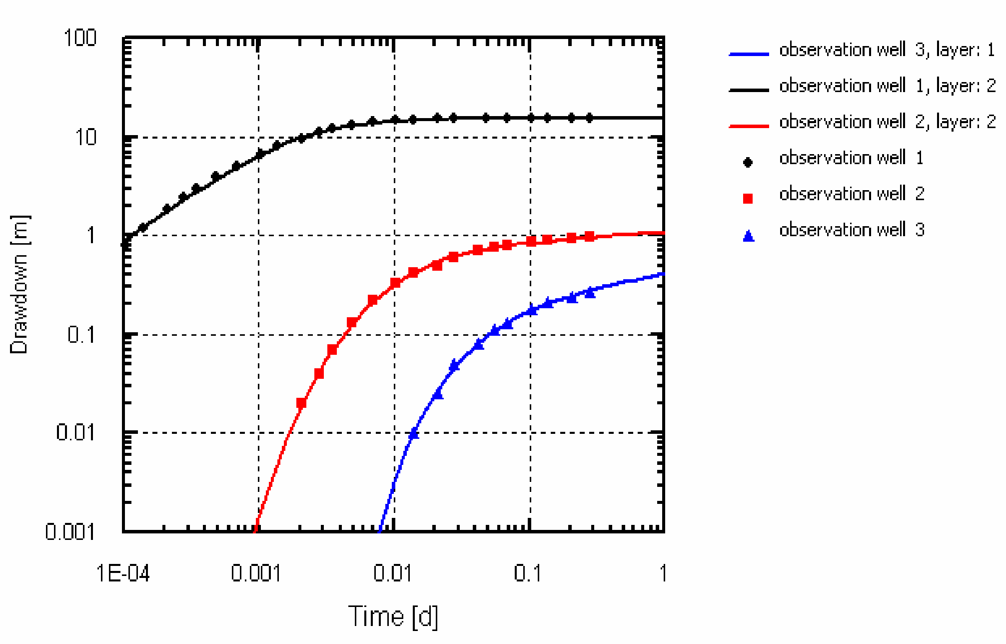
Results of Log drawdown curve fitting.

Parameter value		+	Standard error		
T 1	58.0	+	3.3	(6 %)	Transm. upper aquifer (m^2/d)
T 2	5.156	+	6.381E-2	(1 %)	Transm. lower aquifer (m^2/d)
c 2	248.6	+	6.2	(3 %)	Hydr. resistance aquitard (d)
S 1	4.865E-4	+	5.231E-5	(11 %)	Storativity upper aquifer (-)
S 2	1.678E-5	+	1.030E-6	(6 %)	Storativity lower aquifer (-)
S' 2	1.467E-4	+	9.490E-6	(6 %)	Storativity aquitard (-)
rc 1	5.277E-2	+	4.385E-4	(1 %)	Radius of well casing (m)

Initial sum of squares is	2.7390
Residual sum of squares is	0.0131
Residual sum of squares (m^2)	0.6031
Number of iterations	6
Condition number	463.4

Correlation matrix (%)

T 1	100						
T 2	1	100					
c 2	60	21	100				
S 1	-82	-14	-78	100			
S 2	-39	53	-3	43	100		
S' 2	70	3	55	-90	-67	100	
rc 1	1	-25	-6	3	-31	-1	100



MLU data file layout

```
=== MLU data file (c) 2009 Kick Hemker & Vincent Post
=== Multilayer aquifer system - Pumping test analysis
=== MLU Version 1.54.00: www.microfem.nl/products/mlu.html
=== General Information ============================
Name :Schroth & Narasimhan
Test :2 aquifers and 1 aquitard
Loc. :
Date :
Rem. :Ground water Vol 35. no 2 p.371-375   Measured drawdowns are
Rem. :only estimatedfrom the graphs in the paper
Rem. :
Data :parameters = results of S & N
File :schroth
Date :
Rem. :cjh 24 sept 1997  change units to seconds
Rem. :
Rem. :
Rem. :
=== Parameter Optimization ==========================
Rel.: 1.000000E-04
Abs.: 1.000000E-04
Linear drawdown curve fitting
=== Aquifer System =================================
Length    : m
Time      : sec
Top level :       0.00000
No of (sub)aquifers : 2
Top Aquitard : Impervious
Base Aquitard : Impervious
=== Thickness ===  T|c = x === S|S' = x === Name ====
    46.00000  1.000000E+10  0       0.00000  0
     3.00000      57.97095 49  4.861797E-04 52
     3.00000     248.62465 50  1.467240E-04 53
     3.00000       5.15558 51  1.677179E-05 54
   100.00000  1.000000E+10  0       0.00000  0
=== Pumping Wells and Discharges ===================
No. of wells : 1
=== X     Y     Casing x Screen x Skin x Periods Name
     0.00000       0.00000  5.276889E-02 55  1.000000E-01  0       0.00000  0 2 Pumping well 1
 1.000000E-31      82.08000
 1.000000E+08       0.00000
=== Well screens per layer for all pumping wells ====
.
1
=== Observation wells and Drawdowns =================
No. of observation wells : 3
=== X Y Layer Casing x Screen x Skin x drawdowns Name
     0.00000       0.00000 2  2.000000E-02 0  2.000000E-02 0       0.00000 0 24 observation well  1
 1.041670E-04  8.000000E-01
 1.388890E-04       1.20000
 2.083330E-04       1.80000
 2.777780E-04       2.40000
 3.472220E-04       3.00000

[…etc. ]

2.083330E-01  2.400000E-01
 2.777780E-01  2.700000E-01
=== Time graph settings ============================
=== Drawdown curves (reserved for future use): 0
=== Well-face fluxes (reserved for future use): 0
=== Contour plot settings ==========================
=== west east south north start steps final layer del
  -5000.00000    5000.00000  -3000.00000    3000.00000     0.00000    50    10.00000  1  1.000000E-02
```

References

The techniques used in MLU are based on the theory as described in the following publications:

Hemker, C.J. (1984) Steady groundwater flow in leaky multiple-aquifer systems. Journal of Hydrology, 72: 355-374.

Hemker, C.J. (1985) Transient well flow in leaky multiple-aquifer systems. Journal of Hydrology, 81: 111-126.

Hemker, C.J. (1985) A General Purpose Microcomputer Aquifer Test Evaluation Technique. Ground Water 23: 247-253.

Hemker, C.J. and C. Maas (1987) Unsteady flow to wells in layered and fissured aquifer systems. Journal of Hydrology, 90: 231-249.

Hemker, C.J. and C. Maas (1994) Comment on "Multilayered leaky aquifer systems, 1, Pumping well solutions" by A.H.-D Cheng and O.K. Morohunfola Water Resources Research, Vol. 30, No. 11, p. 3229-3230.

Hemker, C.J. (1999a) Transient well flow in vertically heterogeneous aquifers. Journal of Hydrology, 225: 1-18.

Hemker, C.J. (1999b) Transient well flow in layered aquifer systems: the uniform well-face drawdown solution. Journal of Hydrology, 225: 19-44.

You may contact the author hemker@microfem.com for a PDF of the above publications.

References made in the description of the example models:

Barlow, P.M. and A.F. Moench (1999) WTAQ - A computer program for calculating drawdowns and estimating hydraulic properties for confined and water-table aquifers, U.S. Geol. Survey Water-Resources Investigations Report 99-4225, 74 pp.

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Cooper, H.H, J.D. Bredehoeft and S.S. Papadopoulos (1967) Response of a finite-diameter well to an instantaneous charge of water. Water Resour. Res. 3: 263-269.

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Lebbe, L. and W. De Breuck (1995) Validation of an inverse numerical model for interpretation of pumping tests and the study of factors influencing accuracy of results. Journal of Hydrology, 172: 61-85.

Moench, A.F. (1984) Double-porosity models for a fissured groundwater reservoir with fracture skin, Water Resour. Res. 20: 831–846.

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Schroth, B, and T. N. Narasimhan, Application of a numerical model in the interpretation of a leaky aquifer test. Ground water 35: 371-375.

Ségol, G. (1994) Classic groundwater simulations: Proving and improving numerical models. Prentice-Hall. 531 pp.

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