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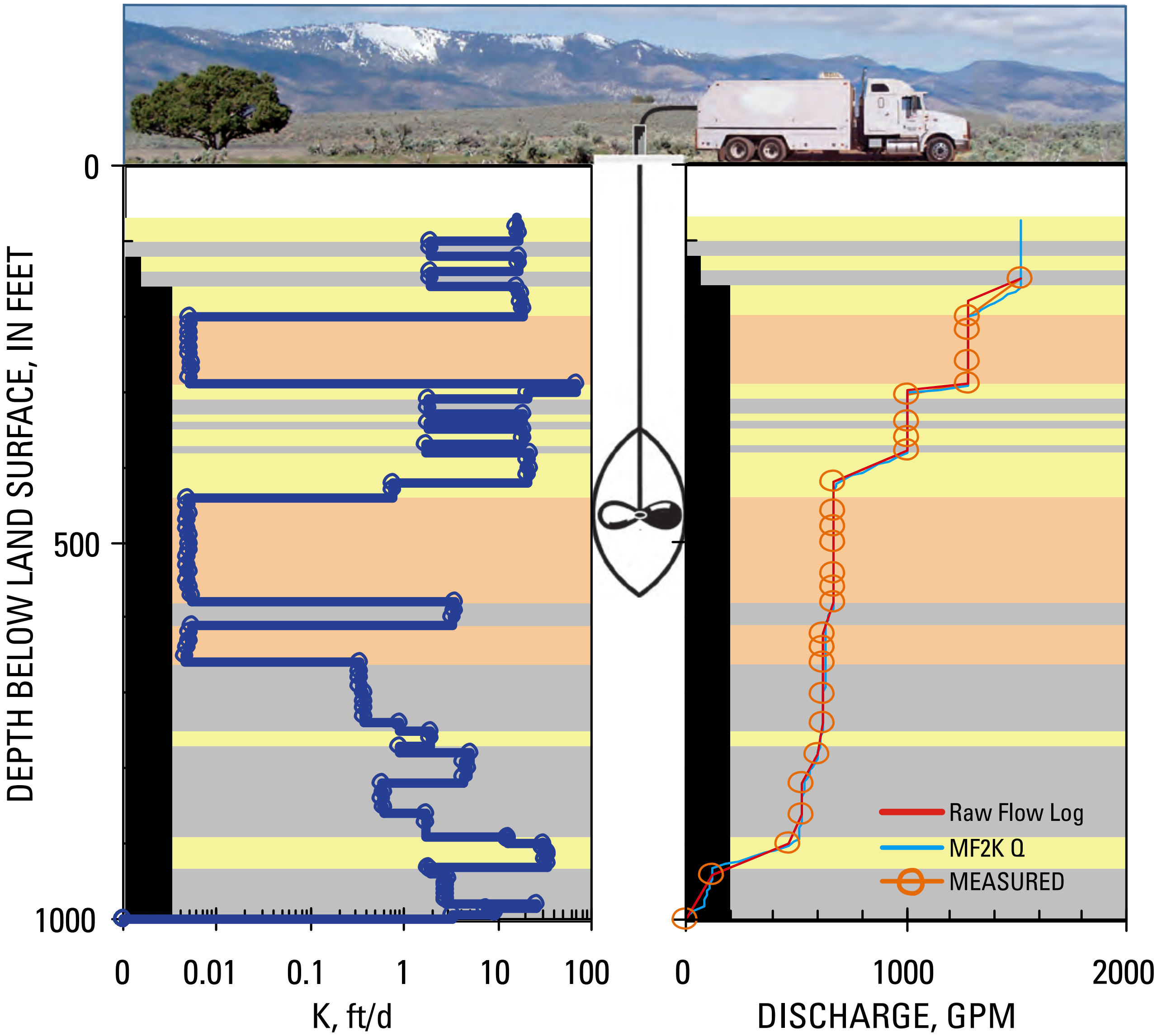
AnalyzeHOLE—An Integrated Wellbore Flow Analysis Tool

Chapter 2 of
Section F, Groundwater
Book 4, Hydrologic Analysis and Interpretation



Techniques and Methods 4–F2

U.S. Department of the Interior
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Cover: An example of logging flow and interpreting results with AnalyzeHOLE.

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By Keith Halford

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Preface

This report documents a spreadsheet interface for the integrated analysis of flow logs, pumping tests, and water quality interpretation. The spreadsheet interface was developed in Microsoft© Excel 2003 and Microsoft© Excel 2007. The spreadsheet interface has been tested for accuracy using multiple datasets. If users find or suspect errors, please contact the U.S. Geological Survey (USGS).

Every effort has been made by the USGS or the U.S. Government to ensure the spreadsheet interface is error free; however, errors may exist in the spreadsheet interface. The distribution of the spreadsheets does not constitute any warranty by the USGS, and no responsibility is assumed by the USGS in connection therewith.

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AnalyzeHOLE—An Integrated Wellbore Flow Analysis Tool

By Keith Halford

Abstract

Conventional interpretation of flow logs assumes that hydraulic conductivity is directly proportional to flow change with depth. However, well construction can significantly alter the expected relation between changes in fluid velocity and hydraulic conductivity. Strong hydraulic conductivity contrasts between lithologic intervals can be masked in continuously screened wells. Alternating intervals of screen and blank casing also can greatly complicate the relation between flow and hydraulic properties. More permeable units are not necessarily associated with rapid fluid-velocity increases. Thin, highly permeable units can be misinterpreted as thick and less permeable intervals or not identified at all. These conditions compromise standard flow-log interpretation because vertical flow fields are induced near the wellbore.

AnalyzeHOLE, an integrated wellbore analysis tool for simulating flow and transport in wells and aquifer systems, provides a better alternative for simulating and evaluating complex well-aquifer system interaction. A pumping well and adjacent aquifer system are simulated with an axisymmetric, radial geometry in a two-dimensional MODFLOW model. Hydraulic conductivities are distributed by depth and estimated with PEST by minimizing squared differences between simulated and measured flows and drawdowns. Hydraulic conductivity can vary within a lithology but variance is limited with regularization. Transmissivity of the simulated system also can be constrained to estimates from single-well, pumping tests. Water-quality changes in the pumping well are simulated with simple mixing models between zones of differing water quality. These zones are differentiated by backtracking thousands of particles from the well screens with MODPATH. An Excel spreadsheet is used to interface the various components of AnalyzeHOLE by (1) creating model input files, (2) executing MODFLOW, MODPATH, PEST, and supporting FORTRAN routines, and (3) importing and graphically displaying pertinent results.

Introduction

Flow logs are interpreted conventionally by assuming that hydraulic conductivity is directly proportional to flow change with depth. Parallel flow through adjacent aquifers is assumed for steady state interpretation (Molz and others, 1989). Transient responses of a few aquifer systems can be analyzed with analytical methods, provided that these systems are independent aquifers that communicate exclusively through a wellbore (Paillet, 1998). These analytical methods assume that vertical flow redistribution through aquifer and gravel pack is minimal.

Vertical flow is induced near pumping wells, which can affect flow-log and water-quality interpretations. Well construction can vertically redistribute flow creating anomalous flow increases at the top of screen intervals (Bowman and others, 1997). Upconing to partially penetrating wells also can create anomalous flow increases near the bottom of a screen interval. Hydraulic-conductivity contrasts between formations that are more permeable than the gravel pack are masked by vertical redistribution of flow in the aquifer (Halford, 2000). Erroneous estimates of contributing sources for produced water can cause poor-quality sources to be misidentified (Izbicki and others, 2005).

Predicting vertical flow near pumping wells is critical where well construction is modified to improve produced water quality. Deeper units with undesirable constituents, such as arsenic, potentially can be excluded by grouting or cementing across these intervals. This approach is more likely to succeed where units with undesirable constituents are less transmissive than the overlying units and less permeable units exist between these productive units. Predicting how changes in well construction will affect produced water quality requires a model that simulates vertical and horizontal movement of groundwater flow. Numerical models are more functional than analytical models for simulating heterogeneities in the flow system and in the wellbore.

AnalyzeHOLE integrates readily available groundwater flow and particle tracking models in a comprehensive tool for analyzing flow-log differences, drawdowns, and water-quality changes. Groundwater flow is simulated with an axisymmetric, radial geometry in a two-dimensional, MODFLOW model (Harbaugh and others, 2000). Hydraulic conductivities of aquifer and wellbore annulus are estimated with PEST (Doherty, 2005). Lithology distributions inform hydraulic conductivity estimates through regularization. Water-quality changes in the pumping well are simulated with simple mixing models between zones of differing water quality. These zones are differentiated by backtracking thousands of particles from the well screens with MODPATH (Pollock, 1994). The interface for AnalyzeHOLE is an Microsoft© Excel spreadsheet (fig. 1).

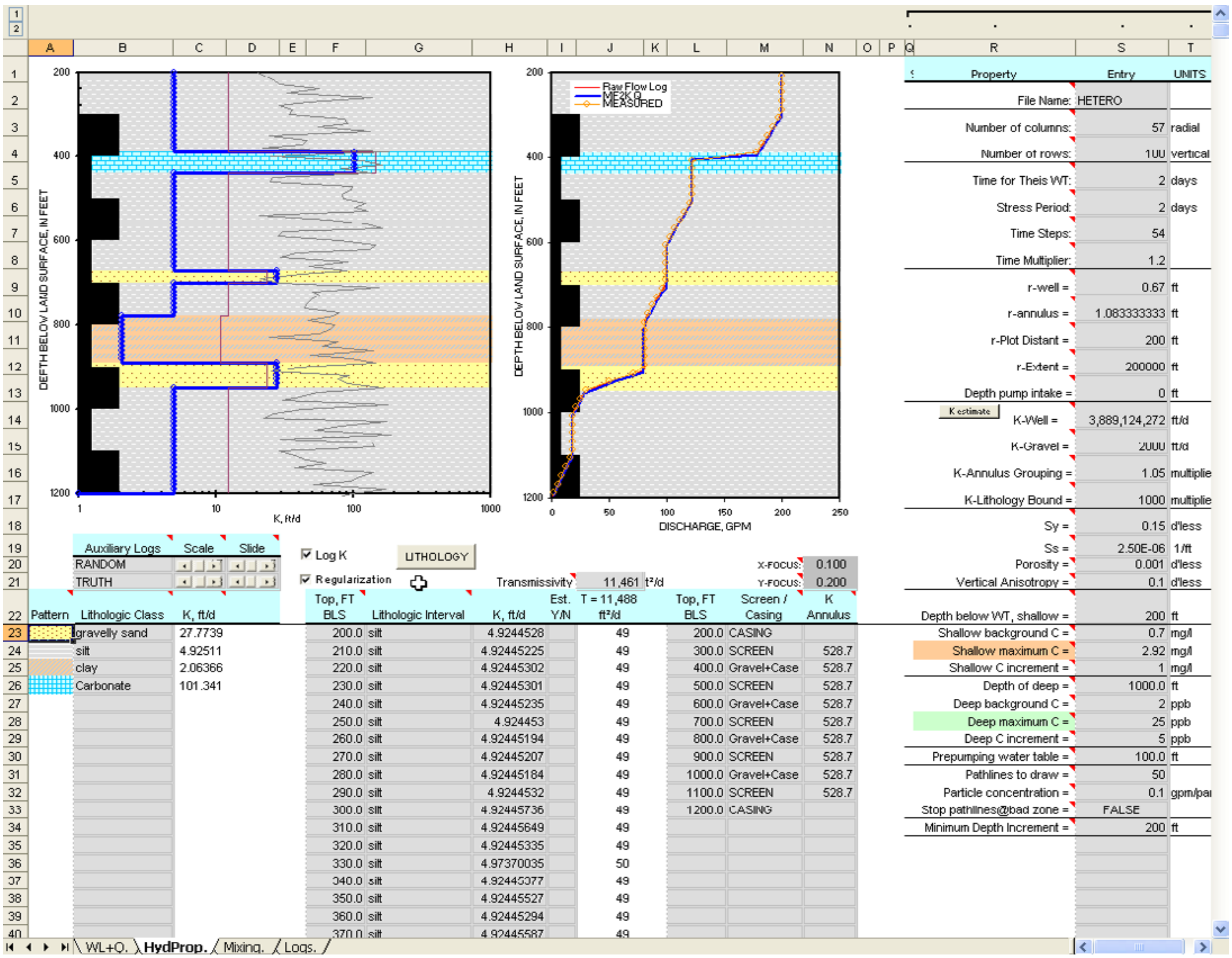


Figure 1. Worksheet used for defining vertical hydraulic conductivity distribution, lithology, well construction, and viewing results.

Purpose and Scope

The purpose of this report is to document an approach for the consistent and integrated analysis of flow logs, drawdowns, and water-quality changes through the use of numerical models. Simulated flow and drawdown in the pumping well are fitted to measured values by minimizing a composite, sum-of-squares objective function. These approaches and methods are implemented in a spreadsheet interface, AnalyzeHOLE. The spreadsheet interface is compatible with Microsoft® Excel versions 10.0 or higher. Use of the spreadsheet interface requires basic knowledge of Excel. Use and applicability of this software is documented in this report. The hydrologic concepts and methods used in the data processing also are described briefly.

Approach

Changes induced by a pumping well are simulated with AnalyzeHOLE so all results are compared to measured differences to eliminate wellbore and other environmental effects. The approach analyzes differences between two flow logs that were measured under quasi-steady state conditions at two different, steady pumping rates (Molz and others, 1989). Ambient conditions in a wellbore with no pumping also can be a pumping rate. Alternatively, a single, stressed flow log can be analyzed when ambient wellbore flow can be assumed negligible compared to wellbore flow that was induced by pumping. Drawdowns in the pumping well provide a means to estimate transmissivity and skin effects. Drawdowns in adjacent observation wells also can be compared to better characterize the water-transmitting properties of the aquifer system. Hydraulic properties are estimated by minimizing differences between simulated and measured observations.

AnalyzeHOLE was developed primarily in Excel to support data entry, facilitate parameter estimation, and visualize simulated results. Lithology, hydraulic properties, well construction, and pumping flow log or differenced flow log are specified by the user (fig. 1). AnalyzeHOLE creates all necessary MODFLOW-2000 (Harbaugh and others, 2000), MODPATH (Pollock, 1994), ModelViewer (Hsieh and Winston, 2002), and PEST (Doherty, 2005) input files. Batch files for executing associated FORTRAN programs also are created. Groundwater flow and particle-tracking results for a single simulation can be executed and imported directly from the AnalyzeHOLE console. Parameter estimation is done using PEST and is executed remotely with a batch file that is written to the directory with AnalyzeHOLE. Parameter estimation is not executed from the AnalyzeHOLE console because most optimization problems are not quickly solved.

Groundwater Flow

The aquifer system and pumping wells are simulated with an axisymmetric, radial geometry in a one-layer MODFLOW-2000 model. Radial distance increases with increasing column indices and depth increases with increasing row indices. Hydraulic conductivities and storage coefficients of the *i*th column are multiplied by $2\pi r_i$ to simulate radial flow; where, r_i is the distance from the outer edge of the first column to the center of the *i*th column. Interblock transmissivity is weighted logarithmically to simulate the linear change in hydraulic conductance within a single finite-difference cell (Langevin, 2008). Axisymmetric, radial flow previously was solved with MODFLOW by using many layers and a single row (Rutledge, 1991; Reily and Harbaugh 1993; Clemo, 2002). A single MODFLOW layer is more convenient because input is defined easily, all conductances are computed within the Block-Centered Flow (BCF) package, and output is quickly checked.

The MODFLOW model is discretized uniformly with depth, which is simulated with rows. Vertical discretization is uniform because the hydraulic conductivity profile initially is unknown and transient leakage from confining units is assumed to minimally affect the simulated flow log. The aquifer system is simulated across the range of depths where lithologic intervals have been specified. An unconfined aquifer system is simulated where the initial depth to water is deeper than shallowest lithologic interval. Dry rows are simulated as inactive cells and storage coefficients in the uppermost active row equal specific yield. Drying and wetting of cells are prohibited. A confined aquifer system is simulated where the initial depth to water is shallower than the shallowest lithologic interval and all storage coefficients equal specific storage times row thickness. The last row is the base of the aquifer system that is assumed to be an impermeable boundary.

Drawdowns and flow differences are simulated directly so initial heads are zero throughout the model. Water is injected so that all simulated head changes are positive and equivalent to drawdowns. Simulation is limited to one pumping rate during aquifer testing so a single stress period of greater duration than the aquifer test is assigned. Simulated wellbore flows are extracted for viewing and comparison to measured flows at the end of the stress period. The simulated flow log is scaled to the measured flow log by the ratio of pumping rates if aquifer-test and flow-log pumping rates differ.

Flow in the pumping well is simulated as turbulent pipe flow through the use of an equivalent hydraulic conductivity in column 1 (Halford, 2000). Equivalent hydraulic conductivities of wells with diameters between 4 and 36 in. range from 0.03 to 30 billion ft/d, respectively. A constant injection rate is specified with the WEL package in the uppermost node of the high hydraulic conductivity zone that simulates the wellbore (fig. 2). Flow is distributed in the wellbore by MODFLOW before crossing screens and entering the aquifer.

Well construction and annular fill are simulated with columns 2 and 3, respectively (fig. 2). Casing and screens are simulated in column 2 where cased sections are simulated as impermeable zones and screens are assigned the hydraulic conductivity of the adjacent gravel pack. Gravel packs are simulated as intervals of different hydraulic conductivity in column 3. Effects of well construction, development, and encrustation are simulated by varying hydraulic conductivity of the gravel packs. Cemented annular fill is simulated as an impermeable zone in column 3 and the cells are inactive. Well losses are simulated with hydraulic conductivity of the annular fill rather than skin because skin is difficult to define and comprehend in a heterogeneous aquifer.

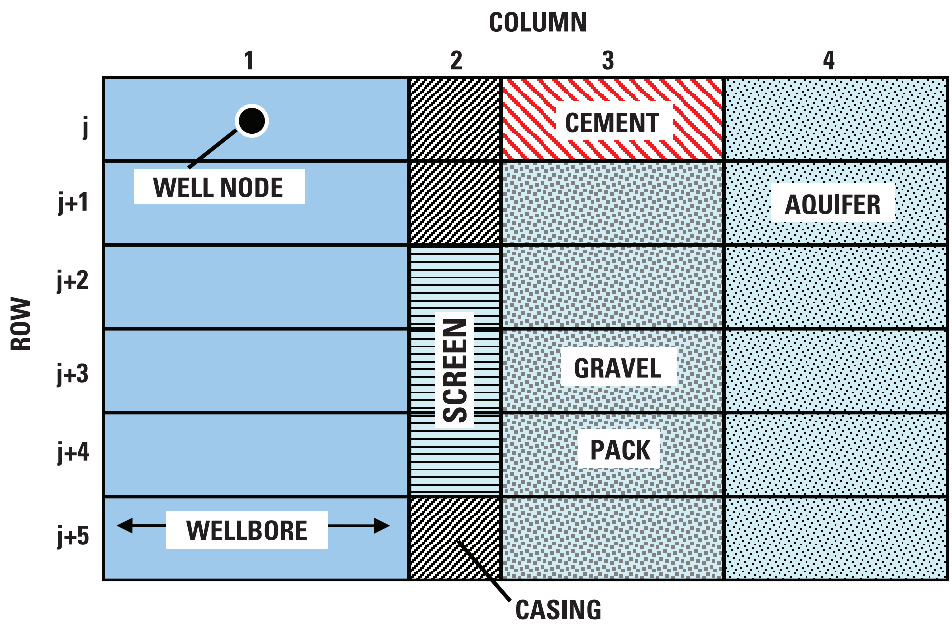


Figure 2. Discretization for simulating wellbore, screen, gravel pack, and the first column of the aquifer.

The aquifer system is simulated beginning with column 4 through the remaining radial extent of the model (fig. 2). Hydraulic conductivities are radially uniform between columns, but can vary with depth between rows. Vertical variations in hydraulic conductivity can be assigned through lithologic classes or directly to each lithologic interval.

Mixing Model

Concentration changes for two water-quality constituents in the pumping well can be simulated with a mixing model. The aquifer is divided into a background zone and maximum concentration zone for each constituent (fig. 3). The maximum concentration zone for the shallow constituent is a user-specified depth below the water table. High total-dissolved solids (TDS) water from return flow is an example of a shallow constituent that can be simulated. The maximum concentration zone for the deep constituent is a user-specified depth below land surface. Elevated arsenic in deeper aquifers is an example of a deep constituent that can be simulated. Shallow and deep zones are fixed by the user and do not change volume in response to pumping. This approach assumes that the pumping well is the dominant stress.

Particles are back-tracked from the well screens with MODPATH to estimate shallow-constituent and deep-constituent concentrations in the pumping well. Particles are seeded in screen cells in column 2 (fig. 2) and are distributed proportionately to the simulated flow into each cell. Each particle then simulates the same amount of flow into the pumping well. The shallow and deep zones are specified as places where particles stop. Particle travel times between screens and the two zones and stopping depths are computed by MODPATH and imported into AnalyzeHOLE. Stopped particles are separated between shallow and deep by stopping depths.

Constituent concentration in the ith zone, $C(t)_i$, at time t is

$$C(t)_i = \frac{n(t)_{i-STOPPED}}{N}(C_{Maximum} - C_{Background}) + C_{Background}, \quad (1)$$

where

$n(t)_{i-STOPPED}$ is the number of stopped particles at time t in zone i,

N is the number of released particles,

$C_{Maximum}$ is the maximum concentration of constituent i, and

$C_{Background}$ is the background concentration of constituent i.

The index i is limited to 2 because only two constituents, shallow and deep, are tracked. For example, the shallow concentration is 7.11 after 5 days of pumping because three of the nine particles stopped in the shallow zone (fig. 4).

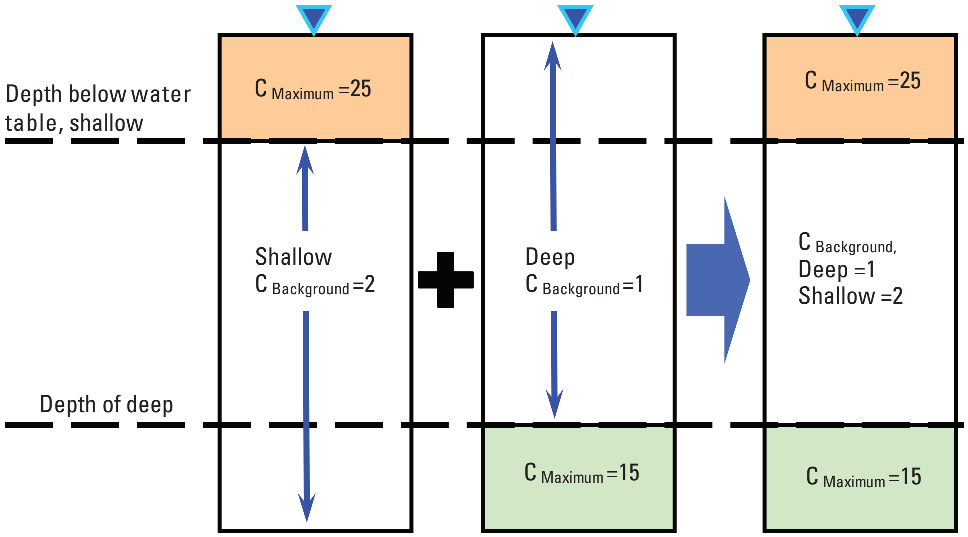


Figure 3. Shallow and deep zones where water-quality constituents have concentrations that are greater than background concentrations.

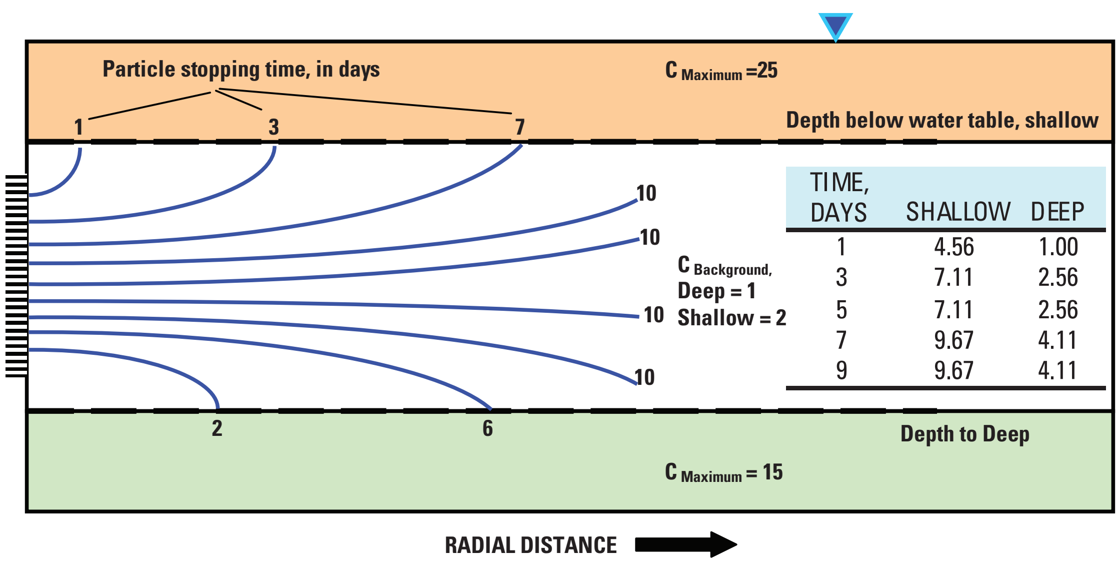


Figure 4. Nine particle example for computing shallow and deep constituent concentrations in a well that was pumping for 10 days.

Parameter Estimation

Hydraulic conductivities of the aquifer system and gravel pack are estimated with PEST (Doherty, 2005) by minimizing a composite, sum-of-squares objective function, which includes measurement and regularization observations. Measurement observations include flows, drawdowns, and transmissivity. Tikhonov regularization observations minimize hydraulic conductivity differences within each lithologic class. Hydraulic conductivities of the aquifer system are subdivided into a series of intervals that are less than or equal to the number of model rows. Intervals must be thicker than a model row and should be adjusted to coincide with screen-casing joints and lithologic contacts. Hydraulic conductivity is uniform in each of these laterally extensive intervals.

Hydraulic conductivities of the aquifer system can be estimated by lithologic class or each defined interval. A single hydraulic conductivity is estimated for each lithology if estimated by lithologic class. This approach is best for estimating initial hydraulic conductivities. Each hydraulic-conductivity interval also can be estimated independently where lithology constrains parameter estimates through Tikhonov regularization. The variability of hydraulic conductivity estimates in each lithology is minimized when Tikhonov regularization is applied (Doherty and Johnston, 2003).

Hydraulic conductivities of the gravel pack are grouped into parameters by similar initial values. Initial gravel-pack hydraulic conductivities that are within a user-specified multiple of one another are grouped as a parameter to be estimated. For example, annular hydraulic conductivities of 5, 5.5, 10, and 11 ft/d would be 1, 2, or 4 parameters if the grouping multiplier were 3, 1.5, or 1.05, respectively.

Minimum and maximum values limit all hydraulic conductivity estimates with PEST (Doherty, 2005). Minimum and maximum values are specified as a value greater than 1 that is both a divisor and multiplier of the thickness-weighted mean hydraulic conductivity for each lithologic class. For example, hydraulic conductivity estimates of a sand with an initial value of 15 ft/d could range from 1.5 to 150 ft/d if the divisor/multiplier was 10. The divisor/multiplier is identified as the "K-Lithology Bound" in the AnalyzeHOLE global property column.

Measured and simulated wellbore flows, drawdowns, and a transmissivity estimate are compared in the measurement, objective function, which is denoted as PHI in PEST (Doherty, 2005). Wellbore flows affect the relative magnitude of hydraulic-conductivity estimates. Drawdowns constrain overall head loss across the gravel pack and late-time change in drawdown constrains transmissivity of the aquifer system. Drawdown data are entered on the WL+Q worksheet (fig. 5).

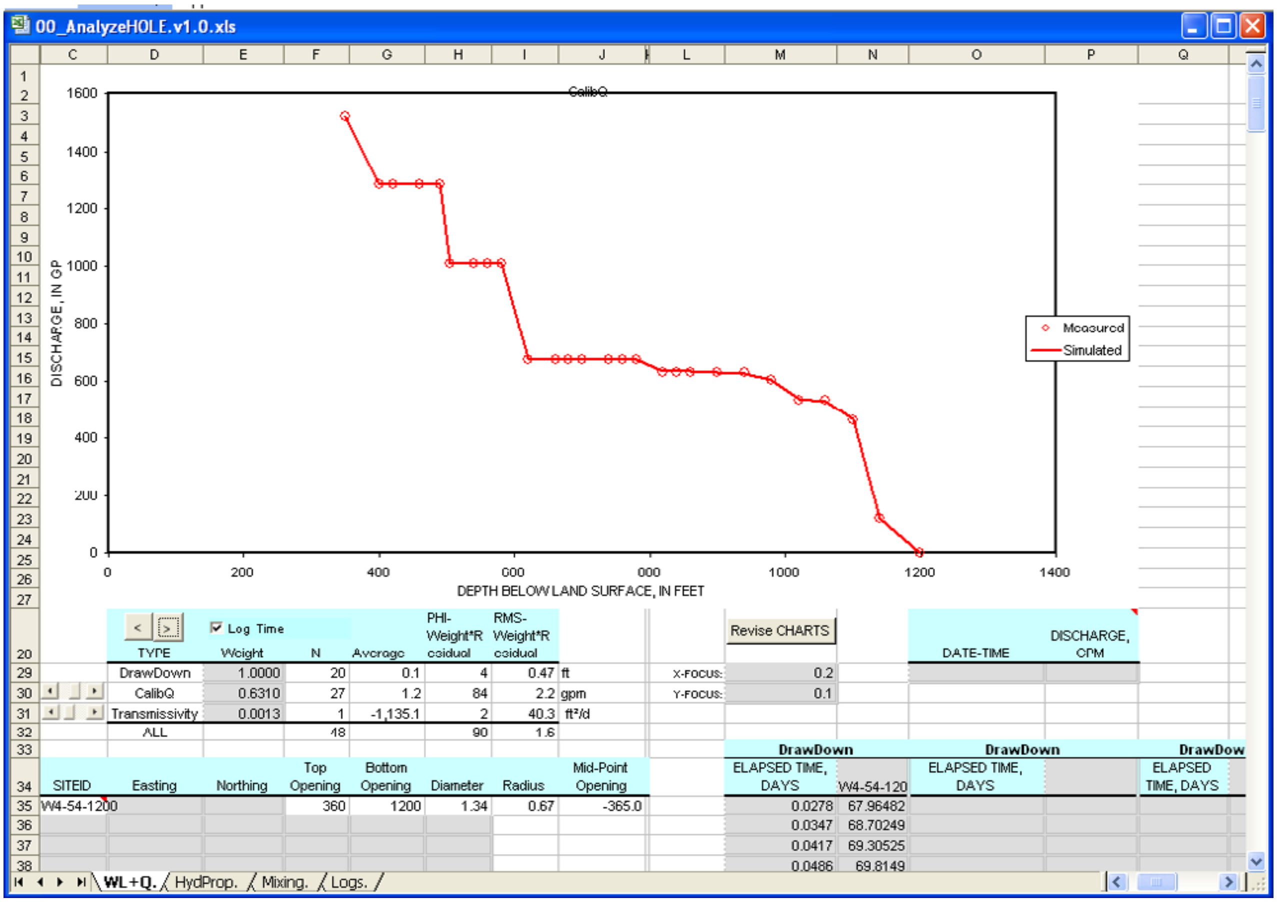


Figure 5. WL+Q worksheet where well locations, discharge, drawdowns, and observation weights are assigned.

Specifying a transmissivity estimate for the aquifer system (fig. 1) allows results from other wells and aquifer tests to constrain interpretation of the flow log when drawdown data are minimal in the logged well. A transmissivity observation is redundant where sufficient drawdown data are available in the logged well.

The relative contribution of observation types; wellbore flow, drawdown, and transmissivity, on hydraulic conductivity estimates are adjusted by weighting the observations. Initial weights typically are decreased for more numerous observations, such as drawdowns, or a numerically greater observation, such as transmissivity. These initial weights are tracked by observation type in PEST and adjusted between optimization iterations so the parameter estimation process is not dominated by a single observation type. Adjustment within PEST can be insufficient if initial discrepancies between observation types are too great. Excessive weighting of an observation type is characterized by a very good fit to just that observation type. Weights are adjusted with the slides in cells C30:C31 on the WL+Q worksheet (fig. 6).

Preferred biases also can influence hydraulic conductivity estimates as additional observations in the composite objective function. These additional observations collectively are referred to as regularization observations in PEST (Doherty, 2005). Regularization observations typically are equations that define assumed relations between two estimated hydraulic properties. For example, the hydraulic conductivity of two sands should be the same.

Lithology affects hydraulic conductivity estimates as regularization observations in the composite, objective function. These observations enforce the assumption that the hydraulic conductivity of each interval with the same lithology should be similar. Lithology is incorporated as an observation, instead of a parameter, so hydraulic conductivities in a lithology can differ where dictated by measurements. This approach is a form of Tikhonov regularization that minimizes differences between parameters and affect the objective function little (Doherty and Johnston, 2003). Regularization also extrapolates estimates to cased sections by minimizing the variability of hydraulic conductivity in a lithology and preserving the transmissivity of the aquifer system. Relative weighting between measurement and regularization observations are adjusted between optimization iterations in PEST as occurs for different types of measurement observations (Doherty, 2005).

The balance between fitting measurements and regularization of parameter estimates is controlled by the sum-of-squares measurement error, PHIMLIM, in PEST (Doherty, 2005). PHIMLIM is estimated in AnalyzeHOLE as,

$$PHIMLIM = 0.01 \sum_{i=1}^{3} w_i n_i \sigma_i , \qquad (2)$$

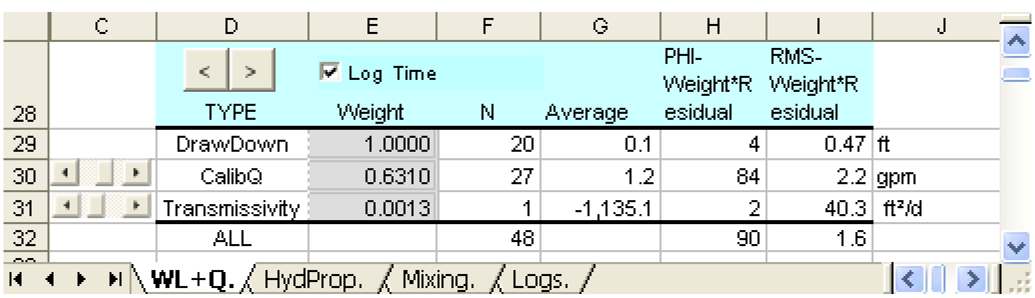
where

w_i is the weight of the ith observation type,

n_i is the number of observations in the ith observation type, and

σ_i is the standard deviation of the observations of the ith observation type.

This is a general approximation that works in many cases. Users should adjust PHIMLIM manually in the file that is written by AnalyzeHOLE, PEST_UserName.PST_commented.txt, where PHIMLIM occurs within 20 lines of the end of the file.



	C	D	E	F	G	H	I	J
28		< > TYPE	Log Time Weight	N	Average	PHI-Weight*Residual	RMS-Weight*Residual	
29		DrawDown	1.0000	20	0.1	4	0.47	ft
30		CalibQ	0.6310	27	1.2	84	2.2	gpm
31		Transmissivity	0.0013	1	-1,135.1	2	40.3	ft²/d
32		ALL		48		90	1.6	

Figure 6. Table and controls for adjusting relative weighting of drawdown, wellbore flows, and transmissivity observations on the WL+Q worksheet.

Example Applications

Application of AnalyzeHOLE is demonstrated with two hypothetical example and two field investigations. The examples,

- 01_MoenchComparison_AnalyzeHOLE.v1.0.xls,
- 02_IdealHetero_A-HOLE.v1.0.xls,
- 03_ER-EC-1_REG_A-HOLE.v1.0.xls, and
- 04_Stockton-CA_A-HOLE.v1.0.xls

are in the subfolder ***ExampleApplications***. The Moench comparison demonstrates that the radial flow equations are solved correctly. Estimating the hydraulic conductivity distribution around well ER-EC-4 at the Nevada Test Site demonstrates indirectly constraining estimates with regularization. Controlling the quality of produced water by altering the completion in well 20N1 near Stockton, California, demonstrates the mixing model.

Analytical Comparison in an Unconfined Aquifer

Solution of radial flow was verified by comparing AnalyzeHOLE results with the analytical solution of flow in an unconfined aquifer (Moench, 1993; Barlow and Moench, 1999). The hypothetical aquifer extended from 125 to 995 ft below land surface and had a horizontal hydraulic conductivity of 8 ft/d, a vertical-to-horizontal anisotropy of 0.1, a specific storage of 2×10^{-6} 1/ft, and a specific yield of 0.25. The hypothetical aquifer was stressed 10 days by pumping 750 gal/min from an 8-in. well that was screened between 600 and 995 ft below land surface (fig. 7). Drawdowns were compared in a pumping well and in four 2-inch observation wells with 20-ft long screens.

The analytical solution and AnalyzeHOLE results differed by less than 1 percent when drawdowns exceeded 0.05 ft except in well R200-D (fig. 8). AnalyzeHOLE simulated about 2 percent less drawdown in well R200-D because flow to the pumping well in the Moench solution is distributed uniformly with depth while AnalyzeHOLE dynamically distributes flow. This resulted in AnalyzeHOLE simulating 3 percent less flow than Moench between 800 and 820 ft below land surface.

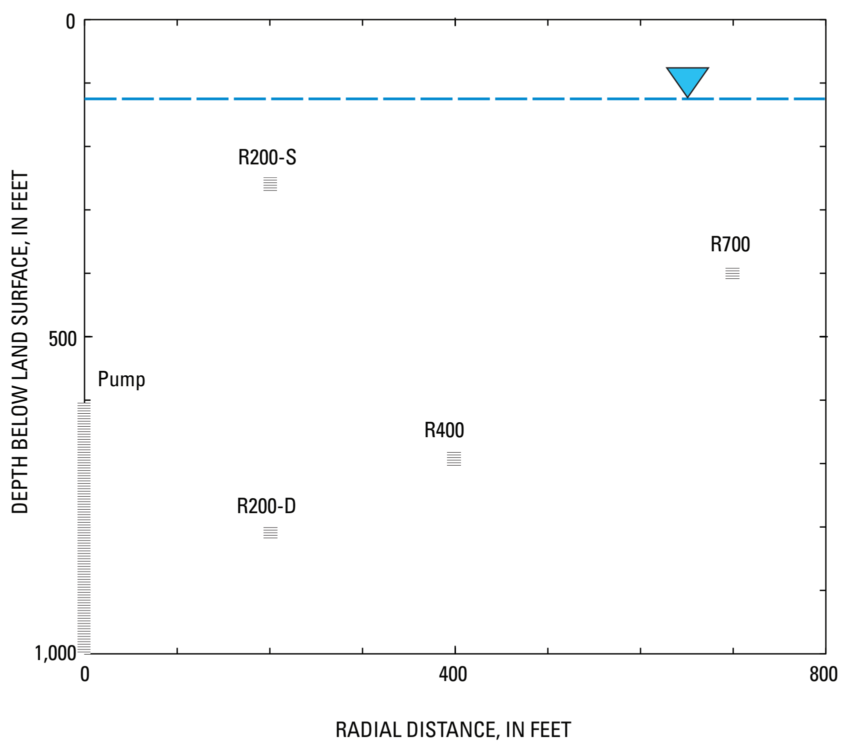


Figure 7. Hypothetical well and aquifer system that was simulated with an analytical solution (Barlow and Moench, 1999) and AnalyzeHOLE.

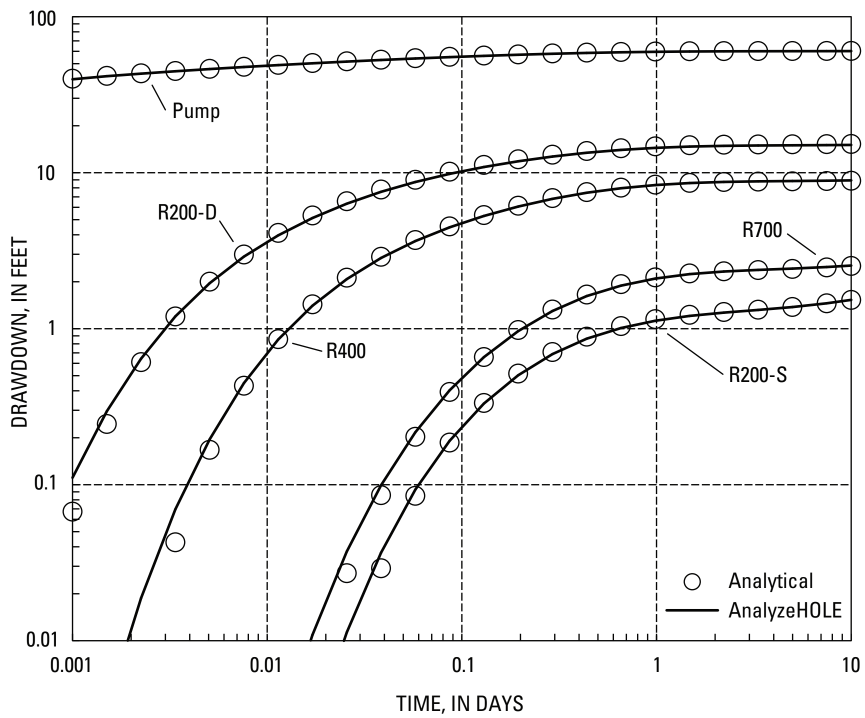


Figure 8. Drawdowns simulated with Moench solution and AnalyzeHOLE during 10 days of pumping 750 gal/min.

Idealized Heterogeneity

Artificial variance of hydraulic conductivity estimates commonly is small because preferred homogeneity is imposed with regularization, which limits the variability of hydraulic conductivity estimates within each lithology. Artificial variability can be introduced as many parameters are estimated if an exceedingly small measurement error, PHIMLIM, is assigned in PEST (Fienen and others, 2009). Tikhonov regularization is rendered ineffective under these circumstances because hydraulic conductivity estimates are fitted to measurement noise. The robustness of Tikhonov regularization as applied in AnalyzeHOLE is illustrated with a hypothetical, piece-wise heterogeneous aquifer system.

The magnitude of artificial variance in hydraulic conductivity estimates was investigated with a hypothetical aquifer system and pumping well model. The hypothetical well penetrated 1,000 ft of gravelly sand, silt, clay, and carbonate where the water table was 200 ft below land surface. The hypothetical well was completed with 100-ft, alternating intervals of screen and blank casing (fig. 9). All four lithologic classes intersect a screened interval although an interval of gravelly sand lies wholly behind blank casing. The hypothetical aquifer system is unconfined and underlain by an impervious base 1,200 ft below land surface.

Measured wellbore flow rates, drawdowns, and transmissivity were defined with the hypothetical aquifer system using known hydraulic conductivities (table 1). Flow in the wellbore was sampled uniformly every 20 ft for a total of 50 flow-rate observations. Twenty drawdowns were sampled between 40 and 240 minutes after pumping started at 200 gal/min. The known transmissivity of the hypothetical aquifer system totaled 11,461 ft²/d. Noise was not added to any of the measurements.

Table 1. Known, averages of estimated, and standard deviations of estimated hydraulic conductivities by lithologic class in the hypothetical, heterogeneous aquifer system.

[Standard deviation of known hydraulic conductivities is 0]

Lithologic class	Number of intervals	Hydraulic conductivity, in feet per day		
		Known	Estimated	
			Average	Standard deviation
Gravelly sand	9	30.0	27.8	0.000082
Silt	75	5.0	4.9	.000002
Clay	11	.1	2.1	.000003
Carbonate	5	100.0	101.3	.000603

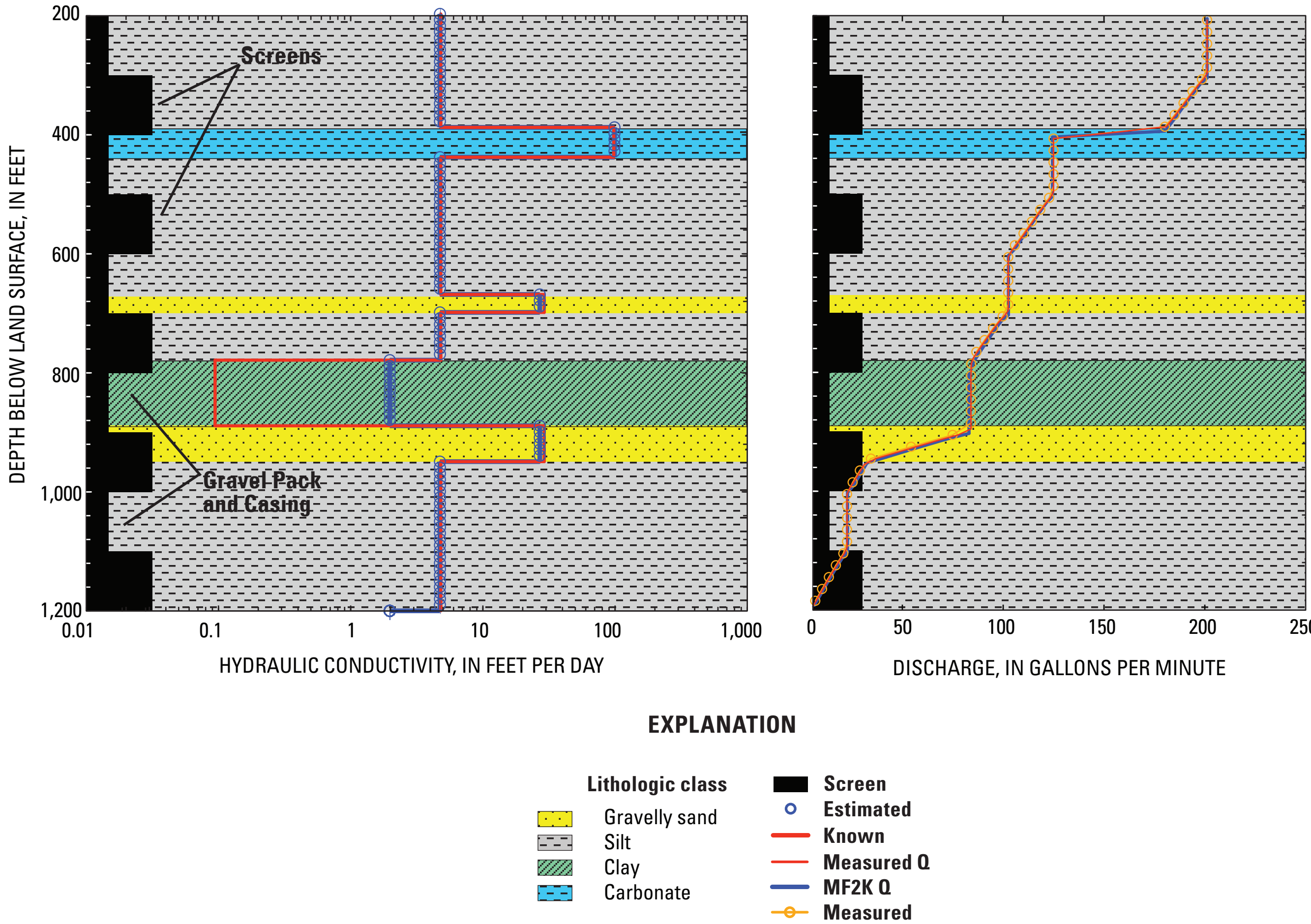


Figure 9. Lithology, well construction, flow logs, and hydraulic conductivity distribution for hypothetical well in a 4-lithology, heterogeneous aquifer system.

The hypothetical aquifer system was divided into 100 lithologic intervals that were each 10-ft thick with uniform initial hydraulic conductivity estimates of 11.46 ft/d. The hydraulic conductivity of each interval was estimated independently, but constrained by lithology with regularization. Flow in the aquifer system was simulated at a finer scale with 200 rows of uniform, 5-ft thickness. The calibrated flow model matches flow measurements (RMS = 0.9 gal/min), drawdowns (RMS = 0.01 ft), and transmissivity (residual = 44 ft^2/d) within the error of the measurements as defined by PHIMLIM.

Artificial variance was virtually non-existent within each lithologic class with the standard deviations of hydraulic conductivity estimates being six orders of magnitude less than the average hydraulic conductivity (table 1). Regularization extrapolated hydraulic conductivity estimates behind cased intervals where hydraulic conductivity contrasts do not directly affect flow-log measurements (fig. 9). Estimating a single hydraulic conductivity for each lithologic class would have yielded similar results.

The average hydraulic conductivity of clay was the only estimate that departed greatly from the known value because of the extreme range of hydraulic conductivities between clay and carbonate (table 1). The extreme range exceeded the detection limit of flow logs. The detection limit of hydraulic conductivity from a flow log is proportional to cumulative ungaged flow times the total thickness of non-contributing intervals divided by the transmissivity of the aquifer system (C.A. Garcia, U.S. Geological Survey, written commun., 2009). Cumulative ungaged flow optimistically totals 1 percent of the pumping rate.

Well ER-EC-4, Nevada Test Site

Well ER-EC-4 penetrated 3,500 ft of volcanic rock in western Pahute Mesa, Nevada Test Site where the water table is 750 ft below land surface. Well ER-EC-4 was completed with predominantly blank casing separated by three, 200-ft intervals of alternating 40-ft sections of screen and blank casing (fig. 10). The annular space behind the intervals

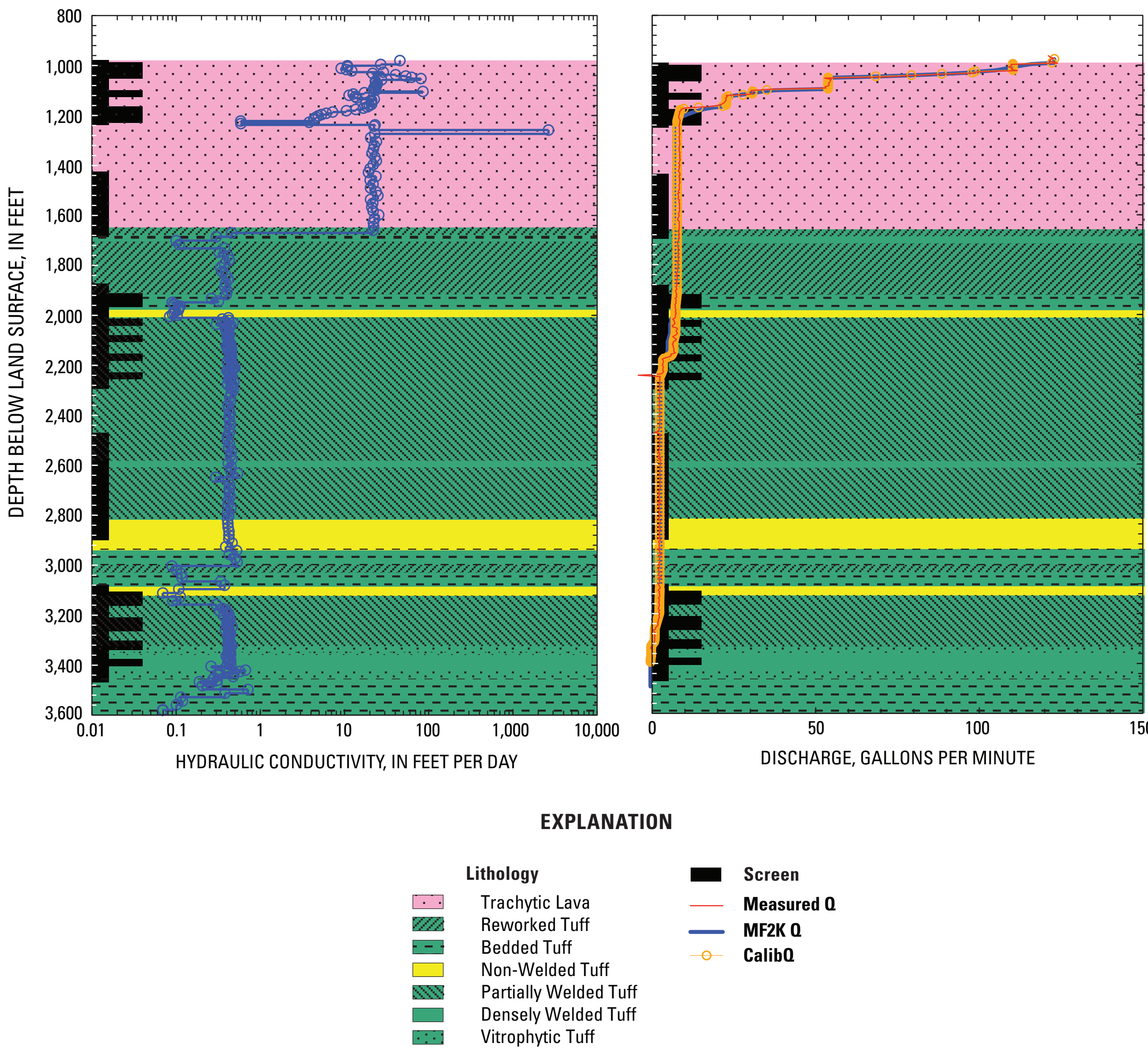


Figure 10. Lithology, well construction, flow logs and hydraulic conductivity distribution for well ER-EC-4.

of alternating screen and casing is gravel and cemented elsewhere. Trachytic lava, welded, and non-welded tuffs are the dominant lithologic classes. Seven lithologic classes exist and all intersect a screened interval (fig. 10). The aquifer system is overlain and confined by a non-welded tuff at 980 ft below land surface.

The hydraulic conductivity distribution in well ER-EC-4 was estimated from multiple flow logs and results from a 5-day, single-well aquifer test. Simulated wellbore flow was fitted to differences between flow logs that were measured while surface discharges were 182 and 60 gal/min. The differenced flow log was reduced to a 19-point polyline that decreased monotonically with depth. Discharge during the 5-day aquifer test averaged 182 gal/min and drawdowns ranged between 8 and 9 ft after the first 15 minutes of pumping (fig. 11). A transmissivity was 60,000 ft²/d was estimated with the Cooper-Jacob (1946) method.

The aquifer system was divided into 252 lithologic intervals that were each 10-ft thick. The hydraulic conductivity of each interval was estimated independently, but constrained by lithology with regularization. Flow in the aquifer system was simulated at a finer scale with 504 rows of uniform 5-ft thickness. The calibrated flow model matches flow measurements (RMS = 2 gal/min, fig. 10), drawdowns (RMS = 0.05 ft, fig. 11), and transmissivity (residual = 131 ft²/d) within the error of the measurements.

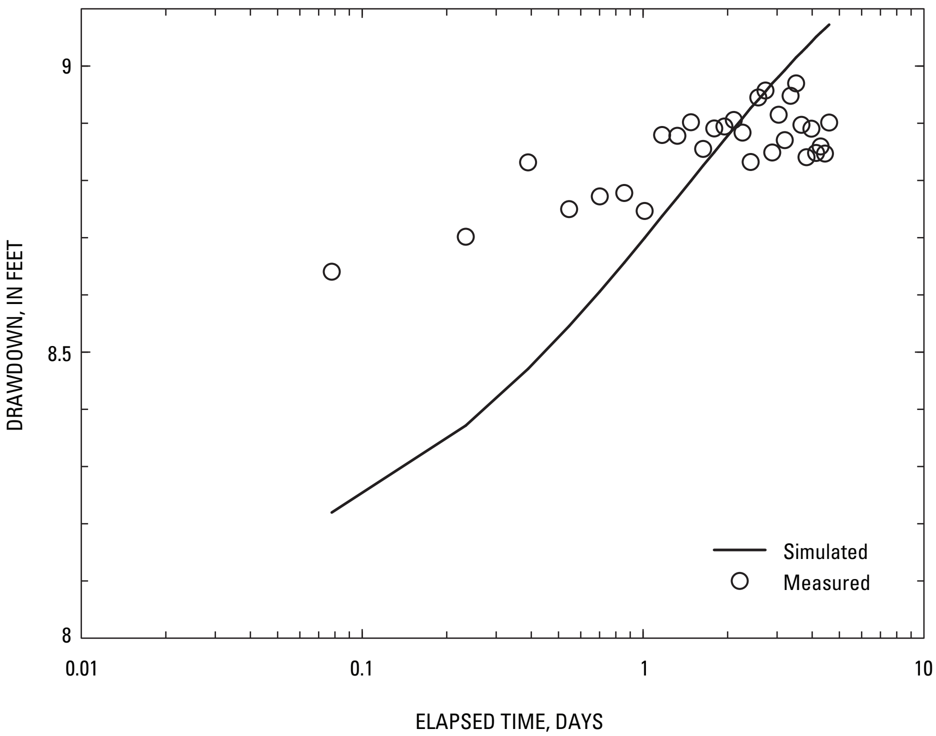


Figure 11. Simulated and measured drawdowns in well ER-EC-4 during 5-day aquifer test that began August 10, 2000.

Hydraulic conductivity estimates for trachytic lava clearly were extrapolated behind cased intervals by regularization. Hydraulic conductivity estimates of the trachytic lava vary more than three orders of magnitude across the screened intervals between 1,000 and 1,200 ft below land surface (fig. 10). The average hydraulic conductivity of 90 ft/d is extrapolated to the 400-ft thick of trachytic lava behind casing. The measureable variability of hydraulic conductivity in the trachytic lava suggests that average hydraulic conductivities should be applied to intervals of more than 100 ft in thickness. Hydraulic conductivity estimates also were extrapolated from screened to cased intervals where bedded and densely welded tuffs are present.

Well 1N/7E-20N1, California

Well 1N/7E-20N1 penetrated 400 ft of unconsolidated sediments in the San Joaquin Delta near Stockton, California, where the water table is about 70 ft below land surface (Izbicki and others, 2008). Well 1N/7E-20N1 was completed with four discrete screens of less than 40 ft where sands had been encountered (fig. 12). The annular space behind the cased intervals of alternating screen and casing is gravel and cemented elsewhere. Gravelly sand, sand, silt, clay and sand, and clay were the lithologic classes and all intersect a screened interval except for the silt (fig. 12). The aquifer system is unconfined and underlain by thick clays more than 400 ft below land surface.

The effectiveness of shortening well 1N/7E-20N1 near Stockton, California, to control arsenic concentrations was investigated with AnalyzeHOLE. Well 1N/7E-20N1 was completed with four screens. Three intervals were screened between 270 and 400 ft below land surface where arsenic concentrations in the aquifer averaged 15 ppb (fig. 12). The potential for water with high arsenic concentrations at depth to upcone was difficult to evaluate without simulation due to the absence of well-defined confining units. The aquifer consists primarily of alternating alluvial-fan and delta deposits. Hydraulic conductivities between the water table and 400 ft below land surface were estimated by calibrating the model to a pumping flow log and drawdowns in well 1N/7E-20N1 (fig. 12). Arsenic concentrations in the water produced from the original four screens in well 1N/7E-20N1 exceeded 9 ppb.

Simulating the grouting of the three screens that were more than 200 ft below land surface caused upconing and reduced produced arsenic concentrations during a 1,000-day simulation period (fig. 13). Arsenic concentrations in the produced water initially decreased to the background concentration of 5 ppb by grouting the lower three screens. Upconing from the deeper zone, where the arsenic concentration was 15 ppb, caused simulated arsenic concentrations in the produced water to increase less than 100 days after grouting well 1N/7E-20N1. Contributions from the deep zone resulted in arsenic concentrations exceeding 7 ppb after 800 days of pumping at a rate of more than 2,300 gal/min.

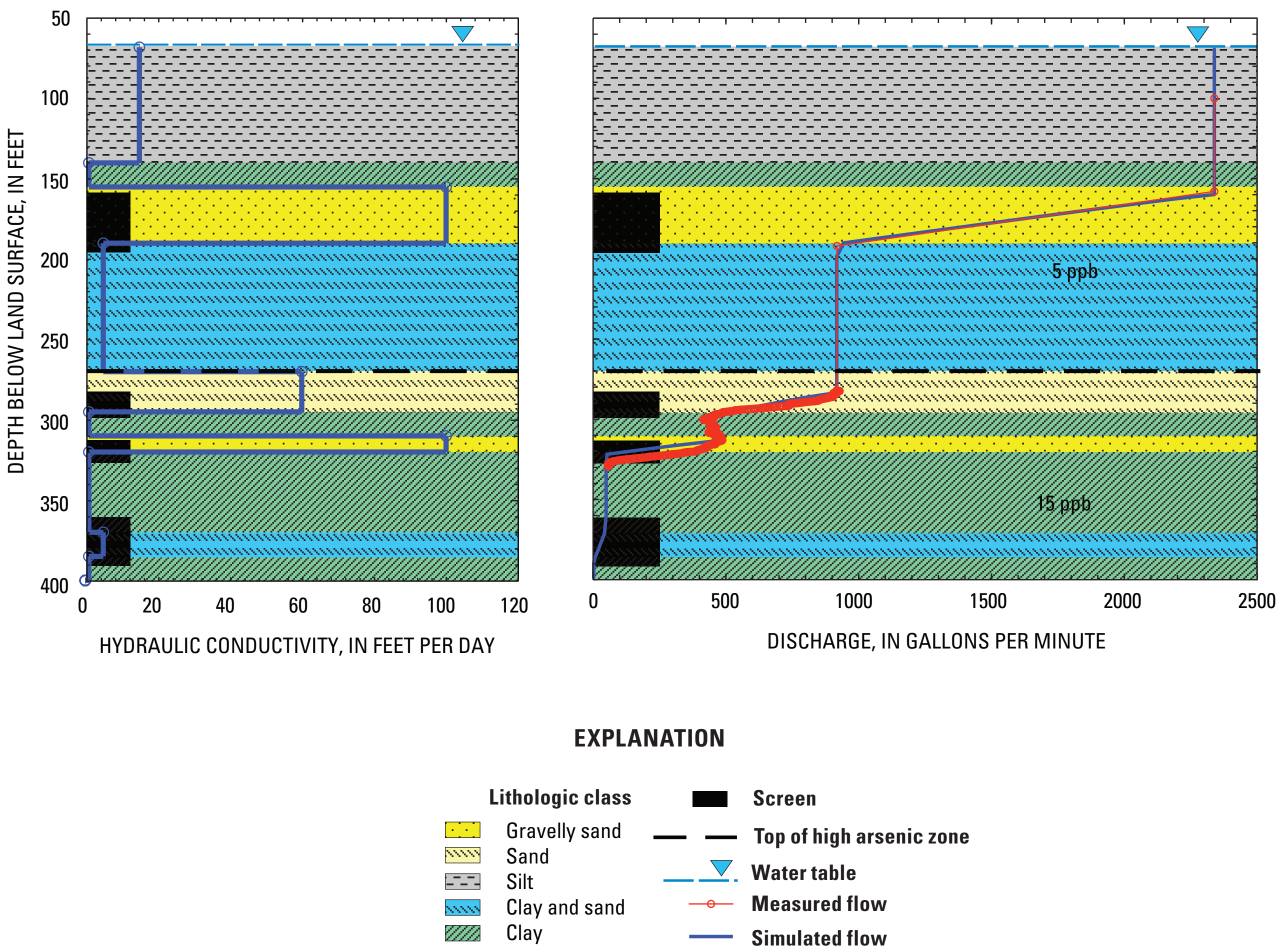


Figure 12. Measured flow log, simulated flow log, hydraulic conductivity distribution, lithology, and well construction of well 1N/7E-20N1, Eastern San Joaquin Groundwater Subbasin, California.

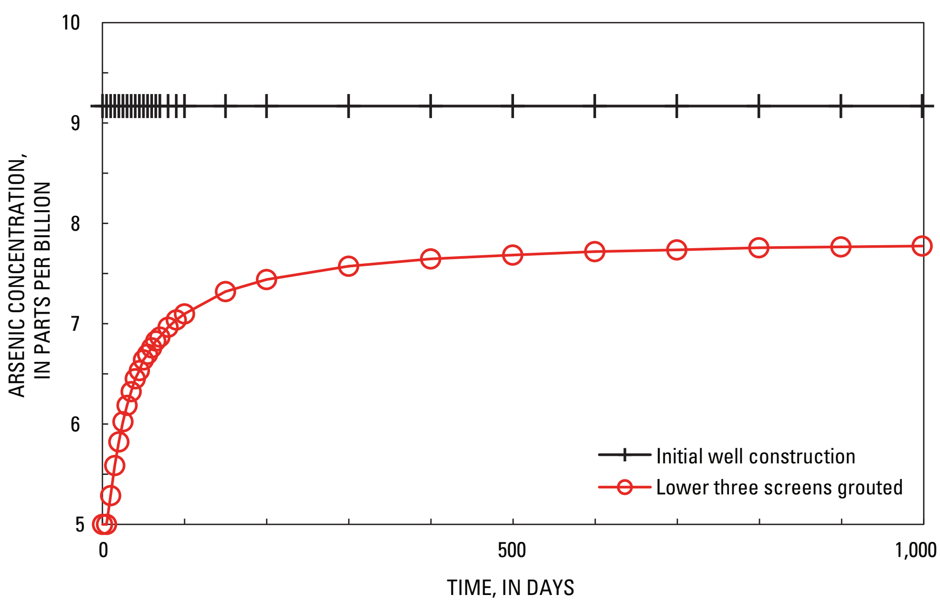


Figure 13. Simulated arsenic concentrations with initial well construction and after grouting the lower three screens in well 1N/7E-20N1.

Description of AnalyzeHOLE

AnalyzeHOLE is an Excel spreadsheet interface for simulating flow logs, drawdowns, and water-quality changes in a pumping well. AnalyzeHOLE contains two dozen worksheets for supporting calculations, code for the creation of ASCII input files for FORTRAN programs through the use of Visual Basic for Applications (VBA), and batch files to execute the FORTRAN programs. Data are entered and results are viewed through four principal worksheets; WL+Q., HydProp., Mixing., and Logs. (fig. 14).

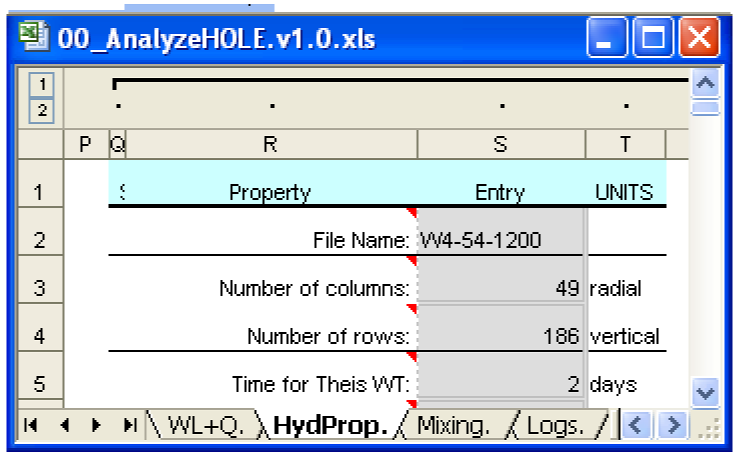
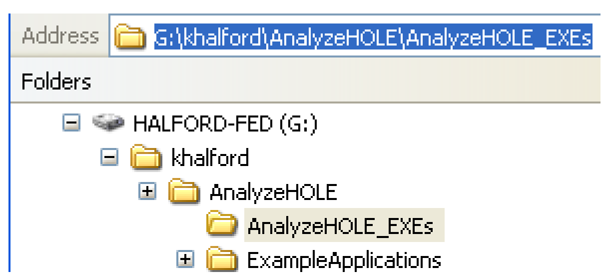
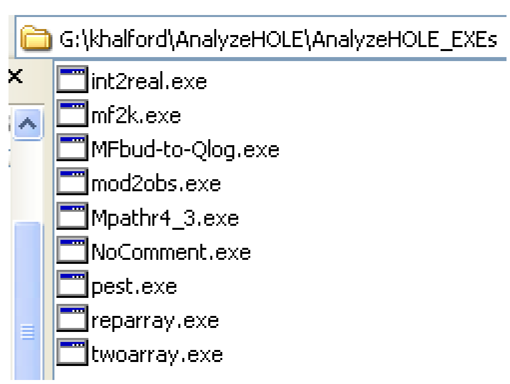


Figure 14. Four principal worksheets for entering data and viewing results.

AnalyzeHOLE calls nine supporting FORTRAN executables through batch files. MODFLOW-2000, mf2k.exe (Harbaugh and others, 2000) and MODPATH, Mpathr4_3.exe (Pollock, 1994) are available independently from the USGS software site, http://water.usgs.gov/software/ground_water.html. MFbud-to-Qlog.exe extracts flow logs from a MODFLOW cell-by-cell file and was developed for AnalyzeHOLE. Parameter estimation is facilitated by the other executables, which comprise PEST and supporting utilities (Doherty, 2005), http://www.sspa.com/Pest/index.shtml.

Installation of AnalyzeHOLE

AnalyzeHOLE creates batch files that call several FORTRAN executables. These executables are best accessed by placing all in a common directory. The directory of executables is added to the PATH variable, which makes the programs available from any location.

<table>
<tr><td>Create a directory for the executables.</td><td>
</td></tr>
<tr><td>Copy all *.exe files into the AnalyzeHOLE directory of FORTRAN executables.</td><td>
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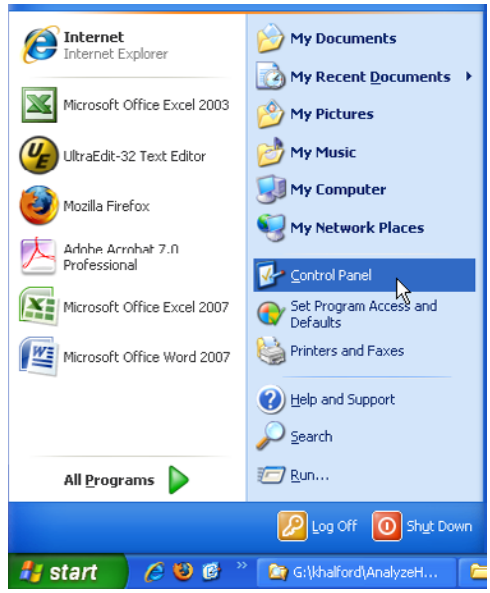
<table>
<tr>
<td>Open the control panel from the Start button.</td>
<td>
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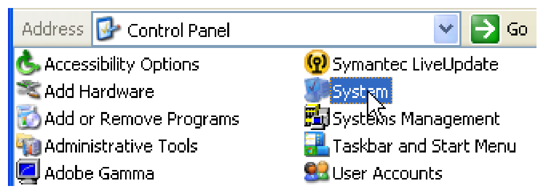
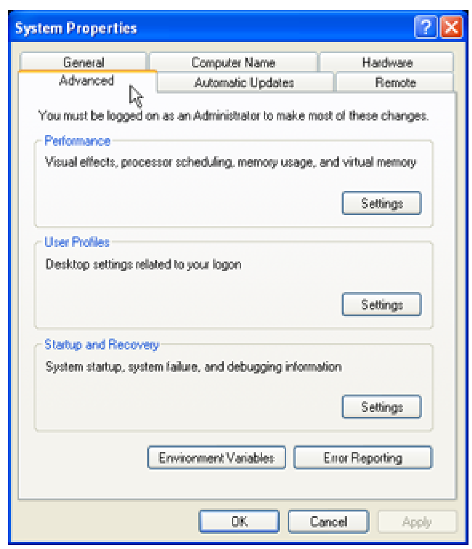
<tr>
<td>Select the System icon.</td>
<td>
</td>
</tr>
<tr>
<td>Select Environment Variables on the “Advanced” tab.</td>
<td>
</td>
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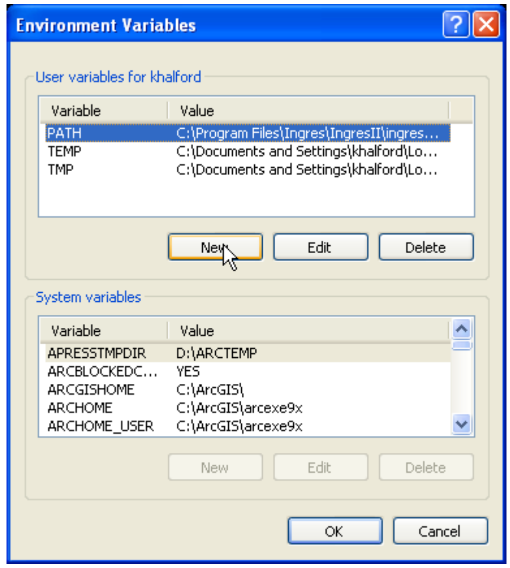
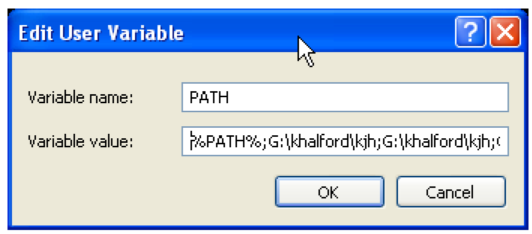
</table>

Select New on the Environment Variables form, which creates the New User Variable form.	
Add the new variable name, "PATH." This contains the previously defined paths, %PATH%, separator, ";" and the full path to the FORTRAN executables for AnalyzeHOLE. The path "G:\AnalyzeHOLE\AnalyzeHOLE_EXEs" was added for illustration.	

Install AnalyzeHOLE

AnalyzeHOLE relies on inherent features of Excel 9.0+ and user-defined macros. The macro security level should be set to Medium in Excel 2003 (fig. 15) or a "Trusted Location" must be established in Excel 2007 (fig. 16) because the program will not function if the macro security level is set to High or Very High. The program will work with a macro security level of Low but this is not advised because all macros, including malicious viruses, are activated without warning upon opening Excel.

Input and heading cells have been identified with consistent formatting. Input cells are formatted with a light gray background and bounded by double lines. Data should be entered by either typing directly or pasting special as values. Help for data input is provided by the comments that are tagged in the associated heading cell.

Clearing the default directory in Excel will make AnalyzeHOLE more stable. Paths specified in batch files that were created by AnalyzeHOLE and in the Visual Basic for Application (VBA) routines sometimes disagree when the default directory is not blank. This approach makes AnalyzeHOLE more stable.

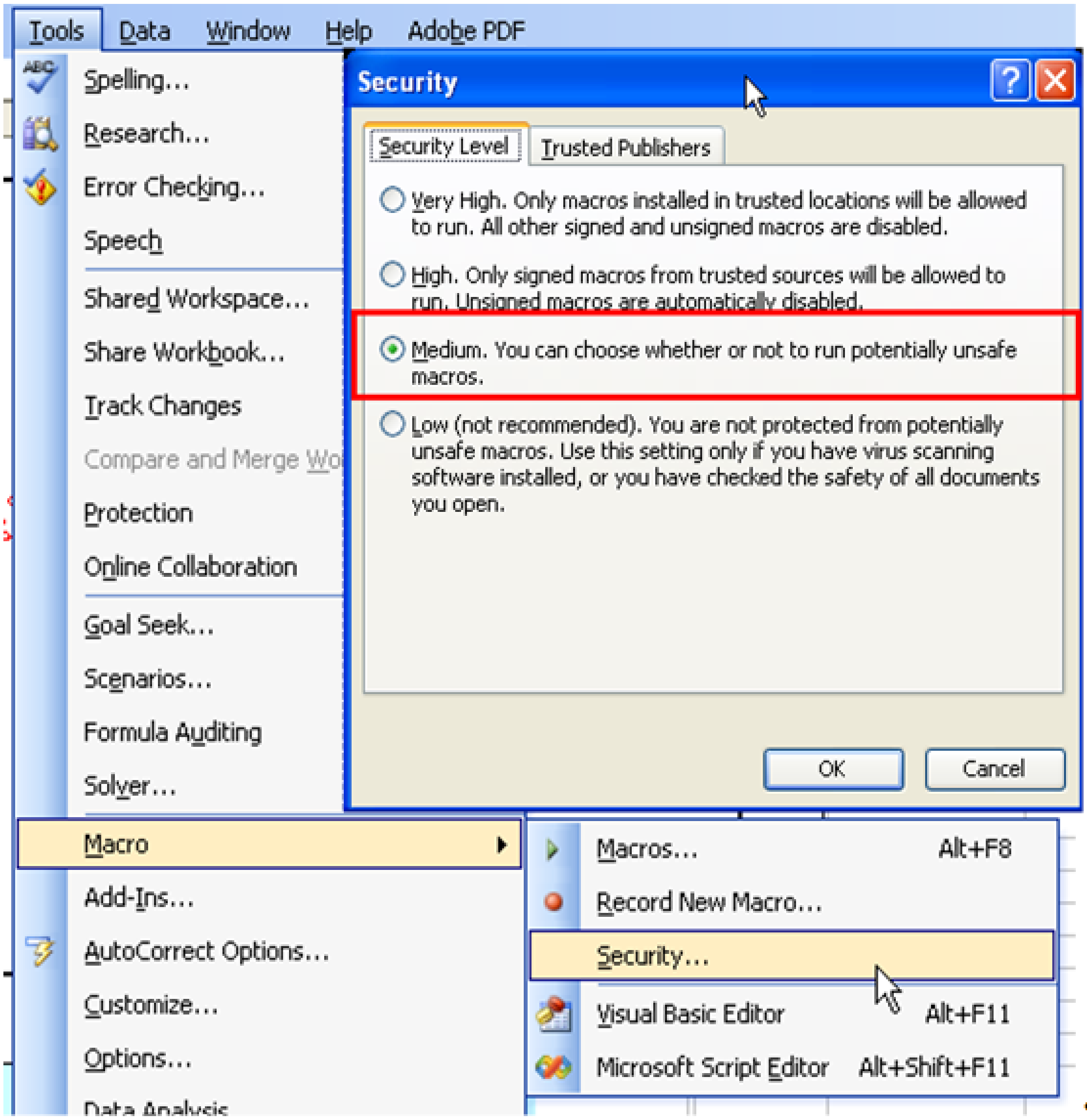


Figure 15. 2003 Excel forms for changing security settings.

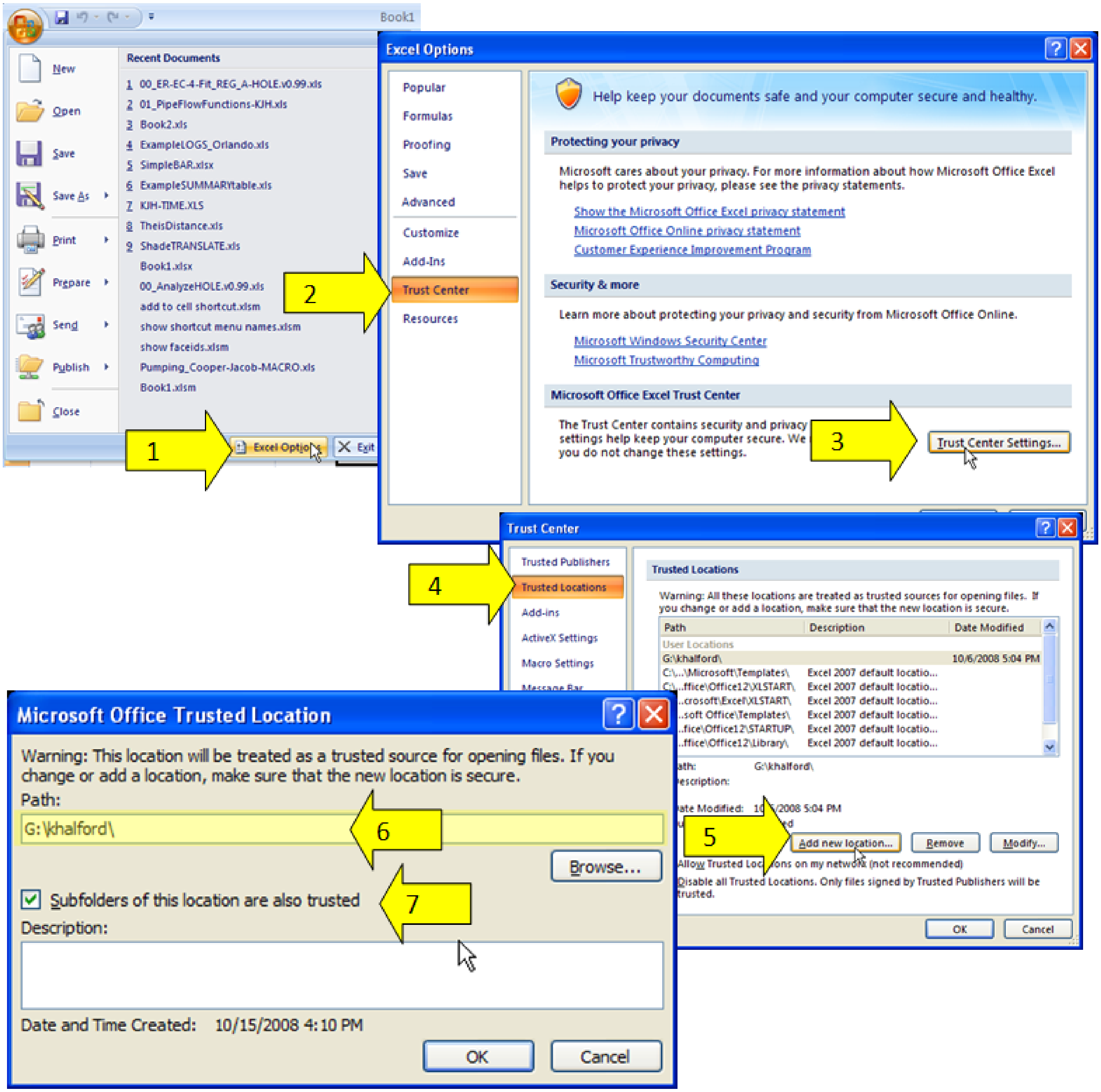
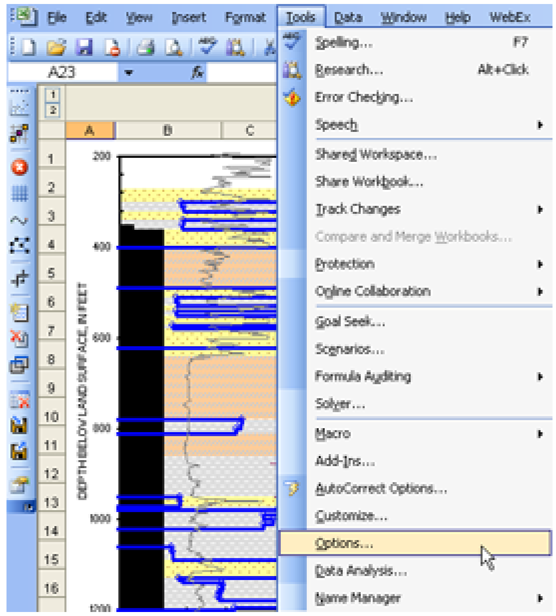


Figure 16. 2007 Excel forms for changing macro security settings. Arrows indicate selections to specify directory and subdirectories where macros can function in Excel 2007.

Clear Default Directory in Excel 2003

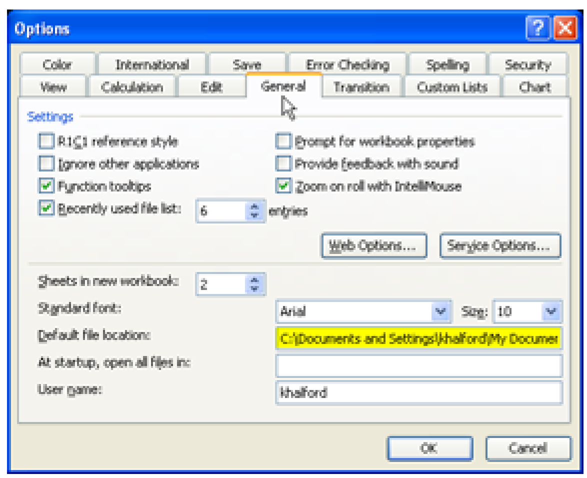
Select the Tools>Options… menu and the Options form will appear.



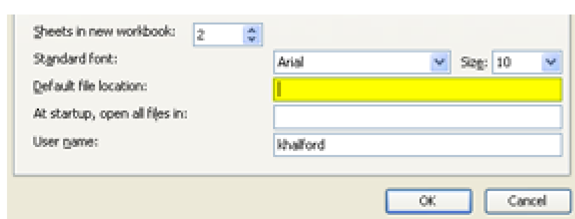
Select the **General** tab.

Highlight and delete all text in the “Default file location:” field.

This will cause your default file location to be the directory where Excel was started.

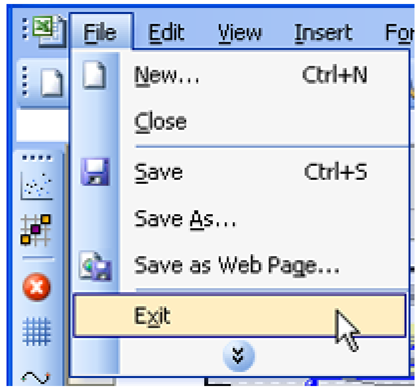


Select OK after clearing “Default file location:” field.

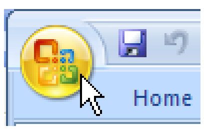


Exit Excel.

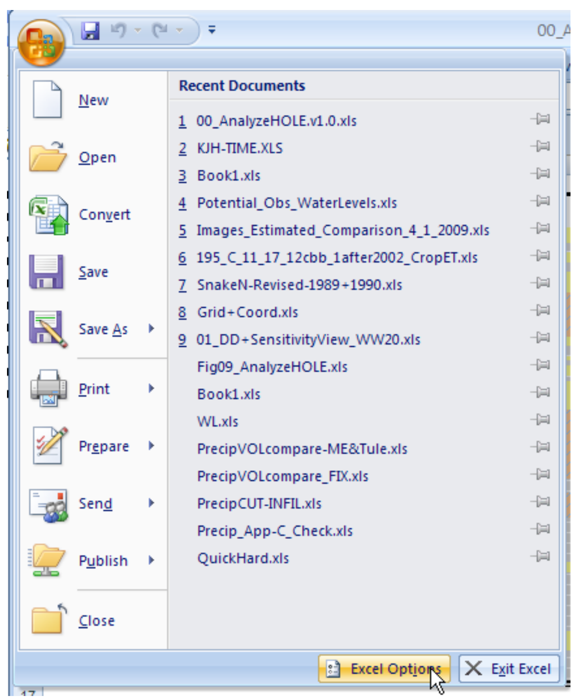
The default file location will be used after Excel is opened again.



Clear Default Directory in Excel 2007



Select the Office Button , Excel Options, and the Excel Options form will appear.



<table>
<tr>
<td>

Select the **Save** option.

Highlight and delete all text in the “Default file location:” field.

This will cause your default file location to be the directory where Excel was started.

</td>
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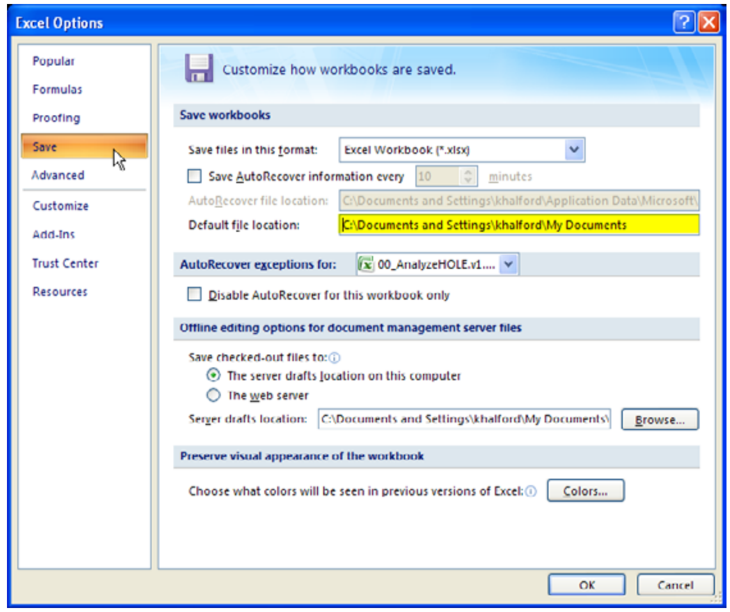

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Select OK after clearing “Default file location:” field.

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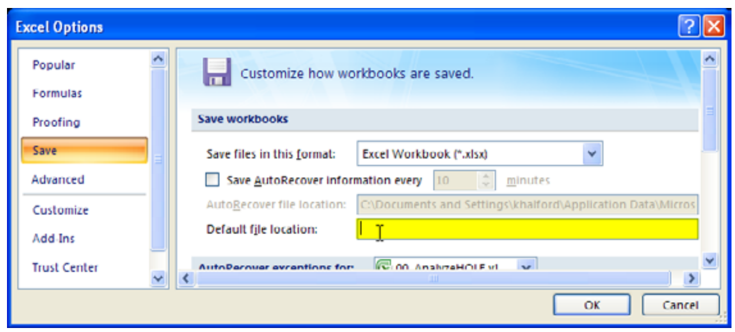

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Exit Excel.

The default file location will be used after Excel is opened again.

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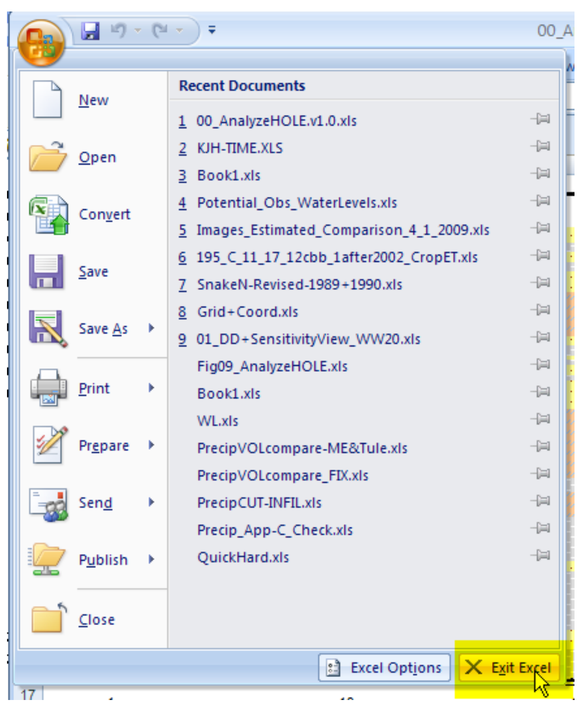

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</table>

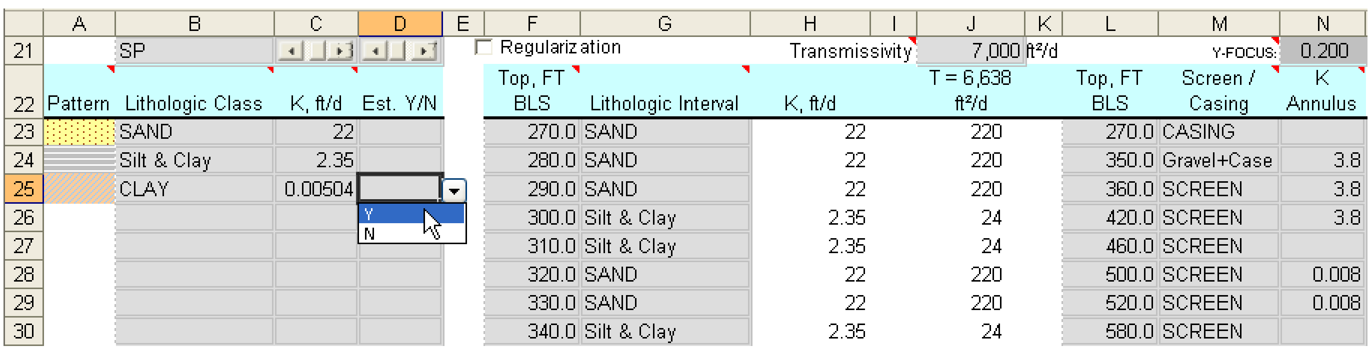
Data Requirements and Entry

Lithology, hydraulic properties, well construction, and a flow log must be specified to simulate a flow log and concentration changes. Measured drawdowns in the pumping well and depth-dependent flow observations also must be specified if estimating hydraulic conductivities of the aquifer system and annular fill with PEST (Doherty, 2005). Lithology, hydraulic properties, and well construction are defined on the HydProp worksheet. Flow log and flow-log calibration depths are entered on the Logs worksheet.

Lithology, Hydraulic Properties, and Well Construction

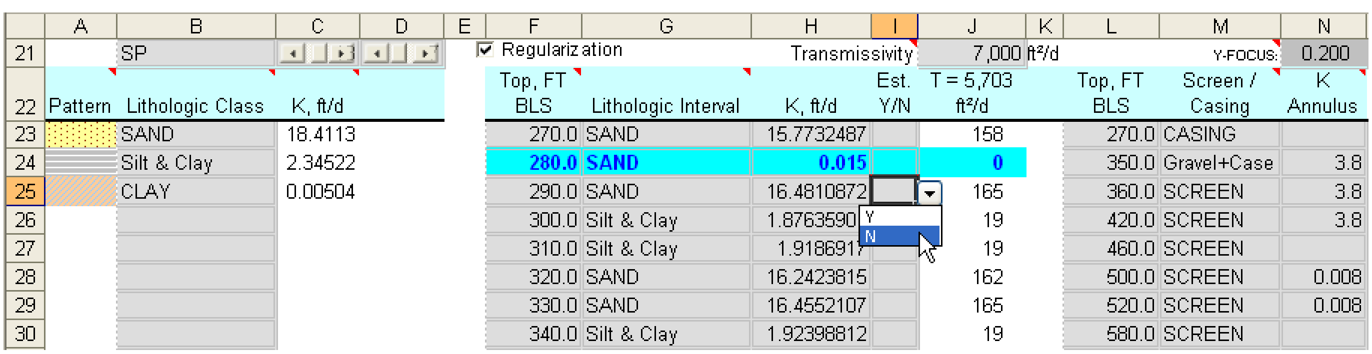
The hydraulic conductivity for each lithologic class, lithologic logs, and well-construction logs are entered as paired values in tables on the HydProp worksheet (fig. 17). Hydraulic conductivity and transmissivity are distributed with depth through the lithologic log. The aquifer system is simulated as unconfined and the prepumping water table is the top where the prepumping water table is deeper than the shallowest lithologic interval in column F. Lithologic intervals above the prepumping water table are not part of the saturated flow system and are simulated as inactive cells. The aquifer system is simulated as confined and shallowest lithologic interval is the top where the prepumping water table is shallower than the shallowest lithologic interval. The base of the simulated aquifer system is the deepest lithologic interval in column F.

A. Lithology-Hydraulic conductivity related directly



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
21		SP				☐ Regularization		Transmissivity		7,000	ft²/d		Y-FOCUS:	0.200
22	Pattern	Lithologic Class	K, ft/d	Est. Y/N		Top, FT BLS	Lithologic Interval	K, ft/d		T = 6,638 ft²/d		Top, FT BLS	Screen / Casing	K Annulus
23		SAND	22			270.0	SAND	22		220		270.0	CASING	
24		Silt & Clay	2.35			280.0	SAND	22		220		350.0	Gravel+Case	3.8
25		CLAY	0.00504			290.0	SAND	22		220		360.0	SCREEN	3.8
26				Y		300.0	Silt & Clay	2.35		24		420.0	SCREEN	3.8
27				N		310.0	Silt & Clay	2.35		24		460.0	SCREEN	
28						320.0	SAND	22		220		500.0	SCREEN	0.008
29						330.0	SAND	22		220		520.0	SCREEN	0.008
30						340.0	Silt & Clay	2.35		24		580.0	SCREEN	

B. Lithology-Hydraulic conductivity related indirectly with regularization



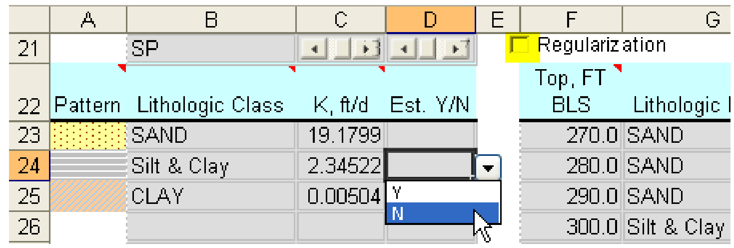
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
21		SP				☑ Regularization		Transmissivity		7,000	ft²/d		Y-FOCUS:	0.200
22	Pattern	Lithologic Class	K, ft/d			Top, FT BLS	Lithologic Interval	K, ft/d	Est. Y/N	T = 5,703 ft²/d		Top, FT BLS	Screen / Casing	K Annulus
23		SAND	18.4113			270.0	SAND	15.7732487		158		270.0	CASING	
24		Silt & Clay	2.34522			**280.0**	**SAND**	**0.015**		**0**		350.0	Gravel+Case	3.8
25		CLAY	0.00504			290.0	SAND	16.4810872		165		360.0	SCREEN	3.8
26						300.0	Silt & Clay	1.8763590	Y	19		420.0	SCREEN	3.8
27						310.0	Silt & Clay	1.9186917	N	19		460.0	SCREEN	
28						320.0	SAND	16.2423815		162		500.0	SCREEN	0.008
29						330.0	SAND	16.4552107		165		520.0	SCREEN	0.008
30						340.0	Silt & Clay	1.92398812		19		580.0	SCREEN	

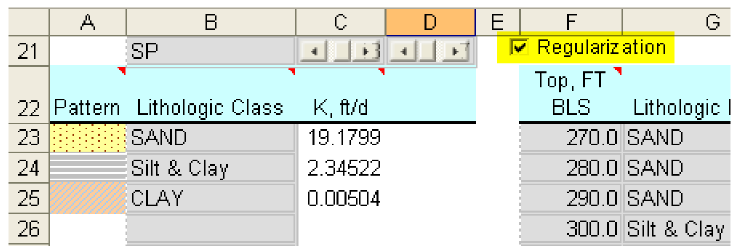
Figure 17. Fields for entering depth dependent data on the HydProp worksheet using (*A*) direct lithology-hydraulic conductivity relations or (*B*) indirectly with regularization.

Lithologic Classes, Lithologic Logs, and Well-Construction Logs

Unique lithologic patterns, lithologic classes, and hydraulic conductivities are assigned in columns A, B, and C, respectively, beginning in row 23. Blank rows cannot exist between user-specified lithologic classes.

Hydraulic conductivities that will not be estimated when PEST is applied ***without regularization*** are denoted by and "N" entry in column D on the same row. A blank or "Y" entry denotes that the parameter will be estimated.



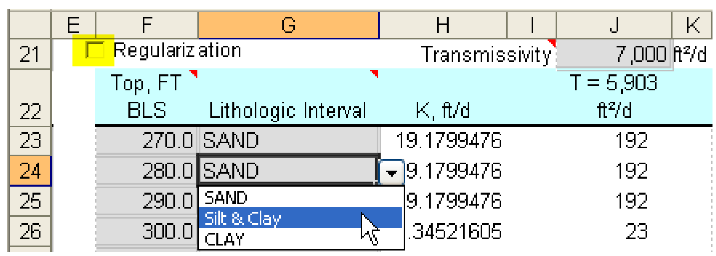


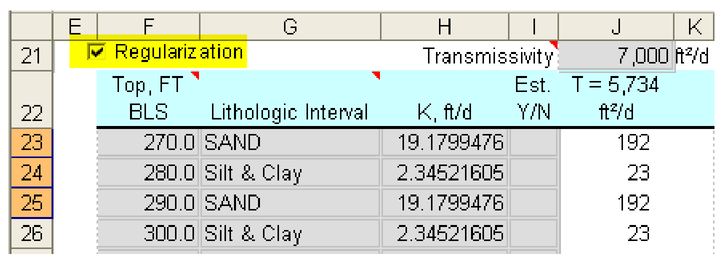
Depths denote the top of an interval. Depths in column F are entered manually or pasted special as values.

Lithologies are selected from pull-down menus in column G that reflect user-specified lithologic classes in column B.

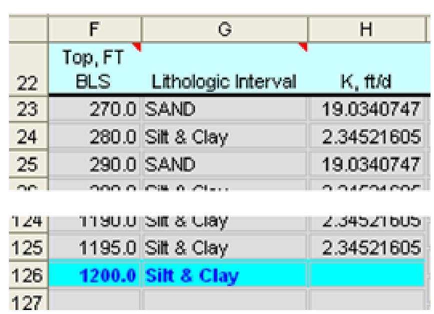
Hydraulic conductivity and transmissivity of each interval is reported in columns H and J. Transmissivity of the entire column is reported in J22.

Hydraulic conductivities that will not be estimated when PEST is applied ***with regularizaion*** are denoted by an "N" entry in column 1 on the same row.



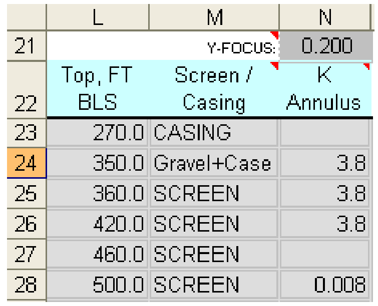


Difference between tops of the shallowest and deepest lithologic intervals defines vertical extent of the simulated aquifer system. For example, vertical extent is between 270 and 1,200 ft below land surface with a thickness of 930 ft.



The transmissivity to be matched is entered in J21 and is only used with PEST.

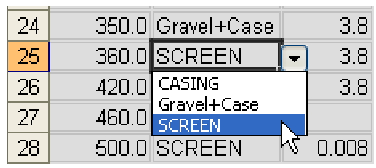
Specifies construction of wellbore wall and annular fill and can be CASING, Gravel+Case, or SCREEN



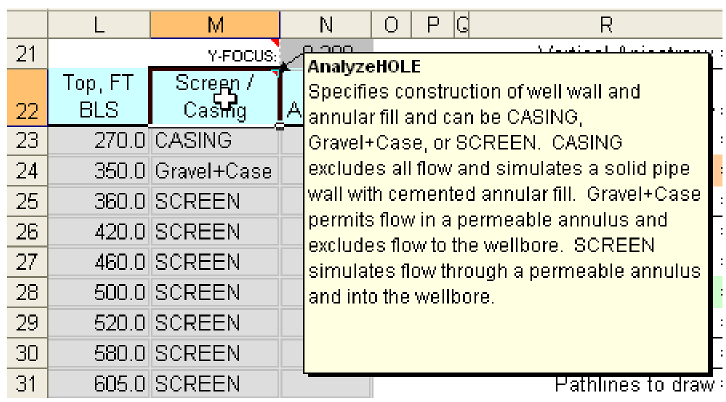
CASING excludes all flow and simulates a solid pipe wall with cemented annular fill.

Gravel+Case simulates flow in a permeable annulus and excludes flow to the wellbore.

SCREEN simulates flow through a permeable annulus and into the wellbore.



CASING, Gravel+Case, and SCREEN are defined in the comment for the Screen/Casing heading.

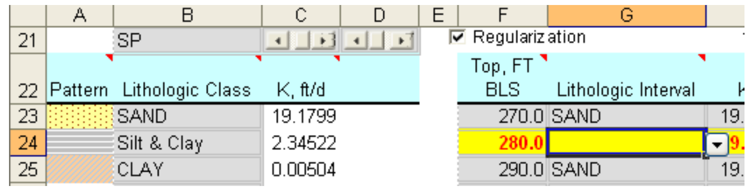


Rows in the lithology-hydraulic conductivity and depth-lithology tables are colored brightly where erroneous data exists. Input cells in these tables typically are light gray (fig. 17). Missing lithologic classes, unused lithologic classes, and lithologic intervals thinner than model rows all generate warnings. These conditions will cause the model batch file that is executed by PEST to fail and must be corrected. Hydraulic conductivities that are specified outside of user-defined ranges also generate warnings. PEST will work, but these hydraulic conductivities are specified and cannot be estimated.

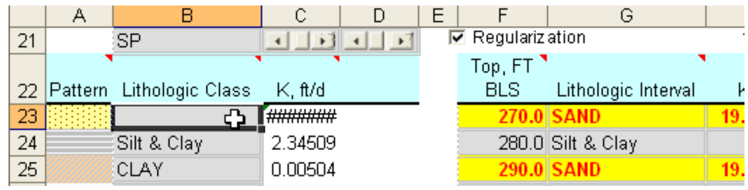
Lithology Warnings

The background of rows in the depth-lithology table will become bright yellow with bold, red text where a lithologic class is missing or undefined in column G.

Errors are fatal for PEST.



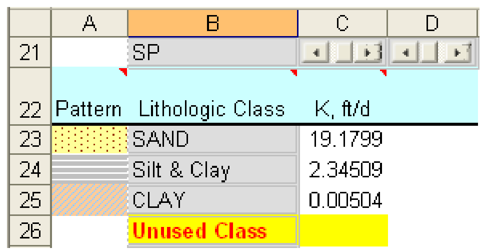
	A	B	C	D	E	F	G	
21		SP				☑ Regularization		
22	Pattern	Lithologic Class	K, ft/d			Top, FT BLS	Lithologic Interval	K
23		SAND	19.1799			270.0	SAND	19.
24		Silt & Clay	2.34522			280.0		9.
25		CLAY	0.00504			290.0	SAND	19.



	A	B	C	D	E	F	G	
21		SP				☑ Regularization		
22	Pattern	Lithologic Class	K, ft/d			Top, FT BLS	Lithologic Interval	K
23			########			270.0	SAND	19.
24		Silt & Clay	2.34509			280.0	Silt & Clay	
25		CLAY	0.00504			290.0	SAND	19.

The background of rows in the lithology-hydraulic conductivity table will become bright yellow with bold, red text where lithologic classes are defined in column B and unused in column G.

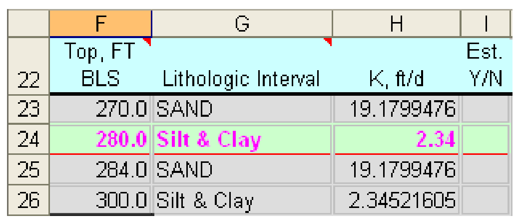
Errors are fatal for PEST.



	A	B	C	D
21		SP		
22	Pattern	Lithologic Class	K, ft/d	
23		SAND	19.1799	
24		Silt & Clay	2.34509	
25		CLAY	0.00504	
26		Unused Class		

The background of rows in the depth-lithology table will become pale green with bold pink text where thickness of lithologic interval is thinner than a model row.

Errors are fatal for PEST.

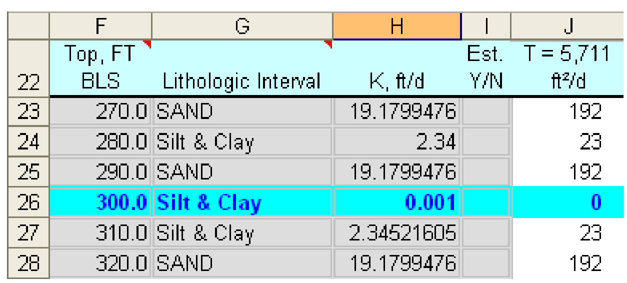


	F	G	H	I
22	Top, FT BLS	Lithologic Interval	K, ft/d	Est. Y/N
23	270.0	SAND	19.1799476	
24	280.0	Silt & Clay	2.34	
25	284.0	SAND	19.1799476	
26	300.0	Silt & Clay	2.34521605	

The background of rows in the depth-lithology table will become bright blue with bold, dark-blue text where initial K is outside the permissible range for the lithologic class.

For example, the thickness-weighted mean hydraulic conductivity of “Silt & Clay” is 3 ft/d and the “K-Lithology Bound” multiplier is 100, so an initial estimate of 0.001 ft/d is less than the lower limit of 0.03 ft/d.

PEST will execute, but highlighted parameters are not estimated.



	F	G	H	I	J
22	Top, FT BLS	Lithologic Interval	K, ft/d	Est. Y/N	T = 5,711 ft²/d
23	270.0	SAND	19.1799476		192
24	280.0	Silt & Clay	2.34		23
25	290.0	SAND	19.1799476		192
26	300.0	Silt & Clay	0.001		0
27	310.0	Silt & Clay	2.34521605		23
28	320.0	SAND	19.1799476		192

Lithology, Water Quality, and Well Construction Backgrounds

Lithologic intervals, water-quality zones, and well construction are displayed as background patterns under the hydraulic conductivity and flow-log plots on the HydProp worksheet (fig. 1) and flow-path section on the Mixing worksheet. Lithologic intervals and water-quality zones are alternated with the LITHOLOGY/QW toggle near cell G19 (fig. 18). The color and patterns of the lithologic classes are assigned by the cell shading in column A under the heading “Pattern” in cell A22 on the HydProp worksheet. The color of the water-quality zones are assigned by shading in the shallow and deep maximum concentration labels in cells R24 and R28, respectively. Well screens are depicted as black zones on the left edge and are always visible.

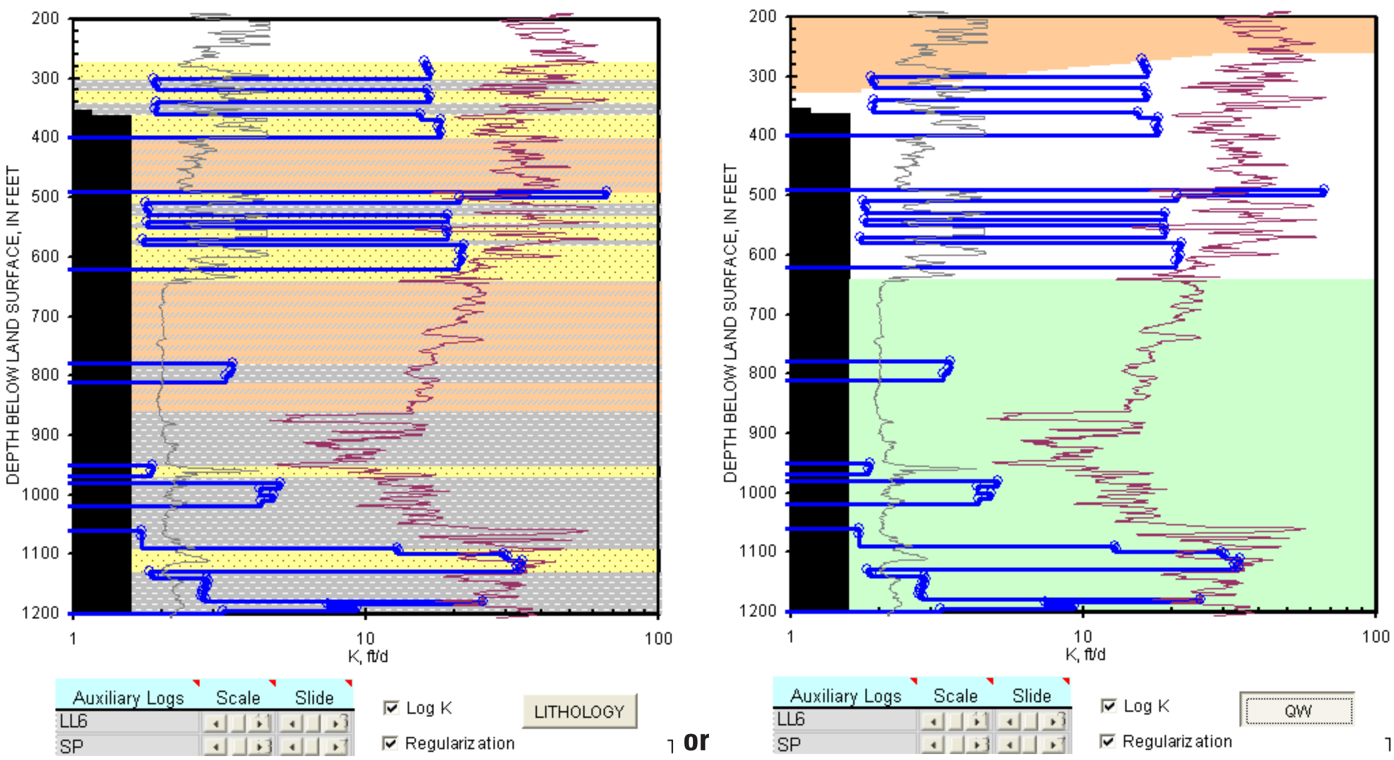
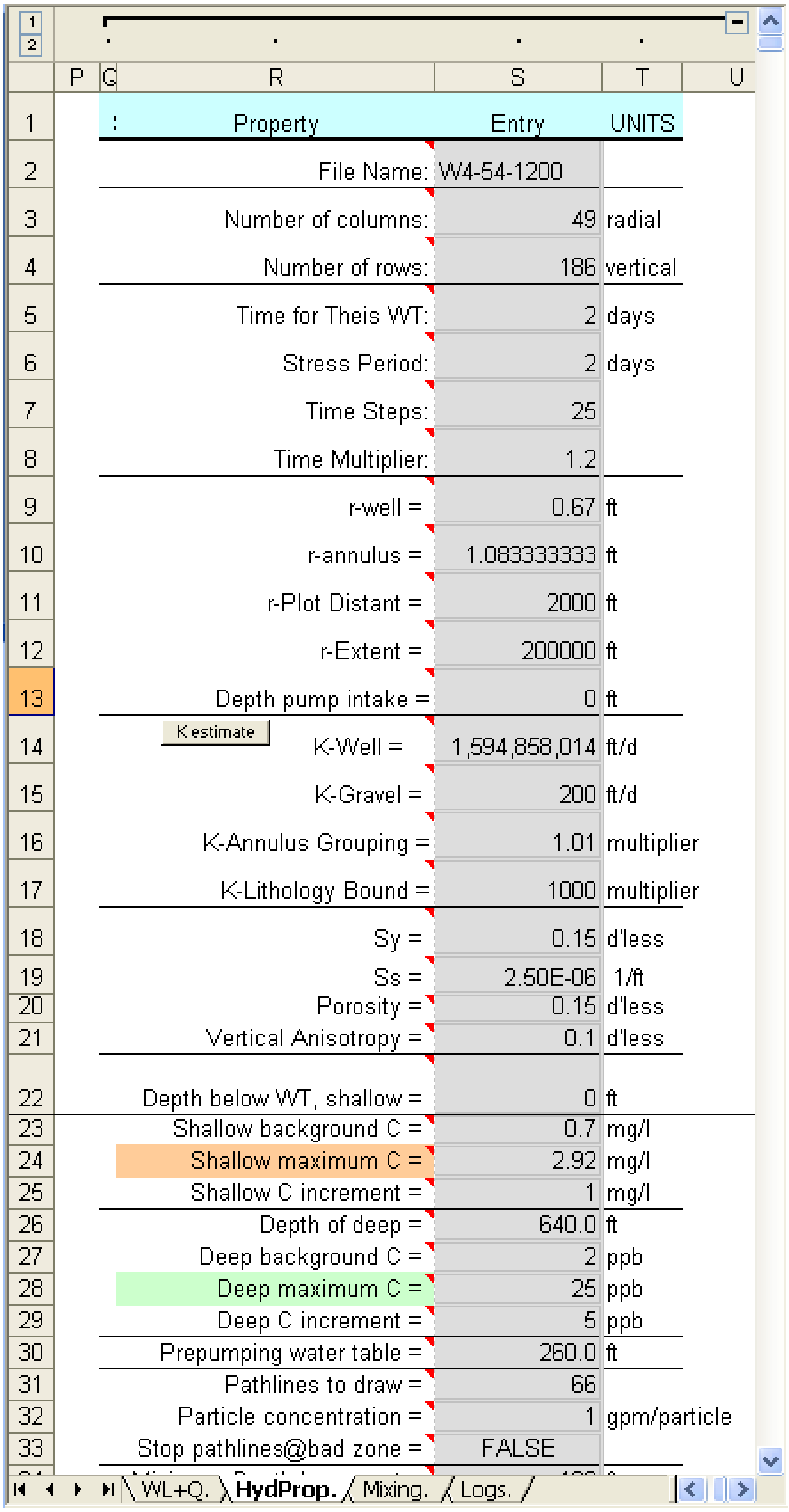


Figure 18. Water-quality zones and lithology backgrounds that can be viewed on the HydProp and Mixing worksheets.

Global Property Column

Global property column is a catch all for defining the flow model, porosity, concentrations, mixing zone extents, particle distributions, and plotting controls. Related variables are grouped with black borders (fig. 19). Variables in the global property column are assigned and not estimated with PEST.



	Property	Entry	UNITS
2	File Name:	W4-54-1200	
3	Number of columns:	49	radial
4	Number of rows:	186	vertical
5	Time for Theis WT:	2	days
6	Stress Period:	2	days
7	Time Steps:	25	
8	Time Multiplier:	1.2	
9	r-well =	0.67	ft
10	r-annulus =	1.083333333	ft
11	r-Plot Distant =	2000	ft
12	r-Extent =	200000	ft
13	Depth pump intake =	0	ft
14	K estimate K-Well =	1,594,858,014	ft/d
15	K-Gravel =	200	ft/d
16	K-Annulus Grouping =	1.01	multiplier
17	K-Lithology Bound =	1000	multiplier
18	Sy =	0.15	d'less
19	Ss =	2.50E-06	1/ft
20	Porosity =	0.15	d'less
21	Vertical Anisotropy =	0.1	d'less
22	Depth below WT, shallow =	0	ft
23	Shallow background C =	0.7	mg/l
24	Shallow maximum C =	2.92	mg/l
25	Shallow C increment =	1	mg/l
26	Depth of deep =	640.0	ft
27	Deep background C =	2	ppb
28	Deep maximum C =	25	ppb
29	Deep C increment =	5	ppb
30	Prepumping water table =	260.0	ft
31	Pathlines to draw =	66	
32	Particle concentration =	1	gpm/particle
33	Stop pathlines@bad zone =	FALSE	

Figure 19. Global property column for defining flow model, well construction, storage properties, porosity, concentrations, mixing zones, particle distributions, and plotting controls.

Global Property Column Input

File name is descriptor in all ASCII file names.

Columns and rows define model grid. Rows are discretized uniformly.

	P	Q	R	S	T
1		:	Property	Entry	UNITS
2			File Name:	W4-54-1200	
3			Number of columns:	49	radial
4			Number of rows:	186	vertical
5			Time for Theis WT:	2	days
6			Stress Period:	2	days
7			Time Steps:	25	
8			Time Multiplier:	1.2	

r-well is inner radius of casing,

r-annulus is radius of drilled hole,

r-Plot Distant is radial extent shown in pathline section, and ModelViewer,

r-Extent is radial exent of MODFLOW model,

Depth pump intake is specified other than 0 if intake is in screen and flow log separately accumulates above and below the intake.

	P	Q	R	S	T
9			r-well =	0.67	ft
10			r-annulus =	1.083333333	ft
11			r-Plot Distant =	2000	ft
12			r-Extent =	200000	ft
13			Depth pump intake =	0	ft

Use pop-up form, K estimate, to estimate

$$K_{WELL} = \frac{\rho g d^2}{32\mu}\sqrt{\frac{f_{LAMINAR}}{f_{TURBULENT}}}$$, (Halford, 2000).

Assign a lesser value of K_{WELL} if the model is numerically unstable. Assign a greater value of K_{WELL} if the minimum and maximum simulated heads in the wellbore differ more than a percent of the drawdown in the pumping well.

K-Gravel is default value and upper bound for K of annulus.

K-Annulus Grouping is a multiplier for grouping K-annulus values into parameters.

K-Lithology Bound is a divisor and multiplier that defines the lower and upper bound of each K estimated with PEST.

	Q	R	S	T
14	K estimate	K-Well =	1,594,858,014	ft/d
15		K-Gravel =	200	ft/d
16		K-Annulus Grouping =	1.01	multiplier
17		K-Lithology Bound =	1000	multiplier

Sy is the specific yield,

Ss is the specific storage in 1/feet,

Porosity is used only in MODPATH, and

Vertical Anistrophy, which is the ration of vertical to horizontal hydraulic conductivity, applies to entire model.

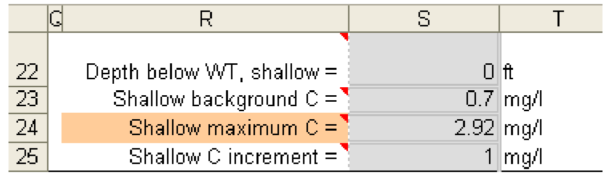
	Q	R	S	T
18		Sy =	0.15	d'less
19		Ss =	2.50E-06	1/ft
20		Porosity =	0.15	d'less
21		Vertical Anisotropy =	0.1	d'less

Depth below WT, shallow is the thickness of the shallow high concentration zone that lies below the water table (fig. 3).

Shallow background C is the background concentration of the shallow constituent.

Shallow maximum C is the concentration of the shallow constituent in the shallow zone. Color of cell, R24, defines color of shallow zone.

Shallow C increment specifies concentration labeling frequency on the Mixing worksheet chart.

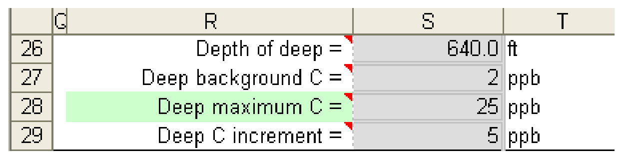


Depth of deep is the top of the deep high concentration zone (fig. 3).

Deep background C is the background concentration of the deep constituent.

Deep maximum C is the concentration of the deep constituent in the deep zone. Color of cell, R28, defines color of deep zone.

Deep C increment specifies concentration labeling frequency on the Mixing worksheet chart.



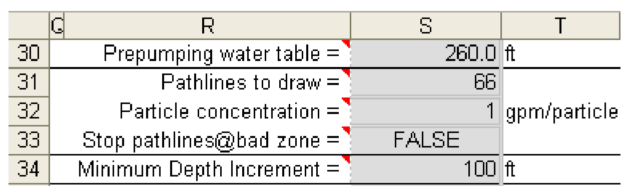
Prepumping water table is the initial depth to water. Set equal or deeper than the shallowest lithologic interval to simulate as an unconfined aquifer system. Set shallower than the top of the defined lithology for confined problems.

"Pathlines to draw" specifies maximum flow-weighted pathlines for cross-section. The minimum is the number of screened cells.

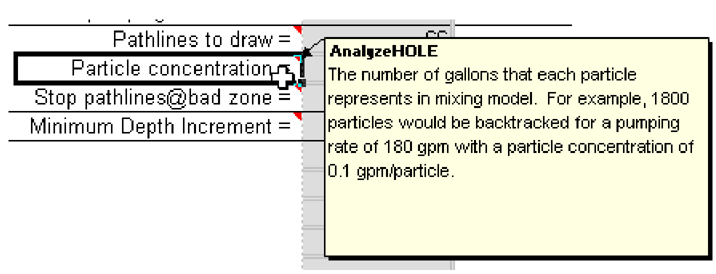
Particle concentration specifies number of flow-weighted particles for computing concentration. Total number of particles should not exceed 10,000.

Stop pathlines@bad zone allows pathlines in cross-section to extend into shallow and deep zones if specified as FALSE.

Minimum Depth increment specifies depth labeling frequency in all charts.



All explanations are comments in AnalyzeHOLE that are attached to the Property cell in each row.



Flow and Additional Logs

Flow and other geophysical logs are specified on the Logs worksheet where depths can be specified independently for each log (fig. 20). Multiple depth columns allow for logs with different or irregular sampling intervals. The headings for all of the depth columns must be identical. Flow logs in columns A:B and C:D must be specified where the raw, noisy log is specified in columns A:B and a reduced log for observations in parameter estimation is specified in columns C:D.

The additional logs beyond column D are optional logs that can be compared visually to the hydraulic conductivity distribution (fig. 21). Two additional logs can be viewed simultaneously. Amplitudes of the additional logs are adjusted with the Scale slides in cells C20:C21 (fig. 21). Positions of the additional logs on the X-axis can be translated with the slides in cells D20:D21 (fig. 21).

	A	B	C	D	E	F	G	H	I	J
1	DEPTH	Raw Flow Log	DEPTH	MEASURED	DEPTH	SP	LL6	DEPTH	MF2K-UNI	DEPTH
2	350.0	1520.0	350.0	1520.00	68	1.4175	49.3236	272.5	1519.936	270
3	380	1283.6	400.0	1283.60	69	3.0517	49.3265	277.5	1519.936	270
4	400	1283.6	420.0	1283.60	70	5.0948	49.3294	282.5	1519.936	275
5	420	1283.6	460	1283.60	71	6.2664	49.3324	287.5	1519.936	275
6	460	1283.6	490	1283.60	72	6.6477	49.3353	292.5	1519.936	280
7	490	1283.6	505.0	1004.78	73	6.9904	49.3382	297.5	1519.936	280
8	500	1004.8	540.0	1004.78	74	7.2817	49.3411	302.5	1519.936	285
9	540	1004.8	560.0	1004.78	75	9.1667	49.344	307.5	1519.936	285
10	580	1004.8	580.0	1004.78	76	10.2731	49.3469	312.5	1519.936	290
11	620	672.1	620.0	672.08	77	9.9072	49.3499	317.5	1519.936	290
12	660	672.1	660.0	672.08	78	9.2496	49.3533	322.5	1519.936	295
13	700	672.1	680.0	672.08	79	7.7192	43.1887	327.5	1519.936	295
14	740	672.1	700.0	672.08	80	5.9634	35.7053	332.5	1519.936	300
15	780	672.1	740.0	672.08	81	4.2109	39.0975	337.5	1519.936	300
16	820	628.4	760.0	672.08	82	6.035	49.292	342.5	1519.936	305
17	860	628.4	780.0	672.08	83	6.5453	49.2834	347.5	1519.936	305
18	900	628.4	820.0	628.36	84	6.0335	49.2728	352.5	1519.936	310
19	940	628.4	840.0	628.36	85	5.2299	49.2623	357.5	1519.936	310
20	980	603.6	860.0	628.36	86	2.7474	49.2518	362.5	1519.936	315
21	1020	530.8	900.0	628.36	87	3.891	49.2413	367.5	1461.591	315
22	1060	530.8	940.0	628.36	88	6.1035	49.2308	372.5	1404.415	320
23	1100	463.7	980.0	603.64	89	7.5627	49.2203	377.5	1361.906	320
24	1140	119.1	1020.0	530.79	90	10.9976	49.2098	382.5	1321.202	325
25	1200	0.0	1060.0	530.79	91	11.7139	49.1993	387.5	1290.886	325
26			1100.0	463.68	92	12.1592	49.1888	392.5	1261.426	330
27			1140.0	119.11	93	11.0635	49.1779	397.5	1258.735	330
28			1199.0	0.00	94	7.4672	37.8461	402.5	1256.285	335
29					95	6.6823	26.3702	407.5	1255.648	335
30					96	5.3678	31.111	412.5	1255.024	340

WL+Q. / HydProp. / Mixing. / Logs.

Figure 20. Logs worksheet for entering complete flow log (A:B), measured flows for calibration (C:D), and auxiliary logs such as caliper, gamma, resistivity, SP, or temperature.

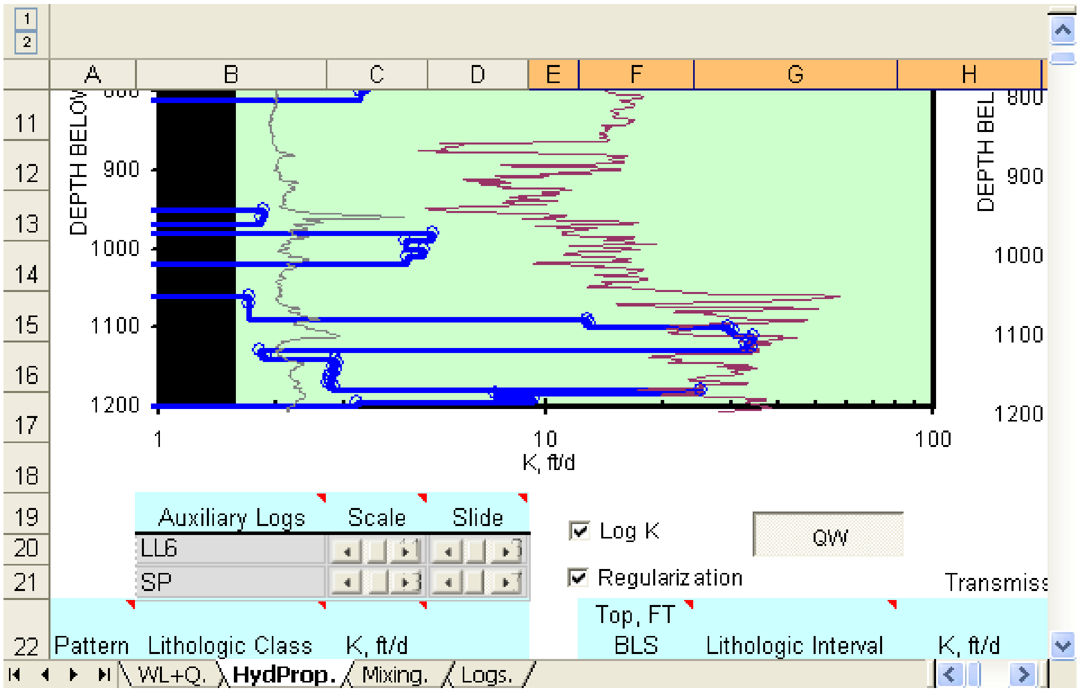


Figure 21. Controls on HydProp worksheet for selecting and viewing auxiliary logs.

Drawdowns and Well Locations

Drawdown data from the pumping well is needed if hydraulic conductivities of the annulus and aquifer system will be estimated with PEST (Doherty, 2005). Drawdown data from the pumping well is pasted at cells M35:N35 on the WL+Q worksheet (fig. 22). The header in cell N34 also must be changed so the correct SITEID exists, which is the root file name defined in cell S2 on the HydProp worksheet.

Additional wells are defined in the well location table (C35:H40) if drawdown data in observation wells are used otherwise these cells remain unfilled (fig. 22). Site ID and basic well construction of the pumping well was specified previously on the HydProp worksheet and is not entered in the well-location table. Radial distances between observation wells and the pumping well are computed with easting and northing. Radial distances and mid-point of openings are computed only if drawdown data in observation wells are used. Drawdown data in observation wells are pasted along row 35 in columns O:P and Q:R (fig. 23).

The pumping rate during the single-well aquifer test can be specified in cell P29 on the WL+Q worksheet if it differs from the pumping rate during flow logging (fig. 24). The maximum rate from the flow log is used if cell P29 is blank. The date and time pumping started are documented in cell O29, but are not used for computations. Additional pumping rates were considered to simulate step-drawdown tests but were not implemented.

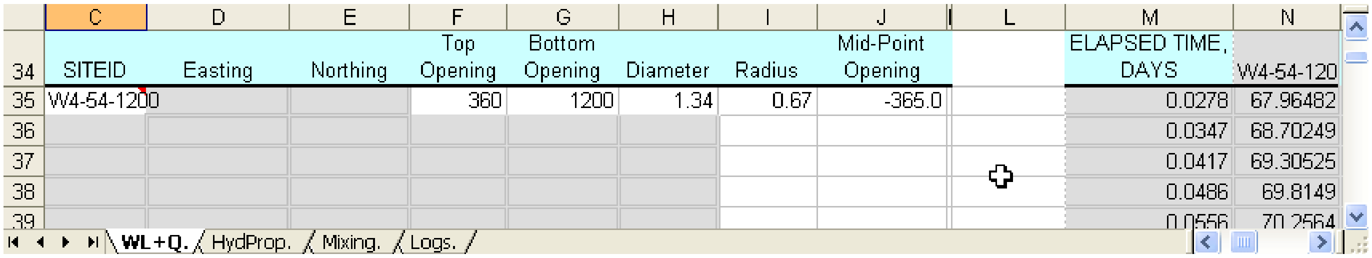


Figure 22. Table for entering optional observation well positions and depths.

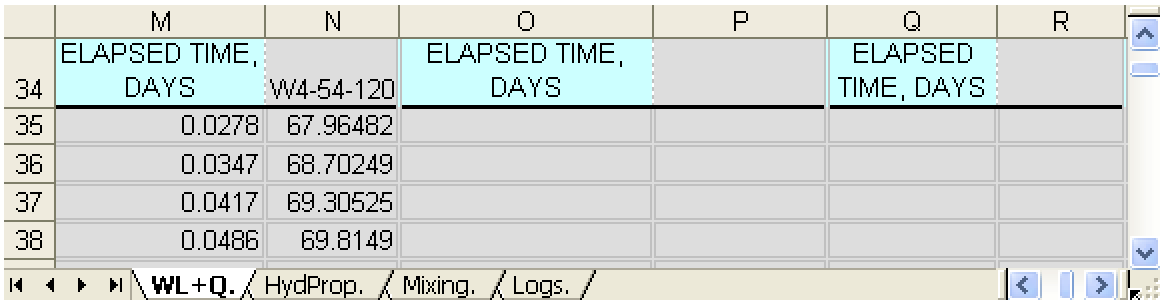


Figure 23. Heading and example drawdown input on the WL+Q worksheet.

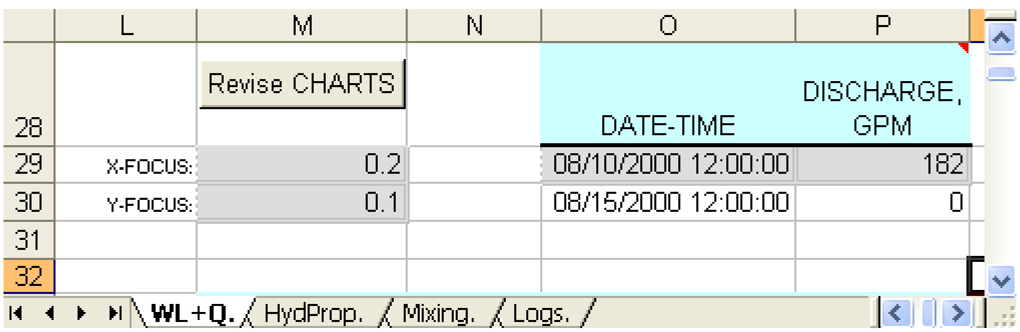


Figure 24. Auxiliary discharge specification on the WL+Q worksheet, which is needed when discharge during flow logging and aquifer testing differ.

AnalyzeHOLE Commands

AnalyzeHOLE commands are accessed through a custom tool bar that is built when an AnalyzeHOLE file is opened (fig. 25). AnalyzeHOLE commands build MODFLOW, MODPATH, and PEST input files. Batch files to create input responses and execute these programs also are written by AnalyzeHOLE. All external FORTRAN programs other than PEST are executed and imported automatically by AnalyzeHOLE.

The AnalyzeHOLE command toolbar can be re-created by the user if it is inadvertently dismissed by typing Alt-F8 and double-clicking the HAMakeMenu macro. The command toolbar normally is created as an AnalyzeHOLE file is opened and dismissed as the file is closed. The command toolbar will be dismissed inadvertently if Excel is exited, unsaved files exist, and the user cancels exiting Excel. The keyboard shortcut “ctrl+m” also will restore the AnalyzeHOLE command toolbar.

AnalyzeHOLE has several utilities for managing charts, files, and worksheets. All charts can be registered and scaled with the Refresh Charts tool. The many ASCII files that are created by AnalyzeHOLE can be deleted with the Wipe Files tool. Supporting worksheets can be hidden or revealed with the Hide/Show tool. A utility for magnifying XY-charts also exists that is accessed through the main AnalyzeHOLE menu, the keyboard shortcut “ctrl+q”, and the right-click menu in only Excel 2003 when a chart area is selected.

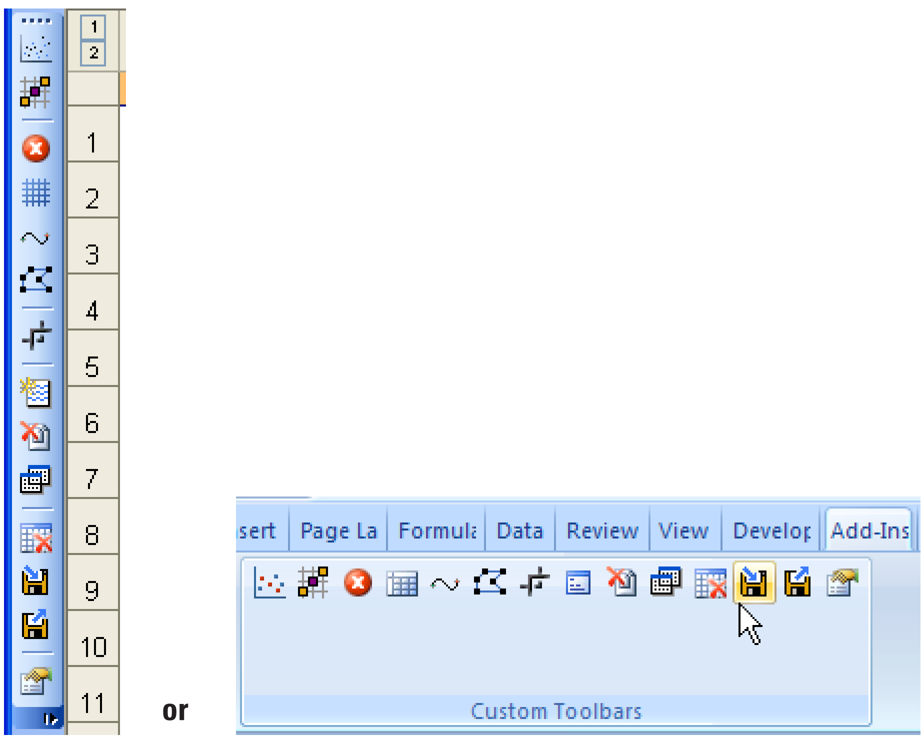
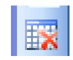


Figure 25. Menu bar for AnalyzeHOLE functions in Microsoft© Excel 2003 and 2007.

AnalyzeHOLE Command Summary

Create PEST files Writes all MF2K, PEST, and batch files for estimating K with PEST	or
Import PEST results Imports simulatd drawdowns, simulated flows at calibration depths, and hydraulic conductivity estimates.	
Stop NOW Stops the process that waits for the MF2K to finish. Press Stop NOW if MF2K crashes and the MF2K button remains activated,	
MF2K Create and Run Writes MF2K, ModelViewer, and batch files. Executes batch files that runs MF2K and extracts simulated flow-log from CBC file. Imports simulated flow-log after batch file finishes. MF2K button remains activated, , while waiting for the batch file to finish.	or
Endpoint + Pathlines Creates file of seed particles in column 2 where screen is present and distributes paricles proportionately to the flow. Executes MODPATH.	
Concentration + Paths Imports MODPATH results. Shallow and deep constituent concentrations are estimated from particle stopping depths and travel times.	
Box Focus Magnifies subareas of charts when a chart is selected. Accessed through the keyboard shortcut “ctrl+q”. Excel 2003 only. Accessed through the right-click menu when a plot area is selected.	or “ctrl+q” in Excel 2003 and Excel 2007 Right-click in plot, BoxFocus Excel 2003 only.
Refresh Charts Registers shallow and deep zones with the overlying charts. Revises scales after changing; Deep C increment, Minimum Depth Increment, r-Plot Distant, or Shallow C increment.	**or**
Wipe Files Deletes all MF2K, PEST, and batch files that were created by AnalyzeHOLE.	

Hide / Show Four worksheets, HydProp., Logs., Mixing., and WL + Q. are needed by the user and always remain visible. The remaining 20 worksheets support workbook functions and are hidden or revealed with the Hide/ Show command.	
Clear All Input Clears all user-specified input from AnalyzeHOLE.	
Export AnalyzeHOLE data Writes all user-specified input from current AnalyzeHOLE file to an AnalyzeHOLE data file which has the extension, AHD.	
Import AnalyzeHOLE data Clears all user-specified input from current AnalyzeHOLE file and transfers user-specified input from an AnalyzeHOLE data file, *.AHD, to the current AnalyzeHOLE file.	
About AnalyzeHOLE Display and copy about AnalyzeHOLE, version 1.0.	

Create PEST Files

Selecting  or  will create all MF2K, PEST, and batch files needed to same folder where AnalyzeHOLE resides. Drawdowns must be specified on the WL+Q worksheet for PEST to work.

Execute the batch file, *02_MF2K_***YourModel***.bat*, to check that the MODFLOW batch file will work correctly. Several of these errors will stop AnalyzeHOLE from writing the PEST files. Observed modes of failure are:

1. Correct well name is not specified in cell N34 on worksheet 'WL+Q', which stops drawdowns from being observed.

2. Aquifer or annular fill zones are specified but do not exist. These mismatches can be found by comparing integer paring between the text files *PEST_***YourModel***.Hcond.irc.txt* and *PEST_***YourModel***.Izone.txt*. This can occur because all K annulus values are specified so the default value, K-Gravel, goes unused.

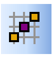
3. A lithology is specified in column B on the HydProp worksheet, but not used in column G.

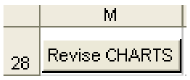
4. Pasting in a lithology type to column G also can create a mismatch with column B.

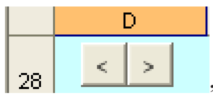
5. Specifying intervals thinner than the vertical discretization of the model in column F on the HydProp worksheet also can create a zone in the file *PEST_***YourModel***.Hcond.irc.txt*, but not in the file *PEST_***YourModel***.Izone.txt*.

PEST is executed with the batch file *00_PEST_***YourModel***.bat* after you are convinced that the file *02_MF2K_***YourModel***.bat* will execute correctly. PEST control parameters are modified in the file *PEST_***YourModel***.PST_commented.txt*. Maximum optimization iteration, NOPTMAX, on line 77 is the most likely variable that you will change. The default is 10. Reduce to 1-3 if you want to check the viability of parameter estimation without wasting as much time.

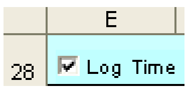
Import PEST Results

Selecting  will import simulated drawdowns, flows, and transmissivity where specified for objective function. New time series and cross plots will be created for the drawdowns and flow logs on the WL+Q worksheet. New hydraulic property estimates also are imported.

Sometimes erroneous charts are generated on the WL+Q worksheet. Press 

in cell M28 to generate a new set of diagnostic charts, which usually corrects incorrectly plotted information. Use the toggle buttons, 

, in cell to view the different diagnostic charts.

The 

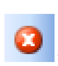
checkbox only affects time series of drawdowns.

MF2K Create and Run

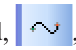
The “MF2K Create and Run” command,  or , writes all MF2K, ModelViewer, MODPATH, and batch files. The batch files are *03_Run-***YourModel***.bat* that simulates flow and *05_MP-Run-***YourModel***.bat* that tracks particles. Initial particle locations are not created with this command because locations are dependent on simulated inflow to the wellbore. The batch file *03_Run-***YourModel***.bat* that executes MODFLOW and extracts the simulated flow log from the cell-by-cell file is executed by this command after ASCII files are created. The command starts a timer and waits for flow log output files to be created while *03_Run-***YourModel***.bat* is executing. Simulated flow-log results in *OUTPUT_Q-log_***YourModel***.txt* are imported into AnalyzeHOLE after the batch file finishes. The “MF2K Create and Run” button remains activated, , while waiting for the batch file, *03_Run-***YourModel***.bat*, to finish.

Execution of this command will overwrite all existing files that were previously written by AnalyzeHOLE.

Stop *NOW*

The Stop NOW command, , exists because sometimes things go bad. MODFLOW can fail or the batch process can be terminated by a user before flow-log output is created. The timer process will continue waiting for the file to appear until more than 1,000 seconds have elapsed. Stop NOW will create an empty file, *StopITnow.txt*, as a flag that halts the MF2K batch file and bypasses reading flow-log output from MFbud-to-Qlog.exe.

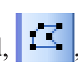
Endpoint + Pathlines

The Endpoint+Pathlines command, , writes ASCII files with initial particle locations in the simulated well screen (column 2). Initial particle locations for computing concentrations, illustrating pathlines, and drawing time fronts are different and are written to separate files. The batch file *05_MP-Run-***YourModel***.bat* is executed after the files *StartCONCpoints.txt*, *Few_points.txt*, and *StartTIMEFRONTpoints.txt* are written with initial particle locations. The batch file calls MODPATH three times and deletes supporting files before finishing.

Initial particle locations for calculating concentration are distributed proportionally to simulated flow across the screens. This allows each particle to simulate an equivalent fraction of the total pumping rate. Particle density is varied exclusively with depth because the models are radially symmetric. Particle density is user specified as discharge per particle in gallons per minute per particle, (gal/min)/p, so the total number of particles is approximately the pumping rate divided by the particle density. For example, about 1,800 particles would be backtracked for a pumping rate of 180 gal/min with a particle concentration of 0.1(gal/min)/p. The total number of particles is an approximate goal because a finite number of particles are distributed to a finite number of model cells.

Flow paths and time fronts that are displayed on the Mixing worksheet are illustrative, not quantitative, tools (fig. 26). Flow paths are tracked with at least a particle for each model row which causes pathlines to be denser where less flow occurs. Initial points for time fronts are the particles for computing concentration and additional particles added where flow is less than the specified gallon per minute per particle in a model cell.

Concentration + Paths

The Concentration+Paths command, , imports MODPATH results, reduces particle stopping times to concentration changes, translates pathlines from model coordinates to depth below land surface, and converts fixed travel time arrays into time fronts.

Concentration changes for the shallow and deep water-quality constituents in the pumping well are computed from particle-stopping times and depths. Final particle-stopping times and depths are imported from the file *OUTPUT_***YourModel***.ENDS.MANY.txt*. Shallow and deep particles that have stopped are segregated by stopping depths. Concentration changes are computed from particle stopping times with equation 1. Concentration changes in the pumping well and the lower and upper range of each constituent also are plotted on the Mixing worksheet (fig. 26).

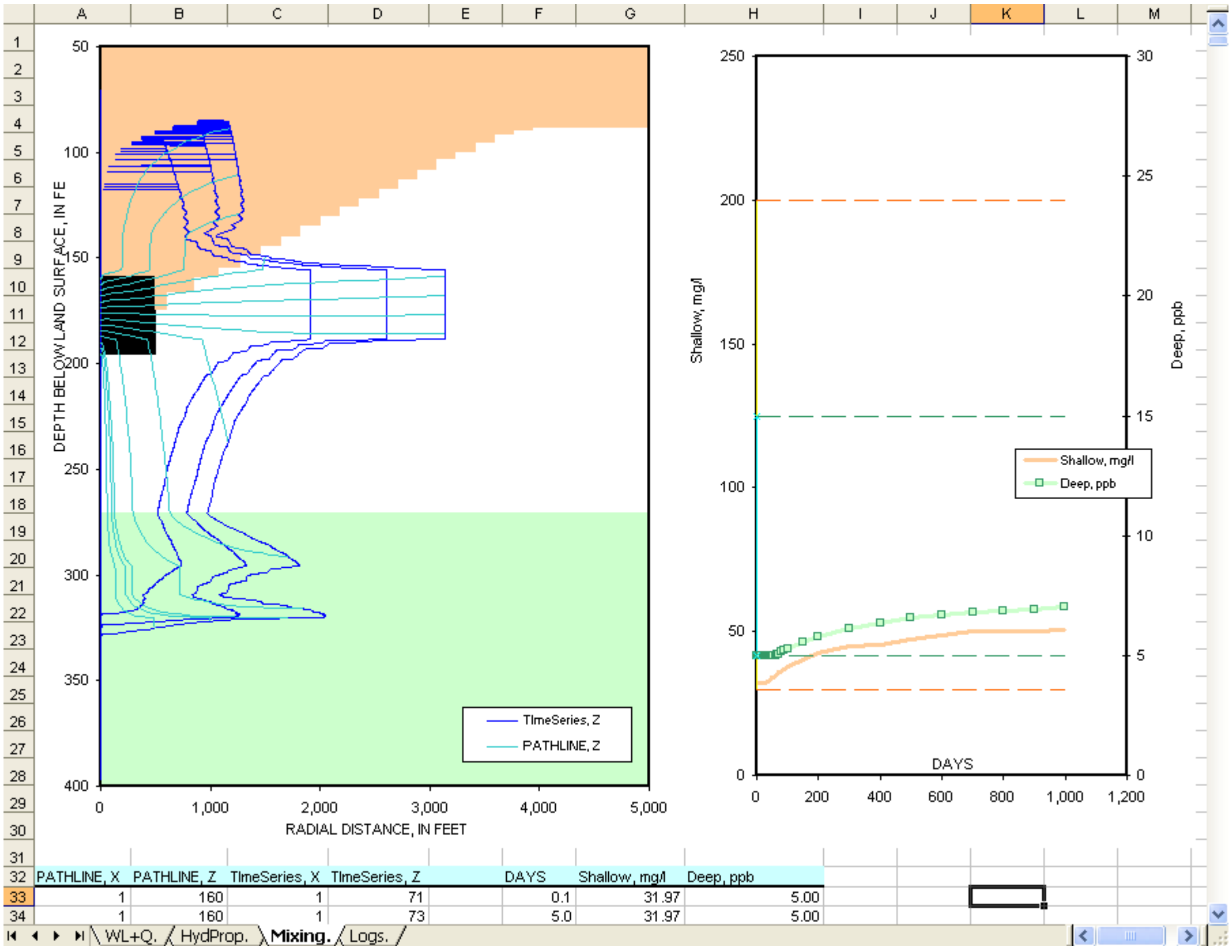


Figure 26. Mixing worksheet for viewing pathlines, time fronts, and water-quality changes.

Pathlines and time fronts are imported from the files *Output_***YourModel***.PATHS.txt* and Output_**YourModel**.*TIMES.txt*, respectively. Pathlines and time fronts are translated from model coordinates to depth below land surface and parsed into individual pathlines and time fronts. Results are plotted on the Mixing worksheet (fig. 26). Animated pathlines can be viewed in Model Viewer from the file *04_***YourModel***.mv*.

Box Focus

The Box Focus tool magnifies subareas of charts (fig. 27) and is a toggle switch with three states. The first click adds a rectangle to the selected plot area and changes the background color. The second click re-scales both axes to the area defined by the rectangle and removes the rectangle. The third click restores the chart to the original scales.

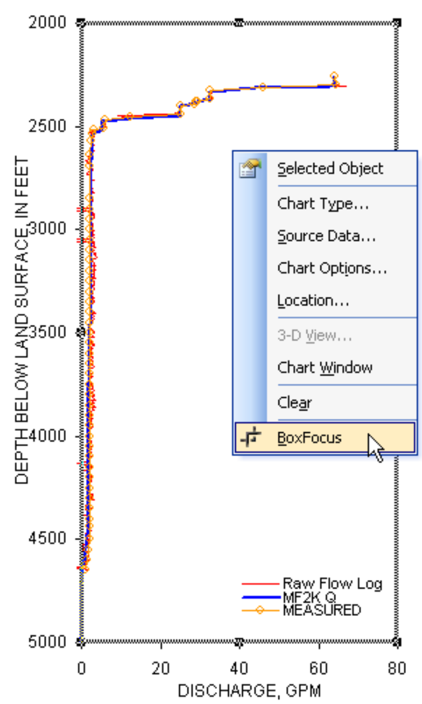
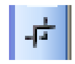
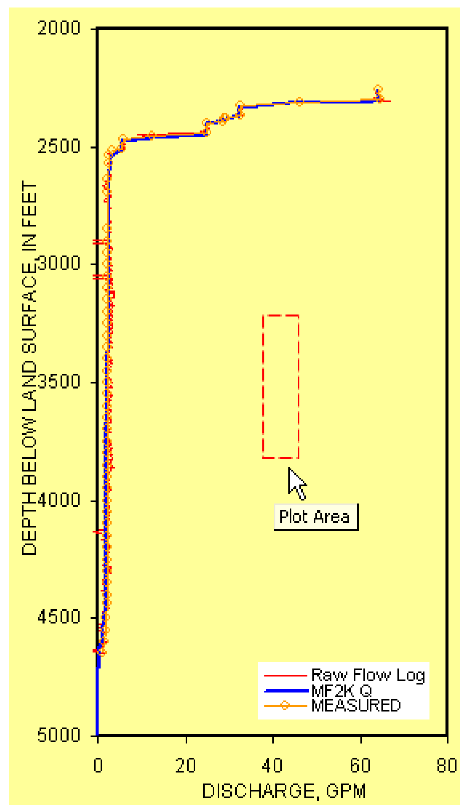
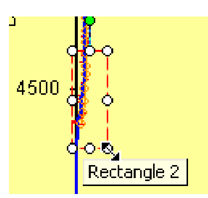


Figure 27. Box Focus tool is accessed through the AnalyzeHOLE menu, the keyboard shortcut “ctrl+q”, or the right-click menu in Excel 2003 when the plot area of a chart is selected. The right-click menu is not a feature in Excel 2007.

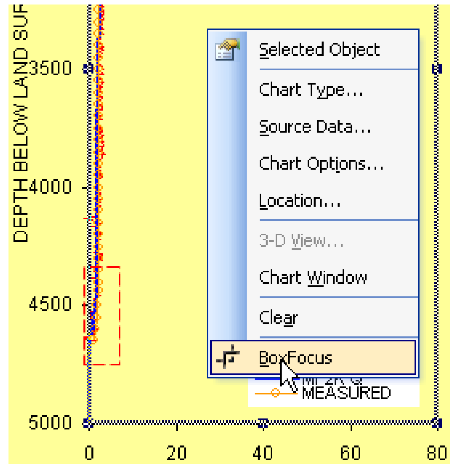
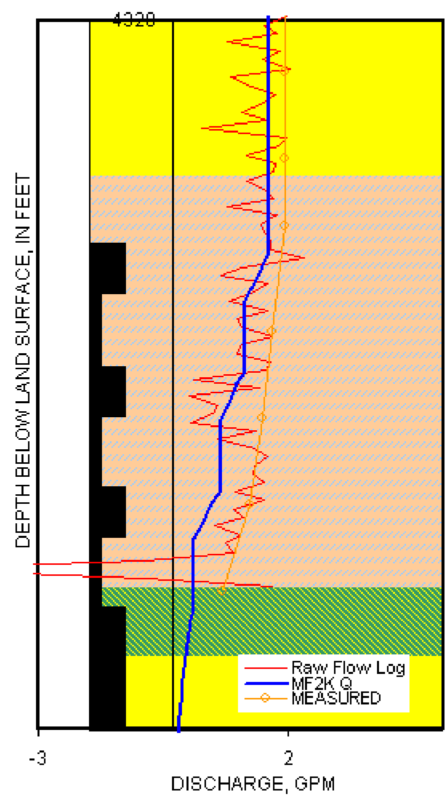
Instructions for Box Focus Tool

<table>
<tr>
<td>
The Box Focus tool appears at the bottom of a right-click menu when a plot area is selected in Excel 2003.
Select chart and use the keyboard shortcut “ctrl+q” in Excel 2003 or 2007.
</td>
<td>
 or “ctrl+q” in Excel 2003 & Excel 2007
Right-click in plot, 

Excel 2003 only
</td>
</tr>
<tr>
<td>
The default size of the Box Focus tool is specified as fractions of the X-axis length and Y-axis height.
</td>
<td>
<table>
<tr><th></th><th>M</th><th>N</th></tr>
<tr><td>20</td><td>X-FOCUS:</td><td>0.100</td></tr>
<tr><td>21</td><td>Y-FOCUS:</td><td>0.200</td></tr>
</table>
</td>
</tr>
<tr>
<td>
Right-click in the plot area and select BoxFocus to add a rectangle to the selected plot area.
Select chart and use the keyboard shortcut “ctrl+q” in Excel 2007.
Background color also changes.
</td>
<td>


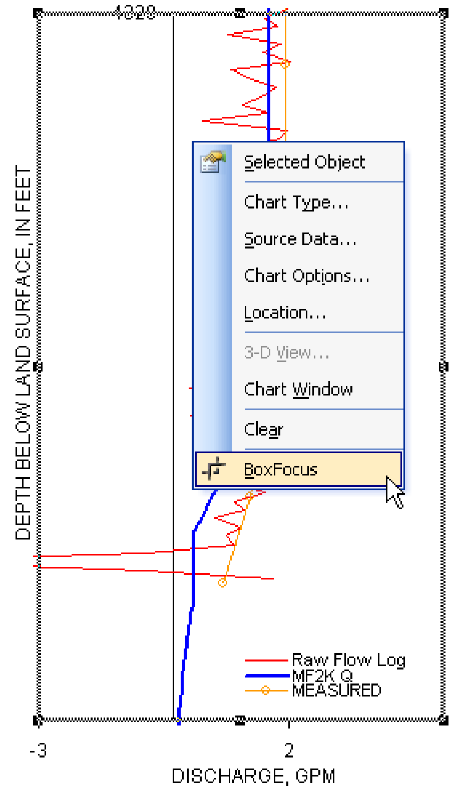
</td>
</tr>
<tr>
<td>
Delineate area to magnify by moving and resizing rectangle.
</td>
<td>


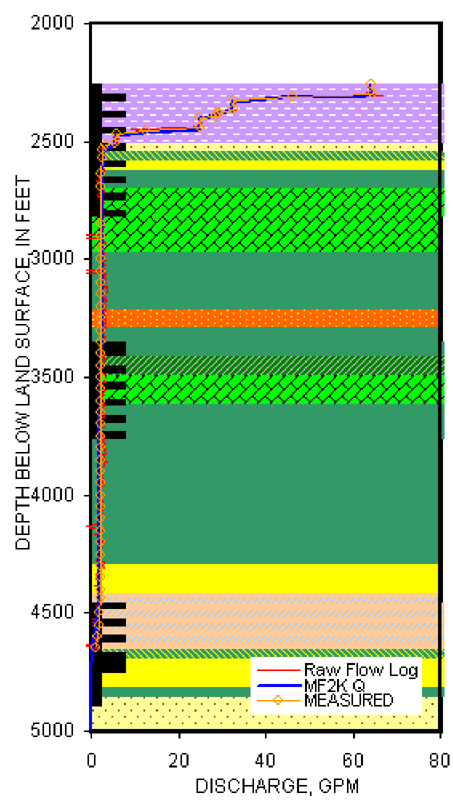
</td>
</tr>
</table>

Right-click in the plot area and select BoxFocus to re-scale both axes to the area defined by the rectangle. Select chart and use the keyboard shortcut “ctrl+q” in Excel 2007.	
Rectangle for defining the magnification area is removed.	

<table>
<tr>
<td>
Right-click in the plot area and select BoxFocus in Excel 2003.

Select chart and use the keyboard shortcut “ctrl+q” in Excel 2007.

Chart will be restored to the original scales.
</td>
<td>


</td>
</tr>
<tr>
<td>
Chart is restored to the original state.
</td>
<td>


</td>
</tr>
</table>

Refresh Charts

The Refresh Charts command, or , operates exclusively on the HydProp and Mixing worksheets and only affects charts when one of those two worksheets are active. The Refresh Charts command registers the underlying water quality/lithology background with the overlying charts and revises scales as defined by the user-specified variables; Deep C increment, Minimum Depth Increment, r-Plot Distant, and Shallow C increment in the global-property column (column S on the HydProp worksheet).

Wipe Files

The Wipe Files command, , deletes the more than 50 ASCII files that can be created by AnalyzeHOLE. MODFLOW, MODPATH, and PEST are all FORTRAN programs that read and write to ASCII files. The FORTRAN programs are controlled by batch files, *.bat, which also are ASCII files. Many ASCII files are created to simulate the aquifer-wellbore system and estimate the hydraulic conductivity distribution with PEST. The Wipe Files command facilitates file management by deleting files that are unnecessary after results have been imported into AnalyzeHOLE.

Hide / Show

The Hide / Show command, , controls the visibility of worksheets in AnalyzeHOLE. Only 4 of the 25 worksheets in AnalyzeHOLE are needed regularly by the user. HydProp., Logs., Mixing., and WL+Q. are needed by the user and always remain visible. The remaining 21 worksheets support workbook functions and are hidden or revealed with the Hide/ Show command.

Clear All Input

The Clear All Input command, , clears all user-specified input from AnalyzeHOLE. A warning form appears before all entries are deleted so users can reconsider their actions (fig. 28).

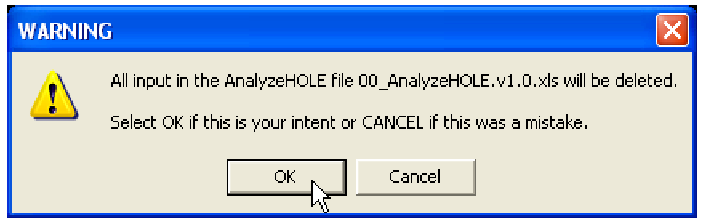


Figure 28. Form that warns all user-specified input will be cleared from AnalyzeHOLE.

Export AnalyzeHOLE Data

The Export AnalyzeHOLE data command, , writes all user-specified input from the current AnalyzeHOLE file to an AnalyzeHOLE data file, which has the extension, AHD. The AHD format is an Excel 97-2003 Workbook (*.xls) with the extension changed from XLS to AHD. Directory location and AHD file name are specified through a file navigation menu that appears after selecting the Export AnalyzeHOLE data command (fig. 29).

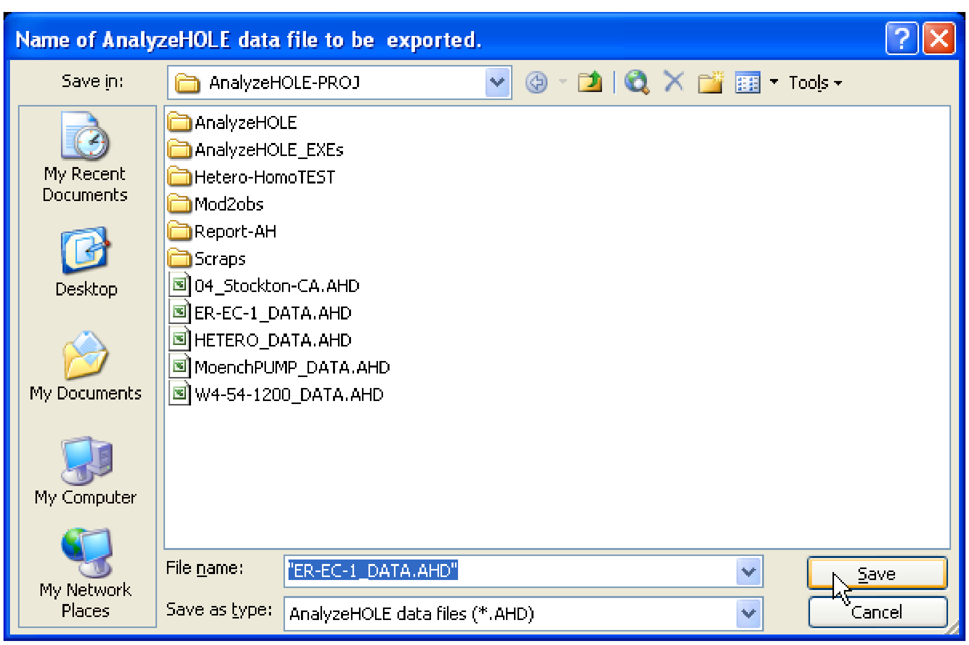


Figure 29. File navigation menu that appears for exporting AnalyzeHOLE data to an AHD file.

Exporting an AHD file will generate a compatibility warning when using Excel 2007 because the AHD format is an Excel 97-2003 Workbook (fig. 30). The warning should be ignored because the potential formatting changes do not affect importation of AHD data.

Import AnalyzeHOLE data

The Import AnalyzeHOLE data command, , clears all user-specified input from current AnalyzeHOLE file and transfers user-specified input from an AnalyzeHOLE data file, *.AHD, to the current AnalyzeHOLE file. Directory location and AHD file are located through a file navigation menu that appears after selecting the Import AnalyzeHOLE data command (fig. 31). A separate warning form does not appear because users can cancel importing an AHD file before clearing the existing data set.

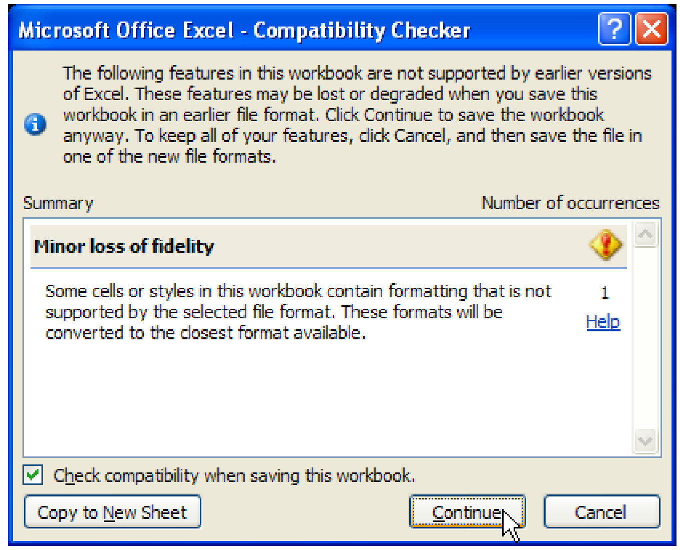
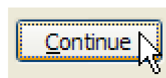


Figure 30. Compatibility warning that appears when exporting AnalyzeHOLE data in Excel 2007 where the user should select  .

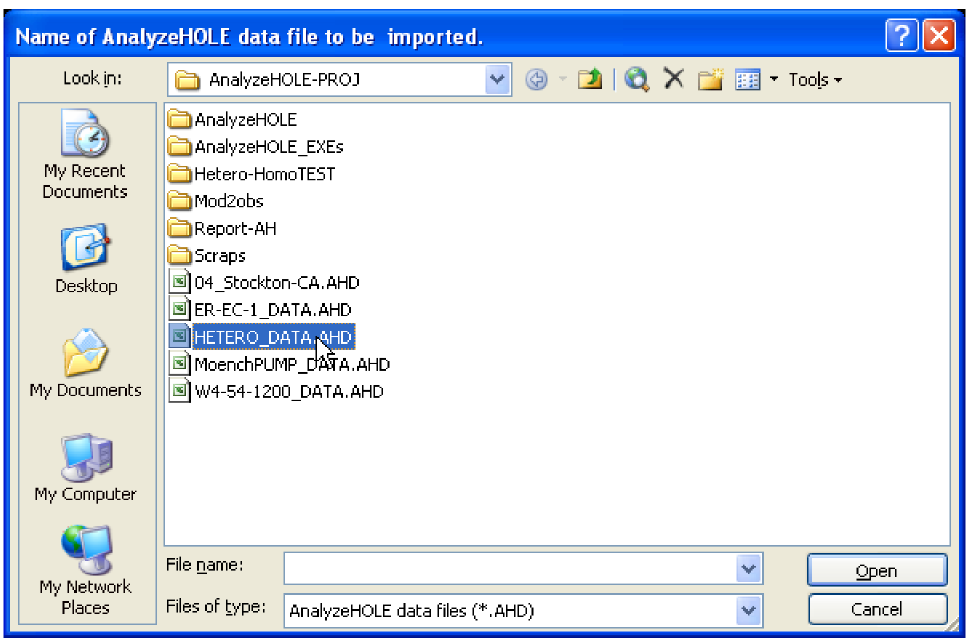


Figure 31. File navigation menu that appears for importing AnalyzeHOLE data from an AHD file.

About AnalyzeHOLE

The About AnalyzeHOLE command, , displays a synopsis of AnalyzeHOLE features and the current version number, 1.00 (fig. 32).

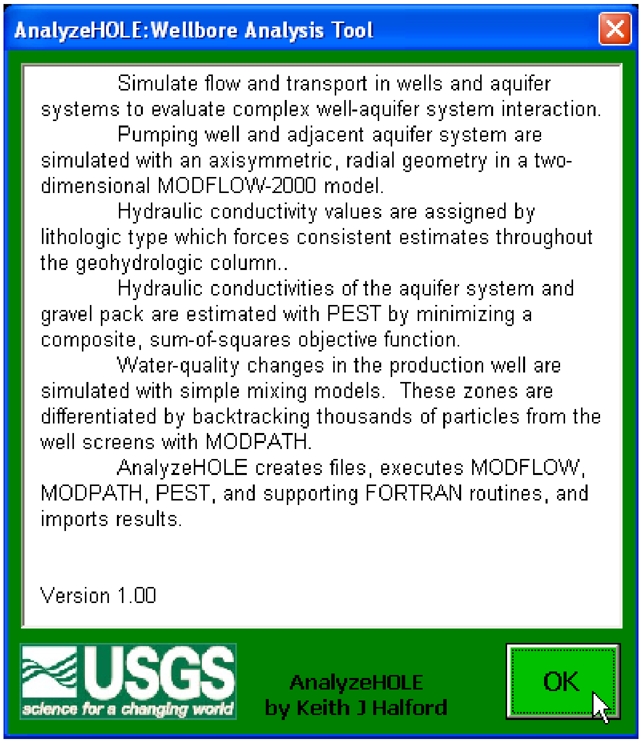


Figure 32. Splash screen that appears after selecting the About AnalyzeHOLE command.

Acknowledgments

The U.S. Department of Energy, National Nuclear Security Administration, Nevada Site Office, Office of Environmental Management supported this work under Interagency Agreement DE-AI52-01NV13944. The author also is deeply indebted to John Doherty for helping embed PEST in AnalyzeHOLE and making it regular.

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Appendix A. Explanation of User-Specified Variables in AnalyzeHOLE

Table A1. User-defined properties on the "HydProp" worksheet.

AnalyzeHOLE	Comments
Auxiliary Logs	Superimpose additional logs on the hydraulic conductivity profile. Additional logs are added to the "Logs." worksheet after column D. Logs are picked from the pick lists in cells B20 and B21.
Deep background C =	Concentration of deep constituent in the background water.
Deep C increment =	Increment of concentration labels for plotting the deep constituent on the "Mixing." worksheet.
Deep maximum C =	Concentration of deep constituent in the lower zone beneath the "Depth of deep."
Depth below WT, shallow =	Depth below the water table defines the thickness of the upper zone with a different water quality than the background. The shallow zone is not allowed to be deeper than the first top of screen. This was created originally to simulate high TDS water from return flow that overlies the background water.
Depth of deep =	Depth below land surface that defines the top of the lower zone with a different water quality than the background. The deep zone was created originally to simulate high concentrations of arsenic in deep aquifers.
Depth pump intake =	Depth below land surface, in feet, of pump intake. Pump is located in the uppermost screen if assigned depth is above the water table.
File Name:	Well specific identifier embedded in MODFLOW, MODPATH, PEST, and batch files that are created by AnalyzeHOLE.
K Annulus	Hydraulic conductivity of the gravel pack in the annular space, in feet per day. Values are specified in column J where well construction, development, or encrustation has decreased the hydraulic conductivity between the wellbore and the aquifer. K-annulus values that differ by less than the "Skin Grouping Multiplier" are grouped into discrete parameters when estimating K-annulus values with PEST.
K, ft/d	Assign a hydraulic conductivity, in feet per day, to each lithology.
K-Annulus Grouping =	K-annulus values that differ by less than the "K-Annulus Grouping" multiplier are grouped into discrete parameters when estimating K-annulus values with PEST.
K-Gravel =	Hydraulic conductivity of the gravel pack in the annular space, in feet per day. This value is used if cells in the K annulus column (N22) are blank. K-Gravel also is the maximum K annulus value that can be estimated with PEST.
K-Lithology Bound =	Hydraulic conductivity estimates are limited by minimum and maximum values. These values are specified by "K-Lithology Bound," which is a divisor and multiplier of the thickness-weighted mean hydraulic conductivity for each lithologic class.
K-Well =	Hydraulic conductivity of the wellbore, in feet per day, and should be great enough that simulated head differences in the wellbore are less than 1 percent of the total drawdown. Compute the equivalent hydraulic conductivity with the "K estimate" button.
Lithologic Class	Define lithologic classes in column B. Blank cells are not allowed between lithologic classes.
Lithologic Interval	Lithologies are selected from pull-down menus in column G that reflect user-specified lithologic classes in column B.
Minimum Depth Increment =	Increment of depth labels for charts on the "HydProp." and "Mixing." worksheets. Change is not reflected until user presses the "Refresh Charts" button on the AnalyzeHOLE toolbar.
Number of columns:	Columns 1, 2, and 3 simulate the wellbore, screen/casing, and annular fill, respectively. The remaining column widths expand by a fixed multiplier to span the user-specified, radial extent of the model.
Number of rows:	Depth is simulated with rows. Row 1 approximates the water table and the last row is the base of the aquifer system.
Particle concentration =	The number of gallons that each particle represents in mixing model. For example, 1800 particles would be backtracked for a pumping rate of 180 gal/min with a particle concentration of 0.1 (gal/min)/p.

Table A1. User-defined properties on the “HydProp” worksheet.—Continued

AnalyzeHOLE	Comments
Pathlines to draw =	The number of pathlines drawn on the “Mixing.” worksheet. Pathlines are for illustration and are not used for computing concentrations.
Pattern	Lithology patterns are specified by shading patterns in cells below this heading. Patterns correspond with lithologic classes that are defined in column B.
Porosity =	Porosity controls particle velocities in the MODPATH simulations.
Prepumping water table =	Depth below land surface to the water table. This will be the top of the model if greater than the shallowest lithology that is specified in cell F23.
r-annulus =	Radius of the drilled hole, in feet, that defines the width of the annular space between drilled hole and casing. This is the width of column 3. The width of the casing, column 2, arbitrarily is assigned 0.1 times the width of column 3.
r-Extent =	Radial extent of the MODFLOW model, in feet.
r-Plot Distant =	Radial distance, in feet, from pumping well for plotting pathlines and time fronts on the “Mixing” worksheet.
r-well =	Radius of the pumping well, in feet. This is the width of column 1.
Scale	Adjust amplitude of auxiliary logs.
Screen / Casing	Specifies construction of well wall and annular fill and can be CASING, Gravel+Case, or SCREEN. CASING excludes all flow and simulates a solid pipe wall with cemented annular fill. Gravel+Case permits flow in a permeable annulus and excludes flow to the wellbore. SCREEN simulates flow through a permeable annulus and into the wellbore.
Shallow background C =	Concentration of shallow constituent in the background water.
Shallow C increment =	Increment of concentration labels for plotting the shallow constituent on the “Mixing” worksheet.
Shallow maximum C =	Concentration of shallow constituent in the zone near the water table.
Slide	Offset intercept with hydraulic conductivity scale.
Ss =	Specific storage, in 1/ft, which typically ranges between 1E-6 and 3E-6 1/ft.
Stop pathlines@bad zone =	Pathlines and time fronts are not drawn through the shallow or deep zones of different water quality if this is TRUE.
Stress Period:	Duration of stress period in days.
Sy =	Specific yield, dimensionless, which typically ranges from 0.01 to 0.2.
Time for Theis WT:	The shape of the drawdown cone is approximated with a Theis (1935) solution at the user-specified time. Cells near the pumping well that are higher than the Theis approximation of the water table are excluded from the model domain. Cells are not allowed to dry or wet so the solutions will be stable and fast even though MODFLOW can solve drying cells near the water table.
Time Multiplier:	The multiplier for the length of successive time steps.
Time Steps:	The number of time steps in a stress period.
Top, FT BLS	Top of each lithologic interval in the geohydrologic column is specified below cell F22. Tops are specified in feet below land surface. Blank cells are not allowed between depths. Lithologies are selected from pick lists in column G. The lithologies are defined in column B.
Transmissivity	The target transmissivity of the entire geohydrologic column when fitting with PEST.
Vertical Anisotropy =	Ratio of vertical to horizontal hydraulic conductivity, which commonly is assigned 0.1 for unconsolidated sedimentary rock aquifers.
X-FOCUS:	X-Focus, N20, is the default size of the Box Focus tool, which magnifies subareas of plots. X-Focus is a fraction of the X-axis length. The Box Focus tool is accessed at the bottom of the right-click menu when a chart is selected.
Y-FOCUS:	Y-Focus, N21, is the default size of the Box Focus tool, which magnifies subareas of plots. Y-Focus is a fraction of the Y-axis height. The Box Focus tool is accessed at the bottom of the right-click menu when a chart is selected.

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