Analysis of Aquifer Test Data – MODFLOW and PEST

Alexandros Spiliotopoulos, Charles B. Andrews
S.S. Papadopulos and Associates, Inc., alexs@sspa.com, candrews@sspa.com, Bethesda, MD, USA

ABSTRACT

The most common hydrogeologic experiment is the aquifer test. A well is pumped and water levels are measured in the pumped well and in observation wells. The standard method of analyzing the aquifer test data is the type-curve method, and a number of easy to use computer programs facilitate the analysis of data. The type curve method of analysis has a number of drawbacks including the fact that it is not generally possible to evaluate all of the data collected during the aquifer test with a consistent approach and aquifer geometries and boundary conditions cannot accurately be represented. Graphical user interfaces for MODFLOW and PEST have now made it possible to efficiently and rapidly analyze aquifer test data without the limitations of the type-curve methods. In this paper, we will describe the analyses of aquifer test data conducted for purposes of developing water supplies from tests of a fractured bedrock aquifer in West Virginia and tests of glacial aquifers in the Midwest using MODFLOW and PEST. In the former example, the aquifer hydraulic conductivities estimated by the two methods differed by an order of magnitude and in the latter example our analyses produced a single value estimate of hydraulic conductivity whereas the type curve method produced a wide range of estimates. The paper concludes with a recommendation for the routine use of this method for the analysis of aquifer test data.

INTRODUCTION

The type-curve method is the most widely used approach for the analysis of aquifer test data. It is based on variations of the nonequilibrium equation and several underlying assumptions, depending on the conceptual model of the groundwater flow at the area of interest and the pumping conditions of the aquifer test. In general, application of the type-curve method requires: development of a conceptual model for the site, describing the hydrogeologic conditions and the groundwater flow pattern; choice of the appropriate method of analysis, based on the conceptual model (e.g. confined versus leaky aquifer, partially penetrating well, etc.); and inspection of the aquifer test data to identify outliers.

Once one has completed these steps, application of one of the user-friendly, available computer programs facilitates an analysis of the data to determine the aquifer parameters. In most cases, this process results in a set of hydraulic parameters that adequately characterize the aquifer in the vicinity of the test wells, and can be used for future predictions of drawdowns under various pumping conditions.

However, in many instances, analysis using the type-curve method provides inconclusive results that need further analysis or interpretation, adding to the underlying uncertainty of the aquifer conditions. In addition, application of such methods is based on a number of assumptions that can oversimplify the hydrogeologic conditions in the area of interest, failing to incorporate complex geologic and/or boundary conditions. In such cases, it is argued that development of a simple numerical model can facilitate a broader and more accurate analysis of the aquifer data. In fact, given the availability of modern graphical user interfaces (GUIs), a MODFLOW model can be developed in relatively short time. Furthermore, PEST can be used for the calculation of the aquifer parameters once the number and distribution of parameters is defined by the user in a few simple steps using the GUI.

The development of a good conceptual model is the most important step in any analysis. Consequently, the results of the analysis are only as good as the conceptual model. The advantage of the second approach is that the development of a numerical model requires the explicit consideration and representation of the conceptual model. A reliable conceptual model reflects all the processes taking place in the area of interest, identifying the geologic structure and the general groundwater flow patterns in the aquifer(s). Therefore the analysis is based on a better representation of the hydrogeologic conditions.

THE TWO APPROACHES

When using a type-curve method for the analysis, choosing the right type-curve method that corresponds to the conceptual model is essential. However, every type-curve method is based on a number of assumptions, regarding aquifer homogeneity and isotropy, areal extent, aquifer thickness, well diameter, and water removal from storage, to name the most important ones. The basic assumption of infinite areal extent of the aquifer that underlies all methods is the most restricting one, especially where physical boundaries exist in short distances from the area of interest. In such cases, implementation of the method of images is necessary to transform the finite flow system and incorporate the hydraulic effects of the boundaries in the analysis. However, when the geometry of the boundaries is complex, application of the method theoretically requires an infinite number of images to correctly include the boundary effect. Another limitation of all type-curve methods is varying aquifer thicknesses or areas of different hydraulic conductivity which cannot be directly incorporated in the analysis. Consideration of such factors requires additional steps in the data evaluation process.

An alternative approach to aquifer test data analysis is the application of new graphical user interfaces. Application of GUIs facilitates relatively quick development of a numerical model allowing:

- Incorporation of regional geomorphology (digitized geologic maps, digital elevation models).
- Inclusion of natural boundaries with accurate areal extent.
- Assignment of zones of hydraulic properties by direct interpretation of geologic maps as initial conditions to the model.
- Easy model modification to match desired level of detail of the conceptual model.
- Quick grid generation and modification for acceptable grid resolution in areas of interest.
- Incorporation of numerous observation data for visual inspection in a user-friendly environment.

Taking advantage of the flexibility of a numerical model, it is easy to test the validity of the conceptual model using as initial parameters those obtained from the type-curve method. Furthermore, the GUI allows easy modification/zonation of aquifer parameters to reflect a more complex/detailed conceptual model. Those advantages are augmented when numerical modeling is combined with parameter estimation techniques through the use of PEST. In such a case, it is easy to prepare the input files for PEST through a simple step within the GUI. PEST runs provide estimates of the hydraulic parameters that better reflect local and regional variation of the hydrogeologic conditions.

In what follows, two cases are presented where the combination of MODFLOW and PEST were applied for the evaluation of the aquifer test data. The first site is in West Virginia and the second site is in the Midwest. Both are characterized by complex geologic conditions and include natural boundaries with direct effect on the groundwater flow patterns.

AQUIFER TEST ANALYSIS USING MODFLOW-PEST

West Virginia Site

For this site, the task was to develop a groundwater flow model to simulate the groundwater conditions. The groundwater model was used to evaluate the availability of groundwater as a water source and to evaluate potential impacts to local pumping wells from groundwater withdrawals.

Conceptual Model

The groundwater system in the study area (Figure 1) was conceptualized based only on data collected during three aquifer tests at the Site and geologic maps of the area. However, no monitoring data were available in the vicinity of the Site, adding to the uncertainty of the conceptual model. Based on the available information, the groundwater system was conceptualized as consisting of three major units: a saturated surficial alluvial overburden, 5-15 feet thick; a layer of interbedded red to green shales, sandy shales and sandstone, 25-50 feet thick (intermediate layer); and an underlying fractured sandstone layer, at least 100 feet thick. The production and deep observation wells are open to both the intermediate and sandstone layers.

The intermediate layer acts as an aquitard, allowing limited vertical leakage. There is limited hydraulic connection between the surficial aquifer and the sandstone aquifer. Although there is limited data regarding hydrogeologic conditions in the area, groundwater movement appears to occur primarily through horizontal fractures in the sandstone formation. Recharge to the aquifers primarily occurs via the vertical fractures along the valley walls. In the study area, the valleys along the two creeks and the river, define the areal extent of the aquifer systems as described above.

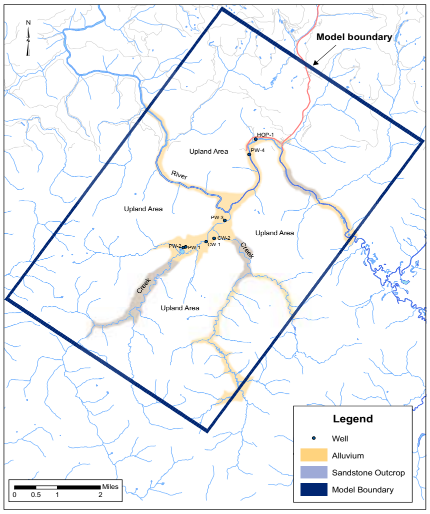

Figure 1. Site Map – West Virginia.

Aquifer Test Analysis using Type-Curve Methods

Three aquifer tests were performed at the Site. The data from the aquifer tests at wells PW-1, PW-3, and PW-4 were analyzed using the commercially available software AQTESOLV (Duffield, 2002). The analytical solution developed by Hantush (1960) for a leaky confined aquifer with storage in the aquitard was used to analyze the drawdown data from the tests.

Analysis of the data from the deep observation wells for the 72-hour aquifer test at well PW-1 indicated that the effective transmissivity and storativity in the vicinity of well PW-1 are approximately 700 ft^2/d and $4x10^{-6}$ respectively; in the vicinity of PW-3 range between 470 and 1,070 ft^2/d, and $1x10^{-5}$ and $1x10^{-7}$ respectively. During the aquifer tests high drawdown was measured at all observation wells very soon after commencement of the test. Also, the distance-drawdown plots for the aquifer tests at PW-1 and PW-3 show very similar drawdowns at the pumping well and the observation wells. Both these observations are indicative of a highly fractured aquifer. Analysis of the available drawdown data in the vicinity of well PW-4 indicated that the effective transmissivity and storativity are approximately 400 ft^2/d and $2x10^{-6}$, respectively.

Groundwater Modeling and Parameter Estimation

Groundwater flow was simulated using MODFLOW-2000 (Harbaugh et al., 2000) and the model was constructed using Groundwater Vistas (Rumbaugh, 2004) as the graphical user interface. The groundwater model encompasses an area of approximately 50 square miles, defined by a grid of 352 rows and 152 columns of variable spacing. The vertical model discretization includes three layers, for the representation of the alluvial overburden, the intervening aquitard layer, and the sandstone layer.

The middle layer was assumed to be not present in areas where the sandstone layer directly underlies the alluvium; this was simulated by specifying a very large vertical hydraulic conductivity for the middle layer in these areas. The model boundary conditions included no-flow boundaries along the model perimeter, and river nodes in the top layer along the major streams. All river nodes were assigned a constant hydraulic head. Different hydraulic conductivity values were specified in the upland and valley areas in all layers. However, the sandstone unit underlying the alluvium along the river in the vicinity of well PW-4 was assigned upland conductivities, to reflect the conclusions from the aquifer test at that well. This suggests that stress relief fracturing is not prevalent in areas where the valleys are very narrow.

Model calibration was facilitated through the use of PEST (Doherty, 2005), a nonlinear parameter estimation and model calibration software. Model calibration parameters included horizontal and vertical hydraulic conductivity, and specific storage. The flow model calibration targets included measured drawdown at the deep observation wells during the aquifer tests at wells PW-1 and PW-3. For simplicity, the models were calibrated to the aquifer tests results independently.

Horizontal and vertical hydraulic conductivities and storage coefficients were determined through the iterative calibration procedure. The values of aquifer parameters calculated from the calibration process were similar for both PW-1 and PW-3 aquifer test data, with the exception of vertical hydraulic conductivities in the valley, which differed by almost an order of magnitude. The calculated horizontal hydraulic conductivity was 100 ft/d. Plots of calculated drawdowns and observed drawdowns from the aquifer tests of PW-1 and PW-3 are shown in Figure 2. After calibration to aquifer test data from PW-4, the calculated horizontal hydraulic conductivity of the sandstone formation underlying the alluvium along the river in the vicinity of PW-4 was 3.0 ft/d. The calculated hydraulic conductivity of 100 ft/d corresponds to an effective transmissivity of approximately 10,000 ft^2/d, or two orders of magnitude higher than that obtained from the type-curve analysis.

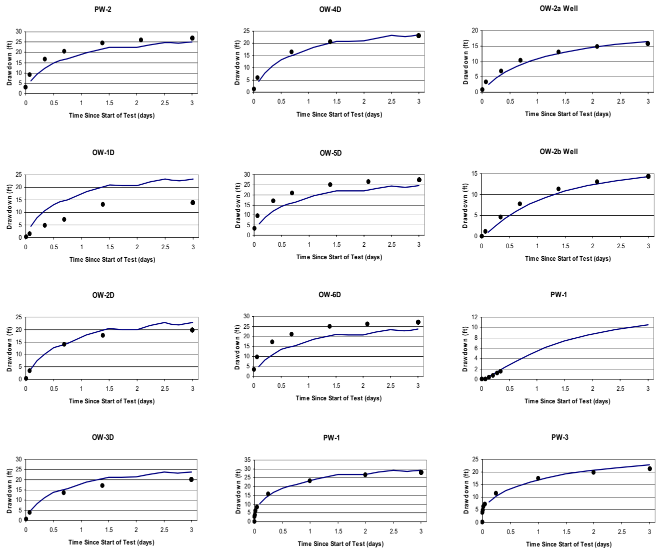

Figure 2. Calculated versus Observed Drawdowns for Aquifer Tests at PW-1 (Columns 1 and 2), PW-3 (Column 3).

Midwest Site

For this site, the task was to develop estimate of aquifer parameters to be used in evaluating source water protection areas for a municipal well and to determine if the well was likely to be in the future under the direct influence of surface water.

Conceptual Model

The municipal well is located in an area of glacial deposits mapped as outwash, coarse-to-fine texture glacial tills and fine-grained glacial tills. In the vicinity of the municipal well, the glacial deposits consist of approximately 10 feet of fine-grained materials underlain by about 50 feet of coarse sand and gravel, which overlies a thick fine-grained glacial till. The municipal well is screened in the lower portion of the coarse grained deposits. The coarse-grained materials are part of a broad band of glacial outwash that is about 3,000 feet wide and trends approximately northeast to southwest. The areal extent of these deposits was mapped primarily on the basis of logs from residential supply wells. A perennial stream (Figure 3) that is located about 150 feet from the municipal well traverses these coarse grained outwash deposits but the stream bed is mainly fine-grained materials. Numerous small seeps occur adjacent to the stream.

Aquifer Test Analysis using Type-Curve Methods

An aquifer test was conducted at well PW-1 for 45 days. This test was a cycled test consisting of seven days of pumping, followed by five days of recovery, followed by an additional 6 days of pumping, and then several days of recovery. The nominal pumping rate was 320 gpm. During the testing of well PW-1, nearby supply wells PW-2, PW-3 and PW-4 were operated at relatively constant rates of 480 gpm, 360 gpm, and 530 gpm, respectively.

Analysis of the aquifer test data was performed using the Neuman solution method for unconfined aquifers. The data were analyzed using the commercially available software AQTESOLV and the analysis provided a wide range of transmissivity and storativity values. For the data from the observation wells near the pumping well, the aquifer transmissivity was estimated at 2,160 ft^2/d and the storativity was 0.008. For the data from observation wells far from the pumping well, the aquifer transmissivity and storativity were 56,700 ft^2/d and 0.029 respectively.

Groundwater Modeling and Parameter Estimation

A groundwater model that encompassed an approximately 8,000 feet by 8,000 feet area in the vicinity of the municipal wells was used to simulate the aquifer test. Two parameter zones were identified for hydraulic conductivity and storativity: a zone corresponding to the outwash deposits and a zone corresponding to coarse-to-fine textured glacial till. Groundwater flow was simulated using MODFLOW-2000 and the model was constructed using Groundwater Vistas as the graphical user interface. The GUI facilitated quick development of the model which consists of six layers, each 10 feet thick. Simple boundary conditions were applied and aquifer properties were assigned to the two zones. Input files were prepared using the GUI for the parameter estimation program PEST which was used to provide a single transmissivity value and a specific yield for the high transmissivity zone as well as the vertical hydraulic conductivity beneath the bed of the creek. Model-calculated and observed drawdowns during the aquifer test at selected monitoring locations, which compare quite well, are shown on Figure 3. The transmissivity was estimated at 7,500 ft^2/d, the specific yield was 0.25, and the vertical hydraulic conductivity beneath the bed of the creek was approximately 1 foot per day.

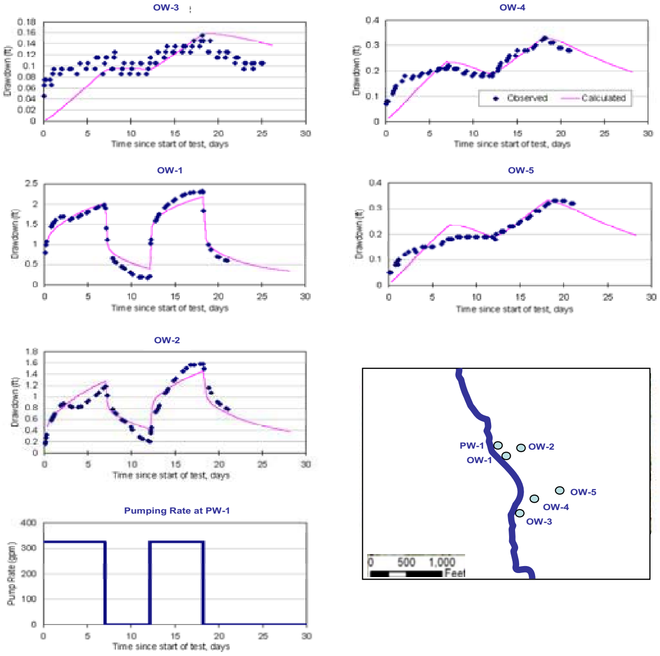

Figure 3. Observed versus Calculated Water Levels, Pumping Pattern, and Well Locations for Midwest Site.

CONCLUSIONS

The purpose of this analysis was to illustrate how graphical user interfaces can facilitate easy and relatively quick development of a numerical model and its calibration to aquifer test data, for better estimation of the aquifer parameters. In both cases examined herein, complex geology and natural boundaries were easily incorporated in the numerical models. That allowed a better representation of the hydrogeologic conditions in the study area. The combination of MODFLOW and PEST provided flexibility to the calculation of aquifer parameters adding important spatial variation necessary to reflect a more detailed conceptual model.

In most cases, numerical models are necessary to be developed in order to address important issues like capture zone analysis, groundwater resources management, and contaminant transport and fate. Aquifer test analysis using type-curve methods can provide an indicative range of values that can later be used as initial estimates of the aquifer parameters in the calibration process of the numerical model.

REFERENCES

Doherty, J., 2005. PEST Version 9 User's Guide. Brisbane, Queensland, Australia: Watermark Numerical Computing.

Duffield, G.M., 2002. AQTESOLV for Windows Version 3.50 Professional, HydroSOLVE, Inc.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald., 2000. MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model--User Guide to Modularization Concepts and the Ground-Water Flow Process. U.S. Geological Survey. Open-File Report 00-92.

Rumbaugh, J., and D. Rumbaugh. 2004. Groundwater Vistas Version 4 User's Guide. Environmental Simulations Inc.