Requirements for Defensible Ground Water Modeling

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ABSTRACT

In times of drought, as we are experiencing at present in the southwest, many difficult questions of water resource management must be answered. The answers to these questions may be costly, substantially change the livelihoods of numerous stakeholders, and affect the futures of growing communities. The New Mexico Office of the State Engineer is on the verge of transition from an administrative system of almost exclusively paper permits and documentation to one of wet water use under valid water rights. If ground water models continue to be used to evaluate these critical water resource management issues, then these models should be applied in a defensible manner. Requirements for conducting defensible ground water modeling should be developed and include a process for (1) the selection and development of the most appropriate tools and (2) the careful evaluation of available data, particularly in cases of contested water resource issues where numerical models are being used. We provide a partial case history to illustrate why we believe there is a need for these types of requirements.

There are two main families of ground water models that can be used: analytical models and numerical models. Analytical models provide solutions to the ground water flow equation using classical mathematics. Analytical models employ stringent assumptions that represent simplifications of the natural system. These models can be successfully applied at the local scale where techniques such as the Theis equation are often used to estimate the effects of pumping in the vicinity of the pumping well. These models are typically not employed beyond the local scale, because it is not possible to represent many important regional hydrologic features affecting ground water movement (e.g., aquifer heterogeneity, structural features, recharge and discharge). Numerical models, whose use began in the 1960s, are solved using numerical analysis techniques. These types of models became more common in the 1980s because of the increased computational speed of computers. Since then, numerical models have continued to be used in the practice of hydrology. They require numerous, repetitive calculations and use a gridding process to divide the aquifer into regularly-shaped portions. Through this gridding process, important spatial features controlling the hydrologic system can be incorporated.

At a proposed development site in New Mexico, one of the issues in controversy was the potential for impacts of operational pumping at the site on a water resource over 10 miles away. The protestors of this project began their analysis employing an analytical model, the Theis equation, and suggested that this should be the method of choice for the impact evaluation. Later work by the protestors included application of a two-dimensional MODFLOW flow model that did not incorporate much of the available subsurface data. As requested by the developer, we built a three-dimensional numerical flow model also using the MODFLOW code. The model was developed and calibrated using ASTM guidelines for model development. Available field data, which were extensive for the area because of exploration activities, were used first to develop a hydrogeologic conceptual model. This conceptual model was then digitally-represented using state-of-the-art computer modeling software including integration of geographical information system (GIS) data using the Environmental Systems Research Incorporated (ESRI) ArcView 3.2 and ArcGis software, the subsurface geologic data using the Ground Water Modeling System (GMS), and the graphical user interface, Ground water Vistas Version 3.

Not surprisingly, the outcomes of these two approaches were substantially different even though the same data were available and the same processes were being modeled. The protestant's model showed appreciable impact to a distant water resource while our model showed little to no impact outside the immediate area of the proposed development. This case history underscores our belief in the need for a process to prevent the misuse and misapplication of ground water models as they are being used with greater and greater frequency to provide the basis for decisions of significant social consequence.

Introduction

In times of drought, as we are presently experiencing in the Southwest, many difficult questions of water resource management must be answered. While in the past, the administration of water rights has been based mainly on "paper rights," because of severe water shortages facing much of the southwest, regulators are looking more closely at the actual availability of "wet water". Since "wet water" is in short supply, it is now more important than ever to develop tools that can quantify water availability and predict with greater accuracy the potential impact of a proposed use on an existing use. The opinions expressed in the this paper are predicated on the assumption that surface water and ground water models are here to stay and will be used with greater frequency to solve more and more complicated and controversial water resource management problems. The focus of our paper is on ground water models; however, the issues of concern have application to other fields (e.g., surface water models, air models) where numerical models are used in decision making. If ground water models are to be used to evaluate questions concerning water resource management, then these models should be applied in a defensible manner. Requirements for defensible ground water modeling should be developed and include a process for the selection of the most appropriate tools, development and application of those tools, and in particular, the careful evaluation of available field data.

It is important to first clarify a few things with respect to the position taken in this paper. We do not advocate for the development of requirements that force the applicant to build a complicated numerical model and always use the most sophisticated approach. There are many cases where computer models have been put forth as a better analysis simply because they are more complicated. Nor are we advocating for the use of computer models for all water resource evaluations. In a paper by Dennis B. McLaughlin completed for the U.S. Army Corps of Engineers Hydrologic Engineering Center entitled *A Comparative Analysis of Groundwater Model Formulation*, three model approaches were compared, and it was clearly shown that the most important issue in this case was that the field data used needed to be properly evaluated (McLaughlin, 1984). Mr. McLaughlin demonstrated that there was no value added by creating the computer models because the data collection and interpretation were not properly completed and that there were not enough field data collected to properly constrain the models. However, what we will show through discussion of the example provided in this paper is that, in cases where there is significant available data and the choice is made to use numerical models, available field data must be carefully evaluated and included in the development of the model. Before presenting the case history, we provide some general background information on ground water modeling.

Ground Water Modeling Background

There are two general categories of ground water models used in hydrology: analytical models and numerical models. Analytical models provide solutions to the ground water flow equation using classical mathematics. These types of models employ stringent assumptions that are simplifications of the natural system. For example, hydrogeologic properties such as transmissivity are considered homogeneous and isotropic and the layering of the modeled system is local in scale as is the case for the Theis solution (Theis, 1935) which assumes homogeneity, two-dimensional confined flow with a constant pumping rate. Other analytic solutions given by Jacob (1946), Hantush and Jacob (1955), Hantush (1960, 1966), and others address issues such as semi-confined or leaky conditions but always assume a homogeneous isotropic system. More recent contributions by Barker (1988), Butler (1988), and Butler and Liu (1991, 1993) have provided analytic solutions that improve the degree of complexity of the aquifer by dividing it into several regions of homogeneous properties.

Numerical models grew out of the limitations associated with analytical models. Numerical models became easier to apply in the 1980s because of the increased computational speed of computers. Numerical models that simulate ground water impacts caused by a pumping well originate back to 1968 when Pinder and Bredehoeft (1968) presented an axisymmetric numerical model designed for well-test interpretation. Since that time, there have been numerous numerical modeling efforts focused on well-test interpretation, pumping impacts and the impact of heterogeneity upon the uncertainty of the interpreted results (e.g., Cooley, 1971; Lachassagne et al., 1989; Herweijer, 1996; and Meier et al., 1998). Applications to actual field test data have led to the development of inverse methods to automatically interpret well-test drawdowns. Examples may be found in Carrera and Neuman (1986), Lebbe and De Breuck (1995), and Meier et al. (1997).

Hydrologists have long understood that proper incorporation of heterogeneity into models has potential for increasing model accuracy. This point was emphasized in a comparison paper in which several international modeling teams attempted to reproduce the 'reality' of a synthetic spatially complex hydrologic system from a limited set of observations (Zimmerman et al., 1998). In general, Zimmerman et al. (1998) found that the models with the ability to incorporate geology with heterogeneous aquifer properties reproduced the 'known' system better than those without this ability. This study also determined that a model's relative performance was directly related to its relative representation of the geologic system.

The last decade has seen the commercialization of numerical modeling tools that have significantly simplified the simulation of ground water flow through highly heterogeneous hydrologic systems. The release of new modeling platforms such as Groundwater Vistas, GMS and Visual Modflow have given ground water models the technology needed to incorporate the requisite complexity into site-specific models.

If the choice is made to use a numerical model, then the model should be 1) constructed with available site data, e.g., topography, geology, recharge and aquifer stresses, 2) calibrated to steady-state and transient water levels and 3) subjected to sensitivity analyses in which uncertain parameters used in the model are modified sequentially to obtain their relative importance upon the metrics of interest in the study (i.e., ground water drawdown, stream depletion, etc.). We provide a partial case history in the next section to illustrate why we believe there is a need for these types of requirements.

Case History

The following case history serves to illustrate the point that when ground water models are used as the basis for decision making, there is a need for a process to prevent misuse and misapplication of this important tool, as well as prevention of overly-conservative analyses which can lead to poor decisions and unnecessary outcomes. At a proposed development site in New Mexico, one of the main issues in controversy was the potential for impacts of operational pumping at the site on a water resource over 10 miles away. Two very different models were developed to evaluate the potential impacts. Due to confidentiality, we will discuss the findings in a general sense and will not provide specific information regarding these two models. We refer to the model developed by the representatives of the adjacent water resource as the "Protestors' Model" and to the model that we designed for the developer as the "Developers' Model".

Protestors Model

The protestors used MODFLOW (McDonald et al., 1988) to develop a "superposition, numerical ground water flow model" to evaluate the potential impacts of pumping from this aquifer on the distant water resource. They employed Groundwater Vistas (Version 3) in conjunction with MODFLOW to construct a single-layer finite-difference model grid and ignored much of the available field data for this site. Additionally, the numerical model was not consistent with their own conceptual model. For example, the aquifer was assumed to be confined throughout the entire modeled area, yet the protestors stated that the aquifer was not confined in areas where it was in contact with saturated alluvium. Additionally, the protestors misused the MODFLOW code by applying a "type 1", or unconfined condition, when they stated that they believe this aquifer to be confined. The effect of this misapplication is to exaggerate drawdown regionally and at the pumping well as the transmissivity is reduced in response to drawdown in the aquifer. Their model assumed zero leakage from adjacent formations and no recharge, yet it is clear from site-specific data and the literature that some leakage as well as recharge would occur in this area. The protestors also neglected to calibrate their model to existing aquifer test data, a highly recommended step in model development when such data are available. Finally, the protestors use of no-flow boundaries when the impacts from the pumping reach the model boundaries is problematic and has the effect of magnifying drawdown everywhere in the model. Site specific data and studies from other similar hydrogeologic environments do not support the use of no flow boundaries.

The combined effects of misuse of the MODFLOW model, the application of unrealistic boundary conditions, the development of a numerical model that was not built to honor their conceptual model or the site-specific geologic data, and the lack of calibration of the model to existing hydrologic data render this model unacceptable for use in water resource impact analysis. Not surprisingly, the application of their model resulted in propagation of drawdown in the aquifer and appreciable impacts to the water resource located over 10 miles away in a relatively short period of time. In the next section, we provide a discussion of the very different approach and results achieved with our model.

Developers Model

With the same objective as the protestors, to evaluate the effects of pumping on a water resource over 10 miles away from a development site, we built a three-dimensional numerical flow model using the MODFLOW code (Harbaugh, et. al 2000). In the development of this model we followed standard industry protocol, honored site-specific date, calibrated the model to steady state and transient conditions, and performed a sensitivity analysis. The model was developed and calibrated using standard industry protocol (ASTM, 1993). Additionally, this model may have been used as a ground water management tool during operations. The MODFLOW model was developed and calibrated for the regional area in the vicinity of the proposed site. The model simulated steady-state and transient ground water flow. Because of the complex nature of the geology, the model grid was developed using many layers to honor the geologic structure. Site and regional aquifer characterization data, including hydrogeologic properties such as conductivity and storativity as well as the historical steady-state water levels and pumping test observations, were included in the model and constrained the model. The available water balance information, recharge and evapotranspiration (ET) were also used to constrain the model.

The development of the model followed the guidelines presented in the American Society of Testing and Materials (ASTM) D5447-93, “Application of a Ground-Water Flow Model to a Site-Specific Problem” (ASTM 1993). The methodology used specifically included the process detailed in the guidelines presented in Sections 4.1.1 through 4.1.8 of ASTM D5447-93. The guidelines include:

- Define study objectives
- Develop a conceptual model
- Select a computer code
- Construct a ground water flow model
- Calibrate model and perform sensitivity analyses
- Make predictive simulations
- Document modeling study
- Perform postaudit

In considering the ability of the model to represent existing field conditions and predict future behaviors of the ground water flow system, a “weight-of-evidence” approach was used. This approach entails the use of numerous data sets (e.g., water levels, geologic structure maps, pumping test results, site-specific climatic data, etc.) during both model construction and calibration. This approach is described further in Guideline 2 presented by Hill (1998), which advocates that one should, “...use a broad range of information to constrain the problem.”

Extensive field data were used to develop the conceptual model of the ground water flow system, and, in turn, are the basis for the numerical model that was developed. It is important that the supporting data be organized and readily available for analysis. For this reason, the construction of the numerical model followed a GIS-based approach to develop a three-dimensional model of the model area. Data were either acquired in electronic format or digitized into electronic format from hard-copy sources. The use of a GIS-based approach allowed integration of data from disparate sources into a coherent whole. For example, point data comprised of stratigraphic elevations from wells were combined with structure contours digitized from hard-copy sources and surface outcrop trace data to generate the best available representation of the subsurface geology.

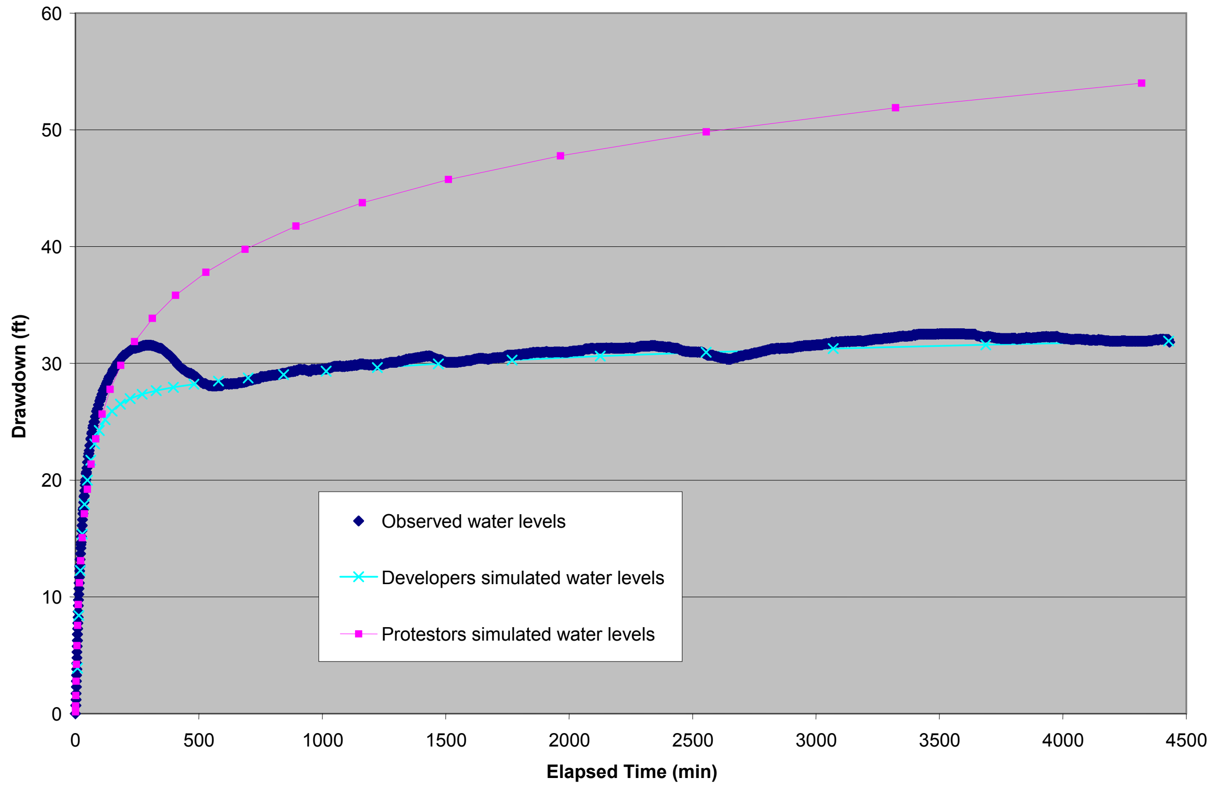
Construction of a comprehensive geologic model for this study involved the integration of GIS data processed and generated using the ESRI ArcView 3.2 and ArcGIS (ArcView 8.2) software packages and geologic modeling tools available in the GMS software package, versions 3.1 and 4.0. For this study, the three-dimensional geologic model was constructed within GMS, then converted into standard MODFLOW format. The MODFLOW model input files were created and MODFLOW output was analyzed using a separate graphical user interface called Groundwater Vistas Version 3.

The model was calibrated in two distinct steps. First, the model was calibrated to pre-development, or steady-state conditions. Steady-state conditions (i.e., water levels) were determined by computing an average value when data over time were available for certain wells. The calibration involved adjusting the model input parameters until the computed water levels matched the observed water levels with the goal of achieving the lowest value possible within the range of accepted model inputs. The recommended value of <10% between the predicted and observed data over the range of observations was achieved (Spitz and Moreno, 1996). This calibration step ensured that the model calculates regional flow directions and flow velocities consistent with those represented by the observed data.

The second step of calibration focused upon matching the pumping test data from aquifer tests that have been conducted. Using the steady-state model properties and assigning the steady-state water levels as initial conditions, the pumping tests conducted at the site were simulated and the results of the simulations were compared to the observed results. Since the model's grid cell size in the site area was large relative to the distance between the pumping and observation wells, the model grid cell size in the site area had to be reduced in order to have enough grid resolution between the pumping and observation wells to compare the computed with the observed results. Therefore, a smaller transient model grid, referred to as the telescopic mesh refinement (TMR) model, was developed from the model grid. The initial transient model parameters were taken from the steady-state model and from site-specific data (e.g., storativity). These parameters were refined while calibrating to the observed measurements. After being calibrated to the observation data, the adjustments made to the transient model were updated in the steady-state model.

The results of this modeling effort revealed that the effects of pumping would not propagate outside the property boundaries (over 10 miles away from the water resource in question) for the entire lifetime of the project. The figure presented below provides one of many comparisons of the opposing model's predictive capabilities. As can be seen in this figure, the two models give appreciably different results as compared to the observed data from a pumping test. This figure illustrates one of the reasons that we believe our model is a much better predictive tool and a better tool to be used for decision making. It is more accurate because we developed a conceptual model using available field data, carefully constructed a mathematical model that honored these data, calibrated this model to both steady-state and transient conditions, and performed a sensitivity analysis. One thing missing from this process was the post-auditing of the model's accuracy during operations which would have allowed for greater improvement in the model's performance.

The McLaughlin study referenced above provides guidelines for developing ground water models that emphasize clearly defining the objectives of the study and closely evaluating hydrologic and geologic data before developing a model (McLaughlin, 1984). McLaughlin (1984) stressed the importance of field geologists and modelers working closely together in the beginning of numerical model development as local geological experience can help make data interpretation and input estimation more realistic. McLaughlin (1984) concludes that it is important when evaluating large complex aquifers to carry out steady-state regional calibration and to use pumping-test results to constrain the regional calibration. Another important point for ground water impact studies mentioned in this paper is the need for locating model boundaries well beyond the region most likely to be impacted.



As discussed further below, we advocate that a process be developed, perhaps in the form of requiring certain standards to be followed, to prevent the misuse and misapplications of ground water models. In the next section we summarize what we believe to be the most useful model development guidance tools and make some general recommendations.

Conclusions and Recommendations

When numerical ground water models are used to guide a decision process, industry requirements are necessary for selection and development of the most appropriate models and the review and incorporation of site-specific hydrogeologic data into the model. We find that too often model types are poorly designed (e.g., unconfined aquifer simulated as a confined model layer) in order to disregard site data that does not support a pre-conceived opinion.

The problem is not the lack of appropriate documents to guide the modeling process. There are some excellent guidance documents and textbooks available to provide the basis for development of a ground water model, and a few of these are referenced and summarized below. We have found the ones listed below to be valuable and to provide necessary background for anyone with the appropriate technical background to do a defensible job in ground water model development.

The American Society for Testing and Materials (ASTM) has developed general protocol for model application (ASTM 1993, 1994, 1995, 1996) including:

- ASTM 5447-93 – Application of a Ground-Water Flow Model to a Site-Specific Problem
- ASTM 5979-96 – Conceptualization and Characterization of Ground-Water Systems
- ASTM 5609-94 – Defining Boundary Conditions in Ground-Water Flow Modeling

- ASTM 5981-96 – Calibrating a Ground-Water Flow Model Application
- ASTM 5490-93 – Comparing Ground-Water Flow Simulations to Site-Specific Information
- ASTM 5718-95 – Documenting a Ground-Water Flow Model Application

The National Research Council's (NRC's) book entitled, "Ground Water Models Scientific and Regulatory Applications" (NRC, 1990), provides an excellent overview of ground water flow and contaminant transport models, provides guidance on model development, examines issues in the development and use of models, and proposes research needs for improving the accuracy and reliability of models.

Anderson and Woessner's (1992) book on "Applied Groundwater Modeling, Simulation of Flow and Advective Transport" is an excellent resource for selecting appropriate models, building models, calibration, sensitivity analysis, and reporting. The protocol for ground water model development and application defined in this textbook could provide the basis for development of the requirements we suggest are necessary.

Developing industry requirements for ground water model development and application is a monumental task. The subject is complex and controversial, the applications are diverse, and the users have highly variable backgrounds and expertise. For these reasons, a process of self-regulation, such as that developed by professional engineers, may be the best way to enhance the defensibility and reliability of using ground water models for decision making.

We believe the use of ground water models for decision making in the environmental and water resource fields will only continue to increase while the questions to be answered become more difficult as our need for clean water increases. As in the case of professional engineers, the development of requirements and a certification process grew from a need to protect life, health and property and to promote the public welfare. We suggest the development of ground water models and the outcomes associated with using them in decision making can have consequences to society which require similar protection. An organization such as the National Ground Water Association should take the lead in development of these requirements and should develop a board of registration for implementation.

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