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Can we simulate regional groundwater flow in a karst system using equivalent porous media models? Case study, Barton Springs Edwards aquifer, USA

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Abstract

Various approaches can be used to simulate groundwater flow in karst systems, including equivalent porous media distributed parameter, lumped parameter, and dual porosity approaches, as well as discrete fracture or conduit approaches. The purpose of this study was to evaluate two different equivalent porous media approaches: lumped and distributed parameter, for simulating regional groundwater flow in a karst aquifer and to evaluate the adequacy of these approaches. The models were applied to the Barton Springs Edwards aquifer, Texas. Unique aspects of this study include availability of detailed information on recharge from stream-loss studies and on synoptic water levels, long-term continuous water level monitoring in wells throughout the aquifer, and spring discharge data to compare with simulation results. The MODFLOW code was used for the distributed parameter model. Estimation of hydraulic conductivity distribution was optimized by using a combination of trial and error and automated inverse methods. The lumped parameter model consists of five cells representing each of the watersheds contributing recharge to the aquifer. Transient simulations were conducted using both distributed and lumped parameter models for a 10-yr period (1989–1998). Both distributed and lumped parameter models fairly accurately simulated the temporal variability in spring discharge; therefore, if the objective of the model is to simulate spring discharge, either distributed or lumped parameter approaches can be used. The distributed parameter model generally reproduced the potentiometric surface at different times. The impact of the amount of pumping on a regional scale on spring discharge can be evaluated using a lumped parameter model; however, more detailed evaluation of the effect of pumping on groundwater levels and spring discharge requires a distributed parameter modeling approach. Sensitivity analyses indicated that spring discharge was much more sensitive to variations in recharge than pumpage, indicating that aquifer management should consider enhanced recharge, in addition to conservation measures, to maintain spring flow. This study shows the ability of equivalent porous media models to simulate regional groundwater flow in a highly karstified aquifer, which is important for water resources and groundwater management.

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1. Introduction

Numerical groundwater models are one of the most important predictive tools available for managing water resources in aquifers. These models can be used to test or refine different conceptual models, estimate hydraulic parameters, and, most importantly for water-resource management, predict how the aquifer might respond to changes in pumping and climate. Numerous models have been successfully developed in clastic aquifers; however, application of numerical models in karst aquifers is more problematic. Karst aquifers are generally highly heterogeneous. They are dominated by secondary (fracture) or tertiary (conduit) porosity and may exhibit hierarchical permeability structure or flow paths. These aquifers are likely to have a turbulent flow component, which may be problematic in that most numerical models are based on Darcy's law, which assumes laminar flow.

However, even with the above limitations, useful numerical flow models can be developed in karst aquifers, as long as their limitations are appreciated and respected. Quinlan et al. (1996) stated that: *"Although modeling of karstic processes is often possible and numerical flow models can sometimes simulate hydraulic heads, ground-water fluxes, and spring discharge, they often fail to correctly predict such fundamental information as flow direction, destination, and velocity."* Therefore, when discussing the relevance of numerical modeling in a karst aquifer, it is important to identify what type of model is being proposed: a flow model (hydraulic heads, groundwater fluxes, spring discharge) or a transport model (flow direction, destination, velocity). Many papers critical of numerical modeling (Huntoon, 1995; Quinlan et al., 1996) are specifically concerned about using numerical models to predict the direction and rate of solute transport, which are difficult to estimate a priori in even simple fractured systems.

It is not surprising that transport models do not perform well in karst aquifers, especially at local scales. Accurate transport predictions require in-depth knowledge of the distribution of the subsurface fracture and conduit systems. Transport of solutes in fractured rocks is an active research area (Bear et al., 1993; National Research Council, 1996). Often acknowledged in these studies is the difficulty of predicting, a priori, the direction and rate of solute transport through a fractured aquifer.

In fractured systems, as in karst systems, the concept of a representative elementary volume is used where size of the area of interest, or the cell in a model, becomes large enough to approximate equivalent porous media (Pankow et al., 1986; Neuman, 1987). Although accurate simulation of transport processes is still problematic, one may be able to model hydraulic heads, flow volumetrics, and general flow directions as supported by the characterization of the aquifer. Regional-scale models are much more likely to be successful than intermediate- or local-scale models (Huntoon, 1995).

It is important to consider the various modeling approaches available for simulating groundwater flow and contaminant transport in karst aquifers and to be aware of the advantages and limitations of each approach. One of the simplest approaches is the lumped parameter model, which has also been termed *black box* or *mixing cell model*. The spatial dimension in the equations is omitted in these models; therefore, only ordinary linear differential equations must be solved. The system is assumed to behave like an equivalent porous medium. These models generally result in good agreement between measured and simulated spring discharge (Yurtsever and Payne, 1986; Wanakule and Anaya, 1993; Barrett and Charbeneau, 1996; Zhang et al., 1996). The advantages of using lumped parameter models are that data requirements are minimal and simulations are rapid. The main disadvantage is lack of information on spatial variability in hydraulic head and directions and rates of groundwater flow.

Distributed parameter models are required to obtain detailed information on spatial variability in groundwater flow. Equivalent porous media distributed parameter models include single continuum and double continuum approaches. In many aquifers, single continuum models have proved adequate for simulating regional groundwater flow (Ryder, 1985; Kuniansky, 1993; Teutsch, 1993; Angelini and Dragoni, 1997; Keeler and Zhang, 1997; Greene et al., 1999 and Larocque et al., 1999). However, other studies have found the single continuum approach inadequate for simulating regional flow in highly karstified aquifers (Teutsch, 1993; Keeler and Zhang, 1997). An equivalent porous medium, dual continuum approach was used by Teutsch (1993) to model moderately to highly karstified systems. One continuum represents moderately karstified aquifer zones (diffuse flow, low conductivity, high storativity), and the other continuum represents highly karstified zones (high conductivity, low storativity). This double continuum approach is similar to the double porosity approach described in other studies, such as those in the oil industry (Warren and Root, 1963). Exchange or cross flow between the two continua is described by equations with exchange coefficients. Flow in both continua is assumed to be laminar. The double continuum model was used to simulate spring discharge, groundwater level fluctuations, and some tracer breakthrough curves in a karst system in southern Germany (Teutsch, 1993). This approach has also been used to delineate hypothetical well-head protection zones in a karst system in Florida (Knochemus and Robinson, 1996). In addition, the discrete fracture approach has been proposed for simulating flow in highly karstified systems; however, information on the location, geometry, and hydraulic properties of each fracture (deterministic models) or on the statistical attributes of fractures (stochastic models) is required. These large data requirements generally restrict the use of the discrete fracture approach to modeling local systems. Some studies have focused primarily on modeling of the conduit system (Halihan and Wicks, 1998; Jeannin, 2001).

A variety of factors are involved in choosing a suitable approach for simulating groundwater flow and transport in a karst aquifer. Teutsch and Sauter (1998) described four problem cases and appropriate modeling approaches—point and integral (or diffuse) source input and point (e.g. well) and integral (spring) observation output. Additional factors that are important in choosing a particular modeling approach include (1) degree of karstification, (2) objective of the modeling study, (3) availability of different types of data, and (4) availability of codes. (1) Karst aquifers have been classified as predominantly diffuse or conduit types, with a continuum between these end members. Equivalent porous media distributed parameter models have generally been applied to aquifers characterized as predominantly diffuse (Teutsch, 1993). Similar modeling approaches may also be appropriate for conduit systems if the conduits are fairly uniformly distributed and well interconnected. Some hydrologists suggest that carbonate aquifers have fairly similar structures and that the diffuse and conduit classification scheme simply reflects the bias in researchers' studies; i.e. those that focus on wells classify aquifers as predominantly diffuse, whereas those that focus on springs characterize the aquifers as conduit types (Davies et al., 1992). (2) The objective of the model is critical in determining an appropriate modeling approach. Examples of model objectives include evaluation of regional groundwater flow for water management, analysis of contaminant transport from point and nonpoint sources, and assessment of aquifer vulnerability to contamination. Equivalent porous media distributed and lumped parameter models have been used to simulate regional groundwater flow and non-point source contaminant transport (Barrett and Charbeneau, 1996). Double continuum equivalent porous media models have been used to simulate tracer transport and can potentially be used to simulate contaminant transport. Such models require detailed information on the location of subsurface conduits, which is often difficult to obtain. (3) Data availability may also constrain the type of modeling approach that can be used. In some cases there is information only on spring discharge (Angelini and Dragoni, 1997), whereas other sites may have detailed information on the flow system, including spring discharge, synoptic water levels, time series of water levels, tracer results for conduit delineation and flow velocities, spring temperature, and chemistry (Teutsch and Sauter, 1991). (4) Availability of codes may also affect choice of modeling approach. Although numerical codes for simulating karst genesis generally incorporate turbulent flow, it is generally not included in codes that simulate groundwater flow in karst systems on a regional scale.

The objective of this study was to evaluate the ability of equivalent porous media distributed and lumped parameter models to simulate regional groundwater flow in a karst aquifer and to assess the advantages and limitations of each approach. Different techniques for parameterizing the distributed model were evaluated, including trial and error and automated inverse methods. The models were applied to the Barton Springs segment of the Edwards aquifer, Texas. The Edwards aquifer has been hydrologically divided into three segments, the northern segment (north of the Colorado River), the central or Barton Springs segment, and the southern or San Antonio segment. The Barton Springs segment refers to the portion of the aquifer that discharges primarily to Barton Springs and is south of the Colorado River and north of a groundwater divide near Kyle, Texas. The primary management issue for this aquifer is maintaining spring flow during drought periods and assessing current and future pumpage effects on spring flow. Maintaining spring flow is a critical objective because the spring outlets are the sole habitat of the Barton Springs salamander, which is listed as an endangered species. The Barton Springs Edwards aquifer represents an excellent field laboratory for testing different models because there is accurate information on recharge using stream gage data, groundwater pumping, spring discharge (for decades), synoptic water levels measured at different times, and continuous water level monitoring records at eight wells distributed throughout the aquifer for up to 10 yr. These data can be used to test the reliability of the models. Although the Barton Springs Edwards aquifer is limited in area (330 km^2, Fig. 1), the term *regional* is used to describe the model to distinguish it from local-scale models. The boundaries of the aquifer are well defined: upper and lower confining layers, recharge zone, and approximate location of the groundwater divides. The lumped parameter model has been described in detail in Barrett (1996) and Barrett and Charbeneau (1996), and only aspects of the lumped parameter model that pertain to the code comparison are described in this paper.

1.1. Study area

This modeling study focuses on the Barton Springs segment of the Edwards aquifer within and adjacent to the city of Austin, Texas, that discharges into Barton Springs and Cold Springs and is hydrologically distinct from the rest of the Edwards aquifer. The model is approximately 330 km^2 in area. The Barton Springs Edwards aquifer (Fig. 1) constitutes the sole source of water to about 45,000 residents. Barton Springs pool also serves as a municipal swimming pool in Zilker Park, downtown Austin. Increased population growth and recent droughts (1996) have focused attention on groundwater resources and sustainability of spring flow.

Model boundaries are all hydrologic boundaries and include the Mount Bonnell fault to the west, which acts as a no-flow boundary (Senger and Kreitler, 1984); a groundwater divide in the south along Onion Creek; the “Bad-water Line” in the east; and the Colorado River (Town Lake) in the north (Fig. 1). Groundwater circulation in the Edwards aquifer decreases to the east and total dissolved solids (TDS) increase. The “Bad-water Line” marks the zone where TDS exceeds 1000 mg/l, which generally coincides with Interstate Highway 35 (IH35, Fig. 1). The groundwater divide in the south separates the Barton Springs segment from the San Antonio segment of the Edwards aquifer, which discharges into Comal Springs and San Marcos Springs.

The Edwards aquifer is up to 165 m thick and it is overlain by the Del Rio Formation, which is predominantly clay and forms a confining unit, and is underlain by the Glen Rose Formation (Fig. 1) (Hovorka et al., 1998). Northeast-trending faults in the study area are part of the Balcones Fault Zone. These faults consist of high-angle normal faults downthrown to the southeast. The faults have displacements of as much as 60 m. The Edwards aquifer is unconfined in the outcrop area where recharge occurs and in part of the section to the east, where it is overlain by the Del Rio Formation (Fig. 1). Farther to the east, the aquifer is confined by the Del Rio Formation. There is no recharge from the land surface to the unconfined section, where it is overlain by the Del Rio Formation. Approximately 80% of the aquifer is unconfined, and the remainder is confined (Slade et al., 1985). The study area is in the subtropical, humid climate zone (Larkin and Bomar, 1983). Mean annual precipitation is 825 mm, with major rainstorms occurring in spring and fall. Groundwater flows from west to east in the unconfined section of the aquifer and generally northeast in the confined section to discharge at Barton Springs.

tracer tests demonstrate that directions and rates of transport can be quite variable. Quinlan et al. (1996) suggested that tracer tests provide the best tools for delineating directions and rates of transport in karst systems. Although some studies have been able to calibrate models to reproduce tracer breakthrough curves (Teutsch, 1993), the level of detail required for input and calibration of such models far exceeds the level of data availability for most karst aquifers. Some have suggested that if information on direction and rates is obtained from tracer tests, modeling is superfluous.

3.5. Future studies

Future studies should consider a variety of improvements to the existing models, including additional data collection, different conceptual model design, and other factors. The current distributed parameter model assumes that recharge is distributed uniformly along streams; however, this is unrealistic. Recent field studies have been conducted to identify major features along the streams that would focus recharge. Future modeling should consider focusing recharge at different points on the basis of field data, and sensitivity of model output to various distributions should be examined. Parameterization of the distributed model depends on accurate information about hydraulic head. Future studies should improve the reliability of the head data by accurately locating wells and measuring the surface elevation. A greater number and wider distribution of head measurements would also improve parameterization of the distributed model. Inverse modeling could be used to guide location of additional head measurements. Synoptic water level maps should also be developed for high flow periods to evaluate model performance under these conditions.

The current distributed parameter model represents the aquifer using a single layer. Some of the transient simulations had difficulties converging because cells went dry. This problem was overcome in the current study by lowering the base of the model and assuming that the Edwards aquifer is hydraulically connected to the underlying Glen Rose Formation. Sensitivity analyses indicated that varying specific storage could improve simulations of water levels in the southern monitoring wells. Future modeling should consider representing the aquifer as two layers that would allow vertical variation in hydraulic properties and use of different specific storage values to reduce water level fluctuations during high flows without impacting simulation of low spring discharge. Variations in hydraulic conductivity with depth, particularly near the springs, could also improve simulation of low spring discharges, as shown by the lumped parameter model.

Distribution of major conduits based on dye tracing studies should be approximated in the model using zones of high hydraulic conductivity. The model grid should be refined near these zones to better represent the conduits. Inclusion of such high conductivity zones should improve simulations of troughs in the potentiometric surface (Fig. 3).

Both types of models should be updated to modify recharge values for Barton Creek since a new gaging station has been installed downstream of the outcrop zone. Recent dye tracing studies revealed that much of the flow in the northwest segment of the aquifer discharges at Cold Springs. This information should also be incorporated into revised models.

4. Conclusions

This study showed that equivalent porous media models could be used to simulate regional groundwater flow in this highly karstified aquifer. Both distributed and lumped parameter models generally reproduced temporal variations in discharge at Barton Springs with RMS errors of about 10% of the discharge fluctuations. Therefore, if the primary goal of the modeling study is to simulate spring discharge for water management purposes, either distributed or lumped parameter models can be used.

Parameterization of the distributed model for steady state was restricted to estimation of hydraulic conductivity because groundwater recharge could be accurately estimated from stream losses. The zonal distribution of hydraulic conductivity could be estimated from information on the hydraulic gradient, which resulted in low conductivities in the unconfined section of the aquifer and high conductivities near the spring where flow is concentrated. Automated inverse modeling was used to further improve the simulation of heads in the aquifer. RMS error for the steady state model of 7 m represents errors in measured and simulated heads. The transient model required very little calibration. Specific yield in the unconfined aquifer was reduced to better simulate low flow discharges in Barton Springs.

Sensitivity analyses indicated that the steady state distributed parameter model is most sensitive to variations in recharge and hydraulic conductivity and fairly insensitive to pumpage and spring drain conductance. These results suggest that future management should consider techniques such as enhanced recharge to buffer the system against future droughts.

Sensitivity analyses indicated that temporal variability in spring discharge is most sensitive to variations in recharge and relatively insensitive to variations in pumpage, specific yield, and specific storage in the -10 to $+50\%$ range. These results suggest that curtailing pumpage during droughts may not be adequate to maintain spring flow and that artificial recharge may also be required. Increasing specific storage by a factor of 10 greatly reduced temporal variability in spring discharge and water level fluctuations.

The distributed parameter model generally reproduced potentiometric surfaces at different times. RMS errors ranged from 8.7 to 11.2 m, which represent about 10% of the water level variations across the aquifer.

Both distributed and lumped parameter models simulated trends in water level fluctuations more accurately than absolute values of water levels in continuously monitored wells. The lumped parameter model could simulate water levels only in wells chosen to represent each cell in the model.

Impact of groundwater pumping on spring discharge can be evaluated using either distributed or lumped parameter modeling approaches; however, detailed evaluation of the effect of pumping on a more local scale, such as a large well field, requires a distributed parameter model.

The main limitations of equivalent porous media models is that they cannot accurately simulate direction or rate of water flow in the aquifer, which precludes them from simulating point source contamination or delineating aquifer protection zones. It is questionable whether any model can simulate these processes because of the complexity of karst systems.

Results of this study show the ability of equivalent porous media distributed and lumped parameter models to simulate regional groundwater flow, which is critical for managing water resources in karst aquifers and predicting the impact of future pumping and potential future drought conditions on spring flow.

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