Structural Controls on Karst Development in Fractured Carbonate Rock, Edwards and Trinity Aquifers, South-Central Texas

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ABSTRACT

The Edwards aquifer of south-central Texas lies within, and adjacent to, the Balcones fault zone and is one of the most productive carbonate aquifers in the United States. The Trinity aquifer outcrops to the north of the Balcones fault zone and supplies baseflow to streams flowing south over the Edwards recharge zone. The geology of Edwards and Trinity aquifers consists of approximately 400 meters of Lower Cretaceous carbonates with interbedded marl and dolostone. Miocene age faults within the Balcones fault zone are *en echelon*, exhibiting primarily normal displacement, trending northeast and downthrown to the southeast. Numerous cross-faults oriented perpendicular to the primary faults trend to the southeast. In the Edwards aquifer, cross-faults breach relay ramps between overlapping faults, providing both a mechanical and hydrologic link between the primary faults.

The fracturing within relay ramps and adjacent to the primary faults in the Edwards aquifer is quite variable, resulting in the development of circuitous and prolific ground-water flow paths. Because of the crystalline nature of the host rock and the susceptibility of the carbonate strata to karst formation, the enhancement of secondary porosity and permeability in fracture zones and fault planes is highly likely in both the Edwards and Trinity aquifers. Vertical displacement of the terrain from north to south by Balcones faults allows for steep hydraulic gradients to develop, maintaining high flow velocities of meteoric groundwater in the shallow sub-surface during recharge events. This process of karst formation resulting from the dissolution of fractures and enhancement of fracture zone permeability occurs primarily parallel to the down-dip direction, along high-angle cross-faults and fracture zones that trend nearly perpendicular to the regional ground-water flow direction. In both the Edwards and Trinity aquifers, a relation between fractures and faults and their susceptibility to dissolution by groundwater can often be observed in outcrop as recrystallized calcite or cavities filled with oxidized clays.

Mapping in the Edwards and Trinity aquifer region in south-central Texas reveals a bimodal distribution of fracture zones and faults and corresponding cave passages oriented both parallel and nearly perpendicular to the northeast-trending, primary faults. The most well-developed caves and solution zones are not aligned with the major faults, but are oriented along the northwest to southeast trend of cross-faults and shorter fracture zones, that parallel the down-dip direction of the Balcones fault zone, and are nearly perpendicular to regional ground-water flow direction. The location and extent of most sensitive karst features in the region are unmapped and those that are have not been released to the public. However, the fracture zones and faults that influence the location and direction of secondary porosity development have been mapped; thus providing a representative surface expression of potential zones of karst enhanced fractures and highly developed cavern systems. Understanding the relation between these fracture zones/faults and the subsequent karst development can assist in the identification and quantification of high volume, high velocity ground-water flow paths in the Edwards and Trinity aquifers.

Simulating Ground-Water Flow in the Karstic Madison Aquifer using a Porous Media Model

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Ground-water flow in karstic aquifers is characterized by the preferential solution enlargement of fractures and openings creating an integrated network of conduits with rapid flow. Although these conduits can be a predominant feature in characterizing ground-water flow, ground-water storage may occur primarily in the surrounding diffuse network of fractures and smaller openings. A porous media model can provide a reasonable approximation of ground-water flow in the diffuse network; however, simulation of conduit flow in conjunction with the diffuse flow is more problematic. Combinations of heterogeneity, anisotropy, flow barriers, and multiple model layers were used to simulate diffuse and conduit ground-water flow in the karstic Madison Limestone near Rapid City, South Dakota. The finite-difference MODFLOW model included 140 rows, 110 columns, and 5 layers. Cells were 492 feet on a side in the Rapid City area and increased to 6,562 feet near the perimeter of the model. Transient calibration included a 10-year period with 20 stress periods of 6 months. Layers 3 and 4 represented the Madison Limestone with layer 3 representing the upper part of the formation that generally contains more karst features than the less permeable lower part of the formation. Layers1 and 2 represented the overlying Minnelusa Formation, and layer 5 represented the underlying Deadwood Formation. High velocity flowpaths in the Madison Limestone were simulated with conduit zones in layer 3 that were about 1,500 feet wide. Hydraulic conductivities within these zones ranged from about 65 to 1,150 feet/day compared to an average for the surrounding area of about 35 feet per day. The average hydraulic conductivity of layer 4 was 0.32 feet/day. Anisotropy ratios aligned with the high velocity flowpaths ranged from 5:1 to 20:1. The Modflow horizontal flow barrier package was used to simulate the hydrologic effect of a fault. Ground-water tracer studies, transient hydraulic heads, and springflow measurements were used to calibrate the model. Simulated ground-water velocities for high velocity flowpaths were about 500 to 1,000 feet/day compared to observed dye tracer velocities that ranged from about 1,000 to 5,000 feet/day. For the transient simulation, the average difference between observed and simulated hydraulic heads for 269 measurements was 7 feet and the average absolute difference was 31 feet. Linear regression of the observed and simulated hydraulic heads had an R^2 of 0.92. Observed average springflow for the transient period was 21.6 cubic feet per second compared to simulated average springflow of 20.4 cubic feet per second.

Dual Conductivity Module (DCM), A MODFLOW Package for Modeling Flow in Karst Aquifers

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ABSTRACT

A MODFLOW module, DCM, has been developed to better represent the dynamic, multiple time-scale hydraulic response of karst aquifers. DCM adopts a dual-conductivity approach in which the aquifer is conceptualized as being composed of two interacting flow systems - a highly transmissive conduit system embedded in a relatively low permeability diffuse flow system. This coupled-system conceptualization allows not only water levels, but also aquifer dynamics related to rapid conduit flows to be represented. The conduit system may be modeled as a pervasive (continuum) system or as a sparse network of individual conduits, depending on the scale of investigation and the nature of the karst system being investigated. Conduits may be partially or fully filled with water, and transitions between the partially filled and fully filled states are accommodated, which makes it possible to model highly complex hydraulic responses. Flow in the conduit system may be turbulent, laminar, or transitional. Our preliminary results show improved match to both water level measurements and spring discharges records.

Conceptualization and Simulation of the Edwards Aquifer, San Antonio Region, Texas

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ABSTRACT

A new numerical ground-water-flow model (Edwards aquifer model) that incorporates important components of the latest information and a conduit-flow dominated conceptualization of the Edwards aquifer was developed. The conceptualization emphasizes conduit development and conduit flow, as opposed to predominately diffuse, porous-media flow. The model incorporates conduits simulated as generally continuously connected, one-cell-wide (1,320 feet) zones with very large hydraulic-conductivity values (as much as 300,000 feet per day). The locations of the conduits are based on a number of factors, including major potentiometric-surface troughs in the aquifer, the presence of sinking streams, geochemical information, and geologic structures (for example, faults and grabens).

The model includes both the San Antonio and Barton Springs segments of the Edwards aquifer in the San Antonio region, Texas, and was calibrated for steady-state (1939–46) and transient (1947–2000) conditions. Transient simulations were conducted using monthly recharge and pumpage (withdrawals) data. The root mean square errors for hydraulic heads represent about 4 to 8 percent of the total head differences across the model area. The root mean square errors for Comal, San Marcos, San Antonio, and San Pedro Springs, as a percentage of the range of discharge fluctuations measured at each of the springs, are less than 10 percent.

The simulated directions of flow in the Edwards aquifer model are most strongly influenced by the presence of simulated conduits and barrier faults. The simulated conduits tend to facilitate flow. The simulated subregional flow directions generally are toward the nearest conduit and subsequently through and parallel to the conduits from the recharge zone into the confined zone and toward the major springs. Structures simulated in the Edwards aquifer model that tend to restrict ground-water flow are barrier faults. The influence of simulated barrier faults on flow directions is most evident in northern Medina County.

INTRODUCTION

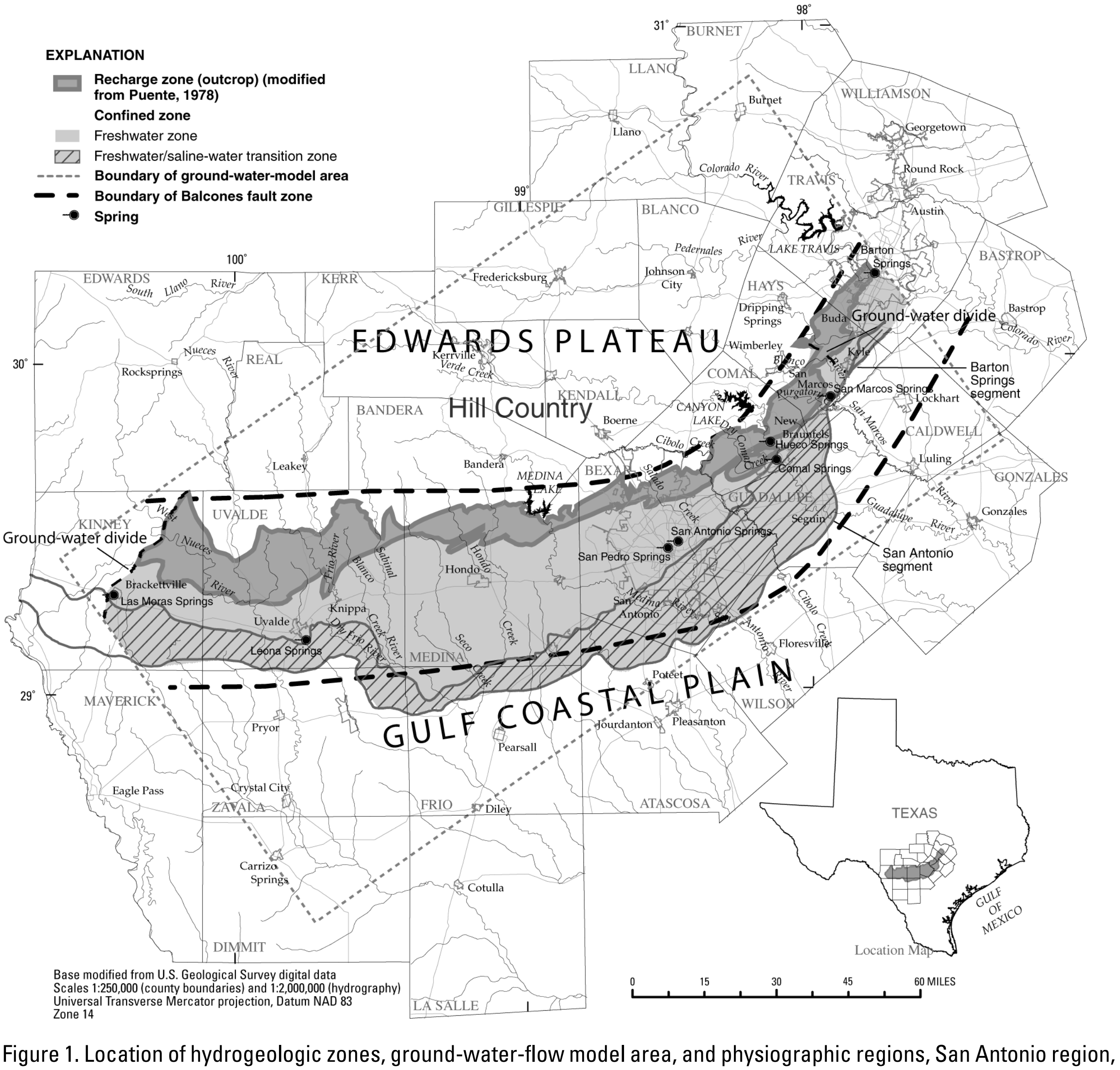
The Edwards aquifer in the Balcones fault zone of south-central Texas (fig. 1) is one of the most permeable and most productive aquifers in the world. The sole source of drinking water supply in the San Antonio and Austin areas, the aquifer is critical to farming and ranching economies west of San Antonio and recreational economies northeast of the city. There is also concern that drought or the increasing demand for ground water, or both, might result in the deterioration of habitats for several endangered species. To evaluate the hydrologic response to various alternative proposals for managing the Edwards aquifer in the San Antonio region, the Edwards Aquifer Authority (EAA), together with other San Antonio water-resource managers and planners, expressed the need for an improved numerical ground-water-flow model. As a result of this need, a study was conducted from 2000 to 2003 by the U.S. Geological Survey (USGS) and The University of Texas at Austin, Bureau of Economic Geology

(BEG), in cooperation with the U.S. Department of Defense (DOD) and the EAA; and a numerical ground-water-flow model was developed (Lindgren and others, 2004).

CONCEPTUALIZATION OF THE EDWARDS AQUIFER

The conceptualization of the Edwards aquifer presented in Lindgren and others (2004) emphasizes conduit development and conduit flow. The degree to which conduits pervade the Edwards aquifer and influence ground-water flow remains controversial, however. An alternate conceptualization, which can be called the diffuse-flow conceptualization, reflects the hypothesis that, although conduits likely are present, flow in the aquifer predominately is through a network of small fractures and openings sufficiently numerous that the aquifer can be considered a porous-media continuum at the regional scale. Whether conduit flow or diffuse flow predominates at the regional scale is an open question.

The Edwards aquifer is part of an aquifer system developed in thick and regionally extensive Lower Cretaceous carbonates that underlie large areas of Texas. The gentle southeastward dip of Cretaceous strata in the Edwards Plateau and Hill



Base modified from U.S. Geological Survey digital data
Scales 1:250,000 (county boundaries) and 1:2,000,000 (hydrography)
Universal Transverse Mercator projection, Datum NAD 83
Zone 14

Figure 1. Location of hydrogeologic zones, ground-water-flow model area, and physiographic regions, San Antonio region, Texas.

Country is interrupted across the Balcones fault zone by a system of en echelon faults that generally strike northeastward (Maclay, 1995). The Edwards aquifer is unconfined adjacent to and in the outcrop (recharge zone) and confined in downdip parts of the Balcones fault zone by overlying hydrogeologic units of small to very small permeability. The confined zone of the aquifer is defined on its downdip (gulfward) margin by a freshwater/saline-water transition zone of brackish water. The aquifer thickness in the confined zone ranges from about 450 feet (ft) near the recharge zone in Bexar, Comal, and Hays Counties to about 1,100 ft in Kinney County.

Permeability in the Edwards aquifer includes matrix, fracture, and conduit permeability, varies more than eight orders of magnitude, and is multimodal with distinct but overlapping data populations (Hovorka and others, 1998). Mean hydraulic conductivity of the confined zone (34 feet per day [ft/d]) is more than 120 times greater than mean hydraulic conductivity in the unconfined, or recharge, zone (0.28 ft/d) (Hovorka and others, 1998). Vertical variations in permeability in the Edwards aquifer indicate that the entire aquifer is highly permeable, as well as highly variable. Painter and others (2002) estimated hydraulic conductivity for the Edwards aquifer in the San Antonio region using a combination of spatial statistical methods and advanced techniques for automatic model calibration. The estimated hydraulic conductivity ranges from less than or equal to 20 to 7,347 ft/d. Hovorka and others (1998) reported that transmissivity ranges from 10^{-1} to 10^{7} feet squared per day (ft^{2}/d), and hydraulic conductivity ranges from 10^{-3} to 10^{5} ft/d, on the basis of specific-capacity and other aquifer tests.

Evidence of the karstic nature of the Edwards aquifer includes outcrop evidence, subsurface data, hydrologic evidence, and tracer tests. More than 400 caves have been inventoried in the Edwards outcrop (Veni, 1988; Elliott and Veni, 1994). Hovorka and others (1998) reported that in two-dimensional cross section, karst features make up 1 to 5 percent of the area of the outcrop. The existence of karst in the deep-subsurface saturated zone is known from borehole televiewer images of caves and solution-enlarged fractures, cave textures and sediments recovered in cores, bit drops during well construction, and oversize caliper logs and off-scale porosity logs.

Evidence of karst flow in the Edwards aquifer is the heterogeneous and rapidly responsive nature of water-level variation. Water levels in the aquifer and discharge at springs rise rapidly after rainfall and then decline at a variable rate, showing drainage from rocks characterized by both conduits and matrix permeability (Atkinson, 1977). Wells close together can have different responses to a single recharge pulse (Johnson and others, 2002). Tomasko and others (2001) and Worthington (2004) documented rapid spring response to rainfall. Tracer testing that began in the San Antonio segment of the Edwards aquifer has shown rapid flow from wells to the nearby high-flow springs (Ogden and others, 1986; Schindel and others, 2002).

A regionally extensive system of high-permeability zones (conduits) is defined by broad troughs in the potentiometric surface in the confined zone of the Edwards aquifer (Hovorka and others, 2004; Worthington, 2004). Particularly favorable locations for development of conduits are in grabens and synclines (Worthington, 2004). In addition, high porosity and permeability in the deepest parts of the aquifer near the freshwater/saline-water transition zone, anomalously high well yields, and sharp chemical gradients all indicate that conduit development and flow might be focused in this area.

The primary source of recharge to the Edwards aquifer is provided by seepage from streams crossing the outcrop area (recharge zone). Estimates of the combined recharge to the San Antonio segment of the Edwards aquifer from stream seepage and infiltration of rainfall range from a low of 43,700 acre-feet (acre-ft) during 1956 to a high of 2,486,000 acre-ft during 1992 (Hamilton and others, 2003). The Edwards aquifer in many areas in the Balcones fault zone is juxtaposed against the Trinity aquifer, both at the surface and at depth; therefore, the Trinity aquifer likely discharges directly into the Edwards aquifer. Estimates of this flow range from 2 percent (LBG-Guyton Associates, 1995) to 9 percent (Mace and others, 2000) of the average estimated annual recharge to the Edwards aquifer.

Most discharge from the Edwards aquifer occurs as: (1) springflow and (2) withdrawals by industrial, irrigation, and public-supply wells. Springflow totaled 69,800 acre-ft during the 1950s drought and reached a record high of 802,800 acre-ft in 1992 (Hamilton and others, 2003). Comal and San Marcos Springs are the largest springs, with total discharges of 274,800 and 195,900 acre-ft, respectively, in 2002 (Hamilton and others, 2003). Total ground-water withdrawals by wells increased steadily at an average annual rate of about 4,500 acre-feet per year (acre-ft/yr), more than tripling between 1939 and 2000.

Water levels in the Edwards aquifer do not show a long-term decline as a result of ground-water withdrawals. The aquifer is dynamic, with water levels generally responding to temporal variations in recharge and spatial distributions of ground-water withdrawals. During periods of drought, water levels decline, but recover rapidly in response to recharge. The drought of the early 1950s is documented in well hydrographs by the downward trends of water levels at these wells. The highest water levels occurred in the early 1990s.

Karstic conduits are major contributors of flow in the Edwards aquifer (Hovorka and others, 2004; Worthington, 2004). The contribution of matrix permeability to regional-scale hydraulic conductivity likely is minor, and most Edwards aquifer water flows through fractures and conduits (Hovorka and others, 1998). Water entering the Edwards aquifer in the recharge zone moves downdip from unconfined to confined parts of the aquifer through generally southeasterly flow paths. In the confined zone of the San Antonio segment of the aquifer, the water moves under low hydraulic gradients through fractured, highly transmissive, cavernous strata toward the east and northeast, where it is discharged through springs (primarily Comal and San Marcos Springs) and high-capacity wells. In the Barton Springs segment of the aquifer, the ground-water-flow direction is generally to the east and northeast toward Barton Springs.

Faults can either increase or decrease total transmissivity in the Edwards aquifer (Hovorka and others, 1998) and thereby tend to convey or to restrict flow. Some of the abundant, interconnected fractures in intensely fractured and brecciated zones adjacent to faults have been enlarged, and they might focus flow parallel to faults. Where calcite cement fills breccia, cross-fault flow might be decreased. Stratigraphic offset of permeable zones along faults might also decrease the cross-fault flow (Maclay and Small, 1986). Maclay (1995) and Groschen (1996) characterized flow in the Edwards aquifer as being controlled laterally by barrier faults that locally compartmentalize, or restrict, flow within, to, and from parts of the aquifer, especially toward the eastern part of the San Antonio segment.

SIMULATION OF GROUND-WATER FLOW

A numerical model of ground-water flow was constructed on the basis of a conduit-flow dominated conceptual model of the Edwards aquifer. The FORTRAN computer-model code MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996; Harbaugh and others, 2000), a modular finite-difference ground-water-flow code developed by the USGS, was used to simulate ground-water flow in the Edwards aquifer. As a way to represent conduits, other than by use of a coupled-continuum pipe flow or dual- or triple-porosity model, conduits are simulated in the Edwards aquifer model by narrow (one-cell wide), continuously connected zones with large hydraulic-conductivity values (fig. 2).

Calibration and evaluation of the Edwards aquifer model were conducted for steady-state (1939–46) and for transient (1947–2000) conditions. Once it was demonstrated that the model could approximate observed historical conditions (1947–90), the model then was used to simulate the effects of stresses for a time period not used initially for model calibration (model testing period, 1991–2000).

Model Description

The Edwards aquifer model area includes the San Antonio and Barton Springs segments of the Edwards aquifer. The model area was subdivided into rectangular finite-difference grid cells within which the properties of the aquifer material represented are assumed to be uniform. The uniformly

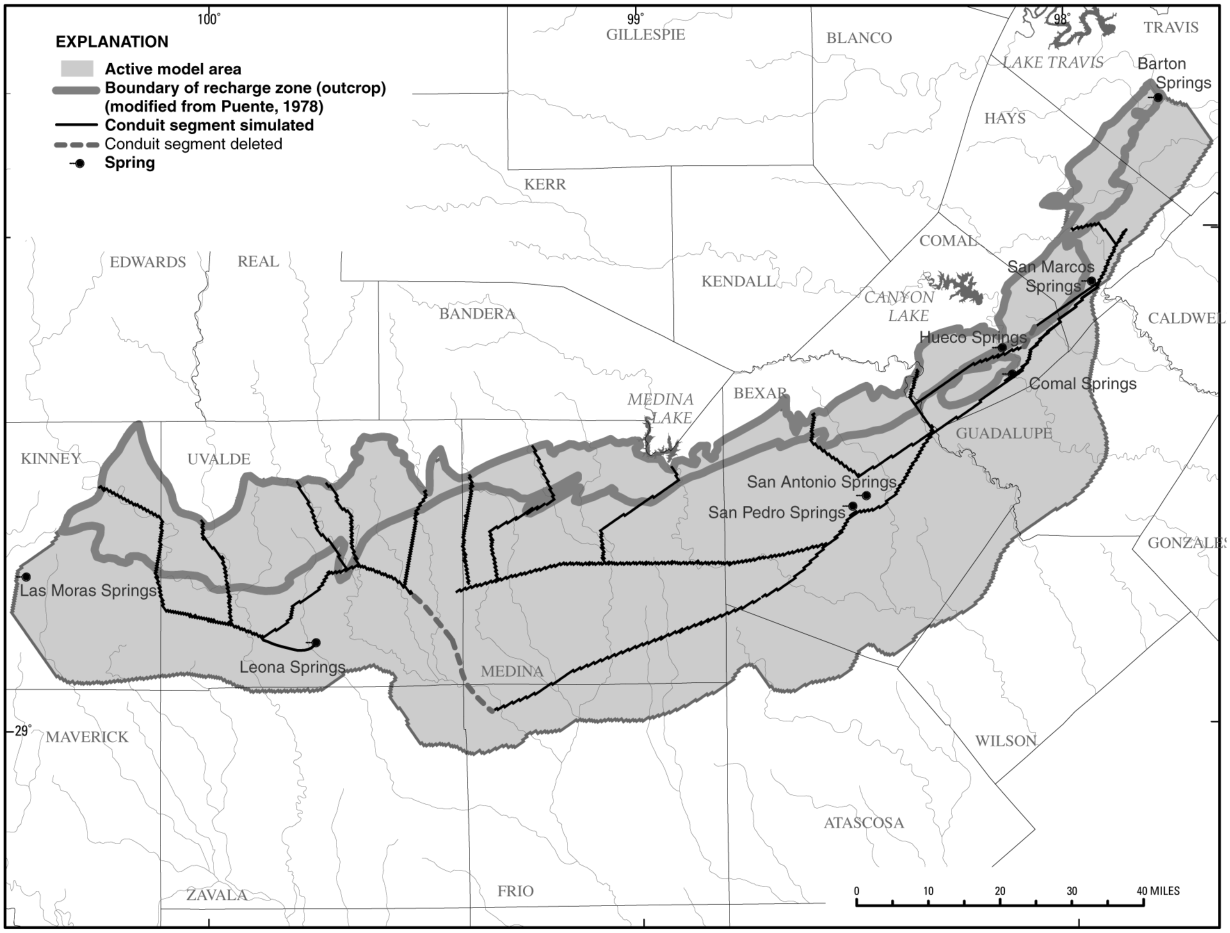


Figure 2. Simulated locations of conduits in the Edwards aquifer model, San Antonio region, Texas.

spaced finite-difference grid used to spatially discretize the model area has 370 rows and 700 columns. The dimensions of the grid cells are uniformly 0.25 mile (mi) (1,320 ft) along rows and columns, with about 33 percent of the cells in the grid being active. The grid was rotated 35 degrees counterclockwise from horizontal to achieve the best alignment with the direction of ground-water flow and orientation of major faults near Comal and San Marcos Springs. A single model layer was used to represent the multiple hydrogeologic units that comprise the Edwards aquifer. The Edwards aquifer was not discretized vertically because of a lack of sufficient hydrogeologic data needed to spatially define individual hydrogeologic units within the geologic section.

Where possible, natural hydrologic boundaries were used to establish the extent of the active area of the Edwards aquifer model. The northern boundary of the model corresponds to the northern limit of the Edwards aquifer recharge zone. A head-dependent flux boundary (MODFLOW general-head boundary package) was used for the northern model boundary to account for the inflow of water from the adjacent Trinity aquifer. During transient simulation, the MODFLOW well package was used to simulate a constant flux, equal to the model-computed general-head boundary flux of the steady-state simulation, through the northern model boundary for all stress periods.

The northern part of the eastern model boundary is defined by the location of the Colorado River, which is a regional sink for the Edwards aquifer. Stream-aquifer leakage is simulated in the model as head-dependent flux nodes using the MODFLOW river package (McDonald and Harbaugh, 1988). The southern part of the eastern model boundary (south of the Colorado River) was assigned a no-flow boundary condition. The western model boundary coincides with the location of a poorly defined ground-water divide near Brackettville in Kinney County (LBG-Guyton Associates, 1995). Minimal flow across this boundary was assumed and a no-flow boundary condition was initially assigned. During model calibration, however, a specified-flux boundary, with inflow into the Edwards aquifer, was imposed for the northern part of the boundary. The southern part of the boundary was maintained as a no-flow boundary.

The southern Edwards aquifer boundary typically has been defined by the 1,000-milligrams per liter (mg/L) line of equal dissolved solids concentration, which coincides with the updip boundary of the transition zone (Schultz, 1993, 1994). The 10,000-mg/L concentration line (A.L. Schultz, consultant, written commun., 2000) was used in the Edwards aquifer model as a more conservative boundary, constituting the limit of ground-water flow in the freshwater zone of the aquifer. A no-flow boundary condition was imposed.

The anisotropic effects of faults were incorporated in the Edwards aquifer model using the MODFLOW horizontal-flow barrier package. The hydraulic characteristic of the barrier (fault) is an inverse measure of the degree to which it acts as a barrier to flow. The greater the assigned value for the hydraulic characteristic of the fault, the less it acts as a barrier to flow. For the model, the assumption was made that the degree to which a fault acts as a barrier to ground-water flow is proportional to the fault displacement, with the hydraulic characteristic of the barrier being inversely proportional to the fault displacement. The final calibrated hydraulic characteristic values assigned to simulated faults range from 1.0×10^{-9} to 2.0×10^{-2} days^{-1}.

The initial locations of conduit zones in the Edwards aquifer model were assigned on the basis of the conduit locations inferred by Worthington (2004, fig. 21). The confined-zone conduit segments are based on potentiometric-surface troughs, geologic structure, and preferential development of conduits near the freshwater/saline water transition zone. In addition, the major sinking streams were interpreted to be connected to the major springs by conduits. During model calibration, revisions were made to the simulated conduit segments, including the deletion of a northwest-southeast trending segment in southeastern Uvalde and northwestern Frio Counties (fig. 2).

The hydraulic-conductivity distribution for the Edwards aquifer model includes two components. The first component is the hydraulic-conductivity distribution developed by Painter and others (2002). An approach based on nonparametric geostatistics, stochastic simulation, and numerical flow simulation was used to upscale and interpolate hydraulic-conductivity estimates to the model grid. The second component, superimposed on the base distribution of Painter and others (2002), is the network of conduits, initially as inferred by Worthington (2004, fig. 21). For the Barton Springs segment of the aquifer, the hydraulic-conductivity distribution from Scanlon and others (2002), rather than that of Painter and others (2002), was used. Horizontal hydraulic conductivities were varied during model calibration to better match measured hydraulic heads and springflows. Hydraulic conductivities were decreased by varying amounts, as compared to the initial simulated values from Painter and others (2002), in Kinney County and south of the 1,000-mg/L dissolved solids concentration line.

Liedl and others (2003) and Worthington (2004) indicate that conduits increase in size or number, or both, in the direction of downgradient springs. Therefore, the final calibrated hydraulic conductivities assigned to the conduits were: (1) 1,000 to 10,000 ft/d for the conduit segments originating in the recharge zone, farthest from Comal and San Marcos Springs and areas of lesser conduit development (Hovorka and others, 1998; Worthington, 2004), (2) 100,000 ft/d for the segments in the confined zone of the aquifer, but still distant from the major springs, and (3) 200,000 ft/d for the segments in the confined zone of the aquifer near the major springs.

Storativity values, including specific storage and specific yield, were assigned to each active cell for the transient simulations. Initially, uniform values for specific storage and specific yield were assigned, on the basis of reported values from previous numerical ground-water-flow models of the aquifer (Maclay and Land, 1988; Scanlon and others, 2002). Storativity values subsequently were varied during model calibration, resulting in a zonation of values. The final calibrated storativity zones include five zones for specific yield, ranging from 0.005 to 0.15, and five zones for specific storage, ranging from 5.0×10^{-7} to 5.0×10^{-6} ft^{-1}. The storativity values of the simulated conduit cells are the same as the values for the non-conduit cells in the storativity zone in which the conduit cells occur.

A specified-flux boundary, simulated using the MODFLOW recharge package, was used to represent recharge to the Edwards aquifer in the recharge zone (McDonald and Harbaugh, 1988). Simulated recharge to the aquifer by seepage from streams and infiltration of rainfall was assigned to cells in the recharge zone for eight major recharging streams and their interstream areas (recharge subzones), on the basis of annual recharge rates to the Edwards aquifer calculated by the USGS for 1934–2000. Average annual recharge rates during 1939–46 were applied for the steady-state simulation. Monthly recharge rates were applied for the transient simulation (1947-2000). The simulated annual and monthly recharge rates for six recharge basins in the Barton Springs segment of the aquifer were derived from published rates in Slade and others (1986) and unpublished rates compiled by B.R. Scanlon (University of Texas, Bureau of Economic Geology, written commun., 2001). For both the San Antonio and Barton Springs segments, 85 percent of the recharge was applied to streambed cells and the remaining 15 percent applied to the interstream cells. As a result of model calibration, the simulated recharge rates for periods of greatly above-normal rainfall and recharge were reduced, as compared to reported rates. The USGS reported monthly recharge rates for the years 1958, 1973, 1981, 1987, 1991, and 1992 were multiplied by factors ranging from 0.60 to 0.85. The reported annual recharge for each of these years was greater than 1,400,000 acre-ft. The USGS reported recharge rates for the Cibolo Creek and Dry Comal Creek recharge subzone were reduced by 50 percent for all stress periods.

The primary simulated discharges of water from the Edwards aquifer are withdrawals by wells and springflows. The MODFLOW well package was used to simulate the withdrawals by wells. As with recharge, average withdrawal rates during 1939–46 were used for steady-state simulations, and monthly rates were assigned for each stress period of the transient simulation. Comal, San Marcos, Leona, San Antonio, and San Pedro Springs were simulated in the Edwards aquifer model and used for model calibration. The springs were simulated in the model using the MODFLOW drain package.

Model Calibration

The steady-state calibration targets for the Edwards aquifer model include: (1) average measured water levels during 1939–46 in 144 wells and (2) median springflows during 1939–46 for Comal, San Marcos, Leona, San Antonio, and San Pedro Springs. The mean absolute difference between simulated and measured hydraulic heads is 19.4 ft, and the mean algebraic difference is 4.5 ft, indicating the positive differences were approximately balanced by the negative differences. The root mean square (RMS) error for the 144 target wells is 26.5 ft, representing about 4 percent of the total head difference across the model area. The closest-match simulated springflows were within 3 and 13 percent of the measured median springflows for Comal and San Marcos Springs, respectively.

The transient calibration targets include: (1) synoptic sets of water levels in multiple wells during periods of below-normal and above-normal rainfall (potentiometric surface maps), (2) a series of measurements of water level within single wells over time (hydrographs), and (3) springflows for 1947–2000 for Comal, San Marcos, Leona, San Antonio, and San Pedro Springs. The closest-match simulated hydraulic heads for the transient simulation for a period of below-normal rainfall (May–November 1956, during the 1950s drought, when the lowest water levels on record were recorded) were within 30 ft of measured water levels at 123 of the 172 wells for which water-level data were available. The RMS error is 58.7 ft, representing about 8 percent of the total head difference across the model area. The closest-match simulated hydraulic heads for a period of above-normal rainfall (November 1974–July 1975, a period of near record-high water levels in wells) were within 30 ft of measured water levels at 129 of the 169 wells for which water-level data were available. The RMS error is 33.5 ft, representing about 5 percent of the total head difference across the model area.

The transient simulation for 1947–2000 acceptably reproduces measured fluctuations in hydraulic heads in the Edwards aquifer. The match between simulated and measured hydraulic heads is generally closer for wells completed in the confined zone of the aquifer than for those in and near the recharge zone. The RMS error ranged from 4.1 to 23.2 ft in 11 wells with water-level measurements for varying periods during 1947–2000; these errors represent 7.8 to 30.8 percent of the range in water-level fluctuations of each well.

Generally acceptable agreement also was obtained between simulated and measured springflow at the simulated springs. The RMS errors for Comal, San Marcos, Leona, San Antonio, and San Pedro Springs ranged from 230,700 cubic feet per day (ft^3/d) for San Pedro Springs to 3,967,000 ft^3/d for Comal Springs. The RMS errors for the five springs, as a percentage of the range of springflow fluctuations measured at the springs, varied from 7.0 percent for San Marcos Springs to 36.6 percent for Leona Springs and were less than 10 percent for all but Leona Springs. The mean algebraic differences between simulated and measured spring discharges are 6.7 and 15.0 ft^3/s for Comal and San Marcos Springs, respectively, indicating a small bias in the residuals toward high flows.

Model Results

A ground-water divide in the Edwards aquifer occurs near Kyle in south-central Hays County, from which ground-water flow is to the east toward Barton Springs or to the west toward San Marcos Springs. Model simulation results indicate that the position of this ground-water divide varies, depending on the water-level conditions. For steady-state and above-normal rainfall and recharge conditions, the simulated position of the ground-water divide is coincident with its commonly defined position near Kyle. In contrast, during drought conditions the position of the simulated ground-water divide shifts westward to near San Marcos Springs.

Simulation results indicate that the simulated flow in the Edwards aquifer model is strongly influenced by the locations of the simulated conduits, which tend to convey flow. The simulated subregional flow directions are generally toward the nearest conduit and subsequently along the conduits from the recharge zone into the confined zone and toward the major springs. The influence of simulated barrier faults on flow directions is most evident in northern Medina County. In this area, the direction of ground-water flow is affected primarily by parallel northeastward-striking faults and conduit segments that divert the flow toward the southwest.

For the steady-state simulation, recharge accounts for 93.5 percent of the sources of water to the Edwards aquifer, and inflow through the northern and northwestern model boundaries contributes 6.5 percent. The largest discharges are spring discharge (73.7 percent) and ground-water withdrawals by wells (25.7 percent). The principal source of water to the aquifer for the transient simulation is recharge. The principal discharges from the aquifer for the transient simulation are springflows and withdrawals by wells. During 1956, representing drought conditions, the change in storage (net water released from storage) is much greater than recharge, comprising 75.9 percent of the total flow compared to 14.5 percent for recharge. Conversely, during 1975, representing above-normal rainfall and recharge conditions, recharge constitutes 79.9 percent of the total flow compared to 7.1 percent for the change in storage (net water added to storage).

A series of sensitivity tests were made to ascertain how the model results were affected by variations greater than and less than the calibrated values of input data. Simulated hydraulic heads and spring discharge in the Edwards aquifer model were most sensitive to recharge, withdrawals, hydraulic conductivity of the conduit segments, and specific yield; and comparatively insensitive to spring-orifice conductance, northern boundary inflow, and specific storage. Larger values of hydraulic conductivity, coupled with reduced recharge because model cells went dry, resulted in smaller simulated springflows.

If the reduced recharge is accounted for, however, larger values of hydraulic conductivity result in increased springflows. The effect of lowering the simulated spring-orifice altitudes of Comal and San Marcos Springs was to appreciably lower simulated hydraulic heads in the aquifer, because the spring-orifice altitudes serve as a controlling base level for hydraulic heads in the aquifer. The effect on simulated springflow was to minimally increase springflow for Comal Springs and appreciably decrease springflow for Leona Springs.

REFERENCES

Atkinson, T.C., 1977, Diffuse flow and conduit flow in limestone terrain in the Mendip Hills, Somerset (Great Britain): Journal of Hydrology, v. 35, no. 1–2, p. 93-110.

Elliott, W.R., and Veni, George, eds., 1994, The caves and karst of Texas—Guidebook for the 1994 convention of the National Speleological Society with emphasis on the southwestern Edwards Plateau: Huntsville, Ala., National Speleological Society, 342 p.

Groschen, G.E., 1996, Hydrogeologic factors that affect the flowpath of water in selected zones of the Edwards aquifer, San Antonio region, Texas: U.S. Geological Survey, Water-Resources Investigations Report 96–4046, 73 p.

Hamilton, J.M., Johnson, S., Esquilin, R., Thompson, E.L., Luevano, G., Wiatrek, A., Mireles, J., Gloyd, T., Sterzenback, J., Hoyt, J.R., and Schindel, G., 2003, Edwards Aquifer Authority hydrogeological data report for 2002: San Antonio, Tex., Edwards Aquifer Authority, 134 p. [Available online at www.edwardsaquifer.org.]

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 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, 121 p.

Harbaugh, A.W., and McDonald, M.G., 1996, User’s documentation for MODFLOW–96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96–485, 56 p.

Hovorka, S.D, Mace, R.E., and Collins. E.W., 1998, Permeability structure of the Edwards aquifer, south Texas—Implications for aquifer management: Austin, University of Texas, Bureau of Economic Geology Report of Investigations 250, 55 p.

Hovorka, S.D., Phu, T, Nicot, J.P., and Lindley, A., 2004, Refining the conceptual model for flow in the Edwards aquifer—Characterizing the role of fractures and conduits in the Balcones fault zone segment: Contract report to Edwards Aquifer Authority, 53 p.

Johnson, S.B., Schindel, G.M., and Hoyt, J.R., 2002, Ground-water chemistry changes during a recharge event in the karstic Edwards aquifer, San Antonio, Texas: Geological Society of America, Online Abstract 186–8.

LBG-Guyton Associates, 1995, Edwards aquifer groundwater divides assessment, San Antonio region, Texas: San Antonio, Edwards Underground Water District Report 95–01, 35 p.

Liedl, R., Sauter, M., Hückinghaus, D., Clemens, T., and Teutsch, G., 2003, Simulation of the development of karst aquifers using a coupled continuum pipe flow model: Water Resources Research, v. 39, no. 3, p. 1,057–1,067.

Lindgren, R.J., Dutton, A.R., Hovorka, S.D., Worthington, S.R.H., and Painter, Scott, 2004, Conceptualization and simulation of the Edwards aquifer, San Antonio region, Texas: U.S. Geological Survey Scientific Investigations Report 2004–5277, 143 p.

Mace, R.E., Chowdhury, A.H., Anaya, Roberto, Way, S.C, 2000, Groundwater availability of the Trinity aquifer, Hill Country area, Texas—Numerical simulations through 2050, Texas Water Development Board Report 353, 169 p.

Maclay, R.W., 1995, Geology and hydrology of the Edwards aquifer in the San Antonio area, Texas: U.S. Geological Survey Water-Resources Investigations Report 95– 4186, 64 p.

Maclay, R.W., and Land, L.F., 1988, Simulation of flow in the Edwards aquifer, San Antonio Region, Texas, and refinements of storage and flow concepts: U.S. Geological Survey Water-Supply Paper 2336–A, 48 p.

Maclay, R.W., and Small, T.A., 1986, Carbonate geology and hydrology of the Edwards aquifer in the San Antonio area, Texas: Texas Water Development Board Report 296, 90 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey, Techniques of Water-Resources Investigations, book 6, chap. A1 [variously paged].

Ogden, A.E., Quick, R.A., Rothermel, S.R., and Lundsford, D.L., 1986, Hydrological and hydrochemical investigation of the Edwards aquifer in the San Marcos area, Hays County, Texas: San Marcos, Tex., Edwards Aquifer Research and Data Center, 364 p.

Painter, Scott, Jiang, Yefang, and Woodbury, Allan, 2002, Edwards aquifer parameter estimation project final report: Southwest Research Institute [variously paged].

Puente, Celso, 1978, Method of estimating natural recharge to the Edwards aquifer in the San Antonio area, Texas: U.S. Geological Survey Water-Resources Investigations Report 78–10, 34 p.

Scanlon, B.R., Mace, R.E., Smith, Brian, Hovorka, S. D., Dutton, A.R., and Reedy, R.C., 2002, Groundwater availability of the Barton Springs segment of the Edwards aquifer, Texas—Numerical simulations through 2050: Austin, University of Texas, Bureau of Economic Geology, final report prepared for Lower Colorado River Authority under contract no. UTA99–0, 36 p.

Schindel, G.M., Johnson, S.B., Worthington, S.R.H., Alexander, E.C., Jr., Alexander, Scott, and Schnitz, Lewis, 2002, Groundwater flow velocities for the deep artesian portion of the Edwards aquifer, near Comal Springs, Texas, *in* Annual Meeting of the Geological Society of America, Denver, Colo., October 27–30, 2002: Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 347.

Schultz, A.L., 1993, Defining the Edwards aquifer freshwater/saline-water interface with geophysical logs and measured data (San Antonio to Kyle, Texas): San Antonio, Edwards Underground Water District Report 93–06, Texas, 81 p.

Schultz, A.L., 1994, 1994 review and update of the position of the Edwards aquifer freshwater/saline-water interface from Uvalde to Kyle, Texas: San Antonio, Edwards Underground Water District Report 94–05, 31 p.

Slade, R.M., Jr., Dorsey, M.E., and Stewart, S.L., 1986, Hydrology and water quality of the Edwards aquifer associated with Barton Springs in the Austin area, Texas: U.S. Geological Survey, Water-Resources Investigations Report 86–4036, 96 p.

Tomasko, David, Fisher, Ann-Marie, Williams, G.P, and Pentecost, E.D, 2001, A statistical study of the hydrologic characteristics of the Edwards aquifer: Chicago, Argonne National Labs, 38 p.

Veni, George, 1988, The caves of Bexar County (2d ed.): Austin, University of Texas, Texas Memorial Museum Speleological Monograph 2, 300 p.

Worthington, S.R.H., 2004, Conduits and turbulent flow in the Edwards aquifer: Worthington Groundwater, contract report to Edwards Aquifer Authority, San Antonio, Tex., 41 p.

The Role of MODFLOW in Numerical Modeling of Karst Flow Systems

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ABSTRACT

Mixed-flow karst systems convey groundwater through a combination of conduit and diffuse flow. Building a conceptual model of the flow system is possible, but advancing to the next stage, a numerical model, poses difficulties because of the complexities inherent to karst flow. Yet a numerical model may be desired to test the conceptual model, quantify fluxes, and identify data gaps.

Approaches to modeling karst flow have included the equivalent porous medium approach, black box reproductions of input and spring discharge, very high hydraulic conductivity flowpaths, fracture network simulations, and open channel equivalents. These are discussed in greater detail in Quinn and Tomasko (2000). All of these methods have advantages and disadvantages relevant to a given modeling purpose.

Numerical models of karst flow systems have traditionally relied on high-permeability zones to handle the karstified portion of a carbonate system, and springs have been represented by a single model feature, such as a drain cell, at the spring location. This approach, however, ignores the bulk of the flow from the conduit system. The question remains whether numerical models, such as the U.S. Geological Survey's MODFLOW, are suitable for creating models of karst flow systems.

This study illustrates a method of numerical modeling that has performed well in two case studies, one in Missouri and one in Germany. In each case, the conduit system is inferred by a variety of indirect evidence and modeled using MODFLOW as a network of connected drains feeding each outflow spring.

INTRODUCTION

The modeling of groundwater flow in karst aquifer systems is difficult because of the complexities of conduit geometries and arrangement and the relationship between diffuse and conduit flow within the aquifer. From local to regional scale, models constructed in karst settings require assumptions regarding the flow regime, as well as supporting data, some of which may be unavailable.

Numerical modeling of karst flow has nonetheless been attempted with a variety of approaches in two- or three-dimensional models of local to regional scale. Finite element examples include Laroque et al. (1999, 2000), who modeled springs as constant head locations, and Gonzalez-Herrara et al. (2002), who modeled karst features in a regional study area using equivalent porous media and large element dimensions. Examples of MODFLOW used in porous media are also in the literature (e.g. Witkowski et al. 2003, Guvanasen et al. 2000, Scanlon et al. 2003, Zhang and Keeler 1998, Langevin 2003, and Sepulveda 2002). Several of these papers are cases in which each spring was simulated as a single model cell with a MODFLOW drain (Scanlon et al. 2003, Sepulveda 2003) or with a MODFLOW general head boundary (Zhang and Keeler 1998). The approach of equivalent porous media with a single model feature representing each spring is limiting and generally restricted to regional water resources studies, and is not useful for local issues such as flow directions, flow rates, protection zone delineation, or point source contamination modeling (Scanlon et al. 2003, Langevin 2003).

APPROACH

In several examples discussed above, conduit flow was modeled by installing a drain or general head feature at a spring location. Calibration was achieved by adjusting hydraulic conductivity in a zone upgradient from the spring. However, this technique ignores the rapid discharge to a conduit system laced throughout large portions of the aquifer.

Our approach relies on a conceptually more complete modeling of the inferred or estimated conduits. They are modeled as continuous, branching networks of MODFLOW drain cells. In this manner, diffuse discharge throughout the aquifer has the potential to reach tributaries of the conduit system, to be essentially removed from the flow system, and to be accounted for as discharge at the outlet spring in combination with all contributing conduit branches.

The MODFLOW drain package was originally developed to simulate drain tiles; however, it is a reasonable analogue for conduits in karst. Two types of information are needed as drain input. Drain elevations must be specified along a modeled conduit. At the downgradient end, these are set to the elevation of discharge spring, while at the upgradient locations, the elevations are specified based on drilling data. The second type of input is drain conductance. Setting this term to a high value promotes removal of water from flow system, and the model is insensitive to changes in its value.

This approach is geared toward solving a mixed-flow karst system, with equipotentials within the diffuse portion of the aquifer matrix bending at conduits (e.g., Field 1993, Quinlan and Ewers 1985).

The Groundwater Modeling System (GMS) is used as a pre- and post-processor. GMS assigns elevations along the drain segments by performing linear interpolation between the nodes of a branching system of drains.

Model calibration is made by manually adjusting elevations of drains, hydraulic conductivity, and recharge to match target heads and fluxes (spring outflow), or by parameter estimation of aquifer and recharge parameters.

SOURCES OF INPUT

Critical to implementing this approach is estimating or inferring the locations of conduits within the karst terrain. Drain networks were assigned in each study area by relying on available data, which could include dye tracing results, geophysical anomalies (lineaments), surficial features (dry valleys, fractures, sinkholes), spring locations, and spring flow measurements.

For assigning initial drain elevations, drilling data is used to estimate the depth of the weathered/unweathered contact within the carbonate. Initial values of hydraulic conductivity are assigned to zones on the basis of aquifer testing data.

MISSOURI CASE STUDY

This site, located on the Burlington-Keokuk limestone of Missouri, has input data in the form of numerous dye traces conducted by the Missouri DNR (Figure 1), a main spring with a long outflow monitoring record, abundant aquifer test data (Figure 2), widespread drilling data to determine the depth of the weathered zone, many monitoring wells for calibrating heads (Figure 3), and infiltration field studies to address specific site features. On the basis of drilling data and aquifer testing, the modeling included two layers: a deeper unweathered unit and a shallower weathered unit.

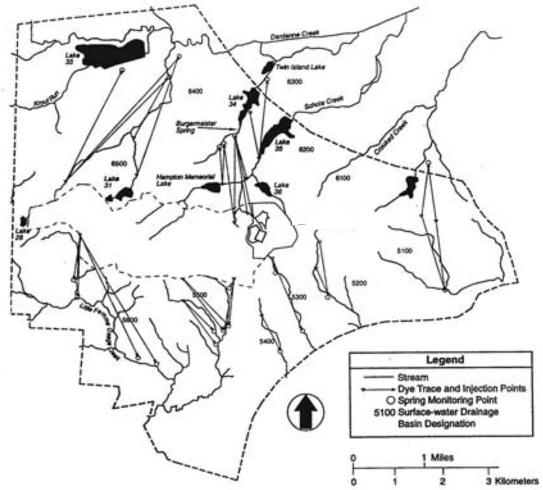

Figure 1. Site setting and results of Missouri DNR tests.

Calibration to the target head surface and to average flux at the main spring to the north was made by adjusting drain elevations. The resulting calibrated model (Figure 4) provided a strong match

Figure 2. Hydraulic conductivity distribution of upper model layer, based on aquifer testing.

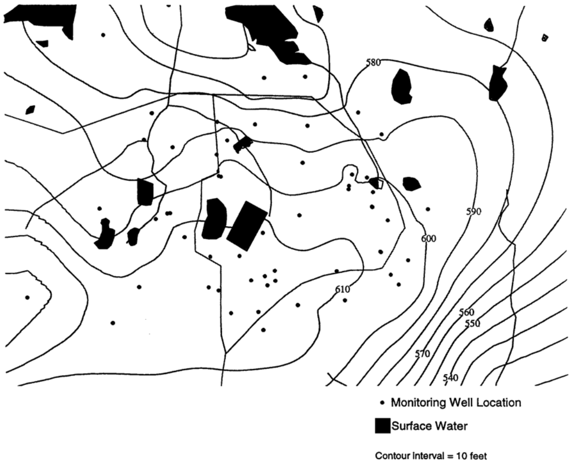

Figure 3. Target heads and monitoring well locations.

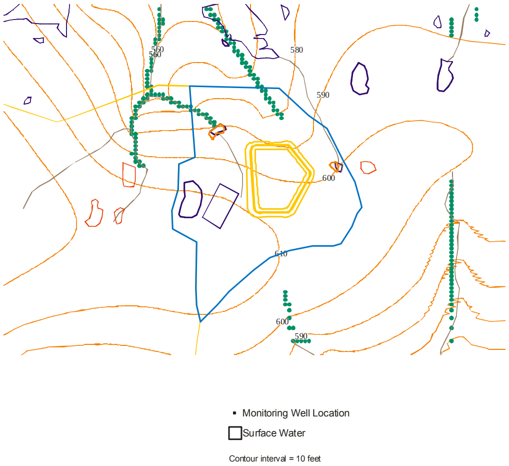

Figure 4. Missouri site calibrated heads.

to target heads and to spring outflow. Details of this study are provided in Quinn and Tomasko (2000). The flow model was used in an application to determine the effect a disposal cell would have on the local flow system.

GERMANY CASE STUDY

This site is the Hohenfels Combat Maneuver Training Center (CMTC), located on the Malm Formation of Bavaria (Figure 5). Portions of the study area have been intensively investigated by geophysicists of Argonne National Laboratory's Energy Systems Division. Their results identified numerous anomalies attributed to the presence of karst conduits (Figure 6). The site is primarily comprised of carbonates of the Malm Formation.

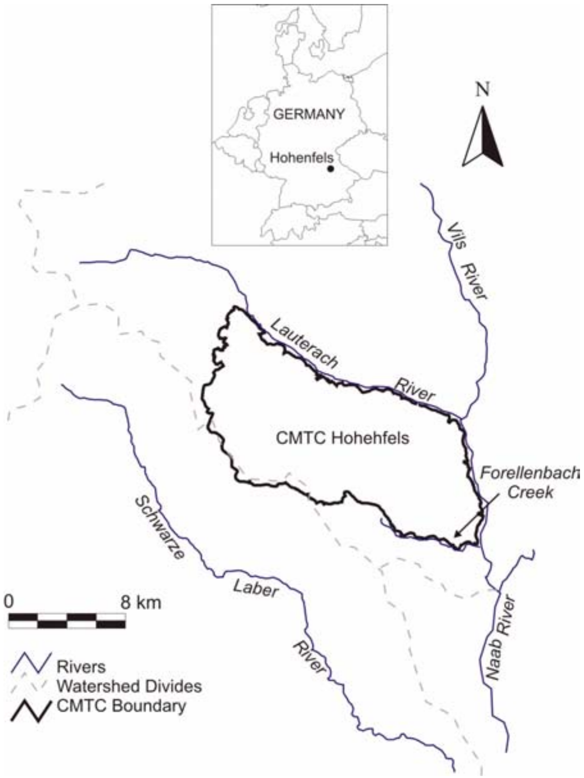

Figure 5. CMTC, Lautertal, and regional features.

The site characterization also includes several dye tracing experiments (Figure 7), limited coverage of monitoring wells and target head data, several measurements of spring flow, and detailed physical feature mapping (sinkholes, dry valleys) only on the training center property. The MODFLOW model of this site included the entire CMTC site and extended to several external areas to make use of regional groundwater divides as boundary conditions. Drains were included in the finite-difference model on the basis of the dye traces, geophysical lineaments, and valley orientations.

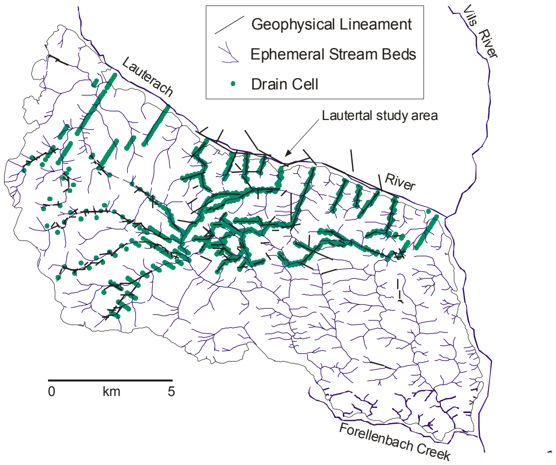

Figure 6. Drain cells and geophysical lineaments.

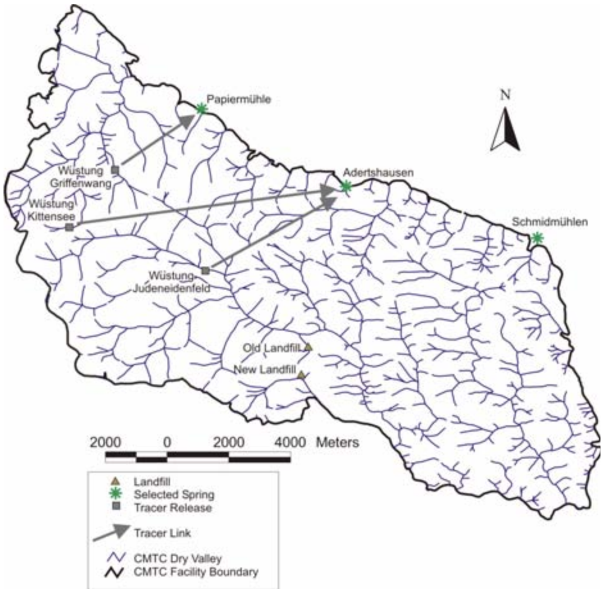

Figure 7. Hydraulic connections established through dye tracing.

The focus of the field and modeling efforts was a portion of the CMTC called the Lautertal. Here, model results clearly show the influence of the interconnected drain cells laced through the aquifer (Figure 8). Because of the sparse amount of target head data at the site, detailed calibration was not possible. However, the resulting heads of the calibrated model provide an adequate match to the available data in the area most intensively characterized with physical features mapping, geophysics, and tracer tests. Drain output matched reasonably well with spot measurements of outflow at several springs. Details of this study are provided in Quinn and Tomasko (2000) and Quinn et al. (in review).

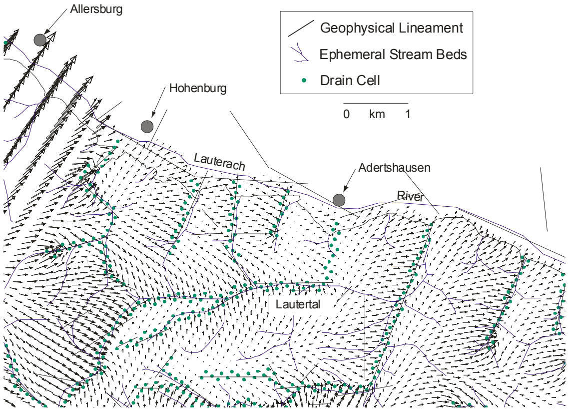

Figure 8. Zoom view of flow vectors near Lautertal, illustrating the relationship between the drain locations and the flow field.

CONCLUSIONS

Results from applying the technique of interconnected MODFLOW drain cells have shown promise in two case studies in mixed-flow karst terrain. Calibration to both target heads and target spring fluxes is achievable, though the calibration of transient models to varying spring discharge has not yet been attempted.

This approach is more realistic compared to other numerical approaches and has served well to test conceptual models and identify data gaps at two sites. It is also easy to implement with currently available software. The accuracy of the method depends on the coverage of quality field data, especially dye tracing, geophysics, hydraulic conductivity estimates, and target heads and fluxes (spring outflow). An advantage of this method is that the modeling is performed without detailed information on the geometry of the conduits, which is difficult or impossible to obtain.

REFERENCES

Field, M.S., 1993. Karst hydrology and chemical contamination. Journal of Environmental Systems, 22 (1), 1-26.

Gonzalez-Herrara, R., Sanchez-y-Pinto, I., and Gamboa-Vargas, J., 2002, Groundwater-flow modeling in the Yucatan karstic aquifer, Mexico: Hydrogeology Journal, vol. 10, p. 539-552.

Guvanasen, V., Wade, S.C., and Barcelo, M.D., 2000, Simulation of Regional Ground Water Flow and Salt Water Intrusion in Hernando County, Florida: Ground Water, vol. 38, no. 5, p. 772-783.

Langevin, C.D., 2003, Simulation of submarine ground water discharge to a marine estuary: Biscayne Bay, Florida: Ground Water, vol. 41, no. 6, p. 758-771.

Larocque, M., Banton, O., and Razack, M., 2000, Transient-State History Matching of a Karst Aquifer Ground Water Flow Model: Ground Water, vol. 38, no. 6, p. 939-946.

Larocque, M., Banton, O., Ackerer , P., and Razack, M., 1999, Determining karst tranmissivities with inverse modeling and an equivalent porous media: Ground Water, vol. 37, no. 6, p. 897-903.

Quinlan, J.F. and Ewers, R.O., 1985. Ground water flow in limestone terraces: strategy, rationale and procedure for reliable, efficient monitoring of ground water quality in karst areas. In: Proceedings, Fifth National Symposium on Aquifer Restoration and Ground Water Monitoring. National Water Well Association, Dublin, Ohio, pp. 197-234.

Quinn, J. and Tomasko, D., 2000, A Numerical Approach to Simulating Mixed Flow in Karst Aquifers, *in* I. Sasowsky and C. Wicks, eds., Groundwater Flow and Contaminant Transport in Carbonate Aquifers: Rotterdam, Holland, A.A. Balkema, p. 147-156.

Quinn, J.J., Tomasko, D., and Kuiper, J.A., in review, Modeling Complex Flow in a Karst Aquifer: submitted to Sedimentary Geology.

Scanlon, B.R., Mace, R.E., Barrett, M.E., and Smith, B., 2003, Can we simulate regional groundwater flow in a karst system using equivalent porous media models: Case study, Barton Springs Edwards aquifer, USA: Journal of Hydrology, vol. 276, p. 137-158.

Sepulveda, N., 2002, Simulation of ground-water flow in the Intermediate and Floridan Aquifer Systems in Peninsular Florida: U.S. Geological Survey, Water-Resources Investigations Report 02-4009.

Witkowski, A.J., Rubin, K., Kowalczyk, A., Rozkowski, A., and Wrobel, J., 2003, Groundwater vulnerability map of the Chrzanow karst-fissured Triassic aquifer (Poland): Environmental Geology, vol. 44, p. 59-67.

Zhang, Y.-K., and Keeler, R., 1998, Modeling of groundwater flow with MODFLOW in a fractured-karst aquifer in the Big Spring Basin, Iowa: Proceedings of MODFLOW `98: Golden, CO, International Ground Water Modeling Center, p. 149-156.