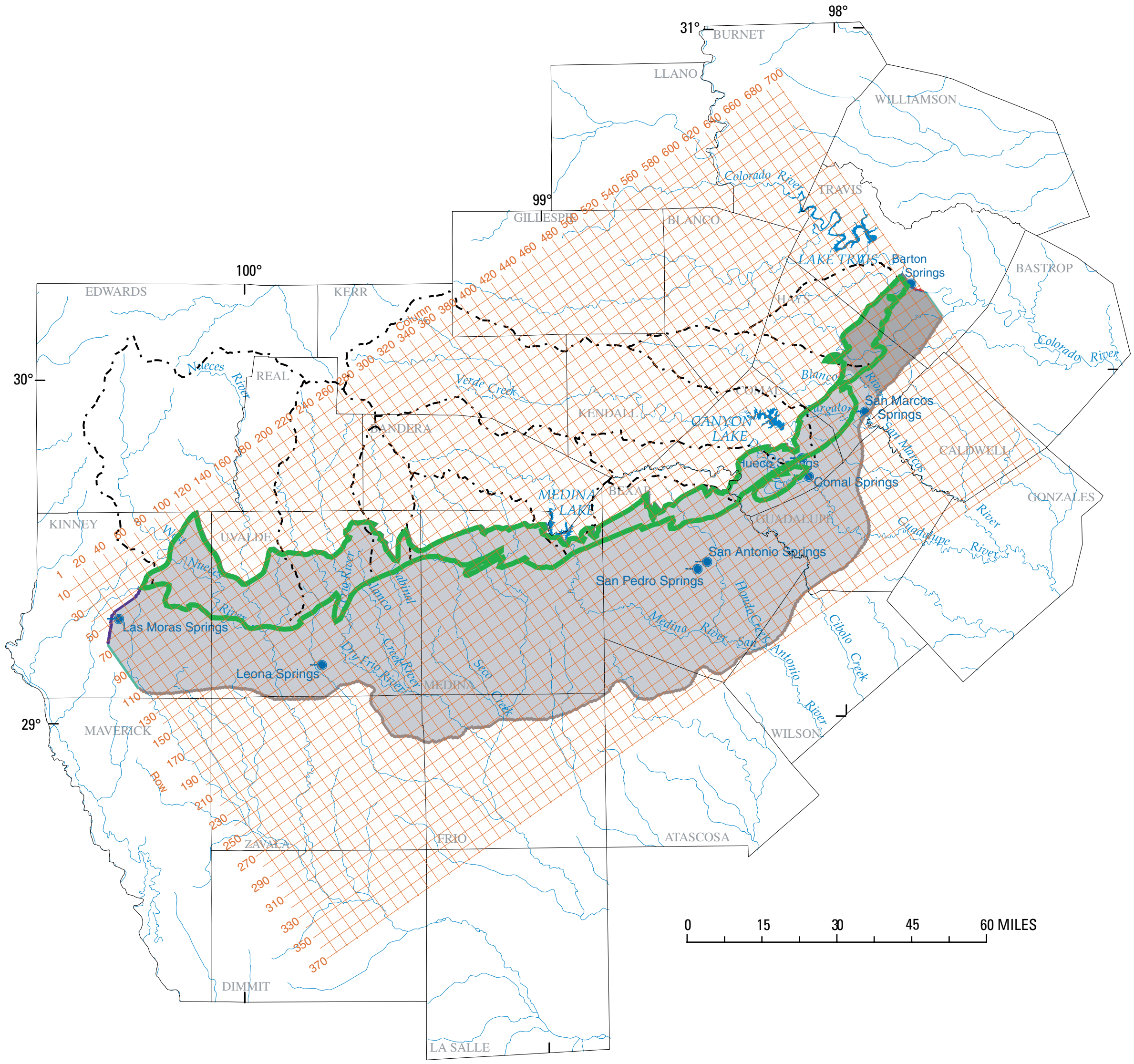
In cooperation with the Texas Commission on Environmental Quality

Description and Evaluation of Numerical Groundwater Flow Models for the Edwards Aquifer, South-Central Texas



Scientific Investigations Report 2009–5183

U.S. Department of the Interior
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Cover: Finite-difference grid for MODFLOW model of San Antonio and Barton Springs segments of Edwards aquifer (modified from Lindgren and others, 2004, fig. 18).

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Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29) and the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

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Abstract

A substantial number of public water system wells in south-central Texas withdraw groundwater from the karstic, highly productive Edwards aquifer. However, the use of numerical groundwater flow models to aid in the delineation of contributing areas for public water system wells in the Edwards aquifer is problematic because of the complex hydrogeologic framework and the presence of conduit-dominated flow paths in the aquifer. The U.S. Geological Survey, in cooperation with the Texas Commission on Environmental Quality, evaluated six published numerical groundwater flow models (all deterministic) that have been developed for the Edwards aquifer San Antonio segment or Barton Springs segment, or both. This report describes the models developed and evaluates each with respect to accessibility and ease of use, range of conditions simulated, accuracy of simulations, agreement with dye-tracer tests, and limitations of the models. These models are (1) GWSIM model of the San Antonio segment, a FORTRAN computer-model code that pre-dates the development of MODFLOW; (2) MODFLOW conduit-flow model of San Antonio and Barton Springs segments; (3) MODFLOW diffuse-flow model of San Antonio and Barton Springs segments; (4) MODFLOW Groundwater Availability Modeling [GAM] model of the Barton Springs segment; (5) MODFLOW recalibrated GAM model of the Barton Springs segment; and (6) MODFLOW–DCM (dual conductivity model) conduit model of the Barton Springs segment. The GWSIM model code is not commercially available, is limited in its application to the San Antonio segment of the Edwards aquifer, and lacks the ability of MODFLOW to easily incorporate newly developed processes and packages to better simulate hydrologic processes. MODFLOW is a widely used and tested code for numerical modeling of groundwater flow, is well documented, and is in the public domain. These attributes make MODFLOW a preferred code with regard to accessibility and ease of use. The MODFLOW conduit-flow model incorporates improvements over previous models by using (1) a user-friendly interface, (2) updated computer codes (MODFLOW–96 and MODFLOW–2000), (3) a finer grid resolution, (4) less-restrictive boundary conditions, (5) an improved discretization of hydraulic conductivity, (6) more accurate estimates of pumping stresses, (7) a long transient simulation period (54 years, 1947–2000), and (8) a refined representation of high-permeability zones or conduits. All of the models except the MODFLOW–DCM conduit model have limitations resulting from the use of Darcy's law to simulate groundwater flow in a karst aquifer system where non-Darcian, turbulent flow might actually dominate. The MODFLOW–DCM conduit model is an improvement in the ability to simulate karst-like flow conditions in conjunction with porous-media-type matrix flow. However, the MODFLOW–DCM conduit model has had limited application and testing and currently (2008) lacks commercially available pre- and post-processors. The MODFLOW conduit-flow and diffuse-flow Edwards aquifer models are limited by the lack of calibration for the northern part of the Barton Springs segment (Travis County) and their reliance on the use of the calibrated hydraulic conductivity and storativity values from the calibrated Barton Springs segment GAM model. The major limitation of the Barton Springs segment GAM and recalibrated GAM models is that they were calibrated to match measured water levels and springflows for a restrictive range of hydrologic conditions, with each model having different hydraulic conductivity and storativity values appropriate to the hydrologic conditions that were simulated. The need for two different sets of hydraulic conductivity and storativity values increases the uncertainty associated with the accuracy of either set of values, illustrates the non-uniqueness of the model solution, and probably most importantly demonstrates the limitations of using a one-layer model to represent the heterogeneous hydrostratigraphic units composing the Edwards aquifer. In general, the best matches or agreement between groundwater flow directions inferred by numerical model simulation, and by dye-tracer tests, are observed where model outputs accurately reproduce the configuration of the potentiometric surface with regard to the positions of major and minor groundwater troughs and divides. None of the models, with the possible exception of the MODFLOW–DCM conduit model, has a documented capability to accurately simulate travel times for conduit-dominated velocities in the Edwards aquifer. Public water system assessments of wells in the Barton Springs segment of the Edwards aquifer, and elsewhere where conduit-flow conditions are thought to dominate aquifer hydraulic behavior, might be enhanced

by use of either the MODFLOW–DCM model or the newly developed U.S. Geological Survey MODFLOW Conduit-Flow Process module for MODFLOW–2005, because each incorporates a type of dual or triple hydraulic conductivity approach and has the capability to explicitly simulate turbulent flow and conduit hydraulic characteristics.

Introduction

The Texas Commission on Environmental Quality (TCEQ) has the principal responsibility to assess the sustainability and susceptibility to contamination of source water provided by public water system (PWS) wells (Texas Commission on Environmental Quality, 1999). To carry out this responsibility, the TCEQ uses the most up-to-date hydrogeologic, climatologic, and water-use data available, and output obtained from numerical groundwater flow models and from SWAP–DSS, a customized computer software package developed by the U.S. Geological Survey (USGS), in cooperation with the TCEQ, for source-water assessments (R.L. Ulery, U.S. Geological Survey, written commun., 2003). For PWS wells, the TCEQ requires that the contributing area of each well be delineated as accurately as possible and that potential sources of groundwater contamination be identified within an estimated 100-year time-of-travel area. The delineation of the contributing area for each PWS well is a critical element in the TCEQ assessment process because all other assessment components are dependent upon the accuracy of the delineated contributing area.

A substantial number of PWS wells in south-central Texas withdraw groundwater from the karstic, highly productive Edwards aquifer (fig. 1). For these PWS wells, the boundaries for contributing areas are currently (2008) delineated using a combination of tools that includes numerical groundwater flow models and the SWAP–DSS software. However, the use of numerical groundwater flow models to aid in the delineation of contributing areas for PWS wells in the Edwards aquifer is problematic because of the complex hydrogeologic framework and the presence of conduit-dominated flow paths in the aquifer.

These complications arise in part from technical limitations involved in applying numerical models designed primarily for simulation of aquifers characterized by laminar or non-turbulent groundwater flow conditions. In addition, the hydrogeologic data needed to create proper conceptual, mathematical, and digital models of karst aquifers are considerable and difficult to obtain without use of quantitative methods that take into account the triple porosity and permeability characteristics of karst (Taylor and Greene, 2008). In much of the Edwards aquifer, as in many well-developed karst aquifers, hydrogeologic data are lacking or insufficient to adequately represent karst flow characteristics (Worthington, 2003). It is generally accepted by the water-resources community that, without access to adequate hydrogeologic input data and use of numerical models capable of incorporating, in some way, non-laminar karst flow characteristics, poor to limited success will be achieved in simulating groundwater flow directions, velocities, and contaminant transport characteristics in well-developed karst aquifers (Scanlon and others, 2003; Palmer, 2006).

To assess the sustainability and susceptibility to contamination of source water provided by PWS wells, the TCEQ wishes to apply numerical models that provide the most accurate and scientifically defensible delineation of contributing areas that is possible given the existing technological limitations. To this end, the USGS, in cooperation with the TCEQ, evaluated six published numerical groundwater flow models (all deterministic) that have been developed for the Edwards aquifer.

This report describes the six published groundwater flow models for the Edwards aquifer and evaluates each of the models primarily with respect to the following criteria:

- Accessibility and ease of use of model code and model input and output files
- Range of simulated hydrologic conditions for each calibrated model—that is, are both wet and dry periods simulated
- Accuracy of model simulations—comparison of residuals for hydraulic heads and springflows
- Agreement, to the extent possible, with results obtained from previously conducted dye-tracer tests
- Limitations of the models

Description of Numerical Groundwater Flow Models

Six numerical groundwater flow models for the San Antonio segment of the Edwards aquifer or Barton Springs segment of the Edwards aquifer, or both (fig. 1), that are published and generally accepted by the water-resources community are described and evaluated in this report. These models are

1. Finite-difference model of San Antonio segment of Edwards aquifer (GWSIM) (Klemt and others, 1979; Thorkildsen and McElhaney, 1992)
2. MODFLOW model of San Antonio and Barton Springs segments of Edwards aquifer with hydraulic conductivity distribution based on conduit-flow conceptualization (Lindgren and others, 2004)
3. MODFLOW model of San Antonio and Barton Springs segments of Edwards aquifer with hydraulic conductivity distribution based on diffuse-flow conceptualization (Lindgren, 2006)

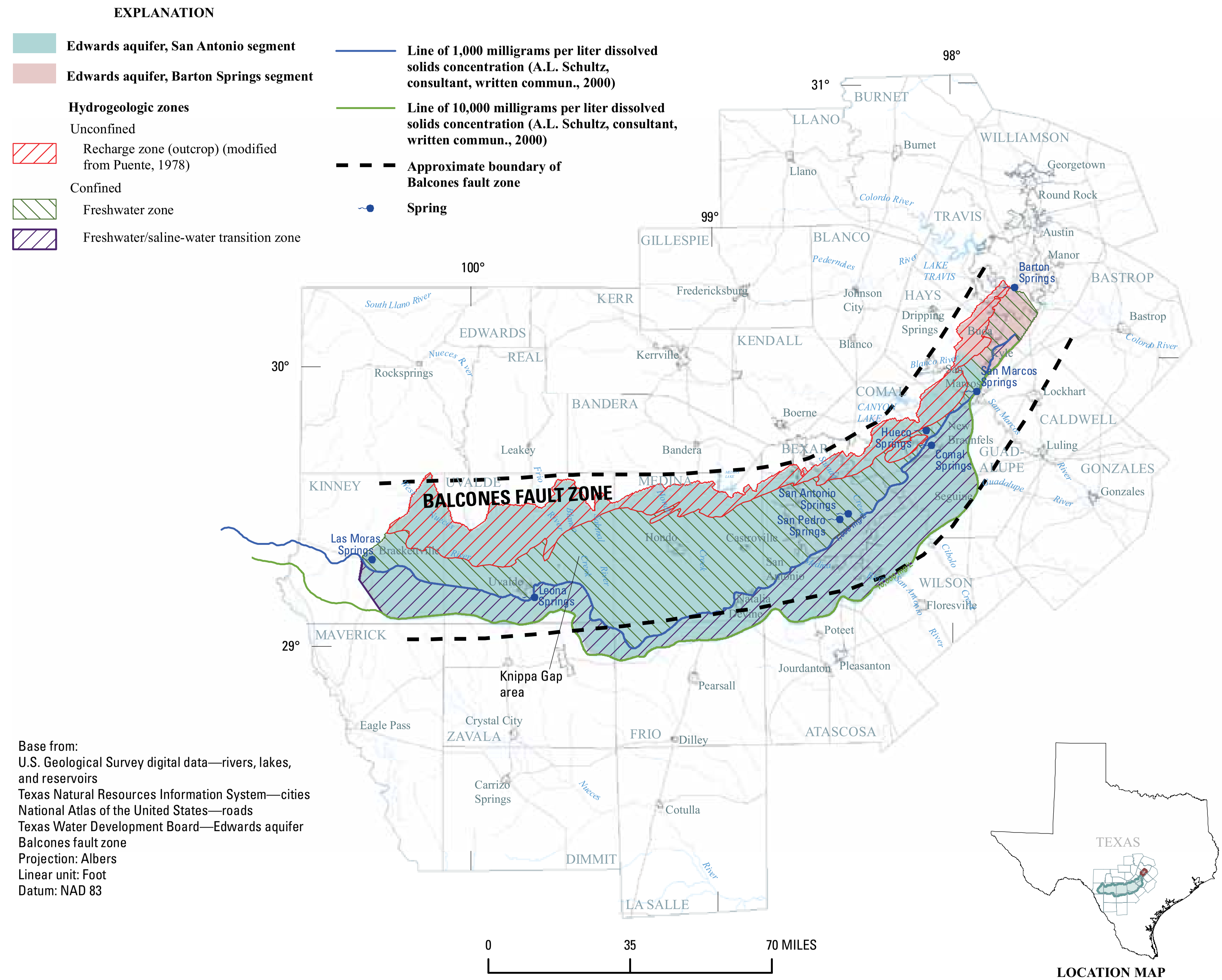

Figure 1. Edwards aquifer, south-central Texas, subdivided into San Antonio and Barton Springs segments and hydrogeologic zones.

4. MODFLOW model of Barton Springs segment of Edwards aquifer (Groundwater Availability Modeling [GAM] model) (Scanlon and others, 2002)
5. MODFLOW model of Barton Springs segment of Edwards aquifer for drought conditions (recalibrated GAM model) (Smith and Hunt, 2004)
6. MODFLOW–DCM (dual conductivity model) conduit model of Barton Springs segment of Edwards aquifer incorporating dual conductivity approach and explicit simulation of conduits (Painter and others, 2007).

The model software and extent, simulated time periods, and model structure and simulated hydraulic properties for each model are shown in table 1. A summary of the characteristics and history of development of each model, organized by aquifer segment encompassed by the model, follows.

San Antonio Segment

A number of numerical groundwater flow models have been constructed for the San Antonio segment of the Edwards aquifer. Klemt and others (1979) developed a numerical groundwater flow model (hereinafter, the GWSIM model [model no. 1 of 6, p. 2 of this report]) for the San Antonio segment of the Edwards aquifer that was used to simulate several groundwater withdrawal and climatic scenarios from 1972 through 2049. The GWSIM model uses a FORTRAN computer-model code that pre-dates the development of MODFLOW to simulate groundwater flow in the San Antonio segment of the Edwards aquifer. The computer program for the GWSIM model, including the program documentation and user's manual, was prepared in 1974 by the Texas Water Development Board (Texas Water Development Board, 1974). The basic simulation program was written by T.A. Prickett and C.G. Lonnquist, Illinois State Water Survey (Prickett-Lonnquist Aquifer Simulation Model) (Prickett and Lonnquist, 1971). Modifications subsequently were made to the basic program to allow better simulation of an aquifer containing both confined and unconfined zones (such as the Edwards aquifer).

Thorkildsen and McElhaney (1992) reevaluated the GWSIM model and refined the simulation of water levels and springflows in the San Antonio region. The GWSIM model has been used extensively for simulating water-level conditions at the Bexar County index well (observation well, commonly referred to as "J–17," in which water-level changes are assumed to reflect Edwards aquifer water-level changes on a regional scale) and springflows at Comal Springs.

LBG-Guyton Associates (1996) did a study to determine whether the GWSIM model accurately predicts water levels throughout the model area. They concluded that the model can be used to accurately simulate hydrologic conditions in the freshwater zone of the Edwards aquifer from eastern Uvalde County to western Hays County (fig. 1). However, a poor correlation, or no correlation, between measured and simulated water levels for 1978–89 was obtained for wells in eastern Hays County, the Knippa Gap area and the area west of the Frio River in Uvalde County, and in the recharge zone. In particular, the model was poorly calibrated for San Marcos Springs, one of two major discharge points for the Edwards aquifer (the other is Comal Springs).

To evaluate the hydrologic response to various alternative proposals for managing the Edwards aquifer, the Edwards Aquifer Authority (EAA, formerly the Edwards Underground Water District), with other San Antonio water-resource managers and planners, expressed the need for an improved numerical groundwater flow model. Rather than attempt to update, modify, or recalibrate existing models, it was decided that a new, comprehensive groundwater flow model, using current (2003) user-friendly pre- and post-processing software that incorporated important components of the latest conceptualization of the aquifer, was needed.

To develop a new, comprehensive model, a study was done during 2000–03 by the USGS and The University of Texas at Austin, Bureau of Economic Geology, in cooperation with the U.S. Department of Defense and the EAA. The objective of this study was to improve understanding of the complex hydrogeologic processes that control water availability of the Edwards aquifer in the San Antonio area through the development, calibration, and testing of a numerical groundwater flow model to optimize resource management. To accomplish this, all available and pertinent hydrogeologic data were compiled and organized into a comprehensive, digital-based system of data storage and retrieval. The new Edwards aquifer numerical groundwater flow model developed in this study (hereinafter, the MODFLOW conduit-flow Edwards aquifer model [model no. 2 of 6, p. 2]) (Lindgren and others, 2004) incorporates improvements over previous models by using (1) a user-friendly interface, (2) updated computer codes (MODFLOW–96 [Harbaugh and McDonald, 1996] and MODFLOW–2000 [Harbaugh and others, 2000]), (3) a finer grid resolution, (4) less-restrictive boundary conditions, (5) an improved discretization of hydraulic conductivity, (6) more accurate estimates of pumping stresses, (7) a long transient simulation period (54 years, 1947–2000), and (8) a refined representation of high-permeability zones or conduits.

The most problematic issue regarding the use of numerical groundwater flow models for delineating contributing areas for PWS wells involves determining the extent and hydraulic influence of karst development in the Edwards aquifer. The aquifer can be conceptualized as having triple porosity and permeability because of the presence of intergranular pores, fractures, and various solutional openings ranging in size from vugs to conduits several meters in diameter (Worthington, 2003). The presence and hydrologic influence of well-integrated, large-diameter conduits is reflected by the presence of large karst springs that discharge from the aquifer and by dye-tracer test results. Local dye-tracer tests and hydrogeologic mapping studies (for example, Worthington, 2003; Hunt and others, 2005; Hunt and others, 2006) have shown that well-integrated conduit networks are important hydraulic components of the aquifer system near the regional discharge

Table 1. Comparison of model software and extent, simulation time periods, and model structure and hydraulic properties for the numerical groundwater flow models for the Edwards aquifer, south-central Texas.

[GAM, Groundwater Availability Modeling; DCM, dual conductivity model; --, not applicable or data not available; mi, miles; ft, feet; mg/L, milligrams per liter; Kx, horizontal hydraulic conductivity; ft/d, feet per day; Ky, vertical hydraulic conductivity]

Model feature/attribute	GWSIM model	MODFLOW conduit-flow Edwards aquifer model	MODFLOW diffuse-flow Edwards aquifer	Barton Springs segment GAM model (MODFLOW)	Barton Springs segment recalibrated GAM model (MODFLOW)	MODFLOW–DCM conduit model
Model software and extent						
Model code	FORTRAN	MODFLOW	MODFLOW	MODFLOW–96	MODFLOW–96	MODFLOW–DCM
Pre- and post-processor	--	Groundwater Vistas	Groundwater Vistas	PMWIN	PMWIN	--
Model extent	San Antonio segment	San Antonio and Barton Springs segments	San Antonio and Barton Springs segments	Barton Springs segment	Barton Springs segment	Barton Springs segment
Simulation time periods						
Steady-state	Average recharge and pumpage 1944–46	Average conditions; 1939–46	Average conditions; 1939–46	Average recharge for 1979–98; monthly pumpage at 1989 rates	--	Average recharge for 1979–98; monthly pumpage at 1989 rates
Transient	Calibration; 1947–59; monthly stress periods Verification; 1978–89; monthly stress periods	Monthly stress periods; 1947–2000	Monthly stress periods; 1947–2000	Monthly stress periods; 1989–98	Monthly stress periods; 1950–59	Monthly stress periods; 1989–98
Model structure and hydraulic properties						
Grid rows and columns	31 rows; 80 columns	370 rows; 700 columns	370 rows; 700 columns	120 rows; 120 columns	120 rows; 120 columns	120 rows; 120 columns
Grid cell dimensions	Variable: 0.90 to 5.0 mi	1,320 by 1,320 ft	1,320 by 1,320 ft	1,000 ft long by 500 ft wide	1,000 ft long by 500 ft wide	1,000 ft long by 500 ft wide
Grid rotation	26.75 degrees from horizontal	35 degrees from horizontal	35 degrees from horizontal	45 degrees from horizontal	45 degrees from horizontal	45 degrees from horizontal
Number of layers	1	1	1	1	1	2 (diffuse and conduit)
Southern model boundary	1,000-mg/L dissolved solids concentration line	10,000-mg/L dissolved solids concentration line	10,000-mg/L dissolved solids concentration line	1,000-mg/L dissolved solids concentration line	1,000-mg/L dissolved solids concentration line	1,000-mg/L dissolved solids concentration line
Hydraulic conductivity (K) distribution	Varies by cell; Kx range 0.13 to 23,727 ft/d, Ky range 0.13 to 10,027 ft/d	Diffuse: varies by cell, range 1 to 7,347 ft/d Conduit cells: range 1,000 to 300,000 ft/d	38 zones; range 3 to 50,000 ft/d	10 zones; range 1 to 1,236 ft/d	12 zones; range 0.3 to 740 ft/d	For 14 conduits: range 1,000 to 160,000 ft/d
Storativity	--	--	--	--	--	--
Specific yield	2 zones; 0.05 and 0.06	5 zones; range 0.005 to 0.15	5 zones; range 0.005 to 0.15	0.005	0.0021	10^{-3} in conduits; $3.0x10^{-3}$ in diffuse system
Specific storage	Varies by cell; range $5.0x10^{-7}$ to $9.25x10^{-7}$ ft^{-1}	5 zones; range $5.0x10^{-7}$ to $5.0x10^{-6}$ ft^{-1}	5 zones; range $5.0x10^{-7}$ to $5.0x10^{-6}$ ft^{-1}	$5.0x10^{-6}$ ft^{-1}	$5.0x10^{-7}$ ft^{-1}	10-5 ft^{-1} in conduits; $3.0x10^{-5}$ ft^{-1} in diffuse system

areas such as Comal Springs for the San Antonio segment and Barton Springs for the Barton Springs segment. Conduits also are important features controlling the subsurface diversion (or piracy) of surface streams along the recharge area of the Edwards aquifer. Most well-developed conduits seem to be aligned not with major faults of the Balcones fault zone (fig. 1) but rather with northwest-southeast trending fractures and cross faults (Faith and others, 2005). A regionally extensive system of high-permeability zones—likely influenced by the presence of conduits—is defined by broad troughs in the potentiometric surface of the freshwater zone of the Edwards aquifer (Lindgren and others, 2004).

The conceptualization that served as the basis for the MODFLOW conduit-flow Edwards aquifer model emphasizes the presence of discrete conduit-dominated flow paths through the aquifer. Because the use of a distributed, porous-media model such as MODFLOW (Harbaugh and others, 2000) is not well suited for the simulation of rapid, turbulent conduit flow, the application of this model to simulate hydraulic heads and groundwater flow requires considerable simplification of the karst aquifer system. Rather than applying a coupled-continuum pipe flow or dual-porosity or triple-porosity model conceptualization (Birk and others, 2003; Liedl and others, 2003), the MODFLOW conduit-flow Edwards aquifer model represents inferred conduit-dominated flow paths as narrow (one-cell, 0.25-mile wide), continuously connected zones of large hydraulic conductivity (Lindgren and others, 2004). Even this simplified conceptualization is subject to considerable uncertainty because the extent to which large conduits permeate the aquifer, their distribution and integration into subsurface drainage networks, and their influence over the hydraulics of the aquifer at local-to-regional scales remain relatively unknown and poorly characterized in much of the aquifer.

The locations of conduit-dominated high-permeability zones applied in the MODFLOW conduit-flow Edwards aquifer model were inferred from data and interpretations described by Worthington (2003) and are subject to some uncertainty. The effect of the uncertainty regarding the locations of conduits becomes more important as the size of the area of interest decreases or, in other words, as the scale of the simulation decreases. Uncertainty also exists regarding the physical dimensions, connectivity, and hydraulic properties of conduits. The physical dimensions of the high-permeability zones in the MODFLOW conduit-flow Edwards aquifer model are constrained by the model cell dimensions, with most conduits much smaller than the 0.25-mile dimensions of the model cells.

An alternative 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. Previous studies of the distribution of permeability provide support for the application of this conceptual model. For example, a statistical analysis done by Halihan and others (2000) indicated that conduits do not seem to contribute appreciably to the average permeability measured in most Edwards aquifer wells, and results of a study by Worthington (2003) estimate the likelihood that wells intersect large conduits at 2 percent or less. Therefore, the diffuse-flow conceptualization might serve as an acceptable means of using a numerical model to delineate contributing areas for most PWS wells.

Previous porous-media groundwater flow models created for the Edwards aquifer have applied a similar conceptualization of hydraulic characteristics (Klemt and others, 1979; Maclay and Land, 1988; Thorkildsen and McElhaney, 1992; Scanlon and others, 2002), as have models created for other karst aquifers that have been used to simulate measured fluctuations in water levels in wells and springflows (for example, the aquifers of the Floridan aquifer system [Bush and Johnston, 1988; Knowles and others, 2002; Sepulveda, 2002; Payne and others, 2005]).

The uncertainties inherent in simulating conduits as one-cell-wide, continuously connected features resulted in incorporating an alternative hydraulic conductivity distribution in the Edwards aquifer model. To develop an alternative hydraulic conductivity distribution for the Edwards aquifer model, a study was done during 2004–05 by the USGS, in cooperation with the San Antonio Water System. The objectives of this study were to (1) modify the hydraulic conductivity distribution of the MODFLOW conduit-flow Edwards aquifer model, including broad zones of upscaled hydraulic conductivity, and (2) compare the hydrographs and residuals (differences between model-computed and measured values) for hydraulic heads and springflows for the MODFLOW conduit-flow Edwards aquifer model with simulated one-cell-wide conduits and the alternative Edwards aquifer model with the broad zones of upscaled hydraulic conductivity (hereinafter, the MODFLOW diffuse-flow Edwards aquifer model [model no. 3 of 6, p. 2]) (Lindgren, 2006). The alternative hydraulic conductivity distribution incorporates the diffuse-flow conceptualization of the aquifer system, with more emphasis on small conduit and fracture flow and less emphasis on large, interconnected conduit flow.

Although the Barton Springs segment of the aquifer is included in the MODFLOW conduit-flow and diffuse-flow Edwards aquifer models, calibration was not done for the northern part of the segment (Travis County). A numerical finite-difference groundwater flow model had recently been completed for the Barton Springs segment (Scanlon and others, 2002), and a duplication of that work was not considered necessary. Calibration was done in the southern part of the Barton Springs segment (northern Hays County), however, because the simulated hydraulic heads and flows in that area influenced the location of the groundwater divide near Kyle (the feature that separates the San Antonio segment from the Barton Springs segment) and the simulated hydraulic heads and flows in the adjoining part of the San Antonio segment of the aquifer.

Barton Springs Segment

A MODFLOW groundwater flow model of the Barton Springs segment of the Edwards aquifer (hereinafter, the Barton Springs segment GAM model [model no. 4 of 6, p. 4]) (Scanlon and others, 2002) was developed as a part of the Texas Groundwater Availability Modeling (GAM) program. The purpose of the Barton Springs segment GAM model was to provide (1) a management tool to the Barton Springs/Edwards Aquifer Conservation District (BSEACD) and to the Regional Water Planning Group[1] and (2) a tool for evaluating groundwater availability under drought-of-record conditions. The Barton Springs segment GAM model was calibrated (1) for steady-state conditions using average recharge for a 20-year period (1979–98) and pumpage at 1989 rates and (2) for transient conditions for the 10-year period 1989–98, with monthly stress periods. Predictive simulations of water levels and springflows for the next 50 years (through 2050) also were done on the basis of projected demands from the Regional Water Planning Group and the BSEACD. The Barton Springs segment GAM model uses streamflow and streamflow-loss data to estimate groundwater recharge for the transient period 1989–98. Predictive simulations were based on 1950s drought (drought-of-record) conditions for which no recharge data are available. For the predictive simulations, recharge was assumed equal to springflow. Because of this assumption, recharge might be slightly overestimated during periods of low recharge because some of the water discharged might be from aquifer storage rather than directly from recharge (Scanlon and others, 2002).

The Barton Springs segment GAM model was constructed to match water levels and springflows from a period wetter than that of the 1950s drought. Because the model was calibrated to a relatively wet period, it overestimates springflows and underestimates water-level altitudes compared with measurements collected during the 1950s drought-of-record. The model was recalibrated so that simulated and measured springflow and water-level data from the 1950s drought matched better. The recalibrated model (hereinafter, the Barton Springs segment recalibrated GAM model [model no. 5 of 6, p. 4]) (Smith and Hunt, 2004) was then used to predict springflow and water-level declines under 1950s drought conditions and various future pumping scenarios.

Incremental changes, through trial and error, were made for the Barton Springs segment recalibrated GAM model to specific yield, specific storage, and hydraulic conductivity values to recalibrate the transient part of the Barton Springs segment GAM model to 1950s drought conditions, resulting in the MODFLOW model of the Barton Springs segment of Edwards aquifer for drought conditions. Adjustments were made to model input data until simulated springflows and water levels closely matched measured springflows and water levels from the 1950s drought. By the end of the recalibration, specific yield was decreased from 0.005 to 0.0021, and hydraulic conductivity ranged from 0.3 to 740 feet per day, compared with a range of 1 to 1,236 feet per day for the Barton Springs segment GAM model. Simulated hydraulic conductivity and storativity values under 1950s drought conditions were lower (compared to those of the Barton Springs segment GAM model) because of lower simulated hydraulic heads in the aquifer. Dissolution of the limestone and consequent conduit development are greater in the shallow part of the aquifer than at greater depths (Ogden and others, 1986; Maclay, 1995; Small and others, 1996). Therefore, lower hydraulic conductivity and storage values are associated with the deeper part of the aquifer, as compared to the shallower part. Additionally, specific-capacity tests have been done in one well in the Barton Springs segment during high- and low-flow conditions. Results indicated that hydraulic property values were lower under low-flow conditions (Smith and Hunt, 2004). As for the Barton Springs segment GAM model, recharge for the Barton Springs segment recalibrated GAM model transient calibration (1950s drought conditions) was assumed to be equal to springflow.

Neither the Barton Springs segment GAM model nor the Barton Springs segment recalibrated GAM model are capable of adequately simulating a wide range of hydrologic conditions (that is, from drought conditions to abnormally wet conditions). A likely explanation for this limitation is the inherent assumption of using Darcy's law within single-continuum models to simulate a dynamic karst system (Painter and others, 2007) where groundwater flow might be laminar or turbulent. A revised model of the Barton Springs segment was constructed using MODFLOW–DCM version 2.0 software to match water-level and springflow hydrographs for drought and abnormally wet conditions (hereinafter, MODFLOW–DCM conduit model [model no. 6 of 6, p. 4]) (Painter and others, 2007). MODFLOW–DCM version 2.0 incorporates a solver capable of solving the highly nonlinear systems associated with the conduit/matrix flow regime under confined/unconfined conditions. Because of data requirements associated with this solver, the dual conductivity model (DCM) could not be implemented in MODFLOW as a self-contained package, and the new variant, MODFLOW–DCM version 2.0, was created (Painter and others, 2007). The Barton Springs segment GAM model was converted to a MODFLOW–DCM model by (1) adding a conduit layer, (2) reducing hydraulic conductivity in the zones of high hydraulic conductivity to values more typical for a diffuse-flow system, and (3) increasing storativity in the diffuse-flow system to values more typical for a diffuse-flow system (Painter and others, 2007). Steps 2 and 3 were necessary because most of the flow and all of the fast flow is accounted for in the simulated conduit system, which is composed of 14 conduit segments. The locations of major groundwater flow paths inferred from the dye-tracer studies of Hauwert and others (2002) and Hunt and others (2006) were used to constrain conduit placement in the model, and inferred conduits also were located so as to intercept focused recharge

[1] Entity responsible for preparing and adopting a regional water plan for the local area per Senate Bill 1 of the 75th Texas Legislature (Texas Water Development Board, 2009).

contributed to the aquifer by sinking surface streams. Because most of the flow and all of the fast flow is in the conduit system, rapid springflow response can be achieved by assigning relatively small values to the conduit storage properties. The storage properties for the diffuse system can then be adjusted so that hydraulic heads match the relatively subdued water-level hydrographs. The MODFLOW–DCM conduit model was calibrated for steady-state conditions using the steady-state recharge and pumping data from the Barton Springs segment GAM model. The MODFLOW–DCM conduit model was calibrated for transient conditions for the 10-year period 1989–98, with monthly stress periods, as was the Barton Springs segment GAM model.

Evaluation of Numerical Groundwater Flow Models

The evaluation of the six groundwater flow models of the San Antonio or Barton Springs segments of the Edwards aquifer, or both, includes a comparison of (1) accessibility and ease of use of the model code and model input and output files, (2) range of hydrologic conditions simulated by the model, (3) accuracy of the simulations, (4) agreement with dye-tracing studies, and (5) limitations of the models.

Accessibility and Ease of Use

The GWSIM model code is not commercially available, is limited in its application to the San Antonio segment of the Edwards aquifer, and lacks the ability of MODFLOW to easily incorporate newly developed processes and packages to better simulate hydrologic processes. MODFLOW is a widely used and tested code for numerical modeling of groundwater flow, is well documented, and is in the public domain. These attributes make MODFLOW a preferred code with regard to accessibility and ease of use. The MODFLOW–DCM code currently (2008) has been used and tested only for the Barton Springs segment of the Edwards aquifer and the Santa Fe River Sink/Rise system in the Floridan aquifer (Painter and others, 2007) and therefore lacks the wide use and testing associated with the MODFLOW code.

A variety of pre- and post-processors have been developed to facilitate data entry and allow analysis of model output. The GWSIM model has not been adapted for any commercially available pre- and post-processors. The software Groundwater Vistas version 3.0 (Environmental Simulations, Inc., 2002) was used as a pre- and post-processor to facilitate data entry and allow analysis of model output for the MODFLOW conduit-flow and diffuse-flow Edwards aquifer models. The Barton Springs segment GAM and recalibrated GAM models used the software Processing MODFLOW for Windows (PMWIN) version 5.0.54 (Chiang and Kinzelbach, 1998) and version 5.1.7 (Chiang and Kinzelbach, 2001), respectively. The addition of a Groundwater Vistas graphical user interface (GUI) for MODFLOW–DCM was coordinated with Environmental Simulations, Inc., and final implementation of the GUI was completed as part of a separate karst modeling project with the University of Florida (Painter and others, 2007). However, the Groundwater Vistas GUI for MODFLOW–DCM currently (2008) is not commercially available. The lack of any commercially available pre- and post-processors for the GWSIM model and the MODFLOW–DCM conduit model is a disadvantage of these models with regard to ease of use.

Range of Hydrologic Conditions Simulated

The GWSIM model was initially calibrated for transient conditions for a 25-year time period, 1947–71 (Klemt and others, 1979). Stress-period lengths, pumpage rates, recharge rates and distributions, and model hydraulic properties (transmissivity, storage coefficient, and aquifer anisotropy) were subsequently revised by Thorkildsen and McElhaney (1992). The revised GWSIM model (Thorkildsen and McElhaney, 1992) was calibrated for transient conditions for two separate time periods, 1947–59 and 1978–89.

The MODFLOW conduit-flow and diffuse-flow Edwards aquifer models were calibrated for transient conditions for a relatively long time period of 54 years (1947–2000). This time period included the drought-of-record during the 1950s as well as annual recharge to the San Antonio segment of the Edwards aquifer during 1992 (2,486,000 acre-feet) that was about 3.5 times the long-term (1934–2002) mean annual recharge (698,930 acre-feet) (Hamilton and others, 2003).

The Barton Springs segment GAM model and the MODFLOW–DCM conduit model were calibrated for transient conditions for a relatively short time period of 10 years (1989–98). The Barton Springs segment recalibrated GAM model was calibrated for transient conditions for a 10-year time period (1950–59) during the 1950s drought-of-record. The Barton Springs segment GAM model was calibrated for a time period most representative of average to abnormally wet hydrologic conditions. Conversely, the Barton Springs segment recalibrated GAM model was calibrated for a time period representative of drought conditions, with a resulting different set of calibrated hydraulic conductivity and storativity values. Hypothetical drought conditions were simulated using the MODFLOW–DCM conduit model by starting with a calibrated steady-state model and then eliminating recharge for a 5-year period (Painter and others, 2007). The simulations adequately represent drought conditions comparable to the 1950s drought-of-record with regard to estimated recharge rates and springflows but do not specifically represent the historical drought period.

The MODFLOW conduit-flow and diffuse-flow Edwards aquifer models and the MODFLOW–DCM conduit model adequately simulate the full range of hydrologic conditions from period-of-record drought conditions to extreme wet conditions (1992) with the same calibrated values for hydraulic properties. In contrast, the transient calibration periods for the GWSIM model and the Barton Springs segment GAM and recalibrated GAM models are relatively short and do not include the full range of hydrologic conditions. The transient calibration period for the GWSIM model does not include extreme wet conditions such as occurred in 1992. The Barton Springs segment GAM model does not include extreme drought conditions such as the 1950s drought, whereas the Barton Springs segment recalibrated GAM model does not include average to extreme wet hydrologic conditions and is restricted to the predominately drought conditions of the 1950s. The relatively short transient calibration periods for the Barton Springs segment GAM and recalibrated GAM models result in two different sets of calibrated values for hydraulic conductivity and storativity that are dependent on the specific hydrologic conditions being simulated. The value and importance of relatively long transient calibration periods that encompass a range of hydrologic conditions is discussed further in the next section of this report, "Accuracy of Simulations."

Accuracy of Simulations

The accuracy of the model simulations was evaluated by comparing the residuals (differences between the simulated and measured values) for hydraulic heads and springflows for the six numerical groundwater flow models. The GWSIM model and the MODFLOW conduit-flow and diffuse-flow Edwards aquifer models are compared for the San Antonio segment of the Edwards aquifer, and the Barton Springs segment GAM and recalibrated GAM models and the MODFLOW–DCM conduit model are compared for the Barton Springs segment.

San Antonio Segment

The goodness of fit between simulated and measured hydraulic heads and springflows can be quantified using the root mean square (RMS) error. The RMS error is derived from the residuals between the measured and simulated hydraulic heads (or springflows), as given below:

$$\mathrm{RMS} = \left[\frac{1}{n} \sum_{i=1}^{n} \left(h_m - h_s \right)_i^2 \right]^{0.5}$$

where

RMS is the root mean square error [L],

n is the number of calibration points,

h_m is the measured hydraulic head (or springflow) at point i [L], and

h_s is the simulated hydraulic head (or springflow) at point i [L].

The RMS error of the residuals and the RMS error as a percentage of the range of the measured values ([RMS error divided by the range of measured values] x 100) for the GWSIM model and the MODFLOW conduit-flow and diffuse-flow Edwards aquifer models are shown in table 2. These statistics are used as quantitative measures of the goodness of fit between the measured and simulated hydraulic heads and springflows. For two synoptic water-level time periods (May–November 1956, drought conditions; November 1974–July 1975, above-normal rainfall) (not applicable for GWSIM model), the RMS error for hydraulic heads for the MODFLOW diffuse-flow Edwards aquifer model are appreciably smaller than those for the MODFLOW conduit-flow Edwards aquifer model (table 2). The RMS errors for the MODFLOW conduit-flow Edwards aquifer model are 76 and 30 percent greater than for the MODFLOW diffuse-flow Edwards aquifer model for the drought conditions and above-normal rainfall synoptic time periods, respectively. The mean RMS error for the 1947–2000 time period for 12 target wells for the MODFLOW conduit-flow and diffuse-flow Edwards aquifer models are similar (14.7 and 15.5 feet, respectively). The mean RMS error for the MODFLOW diffuse-flow Edwards aquifer model is smaller than for the MODFLOW conduit-flow Edwards aquifer model for six of the 12 target wells with long-term water-level measurements. Conversely, the mean RMS error for the MODFLOW diffuse-flow Edwards aquifer model is larger than for the MODFLOW conduit-flow Edwards aquifer model for six of the 12 target wells.

The mean RMS error for the five simulated springs (Comal, San Marcos, Leona, San Antonio, and San Pedro) for the time period 1947–2000 is minimally higher (1.1 cubic feet per second) for the MODFLOW diffuse-flow Edwards aquifer model than for the MODFLOW conduit-flow Edwards aquifer model (table 2). For the same time period, the RMS error is lower (7.1 cubic feet per second) for Comal Springs and higher (1.0 cubic foot per second) for San Marcos Springs for the MODFLOW diffuse-flow Edwards aquifer model than for the MODFLOW conduit-flow Edwards aquifer model. The mean algebraic differences between the simulated and measured springflows indicate that the springflows are lower for all springs, except San Antonio Springs, for the MODFLOW diffuse-flow Edwards aquifer model as compared to the MODFLOW conduit-flow Edwards aquifer model. This, coupled with the observation that greater differences between simulated and measured springflows for the diffuse-flow model than for the conduit-flow model occur during the periods of greatest springflows, might indicate that the MODFLOW diffuse-flow Edwards aquifer model is somewhat less responsive than the MODFLOW conduit-flow Edwards aquifer model (Lindgren, 2006).

Hydraulic heads and springflows simulated by the MODFLOW conduit-flow Edwards aquifer model for selected observation wells and springs were compared to the corresponding hydraulic heads and springflows simulated by the GWSIM model. The time periods used for the comparisons were 1947–59 and 1978–89 because published simulated hydraulic heads and springflows for the GWSIM model were

Table 2. Residual statistics for models of the San Antonio segment of the Edwards aquifer, south-central Texas.

[RMSE, root mean square error between simulated and measured hydraulic heads and springflows; --, not applicable or data not available]

Type of measurement	Time period	Number of wells	Hydraulic head residuals (feet)					
			GWSIM model		MODFLOW conduit-flow model		MODFLOW diffuse-flow model	
			RMSE	(RMSE/range)x100	RMSE	(RMSE/range)x100	RMSE	(RMSE/range)x100
Synoptic	May–November 1956 (drought)	175, 171	--	--	58.7	8.0	33.4	5.0
Synoptic	November 1974–July 1975 (above normal)	172, 169	--	--	33.5	5.0	25.8	4.0
Hydrographs	1947–59	1 (Bexar Co. index well)	7.4	11.3	5.2	7.9	--	--
Hydrographs	1978–89	1 (Bexar Co. index well)	12.7	18.4	9.9	14.5	--	--
Hydrographs	1978–89	26	17.4	35.3	26.3	58.1	--	--
Hydrographs	1947–2000	12	--	--	14.7	13.3	15.5	14.5

Spring	Time period	Number of springs	Springflow residuals (cubic feet per second)					
			GWSIM model		MODFLOW conduit-flow model		MODFLOW diffuse-flow model	
			RMSE	(RMSE/range)x100	RMSE	(RMSE/range)x100	RMSE	(RMSE/range)x100
All simulated[1]	1947–2000	5	--	--	27.1	14.3	28.2	15.0
Comal	1947–59	1	60.2	14.8	30.9	7.6	--	--
Comal	1978–89	1	63.0	15.7	58.8	14.7	--	--
Comal	1947–2000	1	--	--	45.9	9.5	38.8	8.1
San Marcos	1947–59	1	43.5	20.2	23.1	10.7	--	--
San Marcos	1978–89	1	68.0	22.8	38.3	12.8	--	--
San Marcos	1947–2000	1	--	--	31.2	7.0	32.2	7.2

[1] Comal, San Marcos, Leona, San Antonio, and San Pedro Springs.

available for these time periods (Thorkildsen and McElhaney, 1992). Comparisons of simulated hydraulic heads and springflows were made for the 1947–59 and 1978–89 periods using the Bexar County index well (J–17) and Comal and San Marcos Springs. Also, hydraulic heads simulated by the MODFLOW conduit-flow Edwards aquifer model for 25 observation wells, in addition to the Bexar County index well, were compared to the corresponding hydraulic heads simulated by the GWSIM model for the 1978–89 time period. Hydraulic heads simulated by the GWSIM model for this time period were provided by LBG-Guyton Associates (Andrew Donnelly, LBG-Guyton Associates, written commun., 2003). Head data from one well (Frio River well 6935501) provided by LBG-Guyton Associates was not used in the comparison between the MODFLOW conduit-flow Edwards aquifer model and the GWSIM model because an accurate location for the well is not available.

The RMS error of the residuals and the RMS error as a percentage of the range of the measured values for the MODFLOW conduit-flow Edwards aquifer model are appreciably smaller than those for the GWSIM model for both time periods (1947–59 and 1978–89) for the Bexar County index well (J–17) and for San Marcos Springs, and for the 1947–59 time period for Comal Springs (table 2). The RMS errors for the Bexar County index well for the GWSIM model are about 42 and 28 percent greater than those for the Edwards aquifer model for the 1947–59 and 1978–89 time periods, respectively. For San Marcos Springs, the RMS errors for the GWSIM model are about 88 and 78 percent greater for the 1947–59 and 1978–89 time periods, respectively. Conversely, the statistical measures for the MODFLOW conduit-flow Edwards aquifer model generally are larger than those for the GWSIM model for the observation wells in and near the recharge zone (unconfined conditions) (Lindgren and others, 2004). The statistical measures for the MODFLOW conduit-flow Edwards aquifer model and the GWSIM model generally are similar for observation wells in the confined zone of the aquifer (Lindgren and others, 2004).

The RMS error in some cases is not a complete measure of the goodness of fit between the measured and simulated hydraulic heads. In the case of three wells, the hydrographs indicate that the MODFLOW conduit-flow Edwards aquifer model more accurately simulates the magnitude and pattern of fluctuations in measured water levels than does the GWSIM model, although the residual statistics are smaller for the GWSIM model than for the MODFLOW conduit-flow Edwards aquifer model (Lindgren and others, 2004).

The goodness of fit between measured and simulated hydraulic heads and springflows also is influenced by the time period of the comparison. Eight of the 26 wells used in the comparison between the MODFLOW conduit-flow Edwards aquifer model and the GWSIM model were used as calibration targets in the MODFLOW conduit-flow Edwards aquifer model for longer time periods (for most wells, 1947–2000) than the 1947–59 and 1978–89 periods (Lindgren and others, 2004). For four of the eight wells, the residual statistics for the MODFLOW conduit-flow Edwards aquifer model were smaller (indicating a closer match between measured and simulated hydraulic heads) for the longer time period than those for the shorter time period. For three of the eight wells, the residual statistics for the MODFLOW conduit-flow Edwards aquifer model for the longer time period were smaller than the residual statistics for the 1978–89 time period for the GWSIM model. The values of RMS error as a percentage of the range of measured values are smaller for the longer time periods because the decreases or comparatively small increases in the RMS errors are coupled with greater ranges in measured hydraulic heads. The residual statistics for the Bexar County index well (J–17) and for Comal and San Marcos Springs for the longer time period are about equal to the average of those for the 1947–59 and 1978–89 time periods. The residual statistics indicate that, in some cases, the goodness of fit for any given time period does not accurately reflect the goodness of fit for a longer time period for which measured hydraulic heads might be available.

To summarize: The comparison of the RMS error and the RMS error as a percentage of the range of measured values for the MODFLOW conduit-flow and diffuse-flow Edwards aquifer models and the GWSIM model indicates some of the differences and comparative strengths and weaknesses of the models. The MODFLOW conduit-flow and diffuse-flow Edwards aquifer models were calibrated for transient conditions for the entire period from 1947–2000, whereas the GWSIM model was calibrated for two separate, much shorter time periods, 1947–59 and 1978–89. As discussed previously, the residual statistics indicate that, in some cases, the goodness of fit for any given time period does not accurately reflect the goodness of fit for a longer time period for which measured hydraulic heads might be available. This illustrates the value and importance of relatively long transient calibration periods that encompass a range of hydrologic conditions and the potential for erroneous conclusions regarding goodness of fit based on comparatively short periods of comparison between measured and simulated hydraulic heads and springflows.

A noteworthy limitation of the GWSIM model is the means used to best match the measured flows for San Marcos Springs. In the GWSIM model, 43 percent of the total basin recharge for the Blanco River Basin was assigned directly to the spring cell representing San Marcos Springs to better simulate the local component of flow from the outcrop area (Thorkildsen and McElhaney, 1992, p. 7). This means of obtaining the best match between measured and simulated flows for San Marcos Springs was not necessary for calibration of the MODFLOW conduit-flow and diffuse-flow Edwards aquifer models. For San Marcos Springs, the RMS errors for the GWSIM model are (as noted previously in this section) about 88 and 78 percent greater for the 1947–59 and 1978–89 time periods, respectively, than for the MODFLOW conduit-flow Edwards aquifer model, despite the application of recharge water directly to the spring cell representing San Marcos Springs.

Barton Springs Segment

The RMS errors for the Barton Springs segment GAM model, recalibrated GAM model, and MODFLOW–DCM conduit model are shown in table 3. These statistics are used as quantitative measures of the goodness of fit between the measured and simulated hydraulic heads and springflows. The RMS error and the RMS error as a percentage of the range of measured values for hydraulic heads for 10 target wells are much smaller for the Barton Springs segment recalibrated GAM model (RMS error of 18.5 feet) than that for the Barton Springs segment GAM model (RMS error of 86.8 feet) for the period including the 1950s drought (1950–59). The RMS error and the RMS error as a percentage of the range of measured values for springflows are similar for the two models for the 1950–59 period as a whole. However, the values of these statistical measures are lower for the Barton Springs segment recalibrated GAM model than for the Barton Springs segment

Table 3. Residual statistics for models of the Barton Springs segment of the Edwards aquifer, south-central Texas.

[GAM, Groundwater Availability Modeling; RMSE, root mean square error between simulated and measured hydraulic heads and springflows; DCM, dual conductivity model; --, not applicable or data not available]

Type of simulation	Type of measurement	Time period	Number of wells	Hydraulic head residuals (feet)					
				GAM model (MODFLOW)		Recalibrated GAM model (MODFLOW)		MODFLOW–DCM conduit model	
				RMSE	(RMSE/ range)x100	RMSE	(RMSE/ range)x100	RMSE	(RMSE/ range)x100
Steady-state	Synoptic	July–August 1999	99, 74	24	7	--	--	16.8	6
Transient	Synoptic	March–April 1994	27	29	11	--	--	--	--
Transient	Synoptic	July–August 1996	23	37	10	--	--	--	--
Transient	Synoptic	July–August 1998	35	64	22	--	--	--	--
Transient	Hydrographs	1989–98	8	3.8–83.7	16–63+	--	--	--	--
Transient	Synoptic	1950–59; lowest measured values	10	86.8	39.1	18.5	8.3	--	--

Type of simulation	Spring	Time period	Number of springs	Springflow residuals (cubic feet per second)					
				GAM model (MODFLOW)		Recalibrated GAM model (MODFLOW)		MODFLOW–DCM conduit model	
				RMSE	(RMSE/ range)x100	RMSE	(RMSE/ range)x100	RMSE	(RMSE/ range)x100
Steady-state	Barton	July–August 1999	1	0	--	--	--	--	--
Transient	Barton	1989–98	1	12	11	--	--	--	--
Transient	Barton	1950–59	1	12.4	21	13.8	23	--	--
Transient	Barton	1950–59; flow less than 18 cubic feet per second	1	9.7	16	6.0	10	--	--

GAM model for the time periods when springflow is less than 18 cubic feet per second (table 3).

Because the Barton Springs segment GAM model was calibrated to a relatively wet period, it tends to overestimate springflows and underestimate water-level altitudes compared with measurements collected during the 1950s drought-of-record. In contrast, the Barton Springs segment recalibrated GAM model was calibrated specifically to better match measured springflow and water-level data from the 1950s drought, resulting in the lower RMS error and RMS error as a percentage of the range of measured values for the Barton Springs segment recalibrated GAM model.

The Barton Springs segment recalibrated GAM model provides a good match between simulated and measured water levels for the 1950s drought conditions during periods of lowest flow, particularly during July and August 1956 (Smith and Hunt, 2004). During periods when recharge increases to near-average conditions, such as in 1953, simulated water-level altitudes in the Barton Springs segment recalibrated GAM model tend to be higher than the measured values. This might be due to the inability of the model to simulate high rates of conduit flow during high water-level conditions. However, the Barton Springs segment recalibrated GAM model succeeds in adequately simulating periods of low flow, such as during 1952 and 1954–56. The lowest monthly mean flow from Barton Springs was 11 cubic feet per second from four flow measurements in July and August 1956 (Slade and others, 1986). Subtracting a pumping rate of 0.66 cubic foot per second from 13.7 cubic feet per second (simulated springflow by the Barton Springs segment GAM model under 1950s drought conditions with no pumping) yields a difference of about 2 cubic feet per second between the Barton Springs segment GAM model results and measured values of springflow. The Barton Springs segment recalibrated GAM model was able to simulate a springflow of 11 cubic feet per second, matching the lowest monthly mean for measured springflow (Smith and Hunt, 2004).

The RMS error and the RMS error as a percentage of the range of measured values for hydraulic heads are smaller for the MODFLOW–DCM conduit model (74 target wells) than for the Barton Springs segment GAM model (99 target wells) for a steady-state simulation representing average conditions for July–August 1999 (table 3). The MODFLOW–DCM conduit model produces substantially lower springflows and better matches to the measured springflows during the peak discharge events in 1992, 1997, and 1998 than does the Barton Springs segment GAM model. The substantially lower peaks during the periods of high recharge are caused by the simulation of turbulent flow in the model (Painter and others, 2007). In the Edwards aquifer, springflow responds very quickly to changes in recharge. In the Barton Springs segment GAM and recalibrated GAM models, this rapid spring response time was reproduced by decreasing specific yield and specific storage in the system. Although this strategy was successful in matching springflow hydrographs, it resulted in water-level hydrographs that are overly responsive (Painter and others, 2007). The Barton Springs segment GAM and recalibrated GAM models (Scanlon and others, 2002; Smith and Hunt, 2004) produce unrealistic rises in hydraulic head at many wells, with the discrepancy as large as 250 feet at one well during 1992 (Painter and others, 2007). The MODFLOW–DCM conduit model produces a much more subdued water-level hydrograph that better matches the observed water levels. This ability to match both the rapid spring response and the more subdued water-level hydrographs demonstrates the inherent flexibility in the MODFLOW–DCM conduit model to match both low base flows and large spring discharges (Painter and others, 2007).

To summarize: The inherent limitation of the Barton Springs segment GAM and recalibrated GAM models is that they were each calibrated to match measured water levels and springflows for a relatively narrow range of hydrologic conditions. The Barton Springs segment GAM model has calibrated hydraulic conductivity and storativity values that are appropriate for (and best match water levels and springflows for) average and above-average precipitation and recharge conditions. The Barton Springs segment recalibrated GAM model has calibrated hydraulic conductivity and storativity values that are appropriate for (and best match water levels and springflows for) low precipitation and recharge (drought) conditions. Simulated hydraulic conductivity and storativity values for the aquifer under 1950s drought conditions were expected to be lower (as compared to those of the Barton Springs segment GAM model) (Smith and Hunt, 2004) because of differences in the simulated hydrologic conditions and the resulting lower simulated hydraulic heads for the Barton Springs segment recalibrated GAM model. However, the inability of either model to adequately match measured water levels and springflows under differing hydrologic conditions is a substantial limitation, which increases the uncertainty of the simulated results.

The principal advantage of the MODFLOW–DCM conduit model is the ability to adequately simulate measured water levels and springflows for the full range of hydrologic conditions (above-average precipitation and recharge conditions and drought conditions) using the same set of hydraulic properties (hydraulic conductivity and storativity).

Agreement with Dye-Tracer Tests

Many of the capabilities, limitations, and modifications of the various models relative to their handling of karst characteristics have already been described in the preceding sections. One of the continuing points of debate regarding the application of these models to Edwards aquifer well assessments is in regard to the accuracy of model-derived groundwater flow directions and perceived discrepancies between simulated and tracer-inferred flow characteristics. At issue is the predictive capability, that is, how well do model-derived flow paths predict actual groundwater flow directions in parts of the aquifer that are conduit dominated? To make this determination objectively, it would be necessary to design a study wherein a targeted series of dye-tracer tests were conducted to test flow directions predicted by model output (particle tracking) in various parts of the aquifer under specified hydrologic conditions. Given the scarcity of existing tracer-inferred flow paths, variability in the timing and hydrologic conditions under which dye-tracer tests have been conducted, and relative lack of one-to-one correlation between the time periods during which tracer tests have been conducted and model-simulated stress periods, only relatively broad generalizations can be made with regard to agreement between model output and dye-tracer tests.

Groundwater Flow Directions

As noted, dye-tracer test data are relatively sparse or lacking in many parts of the Edwards aquifer. For this evaluation, groundwater flow directions inferred from model outputs (simulated potentiometric surfaces) were compared with tracer-inferred flow paths obtained from dye-tracer tests conducted in the San Antonio and Barton Springs segments of the Edwards aquifer during 1996–2002 and 2005 (Worthington, 2003; Schindel and others, 2005; Hunt and others, 2006). Additional data obtained from several unpublished dye-tracer tests conducted during 2004–05 in the San Marcos Springs

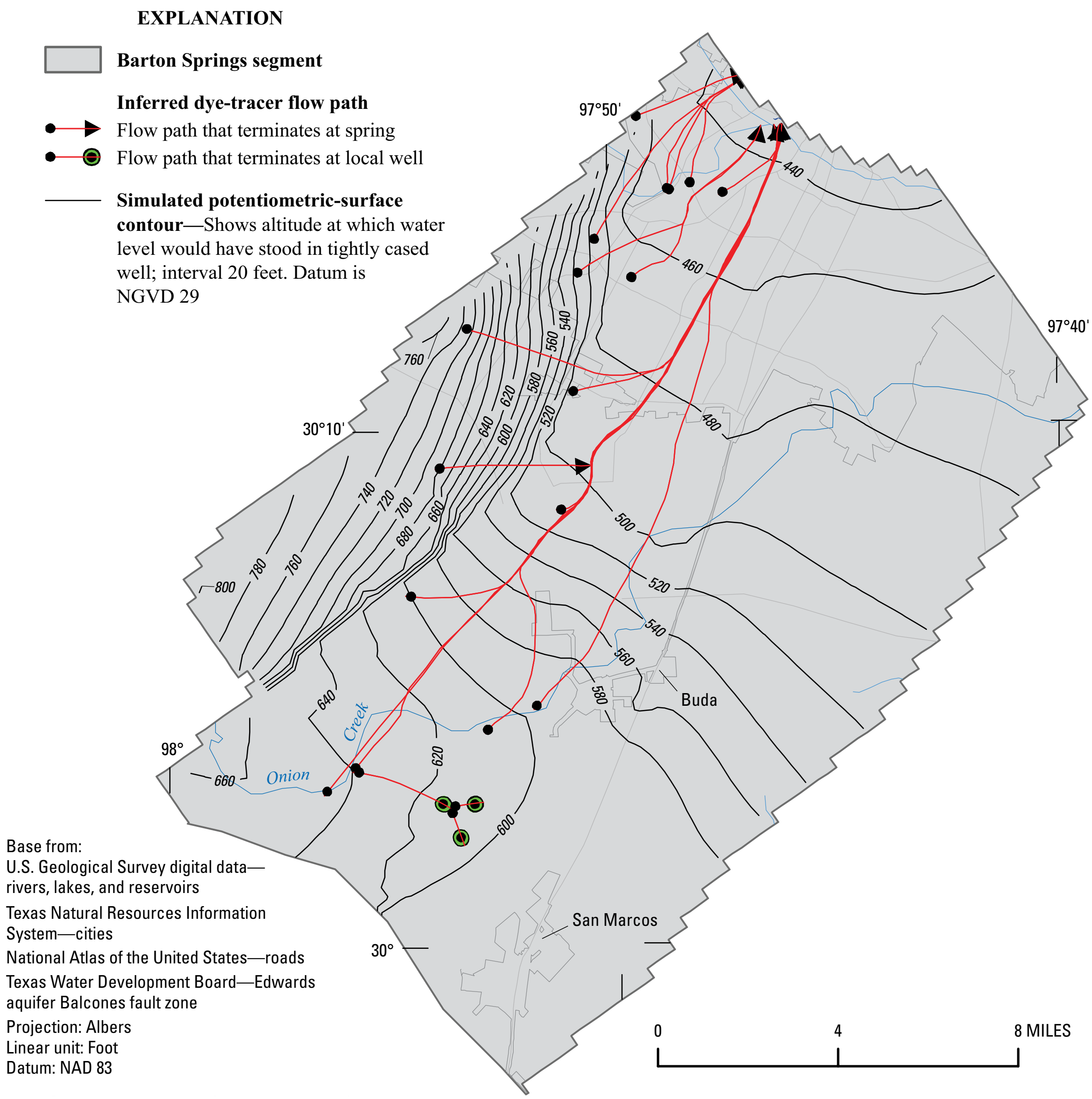

Figure 2. Comparison of inferred dye-tracer flow paths in the Barton Springs segment of the Edwards aquifer, south-central Texas, with simulated potentiometric-surface contours for September 1998 derived from the MODFLOW conduit-flow Edwards aquifer model.

area in the San Antonio segment were provided for evaluation by the EAA (Steven Johnson, Edwards Aquifer Authority, written commun., 2008). Results of approximately 20 dye injections conducted in the Barton Springs segment have been plotted as curvilinear dye flow paths that conform to gradients of mapped potentiometric-surface contours and illustrate conjectured tributary junctions between individual conduit-dominated flow paths (fig. 2).

In other locations, previously reported dye-tracer test results have been plotted as straight-line vectors used solely to represent the point-to-point connections between dye injection sites and dye recovery or dye detection sites (fig. 3). The trajectories, distances, and apparent upstream sources and downstream receptors of water represented by these dye-tracer flow paths are constrained by the time period and detection method used during the individual dye-tracer tests and by the numbers and locations of dye injection and dye recovery sites.

Ideally the comparison between tracer-inferred flow paths and model-derived flow paths would be conducted under the same hydrologic conditions. Most of the reported dye-tracer tests have been conducted under high-flow hydrologic conditions. For the present evaluation, dye-tracer flow paths were compared with simulated potentiometric surfaces obtained from the MODFLOW conduit-flow and diffuse-flow Edwards aquifer models for the September 1998 model stress period, assumed to be representative of average hydrologic conditions (fig. 2), or with simulated particle tracks derived from output of steady-state conditions (1939–46 time period) (fig. 3). These two models include the San Antonio and Barton Springs segments of the Edwards aquifer and adequately

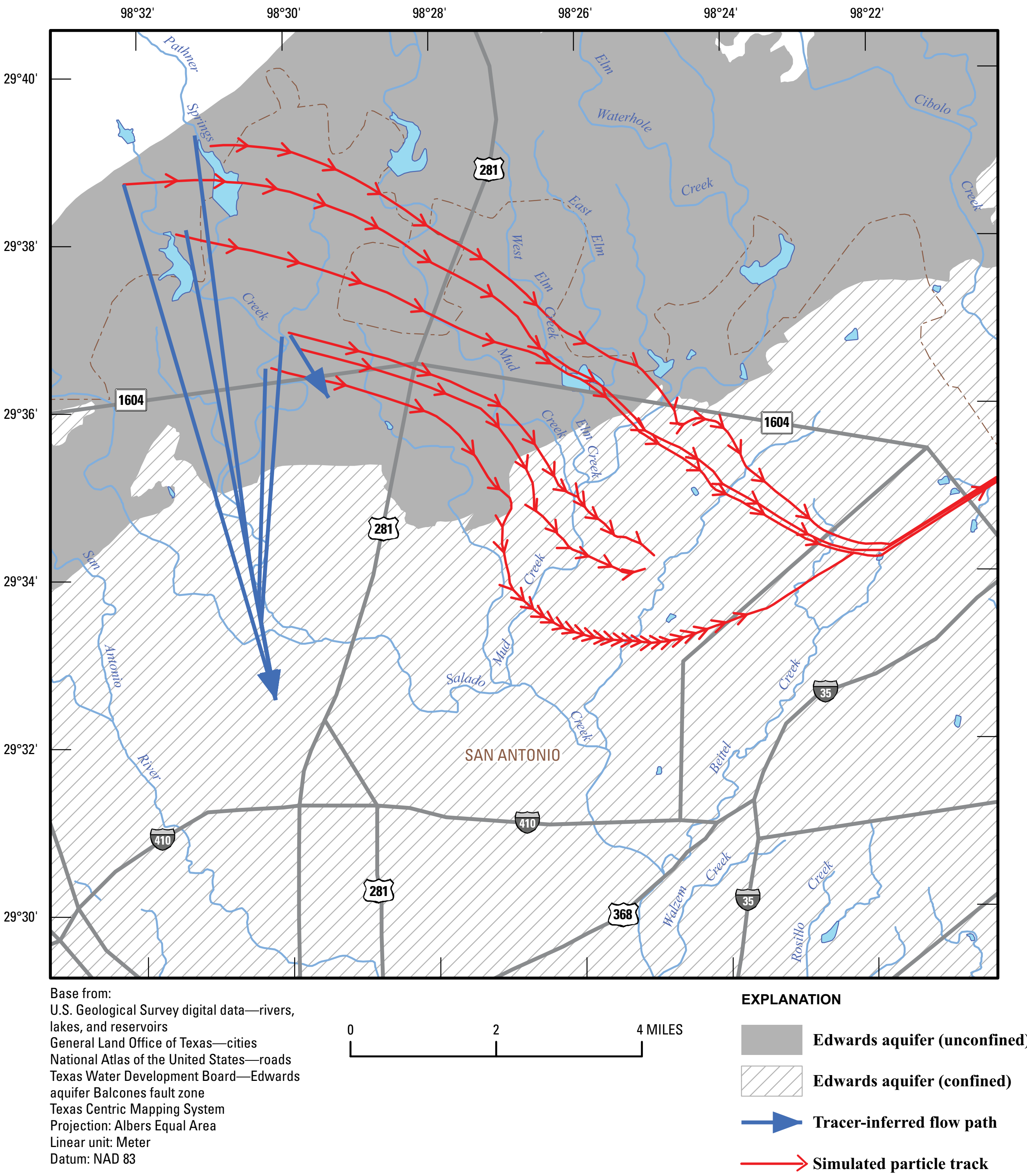

Figure 3. Comparison of inferred dye-tracer flow paths and simulated particle tracks derived from output of MODFLOW conduit-flow model of steady-state conditions (1939–46 time period) in the San Antonio segment of the Edwards aquifer, northern Bexar County, south-central Texas (modified from Steven Johnson, Edwards Aquifer Authority, written commun., 2008).

simulate hydraulic heads and springflows for the full range of hydrologic conditions, except for the eastern part of the Barton Springs segment. For the eastern part of the Barton Springs segment of the aquifer, the MODFLOW conduit-flow and diffuse-flow Edwards aquifer models incorporate the hydraulic properties from the Barton Springs segment GAM model and, therefore, share the limitations of that model for that part of the model area. The hydraulic heads, and particularly the springflows, are poorly simulated for drought conditions. However, the Barton Springs segment GAM model does adequately simulate hydraulic heads and springflows for average and high-flow hydrologic conditions, consistent with the hydrologic conditions for most of the dye-tracer tests.

As a general observation, wherever the models accurately simulate the locations and configurations of major potentiometric-surface troughs and groundwater divides, a good general agreement between model-inferred and tracer-inferred groundwater flow directions can be observed. In the Barton Springs segment, relatively good agreement is observed between output from the MODFLOW conduit-flow and diffuse-flow Edwards aquifer models and plotted dye-tracer flow paths. Here, groundwater flow directions indicated by both model outputs and dye-tracer tests are largely influenced by the presence of a major east-northeast-trending potentiometric-surface trough (fig. 2). In karstic carbonate aquifers, such groundwater troughs generally are coincident with the locations of major conduit drains, zones of enhanced fracture or solution permeability, or some combination of these. A relatively high density of dye-tracer injections conducted in the Barton Springs segment confirms that flow directions in the aquifer follow the slope of hydraulic head gradients that define the presence of the trough. The MODFLOW conduit-flow and diffuse-flow Edwards aquifer models incorporate known and conjectured conduit-dominated flow paths through the Barton Springs segment as zones of higher hydraulic conductivity, as does the Barton Springs segment GAM model, and effectively replicate the configuration of the groundwater trough. The models therefore yield potentiometric-surface contours that match quite well with tracer-inferred flow paths delineated in the Barton Springs segment (fig. 2).

In other locations where groundwater flow directions inferred by MODFLOW conduit-flow and diffuse-flow Edwards aquifer model output show a general agreement with results of dye-tracer tests, it is uncertain to unlikely that interpretations of model output alone, or made prior to data obtained by dye tracing, are sufficient to predict complex, local flow directions in the aquifer. Results of dye-tracer tests conducted in 2005 in the Barton Springs segment and groundwater flow model simulations (Lindgren and others, 2004) indicated the presence of a groundwater divide separating the Barton Springs and San Antonio segments that had been inferred from previous dye-tracer tests conducted in 2002 (Hunt and others, 2005; Hunt and others, 2006). However, the 2005 dye-tracer test results also provided evidence indicating that the position of the groundwater divide might fluctuate in response to changes in local hydrologic conditions (Hunt and others, 2006). During periods of relatively low flow conditions such as those occurring in 2005, the groundwater divide seems to disappear as water levels in wells near San Marcos Springs decrease to altitudes lower than the altitude of the spring pool, implying that, under these conditions, groundwater might flow north across the divide and toward Barton Springs. Similarly, transient groundwater flow model simulations for 1947–2000 (Lindgren and others, 2004) indicated that during drought conditions the position of the groundwater divide shifts westward to near San Marcos Springs, and recharge from the Blanco River moves eastward toward Barton Springs, rather than westward toward San Marcos Springs.

Hydraulic heads in the aquifer are influenced by the amount of water recharging at major karst features such as sinking streams, and local mounding of the potentiometric surface in the vicinity of such recharge features in the San Antonio segment has been observed under high flow conditions (Hunt and others, 2005). Both the 2002 and 2005 dye-tracer tests were conducted during periods of relatively high flow conditions in the aquifer. However, the flow conditions in 2002 were judged to have been higher than those during the 2005 dye injections (Hunt and others, 2006). Substantially lower flows in the Blanco River (fig. 1) and Onion Creek (fig. 2)—two losing or sinking streams in the study area—during 2005 compared to 2002 are thought to have resulted in a reduction of local recharge, decrease of hydraulic heads, and decrease in hydraulic gradients across the groundwater divide in this part of the aquifer. The complexity of groundwater flow directions and hydraulic response in this part of the aquifer could not have been deduced from the regional-scale MODFLOW conduit-flow and diffuse-flow Edwards aquifer models, even though some arching or mounding of the simulated potentiometric surface is recognizable around the 600- to 620-foot contours on the map in figure 2. In karst aquifers where temporal variations in conduit-dominated flow paths are likely to occur, identification and confirmation of flow complexities such as the bifurcation of local flow paths are best made using results of dye-tracer tests and are not likely to be determined on the basis of model-generated potentiometric-surface gradients.

In other locations where Edwards aquifer karst characteristics are not as well characterized and thus not adequately represented by model input data, agreement between model output and tracer-inferred flow paths are not particularly good and are sometimes subject to error. This is illustrated in a part of the Panther Springs Creek Basin of the San Antonio segment where predictions of flow directions in the aquifer in this area are complicated by the presence of faults and uncertainties regarding possible direction and extent of solutional conduit development. There, groundwater flow paths generated by output from the MODFLOW conduit-flow Edwards aquifer model differ considerably from tracer-inferred flow paths (fig. 3) obtained by dye injections conducted during 2004–05 from various well locations in Bexar County (Johnson and others, in press). The tracer-inferred flow paths indicate that groundwater flows south, apparently crossing a series of east-west-trending fault traces (not shown in fig. 3) (Schindel and others, 2005). The apparent trends of the tracer-inferred flow paths are oriented almost orthogonally to the trends of the mapped fault traces and to the simulated groundwater flow paths predicted by the MODFLOW output (Johnson and others, in press). An additional complication is that natural hydraulic gradients in this area have been altered by large withdrawals from San Antonio water-supply wells. Although the tracer-inferred flow directions in the aquifer were not predicted by simulation, model calibration results reported by Lindgren (2004) indicate that major groundwater conduits with relatively high hydraulic capacity might exist in northern Bexar County. Specifically, large positive head residuals resulted from simulations in that area. Therefore, the model probably underrepresents the number of conduit-dominated flow paths or hydraulic influence of conduit-dominated flow paths, or both, in that area.

Tracer-Inferred Groundwater Flow Velocities

The issue of numerically estimated groundwater flow velocities and travel times deserves consideration, for it is this issue that highlights the greatest apparent disparity between model output and dye-tracer test results. The use of a distributed, porous media model to simulate flow in a karst system requires simplification of aquifer hydraulic characteristics, and except for the MODFLOW–DCM model, all models reviewed here apply Darcian flow equations and are incapable of simulating the rapid, turbulent flow conditions likely prevalent along conduit-dominated flow paths. Time-of-travel obtained by the existing numerical groundwater flow models and the SWAP methodology is almost certainly overestimated (is too long) for parts of the aquifer where conduit-dominated flow occurs. Dye-tracer tests conducted in the Edwards aquifer routinely yield results indicating flow velocities of thousands of feet per day, whereas the maximum flow velocities obtained in the numerical simulations typically are two to three orders of magnitude lower. PWS well assessments done using the SWAP–DSS software apply a standardized 27-foot per day average flow velocity, a value based on literature-reported velocities obtained by methods other than tracer tests (R.L. Ulery, U.S. Geological Survey, written commun., 2008). This average flow velocity is in marked contrast with velocity ranges commonly reported for dye-tracer test results. For example, groundwater velocities ranging from 3,000 to 12,000 feet per day were inferred from results of dye-tracer tests conducted during 2003–04 in the San Antonio segment near the recharge zone of the aquifer (Schindel and others, 2005).

A full discussion of this topic, as well as methods that might be applied in addressing it, is beyond the scope of this report. However, future development and use of models such as MODFLOW–DCM that explicitly incorporate conduit hydraulic equations might yield better approximations of the range of groundwater flow velocities and time-of-travel characteristics obtained by dye-tracer tests conducted in the Edwards aquifer.

The USGS has recently released the Conduit Flow Process (CFP) module for MODFLOW–2005 (Shoemaker and others, 2008). The CFP module provides the capability to simulate laminar or turbulent groundwater flow in dual-porosity and conduit-dominated aquifers. The CFP module has three simulation modes: Mode 1 allows for simulation of flow within a discrete network of cylindrical conduits (or pipes); Mode 2 allows for simulation of flow within a preferential, high-conductivity model layer in which flow can transition between laminar and turbulent; and Mode 3 allows for simultaneous simulation of flow within a conduit network and high-conductivity model layer. Conduits might represent dissolution or biological burrowing features in carbonate aquifers, voids in fractured rock, or lava tubes in basaltic aquifers. Preferential flow layers might represent a porous media in which turbulent flow is suspected to occur under the observed hydraulic gradients; a single, secondary-porosity subsurface feature such as a well-defined, laterally extensive cave; or a horizontal layer consisting of many interconnected voids.

Application of the CFP module likely would enhance the ability of USGS MODFLOW-based models to simulate conduit flow in karst aquifers, including the Edwards. However, regardless of which type of conduit-modified modeling code might be applied in future PWS well assessments—MODFLOW–DCM or MODFLOW–2005 with the CFP module—effective simulation of a conduit-dominated flow system in the Edwards aquifer will require the collection of large amounts of field data throughout the extent of the aquifer, particularly through the use of quantitative dye-tracer tests and carefully designed aquifer tests.

Limitations of Models

All numerical groundwater flow models are simplifications of the real system and therefore have limitations. Many limitations are inherent to all six of the models discussed in this report, whereas some limitations are specific to or more apparent for one or more, but not all, of the models. Limitations that are inherent to all six models are related to the quality and quantity of the input data, the scale at which the model can be applied, and the assumptions used to develop the conceptual and numerical models (table 4). The input datasets for all six models are based on sparse information for some properties and in some areas. Regarding hydraulic properties, the available data for storativity is sparse, and the available data for hydraulic conductivity tends to be concentrated in some areas and sparse in other areas. Water-level data for constructing potentiometric surfaces and well hydrographs might affect the evaluation of the goodness of fit of the models because comparisons of simulated and measured water levels are limited to areas where water levels have been measured. The available hydrogeologic data are relatively meager for the recharge zone, for the freshwater/saline-water transition zone, and for the Kinney County area of the San Antonio segment.

Table 4. Limitations of models for the Edwards aquifer, south-central Texas.

[GAM, Groundwater Availability Modeling; DCM, dual conductivity model]

Common to all six models:

1. Quality and quantity of input data:

(A) Datasets based on sparse or clustered information for some properties and in some areas

- Properties and data based on sparse or clustered information: (1) hydraulic conductivity, (2) storativity distribution, and (3) water-level data
- Areas with sparse information: (1) recharge zone, (2) freshwater/saline-water transition zone (MODFLOW conduit-flow and diffuse-flow Edwards aquifer models), and (3) Kinney County (San Antonio segment models)

(B) Data of uncertain accuracy that warrant further analysis

- Spatial and temporal distribution of recharge
- Spatial and temporal distribution of withdrawals by wells

2. Scale of application:

(A) Models are regional scale, and therefore their application to local, site-specific issues is not appropriate

(B) Local effects and water-level declines and flow directions depend on site-specific hydraulic properties and hydrologic conditions and thus need to be addressed with a finer grid discretization and with estimates of local hydraulic properties and hydrologic conditions

3. Assumptions for conceptual and numerical models:

(A) Discretization of the model grid

- Vertical—one model layer
- Horizontal—relatively coarse cell size

(B) Temporal discretization for transient simulation—monthly stress periods

(C) Uncertainties regarding flow across northern, southern, and lower model boundaries

Common to all models except the MODFLOW–DCM conduit model:

1. Use of a Darcian, laminar flow model to simulate flow in a karst system results in

(A) Inability to simulate rapid, potentially turbulent flow in conduits

(B) Inability to simulate fast travel times in the aquifer

(C) Inability to simulate vertical heterogeneity of the aquifer

Table 4. Limitations of models for the Edwards aquifer, south-central Texas—Continued.

Applicable to GWSIM model:

1. Lack of accessibility and portability of the model code
2. Limited in its application to the San Antonio segment of the Edwards aquifer
3. Lack of pre- and post-processors for the model
4. Application of a part of the total basin recharge for the Blanco River Basin directly to the spring cell representing San Marcos Springs to better simulate the local component of flow from the outcrop area

Applicable to the MODFLOW conduit-flow and diffuse-flow Edwards aquifer models:

1. Although the Barton Springs segment of the aquifer is included in the models, calibration was not done for the northern part of the segment (Travis County)

Applicable to Barton Springs segment GAM and recalibrated GAM models:

1. Calibrated to match measured water levels and springflows for a restrictive range of hydrologic conditions, with each model having different hydraulic conductivity and storativity values appropriate to the hydrologic conditions that were simulated

Applicable to the MODFLOW–DCM conduit model:

1. Relative newness of the model code (documented in 2007) and its limited application and testing
2. Present lack of commercially available pre- and post-processors for the model

Recharge data for the area of the models generally are considered much more accurate than are recharge data available for many other regions. However, the recharge estimates are based on streamflow data from gaging stations that in some cases are appreciably upstream from or downstream from the Edwards aquifer outcrop area; and for the San Antonio segment, computation of recharge estimates involves estimated runoff in ungaged areas (about 30 percent of the recharge area). Estimates of monthly recharge during periods of high runoff probably contain the major errors (Puente, 1978). In addition, assumptions are made regarding the distribution of the recharge applied in the models, with most of the simulated recharge being distributed uniformly along the streambeds in the outcrop area. However, little information is available regarding the spatial focusing of recharge in particular locations, and the spatial distribution of recharge might substantially affect the simulated directions of groundwater flow. Withdrawals by wells were compiled and distributed temporally and spatially for the models. Factors contributing to uncertainty in temporal and spatial distribution of simulated withdrawals include (1) incomplete information for well location and construction, (2) lack of withdrawal data for individual wells, and (3) the need to temporally and spatially distribute withdrawals on the basis of properties other than individual withdrawal rates.

All six of the models are regional scale, best suited to evaluate variations in spring discharge, regional water-level changes, and the relative comparison of regional water-management scenarios. Accuracy and applicability of the models decrease when changing from regional to local scale. The models are not appropriate for local issues, such as water-level declines surrounding individual wells, because of the relatively coarse grid sizes. Water-level declines and flow directions depend on site-specific hydraulic properties and hydrologic conditions and thus need to be addressed with a finer grid discretization and with estimates of local hydraulic properties and hydrologic conditions.

The assumptions used to develop the conceptual and numerical models are related to the discretization of the model grids, the temporal discretization for transient simulations, and uncertainties regarding flow across the model boundaries. All six of the models use a relatively coarse cell size and one model layer. Although substantial vertical heterogeneity occurs in the Edwards aquifer, the available information is insufficient to delineate hydrogeologic units, and corresponding model layers, on a regional scale. All six of the models also use monthly stress periods, although appreciable fluctuations occur in hydraulic heads and springflows over much shorter time periods. However, well withdrawals and recharge rates are not generally available for shorter than monthly time periods, constraining the length of simulated stress periods. The San Antonio segment models simulate a no-flow boundary at the western model boundary, based on the location of a mapped groundwater divide. However, the location of the groundwater divide is known to change temporally, introducing uncertainty regarding flow at the simulated boundary. In addition, uncertainty exists regarding the hydraulic connection between the Edwards and Trinity aquifers at the northern boundaries of the models and the potential for and rate of movement of water across the northern model boundaries.

Numerical groundwater flow model codes, such as the GWSIM model code and MODFLOW, developed for Darcian flow in porous media-type aquifers, cannot accurately simulate both the rapid flow of groundwater through conduits and the slow flow and storage of groundwater in the matrix of karst aquifers. Because all the models except the MODFLOW–DCM conduit model are Darcian-flow models, substantial limitations are associated with their ability to simulate triple porosity and permeability and conduit-dominated flow paths characteristic of well-developed karst aquifers. Also the limitation associated with simulating only one model layer (inability to simulate vertical heterogeneity of the aquifer) is common to all the models except the MODFLOW–DCM conduit model. And none of the models, with the possible exception of the MODFLOW–DCM conduit model, has a documented capability to accurately simulate travel times for conduit-dominated velocities in the Edwards aquifer. Time-of-travel obtained by the existing numerical groundwater flow models and the SWAP methodology is almost certainly overestimated for parts of the aquifer where conduit-dominated flow occurs. However, tracer-test-based estimates of flow velocities, particularly for varying hydrologic conditions, presently are not readily available for most locations. Assuming tracer-inferred velocity data are available for use in model calibration, the MODFLOW–DCM conduit model might potentially provide improved simulation of fast travel times, but currently (2008) that model does not have a particle-tracking capability.

The GWSIM model, MODFLOW conduit-flow and diffuse-flow Edwards aquifer models, and Barton Springs segment GAM and recalibrated GAM models all use zones of high hydraulic conductivity to approximate conduit flow. This works well for simulating potentiometric surfaces, springflows, and regional groundwater flow, but it is unsuitable for simulating the rapid, turbulent flow of groundwater through conduits and for simulating conduit-like (non-Darcian) travel times (Scanlon and others, 2003). The GWSIM model, MODFLOW diffuse-flow Edwards aquifer model, and Barton Springs segment GAM and recalibrated GAM models use relatively broad zones of high hydraulic conductivity, with hydraulic conductivity values on the order of thousands or tens of thousands of feet per day, to approximate conduit flow. The MODFLOW conduit-flow Edwards aquifer model uses generally continuously connected, one-cell-wide zones with hydraulic conductivity values of as much as 300,000 feet per day to approximate conduit flow. A substantial limitation of the MODFLOW conduit-flow Edwards aquifer model associated with the representation of conduits is the lack of knowledge of the appropriate location and characteristics of the simulated one-cell-wide high-permeability zones used to represent conduit flow. A network of conduits (generally continuously connected, one-cell-wide zones) was simulated, although the conduit locations were inferred from few data and subject to considerable uncertainty. Considerable uncertainty also exists regarding the physical dimensions, connectivity, and hydraulic properties of conduits. The physical dimensions of the conduits in the model are constrained by the model cell dimensions.

Simulations done for the Barton Springs segment of the Edwards aquifer using the MODFLOW–DCM conduit model have demonstrated its ability to match both the rapid flow of groundwater through conduits and the slow flow and storage of groundwater in the matrix of karst aquifers, as reflected in the rapid springflow response and the more subdued water-level hydrographs observed for the Edwards aquifer (Painter and others, 2007). For the five models other than the MODFLOW–DCM conduit model, simulated recessions in the springflows tend to be slower than observed, and simulated springflows during high-flow periods tend to be larger than observed. Also, the simulated water-level hydrographs for monitoring wells tend to fluctuate more in response to changes in recharge than the observed water-level hydrographs. The MODFLOW–DCM conduit model produces substantially lower discharge and better matches to the measured discharge during the peak discharge events in 1992, 1997, and 1998 than does the Barton Springs segment GAM model (Painter and others, 2007). The substantially lower peaks during the periods of high recharge are because of the ability of the MODFLOW–DCM conduit model to simulate turbulent conduit flow, which decreases flow velocities due to the formation of complex flow patterns, such as eddies. The overly responsive simulated water-level hydrographs for the five models other than the MODFLOW–DCM conduit model are the result of inputting relatively small storativity values to simulate the observed rapid springflow response to changes in recharge. The MODFLOW–DCM conduit model produces a much more subdued water-level hydrograph that better matches the observed water levels. Because most of the flow and all of the fast flow is in the conduit system of the MODFLOW–DCM conduit model, rapid springflow response can be achieved by assigning small values to the conduit storage parameters. The storage properties for the diffuse system are then free to be adjusted to match the relatively subdued water-level hydrographs.

Limitations specific to the GWSIM model include (1) the lack of accessibility and portability of the model code, (2) applicable only to the San Antonio segment of the Edwards aquifer, (3) a lack of pre- and post-processors for the model, and (4) the application of a part of the total basin recharge for the Blanco River Basin directly to the spring cell representing San Marcos Springs to better simulate the local component of flow from the outcrop area.

A limitation specific to the MODFLOW conduit-flow and diffuse-flow Edwards aquifer models is that, although the Barton Springs segment of the aquifer is included in the models, calibration was not done for the northern part of the segment (Travis County), and the calibrated hydraulic conductivity and storativity values from the Barton Springs segment GAM model were used without revision. Therefore that part of the MODFLOW conduit-flow and diffuse-flow Edwards aquifer models is subject to the same limitations that are applicable to the Barton Springs segment GAM model.

The limitation specific to the Barton Springs segment GAM and recalibrated GAM models is that they were each calibrated to match measured water levels and springflows for a restrictive range of hydrologic conditions, with each model having different hydraulic conductivity and storativity values appropriate to the hydrologic conditions that were simulated. The Barton Springs segment GAM model has calibrated hydraulic conductivity and storativity values that are appropriate for (and best match water levels and springflows for) average and above-average precipitation and recharge conditions. The Barton Springs segment recalibrated GAM model has calibrated hydraulic conductivity and storativity values that are appropriate for (and that best match water levels and springflows for) low precipitation and recharge (drought) conditions. The need for two different sets of hydraulic conductivity and storativity values increases the uncertainty associated with the accuracy of either set of values, illustrates the non-uniqueness of the model solution, and probably most importantly demonstrates the limitation of using a one-layer model to represent the heterogeneous hydrostratigraphic units (Maclay, 1995, fig. 11) composing the Edwards aquifer.

Limitations specific to the MODFLOW–DCM conduit model include (1) the relative newness of the model code (documented in 2007) and its limited application and testing and (2) the lack of commercially available pre- and post-processors for the model. Additional validation and testing of MODFLOW–DCM is needed. Although hypothetical drought conditions with severity comparable to the drought-of-record were simulated for the Barton Springs segment of the Edwards aquifer using the MODFLOW–DCM conduit model, they do not specifically represent the drought of the 1950s.

Summary and Conclusions

The Texas Commission on Environmental Quality (TCEQ) has the principal responsibility to assess the sustainability and susceptibility to contamination of source water provided by public water system (PWS) wells. A substantial number of PWS wells in south-central Texas withdraw groundwater from the karstic, highly productive Edwards aquifer. To assess the sustainability and susceptibility to contamination of source water provided by PWS wells, the TCEQ wishes to apply numerical groundwater flow models that provide the most accurate and scientifically defensible delineation of contributing areas that is possible given the existing technological limitations. However, the use of numerical groundwater flow models to aid in the delineation of contributing areas for PWS wells in the Edwards aquifer is problematic because of the complex hydrogeologic framework and the presence of conduit-dominated flow paths in the aquifer.

The U.S. Geological Survey (USGS), in cooperation with the TCEQ, evaluated six published numerical groundwater flow models (all deterministic) that have been developed for the Edwards aquifer. This report describes the six published groundwater flow models developed for the Edwards aquifer (San Antonio segment or Barton Springs segment, or both) and evaluates the models with respect to accessibility and ease of use, range of conditions simulated, accuracy of simulations, agreement with dye-tracer tests, and limitations of the models. These models are

1. Finite-difference model of San Antonio segment of Edwards aquifer (GWSIM). The GWSIM model uses a FORTRAN computer-model code that pre-dates the development of MODFLOW to simulate groundwater flow in the San Antonio segment of the Edwards aquifer. The computer program for the GWSIM model is based on the 1971 Prickett-Lonnquist Aquifer Simulation Model.

2. MODFLOW conduit-flow model of San Antonio and Barton Springs segments of Edwards aquifer. The MODFLOW conduit-flow model incorporates improvements over previous models by using (1) a user-friendly interface, (2) updated computer codes (MODFLOW–96 and MODFLOW–2000), (3) a finer grid resolution, (4) less-restrictive boundary conditions, (5) an improved discretization of hydraulic conductivity, (6) more accurate estimates of pumping stresses, (7) a long transient simulation period (54 years, 1947–2000), and (8) a refined representation of high-permeability zones or conduits.

3. MODFLOW diffuse-flow model of San Antonio and Barton Springs segments of Edwards aquifer. This model incorporates an alternative, diffuse-flow conceptualization, which 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.

4. MODFLOW model of Barton Springs segment of Edwards aquifer (Groundwater Availability Modeling [GAM] model). The Barton Springs segment GAM model was developed to provide (1) a management tool to the Barton Springs/Edwards Aquifer Conservation District and to the local Regional Water Planning Group and (2) a tool for evaluating groundwater availability under drought-of-record conditions.

5. MODFLOW model of Barton Springs segment of Edwards aquifer for drought conditions (recalibrated GAM model). The Barton Springs segment GAM model was recalibrated so that simulated and measured springflow and water-level data from the 1950s drought matched better.

6. MODFLOW–DCM (dual conductivity model) conduit model of Barton Springs segment of Edwards aquifer incorporating dual conductivity approach and explicit simulation of conduits. The MODFLOW–DCM conduit model incorporates a solver capable of solving the highly nonlinear systems associated with the conduit/matrix flow regime under confined/unconfined conditions. The Barton Springs segment GAM model was converted to a MODFLOW–DCM model by (1) adding a conduit layer, (2) reducing hydraulic conductivity in the zones of high hydraulic conductivity to values more typical for a diffuse-flow system, and (3) increasing storativity in the diffuse-flow system to values more typical for a diffuse-flow system.

The GWSIM model code is not commercially available, is limited in its application to the San Antonio segment of the Edwards aquifer, and lacks the ability of MODFLOW to easily incorporate newly developed processes and packages to better simulate hydrologic processes. MODFLOW is a widely used and tested code for numerical modeling of groundwater flow, is well documented, and is in the public domain. These attributes make MODFLOW a preferred code with regard to accessibility and ease of use. The MODFLOW–DCM code currently (2008) lacks the wide use and testing associated with the MODFLOW code.

The MODFLOW conduit-flow and diffuse-flow Edwards aquifer models were calibrated for transient conditions for the entire period from 1947–2000, whereas the GWSIM model was calibrated for two separate, much shorter time periods, 1947–59 and 1978–89. The residual statistics indicate that, in some cases, the goodness of fit for any given time period does not accurately reflect the goodness of fit for a longer time period for which measured hydraulic heads might be available. This illustrates the value and importance of relatively long transient calibration periods that encompass a range of hydrologic conditions and the potential for erroneous conclusions regarding goodness of fit based on comparatively short periods of comparison between measured and simulated hydraulic heads and springflows.

The inherent limitation of the Barton Springs segment GAM and recalibrated GAM models is that they were each calibrated to match measured water levels and springflows for a relatively narrow range of hydrologic conditions. The Barton Springs segment GAM model has calibrated hydraulic conductivity and storativity values that are appropriate for average and above-average precipitation and recharge conditions. The Barton Springs segment recalibrated GAM model has calibrated hydraulic conductivity and storativity values that are appropriate for low precipitation and recharge (drought) conditions. The inability of either model to adequately match measured water levels and springflows under differing hydrologic conditions is a substantial limitation, which increases the uncertainty of the simulated results.

The principal advantage of the MODFLOW–DCM conduit model is the ability to adequately simulate measured water levels and springflows for the full range of hydrologic conditions (above-average precipitation and recharge conditions and drought conditions) using the same set of hydraulic properties (hydraulic conductivity and storativity).

All of the models except the MODFLOW–DCM conduit model have limitations resulting from the use of Darcy's law to simulate groundwater flow in a karst aquifer system where non-Darcian, turbulent flow might actually dominate. The MODFLOW–DCM conduit model is an improvement in the ability to simulate karst-like flow conditions in conjunction with porous-media-type matrix flow. However, the MODFLOW–DCM conduit model has had limited application and testing and currently (2008) lacks commercially available pre- and post-processors. A variety of practical and technical limitations characterize the other numerical models. For example, the GWSIM model is limited by (1) the lack of accessibility, portability, and applicability of the model code, (2) the lack of pre- and post-processors, and (3) the method used to improve the match with measured springflows for San Marcos Springs. The MODFLOW conduit-flow and diffuse-flow Edwards aquifer models are limited by the lack of calibration for the northern part of the Barton Springs segment (Travis County) and their reliance on the use of the calibrated hydraulic conductivity and storativity values from the calibrated Barton Springs segment GAM model. The major limitation of the Barton Springs segment GAM and recalibrated GAM models is that they were calibrated to match measured water levels and springflows for a restrictive range of hydrologic conditions, with each model having different hydraulic conductivity and storativity values appropriate to the hydrologic conditions that were simulated. The need for two different sets of hydraulic conductivity and storativity values increases the uncertainty associated with the accuracy of either set of values, illustrates the non-uniqueness of the model solution, and probably most importantly demonstrates the limitations of using a one-layer model to represent the heterogeneous hydrostratigraphic units composing the Edwards aquifer.

In general, the best matches or agreement between groundwater flow directions inferred by numerical model simulation, and by dye-tracer tests, are observed where model outputs accurately reproduce the configuration of the potentiometric surface with regard to the positions of major and minor groundwater troughs and divides. Comparison of model outputs with actual dye-tracer test data, if available, can be helpful in validating predicted groundwater flow paths and in correcting or refining simulated groundwater flow directions, velocities, and contaminant-transport characteristics, especially in locations where major conduit-dominated flow paths are known or suspected to exist.

None of the models, with the possible exception of the MODFLOW–DCM conduit model, has a documented capability to accurately simulate travel times for conduit-dominated velocities in the Edwards aquifer. Time-of-travel obtained by the existing numerical groundwater flow models and the SWAP methodology is almost certainly overestimated for parts of the aquifer where conduit-dominated flow occurs. However, tracer-test-based estimates of flow velocities, particularly for varying hydrologic conditions, presently are not readily available for most locations. Assuming tracer-inferred velocity data are available for use in model calibration, the MODFLOW–DCM conduit model might potentially provide improved simulation of fast travel times, but currently (2008) does not have a particle-tracking capability.

PWS assessments of wells in the Barton Springs segment of the Edwards aquifer, and elsewhere where conduit-flow conditions are thought to dominate aquifer hydraulic behavior, might be enhanced by use of either the MODFLOW–DCM model or the newly developed USGS MODFLOW Conduit-Flow Process module for MODFLOW–2005, because each incorporates a type of dual or triple hydraulic conductivity approach and has the capability to explicitly simulate turbulent flow and conduit hydraulic characteristics. Predictions made with these models might continue to be subject to large uncertainties as the models will require more field data about groundwater flow and hydraulic properties in conduit-dominated parts of the aquifer than are available at present. Data limitations are particularly acute at present in the San Antonio segment, where there is a paucity of available dye-tracer tests and a relative lack of knowledge of the location and trends of active groundwater conduits.

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