A Numerical Groundwater Flow Model of the Upper and Middle Trinity Aquifer, Hill Country Area

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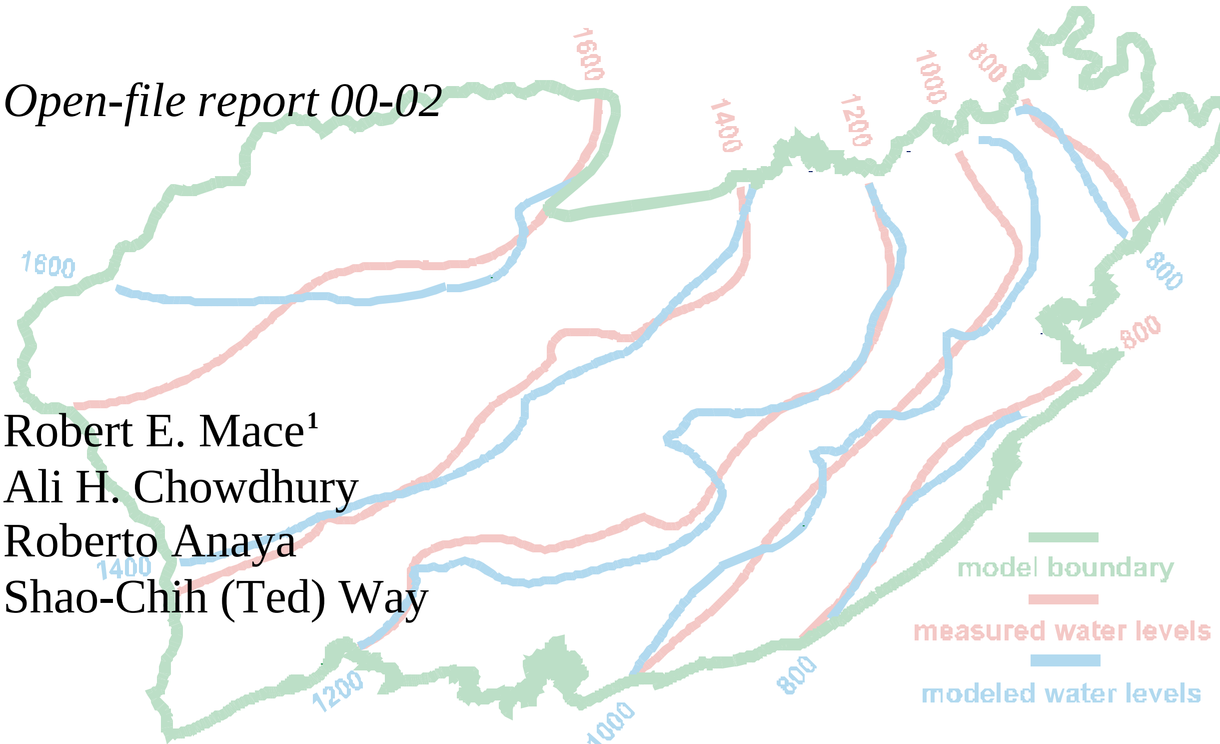

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Abstract

We developed a three-dimensional, numerical groundwater flow model of the Upper and Middle Trinity aquifer in the Hill Country area to help estimate groundwater availability and water levels in response to pumping and potential future droughts. The model includes historical information on the aquifer and incorporates results of new studies on water levels, structure, hydraulic properties, and recharge rates. We calibrated a steady-state model for 1975 hydrologic conditions when water levels in the aquifer were near equilibrium and a transient model for 1996 through 1997 when the climate transitioned from a dry to a wet period. Using the model, we calibrated values of vertical hydraulic conductivity, specific storage, and specific yield for the aquifer and adequately matched measured water levels. Water levels in the model are most sensitive to recharge, the horizontal hydraulic conductivity of the Middle Trinity aquifer, and the vertical hydraulic conductivity of the Upper Trinity aquifer. Water-level changes are most sensitive to the specific yield of each layer. Model calibrated recharge is four percent of mean annual precipitation. Model results suggest that 20 percent of the recharge moves from the Trinity aquifer to the south towards the Edwards (Balcones Fault Zone) aquifer. Future work includes (1) developing predictive datasets for pumping and recharge including the drought of record, (2) enhancing the recharge, structure, hydraulic property

datasets, (3) using the model to predict water levels in the aquifer for various climatic scenarios, and (4) estimating groundwater availability in the area.

Introduction

The Trinity aquifer in south-central Texas is an important source of groundwater to municipalities and individuals in the Hill Country area (fig. 1). Although the Trinity aquifer is recognized by the State as a major aquifer (Ashworth and Hopkins, 1995), yields in the aquifer can be comparatively lower than other major aquifers. For example, average yields in the Trinity aquifer in the Hill Country are about 250 times lower than average yields in the Edwards (Balcones Fault Zone [BFZ]) aquifer immediately to the south. New development and recent droughts have increased interest in the Trinity aquifer and have heightened concerns about groundwater availability in the aquifer. Many want to know how current and future pumping and future droughts will affect water levels over the long term and impact groundwater resources and the environment.

We developed a three-dimensional finite-difference groundwater flow model for the Trinity aquifer in the Hill Country as a tool to (1) evaluate groundwater availability, (2) improve our conceptual understanding of groundwater flow in the region, and (3) develop a management tool to support Senate Bill 1 regional water planning efforts for the Plateau, Lower Colorado, and South Central Texas Regional Water Planning Groups. This interim report describes the construction and calibration of the numerical model. A final report that we expect to complete by May, 2000, will have a much more detailed discussion on the construction and calibration of the model and include predictive simulations of water levels for the next 50 yr. based on projected demands from Regional Water Planning Groups as part of Senate Bill 1 water-planning efforts. The final report will also include refinements of the recharge, hydraulic properties, and structure and a quantification of groundwater availability. As such, the model described in this report may change slightly when this new information is included.

Our general approach involved (1) developing the conceptual model, (2) organizing and distributing aquifer information for entering into the model, (3) calibrating a steady-state model for 1975, and (4) calibrating and verifying a transient model for 1996 and 1997. This report describes (1) the study area, previous work, and hydrogeologic setting used to develop the conceptual model; (2) the code, grid, and model parameters assigned during model construction; (3) the calibration and sensitivity analysis of steady-state and transient models; (4) the limitations of the current model; and (5) plans for future improvements.

Study Area

The study area is located in the Hill Country of south-central Texas and includes all or parts of Bandera, Bexar, Blanco, Comal, Gillespie, Hays, Kendall, Kerr, Medina, Travis, and Uvalde counties (fig. 1). Hydrologic boundaries define the boundaries of the study area. These boundaries include the (1) contact with the Edwards (BFZ) aquifer to the east and south, (2) presumed groundwater flow paths to the west, and (3) outcrop or rivers to the north (fig. 1). Because we chose groundwater flow paths to the west, the study area does not include the entire Hill Country area (i.e. parts of Bandera and Uvalde

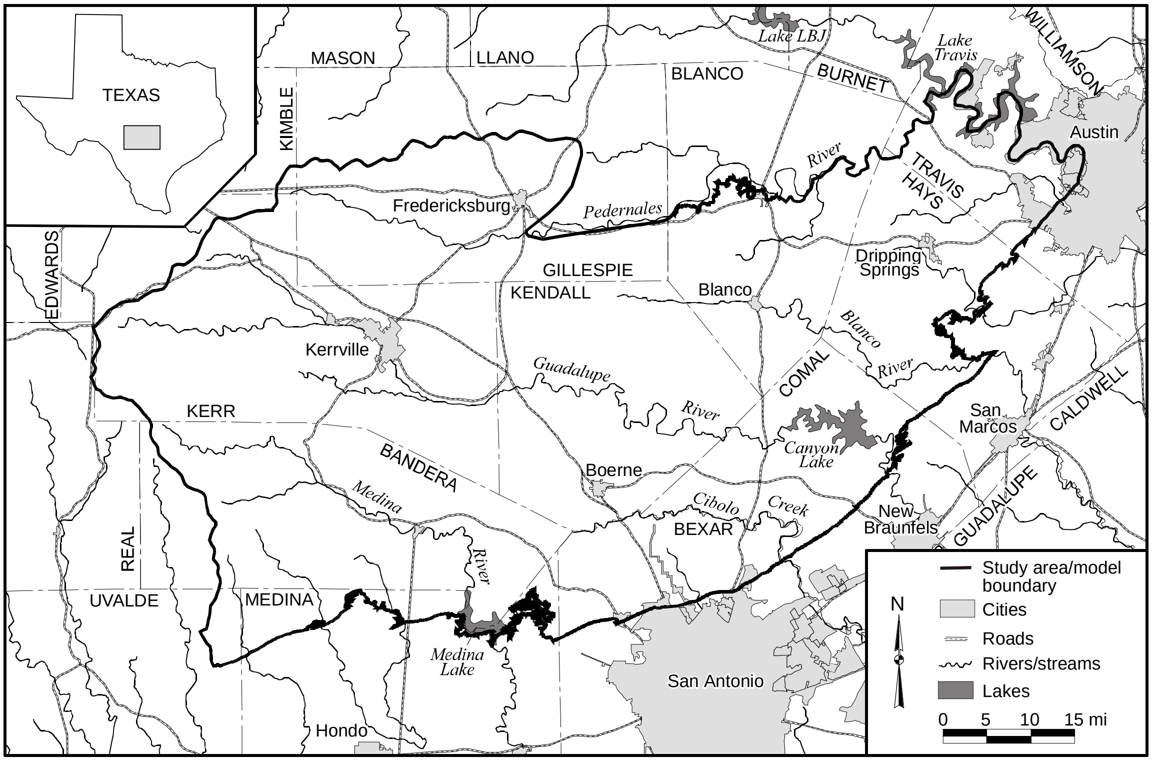

Figure 1: Location of the study area relative to cities, roads, major cities and towns, lakes, and rivers.

County) but does include the easternmost parts of the Edwards-Trinity (Plateau) aquifer in Bandera, Gillespie, Kendall, and Kerr counties (fig. 2). The study area includes parts of three regional water planning areas: (1) the Lower Colorado Region (Region K), (2) the South Central Texas Region (Region L), and (3) the Plateau Region (Region J) (fig. 3).

Physiography and Climate

The study area is located along the southeastern margin of the Edwards Plateau region commonly referred to as the Texas Hill Country. The Texas Hill Country is also known as the Balcones Canyonlands sub-region, a terrain deeply dissected by the head-ward erosion of major streams with steep gradients from the plateau to the base of the Balcones Escarpment. The Balcones Escarpment was formed by Tertiary faulting along the Balcones Fault Zone, a zone of northeast-southwest trending normal faults parallel to the Texas Gulf coast. Land-surface elevations across the study area range from 2,400 feet above sea level in the west to about 800 feet along the Balcones Fault Zone (Ashworth, 1983).

The more massive and resistant carbonate members of the Edwards Group form the nearly flat uplands of the Edwards Plateau in the west and the topographic divides in the central portion of the study area. The differential weathering of alternating beds of hard limestones and dolomites with soft marls and shales of the Glen Rose Limestone form the characteristic stair-step topography of the Balcones Canyonlands. In general, the Glen Rose Limestone is much less resistant to erosion than the Edwards Group caprock. The study area is characterized by a sub-humid to semi-arid climate. A gradual

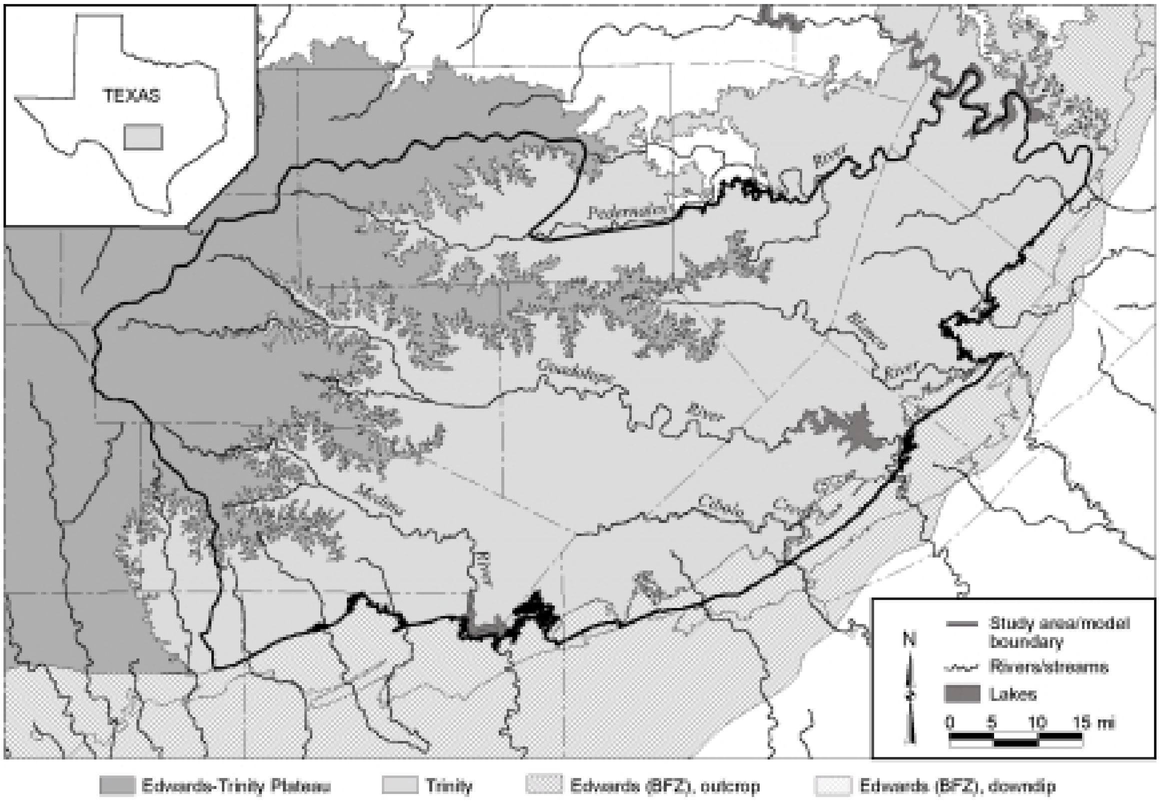

Figure 2. Location of major aquifers in the study area.

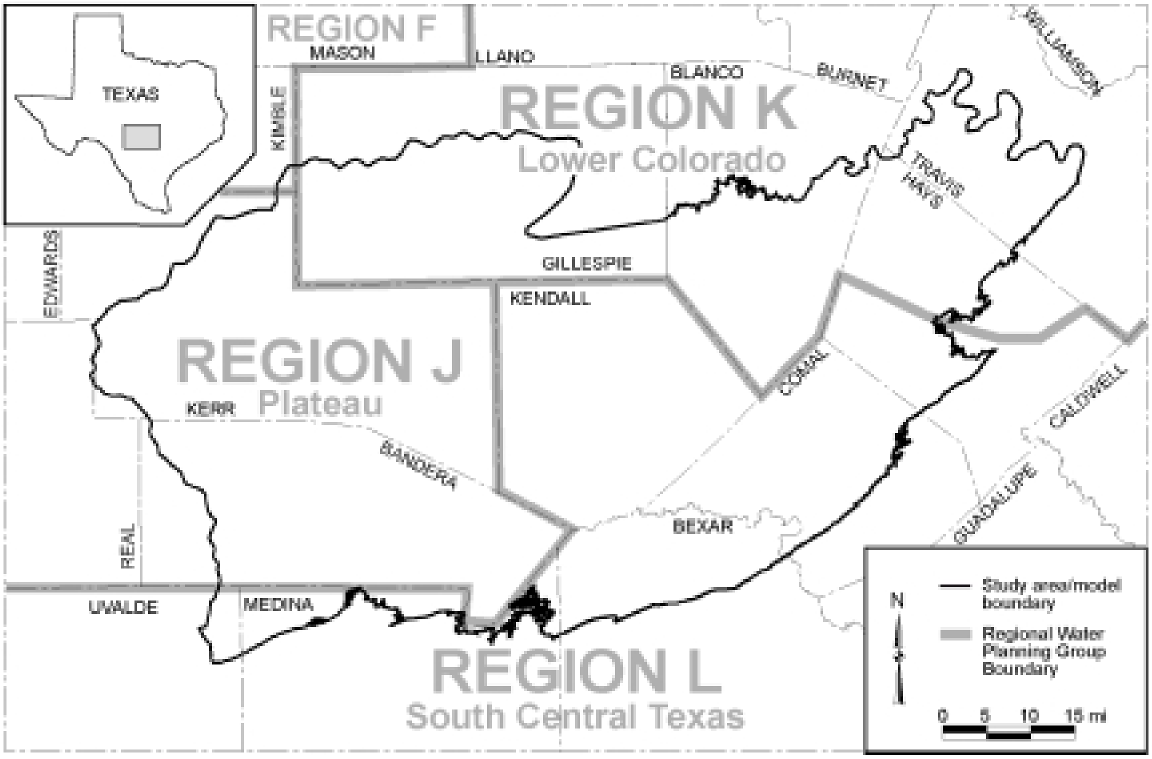

Figure 3. Location of Regional Water Planning Group boundaries in the study area.

decrease in mean annual precipitation occurs from east to west (35 inches to 25 inches) due to an increase in topography and increasing distance from the Gulf of Mexico (Carr, 1967). The mean annual precipitation has a bimodal distribution with most of the rainfall occurring during the spring and fall. During the springtime, weak cool fronts begin to stall and mix with warm moist air from the Gulf of Mexico. During the summer, sparse rainfall is due to infrequent convectional thunderstorms. In early fall, rainfall is due to more frequent convectional thunderstorms and occasional tropical cyclones that make landfall along the Texas coast. Rainfall frequency continues to increase in late fall as cool fronts once again begin to strengthen and mix with the warm moist air masses of the Gulf of Mexico. Mean annual temperature ranges from 69 °F in the west to 63 °F in the east (Kuniansky and Holligan, 1994). The average annual (1940-1965) gross lake surface evaporation is more than twice the mean annual precipitation and ranges from 65 inches in the east to 73 inches in the west (Ashworth, 1983).

Geology

The geology in the study area consists of Cretaceous rocks that unconformably overlie Paleozoic rocks (fig. 4). The Cretaceous rocks in the study area consist of, from oldest to youngest, the Hosston Formation (Sycamore Sand in outcrop), the Sligo Formation, the Hammett Shale, the Cow Creek Limestone, the Hensel Sand, the lower and upper members of the Glen Rose Limestone, and the Fort Terrett and Segovia Formations of the Edwards Group (fig. 4). The Hosston Formation, Sligo Formation, Hammett Shale, Cow Creek Limestone, and Hensel Sand together are the Travis Peak equivalent. The formations of the Travis Peak equivalent and the Glen Rose Limestone

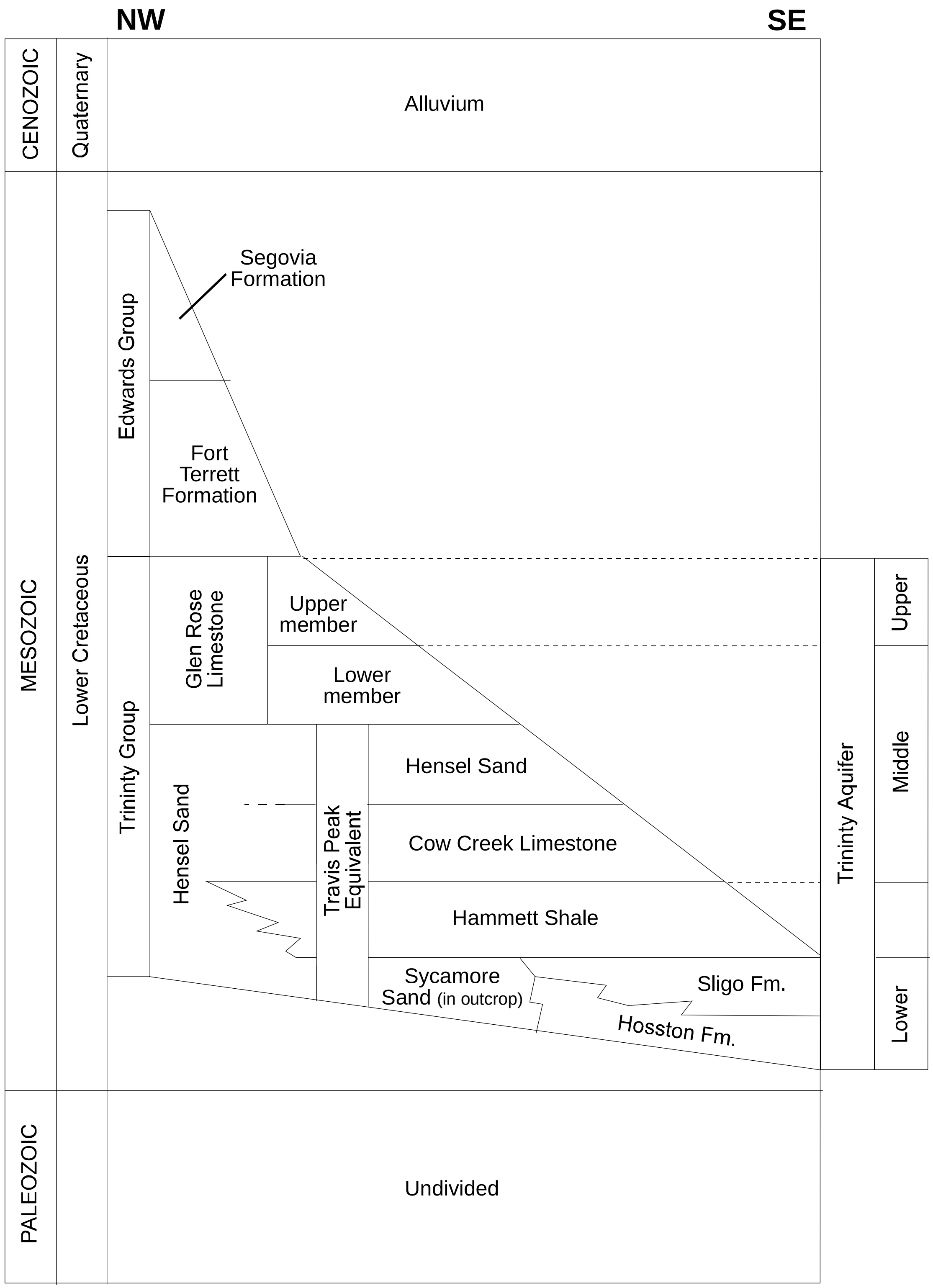

Figure 4. Stratigraphic and hydrostratigraphic section of the Hill Country area (after Ashworth, 1983; Barker and others, 1994).

together form the Trinity Group. Cretaceous sediments are locally covered by Quaternary alluvium, especially near streams and rivers.

The Hensel Sand crops out in the northern part of the study area in Gillespie County (fig. 5). The upper member of the Glen Rose Limestone is exposed at land surface in most of the study area except where the lower member of the Glen Rose Limestone is exposed owing to erosion and where the Edwards Group is exposed on the Edwards-Trinity Plateau to the west and in the Balcones Fault Zone to the east (fig. 5). Details of the geology in the region can be found in Ashworth (1983) and Barker and others (1994).

Previous Work

The Texas Water Development Board (TWDB) and the United States Geologic Survey (USGS) have conducted a number of hydrogeologic studies in the Hill Country area. Ashworth (1983), Bluntzer (1992), and Barker and others (1994) review much of the previous work done in the area.

Only one other regional numerical groundwater flow model has been developed for the area: a super-regional model developed by the USGS (Kuniansky and Holligan, 1994). Besides the Hill Country, this model includes the Edwards-Trinity (Plateau) and Edwards (BFZ) aquifers and extends almost 400 miles across the State. The purpose of this model was to better understand and describe the regional groundwater flow system. Using the model, Kuniansky and Holligan (1994) defined transmissivity ranges,

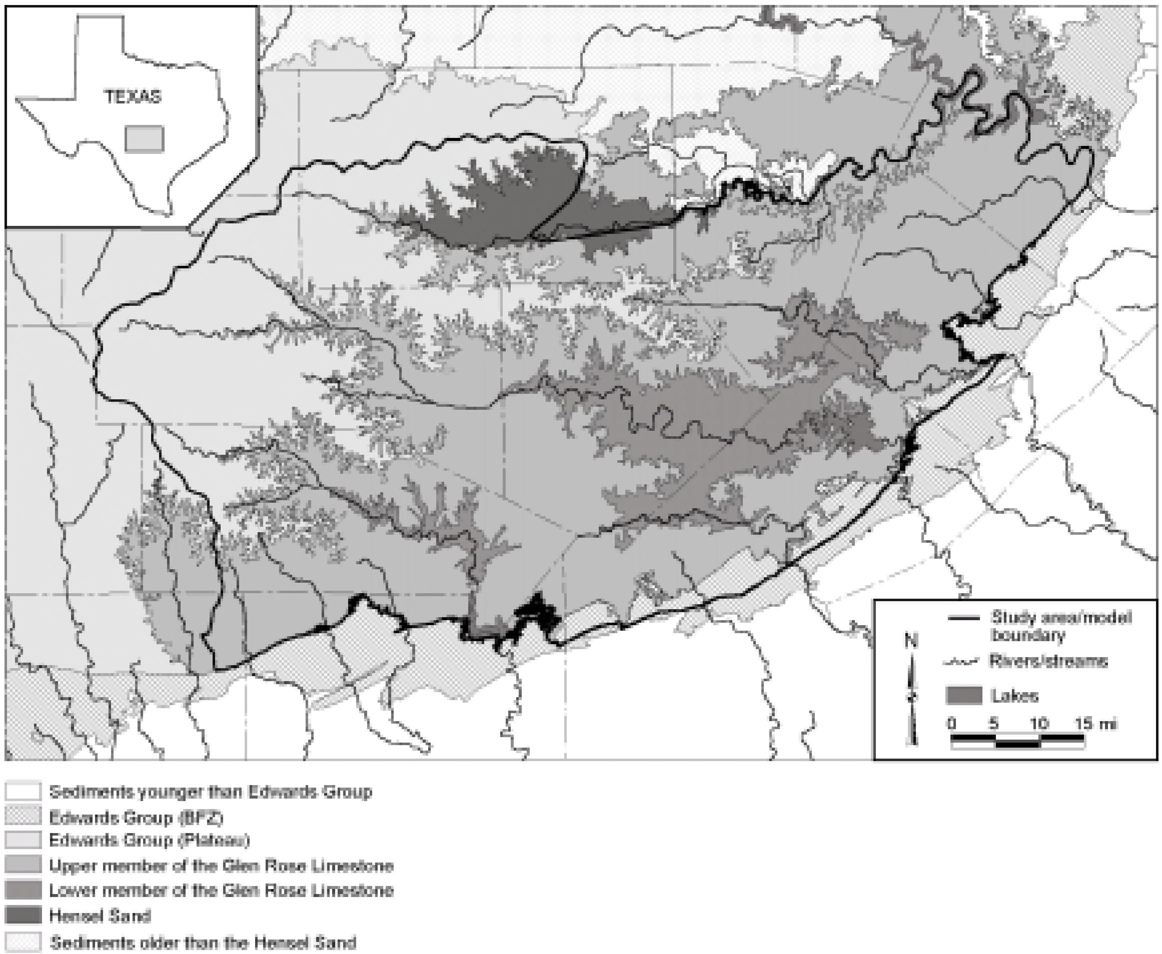

Figure 5. Surface geology in the study area.

estimated total flow through system, estimated recharge to aquifer, and simulated groundwater flow from the Trinity aquifer into Edwards (BFZ) aquifer. The two-dimensional, finite element, steady-state model was developed as the simplest approximation of the regional flow system. Because of the model covers such a large area, lumps many different formations into one layer, and does not simulate changes with time, it is inappropriate for regional water planning.

The USGS was developing a second, more detailed, finite-element model focusing on the Trinity aquifer in the Hill Country area and the San Antonio and Barton Springs segments of the Edwards (BFZ) aquifer (Kuniansky, 1994) using the MODFE code (Torak, 1993). Problems in calibrating the model, specifically the connection between the Trinity and Edwards aquifers, has, to date, prevented completion and release of the model.

Hydrogeologic Setting

The hydrogeologic setting for the Trinity aquifer was based on previous work (e.g. Ashworth, 1983; Bluntzer, 1992; Barker and others, 1994; Kuniansky and Holligan, 1994) and additional studies conducted in support of the modeling effort. These additional studies included defining water-level maps and hydrographs, assembling structure maps, investigating recharge, and conducting aquifer tests.

Hydrostratigraphy

The Trinity aquifer in the Hill Country is comprised of sediments of the Trinity Group and is divided into lower, middle, and upper aquifers (fig. 4) based on hydraulic characteristics of the sediments (Barker and others, 1994). The Upper Trinity aquifer consists of the upper member of the Glen Rose Limestone; the Middle Trinity aquifer consists of the lower member of the Glen Rose Limestone, the Hensel Sand, and the Cow Creek Limestone; and the Lower Trinity aquifer consists of the Sligo and Hosston Formations. Low-permeability sediments in the upper and middle parts of the Glen Rose Limestone separate the Upper and Middle Trinity aquifers. The Middle and Lower Trinity aquifers are separated by the low permeability Hammett Shale except where it pinches out in the northern part of the study area (Amsbury, 1974; Barker and Ardis, 1996).

The Sycamore Sand, updip parts of the Hensel Sand, and the basal parts of the Hosston Formation are mostly sand and contain some of the most permeable sediments in the Hill Country (Barker and others, 1994). The Cow Creek Limestone is highly permeable in outcrop but has relatively lower permeability in the subsurface due to the precipitation of calcitic cements (Barker and others, 1994). Similarly, the lower parts of the Glen Rose Limestone have higher permeabilities in outcrop and lower permeabilities at depth (Barker and others, 1994). The Sligo Formation is a sandy dolomitic limestone that yields small to large quantities of water (Ashworth, 1983).

Our study area is completely underlain by sediments of the Middle Trinity aquifer (fig. 5). The Upper Trinity aquifer exists in most of the study area except where it has been eroded along and near the lower reaches of the Pedernales, Blanco, Guadalupe, Cibolo, and Medina streams (fig. 5). In the western part of the study area, the Fort Terrett and Segovia Formations of the Edwards Group (fig. 5) cap the Trinity aquifer. Where saturated, these formations can produce large amounts of water.

Structure

The structural geometry of Lower Cretaceous sediments for this study is characterized by (1) a southeast regional dip, (2) an uneven surface of pre-Cretaceous rocks at the base of the Trinity Group sediments, (3) the San Marcos arch in the south-east, (4) the Llano Uplift to the north, and (5) the Balcones Fault Zone to the south and east. Both Trinity and Edwards Group sediments have a regional dip to the south and southeast. The dip increases from a rate of about 10 to 15 feet per mile near the Llano Uplift to about 100 feet per mile near the Balcones Fault Zone (Ashworth, 1983). These Lower Cretaceous sediments may be described as a series of stacked wedges that pinch out against the Llano Uplift and thicken down-dip towards the Gulf of Mexico. At the base of Trinity Group sediments, underlying Paleozoic rocks have been moderately folded, uplifted, and eroded to form an unconformable surface upon which the Trinity Group sediments were deposited. However, because the Lower Trinity unit was not modeled in this study, the unconformity is structurally significant only along the northern margin of the study area where Middle and Upper Trinity sediments directly overlay pre-Cretaceous rocks.

The San Marcos arch is a broad anticlinal extension of the Llano Uplift with a southeast plunging axis through central Blanco and southwest Hays counties (Ashworth, 1983). This arch contributed to the formation of a carbonate platform with thinning sediments along the structural ridge of the anticlinal axis. The Llano Uplift is a regional dome formed by a massive pre-Cambrian granitic pluton. The uplift remained a structural high throughout the Quachita orogeny that folded and uplifted the Paleozoic rocks of this area. The Llano Uplift provided a source of sediments for terrigenous and near-shore facies during the deposition of the Trinity Group sediments (Ashworth, 1983; Barker, Bush, and Baker, 1994). The Balcones Fault Zone is a northeast-southwest trending system of high-angle normal faults with down-thrown blocks towards the Gulf of Mexico. The faulting occurred during the Tertiary Period along the sub-surface axis of the Quachita fold belt as a result of extensional forces created by the subsidence of basin sediments in the Gulf of Mexico. The Balcones Fault Zone is a primary structural feature that laterally juxtaposes Trinity Group sediments against Edwards Group sediments.

Building on the work of Ashworth (1983) and geophysical logs from the Hill Country Underground Water Conservation District, additional geophysical logs were used to develop structural elevation maps for the top of the Upper Trinity, Middle Trinity, and Hammett Shale/Lower Trinity sediments (fig. 6, 7, 8).

Water Levels and Regional Groundwater Flow

We compiled water-level measurements and developed water-level maps for the Trinity aquifer for the beginning and end of 1975, 1996, and 1997 (the choice of years is

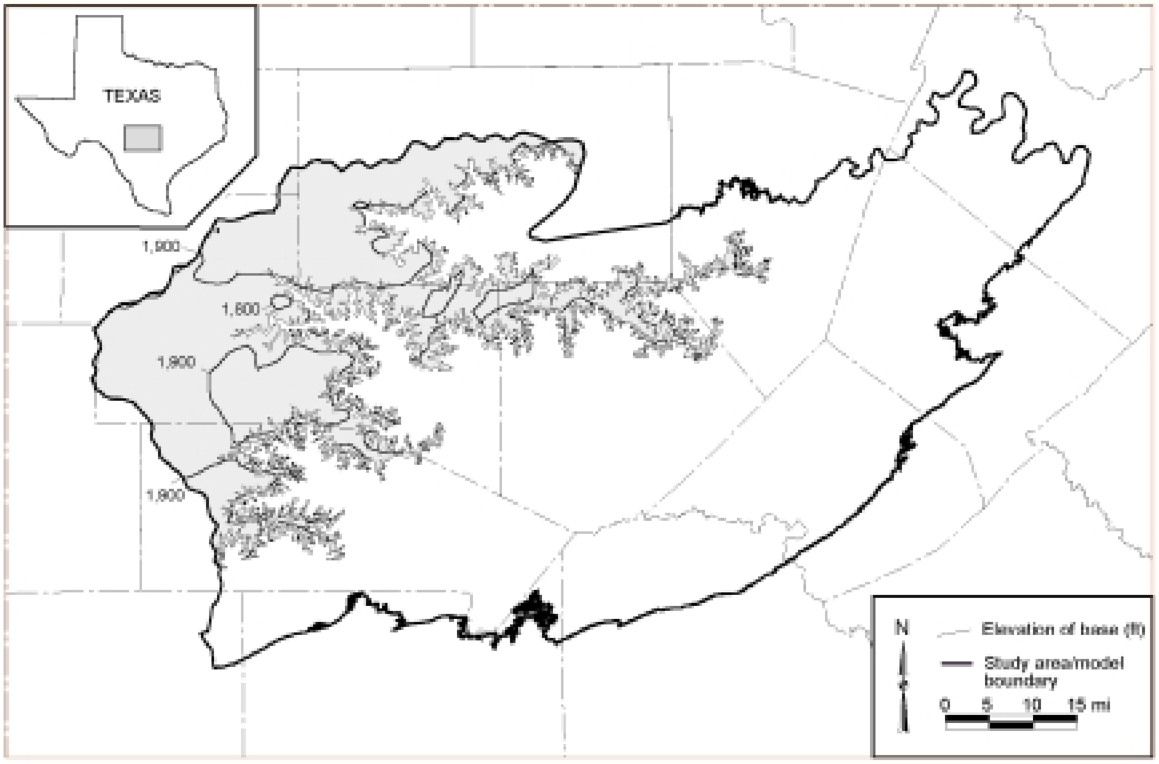

Figure 6. Elevation of the top of the Upper Trinity aquifer (upper member of the Glen Rose Limestone).

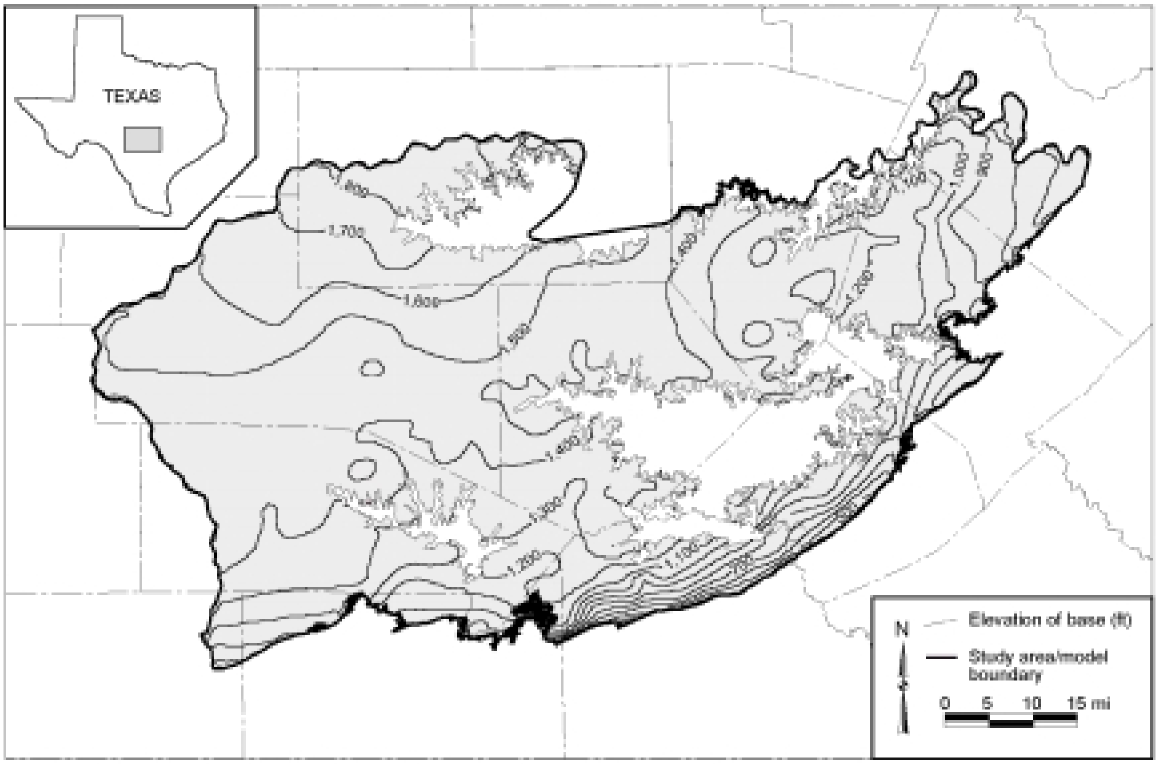

Figure 7. Elevation of the top of the Middle Trinity aquifer (lower member of the Glen Rose Limestone).

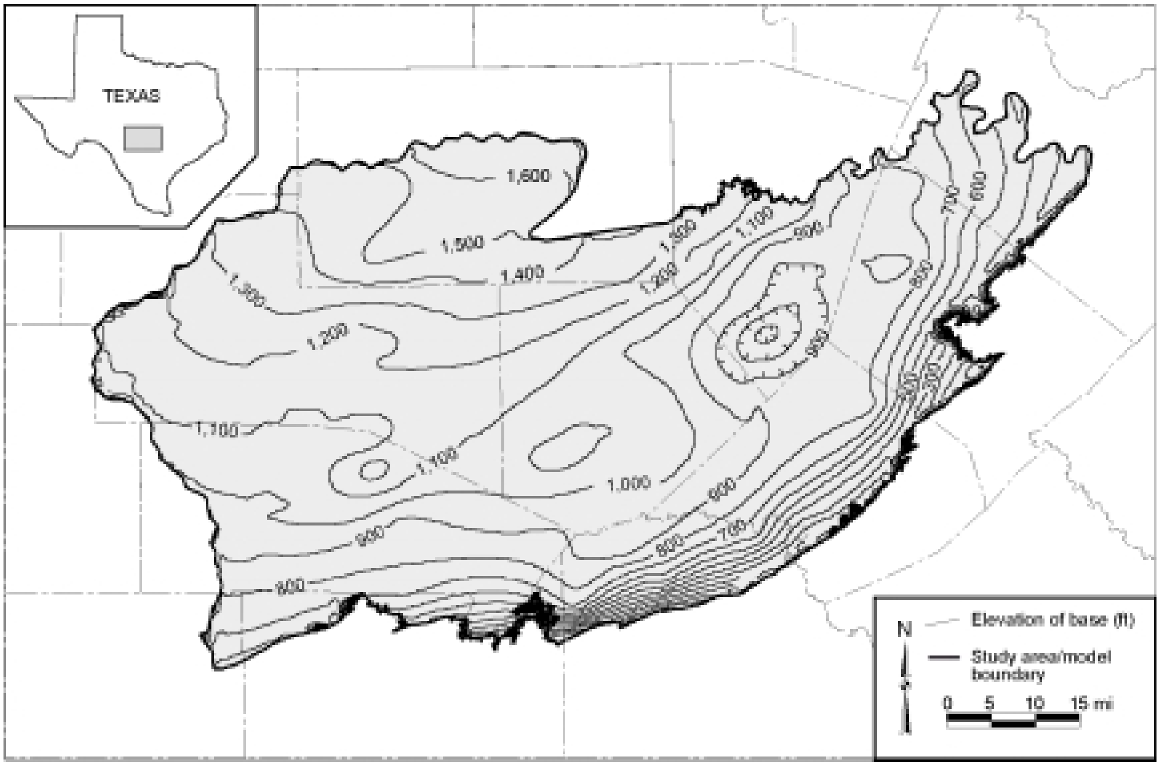

Figure 8. Elevation of the top of the Hammett Shale (where it exists) and the Lower Trinity aquifer (where the Hammett Shale does not exist).

described in 'Modeling Approach' section). We developed the water-level maps for winter (January 1st) conditions when we expect pumping to be lowest and water levels in wells to most likely represent equilibrium aquifer conditions.

To develop the water-level maps for the model, we (1) queried the TWDB water-well database for water-level measurements between the July before January 1st and June after January 1st, (2) selected water levels measured closest to January 1st, (3) assigned the water-level measurements among the different formations, and (4) contoured the water-level surface. When developing the water-level maps for 1975, we noted a lack of water-level measurements in western Kerr, Gillespie, and northeastern Kendall counties. Therefore, we used water levels measured in other years to constrain the potentiometric surface for the aquifer in these areas. When developing water-level maps for 1996 and 1997, we used the water-level map from 1975 to constrain water-level contours in areas with little data. We made two water-level maps for each year: one for the Middle Trinity aquifer and another for the Upper Trinity aquifer and the Edwards Formation of the Edwards-Trinity (Plateau). We combined the Upper Trinity aquifer and the Edwards Formation of the Edwards-Trinity (Plateau) because water-level information was scarce in these aquifers.

Water levels in the Middle Trinity aquifer are generally higher in the northwest and decrease in elevation toward the east and northeast (fig. 9). Water levels in the Upper Trinity aquifer and Edwards Group of the Edwards-Trinity (Plateau) aquifer are similar to water levels in the Middle Trinity aquifer. These water levels suggest that groundwater flows similarly from the west to the east. Water-level contours that bend upstream around

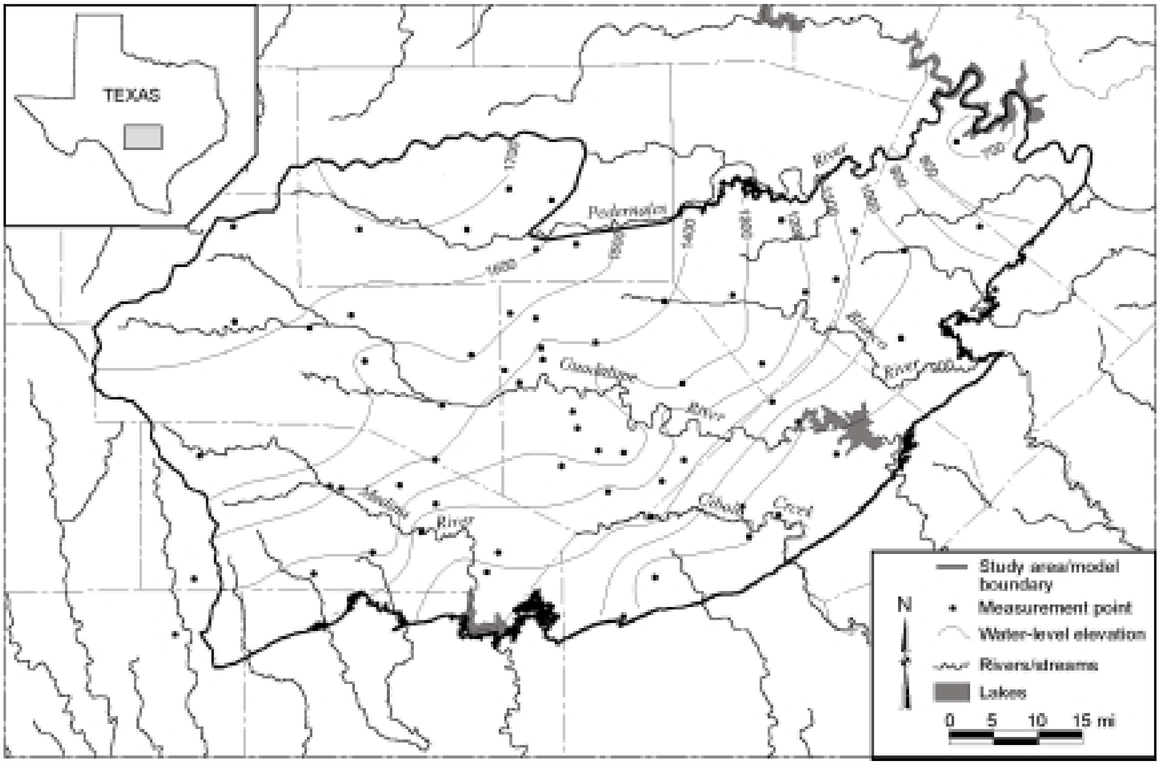

Figure 9. Water-level elevations in the Middle Trinity aquifer for fall, 1975.

rivers suggest that the aquifer discharges to these rivers (fig. 9). Barker and Ardis (1996) note that water-level elevations and the direction of groundwater flow are largely controlled by the position of springs and streams. Water levels, especially in shallow wells (<100-ft deep), can seasonally vary up to 50-ft (Barker and Ardis, 1996) in response to changes in precipitation and drought conditions. Kuniansky and Holligan (1994) suggest that water levels in this area are a subdued representation of surface topography.

Water levels suggest that groundwater flows from the Trinity aquifer into the Edwards (BFZ) aquifer to the south: (1) water-level contours in much of the study area are parallel to the boundary with the Edwards (BFZ) aquifer (fig. 9) and (2) water levels in the Edwards (BFZ) aquifer across major faults tend to be lower than water levels in the Trinity aquifer. The 'Discharge' section discusses the potential amount of flow between these two aquifers.

Recharge

The primary sources of recharge to the Trinity aquifer in the Hill Country area are from rainfall on the outcrop and seepage from lakes and streams (Ashworth, 1983, p. 47). Interbedded impermeable sediments within the Glen Rose Limestone impede the downward percolation of recharge and provide baseflow and springflow to the mostly gaining perennial streams that drain the Hill Country (Barker and Ardis, 1996; Ashworth, 1983). Sinkholes and caverns along stream beds in the Glen Rose Limestone in southern Bandera, southern Kendall, northern Bexar, northwestern Comal, and southwestern Hays counties may transmit large quantities of recharge to the Trinity aquifer. This type of karst-enhanced recharge is especially significant for the stream reach in Cibolo Creek between Boerne and Bulverde (Ashworth, 1983; Veni, 1994).

Several investigators have estimated recharge rates for the Trinity aquifer. Most of them used stream baseflow to estimate recharge. Muller and Price (1979) assumed a recharge rate of 1.5 percent (of mean annual precipitation) for their estimates of groundwater availability. This estimate of recharge is probably an 'availability recharge' that is meant to minimize impacts to baseflow and groundwater flow to the Edwards (BFZ) aquifer. Based on a study of baseflow gains in the Guadalupe River between the Comfort and Spring Branch gaging stations during a 20-year period between 1940 and 1960, Ashworth (1983) estimated a mean annual effective recharge rate of 4 percent of mean annual rainfall for the Hill Country. Kuniansky (1989) estimated baseflow for 11 drainage basins in our study area for a 28-month period between December 1974 and March 1977 and estimated an annual recharge rate of about 11 percent of mean annual rainfall. However, Kuniansky and Holligan (1994) reduced this recharge rate to 7 percent of mean annual rainfall to calibrate a groundwater model that included the Trinity aquifer. They suggested that the numerical model did not include all the local streams accepting discharge from the aquifer.

Bluntzer (1992) calculated long-term mean annual baseflow from the Pedernales, Blanco, Guadalupe, Medina, and Sabinal Rivers and Cibolo and Seco Creeks to be 369,100 acre-ft yr^{-1}, which is equivalent to a recharge rate of 6.7 percent of mean annual precipitation (using a long-term mean annual precipitation of 30 in yr^{-1} [Riggio and others, 1987]). However, Bluntzer (1992) suggests that a recharge rate of 5 percent is more appropriate to account for human impacts on baseflow such as nearby groundwater pumpage, stream-flow diversions, municipal and irrigation return flows, and retention structures. Bluntzer (1992) also noted that baseflow was highly variable over time (e.g. 0.07 in yr^{-1} for 1956 and 4.57 in yr^{-1} for 1975).

Our analysis suggests that differences in recharge rates reflect biases in the record of analysis due to variation of precipitation. The higher recharge rate estimated by Kuniansky (1989) is likely due to the higher than normal precipitation between December 1974 and March 1977, her record of analysis. Ashworth's (1983) recharge rate is probably biased toward a lower value because his record of analysis includes the 1950's drought.

To account for differences between the recharge rates, we developed an automated digital hydrograph-separation technique (based on Nathan and McMahon, 1990; Arnold and others, 1995) to estimate baseflow for the drainage basin defined by the Guadalupe River gaging stations between Comfort and Spring Branch. We used the program to estimate baseflow from 1940 to 1990 and adjusted parameters to attain the best fit with Ashworth’s (1983) and Kuniansky’s (1989) baseflow values for the same stream reach. Using this technique, we estimate a recharge rate of 6.6 percent of mean annual precipitation (note that the recharge rate calibrated with the model is about 4 percent).

Rivers, Streams, and Springs

Most of the rivers in the area arise along the eastern margins of the Edwards Plateau and descend with a steep gradient into the Hill Country. Upper reaches of many of these streams are contained within narrow canyons but broaden into flat-bottomed valleys further downstream (Barker and Ardis, 1996). Three major drainage basins, including the San Antonio, Guadalupe, and Colorado Rivers, traverse the study area and funnel flow towards the southeast.

Most of the rivers in the study area gain water from the Trinity aquifer. Tight interbeds in the upper member of the Glen Rose Limestone allow water to perch in interstream areas and allow streams to be hydraulically connected to the regional flow system (Kuniansky, 1990). Groundwater seeps into streams and springs along the tops of impermeable bedding where cut by the rugged topography of the Hill Country (Barker and Ardis, 1996). Much of the water in shallow parts of the Trinity aquifer discharge to deeply entrenched, perennial streams that drain the area instead of flowing to deeper portions of the aquifer (Ashworth, 1983, p. 47). Many springs issue from the Edwards Group along the plateau in the western part of the study area (Ashworth, 1983, p. 33).

While most of the rivers are perennial, Cibolo Creek loses flow between Boerne and Bulverde where it flows over the lower member of the Glen Rose Limestone (Ashworth, 1983, p. 47). The upper reaches of Cibolo Creek (upstream of Boerne) are gaining water (Guyton and Associates, 1958, 1970; Espey, Huston, and Associates, 1982; Stein and Klemt, 1995). Lower reaches of most of the streams lose significant quantities flow where they cross the recharge zone of the Edwards (BFZ) aquifer (Barker and others, 1994).

Hydraulic Properties

Although the Trinity aquifer is recognized by the State as a major aquifer (Ashworth and Hopkins, 1995), its yields can be comparatively lower than other aquifers. For example, average yields in the Trinity aquifer in the Hill Country are about 250 times lower than average yields in the Edwards (BFZ) aquifer immediately to the south. Yields in the aquifer can vary considerably over a short distance because many of the formations that make up the Trinity aquifer are limestone.

Ashworth (1983, p. 48) reports average transmissivities of about 1,300 ft^2d^{-1} and 230 ft^2d^{-1} for the Lower and Middle Trinity aquifers, respectively, and that substantially lower transmissivities are expected for the Upper Trinity aquifer. Kuniansky and Holligan (1994) determined that transmissivity for the Trinity aquifer in the Hill Country region ranged from 100 to 58,000 ft^2d^{-1}. Stein and Klemt (1995) summarized 53 aquifer tests in the Glen Rose Limestone along the Edwards (BFZ) aquifer and found a median transmissivity of about 220 ft^2d^{-1}. The Glen Rose Limestone is unusually permeable in outcrop and shallow subcrop in areas north of Bexar County and southwestern Comal County (Kastning, 1986; Veni, 1994). Barker and Ardis (1996, fig. 18) developed a map of transmissivity for the Trinity aquifer in the Hill Country area based on aquifer tests, geologic observation, and computer modeling. They determined that transmissivity is generally less than 5,000 ft^2d^{-1} but increases from 5,000 to 50,000 ft^2d^{-1} along the boundary between Comal and Bexar counties and through Kendall and the eastern part of Kerr County. The quarztose clastic facies of the updip Hensel Sand include some of the most permeable sediments in the Trinity aquifer (Barker and Ardis, 1996). Ardis and Barker (1993) and Barker and Ardis (1996) surmised that the variations in transmissivity in the Hill Country are probably due more to variations in aquifer thickness than in tectonic or diagenetic character. However, Barker and Ardis (1996) state that the evolution of stable minerals has diminished permeability in most downgradient, subcropping strata and that the leaching of carbonate constituents has enhanced permeability in some of the outcrop.

Based on 15 aquifer tests, Hammond (1984) determined that hydraulic conductivity ranges from 0.1 to 10 ft d^{-1} in the Lower Glen Rose Formation. Barker and Ardis (1996) thought that hydraulic conductivity probably averages about 10 ft d^{-1} in the aquifer. No one has investigated vertical hydraulic conductivities, although vertical hydraulic conductivities are likely to be lower than horizontal hydraulic conductivities. Barker and Ardis (1996) note that recharging water more easily moves laterally atop dense interbeds than vertically through them. In their model that included the Trinity aquifer, Kuniansky and Holligan (1994, p. 31) considered part of the Trinity aquifer along the Edwards (BFZ) aquifer to have anisotropic properties: greater hydraulic conductivity in the direction of faulting than perpendicular to the direction of faulting.

Walker (1979, p. 73) found an average storativity of 0.074 for four aquifer tests in the basal Cretaceous sands in the area. Ashworth (1983, p. 48) estimates that the confined storativity ranges between 10^{-5} and 10^{-3} (a specific storage of about 10^{-6} ft^{-1}) and that the unconfined storativity (specific yield) ranges between 0.1 and 0.3. Based on two aquifer tests, Hammond (1984) determined a storativity of 3×10^{-5} for the lower member of the Glen Rose Limestone. The specific yield for the Edwards (BFZ) aquifer is 0.03 where it is unconfined (Maclay and Small, 1986, p. 68-69).

To determine hydraulic properties for our study area and expand upon previous studies, we (1) compiled available information on aquifer properties or tests from published reports and well records, (2) conducted and analyzed detailed aquifer tests in the study area, (3) used specific-capacity information to estimate transmissivity, and (4) use statistics to summarize the results of our analysis.

We compiled aquifer tests from Meyers (1969), Hammond (1984), W.E. Simpson Company Inc. and W.F. Guyton Associates, Inc. (1993), LBJ-Guyton Associates (1995), and Bradley and others (1997). In addition, we conducted 35 aquifer tests in the study area and analyzed the results using standard techniques (e.g. Theis, 1935; Cooper and Jacob, 1946; Kruseman and de Ridder, 1994). We also compiled information on 297 well performance (specific-capacity) tests from the TWDB water well database and used an analytical technique (Theis, 1963) to estimate transmissivity. Twenty-one of these tests was from the Upper Trinity aquifer, 260 were from the Middle Trinity aquifer, and 16 were from the Lower Trinity aquifer.

Based on results from the data compilation, aquifer testing, and specific-capacity analysis, we found that the geometric mean value of transmissivity for the Upper Trinity and Middle Trinity aquifers are 78 and 150 ft^2d^{-1}, respectively, and that the geometric mean value of hydraulic conductivity for the Upper Trinity and Middle Trinity aquifers are 0.55 and 1.3 ft d^{-1}, respectively.

Using geostatistics, we showed that hydraulic conductivity in the Middle Trinity aquifer is spatially correlated. We used a semivariogram and kriging to distribute hydraulic conductivity in the Middle Trinity aquifer (fig. 10). Geostatistical analysis showed no spatial correlation of hydraulic conductivity in the Upper Trinity aquifer (likely due to too few measurement points). There were too few measurements to apply geostatistics in the Edwards Group.

Discharge

Discharge from the Upper and Lower Trinity aquifer in the Hill Country area is, from greatest to lowest, through (1) discharge to streams and springs (Ashworth, 1983, p. 48), (2) lateral subsurface flow and diffuse upward leakage to the Edwards (BFZ) aquifer (Veni, 1994), (3) pumping of the aquifer, and (4) vertical leakage to the Lower Trinity aquifer. Kuniansky (1989) estimates that baseflow (flow from the aquifer to rivers) accounts for 25 to 90 percent of total streamflow from December, 1974, to March, 1977. Kuniansky and Holligan's (1994, fig. 14) calibrated model shows streams gaining 408,000 acre-ft yr^{-1}. The volume of baseflow varies from year-to-year depending on precipitation.

The volume of water that moves laterally from the Trinity aquifer into the Edwards (BFZ) aquifer is not known, partially because of the difficulty in estimating the amount of flow. A number of studies have shown, either through hydraulic or chemical

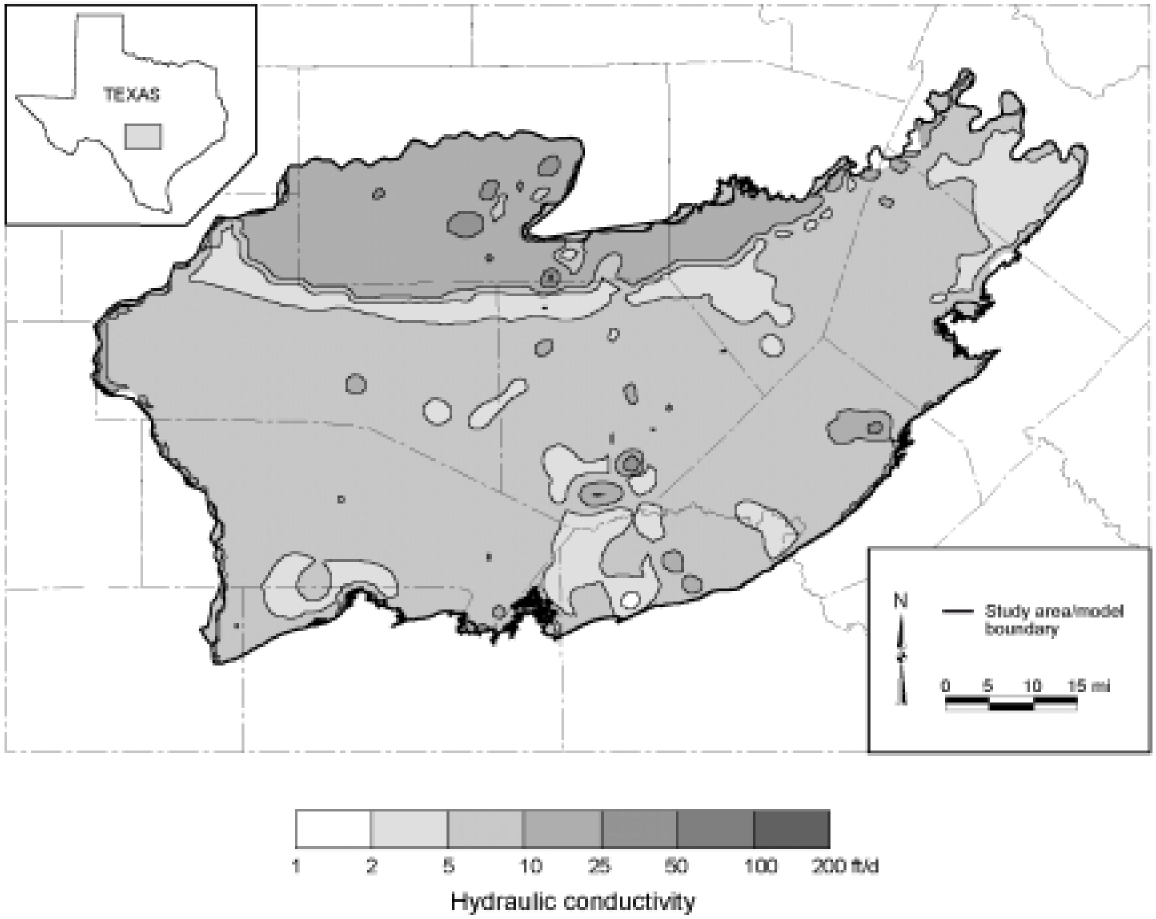

Figure 10. Distribution of hydraulic conductivity in the Middle Trinity aquifer.

analyses, that groundwater likely flows from the Trinity aquifer into the Edwards (BFZ) aquifer (e.g. Long, 1962; Klemt and others, 1979; Walker, 1979; Senger and Kreitler, 1984; Slade and others, 1985; Maclay and Land, 1988; Waterreus, 1992; Veni, 1994, 1995). Most of the studies have focused on the movement of groundwater from the Glen Rose Limestone into the Edwards aquifer. However, water-level maps (e.g. fig. 9) suggest that groundwater from the entire Trinity aquifer discharges to the south and east in the direction of the Edwards (BFZ) aquifer. Kuniansky and Holligan's (1994) model directs all of the flow from the Trinity aquifer into the Edwards (BFZ) aquifer. However, it is possible that a portion of this flow moves into and through formations beneath the Edwards (BFZ) aquifer or discharges locally near the fault zone. The Glen Rose Limestone in the Cibolo Creek area has been argued to be a part of the Edwards (BFZ) aquifer due to the hydraulic response and continuity of the formations (George, 1947; Pearson and others, 1975; Veni 1994, 1995).

A few studies have estimated the volume of flow from the Trinity aquifer into the Edwards (BFZ) aquifer. Lowry (1955) attributed a five percent error between measured inflows and outflows in the Edwards (BFZ) aquifer to cross-formational flow from the Glen Rose Limestone. Woodruff and Abbott (1986), citing a personal communication with Bob Klemt, report that recharge from cross-formational flow accounts for six percent of total recharge (about 41,000 acre-ft yr^{-1} on average) to the Edwards (BFZ) aquifer. Kuniansky and Holligan's (1994) model suggests about 360,000 acre-ft yr^{-1} flows from the Trinity aquifer to the Edwards (BFZ) aquifer. However, this value, about 53 percent of average annual recharge to the Edwards (BFZ) aquifer, is unrealistically high.

LBG-Guyton Associates (1995) estimated cross-formational flow from the Glen Rose Limestone to the Edwards (BFZ) aquifer in the San Antonio area, excluding recharge from Cibolo Creek, to be about two percent of total recharge to the aquifer. None of the numerical groundwater flow models of the Edwards (BFZ) aquifer (e.g. Klemt and others, 1979; Maclay and Land, 1988; Slade and others, 1985; Wanakule and Anaya, 1993; Barrett, 1996) include cross-formational flow from the Trinity aquifer.

Lurry and Pavlicek (1991), Barker and Ardis (1996, p. 47), Kuniansky and Holligan (1994, fig 14) estimate pumping from the Trinity aquifer in the Hill Country area to be between 10,000 and 15,000 acre-ft yr^{-1} in the 1970s. Based on information from the Water Uses Section of the TWDB, about 11,000 acre-ft yr^{-1} was pumped in our study area in 1975. This pumping increased to about 58,000 acre-ft yr^{-1} by 1997.

Conceptual Model of Groundwater Flow in the Aquifer

Our conceptual model of groundwater flow in the aquifer, based on the hydrogeologic setting described, divides the aquifer in the area into three layers: (1) the Edwards Group in the Plateau area, (2) the Upper Trinity aquifer, and (3) the Middle Trinity aquifer. We do not include the Lower Trinity aquifer in the model because (1) the Middle and Lower Trinity aquifers are separated by a confining bed (the Hammett Shale) in most of the study area (Ashworth, 1983, p. 27), (2) the Lower Trinity aquifer is not extensively used in most of our study area, and (3) there is not much information on the Lower Trinity aquifer.

When precipitation falls on the outcrop of the aquifers in the study area, most of the water runs off into to local streams and eventually discharges through major streams out of the study area. However, some of the precipitation, about four to six percent, infiltrates into and recharges the underlying aquifer. Losing streams also recharge the Edwards Group of the Edwards-Trinity (Plateau) aquifer because the Edwards Group in the plateau area has high permeability and mostly contains stream headwaters. Most of the recharge in the Edwards Group in the plateau area discharges along the edge of the plateau through springs, seeps, lower reaches of streams, and evapotranspiration. A small amount of the flow from the Edwards Group in the plateau area moves downward into the Upper and Middle Trinity aquifer.

Most of the precipitation that recharges the Upper and Middle Trinity aquifer discharges to local and major streams feeding baseflow in these surface-water features. An exception is Cibolo Creek, where karstification of the lower member of the Glen Rose Limestone changes the creek from a gaining to a losing stream between Boerne and Bulverde. Most of the remaining recharge in the aquifer discharges either through production from the aquifer or moves laterally into the Edwards (BFZ) aquifer to the south. In general, groundwater flows from areas of higher topography to areas of lower topography from the west to the east.

In general, the lithology and local faulting control the permeability of the formations. The Edwards Group in the Plateau area has high vertical and horizontal permeability owing to karstification. The Upper Trinity aquifer (i.e. the upper member of the Glen Rose Limestone) generally has lower permeabilities (but can be locally very permeable, especially in outcrop) and, because of shaley interbeds, has a much lower vertical than horizontal permeability. The Middle Trinity aquifer has moderate permeabilities and greater ability to transmit water vertically than the Upper Trinity aquifer. The Middle Trinity aquifer is most permeable in the sandy outcrop area of Gillespie County.

Model Design

The design of the model includes the choice of code and processor, the discretization of the aquifer into layers and cells, and the assignment of model parameters. The model is designed to agree as much as possible with the conceptual model of groundwater flow in the aquifer.

Code and Processor

We used MODFLOW-96 (Harbaugh and McDonald, 1996), a widely-used modular finite-difference groundwater flow code written by the USGS, to model groundwater flow in the Trinity aquifer. We chose MODFLOW-96 because it (1) has the numerical features necessary to model the Trinity aquifer, (2) is well documented (McDonald and Harbaugh, 1988) and widely used (Anderson and Woessner, 1992, p. xvi), (3) has a number of third-party pre- and post-processors available to make the model easy to use, and (4) is available through the public domain. To help us with loading information into the model and observing model results, we used Processing MODFLOW for Windows (PMWIN) version 5.0.54 (Chiang and Kinzelbach, 1998).

Other pre- and post-processors should be able to read the source files for MODFLOW-96. We developed and ran the model on a Dell OptiPlex GX1p with a Pentium II Processor and 128.0 MB RAM running Windows 98 (4.10.98).

Layers and Grid

The lateral extent of the model corresponds to natural hydrologic boundaries, such as erosional limits, rivers, and the structural boundary with the Edwards (BFZ) aquifer, and hydraulic boundaries to the west that coincide with groundwater divides. According to the hydrostratigraphy and conceptual model, we designed the model to have three layers. Layer 1 consists of the Edwards Group of the Edwards-Trinity Plateau aquifer, Layer 2 consists of the Upper Trinity aquifer, and Layer 3 consists of the Middle Trinity aquifer. Each layer has 69 rows and 115 columns for a total of 23,805 cells in the model. All the cells have uniform lateral dimensions of 1 mile by 1 mile. We chose this cell size to be small enough to reflect the density of input data and the desired output detail and large enough for the model to be manageable. The uniform cell size allowed us to use spreadsheets and grid-based contouring programs to easily manipulate input data. Cell thickness depended on the elevation of the contact between the different layers. After we made cells outside of the model area and outside the lateral extent of each layer inactive, the model had a total of 9,262 active cells: 1,112 active cells in layer 1, 3,625 active cells in layer 2, and 4,525 active cells in layer 3 (fig. 11, 12, 13, respectively).

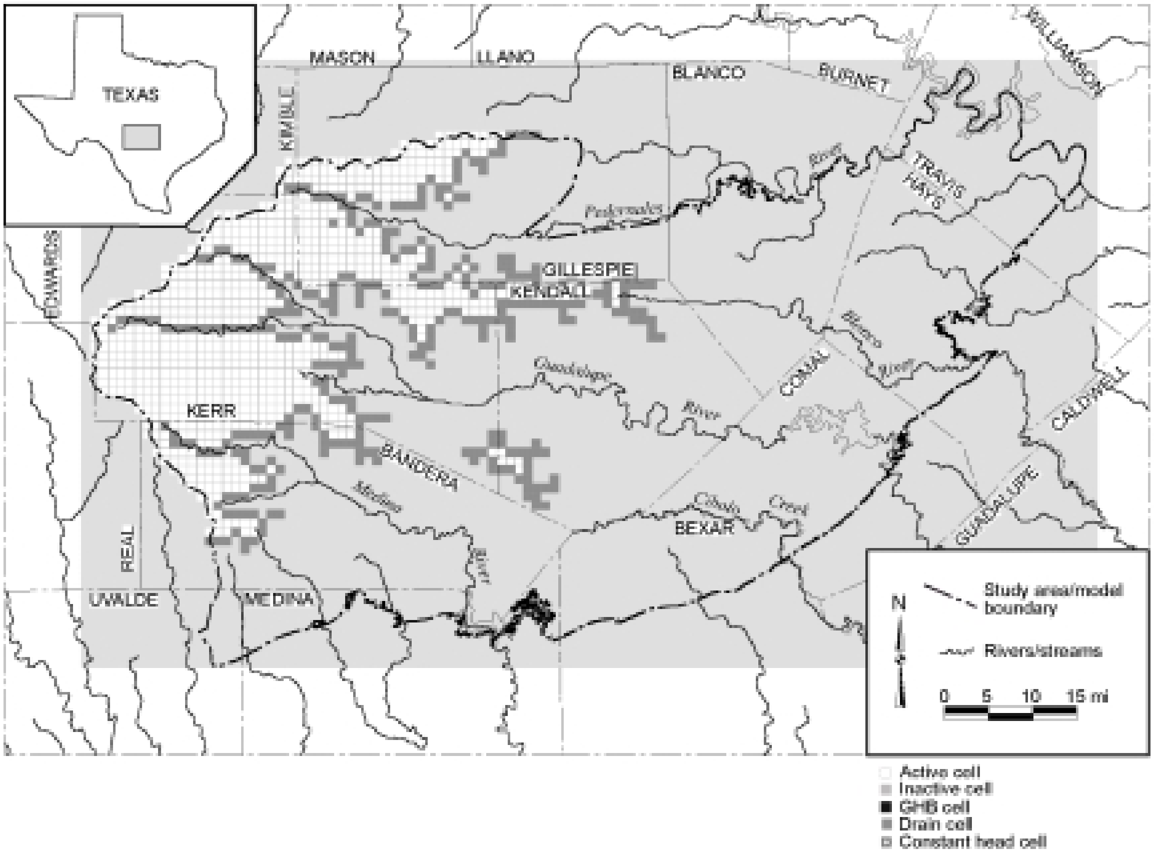

Figure 11. Active cells and boundary assignments in Layer 1 (Edwards Group of the Edwards-Trinity [Plateau] aquifer).

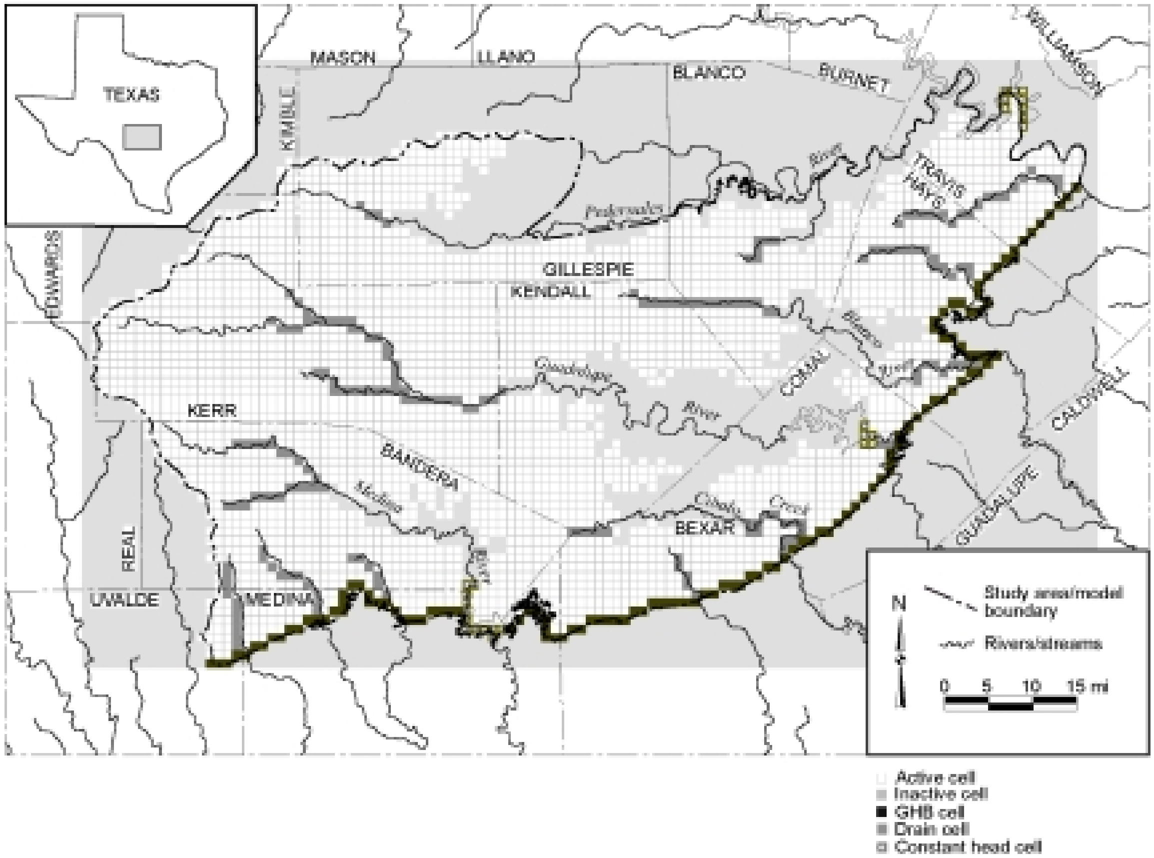

Figure 12. Active cells and boundary assignments in Layer 2 (Upper Trinity aquifer).

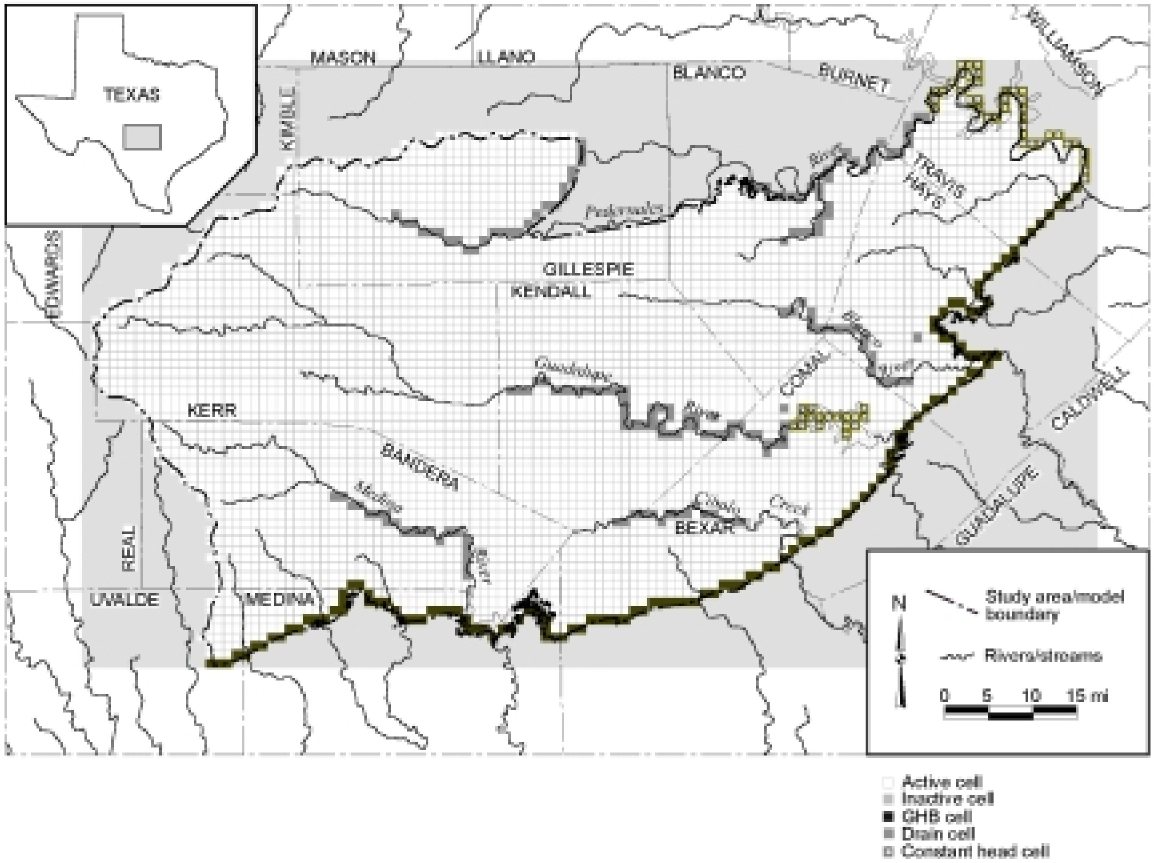

Figure 13. Active cells and boundary assignments in Layer 3 (Middle Trinity aquifer).

Model Parameters

We distributed model parameters, including (1) the IBOUND (active and inactive cells), (2) elevations of the top and bottom of each layer, (3) horizontal and vertical hydraulic conductivity, (4) specific storage, (5) specific yield, (6) recharge, (7) initial hydraulic heads, and (8) pumping, using either Surfer (Golden Software, 1995) or ArcInfo (ESRI, 1991).

We defined the IBOUND by first establishing the lateral extent of the formations in each layer using the geologic map (e.g. fig. 5). We assigned a cell as active if the formation covered more than 50 percent of the cell area. We did not include the thin sliver of the Edwards Group in the eastern part of the study area because (1) our structure maps do not accurately represent the complexity of faulting in the area, (2) flow in these blocks is more associated with the Edwards (BFZ) aquifer than the Trinity aquifer, and (3) the focus of the model is the Middle Trinity aquifer.

We defined top and bottom elevations for each layer from the structure maps and land-surface elevations from digital elevation models downloaded from the USGS. We used ArcInfo to assign top and bottom elevations. For layer 1 (the Edwards Group in the plateau area), we assigned the top as the land-surface elevation and the bottom according to the structure map of the top of the Upper Trinity aquifer (fig. 6). The top of layer 2 (Upper Trinity aquifer) was assigned according to the structure map (fig. 6) where covered by Layer 1 and the land-surface elevation where exposed. The bottom was defined by the top of layer 3 (Middle Trinity aquifer) (fig. 7). The top of layer 3 (Middle

Trinity aquifer) was assigned according to the structure map (fig. 7) where covered by Layer 2 and the land-surface elevation where exposed. The bottom of layer 3 was assigned using the elevation of the top of the Hammett Shale, the Lower Trinity aquifer, or the top of Paleozoic formations along the northern boundary (fig. 8).

We assigned initial values of hydraulic conductivity in layer 3 using Surfer according to our geostatistical interpretation (fig. 10). We assigned uniform values of hydraulic conductivity in layers 1 and 2 because of too few data points. We initially assigned vertical hydraulic conductivity to be 100 times less than the horizontal hydraulic conductivity. We assigned uniform values of specific storage and specific yield. Isotropy was assumed in each layer.

We assigned initial values of recharge according to our ArcInfo analysis described in the recharge section of this report. We used our interpretation of water levels at the beginning of 1975 as an initial heads for the steady-state model.

We assigned pumping for 1975, 1996, and 1997 as accurately as possible according to estimates from the Water Uses Division (WUD) at the TWDB. For the Hill Country area, the primary categories for water use are: (1) municipal, (2) industrial, (3) unreported domestic, (4) livestock, and (5) irrigation. Municipal and industrial water use are based on reported values from the users. We associated these values with well locations and aquifer by cross referencing the water user to their wells through the Texas Natural Resource Conservation Commission (TNRCC) municipal well database, the TWDB water-well database, and through telephone interviews with the water users. Livestock, unreported domestic (rural), and irrigation water use are based on county-wide estimates. We distributed this pumping according to land-use maps developed by the USGS, digitized by the United States Environmental Protection Agency, and stored by the Texas Natural Resources Information System at their Web site. Livestock and unreported domestic use were uniformly distributed according to rangeland land use, and irrigation was uniformly assigned according to agricultural land use.

We used the Drain Package of MODFLOW to represent rivers and streams in the model. We used this package to only allow the streams to gain water from the aquifer. The River Package, which was one alternative, allows streams to gain and lose water. Sensitivity analysis during initial construction of the model showed that the River Package could allow an unrealistic amount of water to move from the rivers and streams into the aquifer and thus underestimate potential water-level declines due to pumping or drought. The Drain Package requires a drain elevation (the elevation upon which water can flow out of the drain) and a drain conductance. We defined the drain elevation by intersecting stream-bed location with the digital elevation model in ArcInfo. We assigned the drain conductance according to the estimated width of the stream, a stream length of 1-mi, and a vertical hydraulic conductivity of 0.1 ft d^{-1}.

We also used drains to represent springflow, seepage from the erosional edge of the Edwards Group in the plateau area, and flow out of the Middle Trinity aquifer in Gillespie County. For the springs, we assigned the drain elevation as the spring elevation and a conductance based on an assumed one foot thickness and the geometric mean hydraulic conductivity of the layer. For the erosional edge of the Edwards Group and flow out of the Middle Trinity aquifer in Gillespie County, we assigned a drain elevation

10-ft above the base of Layer 1 and a drain conductance based on a one foot thickness and the geometric mean hydraulic conductivity of the layer. We simulated the influence of Medina, Canyon, Travis, and Austin Lakes using constant-head cells and average lake-level elevations.

To model the movement of water out of the model and through the Balcones Fault Zone, we used the General Head Boundary (GHB) Package of MODFLOW. We placed GHB cells all along the contact with the Edwards (BFZ) aquifer in layers 2 and 3 unless there was a constant-head cell for a lake. The GHB Package requires values for hydraulic-head and conductance. We assigned the hydraulic head according to the interpreted water level map (fig. 9 for Layer 3) in the area of the GHB cells. We assigned the GHB conductance according to the hydraulic conductivity of the cell and an assumed one foot thickness.

We assigned Layer 1 as unconfined and Layers 2 and 3 as confined/unconfined. We allowed the model to calculate transmissivity and storativity according to saturated thickness. We used units of feet for length and days for time for all input data to the model. To solve the groundwater flow equation, we used the slice successive overrelaxation (SSOR) solver with a convergence criterion of 0.01 ft. We used interpreted water-level maps (fig. 9 for Layer 3) as initial heads for the steady-state model.

Modeling Approach

Our approach for modeling the aquifer included two major steps: (1) developing a steady-state model and (2) developing a transient model. A future, third major step is assembling the datasets and running the model for predictive runs. We first developed a steady-state model because steady-state models are often much easier to calibrate than transient models and results of the steady-state model can easily be used as a starting point in the transient model. We developed the steady-state model for aquifer conditions in 1975. This year was chosen because the aquifer had approximately the same water levels at the beginning and end of the year and pumping from the aquifer was relatively low (Kuniansky and Holligan, 1994). We used the steady-state model to investigate (1) recharge rates, (2) hydraulic properties, (3) boundary conditions, (4) discharge from the Trinity aquifer into the Edwards (BFZ) aquifer, and (5) sensitivity of the different model parameters on model results.

Once we completed the steady-state model, we used the framework of the model to develop a transient model for the years of 1996 and 1997 using monthly time steps. We chose 1996 and 1997 because they (1) represented the last two years of available water-use data available at the time (and therefore provide a good starting point for predictive simulations) and (2) transition from dry conditions in 1996 to wet conditions in 1997. This transition allowed us to test how well the model could reproduce water-level changes in the aquifer.

Our approach for calibrating the model was to match water levels (for steady-state conditions) and water-level fluctuations (for transient conditions) using the simplest possible conceptual model. The calibration of the model focused on the Middle Trinity aquifer because it had the most water levels to calibrate to and because it is the main water-producing horizon of the modeled intervals. However, we also checked that water levels in Layers 1 and 2 were hydrologically reasonable.

Steady-State Model

Once we assembled the input datasets and constructed the framework of the model, we calibrated the steady-state model and assessed the sensitivity of the model to different hydrologic parameters.

Calibration

We calibrated the model to measured water levels for the winter of 1975-1976. To calibrate the model, we first adjusted the different model parameters to determine which parameters had the most effect on simulated water levels. Through this initial sensitivity analysis, we determined that the model was most sensitive to the recharge rate and the hydraulic conductivity in the Middle Trinity aquifer. We could attain a calibrated model as long as the ratio of the recharge rate to the geometric mean hydraulic conductivity of the Middle Trinity aquifer was about 1.7. In other words, model calibration was non-unique. After reviewing previous studies of the recharge, we decided to fix the hydraulic-conductivity values according to measured values because the resulting, model-calibrated recharge rate agreed with values estimated from baseflow (e.g. Ashworth, 1983; Bluntzer, 1992; this study). This model-calibrated, aquifer-wide recharge rate amounts to four percent of mean annual precipitation. This value may be lower than the actual recharge rate because the model does not include discharge to all possible local streams.

After fitting the model as best as possible by only adjusting mean recharge and geometric mean hydraulic conductivity in the Middle Trinity aquifer, we noticed that the model underestimated water levels in the westernmost part of the model in Bandera, Gillespie, and Kerr counties. We found that lowering the vertical hydraulic conductivity in the Upper Trinity aquifer to 0.00003 ft d^{-1} allowed the model to better fit the measured water levels in this area. Unfortunately, there are no available measurements of vertical hydraulic conductivity in the Upper Trinity aquifer, although we expect the vertical hydraulic conductivity to be low due to the presence of low-permeability interbeds.

The final, calibrated model does a good job of reproducing the spatial distribution of water levels in the Middle Trinity aquifer for the winter of 1975-1976 (fig. 14). The model reproduces the interpreted direction of groundwater flow and approximates water levels in most parts of the study area. The root-mean squared (RMS) error is 56-ft (fig. 15). The RMS error means that, on average, the simulated water level differs by about 56-ft. This RMS error is about 5 percent of the total hydraulic head drop across the modeled area, well within the 10 percent usually required for model calibration. Most of the errors are randomly distributed across the modeled area except in the western counties where simulated water levels are consistently below measured values.

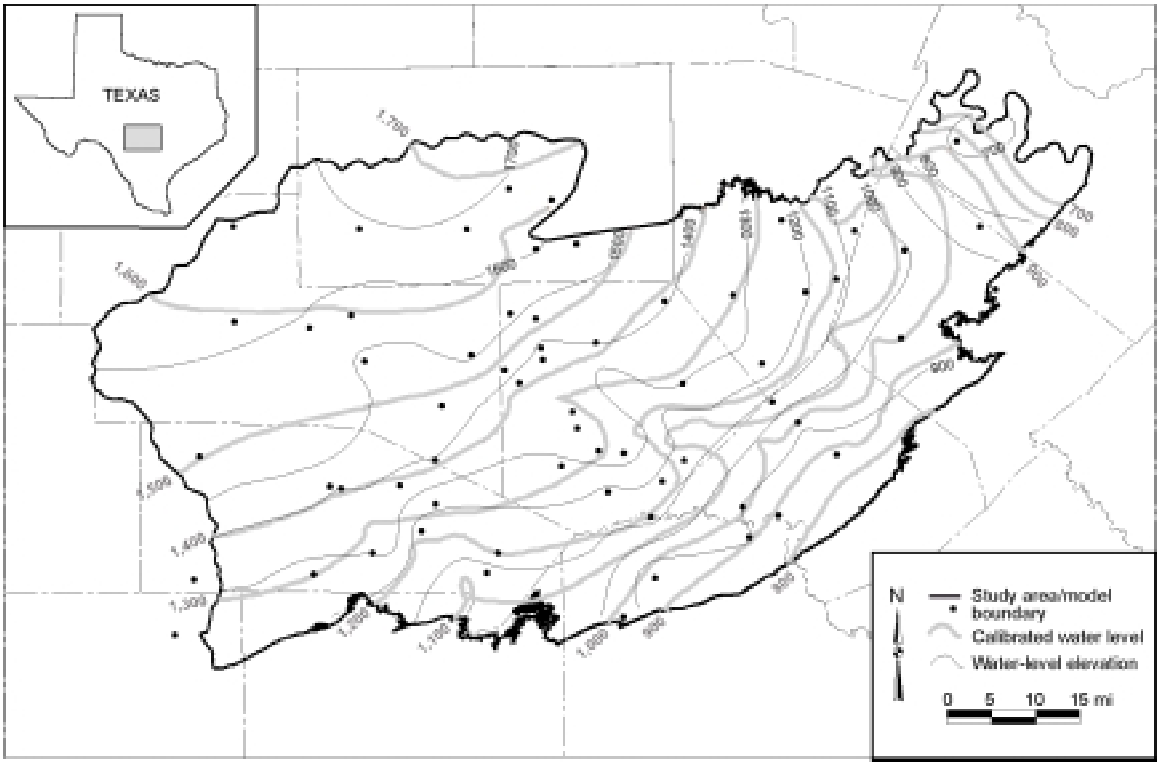

Figure 14. Comparison of simulated and measured water-level contours for the Middle Trinity aquifer for the 1975 steady-state model.

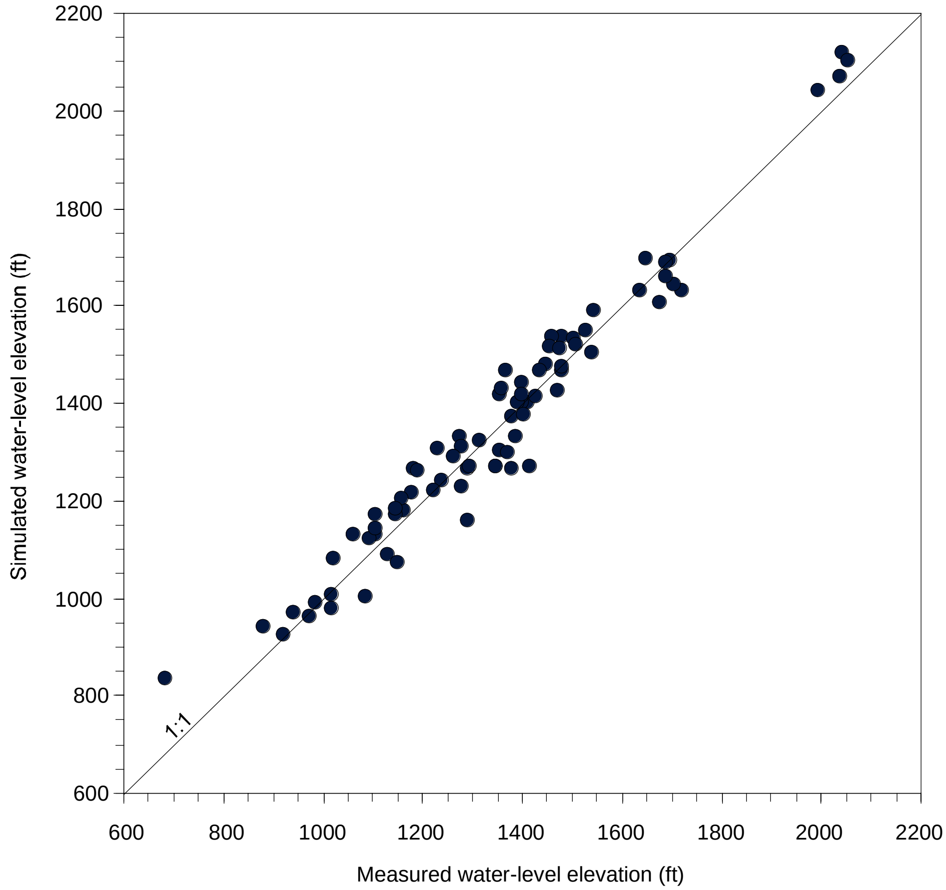

Figure 15. Comparison of simulated to measured water levels for the Middle Trinity aquifer for the 1975 steady-state model.

Our model predicts that about 64,000 acre-ft yr^{-1} of water moves from the Upper and Middle Trinity aquifer in the direction of the Edwards (BFZ) aquifer. As we discussed in the discharge section, a single, defensible number has not been established for this flow. However, this volume may not be unreasonable.

During calibration, we found that the stability of the model was very sensitive to the structure in Gillespie County where the layers pinch out against the Llano Uplift. To increase the stability of the model, we made considerable adjustments to smooth the structure in this area.

Sensitivity Analysis

After we calibrated the model, we performed a formal sensitivity analysis on the different parameters. We found that recharge, horizontal hydraulic conductivity of the Middle Trinity aquifer, and vertical hydraulic conductivity of the Upper Trinity aquifer had the most effect on model results. Recharge and horizontal hydraulic conductivity of the Middle Trinity aquifer affected results in the entire model area while vertical hydraulic conductivity of the Upper Trinity aquifer mostly affected water levels in the western part of the model area. Conductances for the drains and general-head boundary were large enough that relative changes had little effect on water levels in the model.

We also did a sensitivity analysis on the lower boundary condition. When we developed the model, we assumed no flow between the Middle and Lower Trinity aquifers. To test this assumption in the outcrop area where some water may recharge the

Lower Trinity aquifer, we raised the recharge rate in the area of the model where the Hammett shale does not exist in the northwestern part of the study area. We found that doubling the recharge in this area had little impact on water levels in the rest of the model.

Transient Model

Once we calibrated the steady-state model for conditions in the winter of 1975-1976, we then calibrated the model for transient conditions in 1996 and 1997. Because of the time gap between the end of 1975 and the beginning of 1996, we first needed to develop an initial condition appropriate for the beginning of 1996. To develop this initial condition, we ran the calibrated steady-state model using recharge for 1995 and pumping for 1996 and gauged the relevance of the resulting water levels to water levels measured in early 1996. Because the aquifer was not in equilibrium with 1996 pumping rates in Travis and Bexar counties, we artificially lowered pumping rates in these areas by trial-and-error to develop a more representative water-level surface (RMS = 61-ft). This surface served as the initial condition for the 1996 to 1997 transient simulations.

Calibration and Verification

Using monthly time steps, we simulated water-level fluctuations according to recharge and pumping variations in 1996 and 1997. To calibrate, we adjusted specific-storage values until the model approximately reproduced the range of water-level fluctuations observed in wells in the model area. We assumed uniform values of specific storage in each layer. We found that specific-storage values of 0.00001, 0.000001, and 0.0000001 ft^{-1} for layers 1, 2, and 3, respectively, and specific-yield values of 0.008, 0.0005, and 0.0008 for layers 1, 2, and 3, respectively, worked best for reproducing observed water-level fluctuations. The calibrated specific-yield values are consistent with porosity of fractured rocks (0.01 to 0.0001 [Freeze and Cherry, 1979, p. 408]).

The model does a good job of matching observed water-level fluctuations in some areas and not as well in matching water-level fluctuations in other areas (fig. 16, note that baseline shift in water levels is due to error in the steady-state model). Differences may be due to the influence of local-scale conditions not represented in the regional model or errors in our parameterization of the aquifer data. Although there are limitations, the model does a good job in most wells of reproducing seasonal and year-to-year variations and accurately representing areas where wells respond quickly and substantially to variations in recharge and areas where the response is much more subdued.

Limitations of the Model

All numerical groundwater flow models have limitations. These limitations are usually associated with (1) the quality and quantity of input data, (2) assumptions and simplifications used to develop the conceptual and numerical models, and (3) the scale of application of the model.

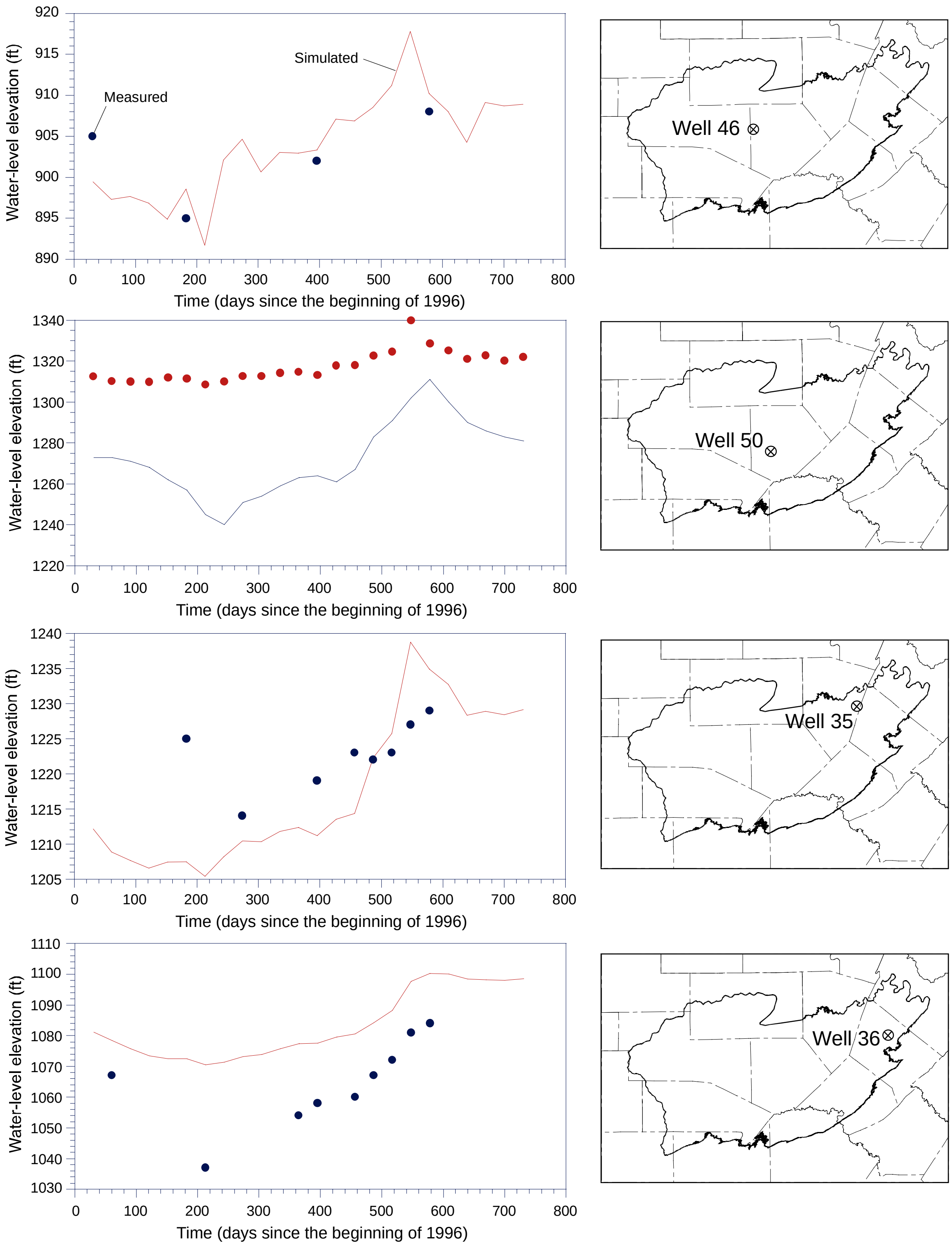

Figure 16. Comparison of simulated water-level fluctuations to measured water-level fluctuations in several wells in the Middle Trinity aquifer.

Input Data

Several of the input data sets for the model are based on limited information. Hydraulic properties, especially for layers 1 and 2, are limited. Although the current data may be fine for the regional model, they are probably not applicable for local-scale conditions. Recharge rates, both the amount and the areal distribution, are limited because they are based on a baseflow analysis that does not cover the entire model area and only one year of data. In addition, we assume that the relationship between precipitation and recharge is linear. This relationship may be nonlinear. Therefore, we may be underestimating or overestimating recharge in years with different amounts of precipitation. Our current distribution of recharge is based on basins. Local attributes, such as soil type and topography, may control recharge at a smaller-than-basin scale.

Our structure maps simplify faulting on the southeastern side of the model and smooth out the base of the Middle Trinity aquifer in the northern part of the model. This simplification causes the model to not accurately represent structural control on local groundwater flow in these areas. Water-level maps are affected by limited data, especially in layers 1 and 2 where there are few measurements. Layer 3 has the greatest number of measurements, but not many in the western and north-eastern parts of the model. Limited water-level measurements biases model calibration to areas where water levels have been measured.

Assumptions

We used several assumptions to simplify construction of the model. The most important assumptions are: (1) there is no flow between the Middle and Lower Trinity aquifers, (2) the Drain Package of MODFLOW can be used to simulate discharge to streams and rivers, and (3) the GHB Package of MODFLOW can be used to simulate discharge to the Edwards aquifer.

Most of the bottom of the model is underlain by the Hammett Shale (Amsbury, 1974; Barker and Ardis, 1996), which is relatively impermeable and serves as a hydrologic barrier between the Lower and Middle Trinity aquifers (Ashworth, 1983, p. 27). However groundwater flow between the Middle and Lower Trinity aquifers occurs in some parts of the study area. In the outcrop area of the Middle Trinity aquifer in Gillespie County, some of the recharge moves into the Lower Trinity aquifer. We tested the sensitivity of the model to increased recharge (a part of which would move into the Lower Trinity aquifer) and found that the model was not sensitive to increased recharge in this area. Some groundwater likely moves from the Middle Trinity aquifer into the Lower Trinity aquifer through the Hammett Shale. However, the volume of flow is probably small compared to flow through the rest of the aquifer.

Using the Drain Package of MODFLOW to simulate streams and rivers does not accurately represent the interaction of surface water and groundwater. Using the Drain Package, no water is lost to the aquifer when the water level in the aquifer falls below the base of the stream. In reality, when water levels decline beneath a flowing stream, that stream will lose some of its water to the aquifer. Under current hydrologic conditions, this occurs in Cibolo Creek where it crosses the Lower Glen Rose Formation between Boerne and Bulverde. Consistent with field observations, drains that represent Cibolo Creek in the current model gain water upstream of Boerne and downstream from Bulverde but gain no water between the two towns. However, flow that moves past Boerne and leaks into the Lower Glen Rose is not represented in the current model. Essentially, the current model does not model groundwater flow in this part of the aquifer. This may be appropriate as some believe that the lower member of the Glen Rose Limestone in this area should actually be considered part of the Edwards (BFZ) aquifer formations (George, 1947; Pearson and others, 1975; Veni 1994, 1995).

Using the GHB Package along the boundary with the Edwards (BFZ) aquifer assumes that the hydraulic head at this boundary is constant. This is fine for the steady-state simulation and appears to be fine for the transient simulation in 1996 to 1997. However, this boundary condition may not be reasonable as pumping continues and increases in future years. Leaving this boundary as it is will probably cause the model to underestimate water levels in future years.

Scale of Application

The limitations described above and the inherent nature of regional groundwater flow models affect the scale of application of the model. This model is most accurate in assessing regional-scale groundwater issues such as predicting aquifer-wide water-level declines over the next fifty years and the relative comparison of water management scenarios. Accuracy and applicability of the model decreases when moving from the regional to the local scale. This is due to data limitations (described above) and the 1-mile by 1-mile size of the cells in the model. For example, the model will not accurately predict water-level declines around a single well in a community. These water-level declines are too dependent on site-specific hydraulic properties: information the model does not include. The model is more likely to accurately predict water-level declines of a group of wells in a general area. The accuracy of model predictions is partially a function of the hydraulic data for the area.

The model predicts declines in ambient water levels in the aquifer due to pumping, not the actual water-level decline in an individual well (which will be much larger).

Future Work

Additional work can be done to improve the performance and accuracy of the model, and we are currently addressing several issues before the final model is published. Future work involves (1) developing predictive data sets, (2) making short-term model enhancements, and (3) making long-term model enhancements. We are currently continuing work on the first two items.

Developing the predictive datasets and adjusting the model to consider the predictive datasets is an important task to make predictions of water levels in the aquifer in response to current and future pumping and droughts. This task completes the overall goal of developing the model to be used as a management and water-planning tool. The predictive model requires datasets for future pumping and recharge. We are currently developing predictions of future pumping based on TWDB estimates and demand numbers from the Regional Water Planning Groups. The pumping will be distributed according to the pumping distribution for 1997. We will also analyze historical climate data to generate recharge for average and drought conditions. We will also investigate substituting the GHB boundary condition with a more realistic boundary condition for future withdrawals.

We are also working on or plan to work on several short-term model enhancements on hydraulic properties, structure surfaces, and recharge. We have compiled specific-capacity data from well files at the TNRCC and need to estimate transmissivity from this information and possibly include the new values in the model. We will also review a few anomalies in the structure to ensure that they are realistic. Finally, we plan to conduct a long-term baseflow analysis to better characterize basin-scale recharge.

There are also several long-term improvements that we recommend eventually be considered including (1) more structure refinements, (2) adding the Lower Trinity aquifer, (3) better spatial distribution of the recharge, (4) refinement of hydraulic properties, and (5) further studies on cross-formational flow. The structure of the layers could use more refinement, especially along the Balcones fault zone and in Gillespie County. The Lower Trinity aquifer is an important source of groundwater in western part of the study area and is becoming more important in other parts of the aquifer. Therefore, the model should be expanded vertically to include the Lower Trinity aquifer. A model with the Lower Trinity aquifer could be used to investigate cross-formational flow between the Lower and Middle Trinity aquifer. Recharge could be better distributed to account for differences in geology, soils, and other geomorphic parameters. Layers 1 and 2 and many areas of layer 3 could use more information on hydraulic properties. Further studies on cross-formational flow from the Trinity aquifer to the Edwards (BFZ) aquifer would help better define hydraulic properties and recharge in the Trinity aquifer.

Conclusions

The Trinity aquifer is an important source of groundwater in the Hill Country area. We developed a numerical groundwater flow model using MODFLOW that can be used to predict water levels in response to pumping and potential future droughts. The model has three layers (Edwards Group in the plateau area, the Upper Trinity aquifer, and the Lower Trinity aquifer) and 9,262 active cells. We developed the conceptual model of groundwater flow and assigned model input parameters based on a review of previous work and studies we conducted on water levels, structure, recharge, and hydraulic properties in support of the model. Our modeling approach included developing (1) a steady-state model for 1975 hydrologic conditions when the aquifer was near steady-state and (2) a transient model for 1996 and 1997 when the climate transitioned from a dry to a wet period.

The calibrated model does a reasonable job of matching the water-level distribution and water-level fluctuations in the aquifer (RMS error is 56-ft, about five percent of the hydraulic head drop across the study area). Honoring the measured values of hydraulic conductivity in the Middle Trinity aquifer results in an average recharge rate that is about four percent of mean annual precipitation. Water levels in the model are most sensitive to changes in (1) recharge, (2) horizontal hydraulic conductivity of the Middle Trinity aquifer, and (3) vertical hydraulic conductivity of the Upper Trinity aquifer. The model predicts that about 64,000 acre-ft yr^{-1} of water moves from the Upper and Middle Trinity aquifers in the direction of the Edwards (BFZ) aquifer. We also calibrated values of vertical hydraulic conductivity, specific storage, and specific yield for the aquifer. Limitations of the input data, assumptions, and scale limit the accuracy and applicability of the model. Future work includes (1) developing predictive datasets for pumping and recharge, (2) enhancing the recharge, structure, hydraulic properties datasets, and (3) using the model to predict water levels in the aquifer.

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Acronyms

BFZ	Balcones Fault Zone
GHB	General-head boundary
RMS	Root-mean squared
TNRCC	Texas Natural Resource Conservation Commission
TWDB	Texas Water Development Board
USGS	United States Geological Survey
WUD	Water Use Division

References

Amsbury, D. L., 1974, Stratigraphic petrology of Lower and Middle Trinity rocks on the San Marcos platform, south-central Texas: in Perkins, B. F., ed., Aspects of Trinity division geology- a symposium: Louisiana State University, Geoscience and Man, v. 8, p. 1-35.

Anderson, M. P., and Woessner, W. W., 1992, Applied groundwater modeling- Simulation of flow and advective transport: Academic Press, Inc., San Diego, 381 p.

Ardis, A. F., and Barker, R. A., 1993, Historical saturated thickness of the Edwards-Trinity aquifer system and selected contiguous hydraulically connected units, west-central Texas: U.S. Geological Survey Water-Resources Investigation Report 92-4125, 2 plates.

Arnold, J. G., Allen, P. M., Muttiah, R., and Bernhardt, G., 1995, Automated base flow separation and recession analysis techniques: Ground Water, v. 33, no. 6, p. 1010-1018.

Ashworth, J. B., 1983, Ground-water availability of the Lower Cretaceous formations in the Hill Country of south-central Texas: Texas Department of Water Resources Report 273, 173 p.

Ashworth, J. B., and Hopkins, Janie, 1995, Aquifers of Texas: Texas Water Development Board Report 345, 69 p.

Barker, R. A. and Ardis, A. F., 1992, Configuration of the base of the Edwards-Trinity aquifer system and hydrogeology of the underlying pre-Cretaceous rocks, west central Texas: U.S. Geological Survey Water Resources Investigation Report 91-4071, 25p.

Barker, R. A., and Ardis, A. F., 1996, Hydrogeologic framework of the Edwards-Trinity aquifer system, west-central Texas: U.S. Geological Survey Professional Paper 1421-B, 61 p. with plates.

Barker, R. A., Bush, P. W., and Baker, E. T., Jr., 1994, Geologic history and hydrogeologic setting of the Edwards-Trinity aquifer system, west central Texas: U.S. Geological Survey Water Resources Investigation Report 94-4039, 50p.

Barrett, M. E., and Charbeneau, R. J., 1996, A parsimonious model for simulation of flow and transport in a karst aquifer: Center for Research in Water Resources, The University of Texas at Austin, Technical Report CRWR 269, 149 p.

Bluntzer, R. L., 1992, Evaluation of Ground-water Resources of the Paleozoic and Cretaceous Aquifers in the Hill Country of Central Texas: Texas Water Development Board Report 339, 130 p.

Bradley, R. G., Coker, D. B., and Moore, S. W., 1997, Data and results from an aquifer test performed at the Medina Water Supply Corporation well field, Medina, Texas: Texas Water Development Board Open-File Report 97-02, 25p.

Bush, P. W., Ardis, A. F., and Wynn, K. H., 1993, Historical potentiometric surface of the Edwards-Trinity aquifer system and contiguous hydraulically connected units, west-central Texas: U.S. Geological Survey Water-Resources Investigations Report 92-4055, 3 sheets.

Carr, J. T., Jr., 1967, The climate and physiography of Texas: Texas Water Development Board Report 53, 27 p.

Chiang, W.-H., and Kinzelbach, Wolfgang, 1998, Processing Modflow- A simulation system for modeling groundwater flow and pollution: software manual, 325 p.

Cooper, H. H., Jr., and Jacob, C. E., 1946, A generalized graphical method for evaluating formation constants and summarizing well field history: American Geophysical Union Transactions, v. 27, p. 526-534.

Espey, Huston, and Associates, 1982, Feasibility study of recharge facilities on Cibolo Creek: Draft consulting report to the Edwards Underground Water District, 56 p.

ESRI, 1991, ARC/INFO, Version 6.0: Environmental Systems Research Institute, Inc., Redlands, California.

Freeze, R. A., and Cherry, J. A., 1979, Groundwater: Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 604 p.

George, W. O. ,1947, Geology and ground-water resources of Comal County, Texas: Texas Board of Water Engineers, 142 p.

Golden Software, 1995, Surfer for Windows, Version 6, Contouring and 3D surface mapping: Golden Software, Inc., Golden, Colorado, variously paginated.

Guyton, W. F. , and Associates, 1958, Memorandum on ground-water gains in upper Cibolo Creek area: Consulting report to the San Antonio City Water Board, 8 p.

Guyton, W. F. , and Associates, 1970, Memorandum on Cibolo Creek studies: Consulting report to the San Antonio City Water Board, 17 p.
Hammond, W.W., 1984, Hydrogeology of the Lower Glen Rose Aquifer, South-Central Texas: Ph.D. dissertation, The University of Texas at Austin. 243 p.
Harbaugh, A.W., and McDonald, M.G., 1996, User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96-485, 56 p.
Kastning, E. H., 1986, Cavern development in the New Braunfels area, central Texas: in Abbott, P. L., and Woodruff, C. M., Jr., eds., The Balcones escarpment, geology, hydrology, ecology and social development in central Texas: Geological Society of America, p. 91-100.
Klemt, W. B., Knowles, T. R., Elder, G. R., and Sieh, T. W., 1979, Ground-water resources and model applications for the Edwards (Balcones Fault Zone) aquifer in the San Antonio region, Texas: Texas Department of Water Resources Report 239, 88 p.
Kruseman, G. P., and de Ridder, N. A., 1994, Analysis and evaluation of pumping test data, second edition: International Institute for Land Reclamation and Improvement, The Netherlands, 377 p.
Kuniansky, E.L., 1989, Precipitation, streamflow, and baseflow, in west-central Texas, December 1974 through March 1977: U.S. Geological Survey Water-Resources Investigations Report 89-4208, 2 sheets.
Kuniansky, E. L., 1990, Potentiometric surface of the Edwards-Trinity aquifer system and contiguous hydraulically connected units, west-central Texas, winter 1974-75: U.S. Geological Survey Water-Resources Report 89-4208, 2 sheets.
Kuniansky, E. L., 1994, Multilayer finite-element model of the Edwards and Trinity aquifers, Central Texas, *in* Dutton, A. R., ed., Toxic substances and the hydrologic sciences: American Institute of Hydrology, p. 234–249.
Kuniansky, E. L., and Holligan, K. Q.,1994, Simulations of flow in the Edwards–Trinity aquifer system and contiguous hydraulically connected units, west-central Texas: U. S. Geological Survey Water-Resources Investigations Report 93-4039, 40 p.
LBG-Guyton Associates, 1995, Edwards/Glen Rose hydrologic communication, San Antonio region, Texas: final report submitted to the Edwards Underground Water District, 38p. with 7 tables, 13 figures and 4 appendices.
Long, A. T., 1962, Ground-water geology of Edwards County, Texas: Texas Water Commission Bulletin 6208, 123 p.
Lowry, R. L., 1955, Recharge to Edwards ground-water reservoir: Consulting report to the San Antonio City Water Board, 66 p.
Lurry, D. L., and Pavlicek, D. J., 1991, Withdrawals from the Edwards-Trinity aquifer system and contiguous hydraulically connected units, west-central Texas, December 1974 through March 1977: U.S. Geological Survey Water-Resources Investigations Report 91-4021, 1 sheet.
Maclay, R. W., and Land, L. F., 1988, Simulation of flow in the Edwards aquifer, San Antonio Region, Texas, and refinements of storage and flow concepts: U. S. Geological Survey Report Water-Supply Paper 2336, 48 p.

Maclay, R. W., and Small, T. A., 1986, Carbonate geology and hydrology of the Edwards aquifer in the San Antonio area, Texas: Texas Water Development Board Report 296, 90 p.
McDonald, M. G. and A. W. Harbaugh, 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, variously paginated.
Meyers, B.N., 1969, Compilation of results of aquifer tests in Texas: Texas Water Development Board Report 98, 532 p.
Muller, D. A. and Price, R. D., 1979, Ground-water Availability in Texas, Estimates and Projections Through 2030: Texas Department of Water Resources Report 238, 77 p.
Nathan, R. J., and McMahon, T. A., 1990, Evaluation of automated techniques for baseflow and recession analysis: Water Resources Research, v. 26, no. 7, p. 1465-1473.
Pearson, F. J., Jr., Rettman, P. L., and Wyerman, T. A., 1975, Environmental tritium in the Edwards Aquifer, central Texas, 1963-71: U.S. Geological Survey Open-File Report 74-362, 32 p.
Riggio, R. F., Bomar, G. W., and Larkin, T. J., 1987, Texas drought- its recent history (1931-1985): Texas Water Commission LP 87-04, 74 p.
Senger, R. K., and Kreitler, C. W., 1984, Hydrogeology of the Edwards Aquifer, Austin area, Central Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 141, 35 p.
Slade, R. M., Jr., Ruiz, Linda, and Slagle, Diana, 1985, Simulation of the flow system of Barton Springs and associated Edwards Aquifer in the Austin area, Texas: U.S. Geological Survey Water-Resources Investigations Report 85-4299.
Stein, E. G., and Klemt, W. B., 1995, Edwards/Glen Rose hydrologic communication, San Antonio region, Texas: report prepared for the Edwards Underground Water District by LBG-Guyton Associates, Austin, TX, variously paginated.
Theis, C. V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage: American Geophysical Union Transaction, v. 16, p. 519–524.
Theis, C. V., 1963, Estimating the transmissivity of a water-table aquifer from the specific capacity of a well: U.S. Geological Survey Water Supply Paper 1536-I, p. 332-336.
Torak, L. J., 1993, A Modular Finite-Element model (MODFE) for areal and axisymmetric ground-water-flow problems. Part 1, model description and user's manual: U.S. Geological Survey Open-file report 90-194, 153 p.
Veni, G., 1994, Geomorphology, hydrology, geochemistry, and evolution of karstic Lower Glen Rose aquifer, south-central Texas: Pennsylvania State University, Ph.D. Dissertation, 712 p.
Veni, G., 1995, Revising the boundaries of the Edwards (Balcones Fault Zone) aquifer recharge zone: Water for Texas, Proceedings of the 24th Water for Texas Conference, p. 99-107.
Walker, L. E., 1979, Occurrence, availability, and chemical quality of ground water in the Edwards Plateau Region of Texas: Texas Department of Water Resources Report 235, 336 p.

Wanakule, Nisai, and Anaya, Roberto, 1993, A lumped parameter model for the Edwards aquifer: Texas A&M University, Texas Water Resources Institute, Technical Report No. 163, 84 p.

Waterreus, P. A., 1992, Hydrogeology of the Camp Bullis area, northern Bexar County, Texas: Master's thesis, The University of Texas at San Antonio, 186 p.

W.E. Simpson Company, Inc. and W.F. Guyton Associates, Inc., 1993, North Bexar County Water Resources Study for the Edwards Underground Water District: v. 1 and 2, unpaginated.

Woodruff, C. M., Jr., and Abbott, P. L., 1986, Stream piracy and evolution of the Edwards aquifer along the Balcones escarpment, Central Texas: in Abbott, P. L., and Woodruff, C. M., Jr., The Balcones Escarpment, Central Texas: Geological Society of America, p. 77-90.