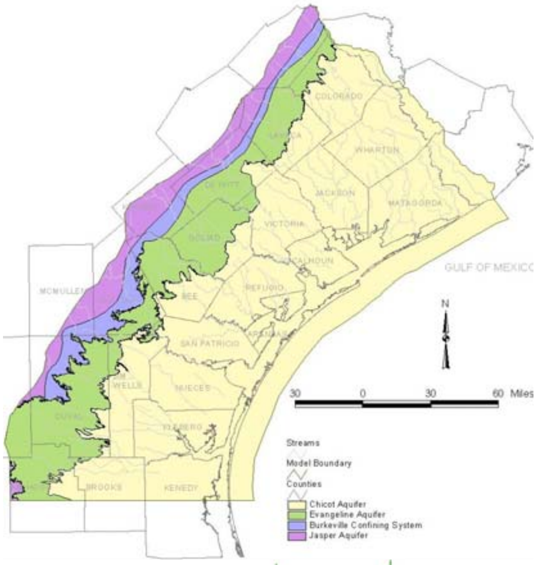
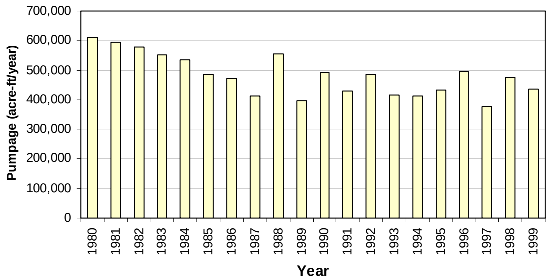
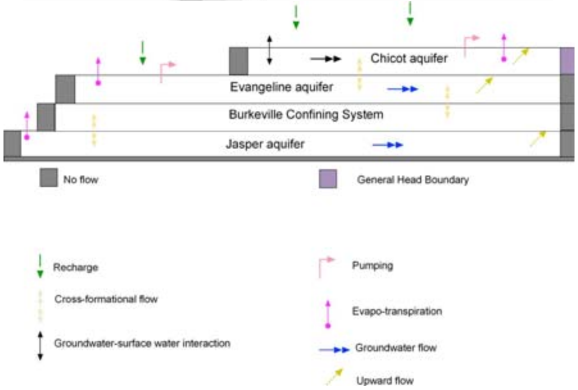
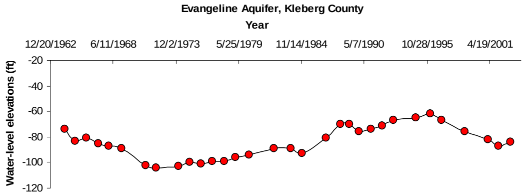
Groundwater Availability Model of the Central Gulf Coast Aquifer System: Numerical Simulations through 1999

Model Report









by

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ABSTRACT

We recalibrated the Central Gulf Coast Groundwater Availability Model (GAM) to water-levels and stream flows for the pre-development (1910 to 1940) and the calibration years (1980 to 1999) using Texas Water Development Board estimates of pumpage and pumpage distribution. We adjusted horizontal hydraulic conductivity of the Evangeline and Jasper aquifers, vertical leakance of the Chicot aquifer, and storage parameters to recalibrate the model. The original calibrated recharge in the model is similar to published values. Therefore, we did not change recharge during recalibration.

Recalibration of the model generally reproduces the spatial distributions of water-levels and water-level changes in well hydrographs. The model reproduces drawdown cones in Wharton, Victoria, and Kleberg counties in 1989 and 1999. To reproduce the drawdown cones, we adjusted horizontal hydraulic conductivity of the Evangeline aquifer to reflect partial penetration of a large percentage of the wells in the aquifer. Therefore, the transmissivity of the Evangeline aquifer in the recalibration could locally be somewhat lower than what has been used in other Gulf Coast models. The root mean squared error (RMSE) for calibration of the pre-development model is about 21 feet which is about 5 percent of the hydraulic head drop (change in water-level elevation) across the model area.

The pre-development model suggests that about 620,000 acre-ft of water flows annually through the central Gulf Coast aquifer. Of this flow, 30 percent sources from rainfall, and 69 percent seeps into the aquifer from streams and remaining 1 percent from the reservoirs. Water levels in the model are sensitive to horizontal hydraulic conductivity, recharge, and vertical leakance. The model appears more sensitive to lower rather than higher recharge because excess recharge escapes as baseflow to the streams and/or wetlands. Including the release of water from storage, about 1,041,581 acre-ft of water flowed through the central Gulf Coast aquifer in 1989. Including the release of water from storage, about 890,000 acre-ft of water flows through the central Gulf Coast aquifer system in 1999. Recovery of water levels in 1999 causes less water to be released from

storage. This recovery in water levels also results in an increase in stream discharge in 1999.

The model should not be used to assess well fields where wells are completed through the entire thickness of the Evangeline aquifer because calibrated hydraulic conductivity of the Evangeline aquifer takes into account partial completion issues of wells in this aquifer.

1 Introduction

Waterstone Environmental Hydrology and Engineering Inc. developed a draft Central Gulf Coast Groundwater Availability Model (GAM) (Waterstone, 2003). We took this model and recalibrated it using Texas Water Development Board (TWDB) estimates of pumpage and pumpage distribution. In addition, we developed water-level surfaces for the pre-development (1910 to 1940) and the calibration years (1980 to 1999) to make calibration targets more consistent with information contained in the TWDB Groundwater Database and earlier published work (Shafer and Baker, 1973).We also compared the water-level information with the bottom elevations of the model layers to determine whether the wells actually belong to the model layer as indicated in the TWDB Groundwater Database.

In this report, we include information on measured water-levels, hydrographs, transmissivity of the Evangeline aquifer, vertical leakance of the Chicot aquifer, and historical groundwater pumping. Our general approach included (1) calibrating a pre-development model to water levels and stream flows for 1910 through 1940 and (2) calibrating a transient model for water levels and stream flows in 1989 and 1999. We describe in this report (1) study area, (2) spatial and temporal distribution of water levels and their changes in well hydrographs, (3) streamflow characteristics, (4) recharge and discharge relationships, (5) steady-state and transient calibration results, and (6) model sensitivity to calibrated parameters.

Information on predictive pumpage and simulated predictive water-levels will be included in this report by the end of December, 2004. A complete final report, including conceptual model information from Waterstone (2003), will be made available in early 2005.

1.1 Study Area

The central Gulf Coast GAM boundary is defined by (1) the limits of the outcrop areas in the west, (2) Gulf of Mexico in the east, (3) groundwater divide to the north through

Colorado-Fort Bend-Brazoria counties, and (4) groundwater divide to the south through Jim Hogg, Brooks, and Kenedy counties (Figure 1).

Each model layer has 177 rows and 269 columns for a total of 190,452 cells. Cells were made inactive when they fell outside the model area or when they were less than 50 feet in thickness because they were found to cause convergence problems during calibration (Waterstone, 2003). The model has a total of 56,736 active cells. Each cell in the model has a lateral dimension of 1 mile. The model has four layers which from top to bottom are (1) the Chicot aquifer, (2) the Evangeline aquifer, (3) the Burkeville Confining System, and (4) the Jasper aquifer. The Catahoula Confining System, containing mainly impermeable volcanic tuff, forms the base of the model (Figure 2). The model area includes all or parts of several confirmed groundwater conservation districts (GCDs) including (1) Fort Bend Subsidence District, (2) Texana GCD, (3) Bluebonnet GCD, (4) Bee GCD, (5) Evergreen Underground Water Conservation District (UWCD), (6) Live Oak UWCD, (7) McMullen GCD, (8) Gonzales County UWCD, (9) Coastal Bend GCD, (10) Coastal Plains GCD, (11) Lost Pines GCD, (12) Goliad County GCD, (13) Refugio GCD, (14) Pecan Valley GCD, and (15) Fayette County GCD (Figure 3). The model area also includes all or parts of several regional water planning groups (RWPGs) including (1) Region H, (2) Lower Colorado (Region K), (3) Lavaca, (4) South Central Texas (Region L), (5) Coastal Bend, and (6) Rio Grande (Figure 3).

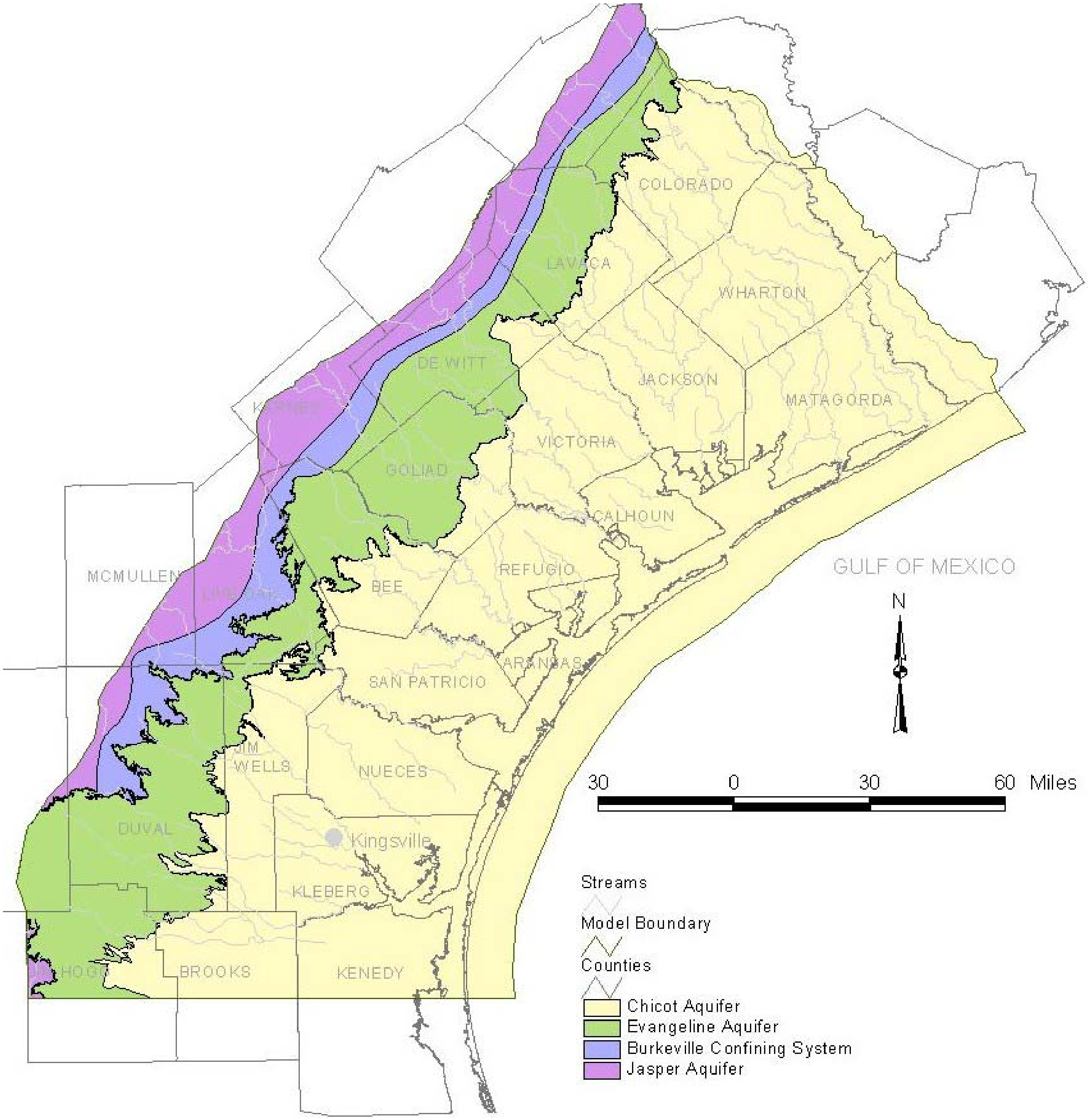
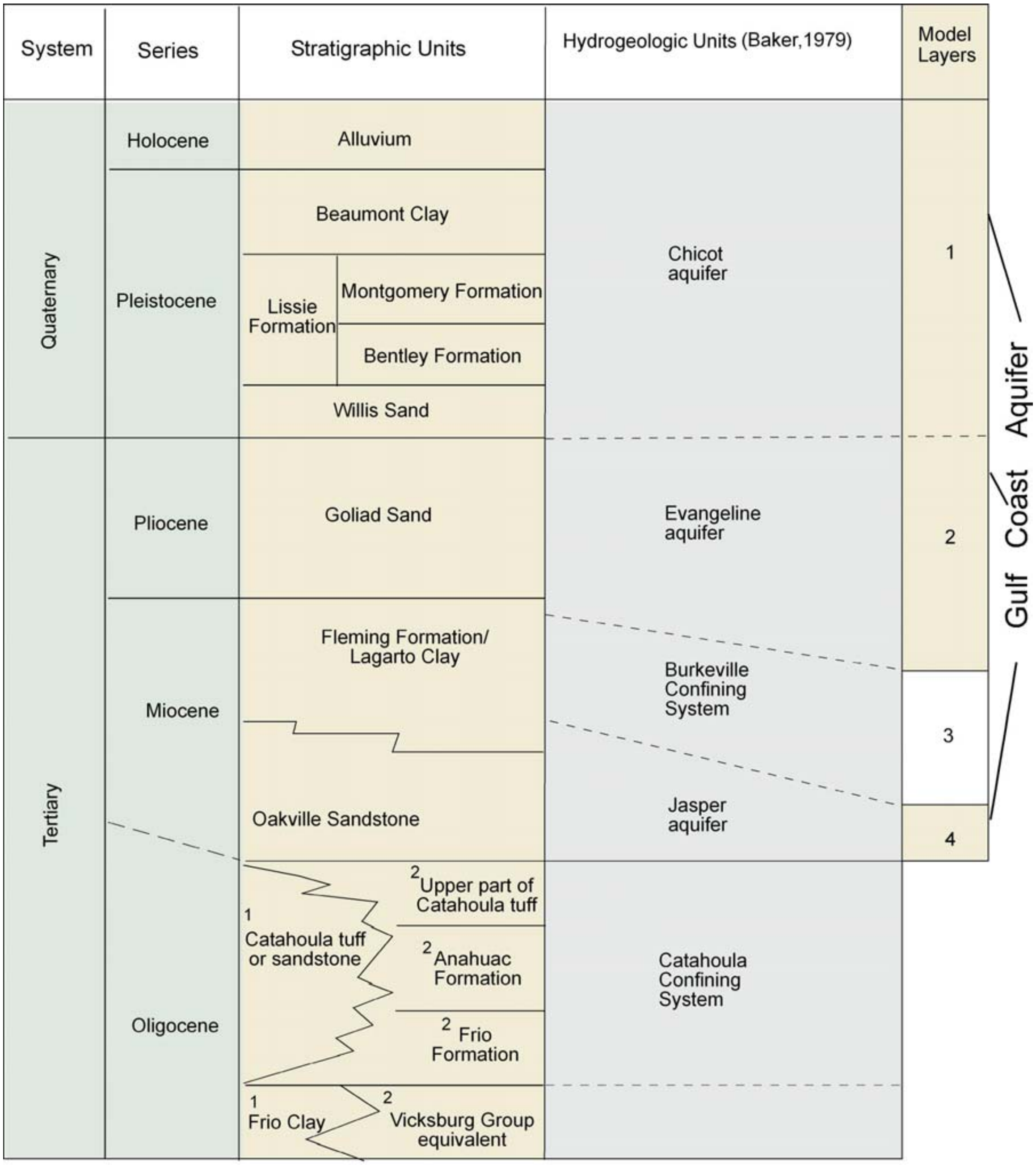


Figure 1: Map showing the limits of the outcrop areas, model boundaries, and counties within the study area.



1 = outcrop
2 = subsurface
* includes the Lower Rio Grande Groundwater Reservoir

Figure 2. Stratigraphy of the Gulf Coast aquifer showing hydrostratigraphic units and corresponding model layers.

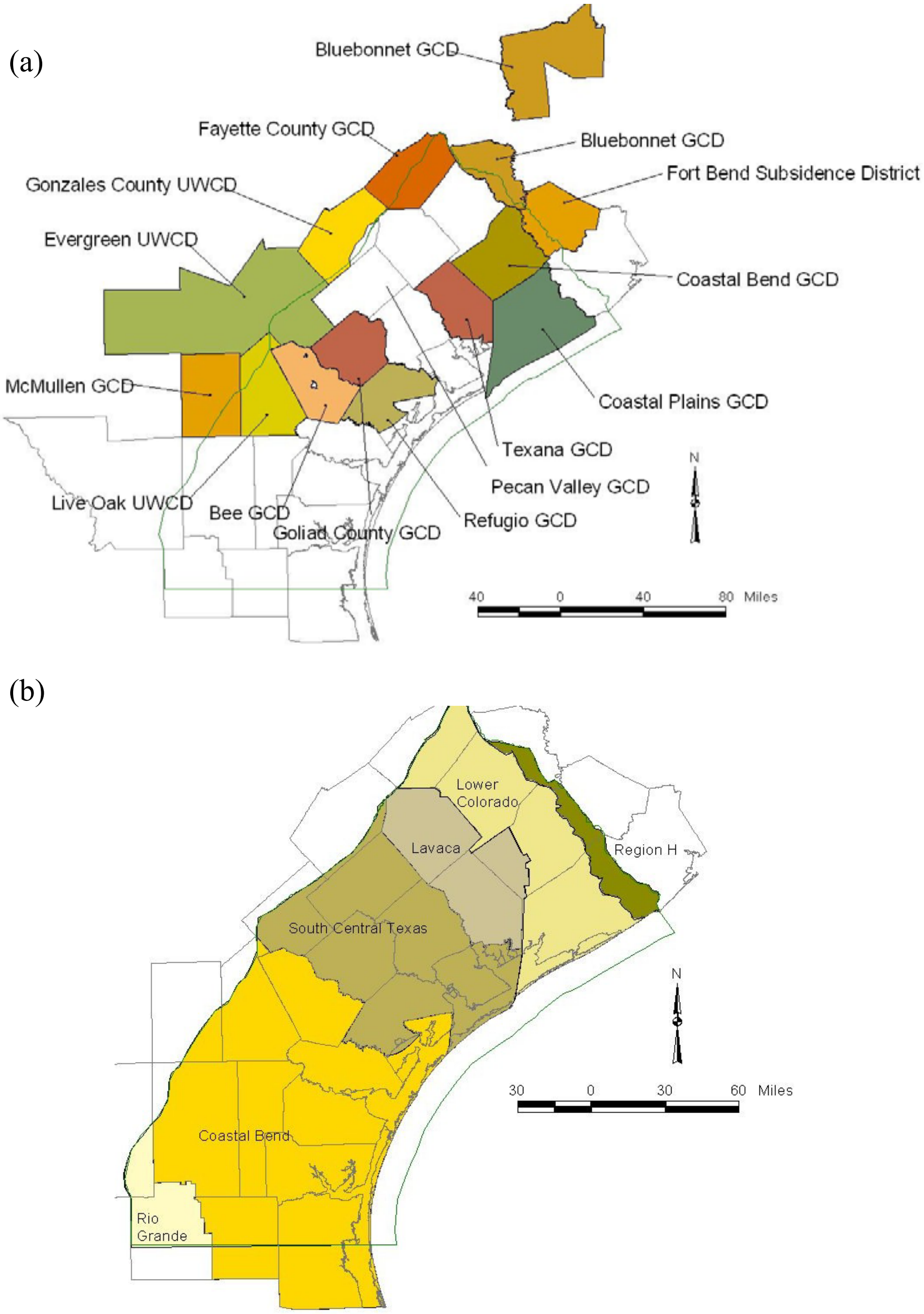


Figure 3. Map showing locations of the (a) confirmed GCDs and (b) Regional Water Planning Groups within the model area.

1.2 Water Levels and Regional Groundwater Flow

Water levels generally follow topography with higher water levels occurring at higher elevations and lower water levels at lower elevations. Natural groundwater flow systems can be described under three categories (1) shallow, (2) intermediate, and (3) regional flow systems (Toth, 1963). Toth (1963) indicated that if the relief is negligible and when there is a slope to the topography, regional flow system develops. An absence of regional slope leads to the development of predominantly local flow systems. Most of the groundwater in the shallow system moves over short distances discharging to nearby streams. Regional flow components travel over long distances through deeper sections of the basin eventually discharging at lower elevations of coastal areas. Intermediate flow components travel moderate distances between the shallow and the deep flow systems reaching nearby discharge points in the central areas of the basin.

We compiled water-level measurements from the TWDB’s water-well database and developed water-level maps for the Chicot and the Evangeline aquifers for the pre-development period. To construct the pre-development water-level maps, we selected water-level measurements from 1910 through 1940 for the Chicot and the Evangeline aquifers (Figures 4, 5) and expanded the time interval to the 1950s to include water-level measurements for the Burkeville Confining System and the Jasper aquifer. We also developed water-level maps for the Chicot and the Evangeline aquifers for 1989 and 1999 (Figures 6, 7, 8, and 9). When there were multiple water-level measurements available in a well, we selected the measurements closer towards the winter months to avoid any effect of pumping on the water levels. Only a few water-level measurements could be found on the Burkeville Confining System and the Jasper aquifer for 1989 and 1999 (Figures 10, 11).

Water generally flows from the outcrop areas in the west towards the Gulf of Mexico in the east (Figures 4, 5, 6, 7, 8, and 9). Most of the water-level contours parallel the coastline. Small variations in the values of the water-level contours over a large distance, particularly near the coastal areas, suggest flatness of the water table. Therefore, groundwater will move sluggishly from these areas towards the coast. Following Toth's (1963) classification, groundwater from these areas will have lateral flow over small distances and local discharge. Much of the water from these areas may be lost through evaporation and plant-transpiration from shallow water tables and cause occasional development of water logged (wetland) areas. The water-level map for the Chicot aquifer in 1989 show a sharp deflection of the 0 to 50 feet contours towards the coast in Wharton, Matagorda, and Jackson counties due to excessive pumping in these areas (Figure 6). Small areas in Jackson and Matagorda counties show drawdown of up to 50 feet in 1989 (Figure 6). Water levels in the Chicot aquifer in Matagorda and Victoria counties show a small recovery in 1999 compared with the previous years (Figure 8).

Water-level contours in the Evangeline aquifer lie parallel to the coastline similar to the Chicot aquifer. However, most of the water-level contours are more closely spaced in the outcrop areas suggesting a steeper slope of the water table and a relatively faster movement of groundwater flow (Figures 7, 9). There are large drawdown areas in Victoria and Kleberg counties in 1989 (Figure 7). Shafer and Baker (1973) similarly reported that the water-levels in the area have declined about 200 feet near Kingsville (Kleberg County) based on water-level measurements from 1932 to 1969. They noted a smaller cone of depression along the Jim Wells–Kleberg county line, 12 miles west-southwest of Kingsville, caused by industrial pumping from a local refinery. When we compare the water-level maps that we produced for the area for 1989 and 1999 to Shafer and Baker's (1973) map, we note that this drawdown along Jim Wells–Kleberg county line has now disappeared with the recovery of water levels in the area (Figure 9). However, drawdowns exceeding 150 feet are still prevalent in the Kingsville area.

Hydrographs show water-level fluctuations in wells due to seasonal changes in recharge and groundwater pumping. Water levels in wells generally increase during the winter and the spring months when most recharge to the aquifer occurs. Groundwater pumping lowers water levels in well hydrographs lower than would occur naturally.

Water levels in the study area show different responses over time. Some water levels show relatively little change, some show a slight recovery, and some show declines in water levels, particularly in Wharton, Victoria, and Kleberg counties (Figures 12, 13, 14, and 15). Water levels in Bee and San Patricio counties are stable over the years and show only minor changes. Wells in Victoria County may either show a decline or recovery in water levels based on their locations (Figures 12, 14). These variations in the water levels are probably due to variation in pumping rather than recharge, which has a long lag time before it affects the aquifer. Water levels in Matagorda and Victoria counties are generally recovering by 1999 (Figures 6, 7, 8, and 9).

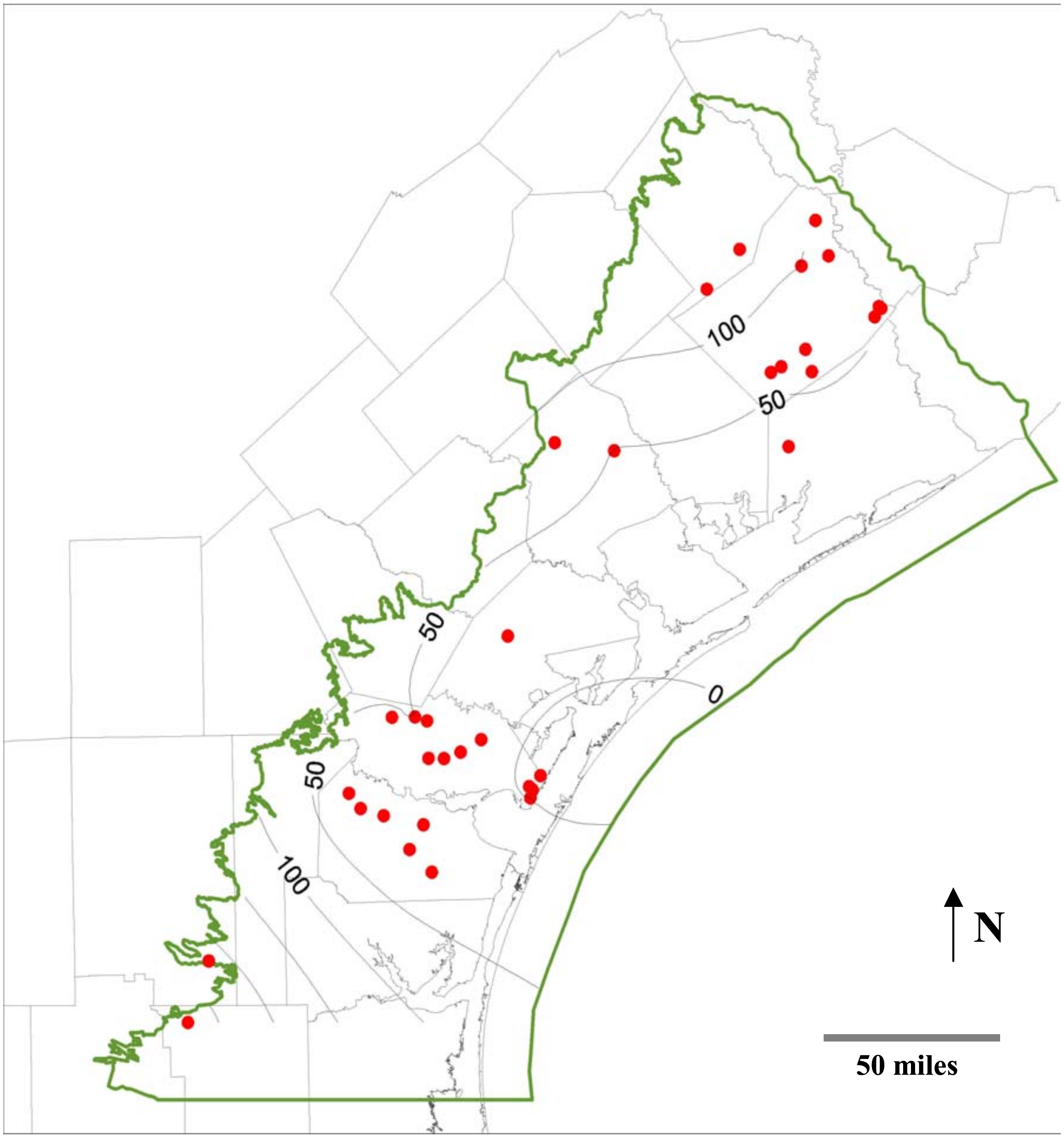


Figure 4: Water-level elevation map of the Chicot aquifer (includes water-level measurements from 1910 to 1940). Water levels are in feet and the datum is the mean sea level. Closed circles represent well control points where water levels were measured. Water-level contours were developed using the Point Kriging method in Surfer.

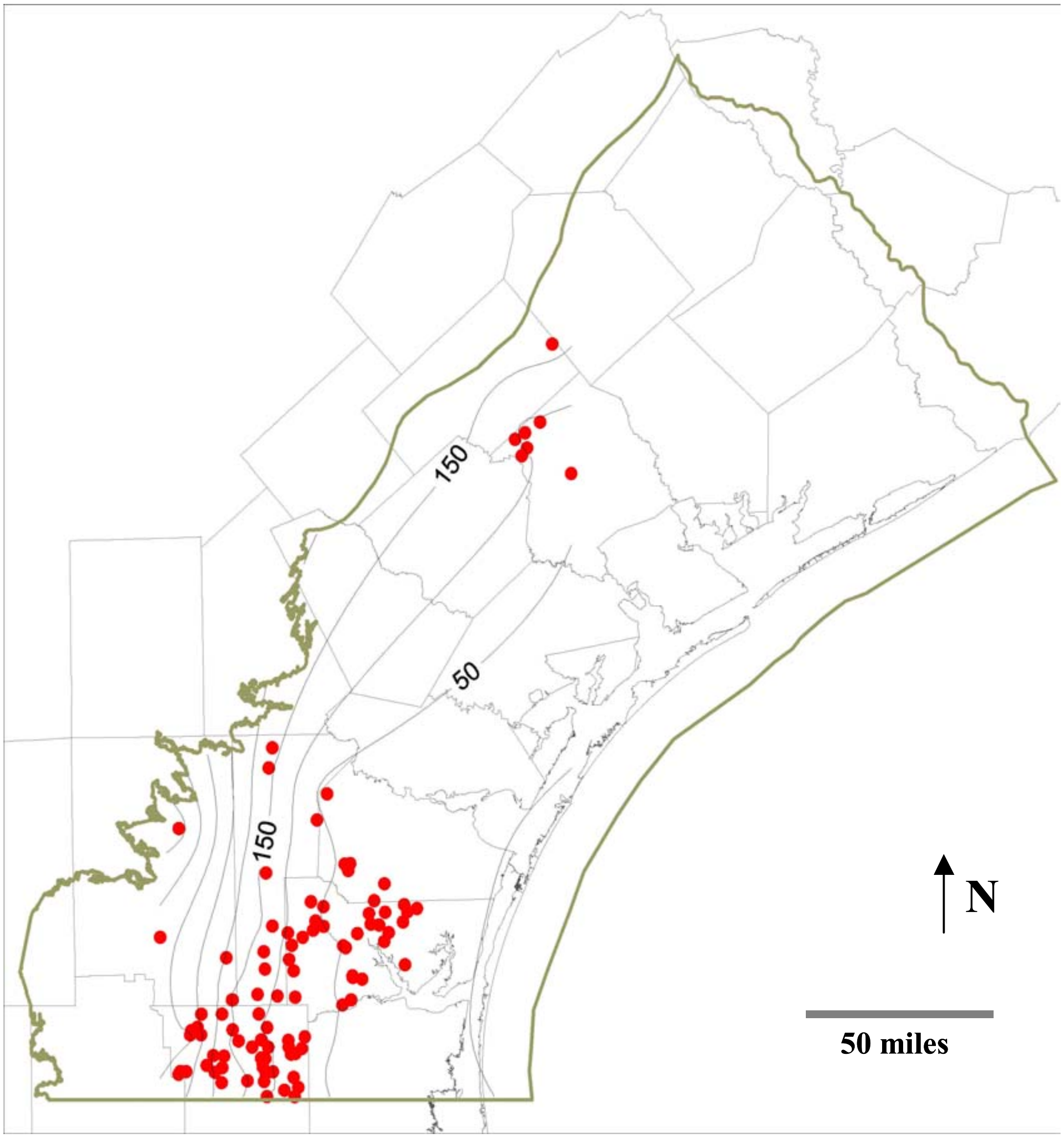


Figure 5: Water-level elevation map of the Evangeline aquifer (includes water-level measurements from 1910 to 1940). Water levels are in feet and the datum is the mean sea level. Closed circles represent well control points where water levels were measured. Water-level contours were developed using the Point Kriging method in Surfer.

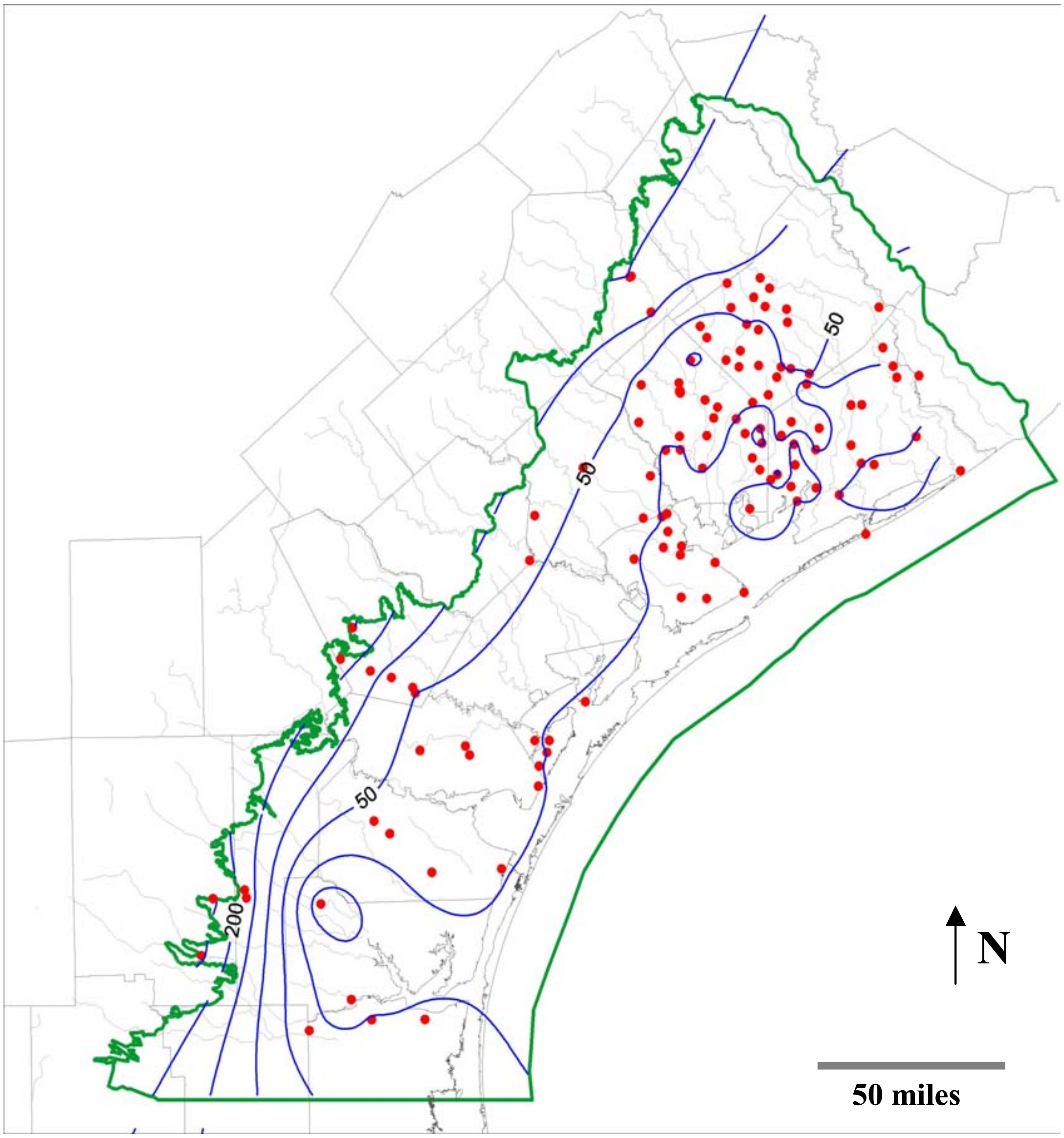


Figure 6: Water-level elevation map of the Chicot aquifer for 1989 (includes water-level measurements from January 1989 to April 1989). Water levels are in feet and the datum is the mean sea level. Closed circles represent well control points where water levels were measured. Water-level contours were developed using the Point Kriging method in Surfer.

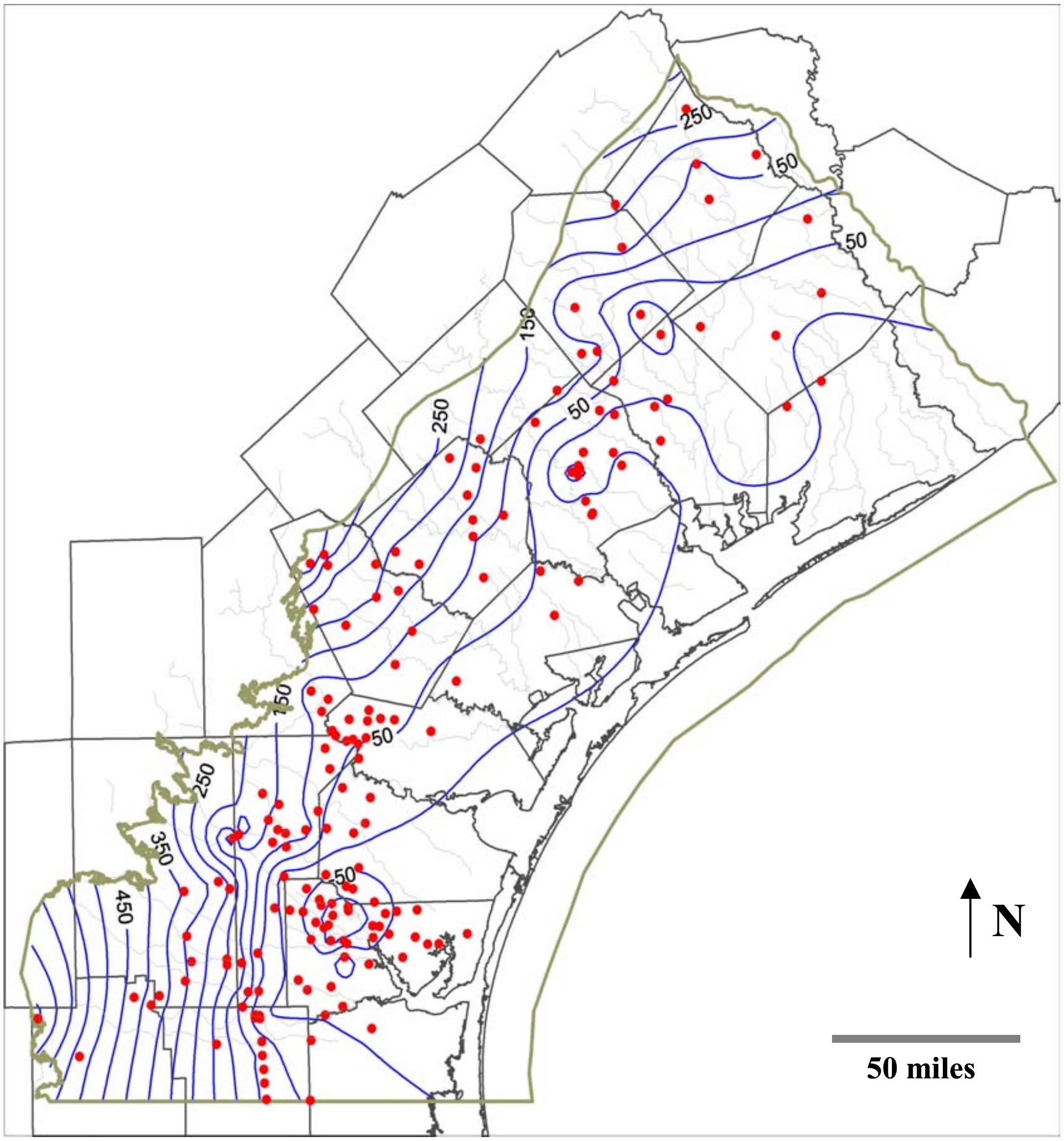


Figure 7: Water-level elevation map of the Evangeline aquifer for 1989 (includes water-level measurements from January 1989 to April 1989). Water levels are in feet and the datum is the mean sea level. Closed circles represent well control points where water levels were measured. Water-level contours were developed using the Point Kriging method in Surfer.

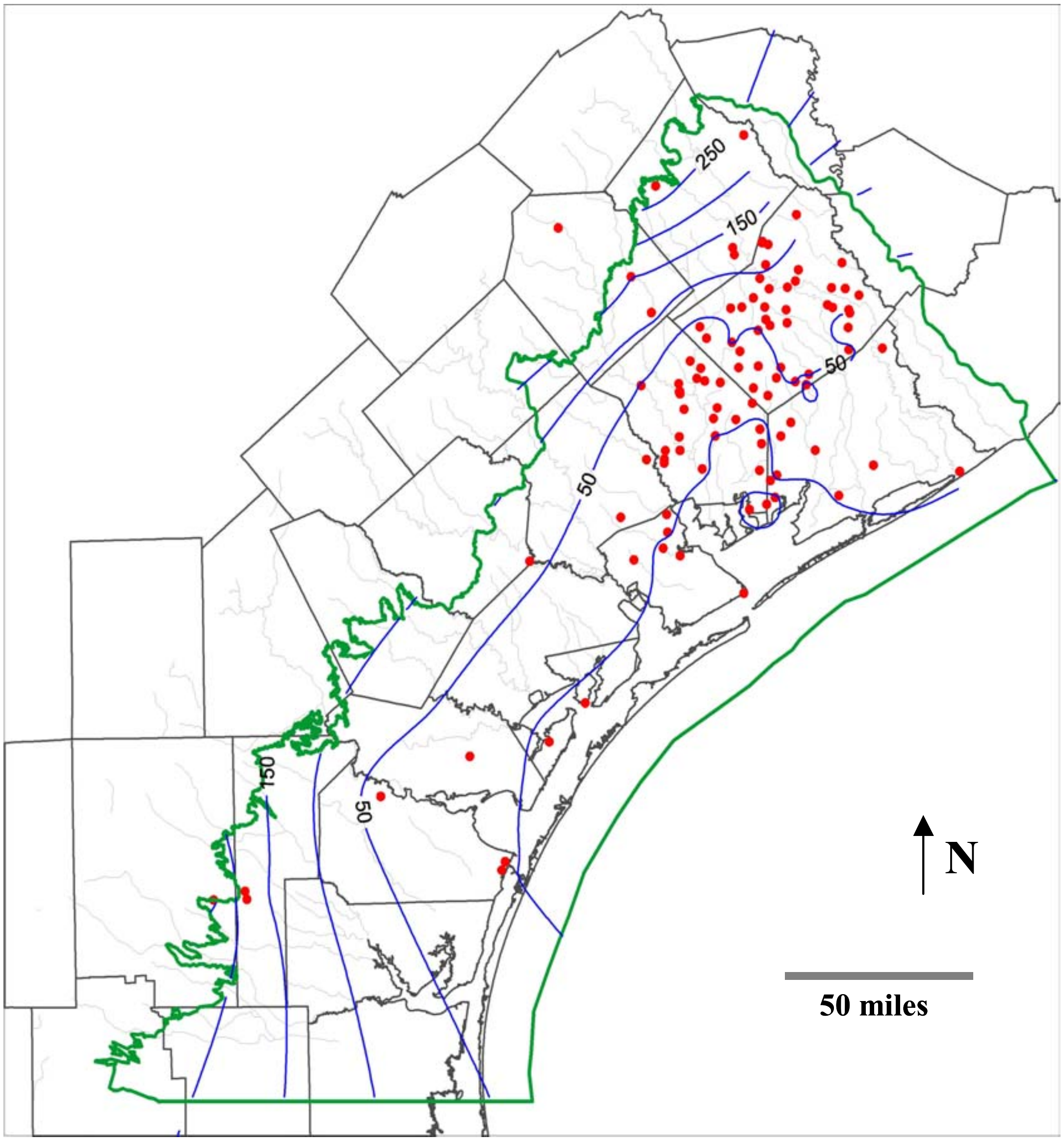


Figure 8: Water-level elevation map of the Chicot aquifer for 1999 (includes water-level measurements from January 1999 to April 1999). Water levels are in feet and the datum is the mean sea level. Closed circles represent well control points where water levels were measured. Water-level contours were developed using the Point Kriging method in Surfer.

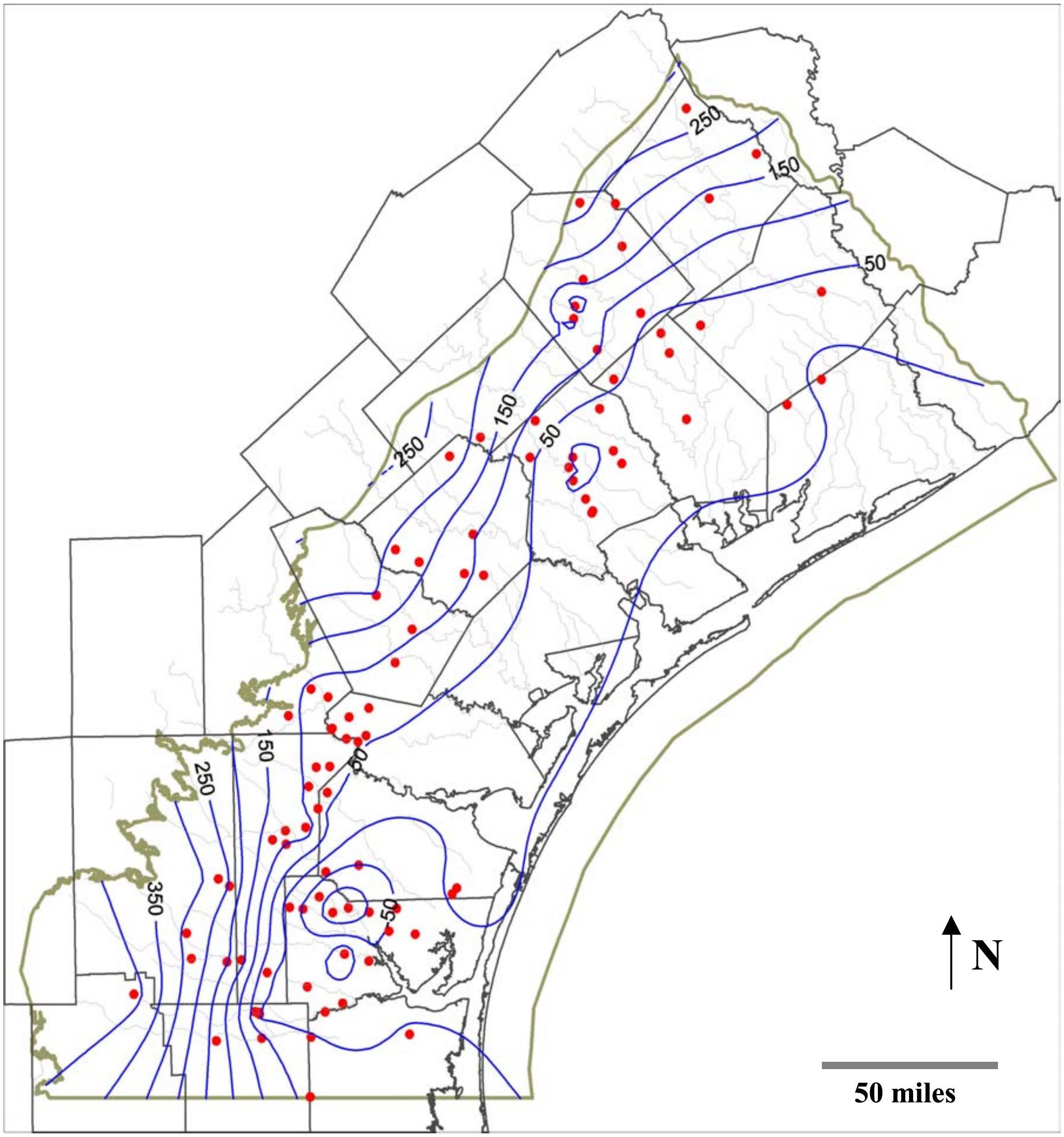


Figure 9: Water-level elevation map of the Evangeline aquifer for 1999 (includes water-level measurements from January 1999 to April 1999). Water levels are in feet and the datum is the mean sea level. Closed circles represent well control points where water levels were measured. Water-level contours were developed using the Point Kriging method in Surfer.

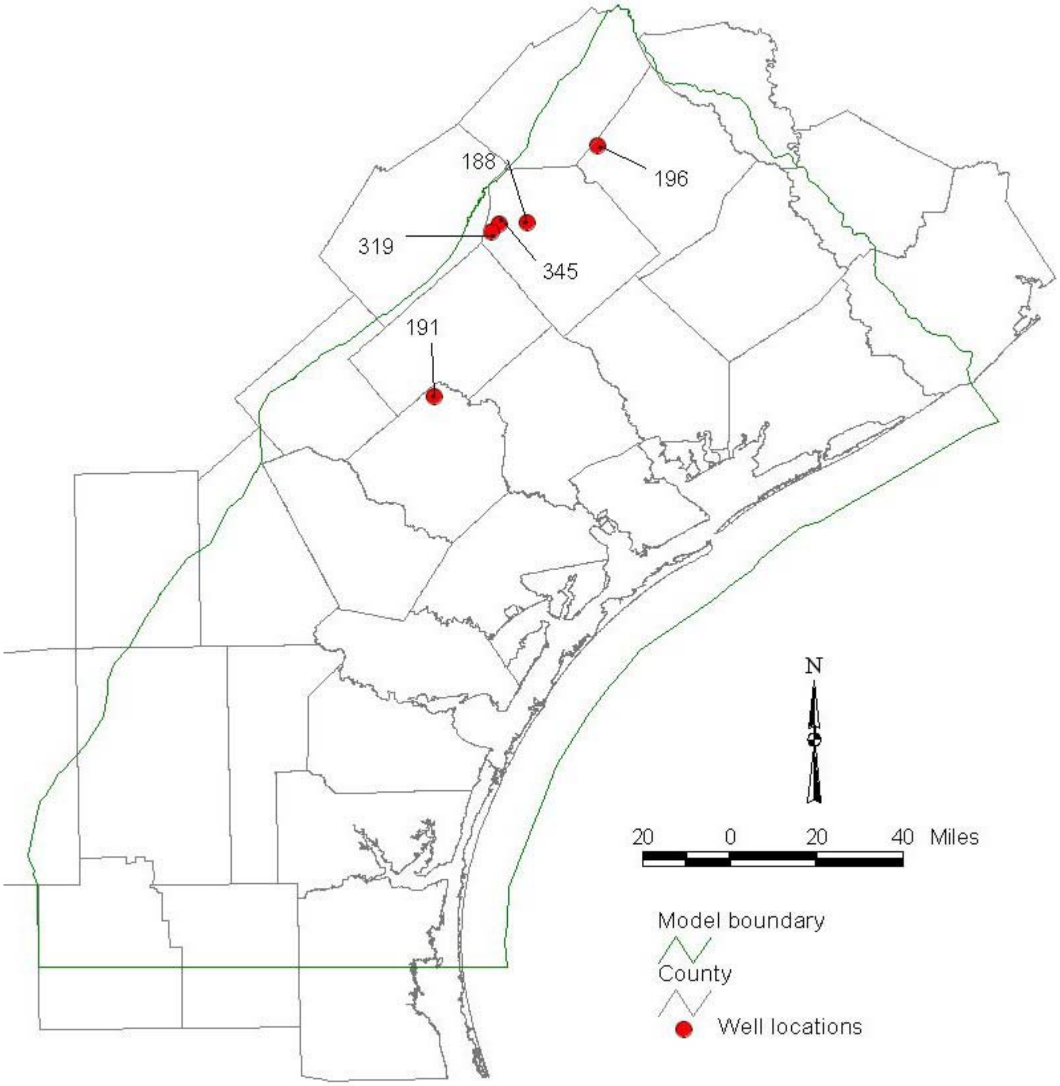


Figure 10: Water-level elevation map of the Jasper aquifer for 1989 (includes water-level measurements from January 1989 to April 1989).

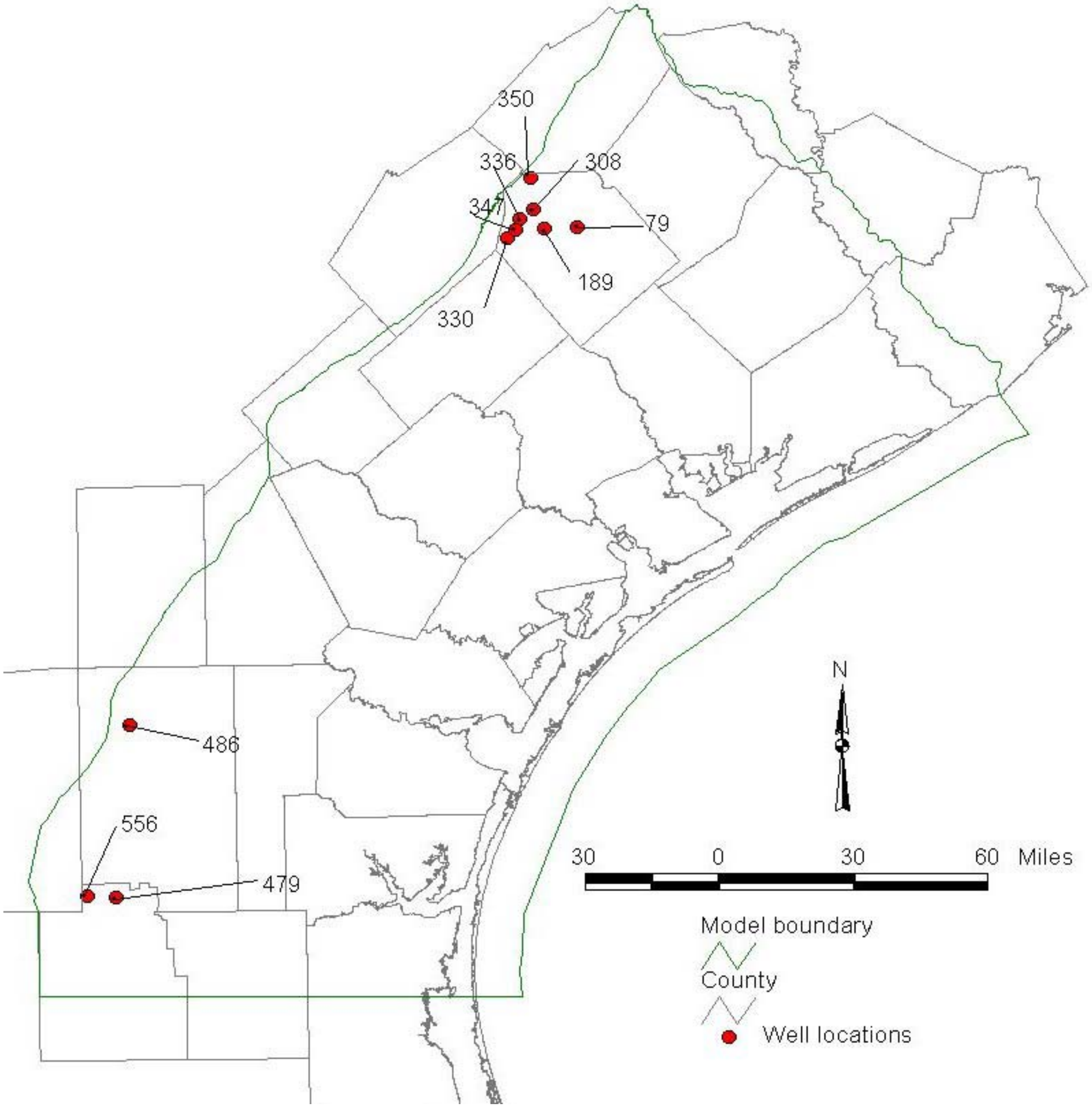


Figure 11: Water-level elevation map of the Jasper aquifer for 1999 (includes water-level measurements from January 1999 to April 1999).

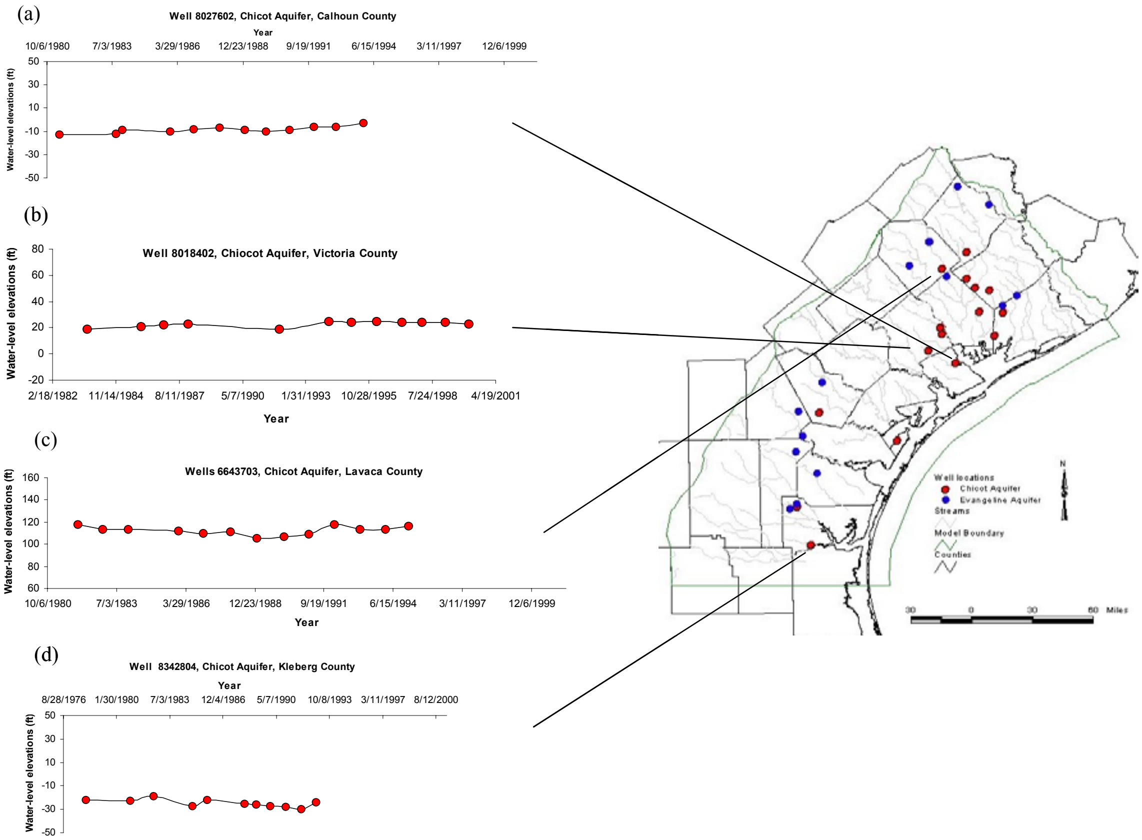


Figure 12: Hydrographs from the Chicot aquifer (a) Well 8027602, (b) Well 8018402, (c) Well 6643703, and (d) Well 8342804.

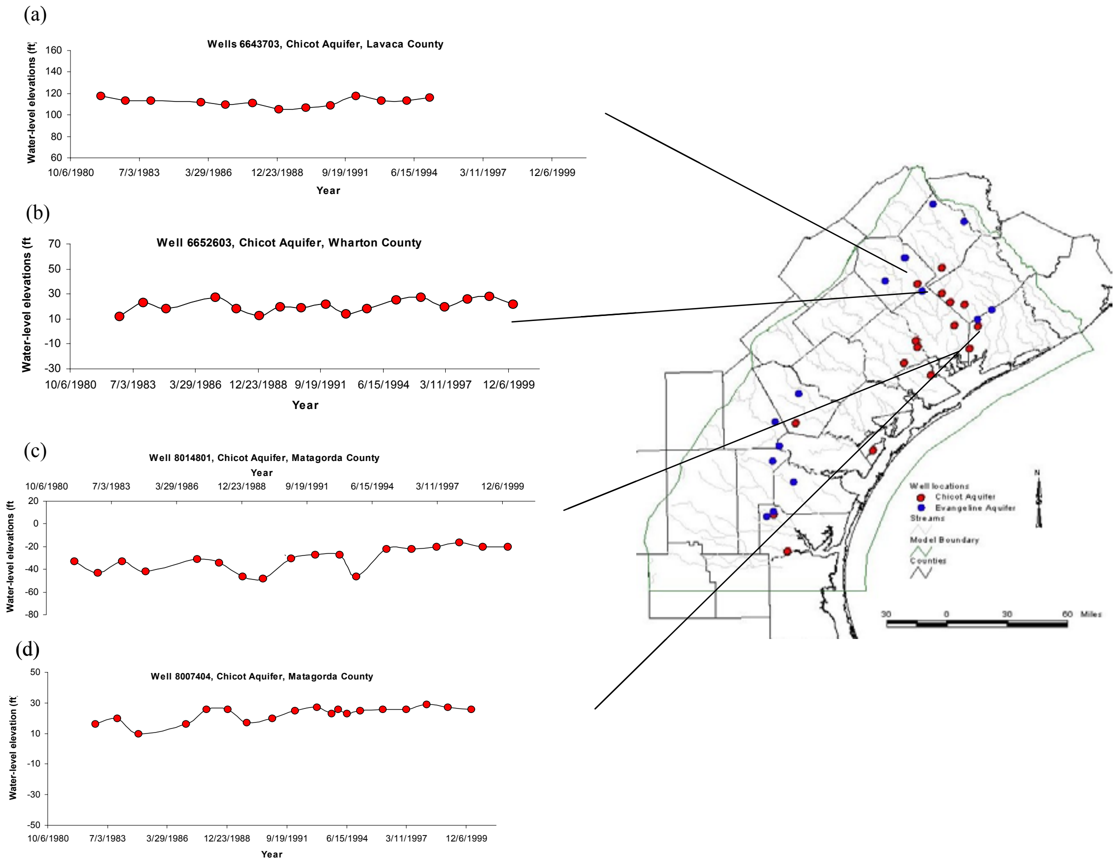


Figure 13. Hydrographs from the Chicot aquifer (a) Well 6643703, (b) Well 6652603, (c) Well 8014801, and (d) Well 8007404.

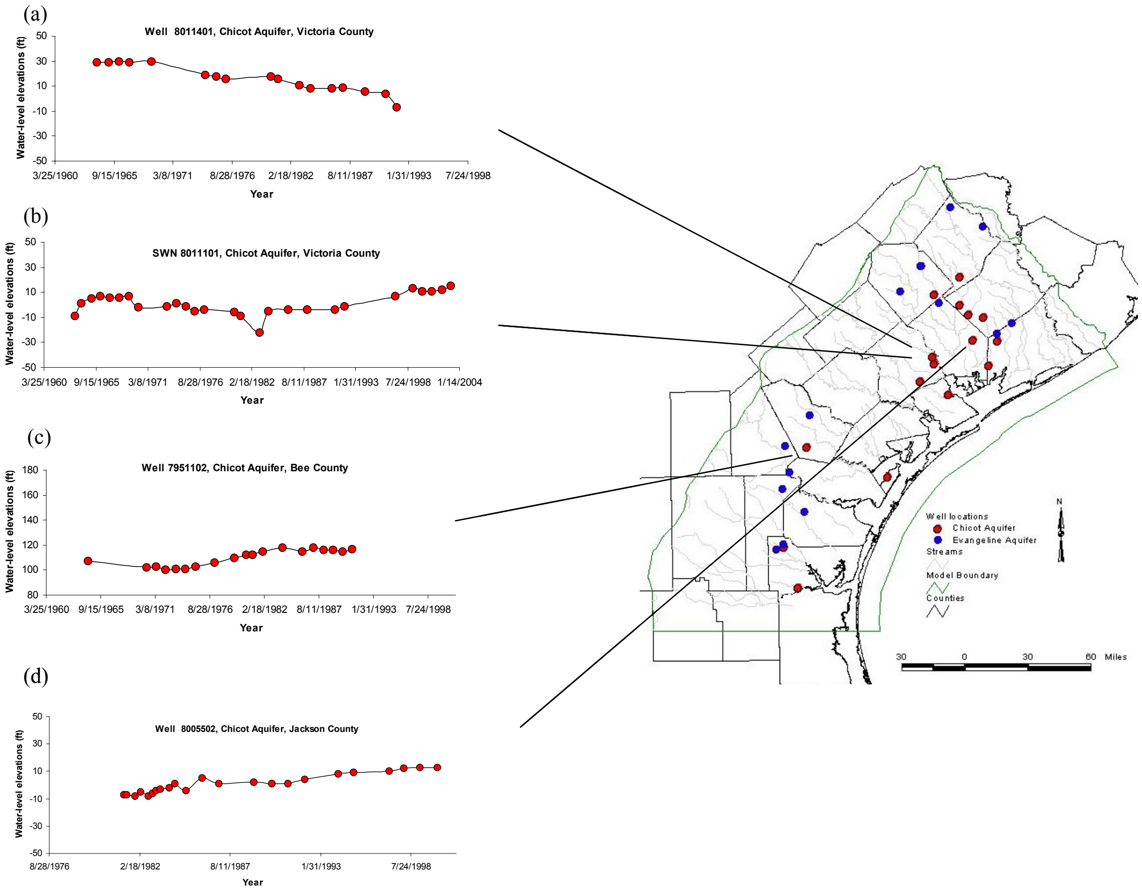


Figure 14. Hydrographs from the Chicot aquifer (a) Well 8011401, (b) Well 8011101, (c) Well 7951102, and (d) Well 8005502.

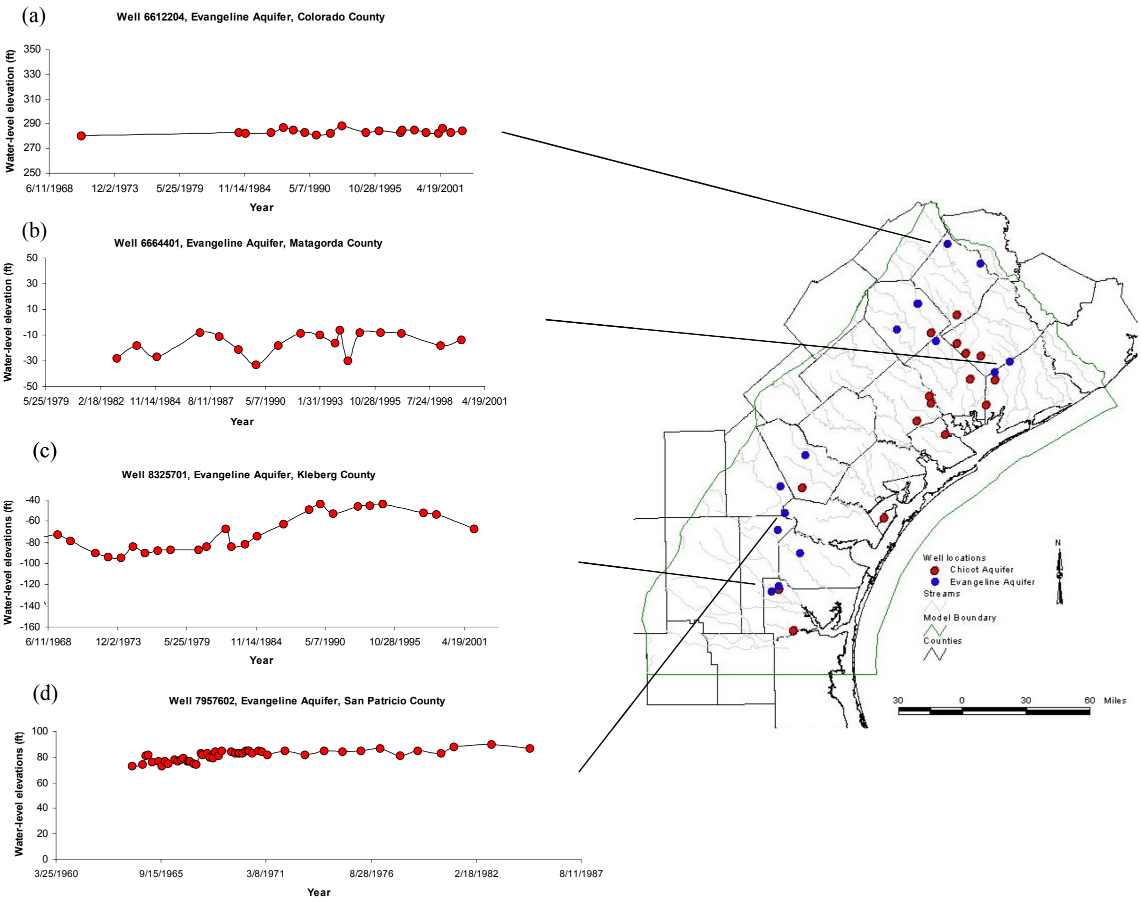


Figure 15. Hydrographs from the Evangeline aquifer (a) Well 6612204, (b) Well 6664401, (c) Well 8325701, and (d) Well 7957602.

1.3 Recharge

Recharge mainly occurs from rainfall that falls on the outcrop areas. Only a small portion of the rainfall reaches the water table. In addition, numerous streams that cross the Gulf Coast aquifer discharge water to the aquifer. Pumping may capture recharged water that had been discharging to local streams thereby increasing downdip recharge. Recharge through the unconfined, permeable sandy portions of the Gulf Coast aquifer may be relatively fast while recharge to the confined portions of the aquifer may take considerably longer. Recharge is small through the Beaumont Clay deposits that outcrop along the coast over most of the model area.

Several investigators have estimated recharge rates for the Gulf Coast aquifer (Groschen 1985; Ryder, 1988; Dutton and Richter, 1990, Ryder and Ardis, 2002; Kasmarek and Robinson, 2004) (Table 1). These recharge rates vary considerably as model areas selected for simulation have varied (1) hydraulic conductivity, (2) rainfall distribution, (3) evapo-transpiration rates, (4) groundwater-surface water interaction, (5) model grid sizes, and (5) occurrences of caliches in the outcrop areas.

Groschen (1985) in his model for the Evangeline aquifer covering San Patricio to Jim Hogg counties estimated an average recharge rate of 0.06 in/yr over the unconfined portions of the aquifer. He postulated that most of the recharge was reaching the Evangeline aquifer as cross-formational flow from the Jasper aquifer beneath because (1) the area is marked by a precipitation deficit of –18 to –28 inches, (2) most of the Goliad outcrop is extensively cemented by caliche that prevents direct recharge from rainfall, and (3) no relationship was observed between water levels in wells and rainfall events, even during the drought-of-record (Sayre, 1937).

Ryder (1988) estimated a maximum recharge of 6 in/yr in the outcrop areas of the upper Gulf Coast with most of it occurring over small areas of topographic highs. An average recharge rate of 0.74 in/yr was used to calibrate the model. Calibrated recharge values for the Goliad sand in the southern Gulf Coast range from 0 to 4 in/yr, 0 to 2 in/yr through the alluvium in southern Cameron County with no recharge through the remainder of the Chicot outcrop over most of Cameron, Hidalgo, and Willacy counties (Ryder, 1988). He used the top layer of the model as a constant head boundary that acts as a driving force for the flow system. In a later model of the entire Gulf Coast aquifer system in Texas, Ryder and Ardis (2002) reported that recharge amounts to about 85 million cubic feet per day over 114,000 square miles modeled area that translates to a recharge rate of 0.12 in/yr. They reported a higher recharge rate 179 million cubic feet per day for 1982, which amounts to 0.25 in/yr.

Dutton and Richter (1990) estimated a recharge rate of 0.1 to 0.4 in/yr for simulating the Chicot and the Evangeline aquifers in Matagorda, Wharton, and Colorado counties with the highest recharge occurring in the outcrop to the west with nearly no recharge down-dip in

Wharton and Matagorda counties. They used a head-dependent flux boundary in the uppermost active model cells and the leakance or the boundary conductance assigned to the cells formed the driving force for the flow system. The heads in the cells were adopted from Ryder's (1988) model.

Noble and others (1996) used tritium isotopes to estimate recharge into the Chicot and the Evangeline aquifers. They estimated an average recharge of 6 in/yr in the Chicot and the Evangeline outcrops of the Upper Gulf Coast using the deepest penetration (80 feet) of tritium isotopes. This may be considered an upper limit of recharge for the Gulf Coast aquifer system as it accounts for deepest penetration of tritium in the sampled 41 wells .

Kasmarek and Robinson (2004) developed a model for the northern Gulf Coast aquifer. They reported that recharge rate to the outcrop areas of the model layers (Chicot, Evangeline, and Jasper aquifers, and the Burkeville Confining System) may amount to 757 cubic feet per second or about 0.9 percent of rainfall in 1977. This recharge rate however increases to 965 cubic feet per second or 1.1 percent of the rainfall in 2000.

Chowdhury and Mace (2004) reported a recharge rate of 0.09 to 0.15 in/yr for the Lower Rio Grande Valley which amounts to 0.52 percent of the average annual rainfall for 1930 to 1980. They indicate that about 87,000 ac-ft of groundwater annually flows through the aquifer system in the model area. Of the total annual flow through the aquifer system, 47 percent of the recharge comes from rainfall and 53 percent seeps in from the Rio Grande. Cross-formational flow is a significant component of the total flow. Deeper groundwater from the Evangeline aquifer flows upward near the coast resulting in greater salinity in the overlying Chicot aquifer.

Recharge rate, estimation methods and extent of the study areas for the various hydrogeologic investigations on the Gulf Coast aquifer system are summarized in Table 1.

Table 1. Recharge rate from other Gulf Coast aquifer studies.

Source	Recharge Rate (in/yr)	Study Area	Recharge Method
Groschen (1985)	0.06	San Patricio to Jim Hogg counties	Constant head
Ryder (1988)	0 to 6	Texas Gulf Coast	Specified head, top layer of the model
Dutton and Richter (1990)	0.1 to 0.4	Matagorda and Wharton counties	Head-dependent flux boundary, top layer of the model
Noble and others (1996)	6	Harris, Montgomery and Walker counties	Isotopes
Hay (1999)	0.078	Navidad River to Willacy County	Constant head
Harden and Associates (2001)	0.1 to 0.2	Brownsville and vicinity	Used maximum potential recharge (3 inches) and MODFLOW's River Package
Ryder and Ardis (2002)	0.12[1]-0.25[2]	Texas Gulf Coast	Specified head, top layer of the model
Kasmarek and Strom (2004)	0.32[3]-0.43[4]	Northern Gulf Coast GAM	Specified head, top layer of the model
Chowdhury and Mace (2004)	0.09 to 0.15	Southern Gulf Coast GAM	Calibrated recharge as a percent of distributed rainfall

1 = average recharge for the predevelopment model, 2 = average recharge for 1982

3 = average recharge for 1977, 4 = average recharge for 2000

1.4 Discharge

Natural discharge in the Gulf Coast aquifer occurs through seeps, springs, evapo-transpiration, baseflow to the streams and upward leakage from the deeper into shallower aquifers. In the southern Gulf Coast aquifer, a considerable amount of water discharges upward from the Evangeline into the Chicot aquifer (Chowdhury and Mace, 2004). Under pre-development conditions, discharge in the Gulf Coast aquifer may vary from 0 to 1 in/yr with local values as high as 1 to 2 in/yr (Ryder and Ardis, 2002). As the Gulf Coast aquifer has been pumped over the decades, estimates show that the discharge area has decreased under pumping compared to non-pumping conditions (Dutton and Richter, 1990; Ryder and Ardis, 2002, Kasmarek and Robinson, 2004).

Groundwater pumping in the Gulf Coast aquifer has caused land subsidence in the Houston-Galveston area (Kasmarek and Robinson, 2004). Although land subsidence has not been reported from the central Gulf Coast model area, considerable pumping has occurred historically (Figure 16). Most of the pumping in the Gulf Coast aquifer in the area occurs from the Chicot and the Evangeline aquifers

Figure 17, 18). Pumping in the Burkeville Confining System and the Jasper aquifer occurs near the outcrop areas because water quality quickly deteriorates with increasing depth and in the confined parts of the aquifer (Figure 19, Figure 20).

For this study, we estimated pumping for the years 1980 through 1999 based on the TWDB Water Use Survey (WUS) database. The primary categories of pumping in the WUS database are (1) municipal, (2) manufacturing, (3) power, (4) mining, (5) rural domestic (6) livestock, and (7) irrigation. Municipal, manufacturing, power and mining have locational information while irrigation and livestock pumping are distributed based on land-use maps. Rural domestic pumping is distributed in the model area based on population density distribution.

A review of the total groundwater pumping from 1980 through 1999 indicate that groundwater pumping declined from about 600,000 ac-ft/yr in 1980 to about 420,000 ac-ft/yr in 1987. Groundwater pumping declined from about 550,000 ac-ft/yr in 1988 to about 420,000 ac-ft/yr in 1999. Most of the pumping in the area occurs in the form of irrigation. Thus, pumping is heavily skewed towards the summer months when most of the irrigation water is used. A large percentage of the total groundwater pumping comes from several pumping centers covering only small areas in the model area. For example, about 35 to 40 percent of pumping in 1999 is used by irrigation in Wharton County. Considering typical annual groundwater use in 1980, about 62 percent of the total pumping comes from the Chicot aquifer, 34 percent comes from the Evangeline aquifer, about 4 percent comes from the Jasper aquifer, and less than 1 percent comes from the sandy outcrop areas of the Burkeville Confining System.

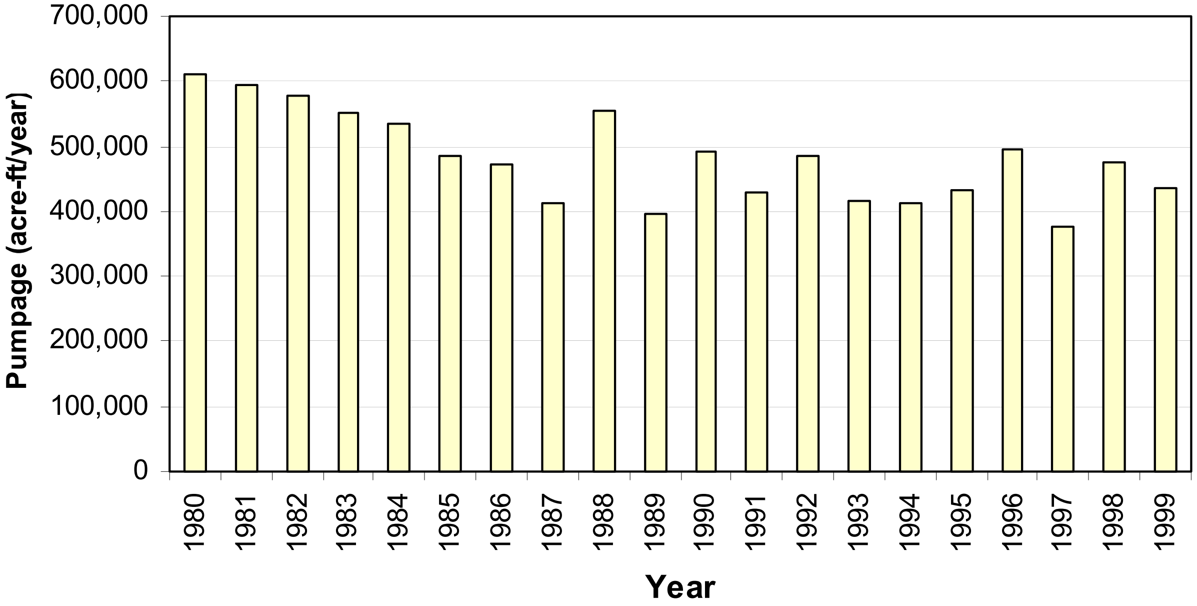


Figure 16. Historical total groundwater pumpage in the model area from 1980 to 1999.

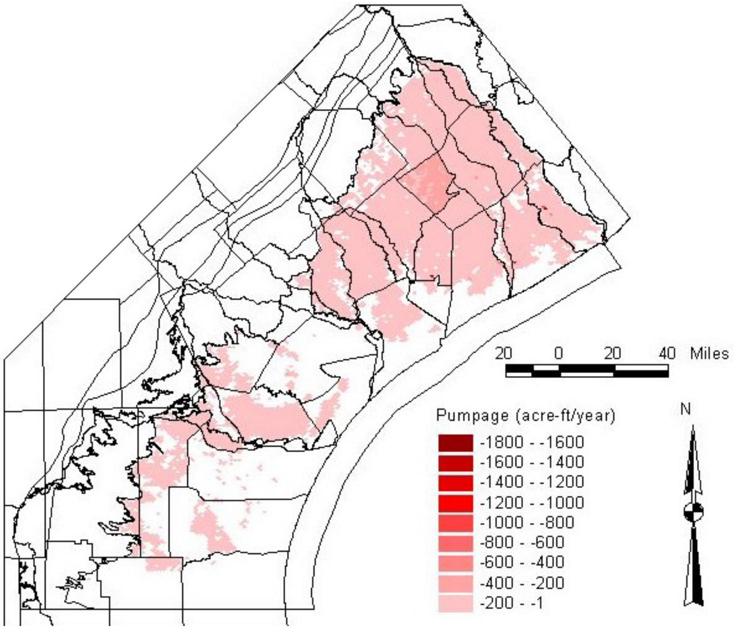


Figure 17: Groundwater pumpage distribution in the Chicot aquifer for 1999.

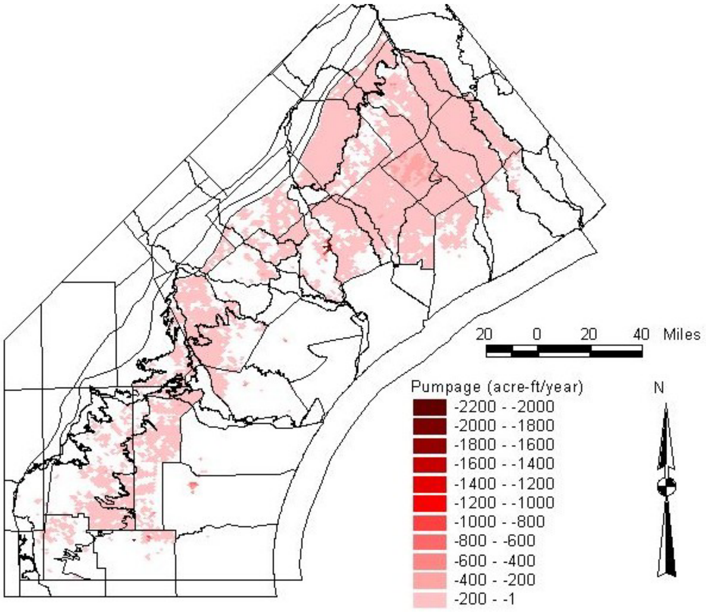


Figure 18: Groundwater pumpage distribution in the Evangeline aquifer for 1999.

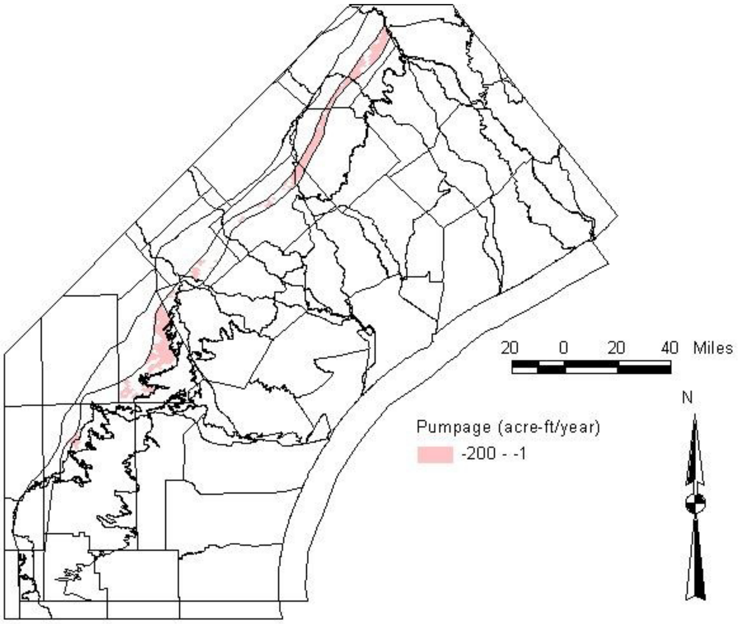


Figure 19: Groundwater pumpage distribution in the Burkeville Confining System for 1999. Note that most pumping occurs near the outcrop.

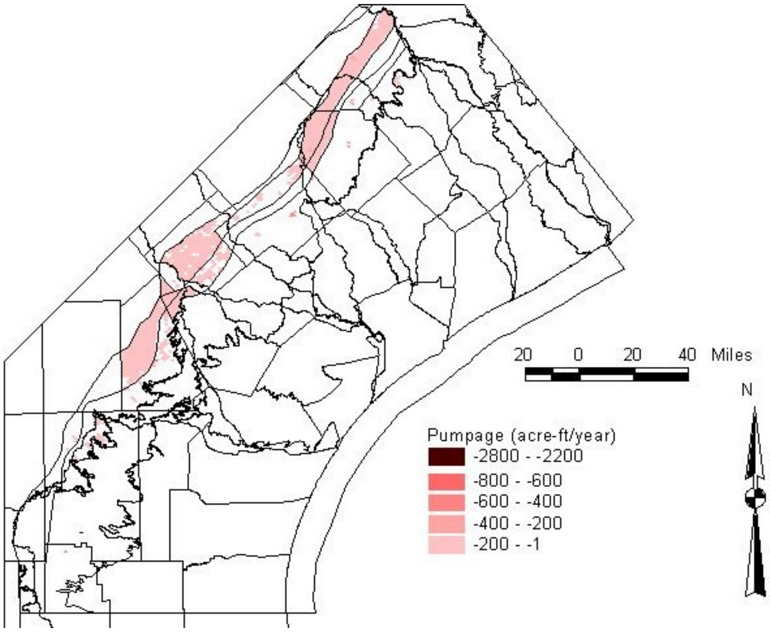


Figure 20: Groundwater pumpage distribution in the Jasper aquifer for 1999. Note that most pumping occurs near the outcrop.

We reviewed streamflow information from several USGS stream gauges from the model area (Figure 21). Most of the rivers are gaining except for the Colorado River which is mainly a losing stream. The Colorado River is much more flashy that the other rivers in the area. Streamflow fluctuates from less than 10 cubic feet per second (cfs) to about 100,000 cfs (Figure 22).

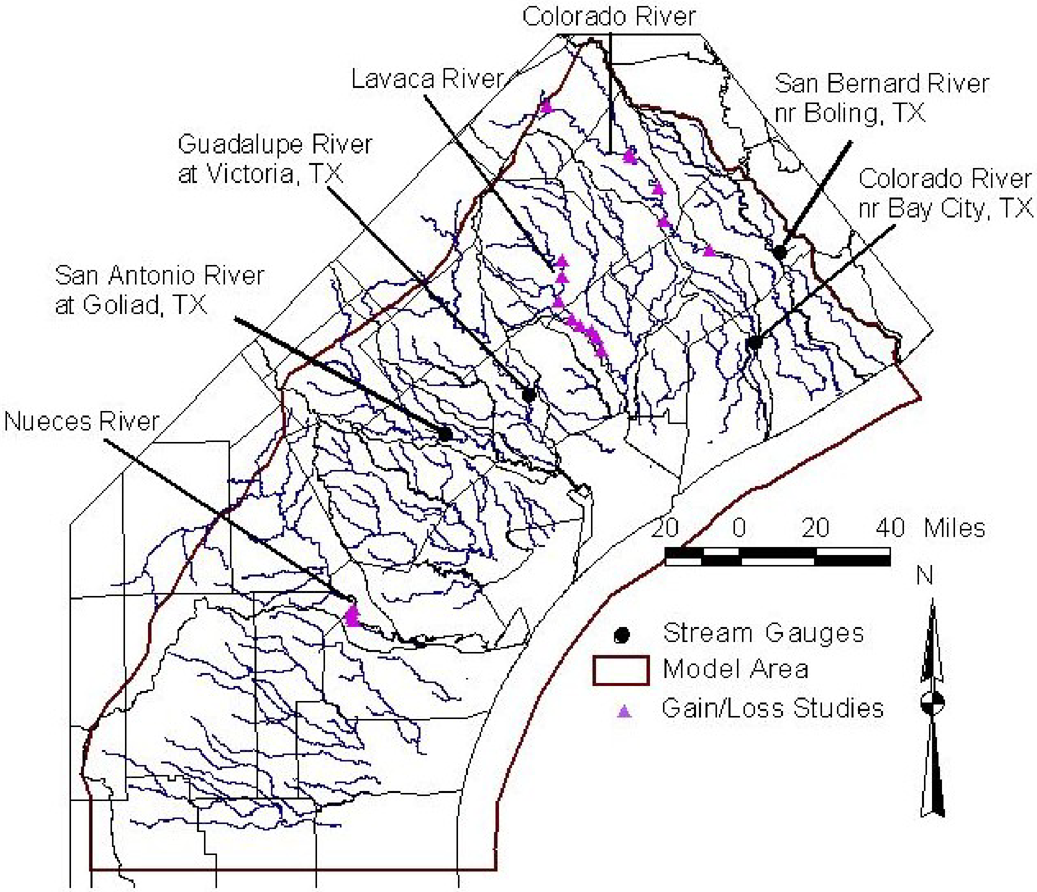


Figure 21: Locations of gaging stations in the model area.

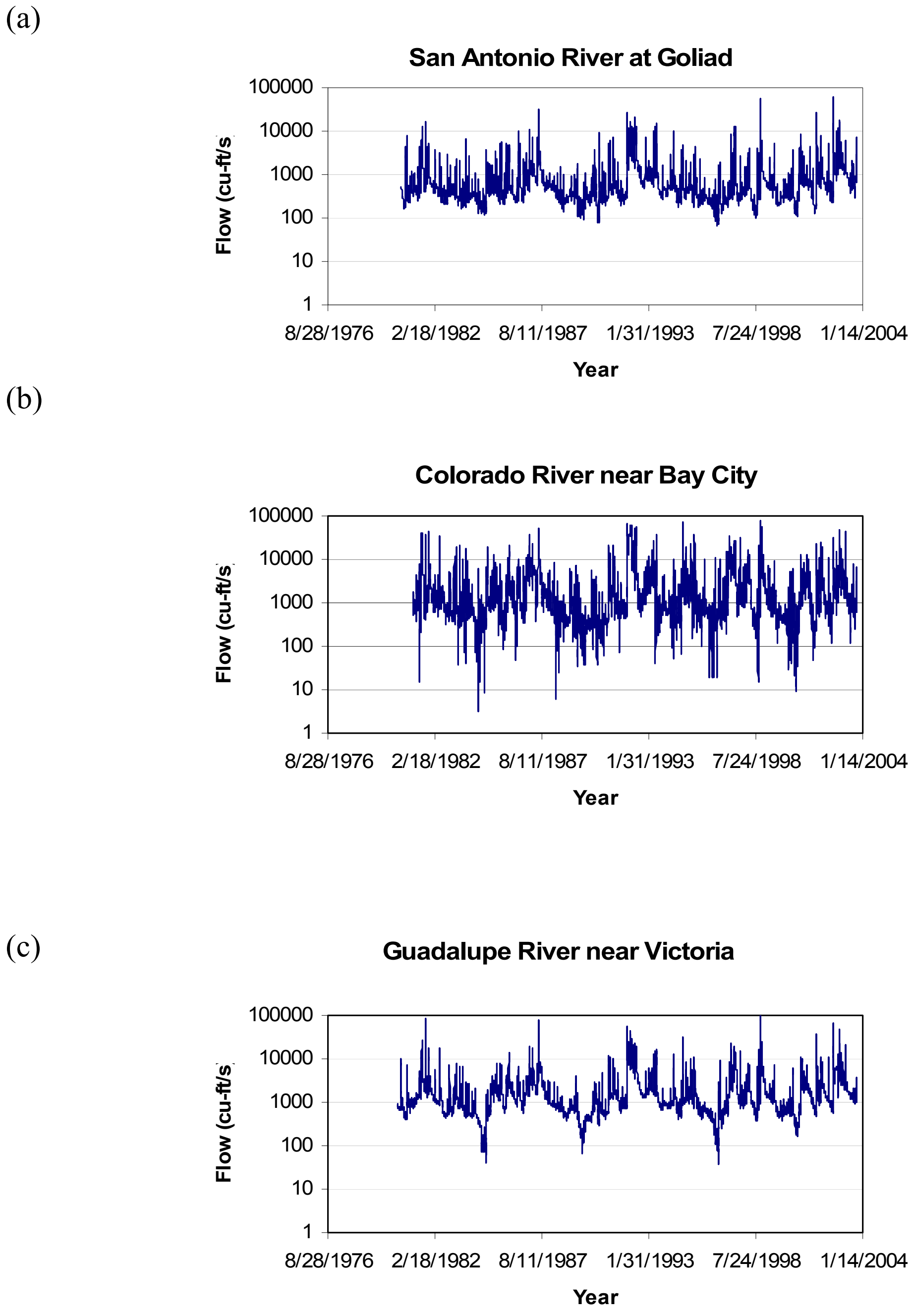


Figure 22: Streamflow hydrographs for USGS stations on (a) the San Antonio River near Goliad, (b) the Colorado River near Bay City, and (c) the Guadalupe River near Victoria. Locations of the stations are shown in Figure 21.

2 Conceptual Model

A conceptual model is our best understanding of the natural groundwater flow system. It describes how recharge, discharge, groundwater-surface water interactions, and cross-formational flow take place through the aquifers and the confining units of a flow system (Figure 23). When rain falls on the outcrop areas, much of it runs off to the rivers, a portion of it is lost through evaporation and transpiration, and about less than one percent reaches the saturated groundwater zone of the Gulf Coast aquifer. A portion of the water that reaches the saturated groundwater zone flows laterally over small distances and discharges back to the streams located at lower elevations. A small portion of the flow reaches the intermediate flow system at depth and a much smaller amount joins the regional flow system traveling considerable distances from the outcrop areas towards the Gulf of Mexico. As the flow reaches the saltwater-fresh water boundary near the coast, the density difference between the fresh water and the salt water cause the regional groundwater flow to shift direction and move vertically upward toward coastal areas at lower elevations.

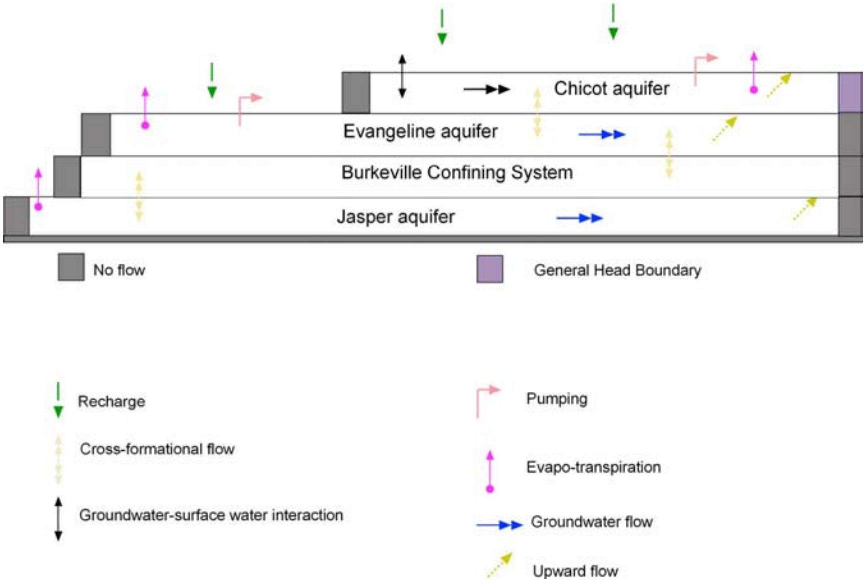


Figure 23: Conceptual model of the Gulf Coast aquifer flow system.

In general, groundwater flows from areas of higher topography towards lower topography. In this case, groundwater flows from the west towards the Gulf of Mexico in the east. However, considerable groundwater pumping in part of the model area has greatly changed groundwater flow directions. For example, extensive groundwater pumping over decades in Wharton, Victoria, and Kleberg counties have altered the natural flow system. In these areas, a decline in the potentiometric (or water-level) surface and an increase in the hydraulic gradient are inducing greater flow into the deeper parts of the aquifer than would have otherwise occurred under natural conditions. The increase in the hydraulic gradient due to groundwater pumping also allows more interaction between the aquifers and their confining units.

Given the small variation in the topography of the model area, considerable interaction occurs between the streams and the groundwater. Some of the streams are almost always losing (Colorado River) where the stream discharges into the groundwater while other streams are both gaining and losing (San Bernard River).

Most of the aquifers in the Gulf Coast contain numerous lenses of interbedded clays providing resistance to the infiltration of rainwater. Thus, even unconfined sections of the outcrop areas of the aquifer may behave as semi-confining units.

3 Modeling Approach

Our modeling approach included: (1) calibrating a steady-state model and (2) calibrating a transient model to reproduce seasonal fluctuations in water levels and flows in streams. We first calibrated the steady-state model to determine stable boundary conditions and to simulate static water levels under pre-pumping conditions. This time period ranges from 1910 to 1940 when there was no significant groundwater pumping in the Gulf Coast aquifer, and the aquifer was near equilibrium. We calibrated the steady-state model to reproduce the water levels for 1940. No pumping was assigned in any of the model layers of the steady-state model. We used the steady-state model to investigate (1) recharge rates, (2) hydraulic properties, (3) boundary conditions, (4) water budget, and (5) sensitivity of the different model parameters on model results.

We initially used distributed horizontal hydraulic conductivity of the Evangeline aquifer to calibrated the steady-state model. However, we were unable to produce the measured drawdown cones in the transient model using these distributed values. We zoned the horizontal hydraulic conductivity in the Evangeline aquifer to address partial completion of many wells, adjusted the vertical leakance of the Chicot aquifer, and horizontal hydraulic conductivity of the Jasper aquifer in the transient model, and propagated these changes to these parameters to calibrate the steady-state model. We applied this set of values to calibrate the steady-state model and used the calibrated heads as initial heads for the transient model.

Our approach for calibrating the model was to reproduce water levels under steady-state conditions and reproduce seasonal water-level changes under transient conditions. We focused our calibration on the Chicot and the Evangeline aquifers that are more widely used and contain numerous wells with water-level measurements. We also calibrated to the few water-level measurements available from the unconfined, sandy portions of the Burkeville Confining System and outcrop areas of the Jasper aquifer.

We quantified the calibration or goodness of fit between the simulated and measured water-level values using the mean error (ME), mean absolute error (MAE), and root mean square error (RMSE):

$$\text{ME} = 1/\text{n} \sum_{i=1}^{n} (h_m - h_s)_i$$

$$\text{MAE} = 1/\text{n} \sum_{i=1}^{n} |\,(h_m - h_s)\,|$$

$$\text{RMSE} = \left[1/n \sum_{i}^{n} (h_m - h_s)_i^{\,2} \right]^{0.5}$$

where n is the number of calibration points, h_m is the measured hydraulic head at any point i, and h_s is the simulated hydraulic head at the same point i.

Once we completed calibrating the steady-state model, we used the model as a starting point for transient calibration for the years 1981 through 1999. We chose the years 1981 to 1999 because this period contained the most accurate and recent water-use and water-level information. We chose monthly time steps for the years 1987 to 1989 and 1995 to 1997 to test model response to recharge and pumping during drought transitions. Use of annual and monthly time steps allowed for transient calibration under both dry and wet climatic conditions thereby increasing confidence in the validity of the steady-state model. We calibrated the transient model by adjusting the storativity values to reproduce the seasonal fluctuations in water levels and minimize the differences between the simulated and measured water levels.

4 Steady-State Model

We calibrated the steady-state model and assessed the sensitivity of the model to different hydrologic input parameters.

4.1 Calibration

We calibrated the steady-state model to mean annual winter water levels (1910 to 1940) in the Chicot and the Evangeline aquifers when there was no significant pumping and negligible changes in the water levels indicating that the aquifer was under near-equilibrium condition (Figures 4, 5). Only a limited number of wells from the outcrop areas of the Jasper aquifer and the sandy portions of the Burkeville Confining System had water-level information to be included in model calibration (Figures 10, 11).

To calibrate the model, we adjusted parameters to observe which parameter had the most effect on simulated water levels. Through this initial sensitivity analysis, we observed that the horizontal hydraulic conductivity of the Evangeline aquifer, recharge, and vertical leakance of the Chicot aquifer affected the model results. We found that the model calibration was non-unique, particularly with respect to the use of hydraulic conductivity and leakance values. Application of increased recharge has no significant bearing on the water levels because excess recharge discharges to the streams as baseflow.

We initially attempted to calibrate the model using distributed horizontal hydraulic conductivity. However, when we assigned new pumpage values in the model layers during the transient calibration, we were unable to reproduce the water levels in most of the model area, particularly in the Evangeline and the Jasper aquifers. The best-fit simulated water levels that we were able to produce uses zoned horizontal hydraulic conductivity for the Evangeline aquifer (Figure 24). We zoned the hydraulic conductivity into three smaller sub-zones and lowered the values following the median of the distribution. The transmissivity values we used in the Evangeline aquifer (Figure 25) may appear lower than earlier published values (Ryder, 1988; Carr and others,1985; Kasmarek and Robinson, 2004). However, if partial penetration effects of well completions are taken out from the calculation, hydraulic conductivity used in the calibration may appear compatible to published values.

For the Chicot aquifer and the Burkeville Confining System, we used the distributed hydraulic conductivity values as applied in the draft model (Waterstone, 2003). We nearly doubled the hydraulic conductivity of the Jasper aquifer, which is still less than a geometric mean of 1 ft/d. Similar values of hydraulic conductivity (about 1 ft/d) have also been used for the Jasper aquifer in other models (Chowdhury and Mace, 2004; Kasmarek and Robinson, 2004). We also adjusted the vertical leakance of the Chicot aquifer. Vertical leakance controls groundwater flow between the Chicot and the Evangeline aquifers. We assigned a leakance value of about 10^{-9} over a small area in the Chicot aquifer near Kingsville to represent the silt and very-fine sand deposits (area denoted as *Qs*i in the geologic maps) (U. S. Army Corps of Engineers, 1975). Calibrated vertical leakance values increase from the east to the west following the depositional pattern expected in a prograding delta–deposition of coarser sediments in the up-dip areas and finer sediments in the down-dip areas. Therefore, differences in the distribution of vertical leakance values across the model area are caused by variations in lithology.

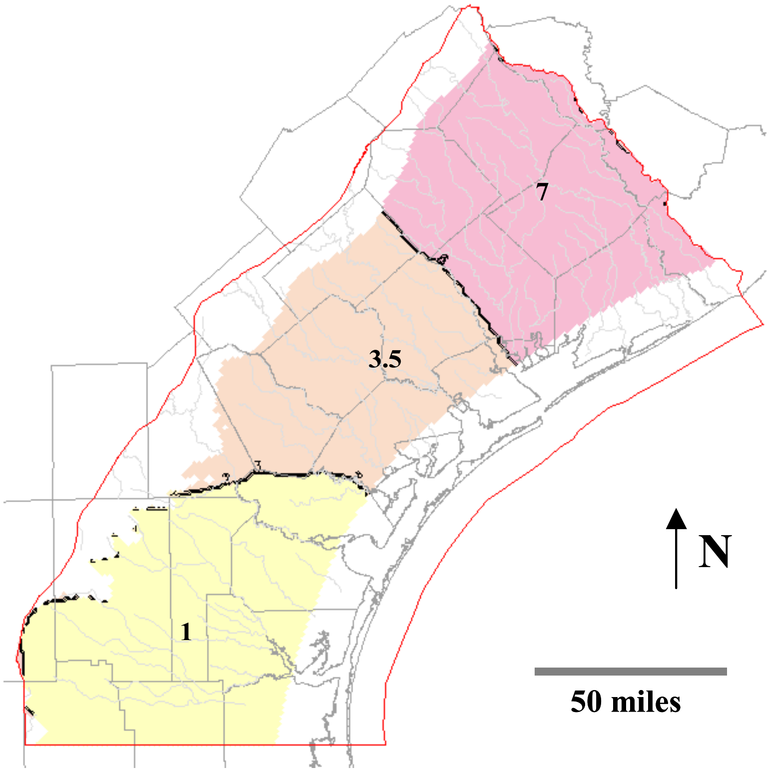


Figure 24: Hydraulic conductivity zones in the Evangeline aquifer used for model calibration. Hydraulic conductivity values labeled for each zone are in ft/d.

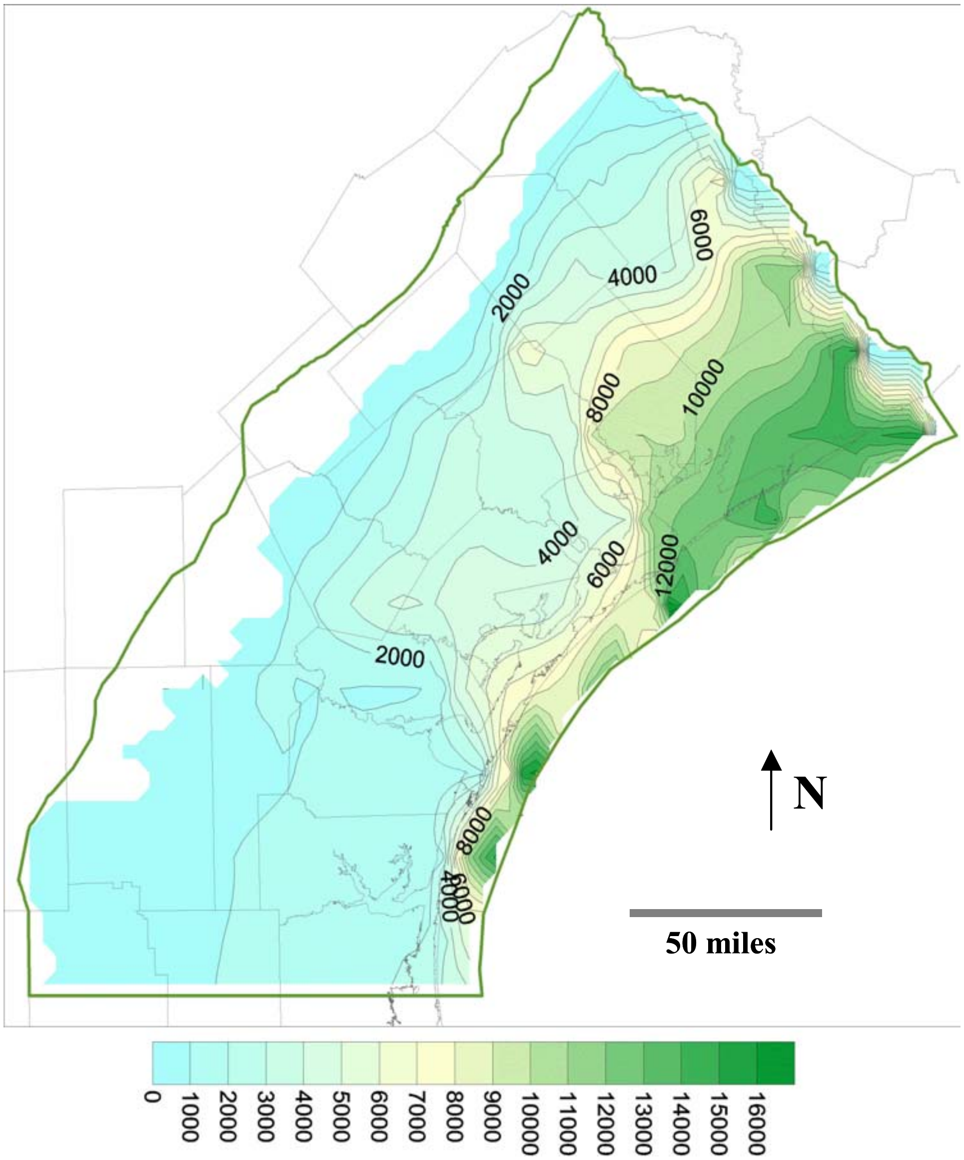


Figure 25: Transmissivity of the Evangeline aquifer using hydraulic conductivity zones used for model calibration (transmissivity values are in ft^2/d).

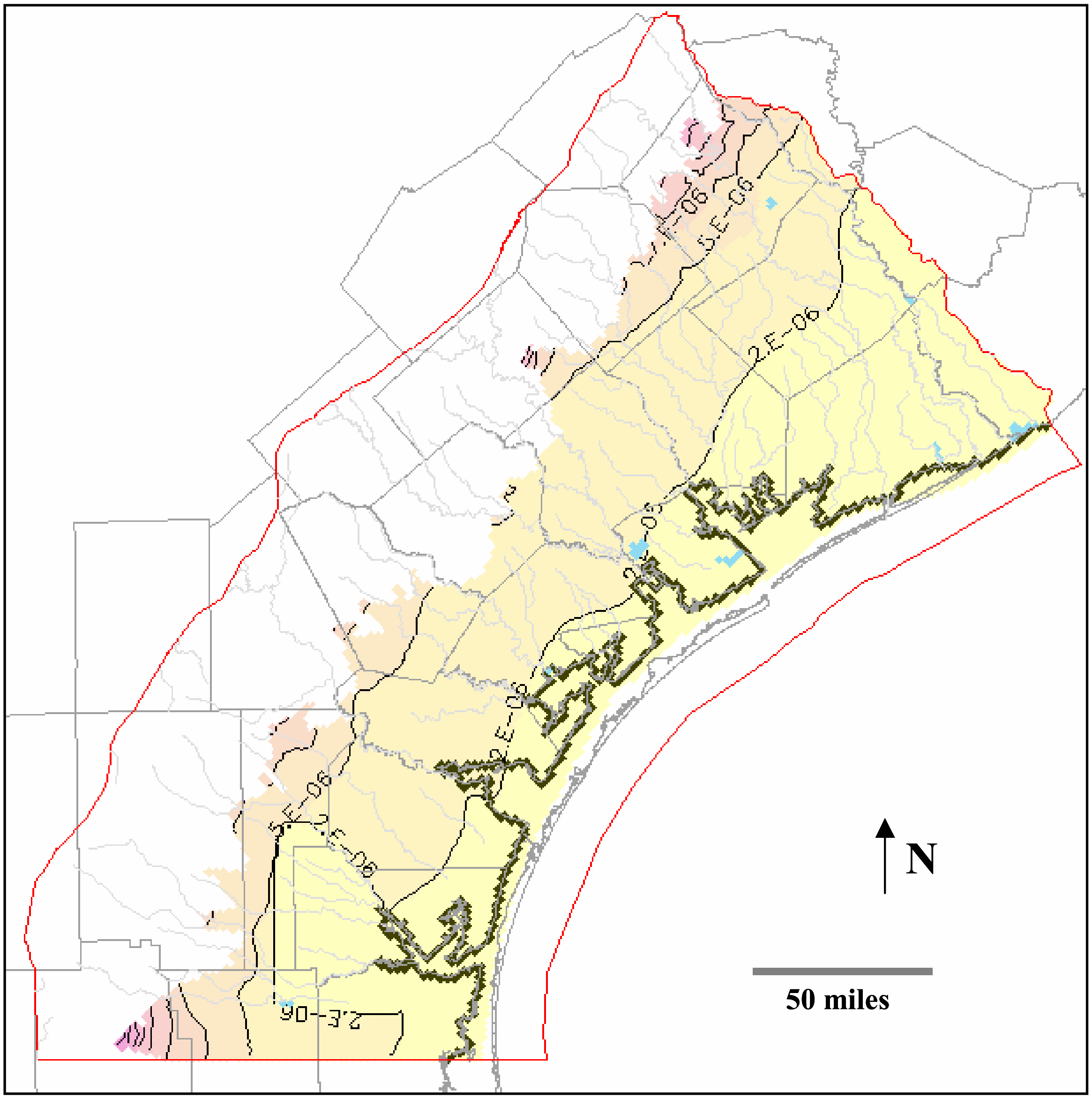


Figure 26: Calibrated vertical leakance distribution in the Chicot aquifer. Vertical leakance values are in day^{-1}.

The vertical leakance values that we used (Figure 26) in the Chicot aquifer are similar to other Gulf Coast models (Chowdhury and Mace, 2004; Kasmarek and Robinson, 2004).

Simulated water-level contours across the model area show that the rivers have considerable influence in shaping water-level contours. Most of the water-level contours bend upstream as would occur in streams receiving baseflow from an aquifer (Figures 27, 28, 29, and 30). Because limited well control points were used in developing the water-level maps, these maps of measured water-level contours do not produce this effect as distinctly.

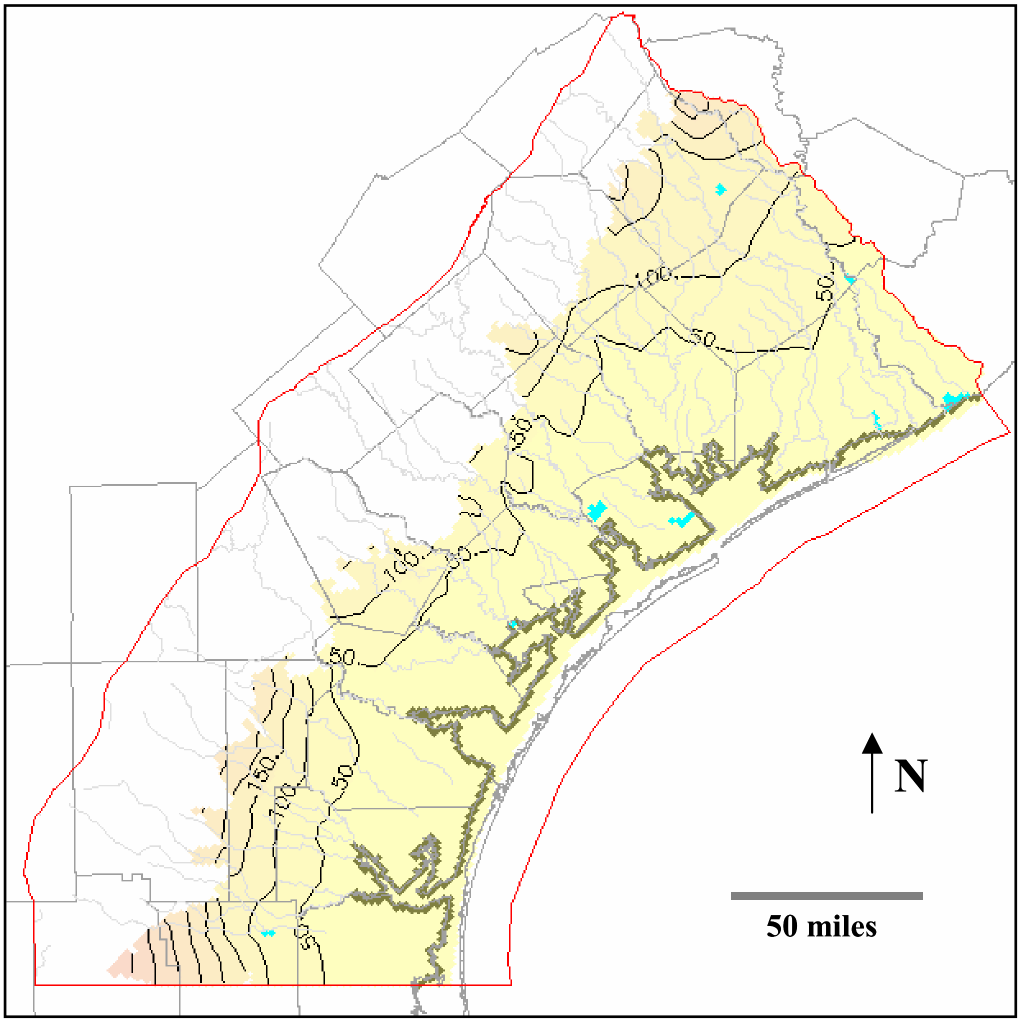


Figure 27: Simulated water levels for the Chicot aquifer for the steady-state model.

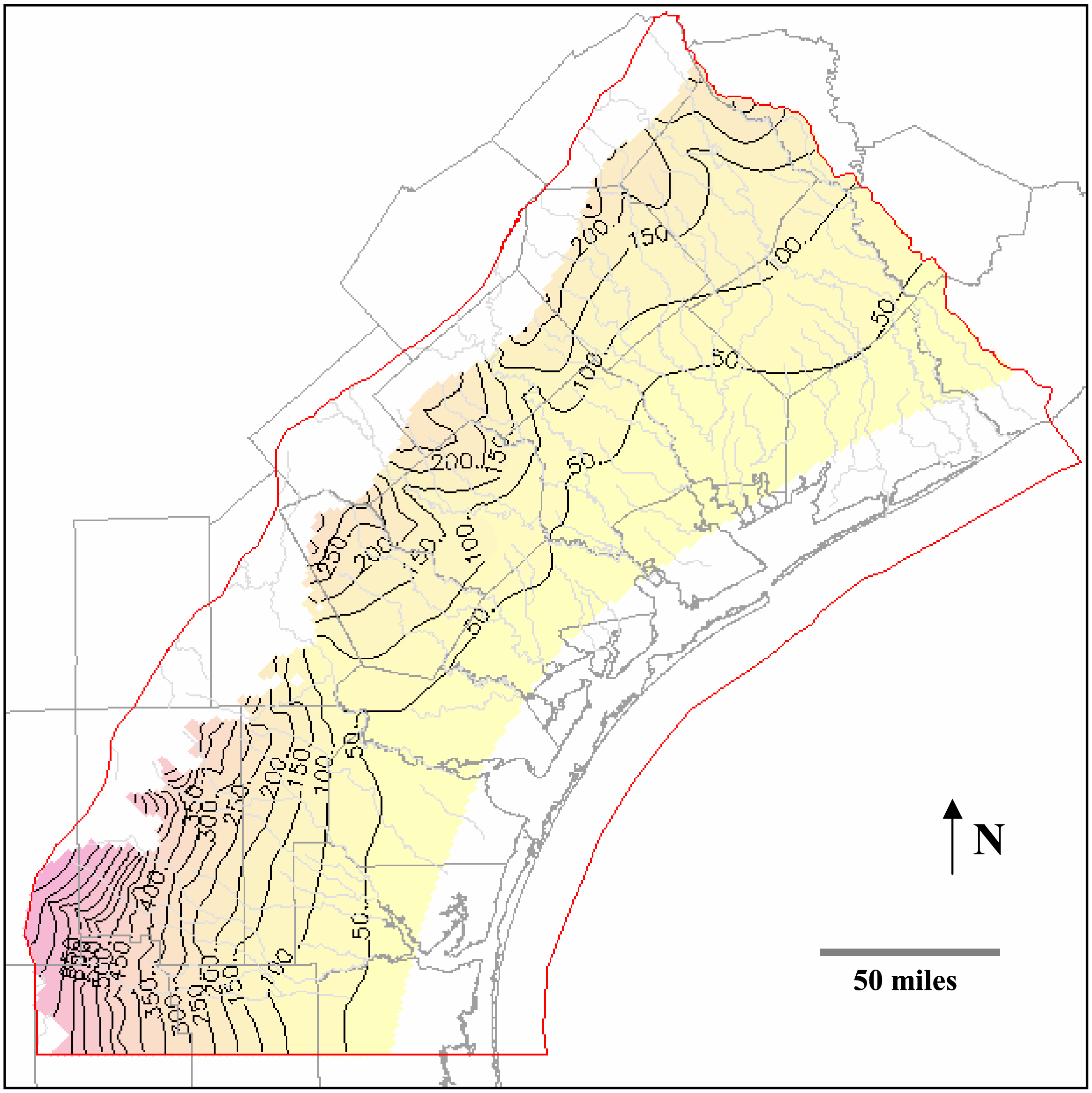


Figure 28: Simulated water levels for the Evangeline aquifer for the steady-state model.

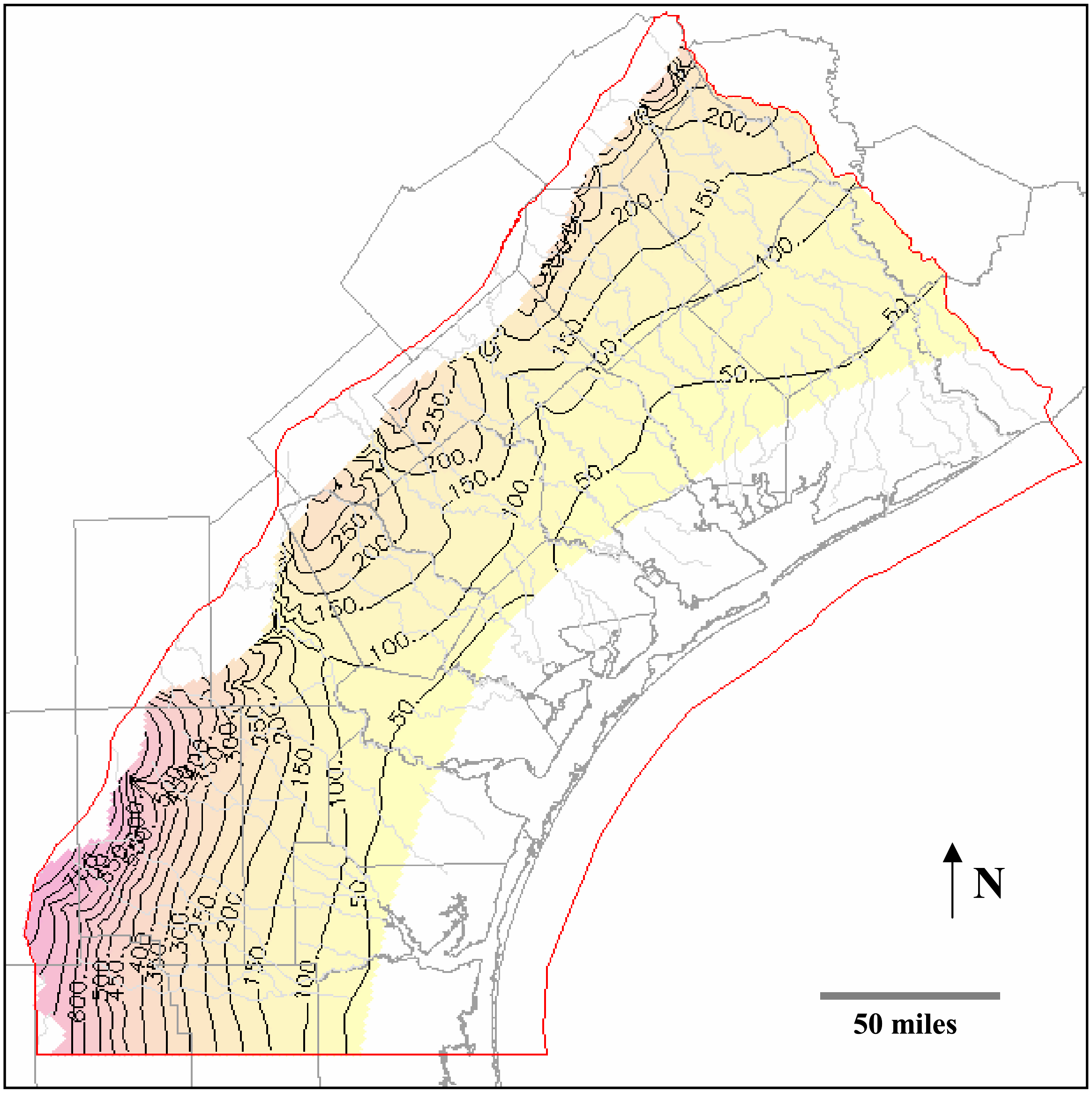


Figure 29: Simulated water levels for the Burkeville Confining System for the steady-state model.

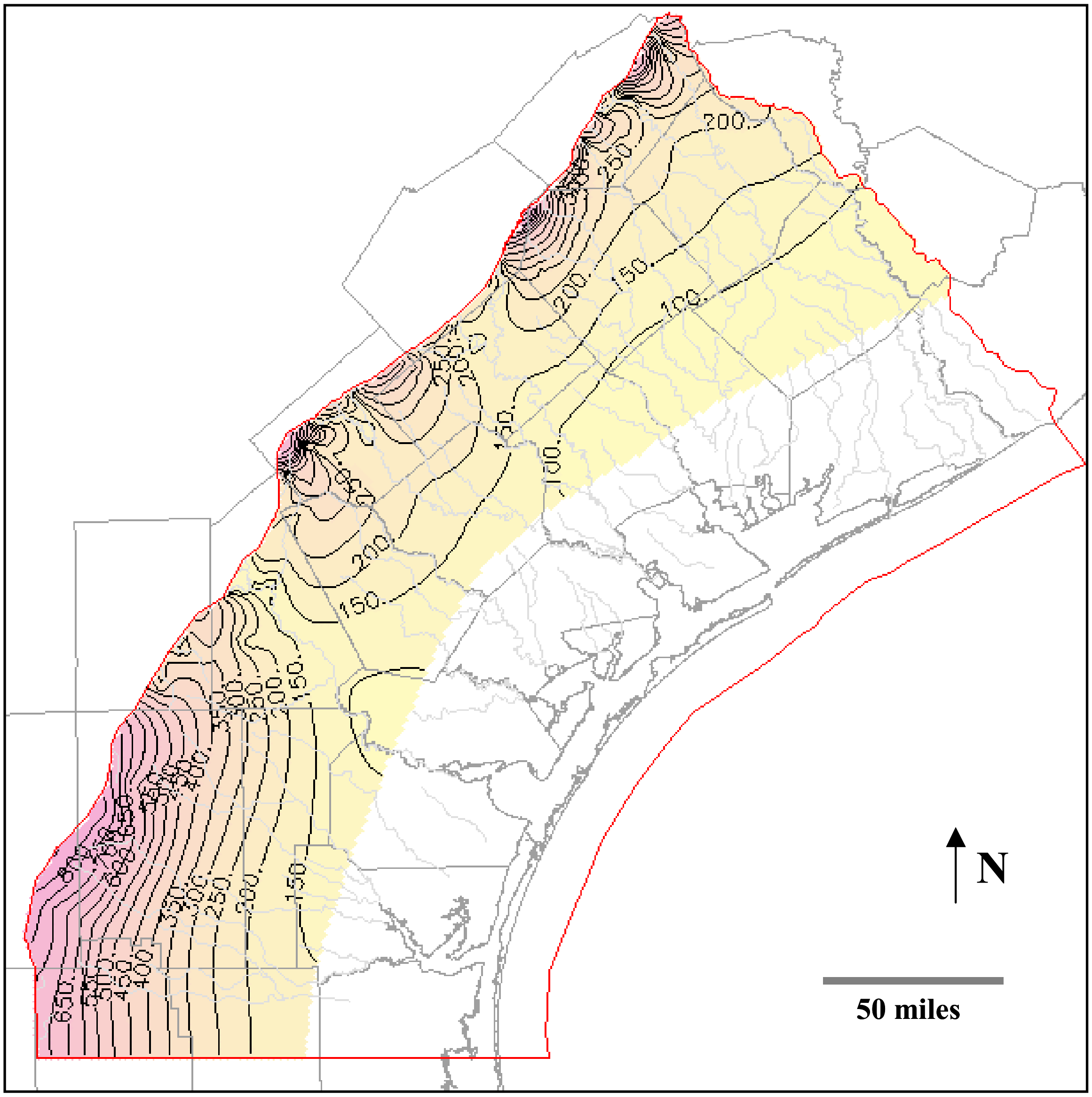


Figure 30: Simulated water levels for the Jasper aquifer for the steady-state model.

The calibrated model reasonably reproduces the spatial distribution of the water levels in the Chicot, Evangeline, and the Jasper aquifers and the Burkeville Confining System for the steady-state conditions of 1910 to 1940. The mean error (ME) for calibration is about 8 feet, the mean absolute error (MAE) is about 16 feet, and the root mean squared (RMS) error is about 21 feet (Figure 31).

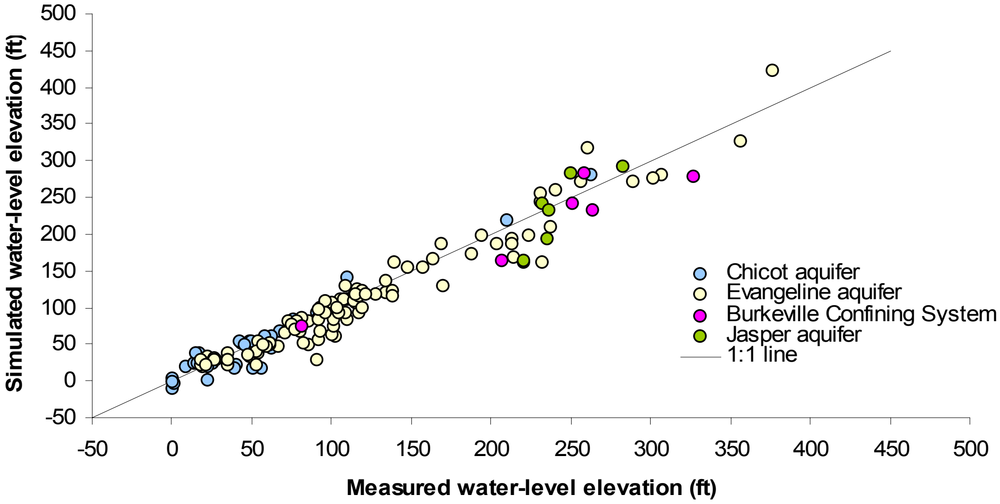


Figure 31: Comparison of simulated to measured water levels for the steady-state calibration model.

The RMS error value that we obtained from calibration is about 5 percent of the head-drop across the model area and is well within the 10 percent error usually sought for model calibration.

The model accurately replicates the interpreted flow directions towards the Gulf of Mexico and the streams (Figure 27). The spatial distribution of water-level residuals (differences between simulated and measured water levels) appears unbiased towards any specific location in the model area (Figure 32).

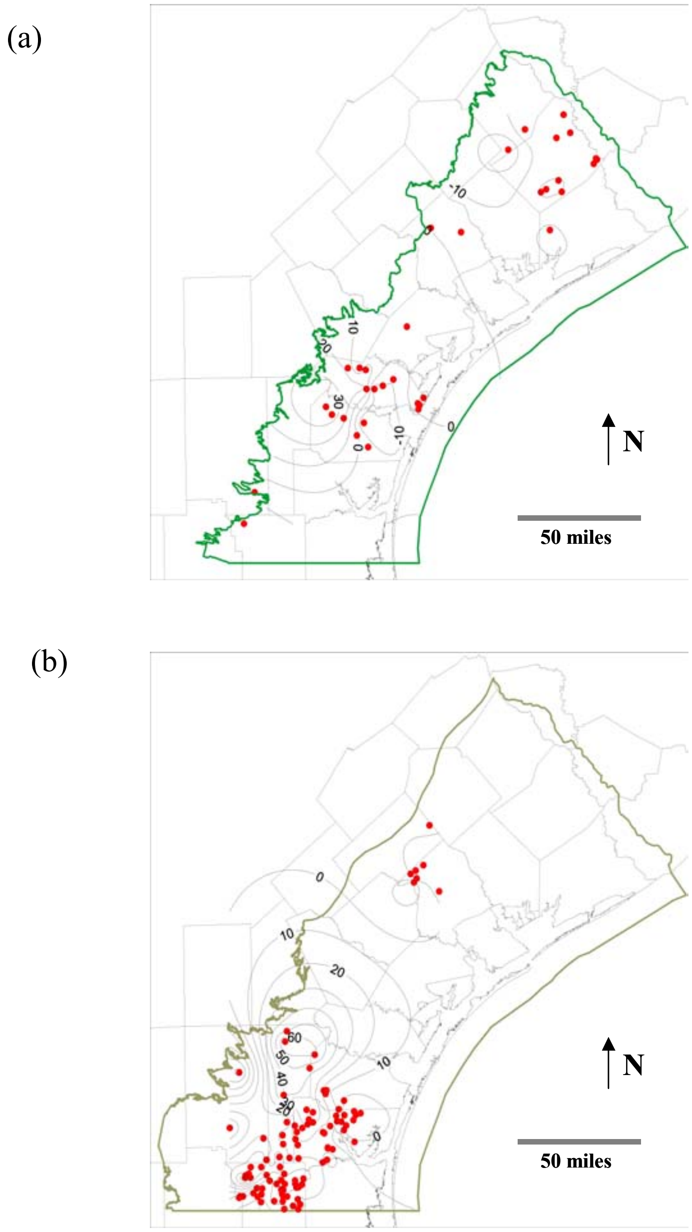


Figure 32: Water-levels residuals in (a) the Chicot aquifer, and (b) the Evangeline aquifer for the pre-development model. Closed circles represent well control points where water level residuals were measured. Water-level contours were developed using the Point Kriging method in Surfer.

We compared simulated net gain-loss values produced by the model through some of the stream reaches with the measured streamflow hydographs (Figure 33). The three stations that we examined included the Guadalupe River at Victoria, the San Bernard River near

Boling, and the San Antonio River near Goliad. Historical stream-flow data from 1910 to 1940 were compared with steady-state simulated baseflow from the model. The daily flow records for the San Bernard River near Boling began in 1954; therefore, steady-state comparisons were not made before that date. Average flow trend lines are also shown in the figures for comparison (Figures 33).

The simulated values should compare to the measured baseflow values, which are a small component of the total streamflow during storm events but may comprise a significant portion (or all of) streamflows during dry periods. Simulated baseflow values plotted on streamflow hydrographs are lower than measured baseflow that commonly lies near the bottom of a stream-flow hydrograph (Figure 33).

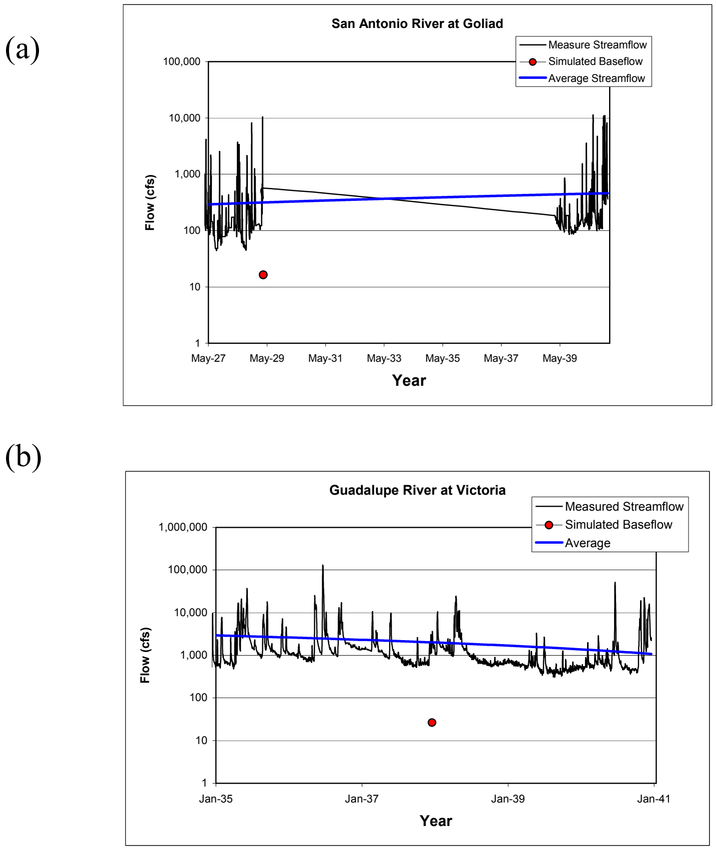


Figure 33: Streamflow hydrographs at two gauges compared with steady-state model results: (a) the San Antonio River at Goliad and (b) the Guadalupe River at Victoria.

Because baseflow is under-estimated, one may suggest that groundwater in the aquifer is overestimated around the gages due to a decrease in baseflow. However, this may not be the case and it may imply that the amount of water discharging at the streams is underestimated. In order to increase base flow it may be necessary to increase recharge beyond reasonable values leading to an overestimation of available water in the aquifer.

4.2 Water Budget

We estimated the total volume of water that enters or leaves the system using the calibrated steady-state model (Table 2). We found that about 620,000 acre-ft of water flows annually through the aquifer system (Figure 34). Of this total flow, 30 percent sources from rainfall that directly falls on the land surface in the outcrop areas of the model, 69 percent seeps into the aquifers from the numerous streams and the remaining small portion from the reservoirs. When recharge values from rainfall alone are considered, we observe that about 66 percent of the recharge from rainfall infiltrates through the outcrops of the Chicot aquifer, about 21 percent infiltrates through the outcrops of the Evangeline aquifer, about 5 percent through the outcrops of the Burkeville Confining System, and about 8 percent through the outcrops of the Jasper aquifer. Cross-formational flow between the different aquifers and the confining units are (1) about 20,000 ac-ft/yr from the Evangeline to the overlying Chicot aquifers, (2) about 6,000 ac-ft/yr from the Burkeville Confining System to the overlying Evangeline aquifer, and (3) about 1,400 ac-ft/yr from the Jasper aquifer to the Burkeville Confining System. Upward cross-formational flow components have higher values than downward flow components. This observation suggests existence of a strong regional upward flow in the central Gulf Coast aquifer system. Of the total annual flow of about 620,000 acre-ft, about 84 percent discharges into the streams, and 16 percent discharges through the general head boundary into the Gulf of Mexico (Figure 34). Baseflow discharges to the rivers are higher than inflow making most of the streams gaining in the area. Net-loss of water from the aquifers (baseflow discharge-water inflow from the river) through (1) the Chicot outcrop is about 46,500 ac-ft/yr, (2) the Evangeline outcrop is about 24,000 ac-ft/yr, (3) the Burkeville Confining System outcrop is about 5,500 ac-ft/yr, and (4) the Jasper outcrop is about 13,000 ac-ft/yr. Both the reservoirs/lakes and the drains used to simulate the wetlands near the coast have only small volumes of water flowing through them.

Figure 34. Water budget for the pre-development model.

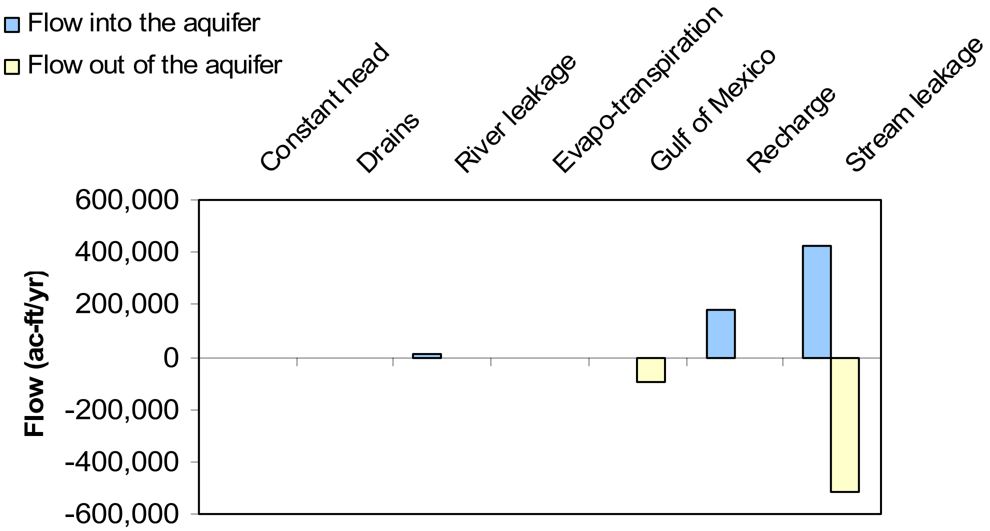


Table 2: Water budget for the pre-development model**.**

Parameter	Flow (in) (ac-ft/yr)	Flow (out) (ac-ft/yr)	Flow (in) (percent)	Flow (out) (percent)
Constant head	0	0	0%	0%
Drains	0	-4,075	0%	1%
River leakage	9,319	0	2%	0%
Evapo-transpiration	0	0	0%	0%
Gulf of Mexico	0	-97,008	0%	16%
Recharge	180,796	0	29%	0%
Stream leakage	426,578	-515,610	69%	84%
Total	616,693	-616,693	100%	100%

4.3 Sensitivity Analysis

Sensitivity analysis is the process of varying model input parameters over a reasonable range and observing the model response to these changes to establish uncertainties in the calibrated values. These uncertainties arise due to difficulties associated with estimating aquifer parameters, stresses, and boundary conditions (Andersson and Woessner, 1992, p.

246). The sensitivity of one model parameter relative to other parameters is also demonstrated. Sensitivity analysis assesses the adequacy of the model with respect to its intended purposes (ASTM, 1994). Sensitivity analyses are also beneficial in determining the direction of future data collection activities. Data for which the model is relatively sensitive may require future characterization, as opposed to data for which the model is relatively insensitive. Model-insensitive data require no further field characterization. When constant head, constant flux, or head-dependent flux boundaries are located in close proximity of the calibration targets, it may result in the model being insensitive to changes in the input parameters.

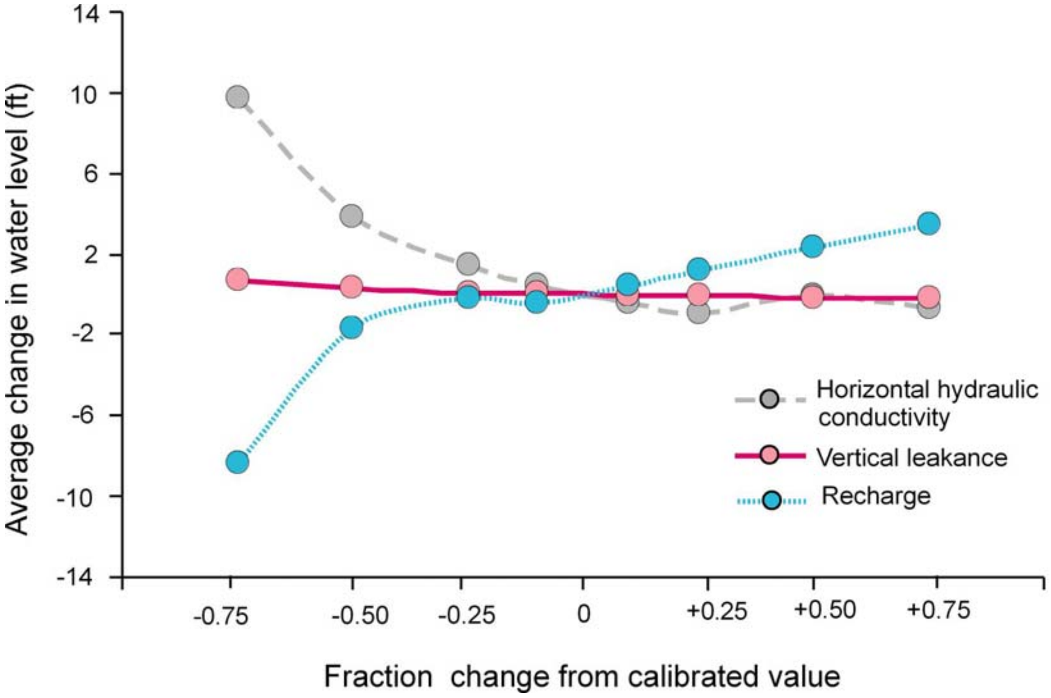


Figure 35 Sensitivity of the simulated water-levels to changes in calibrated values at the calibration well points of the pre-development model.

We tested the sensitivity of the water levels to changes in parameters in the Chicot, the Evangeline, and the Jasper aquifers and the Burkeville Confining System. During the sensitivity analysis, we systematically varied (±75%) the calibrated values of hydraulic conductivity, recharge, and vertical leakance one at a time in all four layers of the model. The magnitude of changes in the water levels in each active cell was considered a measure of sensitivity of the solution to that parameter. We quantified the changes in the water levels at the wells by calculating the mean difference (MD) in the water levels in each active cell according to:

$$\mathrm{MD} = 1/\mathrm{n}\sum(H_{sen} - H_{cal})$$

where n is the number of points, H_{sen} is the simulated water level, and H_{cal} is the calibrated water level. The mean difference is positive if water levels were higher than the calibrated values and negative if lower than the calibrated values.

Water levels in the model are most sensitive to the horizontal hydraulic conductivity of the Evangeline aquifer and vertical leakance of the Chicot aquifer. The Evangeline aquifer is more sensitive to aquifer parameters than the Chicot aquifer. When we varied vertical leakance values uniformly for all the model layers, water levels do not change much indicating that this parameter is not sensitive to model calibration within the range of changes (Figure 35). Lower recharge values caused water levels to decline in the model while higher recharge values cause water levels to rise. Similarly, lower horizontal hydraulic conductivity caused water levels to rise, and higher horizontal hydraulic conductivity caused water levels to decline. The model is more sensitive to lower recharge values than higher recharge values due to discharge of excess recharge as baseflow to the streams and/or wetlands.

5 Transient Model

After we calibrated the steady-state model to water levels in the 1940s, we calibrated the model to transient water levels for 1980 to 1990. We started the transient model calibration from the calibrated steady-state solution so that the initial head and parameter inputs were consistent. We calibrated the model to water-level changes caused by pumping of the aquifer. A stress period spanning over 40 years was assigned before the actual transient model run. This stress period included 1980 pumpage values and water levels from the pre-development model were assigned as initial heads. This was done with the assumption that this run will simulate water-level conditions for the 1980’s. We assigned annual stress periods for 1980 to 2000 except for the drought years in each decade when we assigned monthly stress periods (1987, 1988, 1989 and 1995, 1996, and 1997). We verified the transient calibrated model to water-level changes during 1990 to 2000.

5.1 Calibration and Verification

We calibrated the transient model by adjusting specific storage, specific yield, horizontal hydraulic conductivity of the Evangeline aquifer, and the vertical leakance of the Chicot aquifer. When we only adjusted the storage values, we were unable to reproduce the drawdowns in Wharton, Victoria and Kleberg counties. Therefore, we lowered the distributed horizontal hydraulic conductivity across the Evangeline aquifer and developed three sub-zones based on the median of the distributed values. We also lowered the vertical leakance of the Chicot aquifer uniformly across the model layer and assigned a vertical leakance of 10^{-9} ft/d over a small area near Kingsville to represent local silt and fine sand.

When we changed the horizontal hydraulic conductivity and vertical leakance values, we had to maintain a balance such that we did not under- or over-estimate drawdowns in any particular area. The set of calibrated horizontal hydraulic conductivity and vertical leakance values that we developed for the transient model was then used to calibrate water levels and stream flows in the pre-development model.

We reproduced seasonal water-level changes in the transient model using recharge based on climatic changes. We used specific storage values of 0.000008, 0.000001, 0.00001, and 0.000008 for layers 1, 2, 3 and 4, respectively, and specific yield values of 0.05, 0.01, 0.005, and 0.05 for layers 1, 2, 3, and 4, respectively.

The specific yield values of 0.01 to 0.005 that we used in the transient calibration may seem low for the unconfined portions of the aquifer. Typical specific yields of sedimentary materials in unconfined aquifers range from 0.14 to 0.38 (Freeze and Cherry, 1979). We attempted to calibrate the model using higher specific yields but were unable to reproduce the required fluctuations to match the measured water levels. The lower specific yield that we used is more typical of semi-confined aquifers. We feel that the lower specific yields are appropriate for the Chicot, Evangeline, and the Jasper aquifers as they contain numerous interbedded silt/clay lenses.

The mean error (ME) for calibration is -16 feet for 1989 and -6 feet for 1999. The mean absolute error (MAE) for calibration is 33 feet for 1989 and 26 feet for 1999. The root mean squared error (RMSE) for calibration is 46 feet for 1989 and 36 feet for 1999 (Figures 36, 37). Improvement in the RMSE values for the 1999 transient calibration period was probably caused by (1) a much smaller drawdown observed in 1999 than in 1989 which absorbed the effects of underestimated drawdown and (2) fewer observations wells available with water-level measurements. The RMSE values for the 1989 calibration period and for the 1999 calibration period are 5.1 percent and 4.8 percent, respectively, of the hydraulic head drop across the model area.

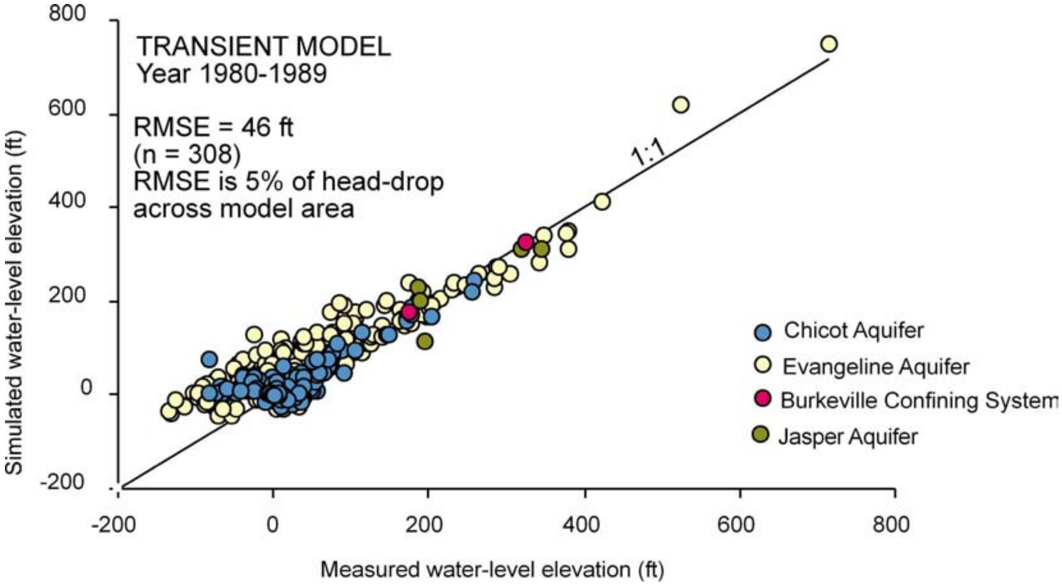


Figure 36: Comparison of simulated water-levels to measured water levels for 1989.

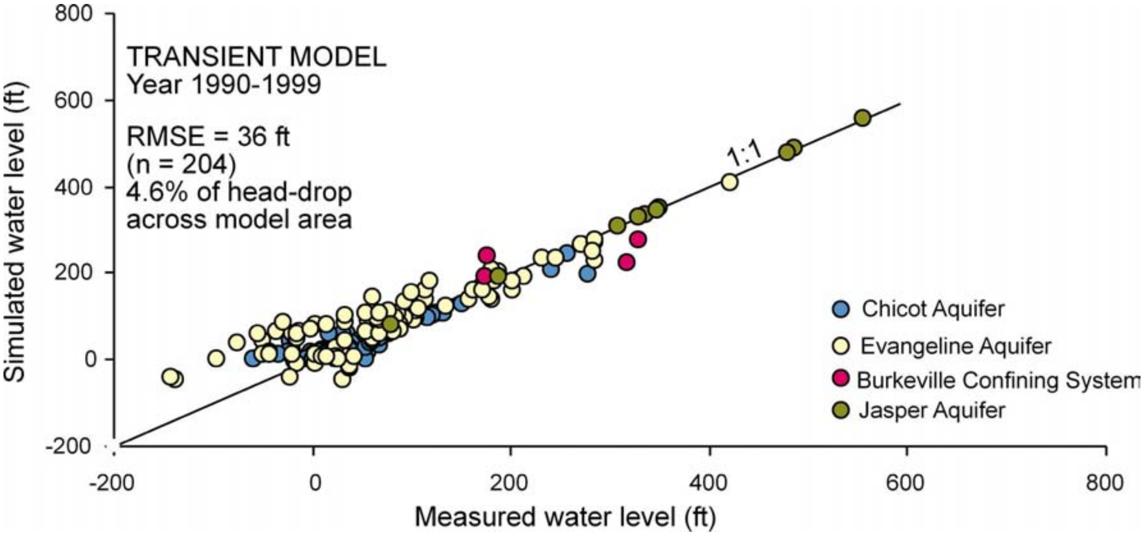


Figure 37. Comparison of simulated water-levels to measured water levels for 1999.

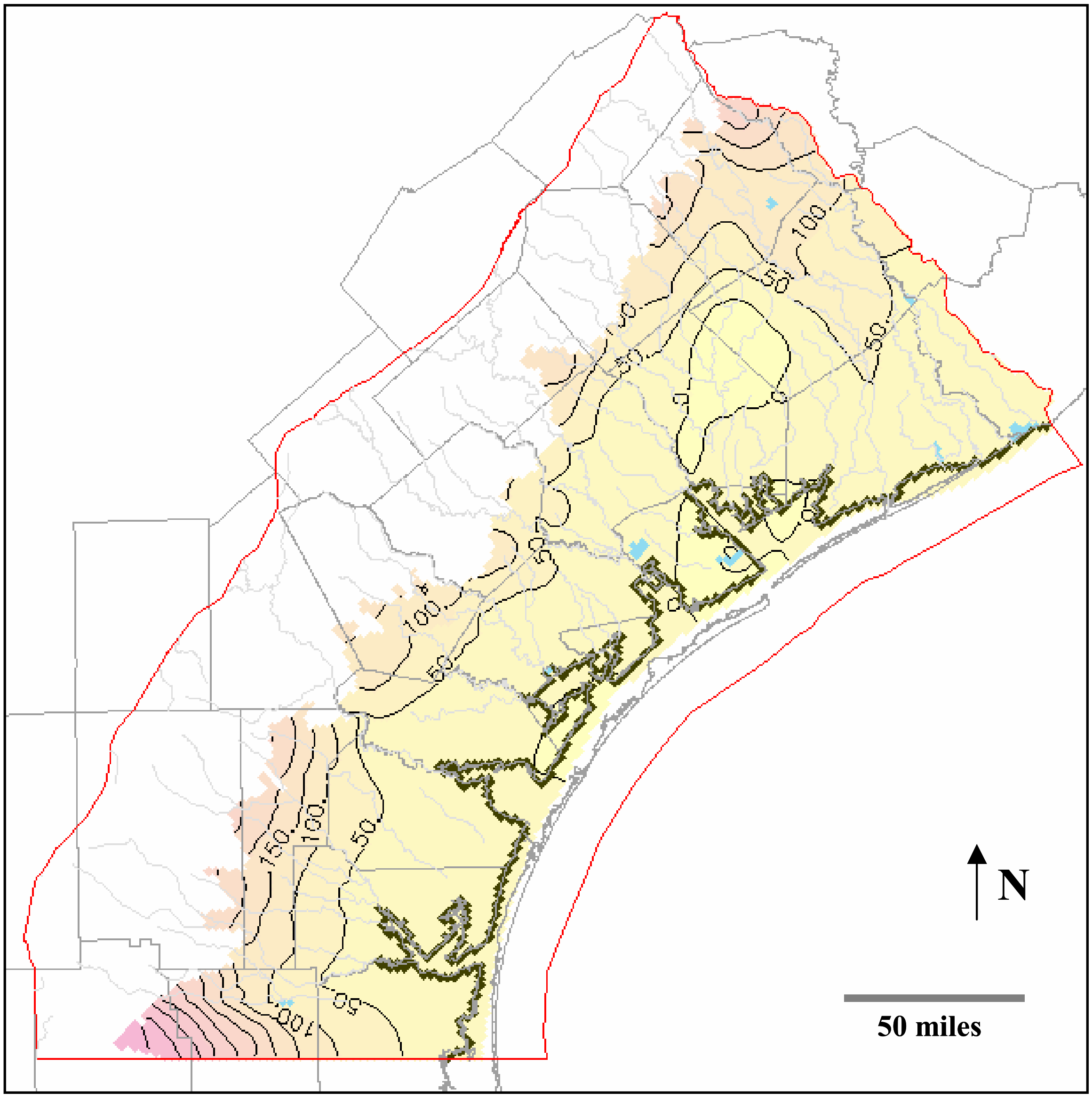


Figure 38: Simulated water-levels in the Chicot aquifer for 1989.

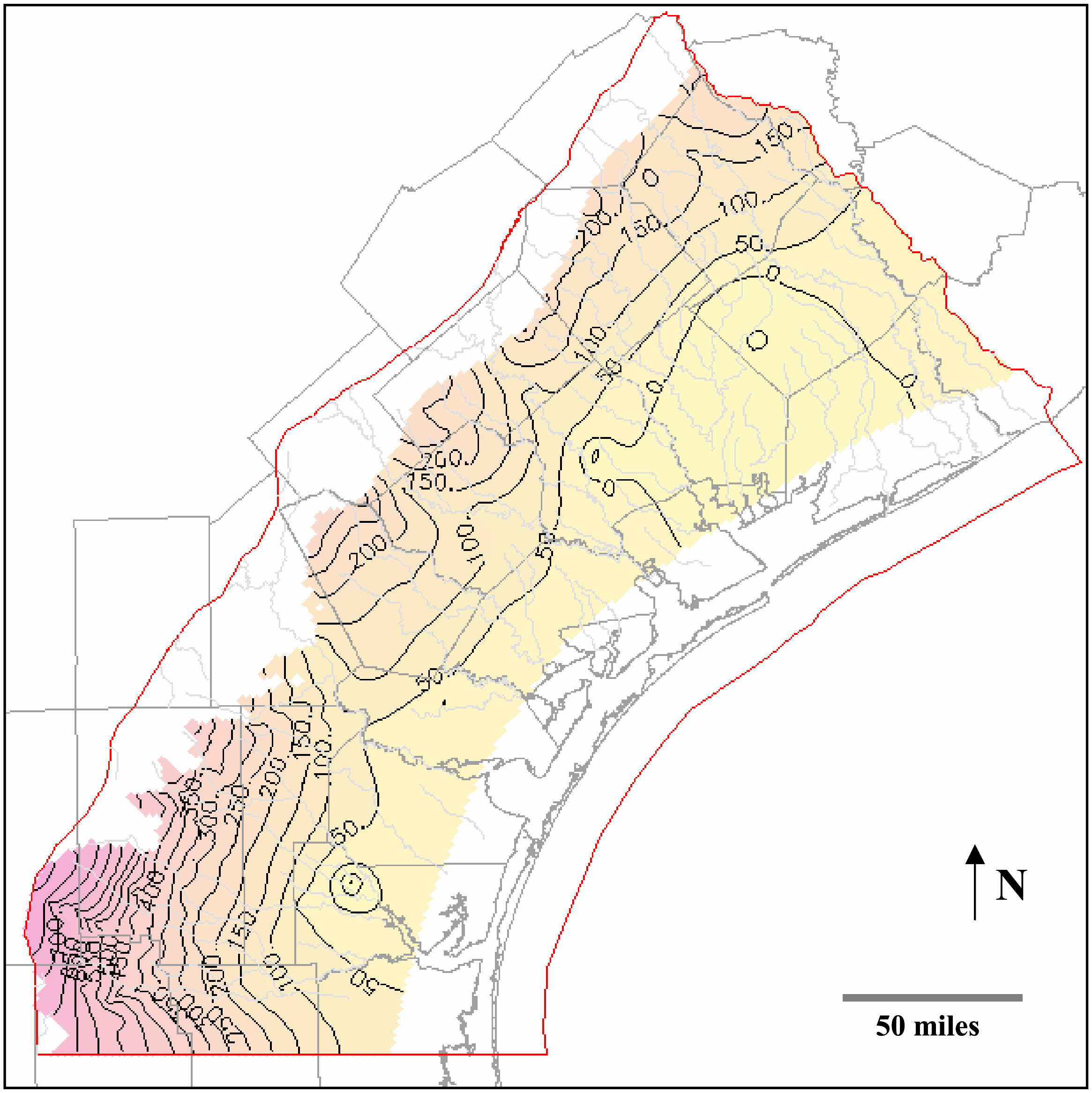


Figure 39: Simulated water-levels in the Evangeline aquifer for 1989.

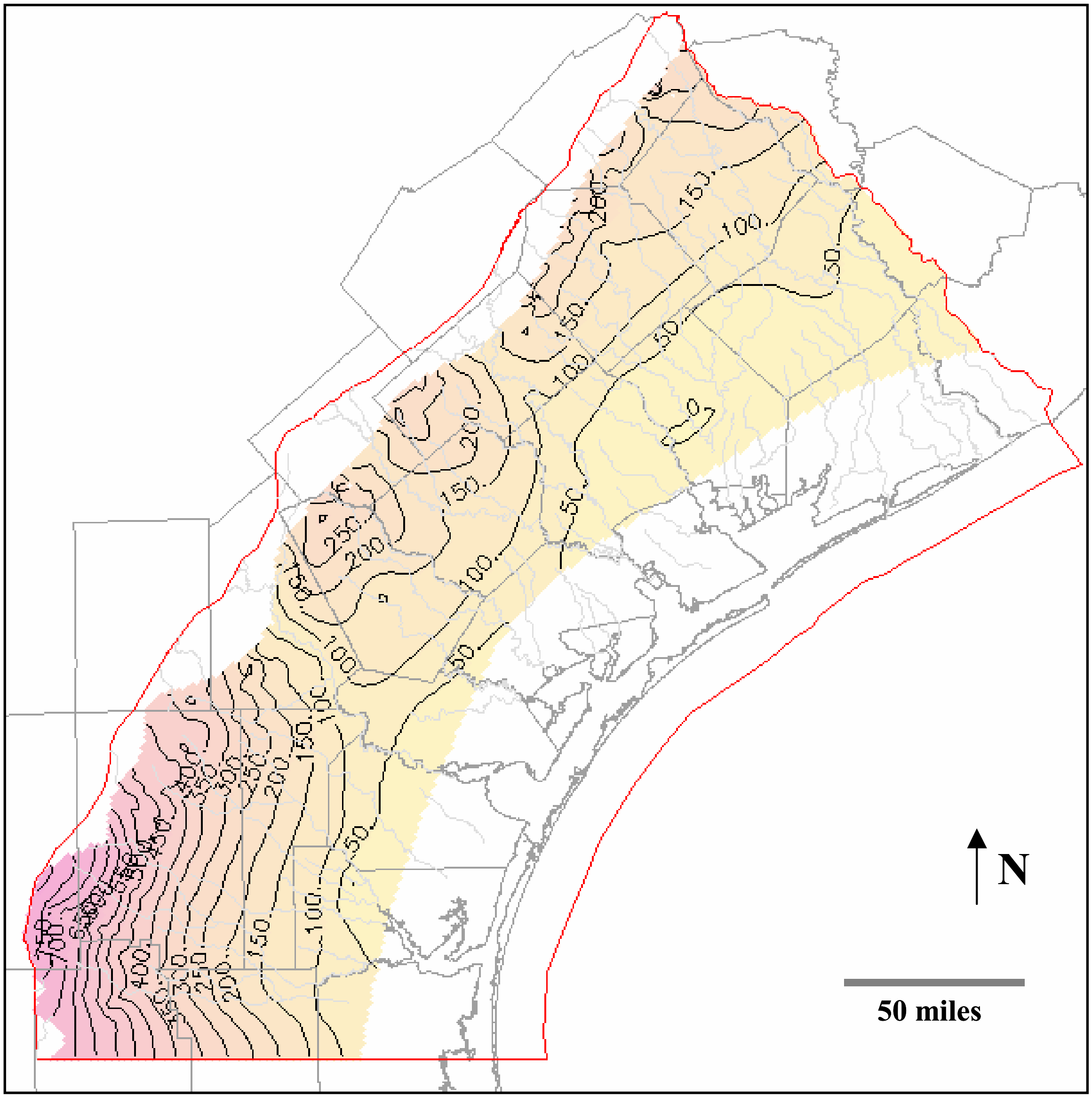


Figure 40: Simulated water-levels in the Burkeville Confining System for 1989.

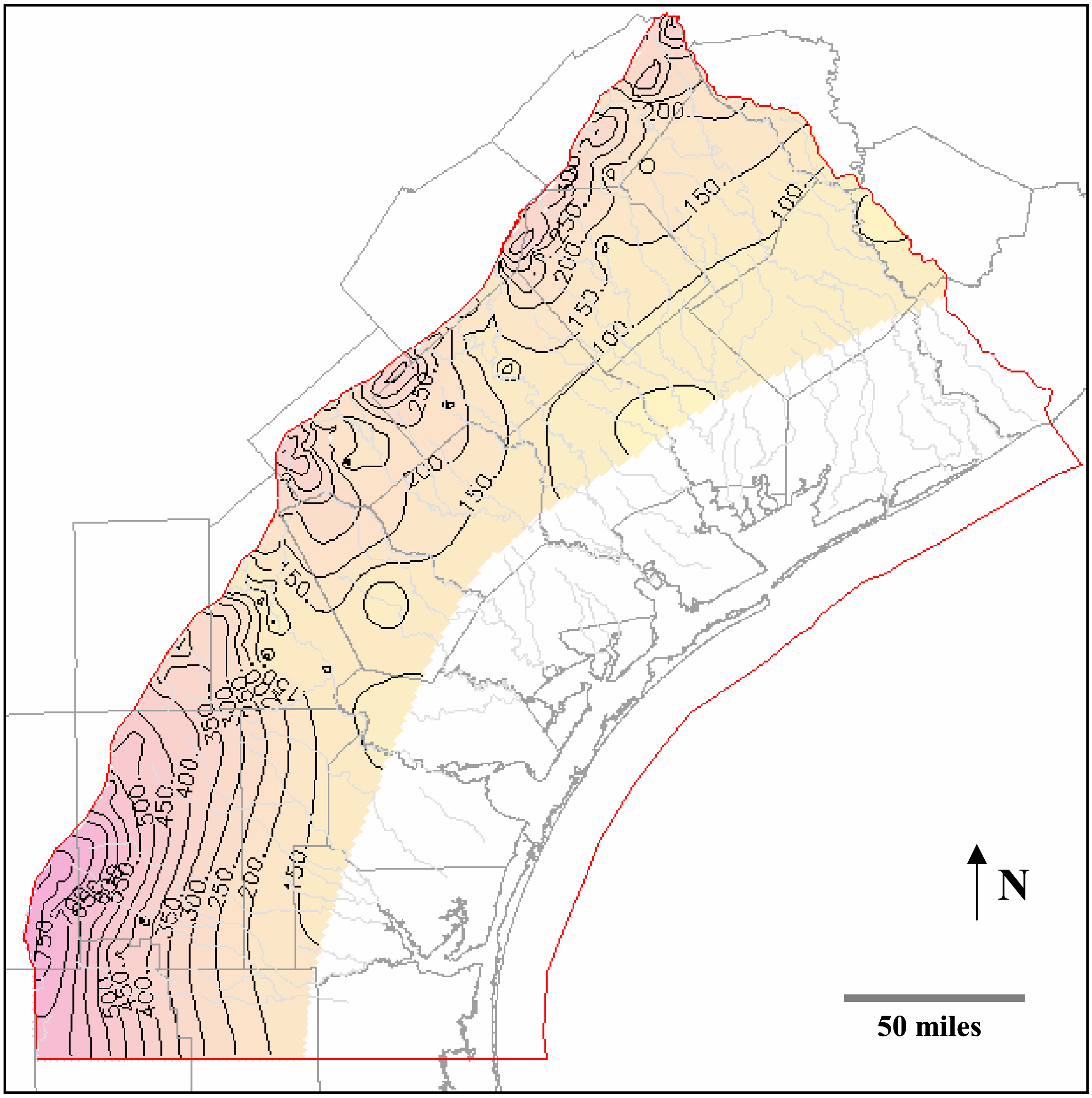


Figure 41: Simulated water-levels in the Jasper aquifer for 1989.

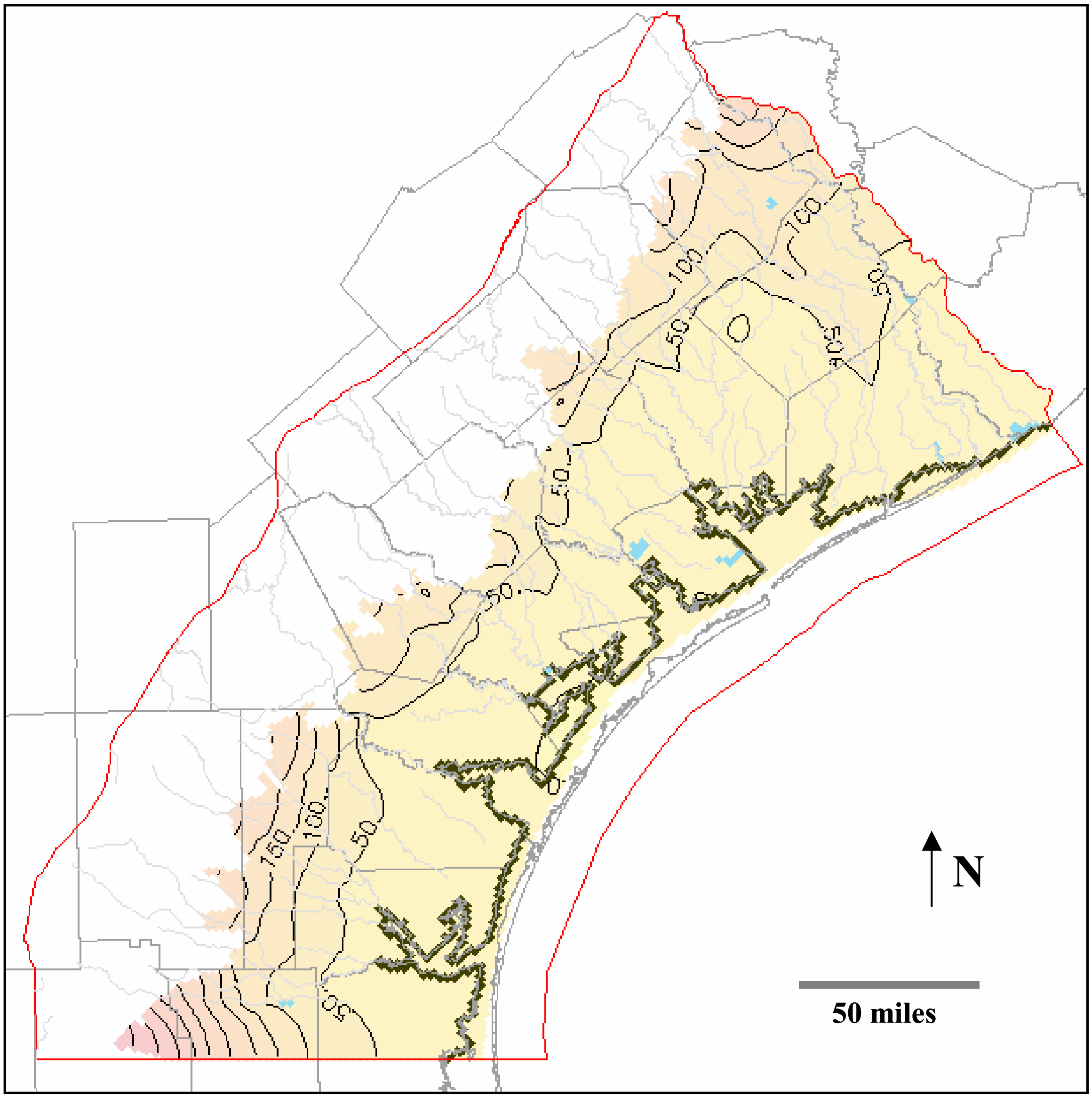


Figure 42: Simulated water-levels in the Chicot aquifer for 1999.

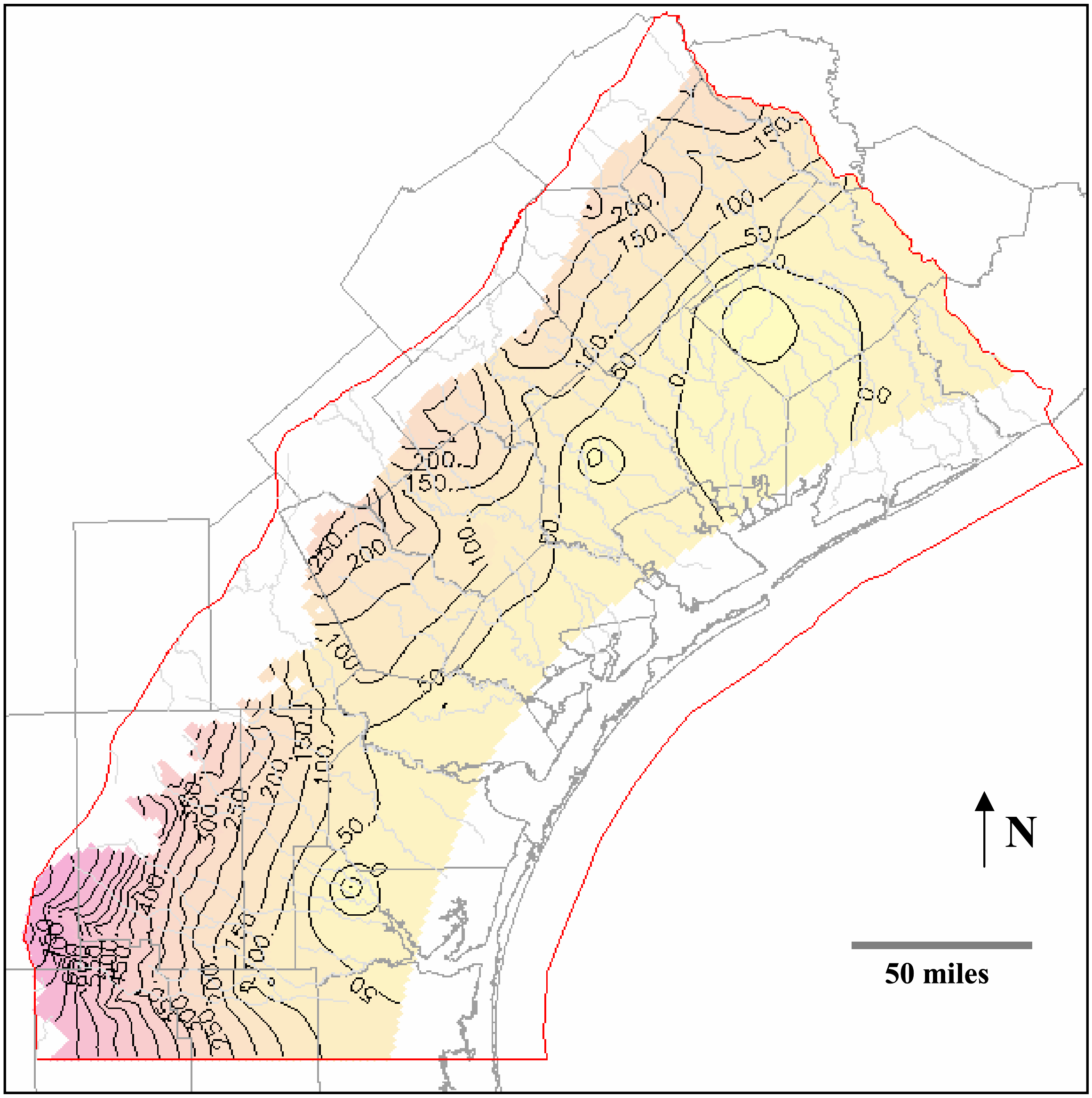


Figure 43: Simulated water-levels in the Evangeline aquifer for 1999**.**

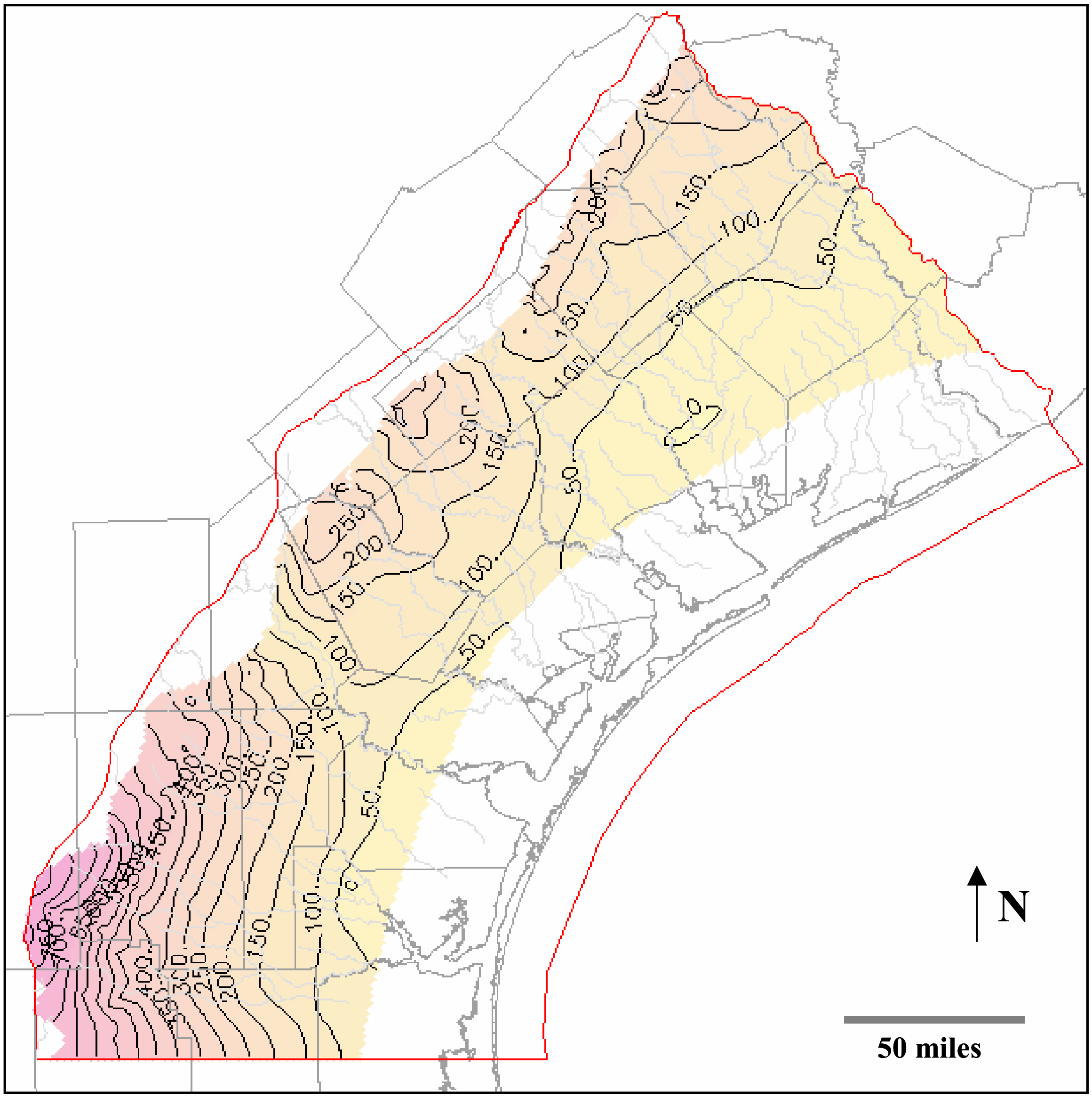


Figure 44: Simulated water-levels in the Burkeville Confining System for 1999.

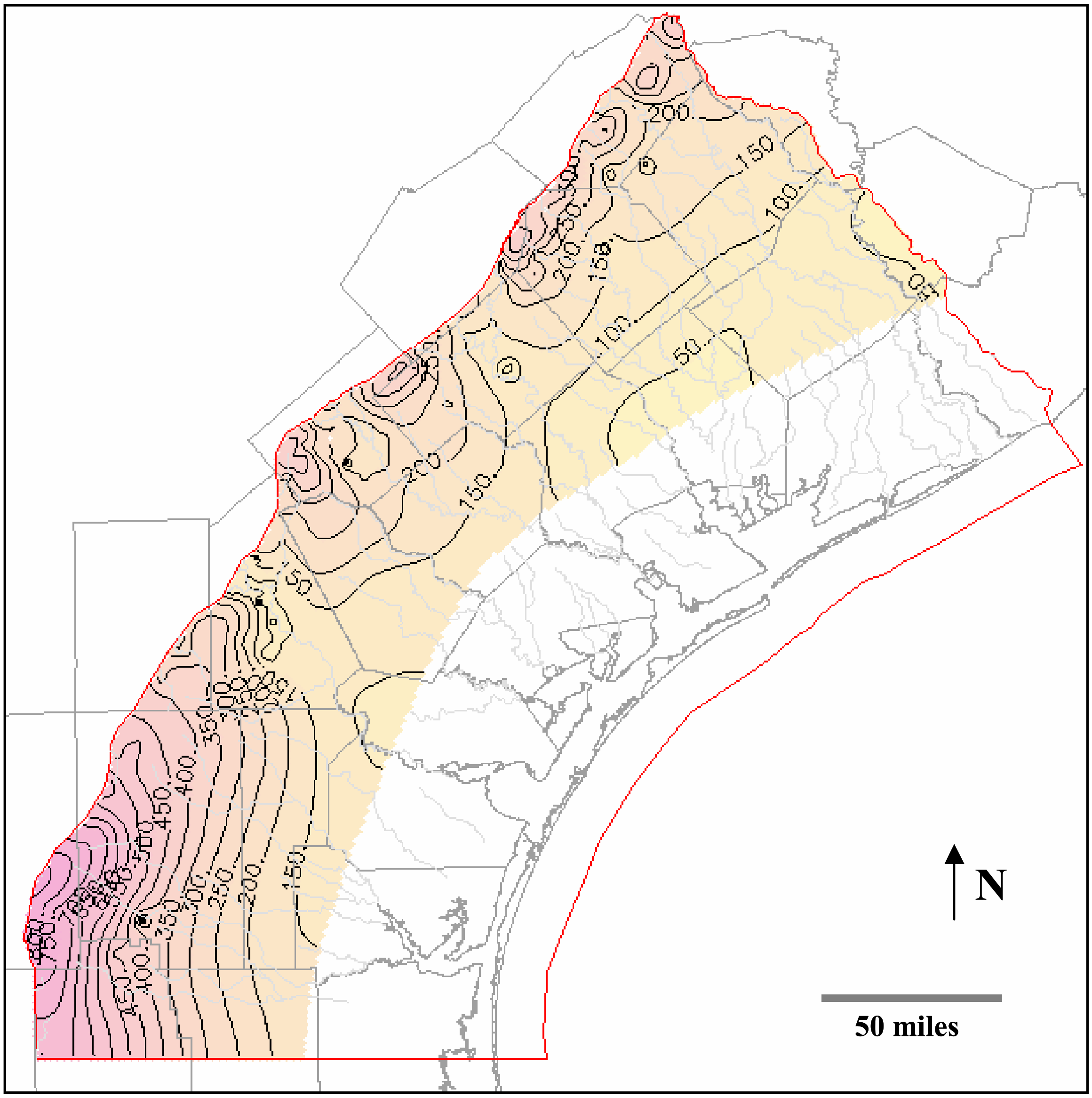


Figure 45: Simulated water-levels in the Jasper aquifer for 1999**.**

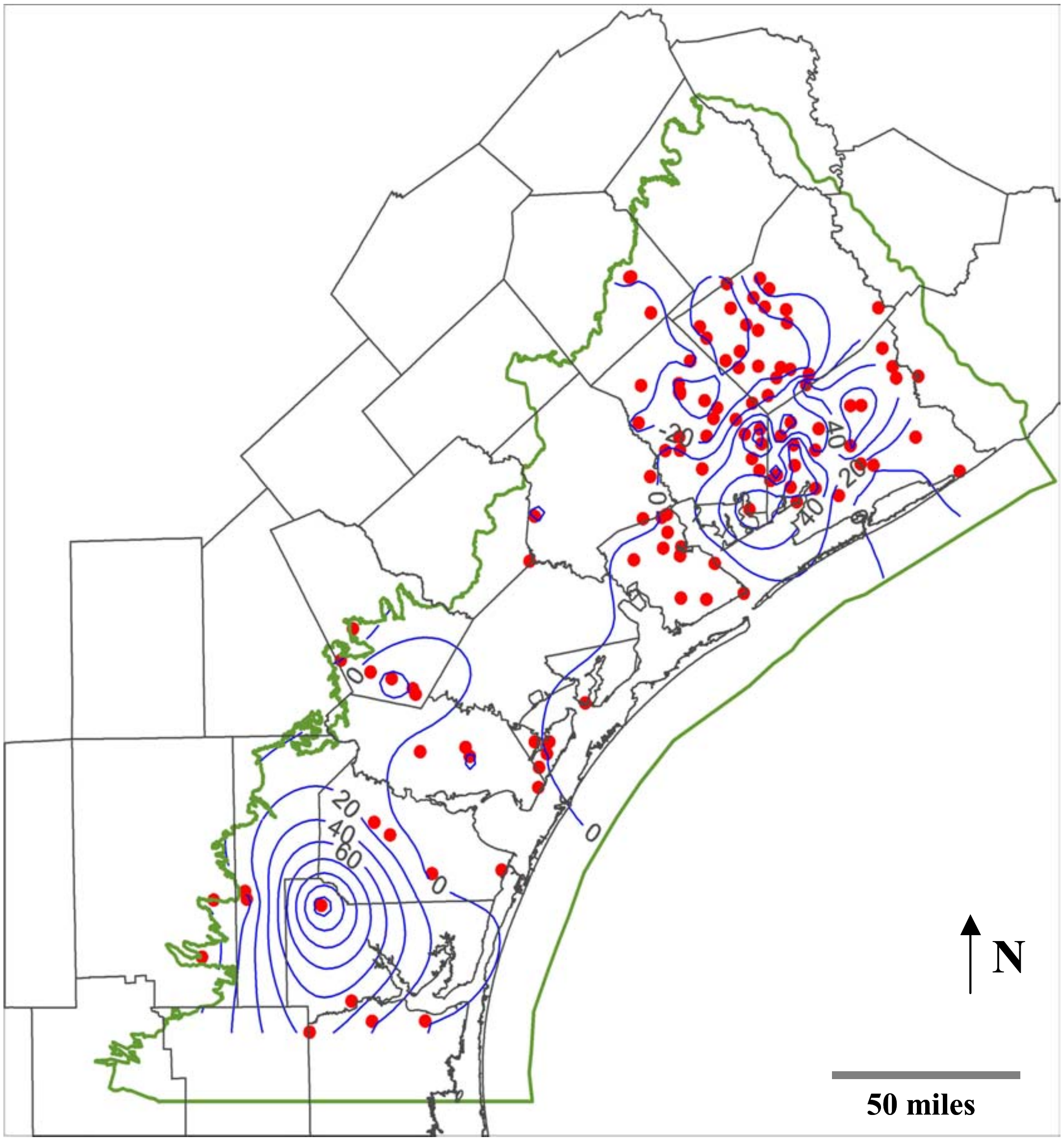


Figure 46: Water-level residuals in the Chicot aquifer for 1989. Closed circles represent well control points where water level residuals were measured. Water-level contours were developed using the Point Kriging method in Surfer.

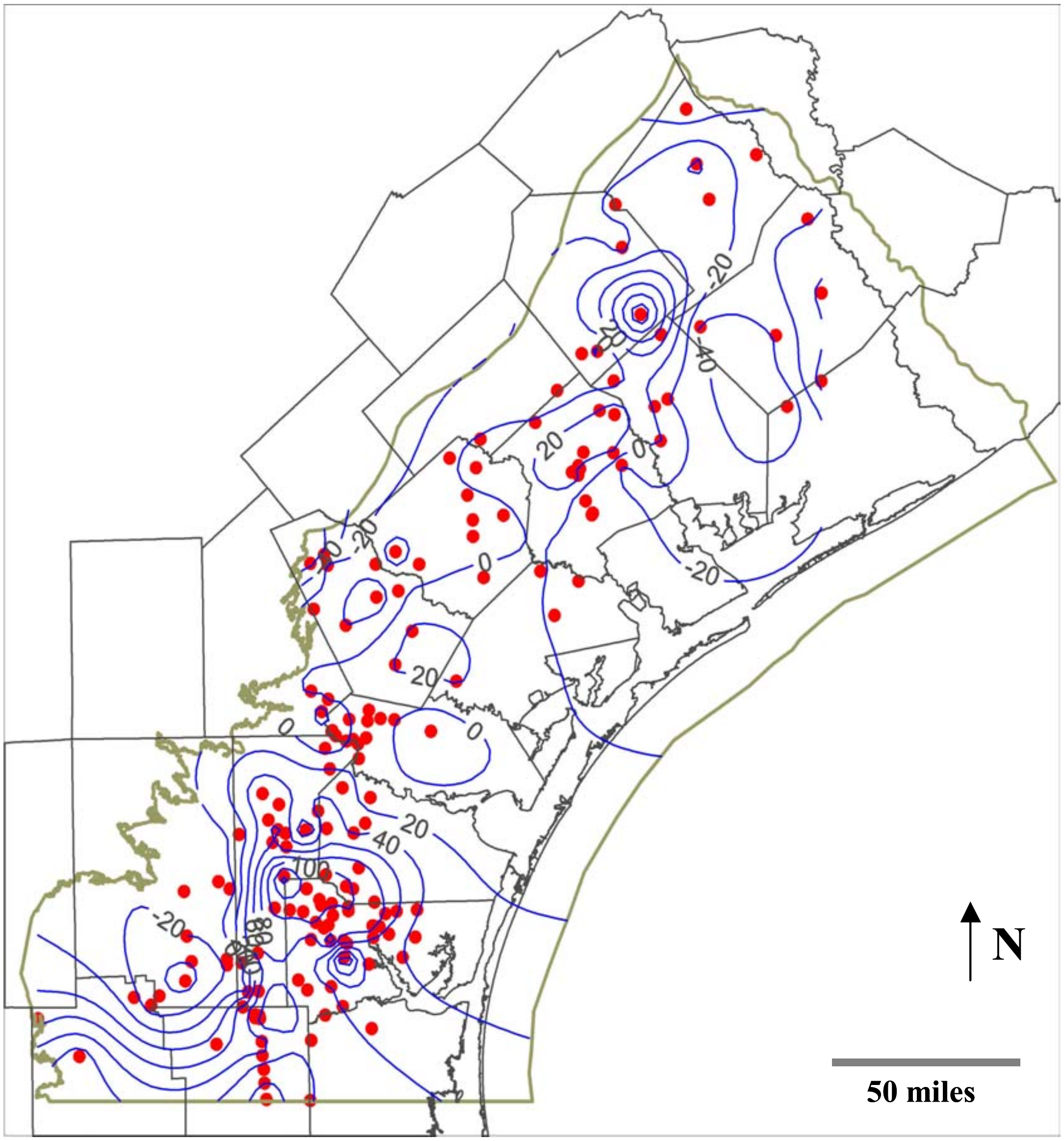


Figure 47: Water-level residuals in the Evangeline aquifer for 1989. Closed circles represent well control points where water level residuals were measured. Water-level contours were developed using the Point Kriging method in Surfer.

Simulated distributions of the water-level surfaces for all model layers in 1989 and 1999 reasonably reproduce the measured values (Figures 38 through 45). Spatial distribution of the water-level residuals (measured water-levels at calibration well points subtracted from the simulated water-levels) appear unbiased across the model area (Figures 46 through 49). In some areas, we have been more successful in minimizing errors. For example, most of the central portion of the model have errors close to zero while in parts of the southern portion of the model area near Kingsville where we have underestimated the drawdown, the errors are as large as 100 ft. When we compare the distribution of the residuals and their magnitudes for 1989 and 1999, we observe that there is an improvement in the water-level residuals because of a general recovery of the water levels in 1999 (Figures 46 through 49).

The transient model does a reasonable job in matching the measured monthly and annual water-level trends throughout most of the model area with the exception of a shift between simulated and measured water levels in some wells. In many wells, however, there is a good match between the measured and the simulated water levels throughout the model area (Figures 50 through 53). The shift in water levels observed in some wells may have been carried over to the transient model from the initial conditions used from the steady-state model. In some wells, the shift in the water levels was more pronounced than in others. This discrepancy is probably due to local scale heterogeneity in the aquifer that we were unable to capture at the scale of the regional model. It is probable that the shift in water levels could probably be caused by gradients within one square mile model grid sizes that are not captured at the model scale.

We compared simulated net gain-loss values on several stream reaches (Figure 54). These simulated net gain-loss values should compare to the measured baseflow values which is commonly a small component of the streamflow hydrographs. Our simulated values are lower than the baseflow that would be expected from the streamflow hydrographs (Figure 54). However, the trend in the simulated net gain-loss follows the trend observed in measured streamflow hydrographs. We compared simulated net gain-loss with the measured gain-loss values through stream reaches in Colorado, Lavaca, and Nueces rivers (Table 3). We observed that the simulated net gain-loss values for Lavaca and Nueces Rivers are in the same orders of magnitude to measured values while for the Colorado River, the simulated baseflow is much lower. In regional groundwater flow models, it is always difficult to reproduce baseflow where the errors in the simulated heads in the aquifers could be potentially large and the stages in the river are fixed. A global increase in stream conductance causes too much of a hydraulic interaction between the aquifers and the streams in the central Gulf Coast GAM (Waterstone, 2003) and would require unreasonable recharge values to calibrate the model.

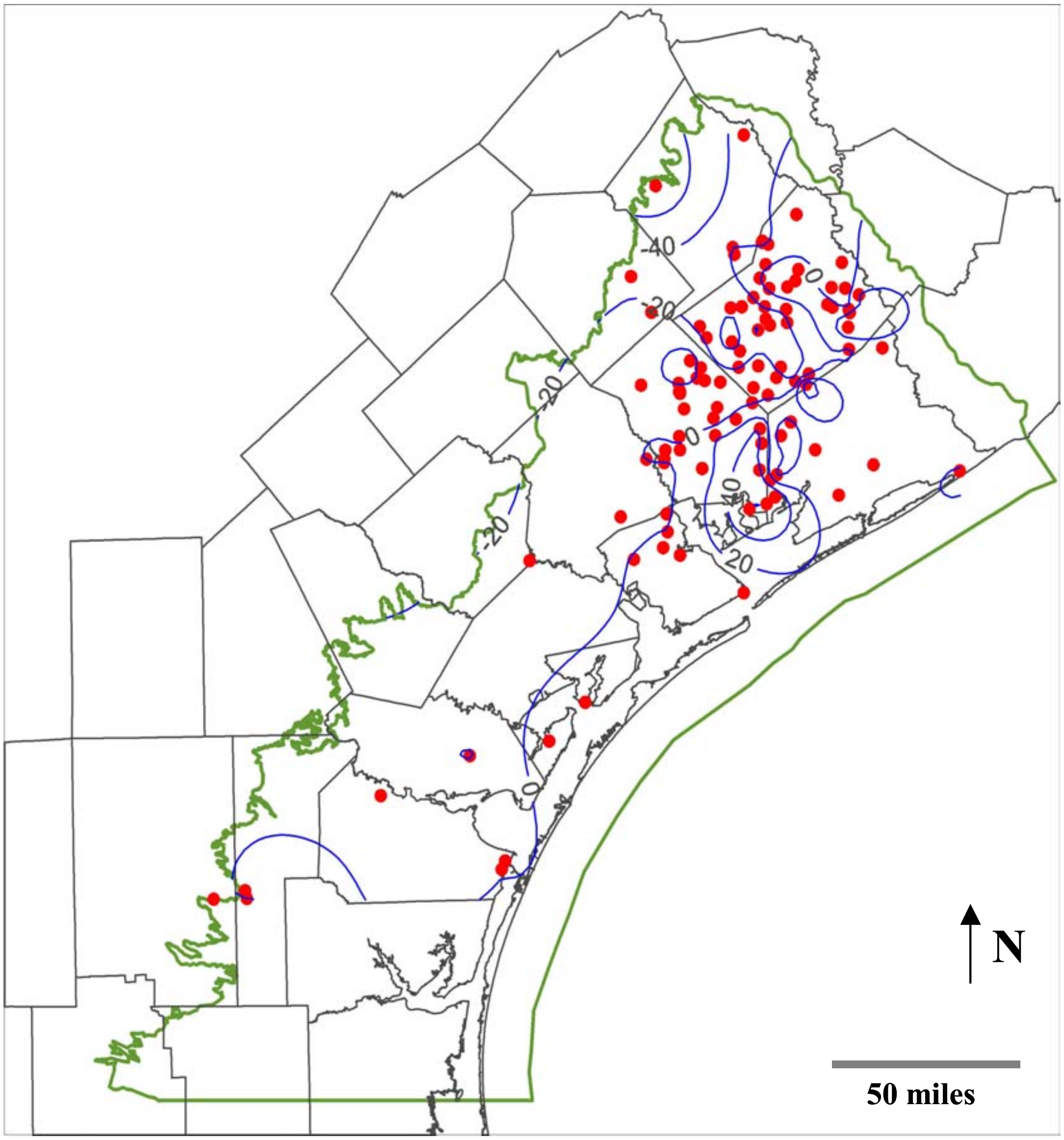


Figure 48: Water-level residuals for the Chicot aquifer for 1999. Closed circles represent well control points where water level residuals were measured. Water-level contours were developed using the Point Kriging method in Surfer.

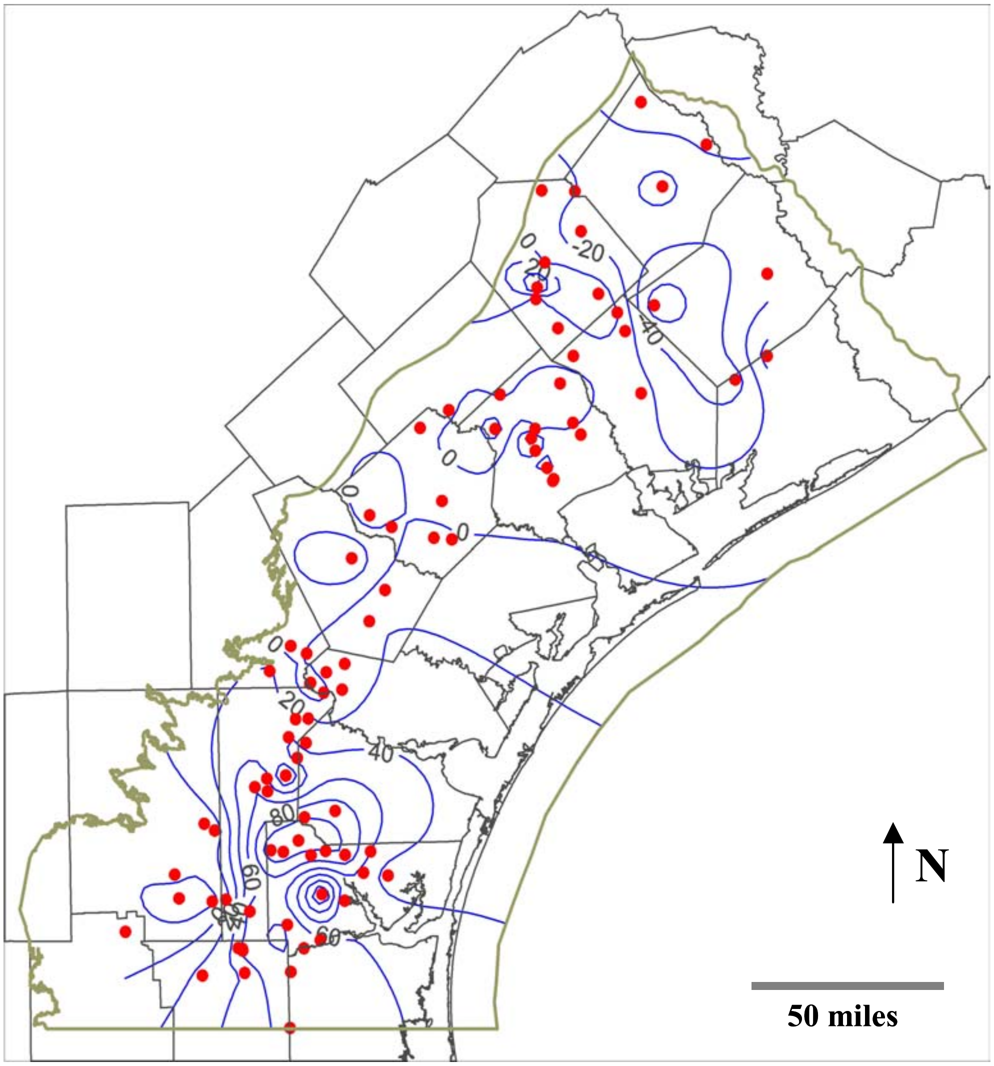


Figure 49: Water-level residuals for the Evangeline aquifer for 1999. Closed circles represent well control points where water level residuals were measured. Water-level contours were developed using the Point Kriging method in Surfer.

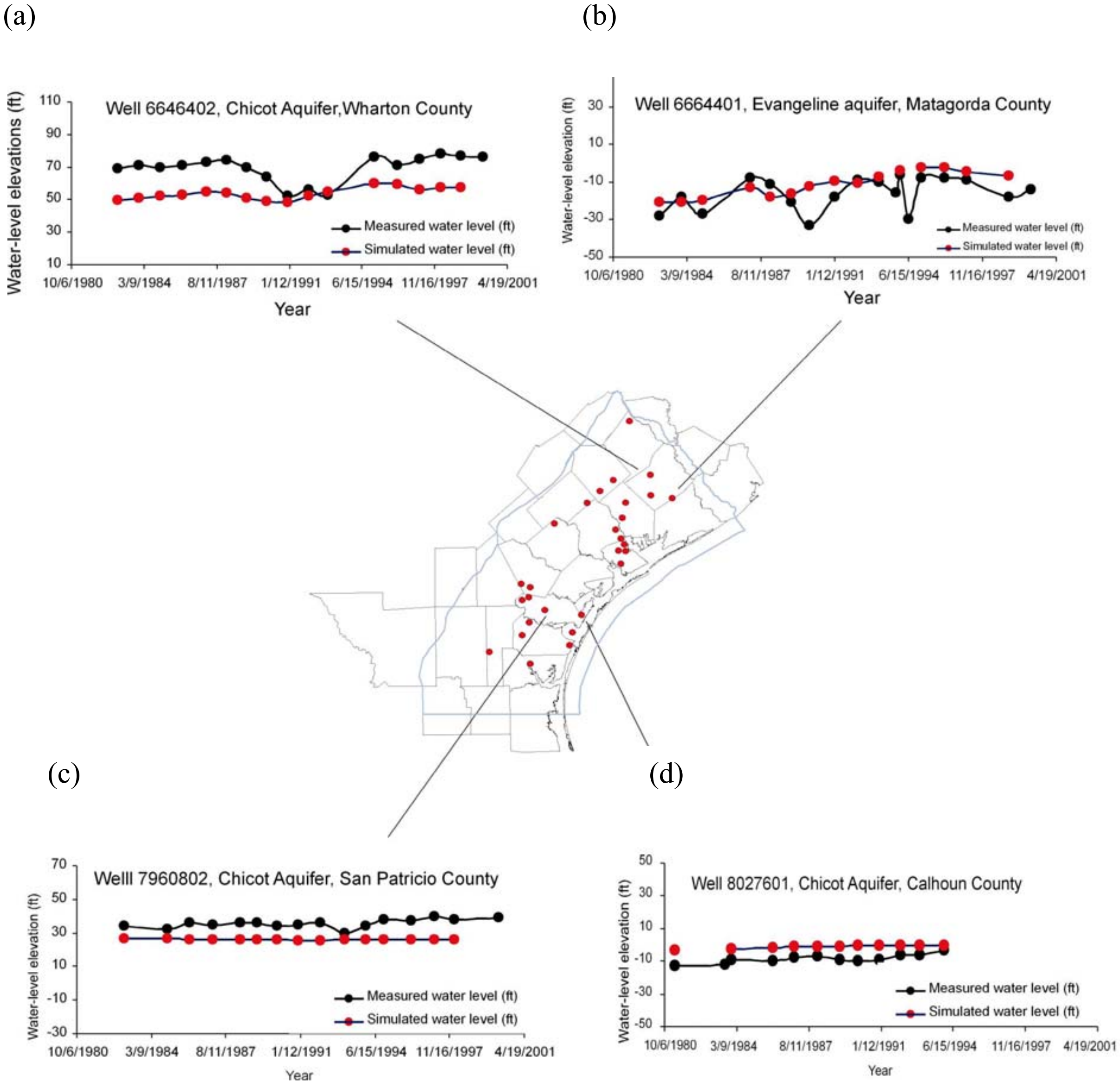


Figure 50: Comparison of simulated and measured water-level fluctuations in several wells for 1980 through 1999 for (a) Well 6646402, (b) Well 6664401, (c) Well 7960802, and (d) Well 8027601.

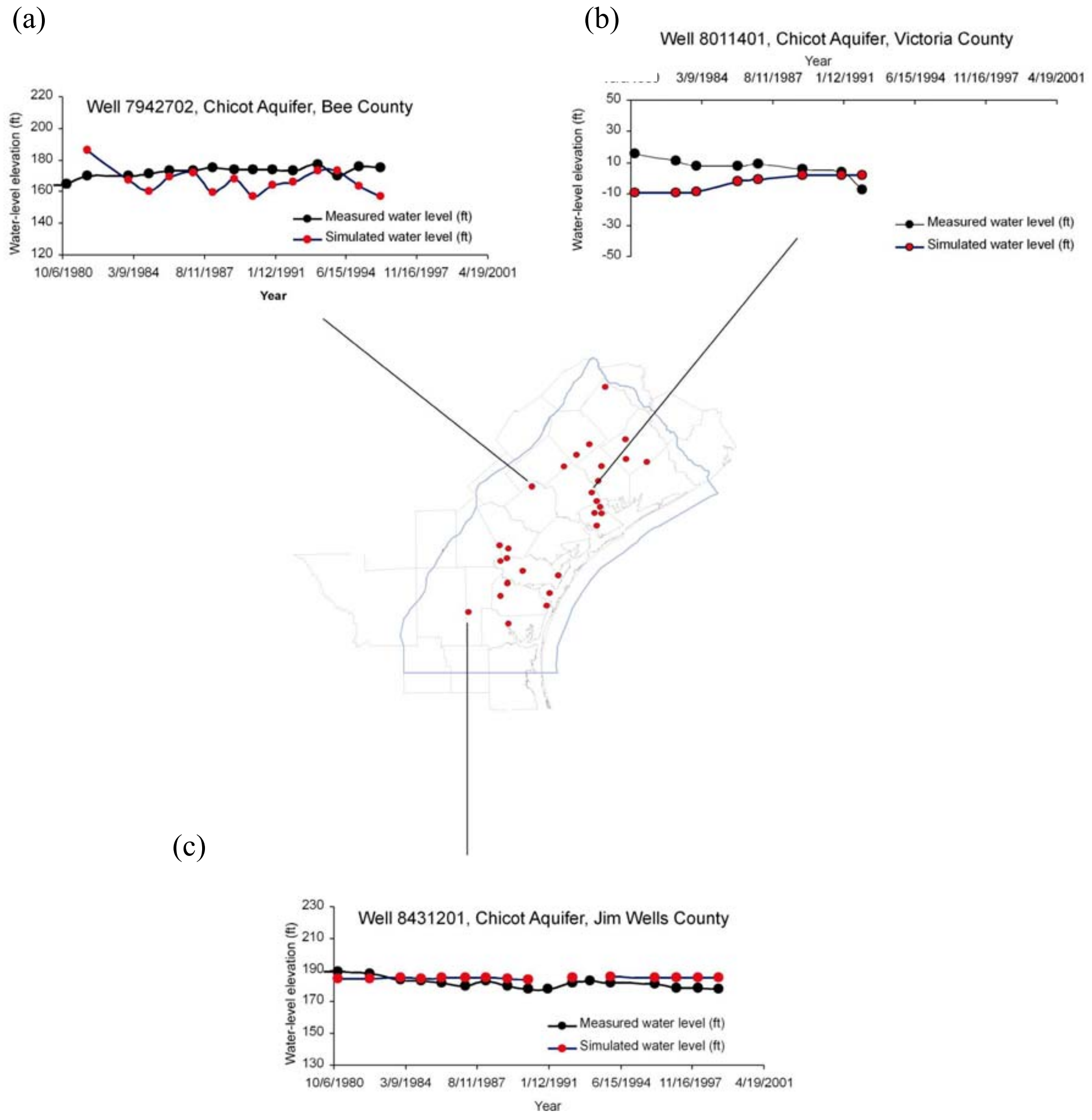


Figure 51: Comparison of simulated and measured water-level fluctuations in several wells for 1980 through 1999 for (a) Well 7942702, (b) Well 8011401, and (c) Well 8431201.

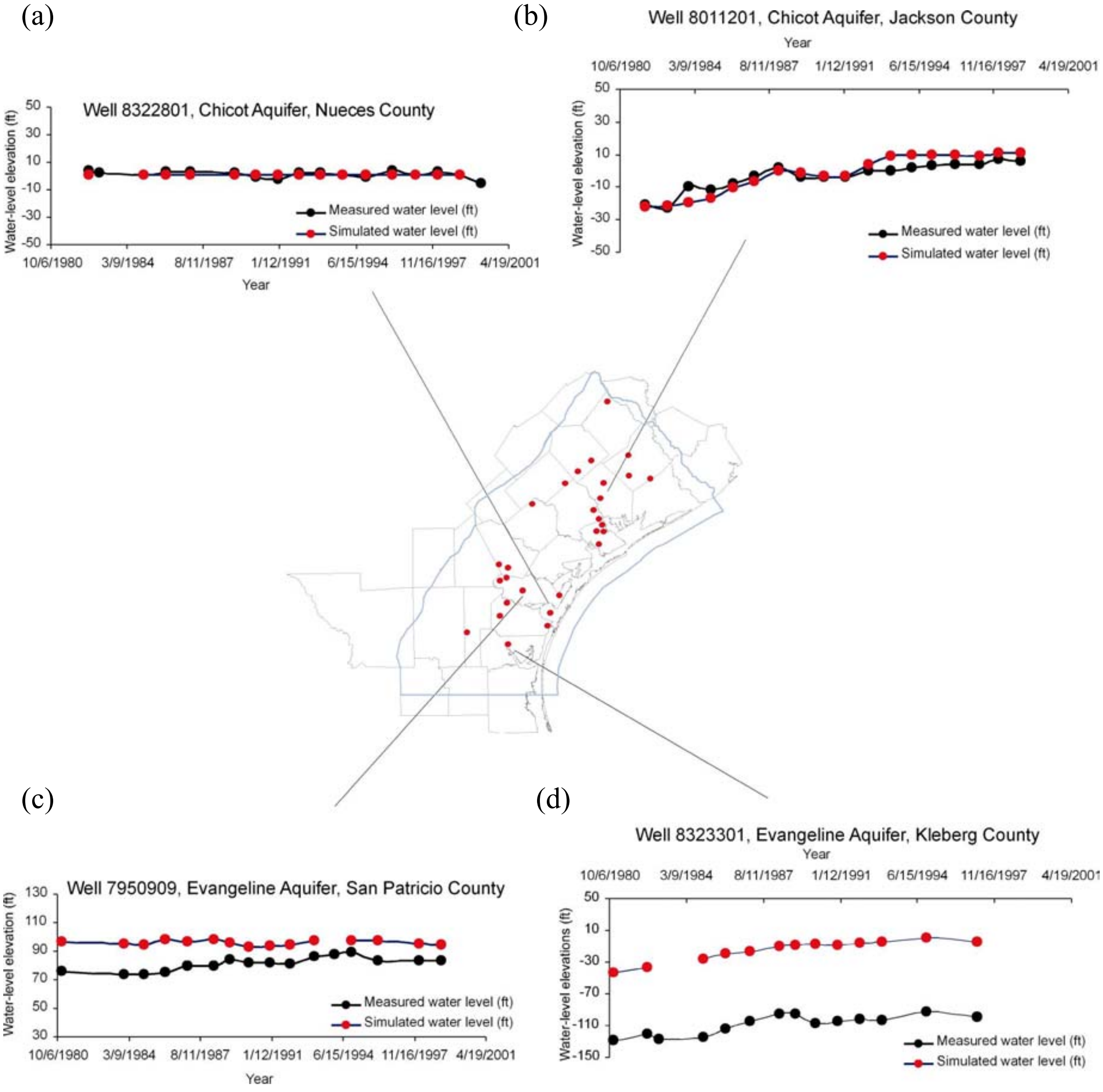


Figure 52: Comparison of simulated and measured water-level fluctuations in several wells for 1980 through 1999 for (a) Well 8322801, (b)Well 8011201, (c) Well 7950909, and (4) Well 8323301.

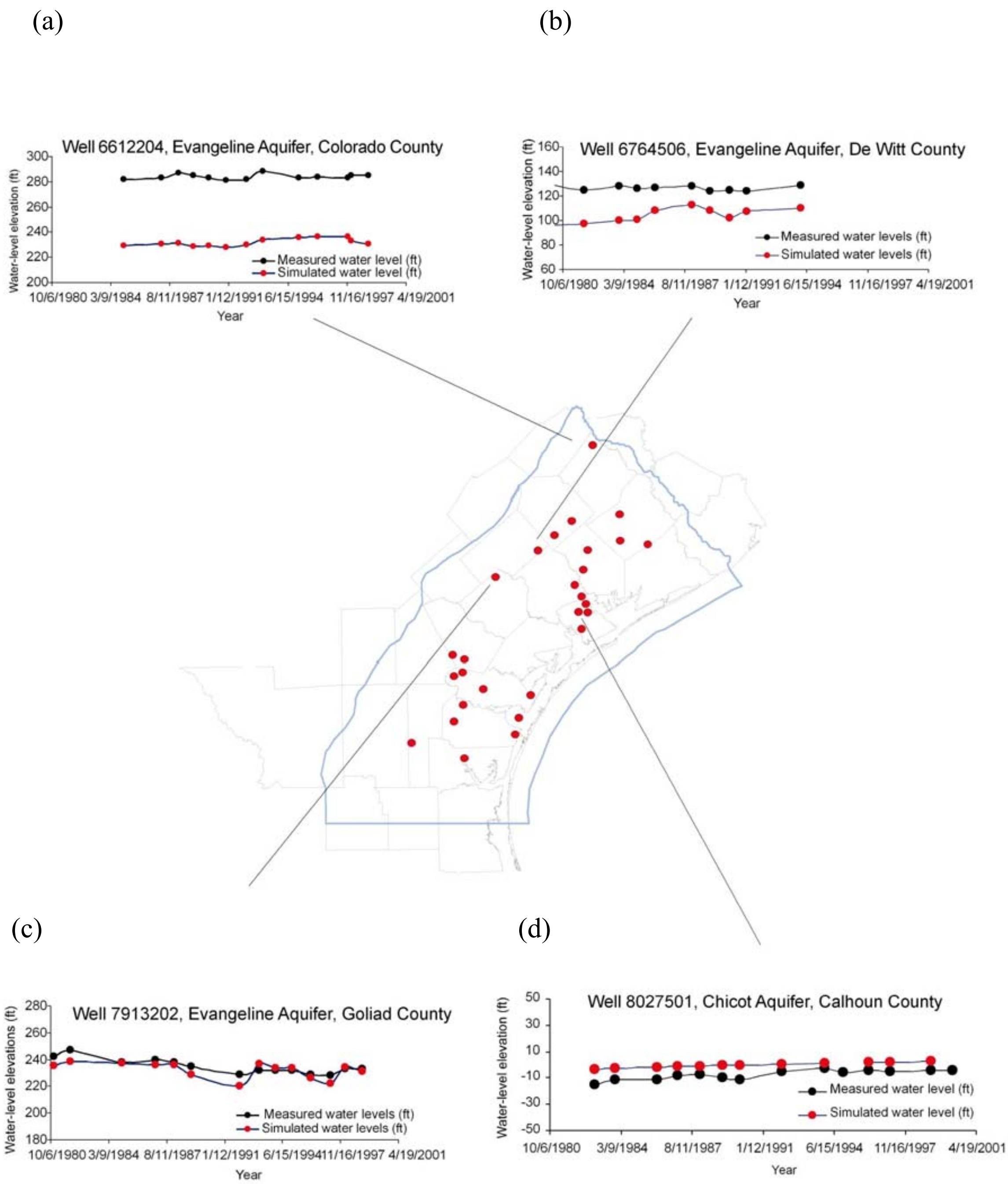


Figure 53: Comparison of simulated and measured water-level fluctuations in several wells for 1980 through 1999 for.(a) Well 8612204, (b) Well 6764506, (c) Well 7913202, and (d) Well 8027501.

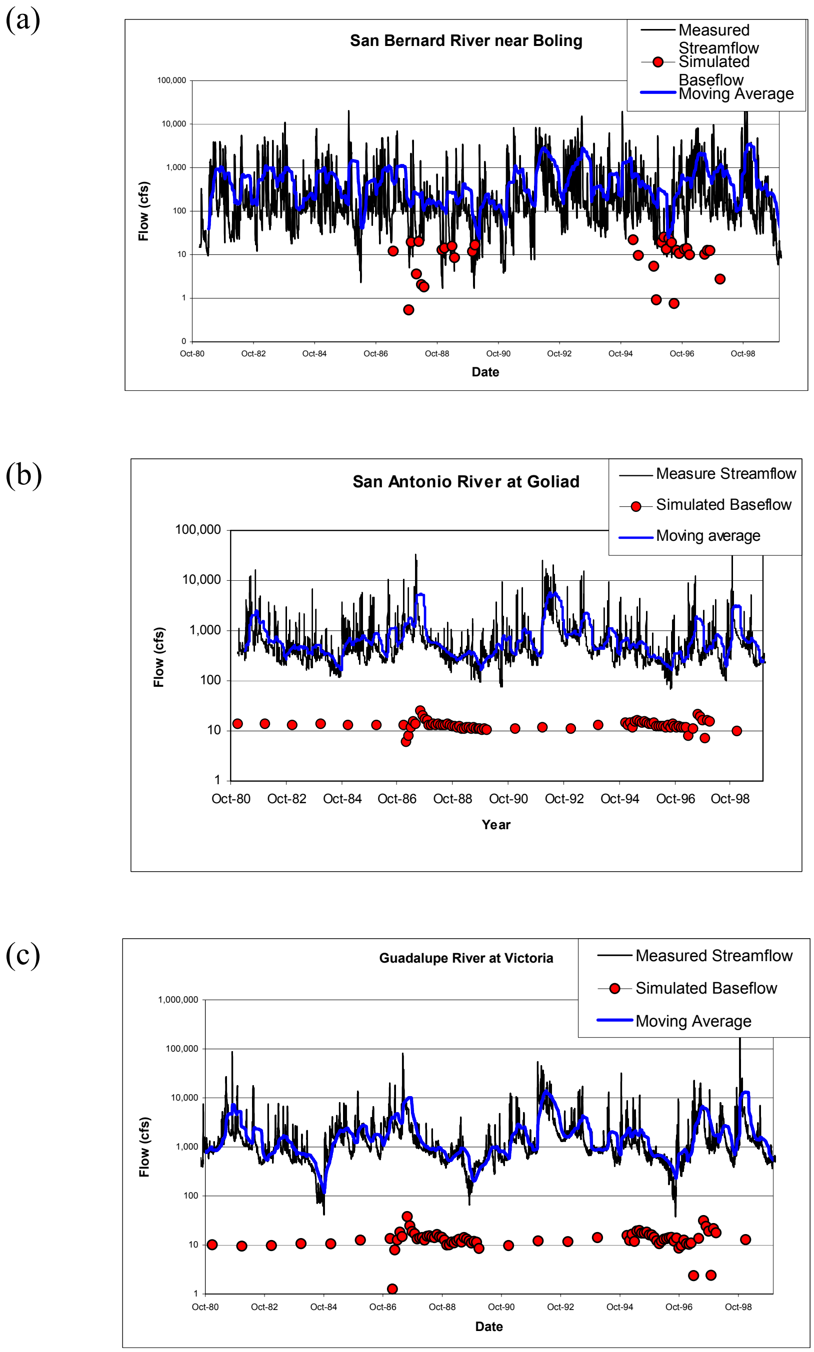


Figure 54: Comparison of streamflow hydrographs with simulated baseflow for the (a) San Bernard River near Boling, (b) San Antonio River at Goliad, and (c) Guadalupe River at Victoria.

Table 3. Measured gain-loss and simulated gain-loss values.

River	Study Number	[1] Gain/Loss (cfs)	Simulated Gain/Loss (cfs)	Length of Reaches (river miles)
Colorado	49	-880.92	-58.06	107.9
Lavaca	135	10.07	-14.12	45.2
Nueces	190	3	6.01	8.4

1 Slade (2002)

5.2 Water Budget

Estimated water budgets for the 1989 and 1999 calibration years are presented in Figures 55, 56, and Tables 4, 5. Stream discharge in 1989 is much more reduced compared to the pre-development model. The reduction in stream discharge in the transient model could presumably be attributed to groundwater pumping. Groundwater pumping is likely to capture groundwater flow that would have otherwise naturally discharged causing reduced flow into and out of the streams. Discharge to the Gulf of Mexico is reduced in 1989 compared to the pre-development model. This observation is consistent with the findings from other recently developed models on the Gulf Coast aquifer system (Dutton and Richter, 1990; Ryder and Ardis, 2002; Kasmarek and Robinson, 2004). For example, Ryder and Ardis (2002) documented that groundwater pumping causes a decrease in the discharge rate from 0 to 1 in/yr (locally from 1 to 2 in/yr along streams) from pre-development to 0 to 1 in/yr throughout the model area under pumping conditions in 1982. Both Dutton and Richter (1990) and Ryder and Ardis (2002) reported that the size of the discharge area decreases under groundwater pumping conditions along with an increase in induced recharge values.

We observe that total recharge directly from rainfall is considerably higher in 1989 than in the pre-development model (Figures 55, 56). Recharge decreases again in1999 coincident with the recovery of the water levels in the aquifer. Recovery of the water levels in 1999 occurs despite the fact that groundwater pumping in 1999 is at the similar level as in 1989. Pumping in 1989 and 1999 is, however, considerably lower (by about 33 percent) compared to pumping of the early 1980s (Figure 16). This is probably why there is more recovery of the water levels in 1999. With the recovery of the water-levels in 1999, there is also a sharp decline in the amount water movement out of storage into the flow system

(Figures 8, 9, 55, and 56). This recovery in the water levels also results in an increase in stream discharge.

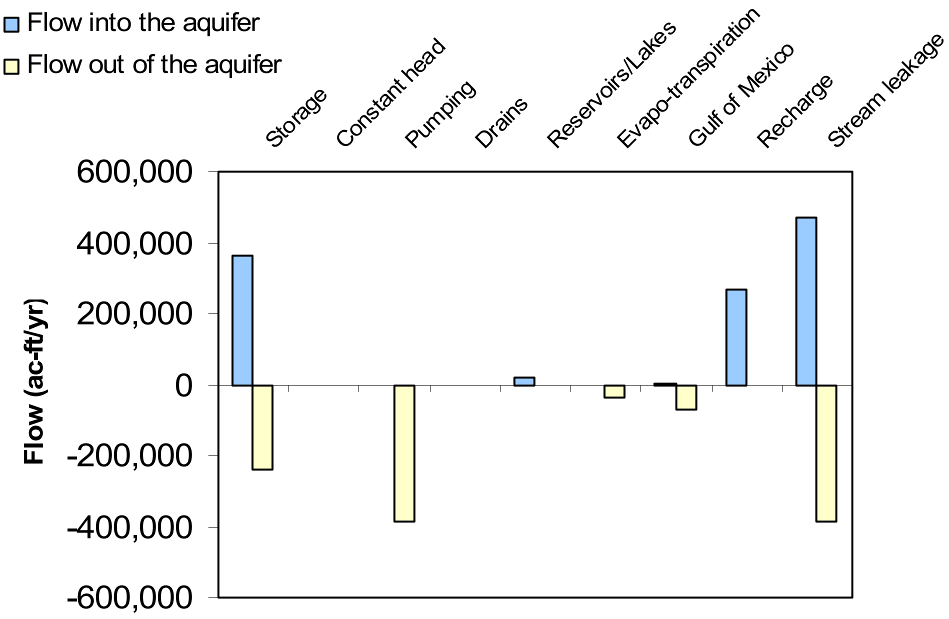


Figure 55: Water-budget for the calibrated transient model, 1989.

Table 4: Water budget for 1989.

Parameter	Flow (in) (ac-ft/yr)	Flow (out) (ac-ft/yr)	Flow (in) (percent)	Flow (out) (percent)
Storage	365,155	-237,054	32.53%	21.12%
Constant head	0	0	0.00%	0.00%
Pumping	0	-386,932	0.00%	34.47%
Drains	0	-1,832	0.00%	0.16%
Reservoirs/Lakes	21,752	0	1.94%	0.00%
Evapo-transpiration	0	-37,920	0.00%	3.38%
Gulf of Mexico	2,579	-71,551	0.23%	6.37%
Recharge	265,448	0	23.65%	0.00%
Stream leakage	467,671	-387,296	41.66%	34.50%
Total	1,122,605	-1,122,584	100.00%	100.00%

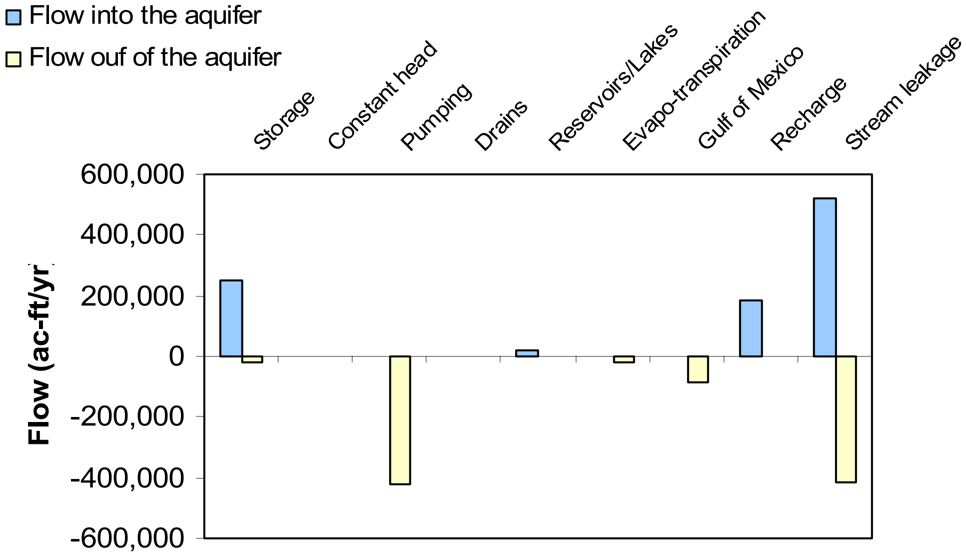


Figure 56: Water-budget for the calibrated transient model,1999.

Table 5: Water budget for 1999.

Parameter	Flow (in) (ac-ft/yr)	Flow (out) (ac-ft/yr)	Flow (in) (percent)	Flow (out) (percent)
Storage	248,228	-22,549	25.53%	2.32%
Constant head	0	0	0.00%	0.00%
Pumping	0	-425,020	0.00%	43.71%
Drains	0	-2,035	0.00%	0.21%
Reservoirs/Lakes	21,409	0	2.20%	0.00%
Evapo-transpiration	0	-20,958	0.00%	2.16%
Gulf of Mexico	1,299	-87,330	0.13%	8.98%
Recharge	182,909	0	18.81%	0.00%
Stream leakage	518,498	-414,450	53.32%	42.62%
Total	972,343	-972,343	100.00%	100.00%

5.2 Sensitivity Analysis

We determined sensitivity of the model to changes in specific yield and specific storage. We uniformly applied the changes in all model layers holding the other parameters constant. We observed small changes in water levels in wells selected from outcrop and confined portions of the aquifers due to changes in storage parameters (Figures 57 through 63). We made several simulations using (1) specific storage 0.25 times less than the calibrated value, (2) specific storage 10 times more than the calibrated value, (3) specific storage 100 times more than the calibrated value, (4) specific yield 0.5 times less than the calibrated value, (5) specific yield 1.1 times more than the calibrated value, (5) specific yield 1.25 times more than the calibrated value, and (6) specific yield 2 times more than the calibrated value. The magnitude of variations applied was within the range of plausible values for each parameter and their sensitivity observed during the calibration process. We allowed lower variations in the specific yield as higher values led to non-convergence of the model.

Overall, the model is not overly sensitive to changes in storage parameters except in drawdown areas (Figures 58 and 60). Changes in storage parameters do not significantly change water levels in wells locally or change water levels spatially across the aquifers. The model appears to be relatively more sensitive to specific storage than specific yield. Lower specific storage and specific yield causes lower water levels in several wells while higher values cause a rise in the water levels (Figures 57 through 63). However, some wells show no changes in water levels either due to lowering or raising of specific yield and specific storage values. Several wells in unconfined portions of the aquifers show little changes in water levels due to changes in specific yield. A higher sensitivity of the model to changes in storage parameters in the drawdown areas is probably caused by groundwater withdrawal in these areas.

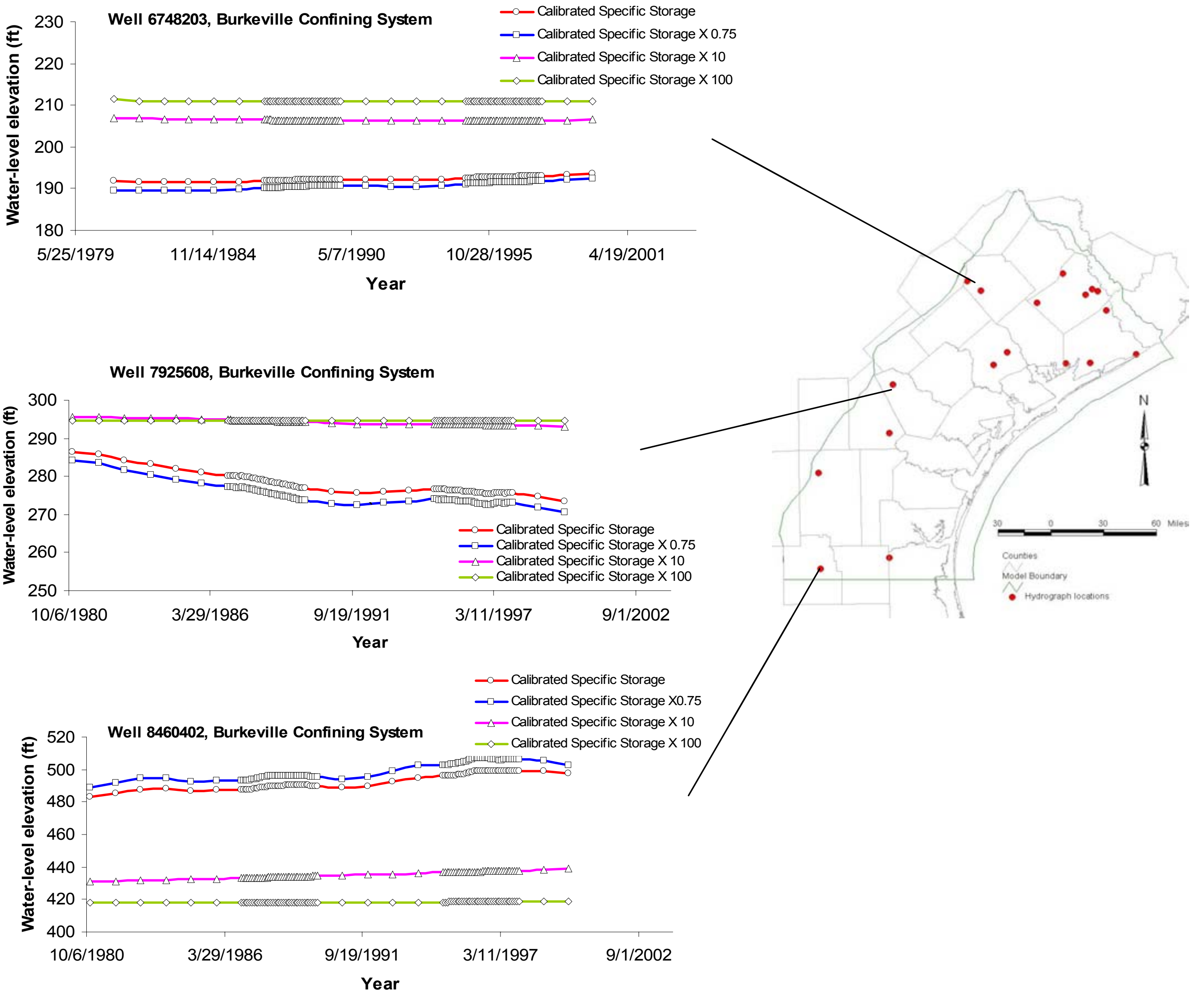


Figure 57: Sensitivity of water levels in wells to changes in specific storage.

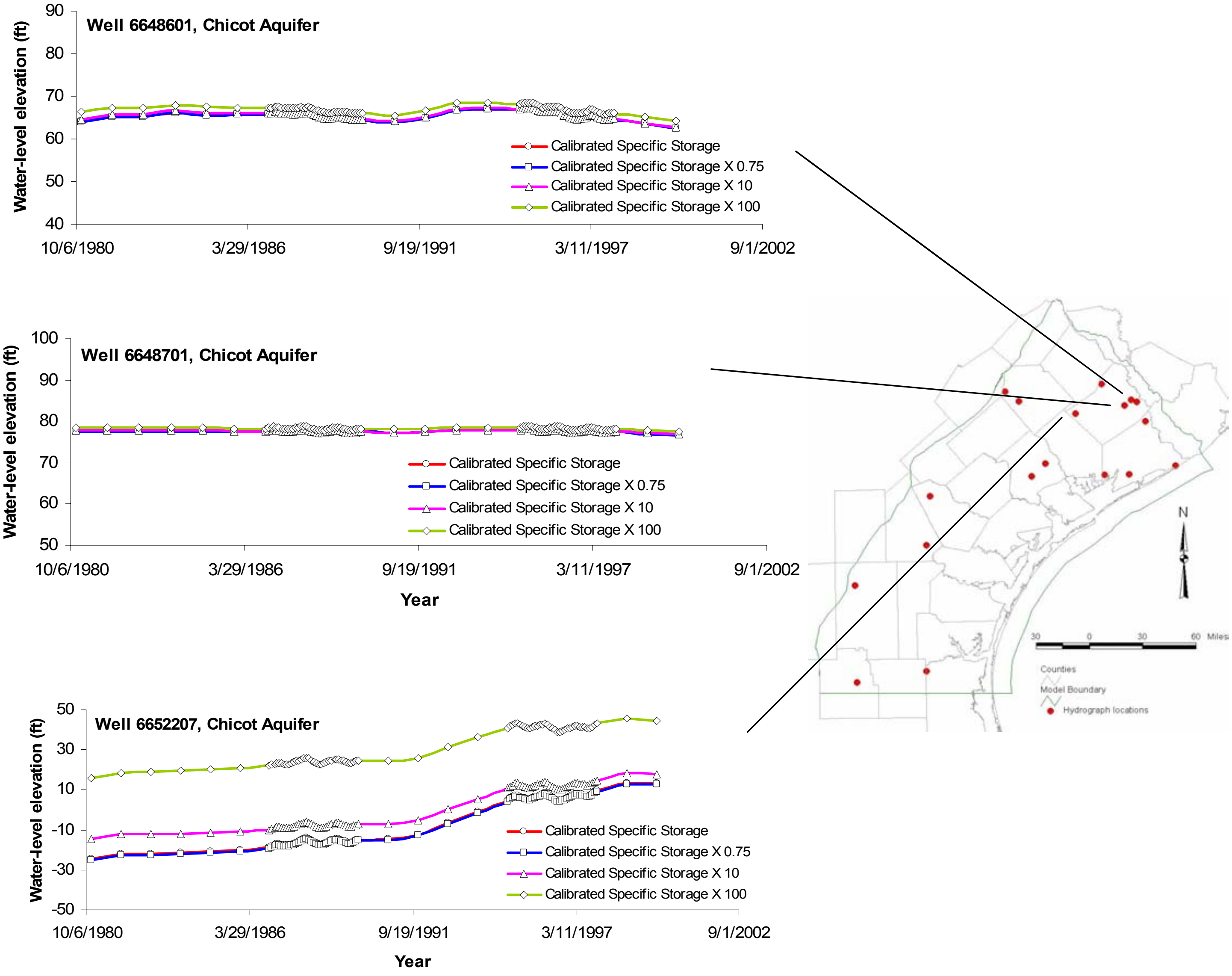


Figure 58: Sensitivity of water levels in wells to changes in specific storage.

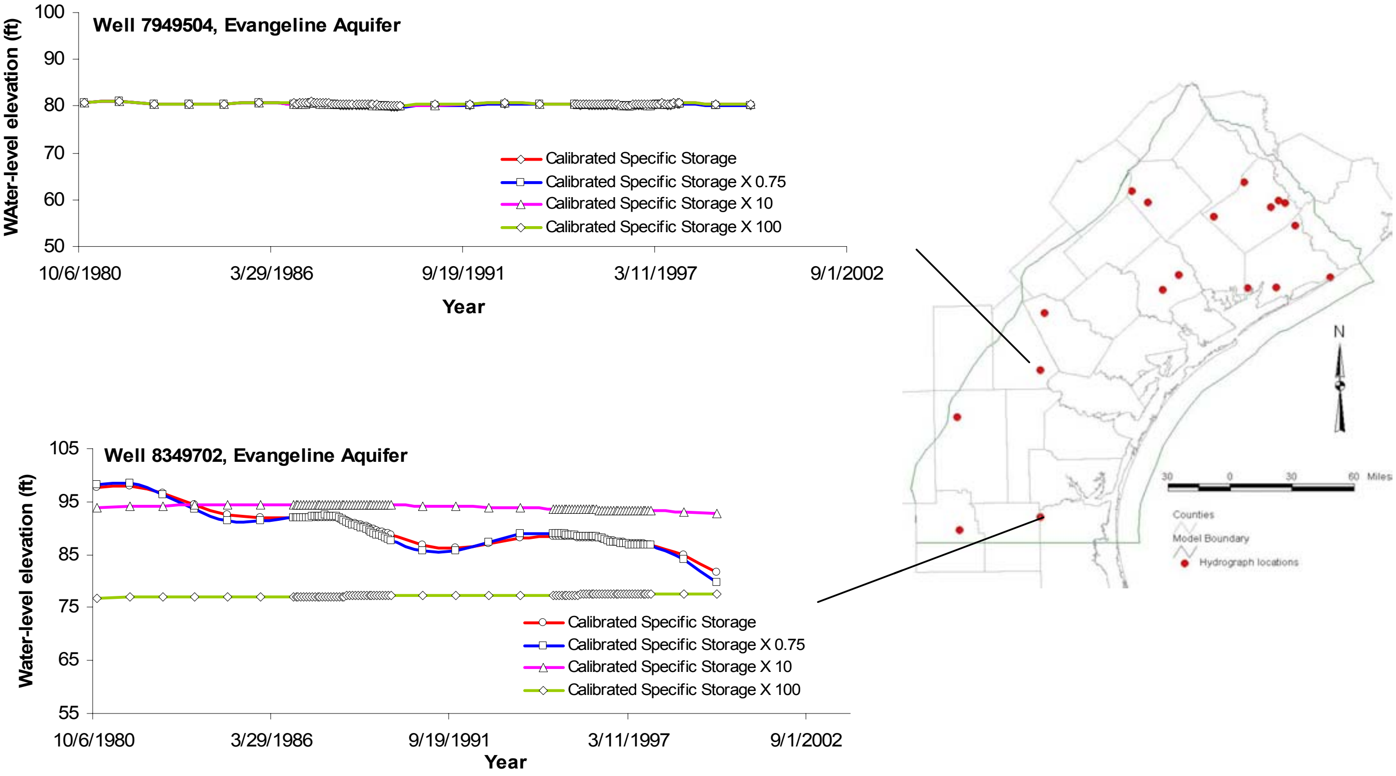


Figure 59: Sensitivity of water levels in wells to changes in specific storage.

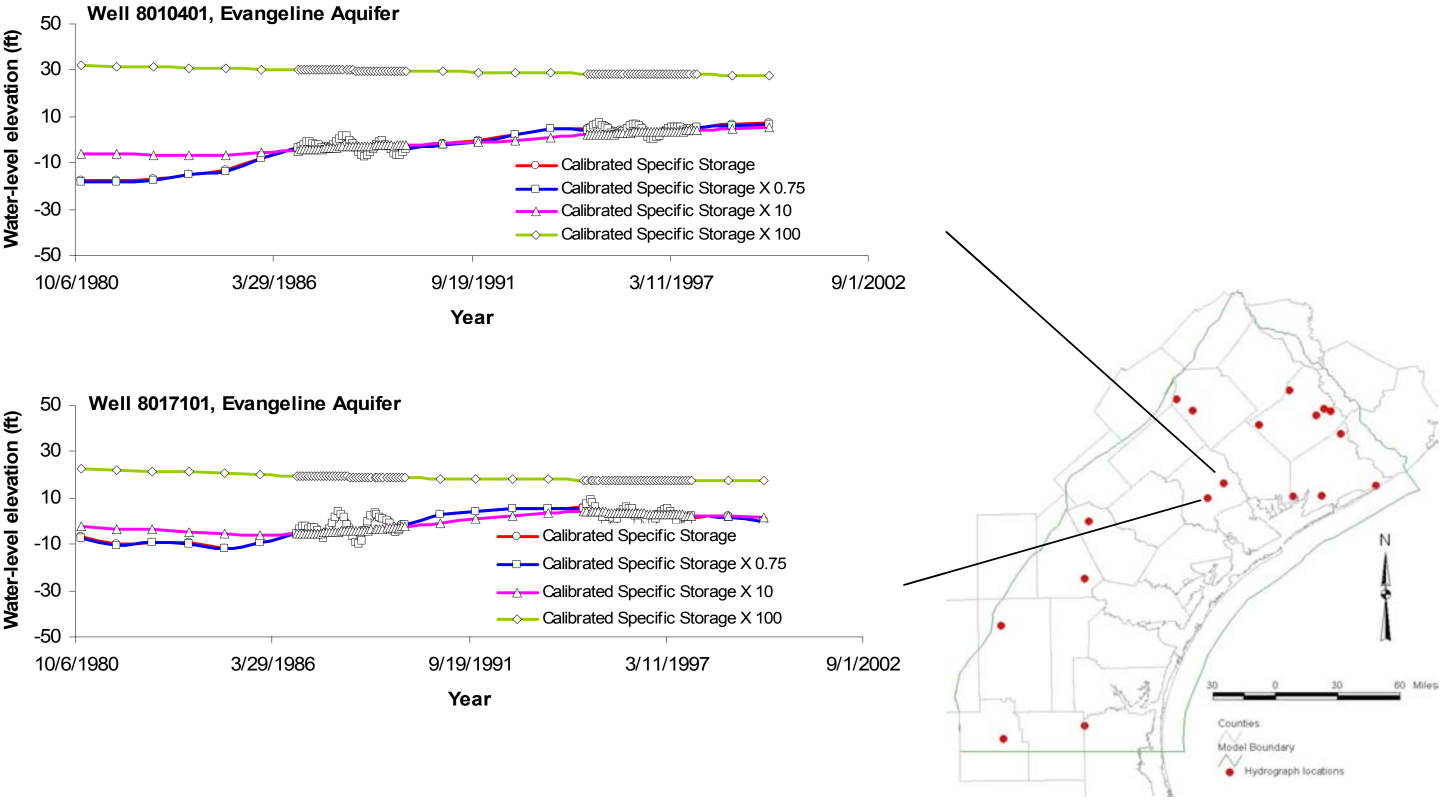


Figure 60: Sensitivity of water levels in wells to changes in specific storage.

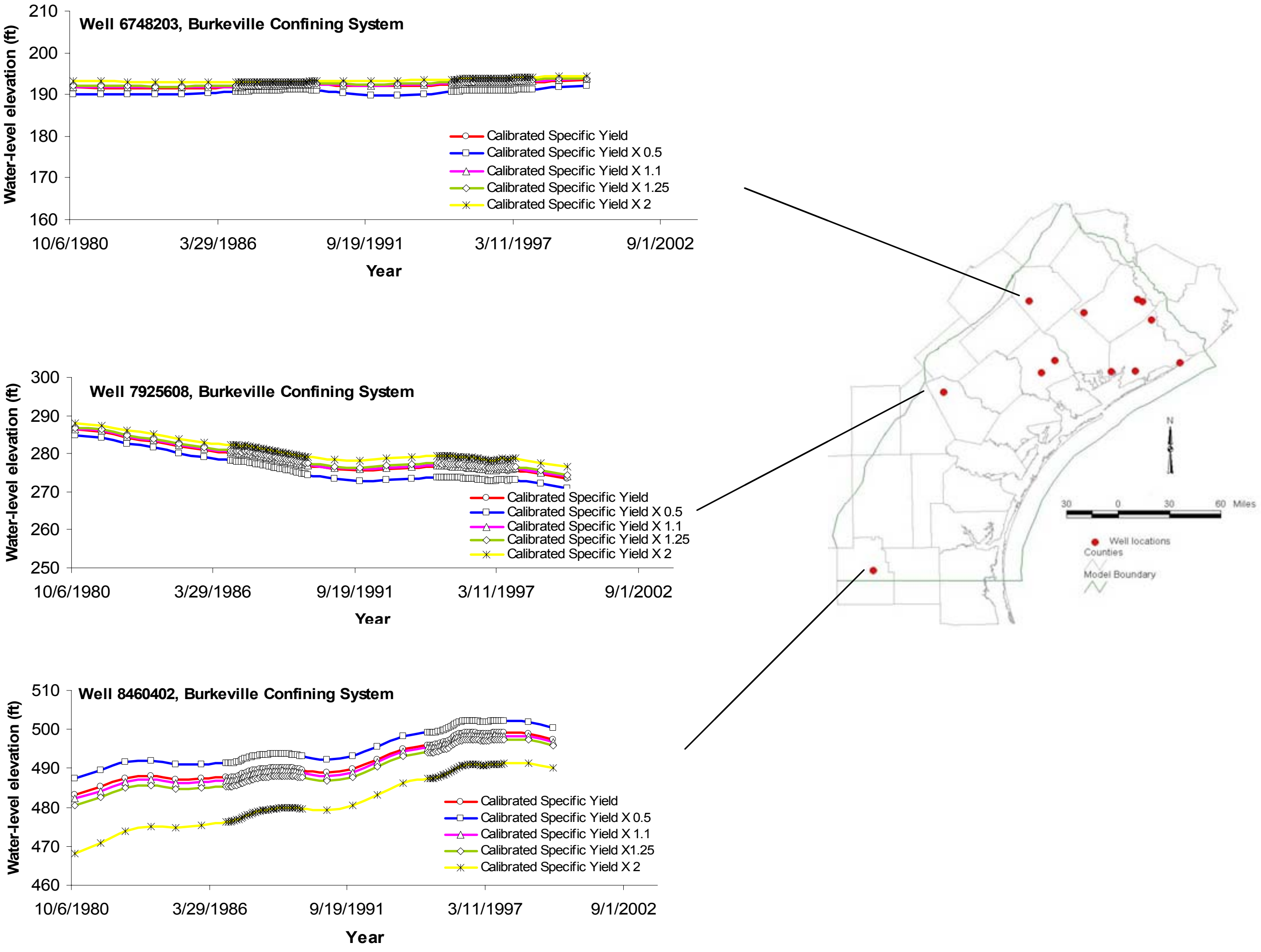


Figure 61. Sensitivity of water levels in wells to changes in specific yield.

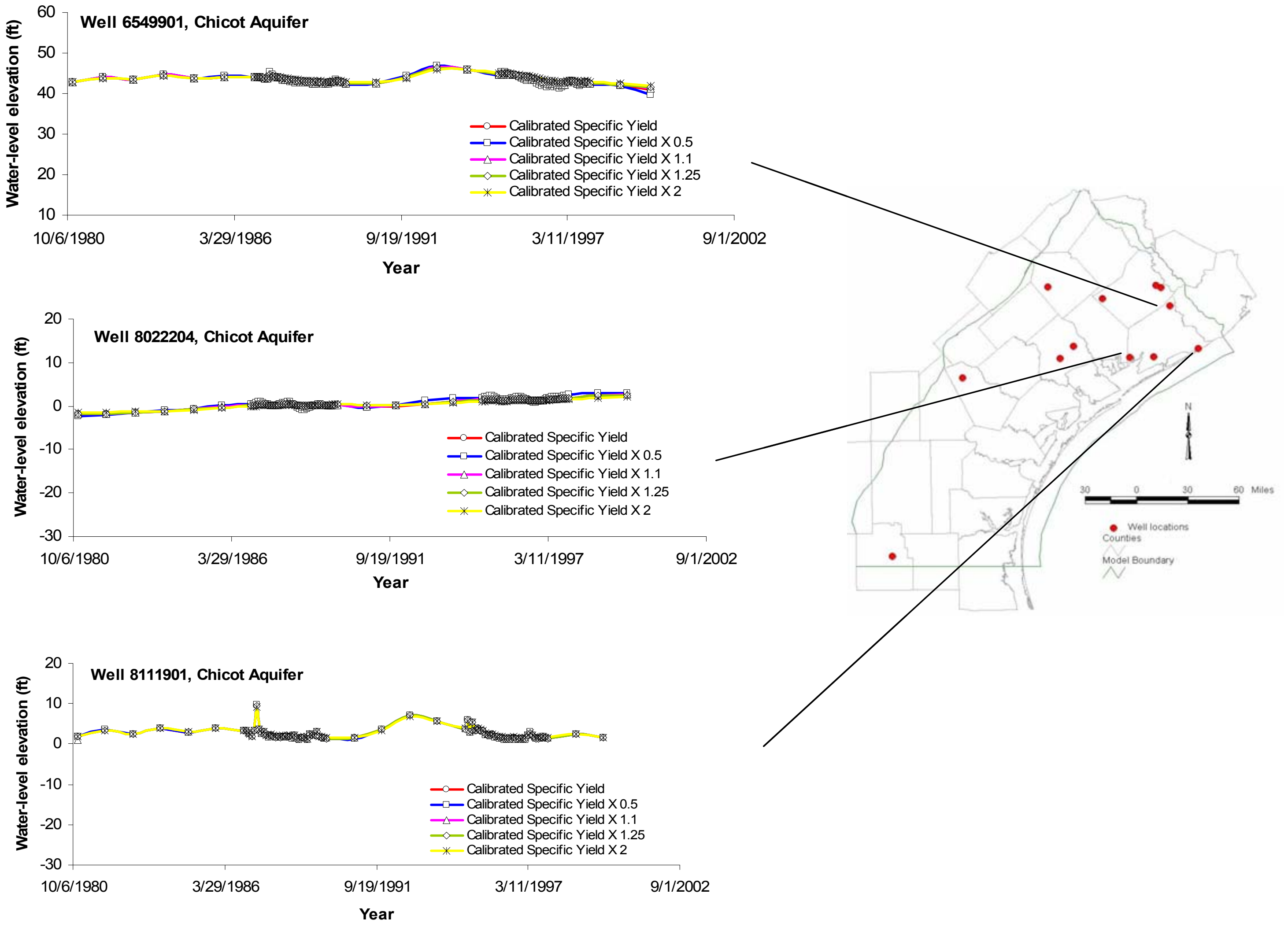


Figure 62. Sensitivity of water levels in wells to changes in specific yield.

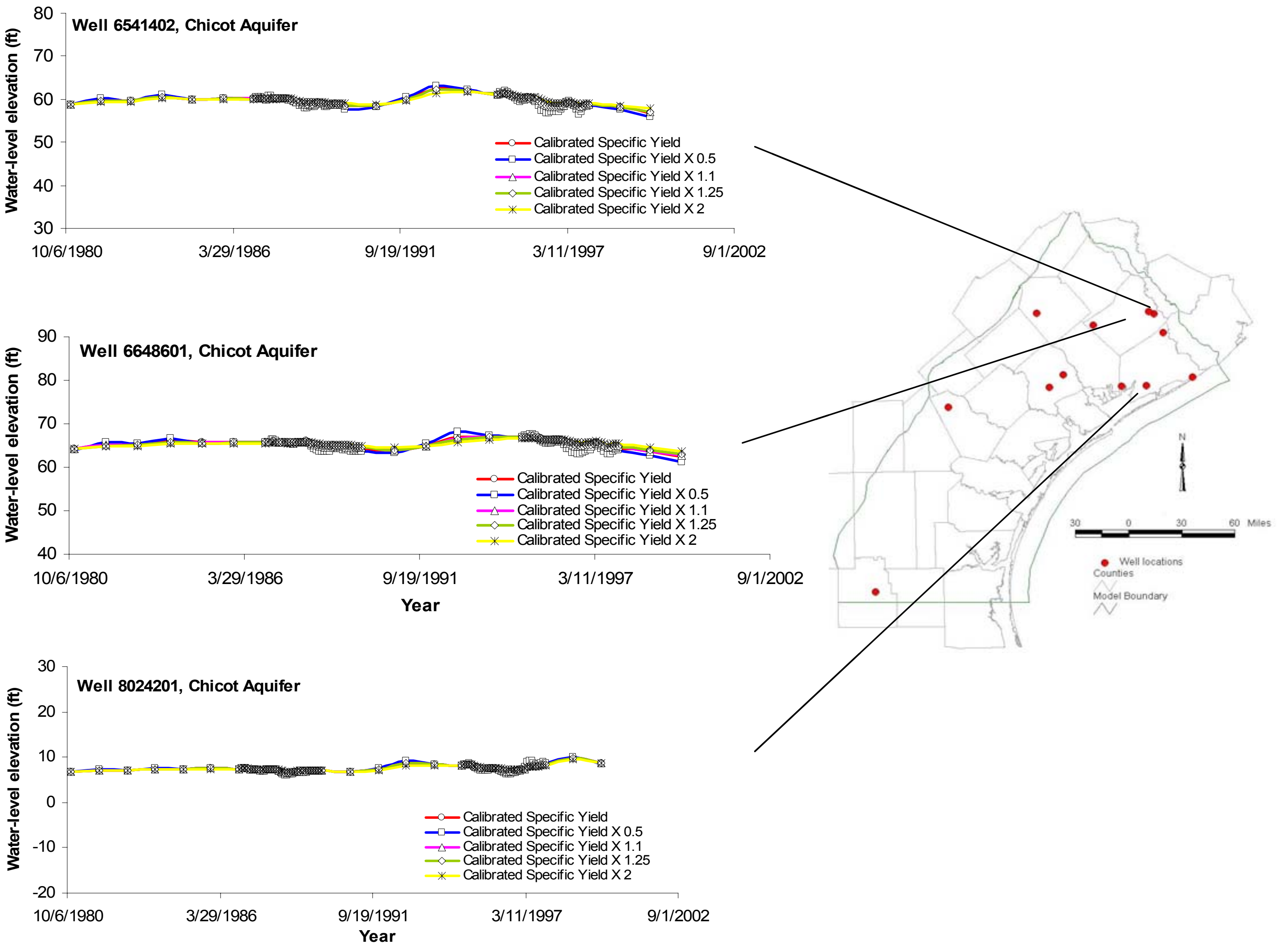


Figure 63. Sensitivity of water levels in wells to changes in specific yield.

6 Analysis of Model Overlap Area

Areas of the northern part of this model overlap part of the northern Gulf Coast GAM developed by the USGS (Kasmarek and Robinson, 2004). All of Colorado, Wharton, and Matagorda and parts of Fayette, Lavaca, and Jackson counties are present in both models. In the following section ,we discuss the differences in the modeling approach between the two models. We also discuss differences in model parameters, their effects on model simulation, and situations where each model is more appropriate. The overlap between the central Gulf Coast GAM and the southern Gulf Coast GAM areas is small and therefore, we did not compare the parameters used in the southern and the central Gulf Coast GAM.

(1) The northern Gulf Coast GAM developed by the USGS (Kasmarek and Robinson, 2004) uses the Interbed Storage Package designed for use with MODFLOW (Leake and Prudic, 1991) to simulate land subsidence in Houston-Galveston area and determine effects of storage in clays from excessive pumping of the aquifers. This model suggests that compaction expels water from the clay interbeds into the aquifer. Water budget analyses of the overlap areas using the northern Gulf Coast GAM indicate that about 3,700 ac-ft/yr of water expels out of the clays into the aquifer in 1990 (Tables 6 and 7). Most of this water is sourced from clay compaction in the Chicot aquifer. This model reproduces measured land subsidence near major pumping centers in the Houston and Galveston areas. The model does not simulate subsidence outside of these two areas as measured subsidence values are not available for calibration of this parameter. The central Gulf Coast GAM does not use the Interbed Storage Package as subsidence has not been well documented in the overlap area. Therefore, if the concern is land subsidence, then the northern Gulf Coast GAM is the choice.

(2) The northern Gulf Coast GAM uses MODFLOW's general-head boundary package to simulate recharge and discharge in the outcrop areas. Therefore, flow between the streams and the aquifer is not explicitly simulated in this model. On the other hand, the central Gulf Coast GAM uses specified flux based on rainfall distribution and soil characteristics to simulate recharge and MODFLOW's streamflow-routing package to simulate discharge.

Water budget analyses from both models suggest that there are similarities in the calibrated recharge values applied over the overlap area. For example, recharge in the overlap area of the northern Gulf Coast GAM in 1990 is about 103,000 ac-ft/yr while in the overlap areas of the central Gulf Coast GAM, recharge is about 95,000 ac-ft/yr in 1990 (Tables 6 and 7). A higher recharge observed in the northern Gulf Coast GAM is expected as it also includes water budget values from groundwater–stream interaction (Kasmarek and Robinson, 2004). However, in the central Gulf Coast GAM, the streams discharge about 225,000 ac-ft/yr of water into the aquifer. In the northern Gulf Coast GAM a similar volume of water, about 280,000 ac-ft/yr is drawn out of storage in 1990 (Tables 6 and 7). The storage value for the central Gulf Coast GAM is much lower, about 61,000 ac-ft/yr in 1990. Therefore, relatively more drawdown may result from the northern Gulf Coast GAM than the central Gulf Coast GAM using similar recharge because significant volumes of water are derived from storage in the former. If the concern is streamflow-groundwater interaction, then the central Gulf Coast GAM appears more applicable.

(3) Horizontal hydraulic conductivity of the Evangeline aquifer in the central Gulf Coast GAM was adjusted and zoned to address partial completion of many of the wells in the aquifer to better reproduce the drawdown cones in Wharton, Victoria, and Kleberg counties. This adjustment of hydraulic conductivity values has lowered the transmissivity values in part of the overlap areas. Therefore, the central Gulf Coast GAM may overestimate drawdowns in the Evangeline aquifer if wells are completed through the entire thickness of the aquifer.

(4) Cross-formational flow is similar in the two models (Tables 6 and 7). For example, total values of cross-formational flow is about 89,000 ac-ft/yr in the northern Gulf Coast GAM and about 87,000 ac-ft/yr in the central Gulf Coast GAM.

(5) There are only minor differences in pumpage values in the overlap area. The annual pumpage total in the overlap area of the northern Gulf Coast GAM is about 373,000 acre-ft in 1990 and about 374,000 acre-ft in 1990 in the central Gulf Coast GAM.

Table 6. Water budget for the overlap area of the northern Gulf Coast GAM for 1990. All values are in acre-ft per year.

Year	Layer	Storage	Horizontal exchange	Exchange (upper)	Exchange (lower)	Pumping	Drains	Recharge	Evapo-transpiration	River Leakage	General head boundary	Stream leakage	Interbed Storage
1990	1	266,282	-7,060	0	-86,943	-267,427	0	0	0	0	92,739	0	2,173
	2	4,475	-7,013	86,943	151	-93,626	0	0	0	0	7,327	0	1,529
	3	2,715	-9	-151	-2,435	-120	0	0	0	0	-1	0	0
	4	6,594	-330	2,435	0	-11,589	0	0	0	0	2,889	0	0
	Total	280,066	-14,411	89,227	-89,227	-372,761	0	0	0	0	102,955	0	3,702

Table 7. Water budget for the overlap area of the central Gulf Coast GAM for 1990. All values are in acre-ft per year.

Year	Layer	Storage	Horizontal exchange	Exchange (upper)	Exchange (lower)	Pumping	Drains	Recharge	Evapo-transpiration	River leakage	Gulf of Mexico	Stream leakage	Interbed Storage
1990	1	45,340	-2,122	0	-95,693	-244,038	-650	90,024	-5,336	7,312	-12,779	217,944	0
	2	5,784	6,150	95,693	6,495	-125,530	0	5,038	-1	0	0	6,372	0
	3	4,483	12	-6,495	2,091	-241	0	3	-20	174	0	-7	0
	4	5,086	316	-2,091	0	-4,389	0	329	-35	102	0	680	0
Total		60,693	4,356	87,107	-87,107	-374,197	-651	95,394	-5,392	7,588	-12,779	224,990	0

7 Limitations of the model

Like all other regional groundwater flow models, this model of the central Gulf Coast aquifer system has limitations. A regional flow model constructed with a grid size of 1 mile by 1 mile is best suited to answer regional-scale groundwater issues such as predicting aquifer-wide water-level fluctuations under various pumping or recharge conditions. The model in its current state may not predict water-level declines around a single well in a community. The model relies on estimates of aquifer properties and stresses and the small-scale spatial variability in storativity and/or hydraulic conductivity present in the aquifer could not be translated to the scale of the model. The predicted water levels should however be accurate at the scale of tens of miles when a group of wells or water levels in an entire county is considered. This model can be further refined at a smaller scale, or alternatively, analytical equations can be used to address local groundwater issues such as developing well-spacing rules. Hydraulic conductivity used for calibration reflects partial completion of many of the wells in the Evangeline aquifer. Therefore, where wells fully-penetrate entire thickness of the Evangeline aquifer, usage of the model may overestimate the drawdowns. Travel times calculated from the model for water particles flowing through the Evangeline aquifer may also be somewhat overestimated. If additional data becomes available, the model layers may be further refined in the future to address partial completion of wells in the Evangeline aquifer. Where there is lack of historical information in a model area, we will not be able to know how good or poor the calibration is for that area until new information is collected. Where there is more data available, there is greater certainty in the model calibration. In the down-dip areas of the Jasper aquifer, very few calibration targets were available and the simulated water levels could not be compared to measured water levels producing greater uncertainty for the area. The model appears to underestimate baseflow in some of the studied reaches. This model, like most groundwater models, is more appropriate to determining relative changes to water levels from application of pumpage reflecting varying water-management scenarios rather than assessing absolute changes to water levels in the future.

8 Future Improvements

The recalibrated model can further be improved with knowledge of additional information:

(1) Like many other aquifers in Texas, recharge information is not adequately known for the Gulf Coast Aquifer System. Additional recharge information collected through experimental analysis over the heterogeneous geologic area of the Gulf Coast Aquifer System may help better constrain the calibrated recharge values.

(2) Baseflow separation of streamflow hydrographs in the model area may provide additional information that can be better compared with simulated baseflow values.

(3) Partial penetration of many wells in the Evangeline aquifer may further be addressed by subdividing the Evangeline aquifer into more model layers based on the abundance of partially completed wells in specific horizons of the aquifer.

(4) Additional water-level measurements in areas with limited water-level information will further help increase validity and improve certainty of model calibration in areas with limited information.

(5) Additional calibration efforts should be targeted to better simulate baseflow values from various stream segments across the model area.

9 Conclusions

The calibrated model does a reasonable job in matching spatial distributions of water-levels and water-level changes in well hydrographs with our data. The model reproduces the drawdown cones observed in Wharton, Victoria, and Kleberg counties in 1989 and 1999. The root mean squared (RMSE) error for calibration of the pre-development period is about 21 feet, 46 feet for 1989, and 36 feet for 1999.

About 620,000 acre-ft of water flows annually through the central Gulf Coast aquifer system in the pre-development model. Of this flow, 30 percent comes from rainfall and 69 percent seeps into the aquifers from the streams, and about 1 percent from the reservoirs.

Water levels in the model are sensitive to horizontal hydraulic conductivity, recharge, and vertical leakance values. The model is more sensitive to the application of lower recharge values than higher recharge values because excess recharge discharges as baseflow to the streams and/or wetlands. The model is not overly sensitive to changes in storage parameters except in drawdown areas.

The model should not be used to evaluate fully-penetrated well fields in the Evangeline aquifer.

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11 Appendix I

Stakeholder Comments on the Central Gulf Coast GAM

In the following discussion of question and comments, we refer to four reports (1) a summary report, (2) a TWDB report, (3) a GAM run report, and (4) a Waterstone (2003) report. The summary report contains information in relation to TWDB recalibration efforts of the central Gulf Coast GAM. Results of this effort are contained in a report entitled "Groundwater Availability Model of the Central Gulf Coast Aquifer System: Numerical Simulations through 1999" dated Sept. 27, 2004, released to stakeholders and simultaneously posted on our website on or before Oct. 1, 2004. We will publish a TWDB report in 2005 containing conceptual model information and any revisions of the information contained in Waterstone (2003) along with information contained in the summary report. A GAM Run report that will be posted on our website in early 2005 will contain information relating to predictive pumpage information and predicted water-levels from 2000 to 2050. A Waterstone (2003) report is the draft information that was submitted by Waterstone Environmental Engineering and Hydrology Inc. to the TWDB.

Public Policy Comments on Waterstone Conceptual Draft Report

Question 1:"The numerical ground water flow model described in this draft report provides an initial framework and conceptual model for understanding the dynamics of ground water flow in this portion of the Gulf Coast Aquifer, however, only on a regional scale. Rather than go into great detail on technical issues we have noted, we can simply affirm that, as Section 11.0 of the draft report describes very accurately, there are a number of significant limitations associated with this model as it has been developed to date, and which, when summed together, are such that it creates serious concerns about the utility of the model.

As a result of these limitations, the usefulness of the model as a management tool for regional water planning and ground water district rule-making is extremely questionable. While TWDB is to be commended for initiating and funding the development of this model, there still exists a tremendous need for further refinement before this model can be used for its intended purposes."

Response: It was not the intent of the GAM effort to provide a comprehensive tool for all GCD rule-making decisions since the data needed to do so was not always available. TWDB recognizes that for some local decisions, such as determining well-spacing restrictions, analytical approaches are more appropriate due to the regional scale of the model. However, the data collected and analyzed during the development of the Central Gulf Coast aquifer Groundwater Availability Model should be sufficient for providing a foundation for the development of groundwater availability estimates on a regional and/or district scale.

Question 2: "It is incumbent on the developers of the model and TWDB staff to make this fact well known. An accurate and honest explanation of these limitations needs to be widely disseminated, particularly to the policy setting bodies of the various state, regional and local entities that would be the potential users of the model, since earlier information regarding the GAM program has created significant expectations regarding the accuracy and application of the model."

Response: From the onset of the GAM process, TWDB staff realized regional models would have various limitations due to the scale and the availability of data. Therefore, TWDB required that the consultant discuss various model limitations in their report that they felt were important to potential users of the model. The final report includes a section of the limitations of the model. A digital copy of the report and the model will be made available to the policy setting bodies upon final acceptance of the project.

Question 3**: "**We would encourage a continuing process of Question input into the further improvement of the regional scale model and the acquisition of additional data that would allow the model to be refined to the appropriate scale necessary to facilitate its intended use by "local" ground water management districts and regional water planning groups."

Response: TWDB also encourages continuing Question input, especially if additional studies or information is collected and documented that may possibly enhance the current model.

Public Question Comments on TWDB Summary Draft Report

Question 4: It appears that there are some leakance values of 10^{-9} in the new BCF for the steady-state file.

Response: The correct vertical leakance file for the steady-state model will be in the final model files.

Question 5: It is recognized that the availability of logs is probably not uniform over the entire domain. However, the stratigraphy will be more accurate in regions with relatively higher log density than in regions with minimal or low log-density. Additional information, with regards to the locations of the logs used is sought to help assess the accuracy of the geologic delineation in the CGC-GAM model within the study area (see Appendix B of the Waterstone, 2003 report).

Response: The structure was based on data from the Source Water Assessment and Protection Program (SWAP) that was developed by the U.S. Geological Survey (USGS) and administered through the Texas Commission on Environmental Quality (TCEQ). The structure was compared against logs and cross-sections and kriged to extend it to the coastline.

Question 6: Specific verbiage that spells out management situations where the model cannot be used (e.g., to develop well spacing rules, especially near property boundaries) would be beneficial to groundwater districts (and other Questions) to understand the parameters of model applicability and reduce potential abuse of the model.

Response: This is discussed in the limitation section of the report.

Question 7: The model has four layers representing the four major geologic units. However, there is little information as to what the depth of each layer was and how these depths were varied across the domain. Again, additional information is sought to assess the accuracy and precision of the geologic conceptualization within the study area.

Response: Structure information was included in the Waterstone (2003) report which will be posted along with the summary report (also see Appendix B of the Waterstone, 2003 report).

Question 8: How many of the 130,476 cells fell outside the domain of interest?

Response: The model has a total of 190,452 cells with 56,736 active cells. Therefore, 133,716 cells fell outside the active domain or lateral extent of the outcrop areas.

Question 9: How many were excluded within the domain if they were less than 50 feet thick?

Response: This information will be included in the TWDB report.

Question 10: Were the pinch-outs (less than 50 feet thick cells) a natural occurrence or sometimes an artifact of contouring?

Response: Pinchout is natural truncation of a stratigraphic unit in the updip areas as it appears on a geologic map. Any artifact from contouring that may occur during kriging process are not considered for defining a pinchout.

Question 11: Were the developed cross-sections compared with logs that were not part of the conceptual model development?

Response: No cross-sections have been included with this summary report.

Question 12: The water level data contour plots are somewhat confusing. It would be helpful to mention that the elevations are in feet on the map. The datum used for elevations has also not been specified and would help in proper interpretation (MSL?).

Response: Water-level information presented in the maps are in feet and the datum is the mean sea level. This information has been included in figure captions (Figures 4 through 9).

Question 13: Figures 4 and 11 depict the steady-state (1910-1940) and dynamic water level fluctuations in different aquifer strata. The red-dots on these maps are assumed to be indicative of the wells used to develop the contour plots. It would be helpful to clarify this point. The wells seem to be distributed unevenly throughout the model domain (especially Figure 5, pg 15). Again, this could be due to absence of data. However, the distribution of the wells usually has a significant impact on any developed contours along with the interpolation methods used to develop them. The following additional information would be helpful to interpret the contour plots correctly:

a) What procedures were used to develop the contour plots (IDW, Kriging, etc.?)

Response: The dots presented in the map represent water-level measurements used in development of the contour maps. Spatial distribution of the wells relates to where water-level measurements are available for that year according to the TWDB Groundwater Database. The contouring method used to develop the contour maps are the default kriging option in Surfer. Surfer uses point kriging for the default option. Point kriging estimates the values of the points at the grid nodes. We have appended the information in the figure captions of the summary report as requested (Figures 4 through 9).

Question 14: Were the accuracy of the developed contours assessed using independent data not used in the development of the contour plots?

Response: No. If we did this, we could not perhaps have even utilized the limited number of observation values for development of contour maps.

Question 15: What impact that addition or removal of some wells has on the developed contour plots?

Response: Contour maps are a function of the control points that are used to develop them. Addition or removal of control points may change positions of the contours but probably not the general groundwater flow direction if added points are consistent with the rest of the water-level measurements.

Question 16: The lack of sufficient data from the six county region in the model development is probably indicative of the lack of field data. Intensive field monitoring efforts are probably warranted in this region to assess regional groundwater flow patterns. Also, as this area has fairly small current usage, it may be possible to compare data from other wells (taken at other times) to further assess water levels and regional groundwater movement and evaluate the reasonableness of the model.

Response: There were not many water-level measurements available from the six county region for the pre-development period. However, several target wells were included for the transient calibration period (1980-1999). Reasonable good matches of the simulated water-levels to measured water-levels in the six county region for the transient calibration period suggest that the model was able to reproduce the measured water levels with some level of accuracy. Additional data collection can further strengthen or test effectiveness of the calibration.

Question 17: The recharge values used in the model were based on calibrated values used to obtain by Waterstone (2003). Waterstone (2003) utilized basin-wide recharge estimates obtained from Muller and Price (1979) along with a spatial disaggregation procedure (based on area of soil type) to allocate recharge to different cells. This procedure is somewhat subjective and the additional discussion of the literature by the authors lends credibility to the process. However, the data summarized (Table 1. of the report) seems to stem from modeling studies and not from experimental observations. Inclusion of any experimental data to the report would certainly be beneficial.

Response: There has been only one experimental analysis on recharge in the Gulf Coast aquifer area. Noble and others (1996) used tritium isotopes to determine recharge in the Gulf Coast aquifer. The summary report includes a short discussion of their findings.

Question 18: The authors have enhanced the credibility of the CGC-GAM by not treating pumping as a calibration parameter. They have instead used the TWDB water use survey (WUS) database. However, it is important to recognize that pumping estimates are just that estimates and subject to considerable uncertainty. A statement or two addressing the uncertainty in the WUS database would be beneficial to place the modeling results in proper context.

Response: It is difficult to quantify uncertainty in the estimation of the WUS database. However, we feel that this is the best data available at this time.

Question 19: Also, the pumpage distribution plots (Figure 17 and 18 of the report) seem to have underestimated pumping in Refugio County especially in the Evangeline aquifer. The city of Refugio utilizes wells penetrating Goliad Sands to meet their water supply. In addition there are several artesian wells in that area that probably tap into the Evangeline aquifer. Again, additional discussion on uncertainties in WUS would be beneficial for proper interpretation of model results.

Response: In the report, pumping distribution from the Evangeline aquifer is shown for 1999 (Figure 18). The map demonstrates some pumping from the City of Refugio from the Evangeline aquifer. We will include in the TWDB report groundwater pumping values assigned in the model for each county for the historical (1980-1999) period.

Question 20: The authors, based on the review of streamflow information from USGS gaging stations, state that most rivers (except for Colorado river) are gaining streams (page 33). However, they present no reasoning to substantiate this claim. Their assessment is probably based on flow rates evidenced during summer months (hydrograph separation). However, additional clarification in this regard would be beneficial. The authors also present three streamflow hydrographs were these hydrographs affected by any diversions? Again, clarification in this regard is deemed necessary for proper interpretation of the results.

Response: The suggestion was based on previous information from gain-loss studies (Slade and others, 2002) and previous modeling studies of the Gulf Coast aquifer (Waterstone, 2003). A more detailed analyses on the gain-loss information will be included in the TWDB report.

Question 21: The steady-state simulations were carried out between 1910–1940 timeframe when pumping was not significant. It is however unclear, if any pumping was included in the steady-state model. The authors do state that the inclusion of pumping led them to develop a new distribution for hydraulic conductivities. Is this pumping during the 1910–1940 time-frame or for 1980. Additional clarification is sought to further evaluate the model results.

Response: No pumping was included for the pre-development model (1910-1940). The summary report has been updated with this information (pages 38 and 40).

Question 22: The authors' state that their calibrated conductivities for the Evangeline aquifer are lower than previous modeling studies and that they had to double the hydraulic conductivity of the Jasper aquifer and reduce the leakance of the Chicot aquifer. As model calibrations are inherently non-unique, it may be better to compare their calibrated hydraulic conductivities to reported field measurements rather than (or in addition to) other modeling studies. In the absence of additional field-derived information, it is not possible to ascertain whether the results of this calibration are better (or worse off) than other previous studies. Additional clarification in this regard would be beneficial.

Response: A map will be included in the TWDB report to enable comparison of distributed measured and calibrated hydraulic conductivity values.

Question 23: The authors state that the vertical leakance was lowered significantly around Kingsville area to simulate fine -sand and silt deposits. Was this change affected in both Chicot and Evangeline aquifers? The assumption being the surficial geology (Qsi) extends all the way across.

Response: Vertical leakance is generally estimated during calibration process as measured values are seldom available for confining units. We ensured that the values used in the model are within the range of values commonly observed in fine silt and/or clays. The lower vertical leakance values were assigned in the Chicot aquifer over the estimated area where silt and fine-sand (Qsi) outcrop. This information has been added in the summary report (page 41).

Question 24: The vertical leakance distribution (Figure 26 of the report) seems to increase westwards. Is this trend corroborated by geological evidence? (possibly due to deposition of fine sands and silts along the coast). Additional discussion will probably help increase the reliability of the model/calibration.

Response: In a deltaic progradation sequence, updip areas receive much coarser sediments compared to the down-dip areas near the coast and, therefore, the differences in observed leakance values are related to geology. This information has been appended to the summary report (page 41).

Question 25: The calibrated model was qualitatively assessed for its fidelity to reproduce observed flow patterns. However, was the calibrated steady-state model compared against any independent datasets? It appears that the RMS calculations are for wells used in the calibration (Figure 28 in the report). Again, comparisons with independent values will help increase confidence in the model. This is particularly important for evaluation in the regions (such as the six county study are a considered here) where very little data was utilized during calibration.

Response: Calibration was performed using measured independent datasets. We included many water-level measurements from different parts of the model area to increase the validity of the calibrated model.

Question 26: The authors compared the model estimated baseflows to observed streamflows at select stations. The Second paragraph (on page 45) is particularly misleading. The authors appear to suggest that baseflows are small components of streamflows particularly during storm events. While this is certainly true, baseflows are a significant portion (or all of) streamflows during dry periods, especially when the stream is gaining (as was stated before).

Response: The text of the summary report has been amended to reflect the comments (page 52).

Question 27: Rather than compare model baseflows to average streamflows (an apples to oranges comparison) it may be better to separate the hydrographs and compare hydrograph-separated baseflows to model simulated baseflows. Also, under steady state conditions, the predicted baseflow will be a constant in time and is probably better depicted as a line rather than a point in Figure 30 of the report.

Response: It is agreed that the comparison between streamflow and baseflow is not appropriate. However, what we indicated in the report is that simulated baseflow will be closer to the measured baseflow that commonly lies along the bottom of a streamflow hydrograph. A more detailed analyses on baseflow separation from streamflow hydrograph though desirable is beyond the scope of our investigation.

Predicted baseflow information will be presented as a line as opposed to a point for the steady-state calibration in the TWDB report.

Question 28: The steady-state model appears to under-estimate the baseflows by more than one order of magnitude (Figure 30 of the report). Under-estimation of the baseflows would simply over-estimation of available water in the aquifer at least near the gaging stations (all other things being equal). As baseflows is under-estimated at both San Antonio River near Goliad and Guadalupe river in Victoria, it appears that the CGC-GAM-Steady-state model over-estimated the amount of water in the aquifer, at least locally in the six-county area of interest here.

Response: We do not agree that over-estimation of water in the aquifer is implied by lower baseflow. Rather the amount of water discharging at the streams is underestimated. (page 51).

Question 29: The stream-aquifer interactions appear to significantly control groundwater availability in the Steady-state model (Table 2 of the report). However, the report is unclear with regards to how many streams were included in the model, how they were modeled or what role these streams played in the calibration process. Additional information on streams would help assess the model better. It appears that there is a drain included in the model which needs to be explained further.

Response: The streams and the drains were discussed in the Waterstone (2003) report. .

Question 30: The x-axis should be labeled as fraction change from calibrated value rather than % change.

Response: The x-axis label for Figure 35 has been corrected as suggested (page 55).

Question 31: The authors calibrated the transient model 1980–1990 and state that they started the transient model calibration from the calibrated steady-state solution so that the initial head and parameter inputs were consistent. Does consistent mean exactly the same? How were differences in pumping between 1940 and 1980 reconciled? Additional clarification is appreciated.

Response: A stress period spanning over 40 years was assigned before the actual transient model run. This stress period included 1980 pumpage values and water levels from the pre-development model were assigned as initial heads. The assumption was that this run will simulate water-level conditions for the 1980's. This information has been appended to the summary report (page 56).

Question 32: The authors on page 49 of the report state that "When we changed the horizontal hydraulic conductivity and vertical leakance values, we had to maintain a balance such that we did not under- or over-estimate drawdowns in any particular area. The set of calibrated horizontal hydraulic conductivity and vertical leakance values that we developed for the transient model was then used to develop water levels and streams flows in the pre-development model". This statement is rather confusing. Does this mean that both Steady-state (pre -development) and transient models were developed in an iterative manner? If so, to what iteration do the results presented in the steady-state calibration section correspond to? Additional clarification in this regard is appreciated.

Response: We were unable to produce the drawdown cones in the transient model using distributed hydraulic conductivity values. We zoned the hydraulic conductivity values for the Evangeline aquifer, adjusted hydraulic conductivity values for the Jasper aquifer and adjusted vertical leakance for the Chicot aquifer. We applied this set of values to calibrate the steady-state model and used the calibrated heads as initial heads for the transient model (page 39).

Question 33: The authors state that they have been successful in minimizing the error in the central portion of the model domain (roughly corresponding to the area of concern of this review) to almost zero (page 54 and Figures 39 and 40 of the report). However, it is unclear as to how many data points were used in this comparison? The errors in the models appear to be proportional to the density of data considered at any location. Additional information on how many data points were used to make this assessment and QA/QC measures adopted to eliminate or minimize contouring artifacts would enhance the confidence in the calibrated model.

Response: The data points considered are shown in the water-level residuals maps (Figures 46-49). We included all available water-level measurements for a locality for the calibration period. Well control points were checked with respect to their assignment to model layers. The errors relate to differences between simulated and measured values at well points.

Question 34: There appears to be a significant repetition of well hydrographs in Figures 41–45 that needs to be corrected.

Response: We have corrected the well hydrographs in the summary report.

Question 35: A comparison of streamflows and model predicted baseflows for the transient case (1980–1999) is presented in Figure 46 of the report. The baseflow predictions are almost two orders of magnitude smaller than the average streamflows during the same period. As with the steady-state simulation, a comparison between model predicted baseflows and baseflows estimated via hydrograph separation would probably be more useful. Again, the model under-predicts baseflows at both the San Antonio river, near Goliad and Guadalupe river near Victoria, suggesting a local over-estimation of available water.

Response: Hydrograph separation is beyond the scope of this investigation. Underestimating baseflow does not necessarily imply that available water is overestimated. In fact it could imply the opposite because in order to increase base flow it may be necessary to increase recharge beyond reasonable values leading to an overestimation of available water in the aquifer. Aquifer-stream interaction occurs at a local scale that is not always reproducible in regional-scale models.

Question 36: The discrepancies between the measured and simulated gain/loss values presented in Table 3 of the report increase with increasing river reach and vary by a factor of 2 over an 8 mile stretch in Nueces River and over 150% in Lavaca River. Hence, the statement on page 55 that the net gain-loss values for Lavaca and Nueces rivers are similar to measured values is somewhat misleading.

Response: The simulated and measured values are in the same order of magnitude. This information is now correctly stated in the summary report (page 70).

Question 37: The transient water budgets Figure 47 and 48 (Figure 47 is mislabeled as Figure 1) and Tables 4 and 5 (Table 4 is mislabeled as Table 1) indicate that evapotranspiration was explicitly included in the model formulation. There is however no discussion on how this process was simulated and what role did this process play in model calibration additional discussion on these aspects would be beneficial.

Response: We have corrected the mislabeling. A discussion on evapo-transpiration as used in Waterstone (2003) report will be included in the TWDB report.

Question 38: A sensitivity analysis of calibration parameters of the Transient model would be useful.

Response: Sensitivity of the model to storage parameters is now included in the summary report.

Question 39: Hydraulic Effects of Partial Well Penetration in Confined Aquifers: The described hydraulic conductivity adjustment is deemed necessary by the authors to reflect partial penetration of a large percentage of wells. However, the zoning of horizontal hydraulic conductivity values over expansive sections of the Evangeline aquifer on the basis of supposed partial penetration effects is unwarranted, as described below, and defies the distribution of observed hydraulic conductivity measurements throughout the Evangeline aquifer in the model area, as documented by Waterstone (2003) in the first draft CGC-GAM report, or as characterized by other Gulf Coast models. Furthermore, in the field of groundwater modeling, it certainly is not standard practice to account for potential effects of partial penetration by hydraulic conductivity adjustments, but rather by subdividing a partially penetrated model layer in such a way as to allow a more representative characterization of actual conditions, for example as described by Anderson and Woessner (1992). In the hydraulic field testing of aquifers, it is commonly observed that there is a negligible difference in the time-drawdown response of partial vs. full penetration wells at a distance of r>1.5b(Kh/Kv)1/2 from a pumped well, or at time t>Sb/2Kv beyond a change in pumping condition, where b is the aquifer thickness, Kh and Kv are the horizontal and vertical hydraulic conductivity values, respectively, and S the storage coefficient (Domenico and Schwartz, 1990; Fetter, 1980). Using hydraulic parameter estimates representative of the Evangeline aquifer in the Central Gulf Coast region (Waterstone, 2003), and assuming an aquifer thickness of 200 to 1000 ft, partial penetration would therefore likely affect observed drawdowns at distances of no more that 2 to 9 miles away from a pumped well for a period of no more than 10 to 50 days following a change in pumping conditions. Moreover, there should be no effect of partial vs. full penetration on drawdowns under steady-state conditions.

Response. The calibrated model reasonably reproduces the water levels across the model area.

We agree that we used a non-conventional approach to address partial penetration issues. However, due to time- and budget-constraints we had to use the approach instead of further subdividing the layer as you suggested. A future model enhancement may well include subdividing the Evangeline aquifer.

The discussion that you presented on partial penetration assumes a homogeneous aquifer. We hypothesized that the Evangeline aquifer is not vertically homogeneous and therefore, will allow for larger effected distances and times.

Hydraulic Gradients vs. Groundwater Flow: Whereas the described hydraulic conductivity adjustment may have resulted in a reasonable match of predicted vs. observed water levels, and hence hydraulic gradients, the resultant effect on the relative amount of groundwater flow through each hydraulic conductivity zone is highly significant within the context of assessing groundwater availability for discrete portions of the model area. In effect, the zoning of K in order to calibrate gradients has correspondingly apportioned the potential flow within each conductivity zone, as is demonstrated by the simple flow equation $Q=-Kb\mathbf{i}$, where Q is the groundwater flow per unit cross-sectional width, K is the hydraulic conductivity, b is the transmissive thickness of the aquifer, and **i** is the gradient vector. As noted above, the zoned hydraulic conductivity values are not consistent with the distribution of observed hydraulic conductivity measurements throughout the Evangeline aquifer in the model area (Waterstone, 2003) or with values used in other Gulf Coast models. Therefore the relative predicted groundwater availability for any sub-areas of the model with differing K values would be nearly proportional to the K values, where other flow parameters, including gradient, are consistent.

This calibration parameter adjustment was effected in order to successfully match predicted and observed drawdowns at specific locations in the model area. However, significant concerns arise regarding the relative predicted flow of water through each hydraulic conductivity zone, and hence, potential ability of the model to reliably assess groundwater availability, based on water budgets, for various subparts within the model area.

Response: We believe that the model can be used to assess groundwater availability of the partially penetrated part of the Evangeline aquifer. The model cannot be used to assess groundwater availability in the lower part of the Evangeline aquifer.

Question 40: Introduction. The user must be able to trace the values presented back to the source of realistic measured information; basic geologic data such as e-logs, measured hydraulic conductivity and pump tests.

Response: Measured hydraulic conductivity maps derived from pump tests will be included in the TWDB report. Hydraulic conductivity and geological structure information is contained in the excerpts from Waterstone (2003) that will be posted along with the summary report.

Question 41: The Draft Central Gulf Coast GAM [TWDB version] suffers from making available only half of the model, the "recalibrated" TWDB version–without the original Waterstone model being available to the general public. The GAM is an apparent collaboration and extension of the Waterstone submittal of the Central Gulf Coast GAM that was briefly available for some purposes several months ago. However, Waterstone [2003] is extensively referenced in this draft and it is very difficult for those who don't have access to the Waterstone work that this TWDB effort "recalibrates", to constructively comment. Clearly, the "final" GAM should include enough information to make a second round of comments worthwhile.

Response: The draft Waterstone (2003) report was available during late 2002. The summary report will be posted along with excerpts from the Waterstone report (2003). We welcome any comments on the excerpts from Waterstone (2003) and the summary report prior to the publication of the TWDB report.

Question 42: Practical application. A GAM is only useful if it can reliably be used to predict the result of groundwater development proposals. If a model maps hydraulic conductivity or vertical leakance from the Chicot to the Evangeline, the measured real data should support that model map. Picture a typical GAM application: a groundwater developer submits an application to create a well field. The proposal presents real data, such as e-logs showing plentiful, thick, clean sands. Perhaps an initial test well provides measurements showing high hydraulic conductivity and minimal drawdown effect at the development boundary. The developer may acquire and run the GAM. Depending on the results of the run, the developer may use or discredit the model because there is no framework of real information. The TWDB GAM, at this stage, does not provide that information, but does state at several points that values were changed from the measured data to meet the model calibration model.

Response: All sources of data used in model calibration have been referred to in the Waterstone (2003) and the summary report. We have some other data that is available on request.

As noted in the report, the parameters that were adjusted are hydraulic conductivity of the Evangeline aquifer to address partial completion of many of the wells completed in it, vertical leakance of the Chicot aquifer, hydraulic conductivity of the Jasper aquifer, and storage parameters. In many cases during a calibration process, a parameter is changed from measured values within acceptable ranges reflecting the natural variations in the properties of that parameter. A parameter may need to be adjusted because limited availability of spatial data or scaling effects may prevent calibration of the model.

Question 43: General. This GAM chose to use "pumping" as the base information to be matched, or honored in the calibration. As a result, a number of measured hydrogeologic values had to be altered in order to match the measured pumping. These alterations are generally qualitatively described, but only occasionally mapped [e.g. fig. 24, 25, 26] so that the reader [decision maker] can't tell the extent of alteration. It would be useful to have a table listing the hydrogeologic variables, range of measured values, values used in calibrated model, and possible geologic reasons for the discrepancy. [This might be similar to an expanded Table 1 of the draft.] Values altered include horizontal conductivity, vertical leakance, baseflow, transmissivity, recharge, specific yield and others [some measured and some derived from field measurements]. It would be helpful if these altered values were mapped and presented along with the mapped measured values for comparison--for example, various Waterstone presentations included mapped measured transmissivity; this map could be presented on the same page as Fig. 25.

Response: The summary report will be posted with excerpts from Waterstone (2003) so that the reader can make any comparison that may appear necessary. Recharge and vertical leakance are parameters that are very difficult to measure in the field and typically they are estimated initially and then adjusted during calibration to match measured heads. Baseflow is a model output rather than a model input and was not adjusted during calibration.

Question 44: Groundwater characterization-limited by historical data [section 1.2].Water levels in the Chicot, Evangeline and Jasper are shown for listed dates ranging from 1910 to 1999. The distribution of data points demonstrates that the well information is limited, but this limitation is not discussed until the "conclusions" section and that discussion too is limited. It should also be noted here that several proposed groundwater projects are planned for areas with little historic well data. Also, the Jasper data is so limited that Jasper predictions seem unrealistic in any case [Jasper development in the Northern Gulf Coast GAM was also a problem.]. Shouldn't there be a frank statement that the model should not be used where there is little historical information?

Response: Where there is lack of historical information in a model area, we will not be able to know how good or poor the calibration is for that area until new information is collected. Where there is more data available, there is more certainty that the model is well calibrated. In the down-dip areas of the Jasper aquifer, very few calibration targets were available and the simulated water levels could not be compared to measured water levels. However, distribution of the potentiometric surfaces in the area suggest that simulated flow is conceptually correct.

Results from a regional model that uses numerous measured parameters and parameter adjustments based on good geological reasoning could still be useful and applicable in absence of better data for the area.

Question 45: Recharge-wide range, poorly known [section 1.3].Recharge is introduced with a list of factors affecting ultimate recharge to the aquifer; then various researchers' estimates are presented along with their reasoning; followed by a table of recharge values. The section would benefit from a straightforward discussion of how little is known about recharge, and how improved knowledge can be used in the future. The presented recharge values vary by an order of magnitude. Decision making based on this information is problematic.

Response:. We discussed the reasons for recharge variation in the summary report and have added this in a section on future improvements.

Question 46: Discharge-subdivide natural discharge and pumpage [section 1.4].Natural discharge from the Chicot and Evangeline, interformational and to the surface, is too important to mix with the primary baseline of the modeling effort, pumpage. The influence of concentrated current pumpage on the overall model is implied, but the discussion should be expanded to include changing pumpage expected over the time frame of the model calibration.

Response: Our standard protocol for this and other GAM are to discuss discharge in one section. Pumpage has been discussed under Discharge section.

Question 47: Streamflow is spread over the entire model area and is important to the balance in each bay system. GAM predictions should be expanded to describe the effect of pumpage on streamflow in addition to matching individual stream hydrographs.

Response:. We will make predictive GAM runs with this model and discuss any effect pumpage may have on baseflow in the GAM run report.

Question 48: Calibration-steady state [section 4.1].Horizontal hydraulic conductivity. In order to meet the steady state calibration goal, the TWDB model changed from a distributed Evangeline hydraulic conductivity to three zones [fig. 24] and the discussion notes that the transmissivity [fig. 25] that results from this change is lower than found in other Gulf Coast Aquifer models. These are important variables and the cited authors as well as the TWDB, in other cases, have carefully documented the derivations. While the Waterstone GAM and contract report are not available, their presentations to the Question Advisory Forums [SAF's] are, and a map of transmissivity in the Central Gulf Coast GAM is a common component. Mapped values of Evangeline conductivity are part of the TWDB Southern Gulf Coast GAM and the USGS Northern Gulf Coast GAM [and, actually, the values do go from lower in the south to higher in the north]. The final Central Gulf Coast GAM should provide maps and discussions of the measured values as well as the altered values of both conductivity and transmissivity [and other variables as well, for that matter]. Clearly, discussions of these values will be a major part of groundwater development decision making.

Response: Measured hydraulic conductivity information will be presented in the TWDB report as requested. Hydraulic conductivity assigned in the Evangeline aquifer might appear lower than what has been used in other Gulf Coast models. However, the "hydraulic conductivity" used in the calibration is not a conventional "hydraulic conductivity" but instead, it is a parameter that accounts for partial penetration of many of the wells in the Evangeline aquifer. If partial penetration effects are taken out, hydraulic conductivity used in the calibration may appear compatible with other Gulf Coast models.

Question 49: Vertical leakance from Chicot to Evangeline. This is an important factor for folks with shallow wells. They might ask how pumping in the Evangeline is going to affect their well, and when will it happen? The vertical leakance in the draft GAM has been lowered [from what? measured? Waterstone unknown?] The draft discussion notes that the values used in this model are similar to those adopted in the southern and northern models. The resulting "calibrated"[or "recalibrated"] leakance [fig. 26] shows little information in the middle part of the GAM where several development projects are proposed. The final GAM should discuss the reasons for the lower value and what the concept might mean to current water users.

Response: Vertical hydraulic conductivity is not a commonly measured parameter especially on a regional basis, and is generally estimated based on characteristics of the confining aquifer material and through model calibration. Calibrated values of vertical leakance for the entire model area in the Chicot aquifer including the middle part of the GAM is shown in Figure 26. The reference to lowered value is with respect to Waterstone (2003) report but since it is not publicly available, we compared the calibrated values with previous publications.

Question 50: Streamflow. Maintaining streamflow and baseflow is also important to current water users throughout the Central GAM area. The discussion states that the simulated baseflow values are "somewhat" lower than the measured baseflow. It appears that the value is an order of magnitude lower. How is this realistic?

Response: This is a limitation of the model and has been included under limitations of the model. This has also been included under future improvement section.

Question 51: Calibration-transient [section 5.1].Again, the values of the several variables were altered and generally lowered in order to fit the transient, or time varying, situation. The same comments apply: expand the discussion to include maps of actual measured values where appropriate and discuss the geologic meaning of adopting the lower values. For example, the model used lower values of specific yield for the Chicot, Evangeline and Jasper and justified this choice over published values by noting that these aquifers "contain numerous interbedded silt/clay lenses." This gives a geologic reason to the choice. The discussion might be expanded to describe the implications of such reduced specific yield.

Response: Measured values of storage parameters are posted with the summary report. The specific yields used in the recalibration effort were not lowered. The specific yields used for calibration are consistent with other Gulf Coast GAM models.

Question 52: "Teeter Totter" effect. The modelers made an understandable effort to keep an adjustment of variables in Wharton from overpowering the effect in Kingsville. This is reasonable for modeling, but could it be that the geology changes along the coast to such an extent that one model is not necessarily reasonable for the entire geologic area? And what effects do the alterations in the northern and southern sections create in the middle of the GAM area?

Response: A single model can be reasonable for the entire geologic area.

We used all available data present across the model area to calibrate the model. Water-level residual maps (Figure 32 and Figures 46 to 49) included in the summary report demonstrate how the calibrated water-levels compare to measured water-levels in the middle of the GAM area.

Question 53: Hydrographs. The simulated versus measured well hydrographs are a mystery since the symbols are the same and black and white printing doesn't differentiate [fig. 41-45].
The simulated versus stream hydrographs are again low by about 2 orders of magnitude (although the San Bernard comparison is erratic but often within the measured range).

Response: The comparison of simulated and measured hydrographs were differentiated using different colors. We will use separate symbols to represent the hydrographs in the TWDB report.

Please refer to response for question 50.

Question 54: Limitations [section 6]. An additional limitation is the lack of well data detail in the middle portion of the GAM area. But detail is not the reason for model-wide lowering of values for several variables. The hydraulic conductivity alteration discussion concerning partial penetration is interesting and the conclusion that the model may overpredict drawdown for a fully penetrating well [or wellfield] is what decision makers need to know. However this number then is no longer hydraulic conductivity and the use for the model is no longer valid. An alternative approach might be to modify historic pumpage to simulate fully penetrating wells or otherwise alter variables that do not have a direct measured counterpart.

Response: We disagree that the model is not valid because of our effort of addressing partial penetration. Although the values for hydraulic conductivity in the model accounts for partial penetration once transmissivity is calculated by the MODFLOW code, groundwater flow through the partially penetrated portion of the aquifer is reasonably represented.

In general, most modelers do not consider pumping as a calibration parameter. Pumping estimates for this area appear reasonable to us. Therefore, we disagree that the pumping should be modified.

Question 55: Underlying dataset. The GAM uses the work of the USGS [Strom, et al, 2003] dataset for the Gulf Coast. This work, in turn, uses the basic data developed from e-logs, drillers logs, samples, surface geology, historical hydrologic data, pump tests, and other measurements. Hopefully, the final report will incorporate maps and sections showing this information.

Response: Please refer to response for question 40.

Question 56: Conclusion. The TWDB draft Central Gulf Coast GAM, as written, is the second part of a two part effort; and the first part, Waterstone's draft GAM, is not available. The Waterstone work, regardless of calibration problems, apparently contains valuable information that should be made available in the final Central Gulf Coast GAM.

The final Central Gulf Coast GAM will include predictions based on future pumping scenarios. But this work will, in the context of the model's present form, incorporate modified hydraulic conductivities made necessary perhaps because historic wells have only partially penetrated the section. New wells involved with large water projects will likely fully penetrate the section. The final GAM should contain enough information to enable all the reader to critically evaluate predictions about future pumping.

Response: Please refer to response for question 40.
We also added explicit statements in the abstract and the conclusion section to explaining that the model should not be used to evaluate fully-penetrated well fields in the Evangeline aquifer.

References:

Noble, J. E., Bush P. W., Kasmarek, M. C. and Barbie, D. L., 1996, Estimated depth to the water table and estimated rate of recharge in outcrops of the Chicot and Evangeline aquifers near Houston, Texas: U.S. Geological Survey Water Resources Investigations Report 96-4018, 19 p.
Slade, R.M., Jr., Bentley, J. T., and Michaud, D., 2002, Results of streamflow gain-loss studies in Texas, with emphasis on gains from and losses to major and minor aquifers, Texas, 2000: U. S. Geological Survey Open-file Report 02-068, 131p.

Waterstone, 2003, Groundwater availability of the central Gulf Coast aquifer: Numerical simulations to 2050, Central Gulf Coast, Texas, Contract draft report submitted to Texas Water Development Board, Austin, Texas, variously paginated.